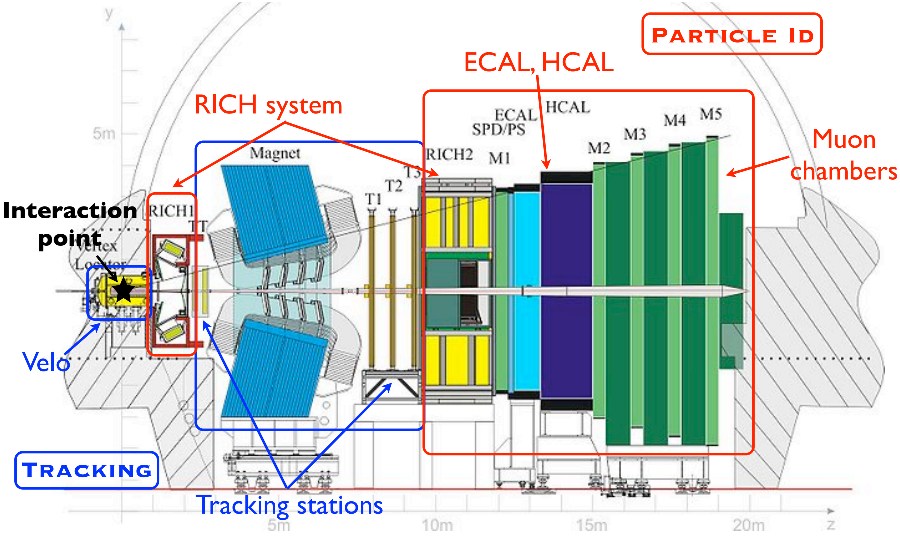
Rare decays of beauty mesons

Samuel Coquereau

on behalf of the LHCb collaboration

SUSY 2013 - August 26th, 2013

The LHCb experiment



1. $B^0_{(s)} \to \mu^+\mu^-$
   - Branching fraction measurement [arXiv:1307.5024]
2. $B^0_{(s)} \to e^\pm\mu^\mp$
   - Branching fraction measurement [arXiv:1307.4889]
3. $B^\pm \to K^\pm\mu^+\mu^-$
   - Observation of a resonance at low recoil: [arXiv:1307.7595]
   - CP asymmetry measurement: [arXiv:1308.1340]
4. $B^0 \to K^*\mu^+\mu^-$
   - New observables: [arXiv:1308.1707]
5. $B^+ \to K^+\pi^+\pi^-\gamma$
   - CP and Up-Down asymmetries [LHCb-CONF-2013-009]

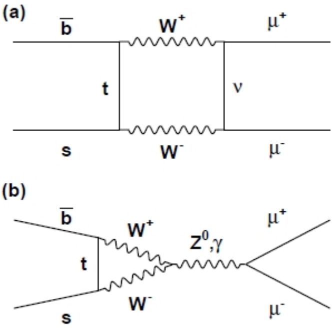
$B_s^0 \to \mu^+\mu^-$

Branching fractions well predicted in the SM:
[Eur. Phys. J. C72 (2012) 2172]

- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

A doubly suppressed decay : FCNC process and helicity suppressed

- Very interesting to test models with an extended Higgs sector

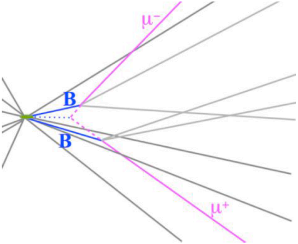


For the combined LHCb and CMS results, see Mitesh's talk

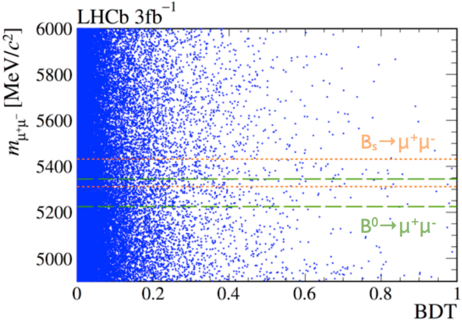
Analysis strategy

Strategy similar to the previous 2012 analysis. [Phys. Rev. Lett. 110 021801]

Blind analysis using the full 3fb^{-1} of data recorded in 2011 and 2012. [arXiv:1307.5024]

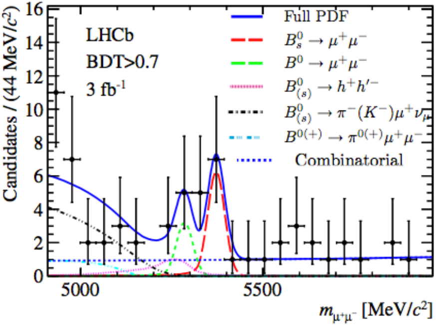


- MultiVariate Analysis (MVA):
  - Kinematic and geometrical variables
  - Train with MC calibrated in data
- Tracking and PID efficiencies and $m_{\mu\mu}$ resolution calibrated from data.
- Normalization using $B^+ \to J/\psi K^+$ and $B_d \to K^\pm \pi^\mp$
- Signal and background classification in BDT vs $m_{\mu\mu}$ plane



Branching fractions

Branching fraction measurement using a simultaneous unbinned likelihood fit to the invariant mass in 8 BDT bins.
The B_s, B^0 and the combinatorial yields are free.

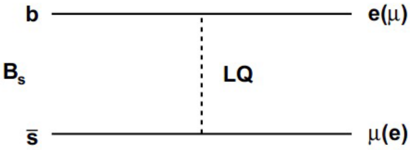


Results: [arXiv:1307.5024]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)\right) \times 10^{-9} : \text{Significance} = 4.0\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)\right) \times 10^{-10} : \text{Significance} = 2.0\sigma$$

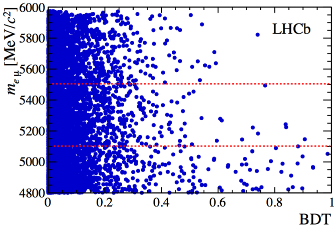
- Charged LFV forbidden in SM $\sim 10^{-54}$
- But allowed in some other models (SUSY, Leptoquarks ...)
- Previous limits from CDF experiment: [Phys. Rev. Lett. 102 (2009) 201901]

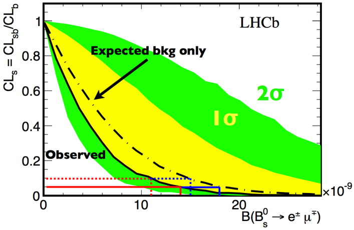


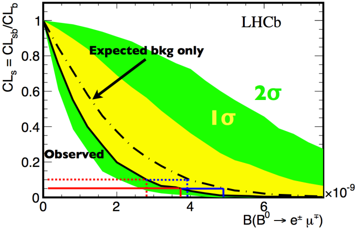
$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 2.0(2.6) \times 10^{-7}$ at 90(95)% CL
$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 6.4(7.9) \times 10^{-8}$ at 90(95)% CL

Using similar analysis strategy as $B_{(s)} \to \mu^+\mu^-$:

- Analysis using $1fb^{-1}$ of data recorded in 2011
- Sign and bkg classification in BDT vs $m_{e\mu}$ plane
- Normalized to $B_d \to K\pi$ yield in data







	$\mathcal{B}(B^0_s \to e^\pm\mu^\mp)$ at 90(95)% CL	$\mathcal{B}(B^0 \to e^\pm\mu^\mp)$ at 90(95)% CL
Expected (LHCb 1fb^{-1})	$1.5\ (1.8) \times 10^{-8}$	$3.8\ (4.8) \times 10^{-9}$
Observed (LHCb 1fb^{-1})	$1.1\ (1.4) \times 10^{-8}$	$2.8\ (3.7) \times 10^{-9}$
Current (CDF 2fb^{-1})	$20.0\ (20.6) \times 10^{-8}$	$64.0\ (79.0) \times 10^{-9}$

Lower bounds on the Pati-Salam Leptoquark [Phys. Rev. D 10 (1974) 275]:

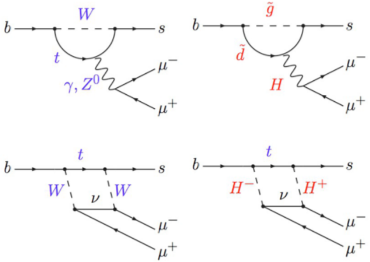
$m_{LQ}(B^0_s \to e^\pm\mu^\mp) > 107\ (101)\ \text{TeV}/c^2$ at 90(95)% CL

$m_{LQ}(B^0 \to e^\pm\mu^\mp) > 135\ (126)\ \text{TeV}/c^2$ at 90(95)% CL

b→ s$\mu\mu$ decays

NP can modify the SM amplitudes in the FCNC processes like the rare decays $b \to s l^+ l^-$

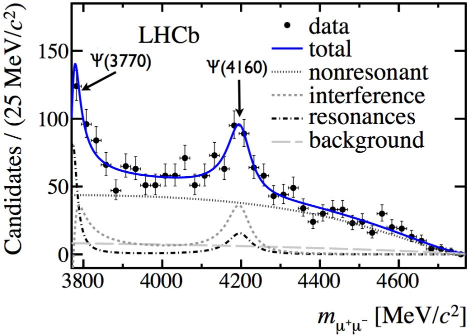
- Theoretically well predicted
- Experimentally clean
- Three or four particle in the final states provide many angular observables, rates and asymmetries sensitive to NP



The $B^\pm \to K^\pm \mu^+\mu^-$ and $B^0 \to K^*\mu^+\mu^-$ have a similar analysis strategy:

- Pre-Selection of the events (a loose cut-based selection)
- BDT against combinatorial backgrounds
- Special vetoes to remove peaking backgrounds (ex: $B_s^0 \to \phi\mu\mu$)

- full dataset, $3 fb^{-1}$ collected in 2011 and 2012
- LHCb is able to see the structure coming from the charmonium states above the DD threshold.



Results: [arXiv:1307.7595]

The structure is identified as the $\psi(4160)$ see by the BES experiment.

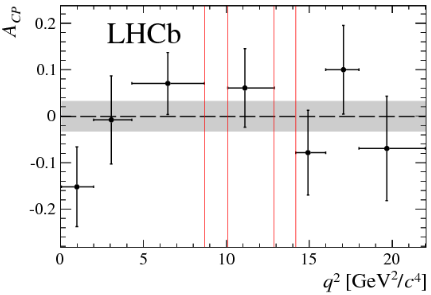
	Unconstrained	$\psi(4160)$
$\mathcal{B}[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$	$3.5\,^{+0.9}_{-0.8}$
Mass [MeV/c^2]	$4191\,^{+9}_{-8}$	4190 ± 5
Width [MeV/c^2]	$65\,^{+22}_{-16}$	66 ± 12
Phase [rad]	-1.7 ± 0.3	-1.8 ± 0.3

$> 6\sigma$ significance, good agreement with BES experiment

CP asymmetry in $B^\pm \to K^\pm \mu^+ \mu^-$

$$\mathcal{A}_{CP}(B^\pm \to K^\pm \mu^+ \mu^-) = \mathcal{A}_{RAW}(B^\pm \to K^\pm \mu^+ \mu^-) - \mathcal{A}_{RAW}(B^\pm \to J/\psi K^\pm)$$

- Analysis using only the $1 fb^{-1}$ recorded in 2011
- Using the $B^\pm \to J/\psi\ K^\pm$ decay to correct the production and detection asymmetry
- Averaging measurement with different magnet polarities to remove the left-right detector asymmetry



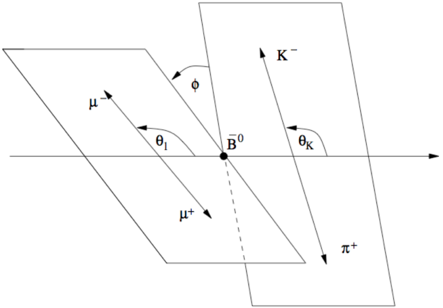
Results: [arXiv:1308.1340]

$\mathcal{A}_{CP}(B^\pm \to K^\pm \mu^+ \mu^-) = 0.000 \pm 0.033(\text{stat.}) \pm 0.005(\text{syst.}) \pm 0.007(J/\psi\ K^+)$

In agreement with the SM and the $B^0 \to K^{*0} \mu\mu$ decay mode

$B^0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$

- The decay rate of the four body final state after combining B and $\bar{\mathrm{B}}$ decays is described by the equation below
- The observables $\mathrm{F_L}$ and S_i are function of Wilson coefficients and form factors.



$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi}=\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K+F_{\mathrm{L}}\cos^2\theta_K+\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell+S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_\ell+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi+S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Some authors have proposed observables with limited dependence in form-factor uncertainty:

Kruger-Matias (2005), Matias et al. (2012), Egede-Matias-Hurth-Ramon-Reece (2008), Bobeth-Hiller-Van Dyk (2010-2011), Beciveric-Schneider (2012)

$$A_{\mathrm{T}}^{(2)} = \frac{2S_3}{(1-F_{\mathrm{L}})} \qquad A_{\mathrm{T}}^{Re} = \frac{S_6}{(1-F_{\mathrm{L}})}$$

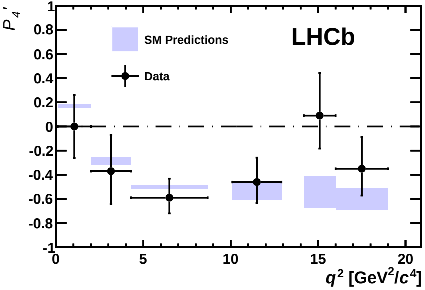
$$P_4' = \frac{S_4}{\sqrt{(1-F_{\mathrm{L}})F_{\mathrm{L}}}} \qquad P_5' = \frac{S_5}{\sqrt{(1-F_{\mathrm{L}})F_{\mathrm{L}}}}$$

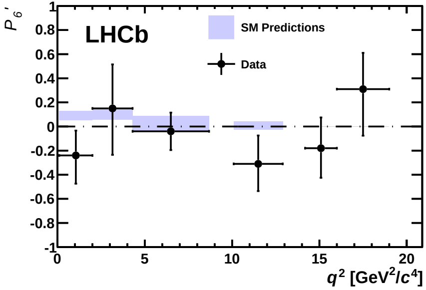
$$P_6' = \frac{S_7}{\sqrt{(1-F_{\mathrm{L}})F_{\mathrm{L}}}} \qquad P_8' = \frac{S_8}{\sqrt{(1-F_{\mathrm{L}})F_{\mathrm{L}}}}$$

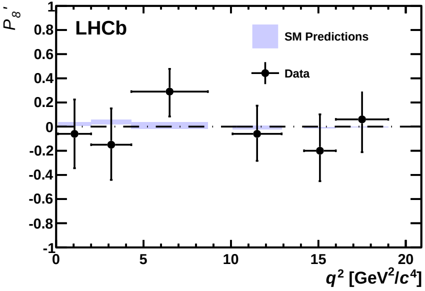
Use the following folding :$\phi \to -\phi$ (if $\phi < 0$) and $\theta_l \to \pi - \theta_l$ (if $\theta_l < \pi/2$), to measure of the P_5' observables.

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

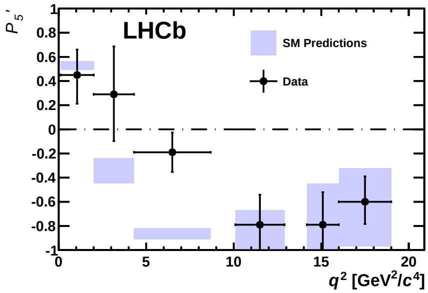
the other transformations for $\mathrm{P}_{4,6,8}'$ are similar.







Analysis using the 1fb^{-1} recorded in 2011, [arXiv: 1308.1707]
Results in good agreement with the SM predictions



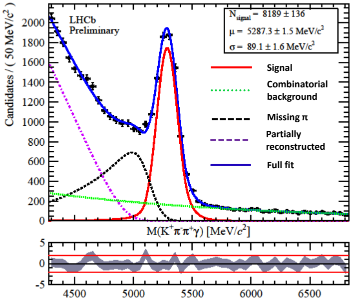
- 3.7 σ local discrepancy in the region $4.3 < q^2 < 8.68$ GeV$^2/c^4$
- 0.5% (2.8 σ)probability to observe such a deviation considering the 24 independent measurements

Some theoretician (Descotes-Genon et *al.* [arXiv:1307.5683], Altmannshofer, Straub [arXiv:1308.1501]) have suggested that the observed discrepancy in the observable P'_5 could be caused by a smaller value of the Wilson coefficient C_9 w.r.t SM.
See saturday Mitesh's talk

Analysis using the $2fb^{-1}$ data recorded in 2012: [LHCb-CONF-2013-009]

- CP asymmetry results:

$\mathcal{A}_{CP} = -0.007 \pm 0.015(\text{stat.}) \pm 0.008(\text{syst.})$
First CP asymmetry measurement in $B^+ \to K^+\pi^+\pi^-\gamma$



- Up-Down asymmetry results:

$$\mathcal{A}_{ud} = \frac{\int_0^1 d\cos\tilde{\theta} \frac{d\Gamma}{d\cos\tilde{\theta}} - \int_{-1}^0 d\cos\tilde{\theta} \frac{d\Gamma}{d\cos\tilde{\theta}}}{\int_{-1}^1 d\cos\tilde{\theta} \frac{d\Gamma}{d\cos\tilde{\theta}}} = \frac{3}{4}\lambda_\gamma \frac{\int ds\, ds_{13}\, ds_{23} \text{Im}\left[\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)\right]}{\int ds\, ds_{13}\, ds_{23} |\mathcal{J}|^2}$$

$\mathcal{A}_{ud} = -0.085 \pm 0.019(\text{stat.}) \pm 0.003(\text{syst.})$
First evidence of photon polarization in $b \to s\gamma$ decay
Significance of 4.6σ

Conclusion

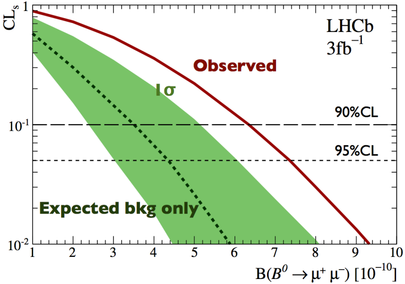
- Rare decay are powerful probe to look for NP
- LHCb it's a powerful tool in the search of rare electroweak decay
- Confirmed evidence of $B_s \to \mu^+\mu^-$ with a 4 σ significance
- New world's best limit on $B^0_{(s)} \to e^\pm\mu^\mp$ branching fraction
- Observation of the $\psi(4160)$ production at high q^2 in $B^+ \to K^+\mu^+\mu^-$ decay
- CP asymmetry of $B^+ \to K^+\mu^+\mu^-$ in agreement with SM
- Observation of a local discrepancy in the low q^2 region in the observable P_5' in the decay $B^0 \to K^{*0}\mu^+\mu^-$
- CP and Up-Down asymmetries in the $B^+ \to K^+\pi^+\pi^-\gamma$

We are now looking at the full dataset sample, stay tuned for the $3fb^{-1}$ analyses

BACKUP

$B^0 \to \mu^+\mu^-$ upper limit

Limit at	90% CL	95%CL
Exp. bkg+SM	4.5×10^{-10}	5.4×10^{-10}
Exp. bkg	3.5×10^{-10}	4.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}



No significant evidence of signal over background

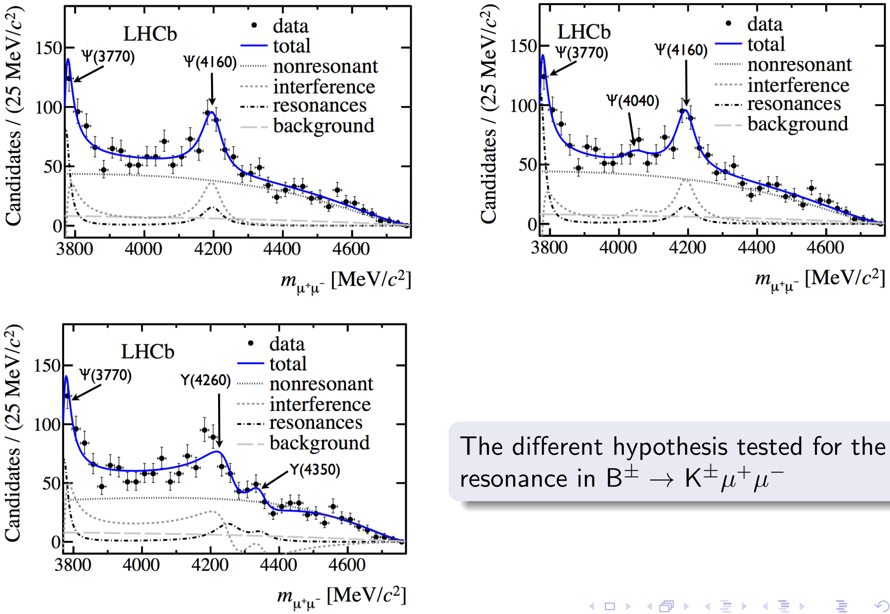
The Pati-Salam Model is a unified model describing a quark-lepton unification.
In this model, the lepton number is identified as a fourth "color".
The Pati-Salam bosons are called "Leptoquarks" since they mediate transition between leptons and quarks.

Search for leptoquarks are also done at ATLAS and CMS:

Limit at 95%CL	ATLAS	CMS
1st generation scalar leptoquarks	$m_{LQ} > 660$ GeV	$m_{LQ} > 830$ GeV
2nd generation scalar leptoquarks	$m_{LQ} > 685$ GeV	$m_{LQ} > 840$ GeV
3rd generation scalar leptoquarks	$m_{LQ} > 534$ GeV	$m_{LQ} > 525$ GeV

ATLAS results: [arXiv: 1112.4828], [arXiv: 1203.3172], [arXiv: 1303.0526]
CMS results: [arXiv: 1207.5406], [arXiv: 1210.5627], [arXiv: 1210.5629]

Resonance in $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ at low recoil



The different hypothesis tested for the resonance in $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$

The folding for P'_4 (S_4) is defined as :
$\phi \to -\phi$ (for $\phi < 0$),
$\phi \to \pi - \phi$ (for $\theta_l > \pi/2$),
$\theta_l \to \pi - \theta_l$ (for $\theta_l > \pi/2$)

and gives:

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{8\pi}\left[\frac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \frac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_{\rm L})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$\left. + \sqrt{F_{\rm L}(1-F_{\rm L})}P'_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi\ \right]$$

Folding for P'_6

The folding for P'_6 (S_7) is defined as :
$\phi \to \pi - \phi$ (for $\phi > \pi/2$),
$\phi \to -\pi - \phi$ (for $\phi < -\pi/2$),
$\theta_l \to \pi - \theta_l$ (for $\theta_l > \pi/2$)

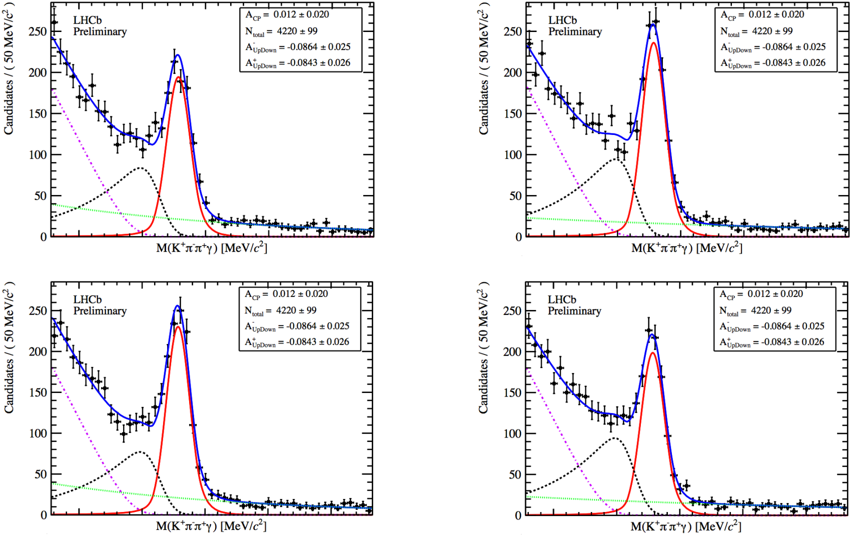
and gives:

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{8\pi}\left[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$\left. + \sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P'_6\sin 2\theta_K\sin\theta_\ell\sin\phi \ \right]$$

The folding for P'_8 (S_8) is defined as :
$\phi \to \pi - \phi$ (for $\phi > \pi/2$),
$\phi \to -\pi - \phi$ (for $\phi < -\pi/2$),
$\theta_l \to \pi - \theta_l$ (for $\theta_l > \pi/2$),
$\theta_K \to \pi - \theta_K$ (for $\theta_l > \pi/2$)

and gives:

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P'_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi\ \Big]$$



Invariant $K\pi\pi\gamma$ mass for B^+ (left) and B^-(right) candidates and Up (top) and Down (bottom) subsamples