Rare Decays at LHCb

WIN 2013 (Natal)

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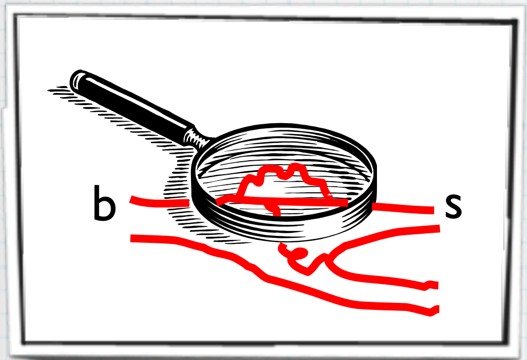
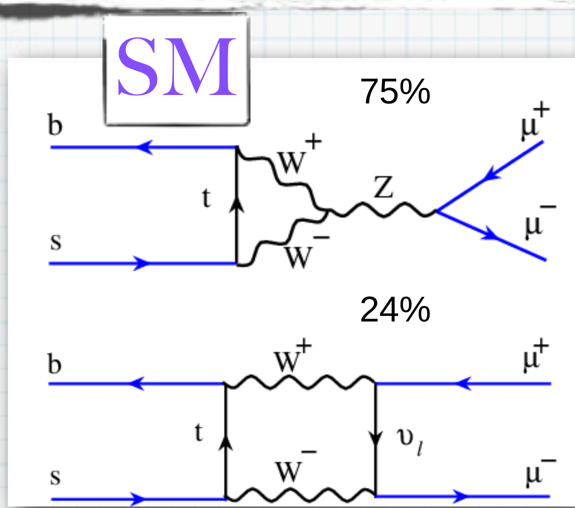
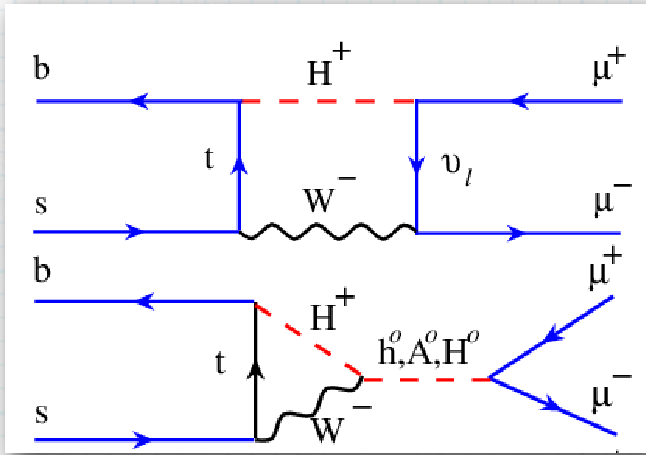
Introduction

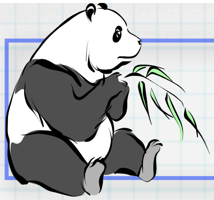
LHCb searches for NP in FCNC with B (and D) decays, new particles can enter in the loops and modify the SM prediction on some observables!







- Some **FCNC** processes have **precise SM prediction**
  - *Branching fractions* and *angular dependence*
- **Luck of NP**
  - *constrains models beyond SM*, set higher energy scale for NP
  - In a model independent interpretation, *constrains Wilson coefficients*

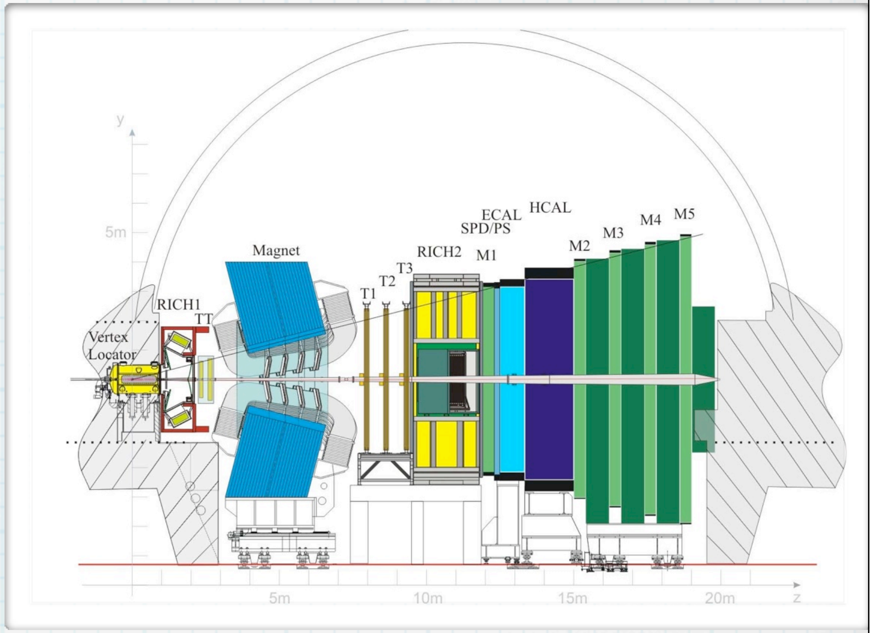


Rare Decays Analysis

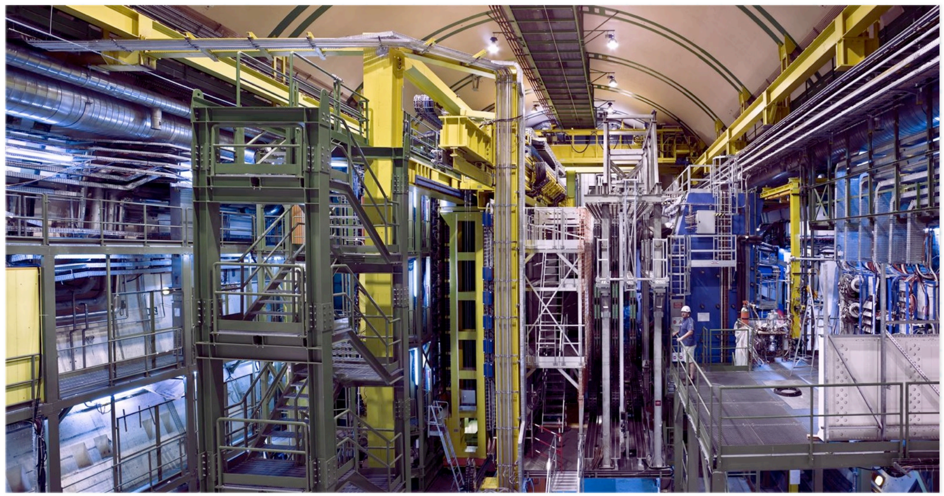
- Very rare decays
  - **$B_{(s)}\to\mu\mu$** [$3fb^{-1}$/arXiv:1307.5024]
  - **$D\to\mu\mu$** [$0.9fb^{-1}$/arXiv:1305.5050]
  - $K_S\to\mu\mu$ [$1fb^{-1}$/arXiv:1209.4029]
  - $B\to4\mu$ [$1fb^{-1}$/arXiv:1303.1092]
  - $B^+\to\pi^+\mu\mu$ [$1fb^{-1}$/arXiv:1210.2645]
- Angular an isospin analysis
  - **$B\to K^*\mu\mu$** [$1fb^{-1}$/arXiv:1308.1707] [$1fb^{-1}$/arXiv:1304.6325]
  - $\Lambda_b\to\Lambda\mu\mu$ [$1fb^{-1}$/arXiv:1306.2577]
  - $B_s\to\phi\mu\mu$ [$1fb^{-1}$/arXiv:1305.2168]
  - **$B\to K^{(*)}\mu\mu$** [$1fb^{-1}$/arXiv:1205.3422]
    - $\psi(4160)$ [$3fb^{-1}$/arXiv:1307.7595]
- CP Asymmetries
  - $B\to K^*\mu\mu$ [$1fb^{-1}$/arXiv:1210.4492]
  - $B^+\to K^+\mu\mu$ [$1fb^{-1}$/arXiv:1308.1340]
- No SM processes
  - $B^+\to X\mu^-\mu^-$ [$0.41fb^{-1}$/arXiv:1201.5600]
  - **$B_{(s)}\to\mu e$** [$1fb^{-1}$/arXiv:1307.4889]
  - $\tau\to3\mu$, $\tau\to p\mu\mu$ [$1fb^{-1}$/arXiv:1304.4518]
- Radiative decays
  - $B\to K^*\gamma$, $B_s\to\phi\gamma$ [$1fb^{-1}$/arXiv:1202.6267]

LHCb detector

- LHCb detector
  - single-arm spectrometer ($2<\eta<5$)
  - B, B_s, B^+,D,Λ_b, ... produced at LHCb
  - trigger on muons, electrons, hadrons with "low" P_T
    - efficiency on dimuon channels ~90%
  - precise vertex (IP ~20 μm at high P_T)
  - excellent momentum resolution $\Delta p/p \simeq 0.5$ %
  - good particle ID (>97% μ-eff, 1-3% mis-ID)



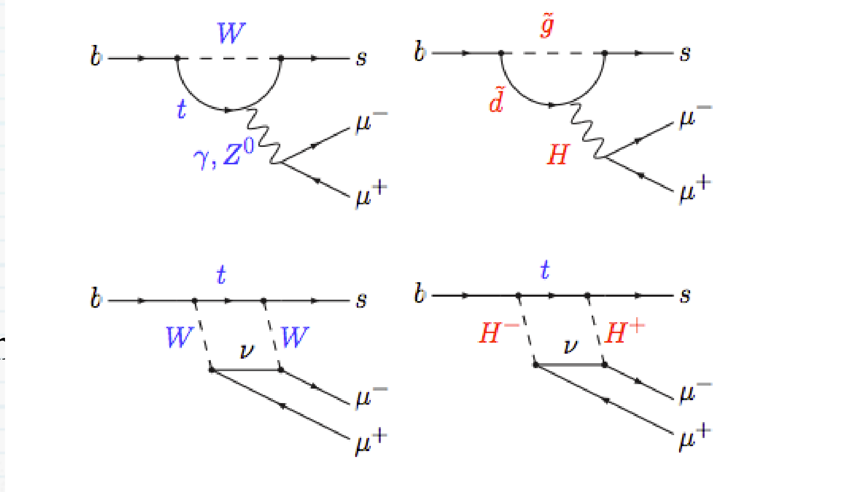
- LHCb operation
  - "beautifully"
  - operating @ 2 nominal luminosity
  - Integrated luminosity **3 fb^{-1}**
    - (2 fb^{-1} 8 TeV, 1 fb^{-1} 7 TeV)



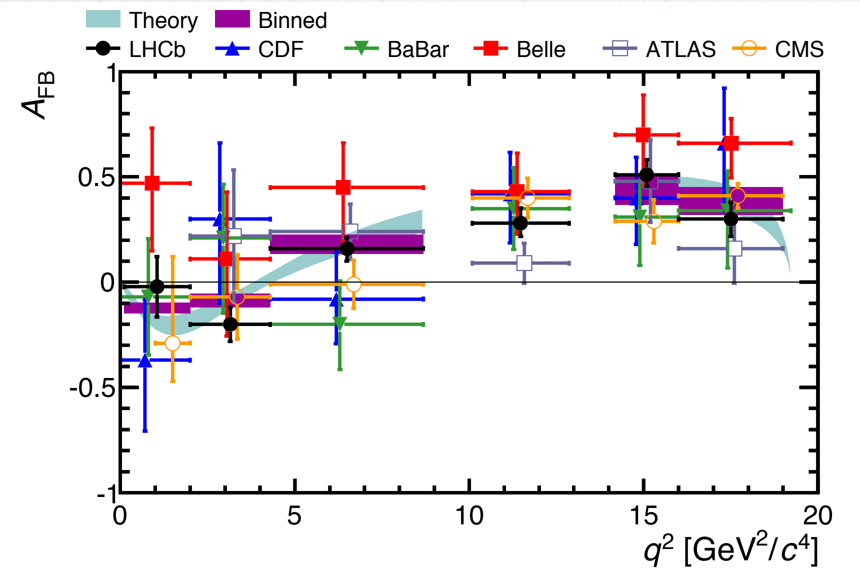
Angular analysis $B \to K^* \mu\mu$

[$1 fb^{-1}$/arXiv:1304.6325]
[JHEP 08 (2013) 131]

- In the SM, the γ/Z penguin introduces a forward/backward asymmetry (A_{FB}) of the muons
- SM prediction of the zero-crossing point of A_{FB}
  - SM $q^2_0 = (4.-4.3)\ GeV^2/c^2$
- This Asymmetry and other observables (F_L, S_3) can be altered by the presence of NP
  - W. Coefficients involved: C_7, C_9, C_{10}
- LHCb measurement clarified the situation after BaBar, Belle, CDF results!



See: F. Kruger, J. Matias PR D71(2005);
J.Matias et al, JHEP, 1204:104,2012



$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$

$$q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4 \quad .$$

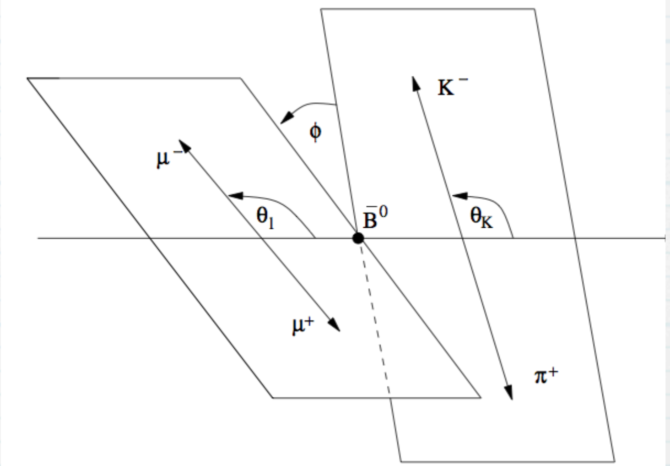
Good agreement with SM!

Angular analysis B→K*μμ

[1fb⁻¹/arXiv:1304.6325]

- The decay is described by 3 angles ($\theta_l, \theta_K, \varphi$) and the q^2 dimuon mass squared
  - Reduced expression of the angular distribution after φ folding:

$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}\, dq^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$

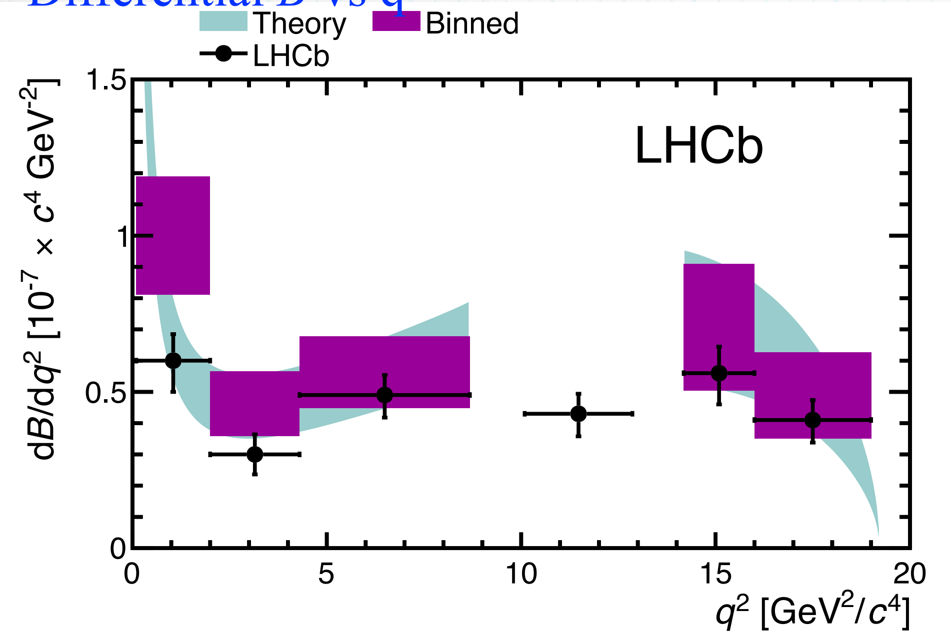


- Analysis:
  - BDT to suppress combinatorial bkg
  - Veto dimuon resonances J/ψ, ψ(2S)
  - Remove peaking background due to swap or misid, B→J/ψK*, $B_s \to \phi$(KK)μμ
  - Acceptance function from simulation but cross-checked with B→J/ψK*
  - ~900 candidates
  - 3D fit in the angles (in bis q^2)
  - F_L, the longitudinal polarization of K*
  - A_{FB}, the forward/backwark dimuon asymmetry

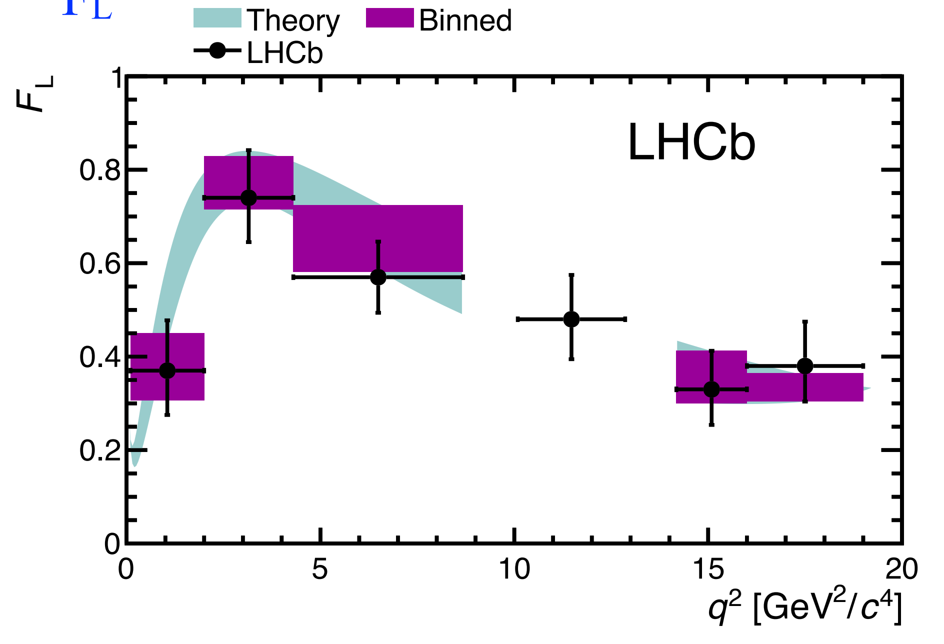
Angular analysis $B \to K^*\mu\mu$

[$1 fb^{-1}$/arXiv:1304.6325]

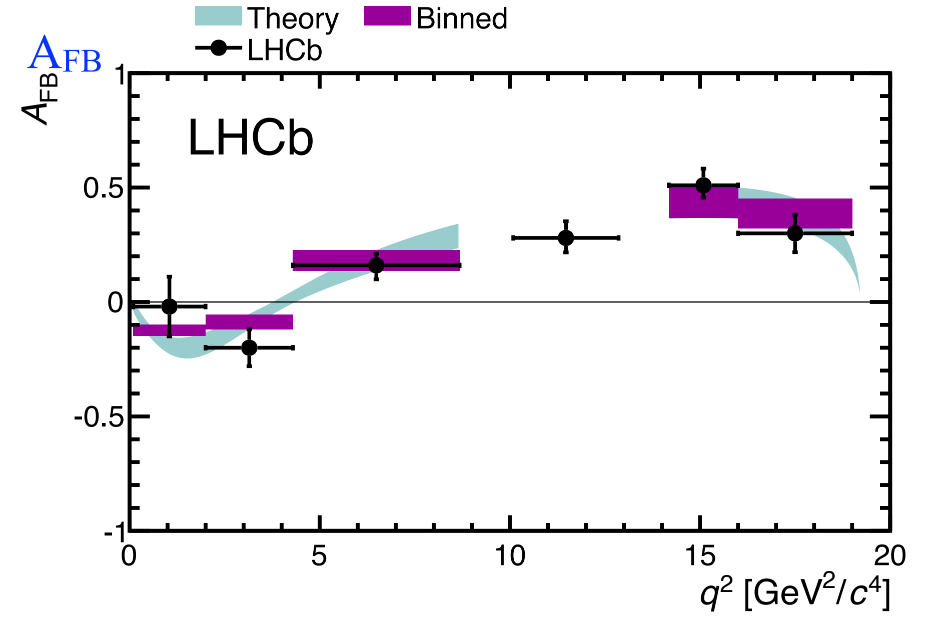
Differential B vs q^2



F_L



A_{FB}



In agreement with SM!

$$A_{FB} = -0.18^{+0.06+0.01}_{-0.06-0.02} \quad (1 < q^2 < 6 GeV^2) \text{ LHCb}$$

Angular analysis B→K*μμ

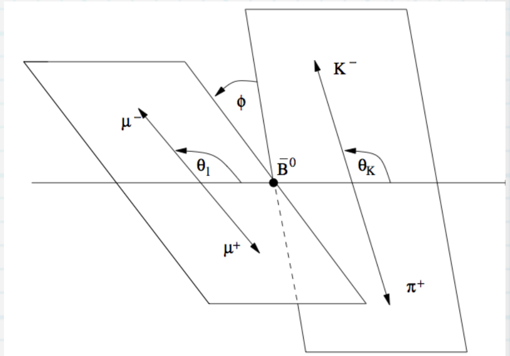
[1fb^{-1}/arXiv:1308.1707]

- Angular analysis with **new observables**:

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}$$

  - S_i are functions of Wilson coefficients and form-factors
  - P'_i observables reduce hadron form-factors uncertainties, are **complementary**! [arXiv:1207.2753]
  - using SM predictions [Descontes-Genon et al. JHEP 05 (2013) 137]

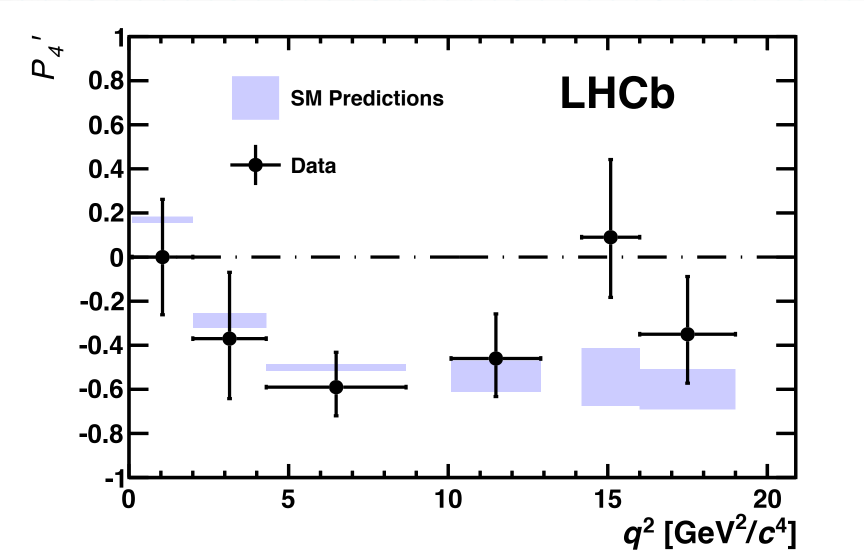
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_{\rm L}\cos^2\theta_K - F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+\tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$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

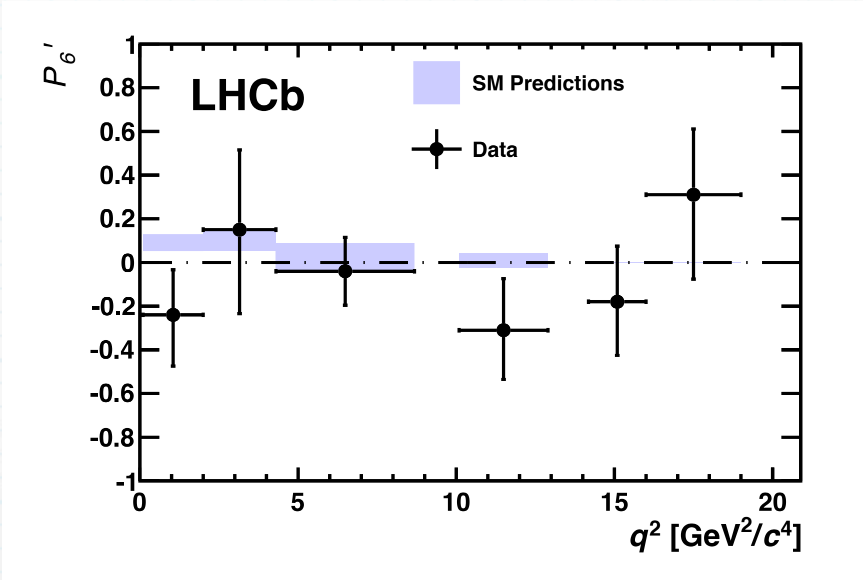


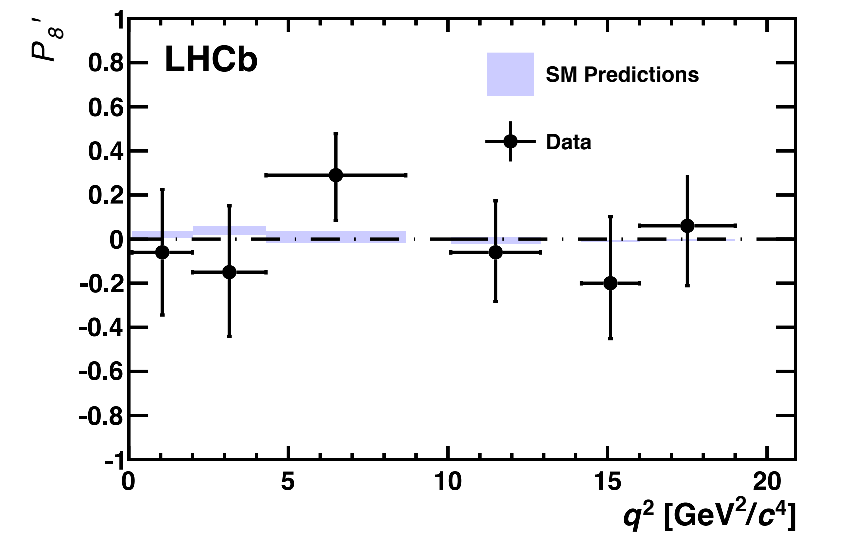
- Analysis:
  - BDT to suppress combinatorial bkg
  - Veto in dimuon resonances J/ψ, ψ(2S)
  - Veto peaking background due to swap or mis-id: B→J/ψK*, B_s→ϕ(KK)μμ
  - Acceptance function from simulation, but cross-checked with B→J/ψK*
  - mass from control channel and bkg distributions from upper side bands
  - Fit to the mass and angular distributions after unfolding ϕ
  - main systematic: background distributions, acceptance function and S-wave contributions

new angular analysis B→K*μμ

[$1fb^{-1}$/arXiv:1308.1707]



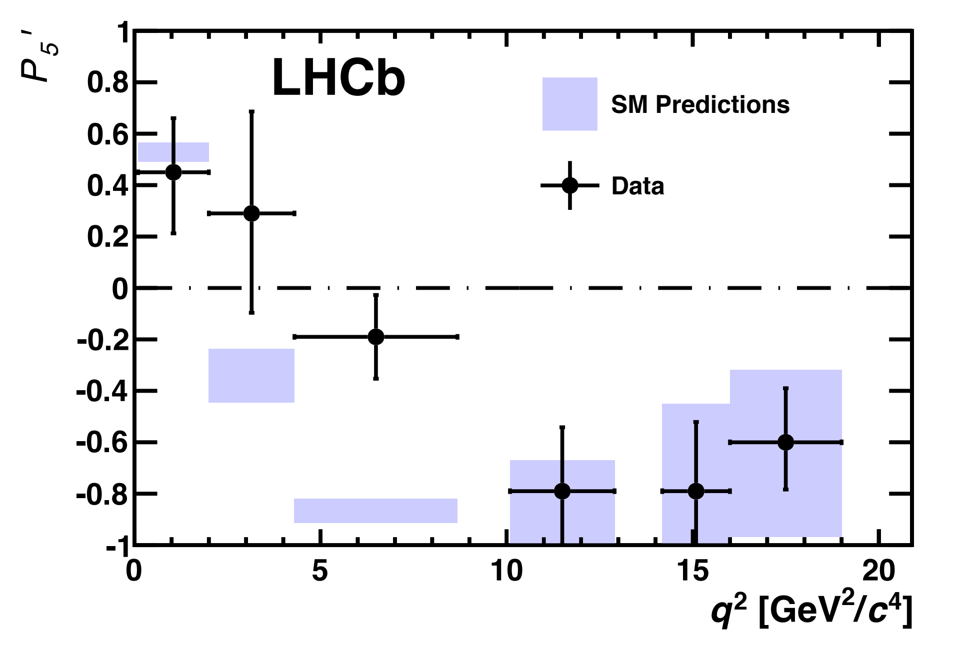




In agreement with SM!

new angular analysis B→K*μμ

[1fb^{-1}/arXiv:1308.1340]



all bins (24) in q² agreement with SM except 1 (at 3.7 σ)!

- if all bins independent, the probability of have such deviation or greater is 0.5%
- it will imply a smaller value of C_9,C_7 with respect SM [arXiv:1308.101, arXiv:1307.5683]
- further theoretical and more data studies are needed to clarify the picture

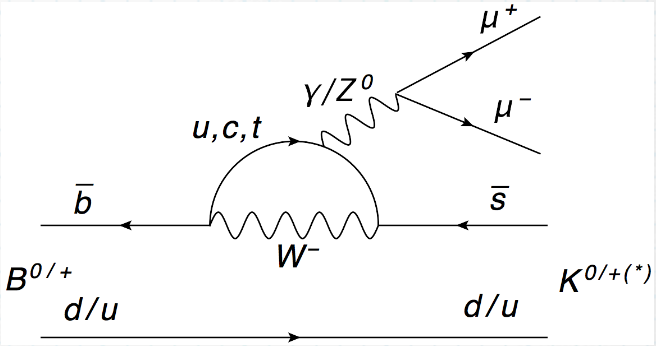
Isospin Analysis $B \to K^{(*)}\mu\mu$

[$1fb^{-1}$/arXiv:1205.3422]
[JHEP 07 (2012) 133]

- Isospin asymmetry:

See: T.Feldmann and J.Matias, JHEP, 01 (2002) 074

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$
$$= \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)},$$



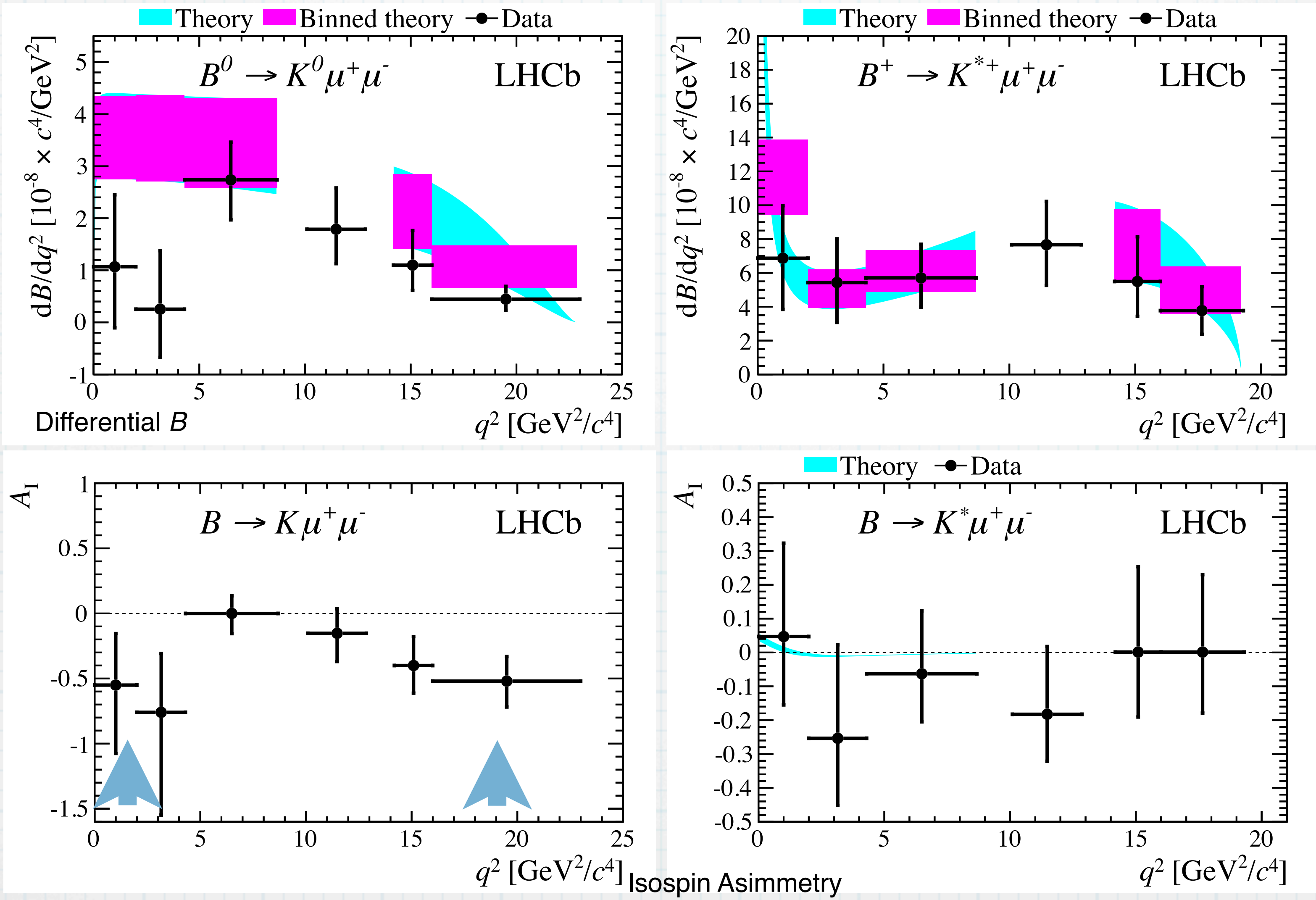
- SM prediction is close to zero

- Measured by BaBar, Belle and CDF. Babar measurement of B with some tension (3.9σ)!

- SM $\mathcal{B}$ predictions suffer from hadron form factors uncertainties
- Measured Differential $\mathcal{B}$:
  - $B^+ \to K^{*+}(K_S\pi^+)\mu\mu$, $B \to K^*\mu\mu$,
  - $B \to K\mu\mu$, $B^+ \to K^+\mu\mu$
- Use as normalization channel $B \to J/\psi(\mu\mu)K^*$; $B^+ \to J/\psi(\mu\mu)K^+$

Isospin Analysis B→K(*)μμ

[1fb-1/arXiv:1205.3422]



Deviation from 0 at 4.4 σ!
Tension!
but difficult to interpret!

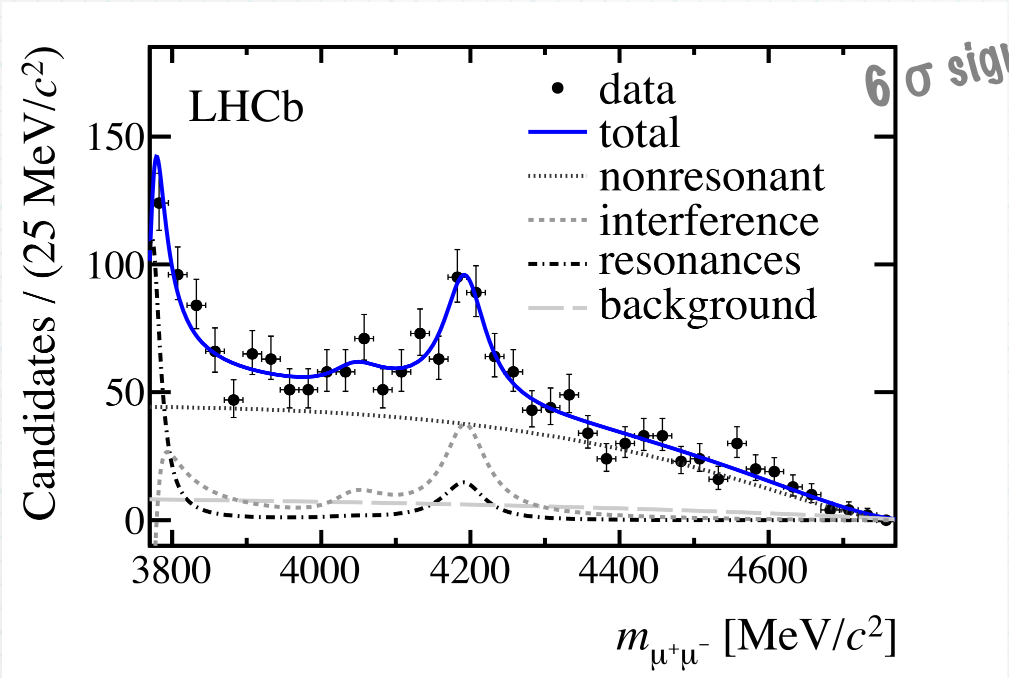
In agreement with SM and with previous measurements!

A new resonance in $B^+ \to K^+ \mu\mu$

[$3fb^{-1}$/arXiv:1307.7595]
[PRL 111 (2013) 112003]

ψ(3370) ψ(4160)

6 σ significance!



$\mathcal{B}[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$
Mass $[\mathrm{MeV}/c^2]$	$4191\,^{+9}_{-8}$
Width $[\mathrm{MeV}/c^2]$	$65\,^{+22}_{-16}$

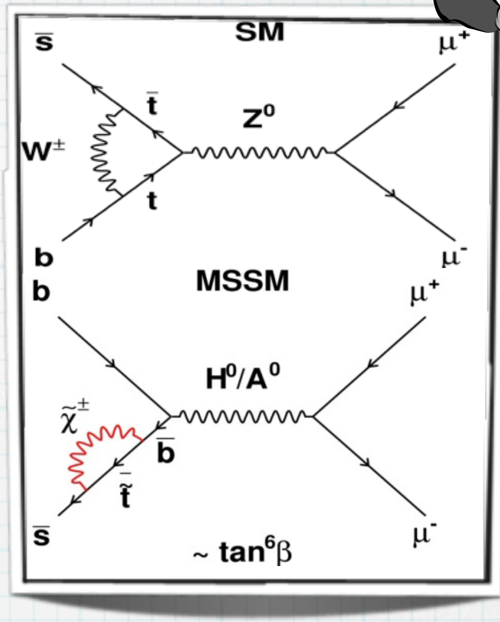
- A resonance structure at high q^2
- Consistent with ψ(4160) measured by BES
- Contribute to 20% of the total signal at high q^2
    - much larger than theoretical estimations

Update of $B_{(s)} \to \mu\mu$ with $3fb^{-1}$

[$3fb^{-1}$/arXiv:1307.5024]
[PRL 08 (2013) 117]

- SM prediction (FCNC, helicity suppressed)
  - SM $B(B_s \to \mu\mu) = (3.56 \pm 0.30)\ 10^{-9}$
  - SM $B(B \to \mu\mu) = (1.07 \pm 0.10)\ 10^{-10}$
- Branching Ratio very sensitive to NP

arXiv:1208.0934
arXiv:1303.3820



- Analysis:
  - BTD to suppress combinatorial bkg ($bb \to X\mu\mu$)
  - Use PID to reduce peaking background and study of specific peaking backgrounds
  - Discrimination in 2D space:
    - BDT (kinematical & geometrical variables) & mass
  - Normalize to $B^+ \to J/\psi K^+$
  - Use CLs method to set a limit and a unbinned maximum likelihood fit to obtain ***B***

Update of $B_{(s)} \to \mu\mu$ with $3fb^{-1}$

[$3fb^{-1}$/arXiv:1307.5024]

- **A multivariate discriminant BDT:**

  kinematical and geometrical variables

  signal uniformly distributed [0,1]

  trained with MC

  estimated with data:

  signal $B \to hh$ trigger unbias

  background: $B_s \to \mu\mu$ sidebands

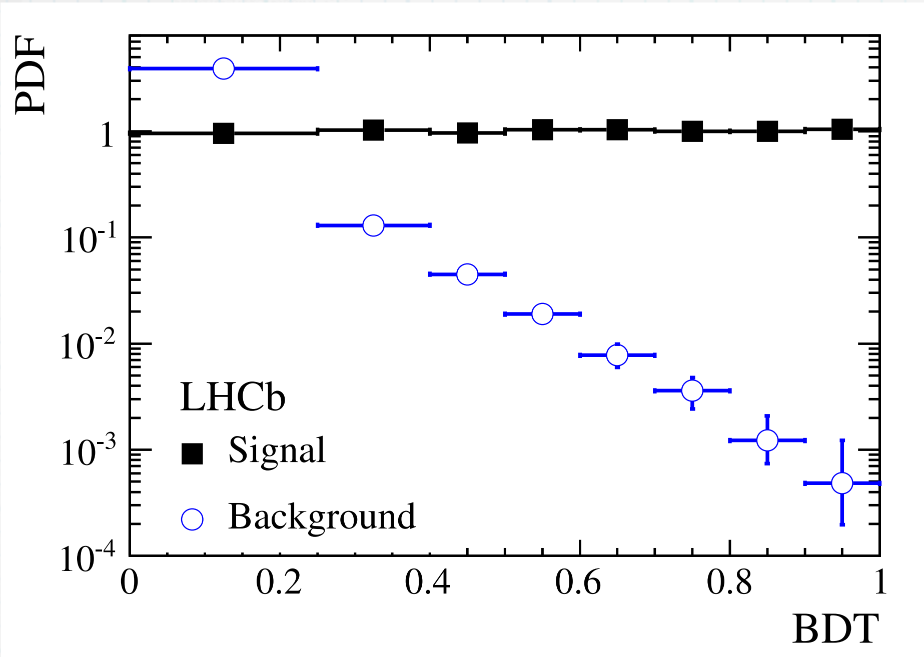
- **Mass:**

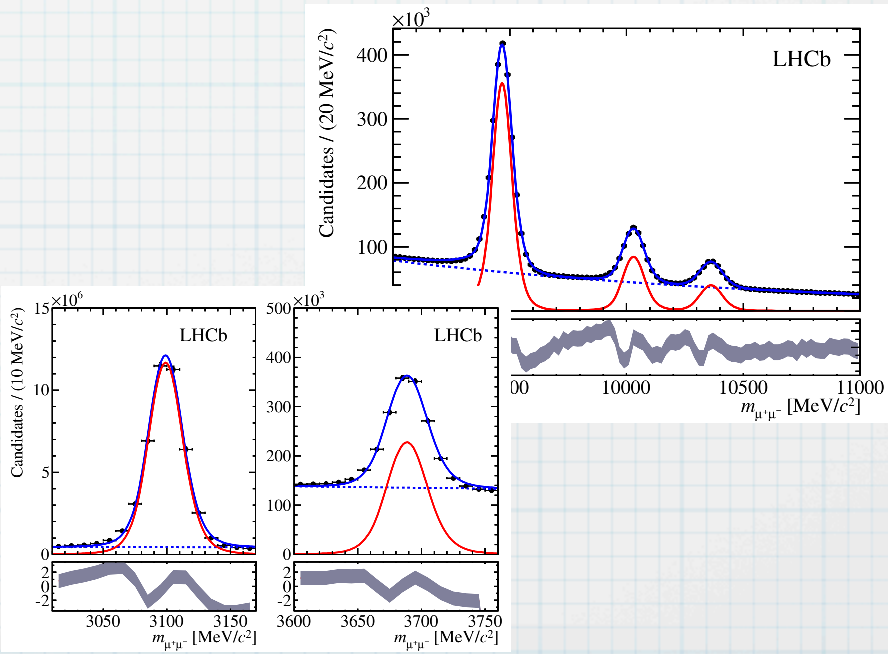
  signal: CB shape

  central values $B \to hh$ fit

  resolution: interpolation between $\mu\mu$ resonances J/ψ, $\Psi(2S)$, $\Upsilon(1S,2S,3S)$

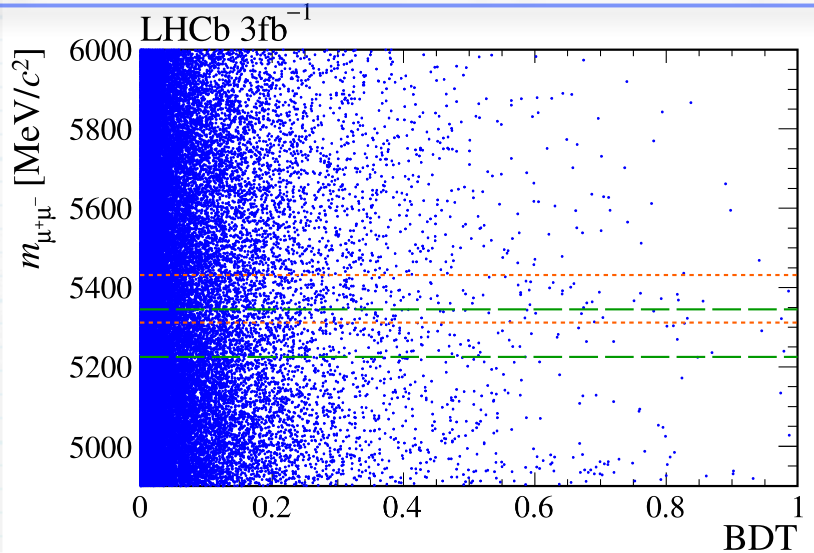
$\sigma(Bs) = 23.2 \pm 0.4$ MeV/c^2
$\sigma(B) = 22.8 \pm 0.4$ MeV/c^2





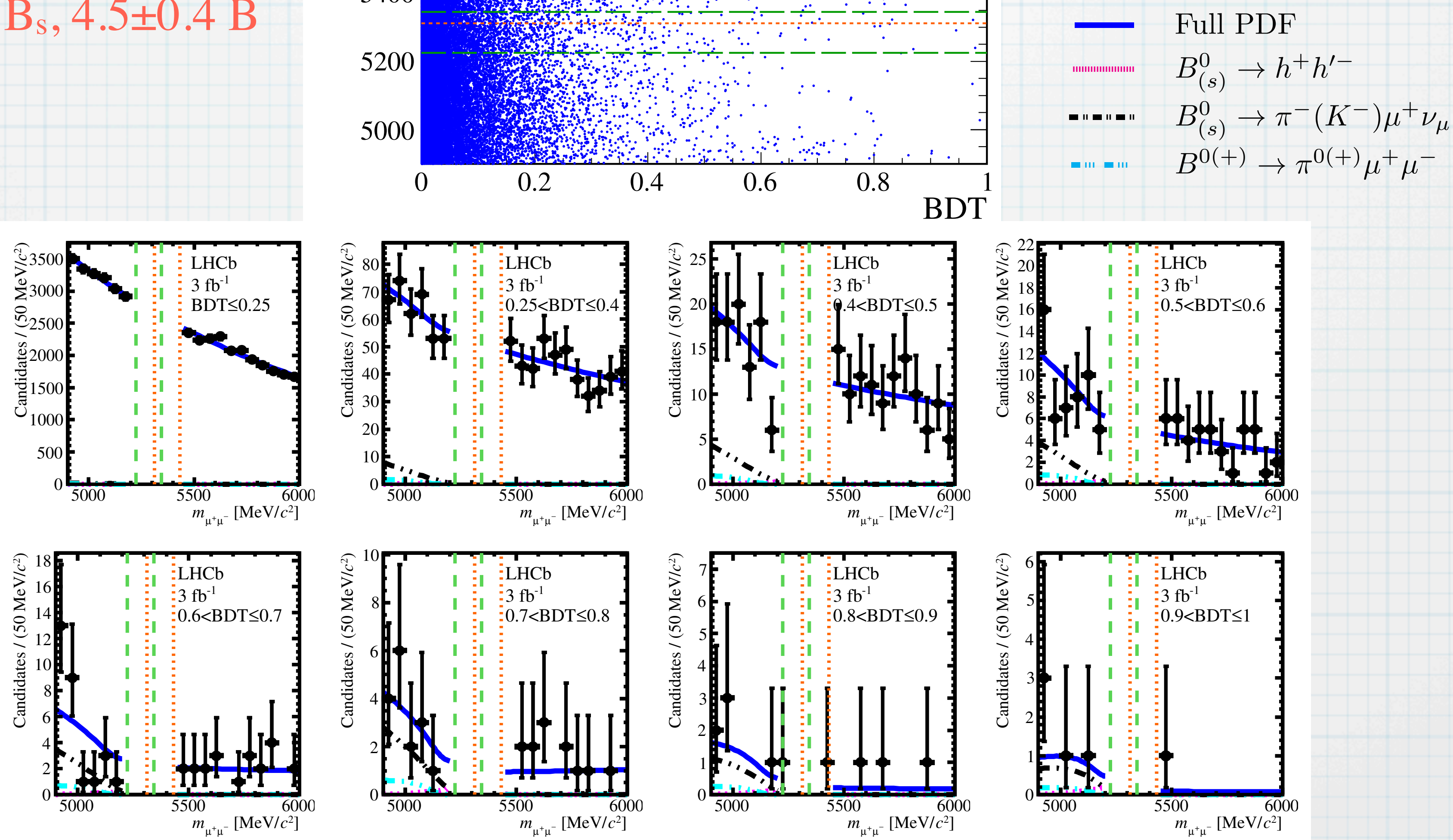
Update of $B_{(s)} \to \mu\mu$ with $3fb^{-1}$

[$3fb^{-1}$/arXiv:1307.5024]



mass vs BDT data

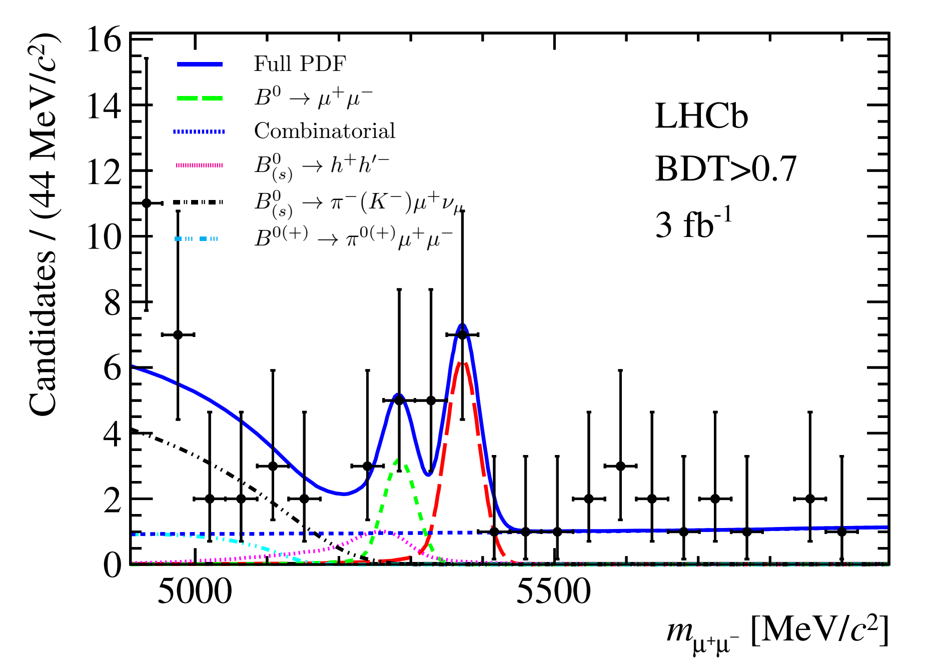
SM expectation:
49±4 B_s, 4.5±0.4 B

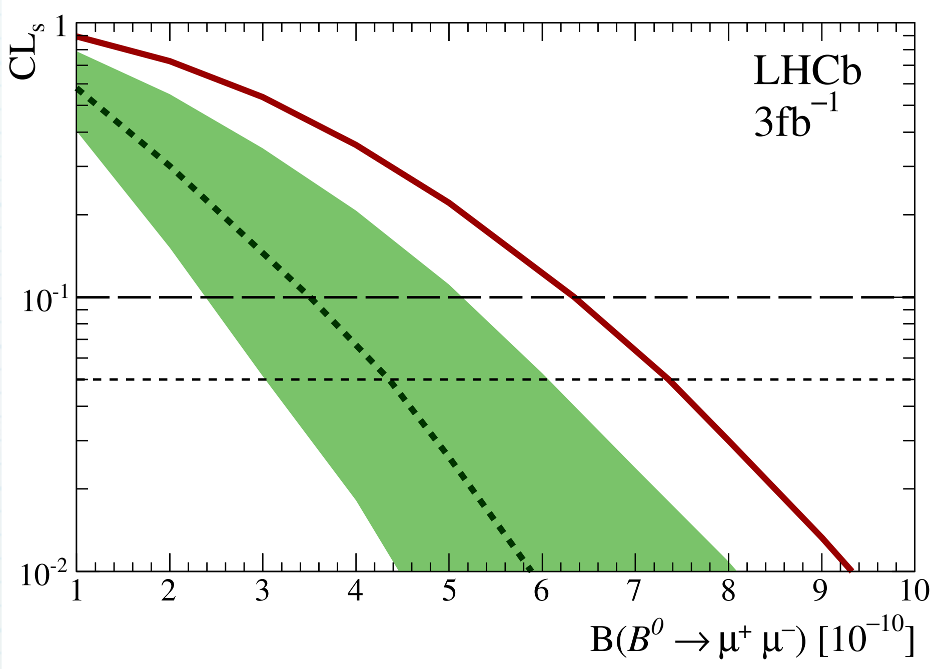


Update of $B_{(s)} \to \mu\mu$ with $3fb^{-1}$

[$3fb^{-1}$/arXiv:1307.5024]

In agreement with SM!





Bs significance 4 σ! B 2 σ!

$\mathcal{B}(B_{(s)})$ measurements

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

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

B limits

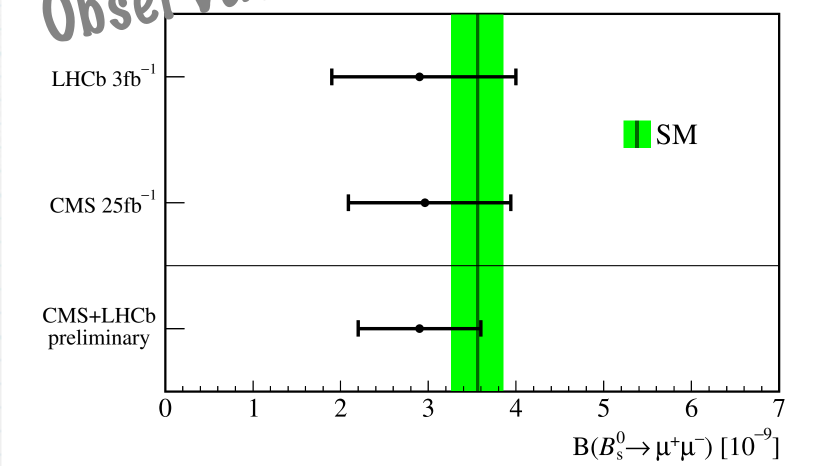
	90 % CL	95 % CL
Exp. bkg	3.5×10^{-10}	4.4×10^{-10}
Exp. bkg+SM	4.5×10^{-10}	5.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}

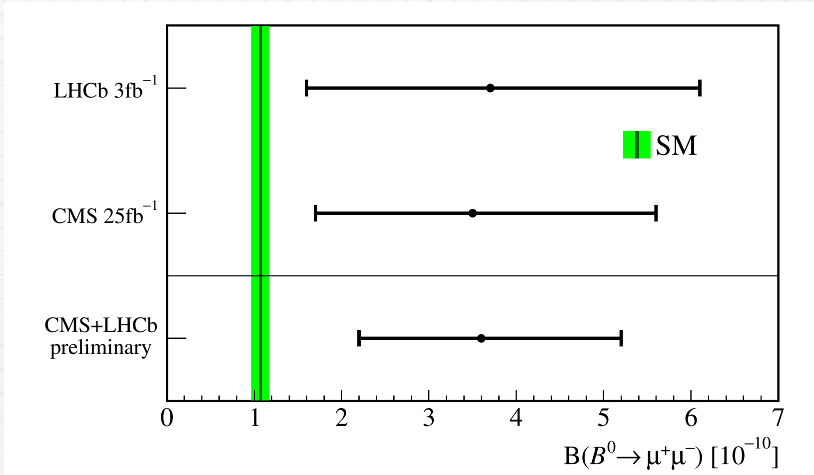
$B_{(s)} \to \mu\mu$ combination with CMS

- Combination with latest CMS result

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10},$$

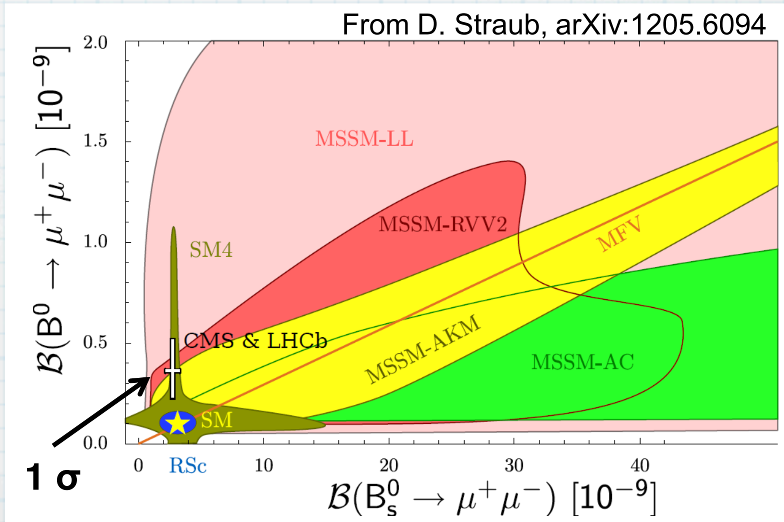
Observation!





- strong constraint to models beyond SM

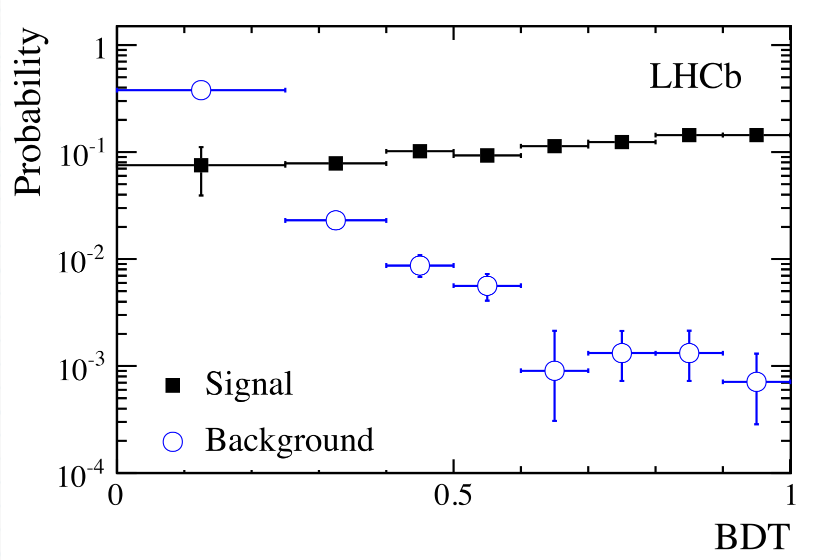
In agreement with SM!

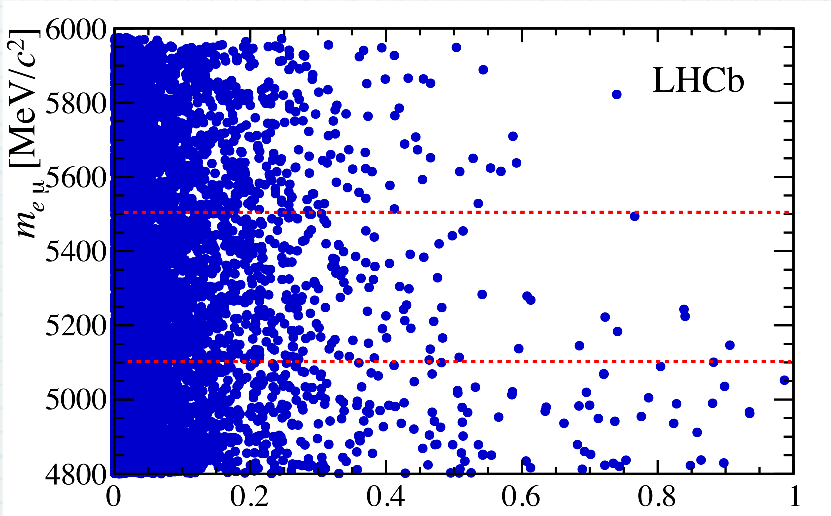


$B_{(s)} \to \mu e$

[1fb-1/arXiv:1307.4889]

- LFV process, sensible to NP, (i.e. leptoquarks)
- similar strategy to $B_s \to \mu\mu$
  - normalization and control channel B→hh’





Mode	Limit	90 % C.L.	95 % C.L.
$B_s^0 \to e^\pm \mu^\mp$	Expected	1.5×10^{-8}	1.8×10^{-8}
	Observed	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^\pm \mu^\mp$	Expected	3.8×10^{-9}	4.8×10^{-9}
	Observed	2.8×10^{-9}	3.7×10^{-9}

best limits on Pati-Salam leptoquarks

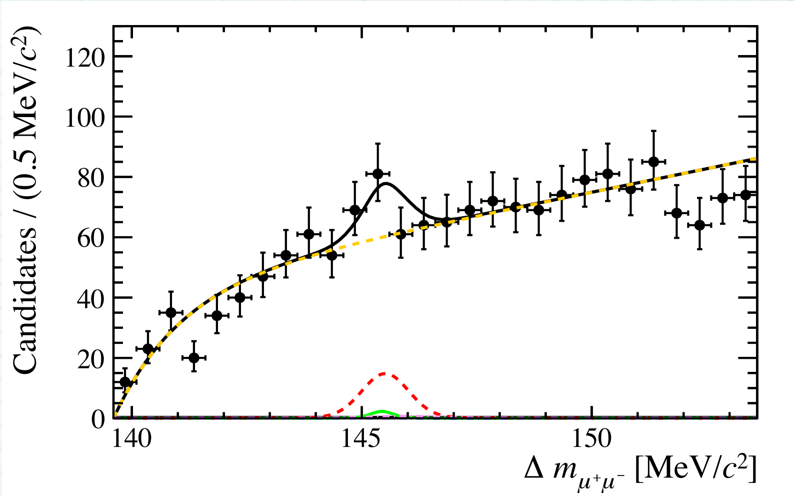
$m_{LQ}(B_s \to e^+\mu^-) > 107(101)\ TeV/c^2$ @ 90(95)%CL,

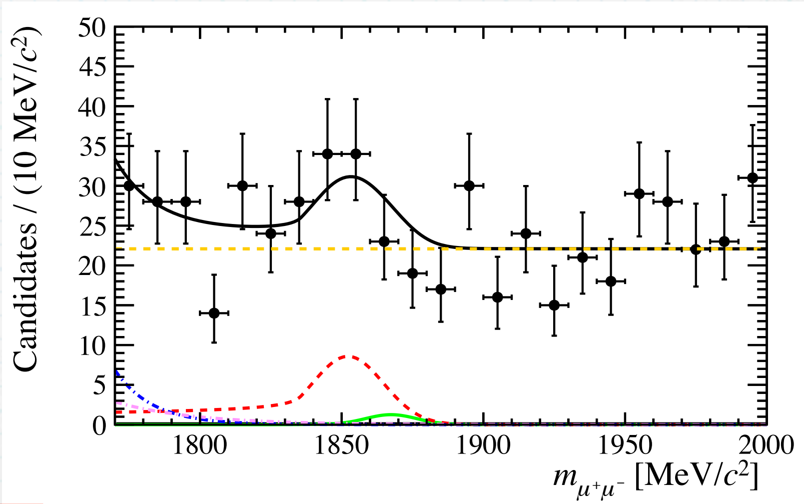
$m_{LQ}(B_d \to e^+\mu^-) > 135(126)\ TeV/c^2$ @ 90(95)%CL

$D \to \mu\mu$

[0.9fb^{-1}/arXiv:1305.5050]
[PL B 725 (2013) 15-24]

- SM: FCNC suppression driven by GIM mechanism
  - SM $B(D \to \mu\mu)$: 10^{-13}-10^{-11}
- NP models can enhance B (R parity violating MSSM)
- Analysis:
  - Use $D^{*+} \to D^0(\mu\mu)\pi^+$
  - 2D fit to $m(D^0)$, $\Delta m(D^{*+}-D^0)$
  - Background: combinatorial, $D \to \pi\pi$
  - Normalize to $D^-_s \to \phi(\mu\mu)\pi^-$





best limit!

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9} \quad \text{at 90\% (95\%) CL.}$$

Conclusions

- LHC and LHCb performing beautifully
- LHCb has an intense program on RD searches:
  - $B \to K^* \mu\mu$ angular analysis
    - new observables! (one bin in 24 shows discrepancy)

$$q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4 \quad .$$

  - Measurement of Isospin Asymmetry $B \to K^{(*)} \mu\mu$
    - new ψ resonance
  - 4 σ $B_s \to \mu\mu$ signal, limit on $B \to \mu\mu$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\mathrm{stat})\,^{+0.3}_{-0.1}(\mathrm{syst})) \times 10^{-9}\,,$$

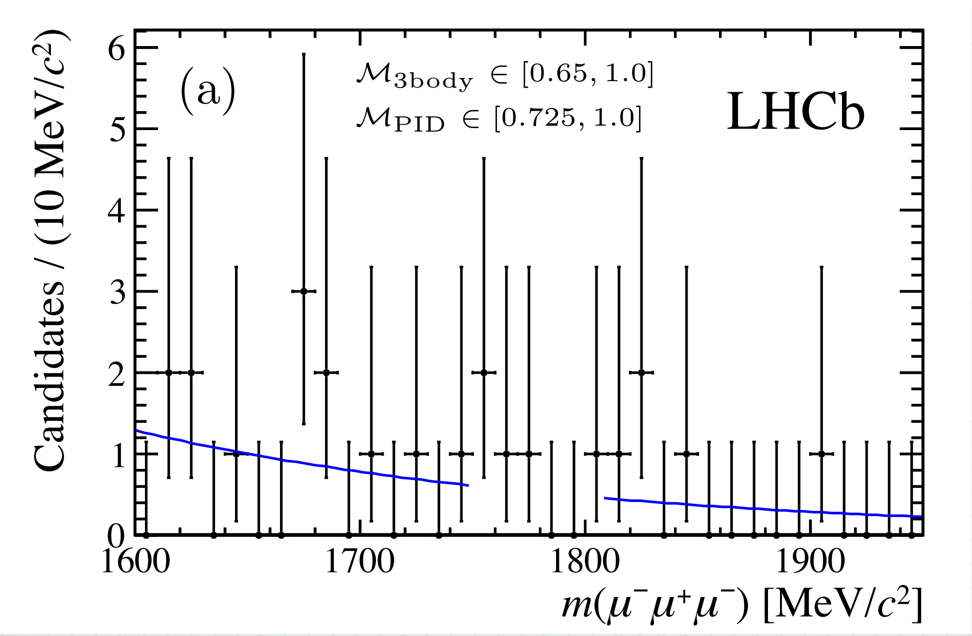
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$$

  - limits on $D \to \mu\mu$, $B_{(s)} \to \mu e$
- Everything in agreement with SM, no NP found (yet)!
  - Stringent constraints in models that extend the SM
  - Now looking for NP smallish effects...

$\tau \to \mu\mu\mu$

[$1\,\mathrm{fb}^{-1}$/arXiv:1304.4518]
[PL B 724 (2013) 36-45]

- LFV process, sensible to NP,
- similar strategy to $B_s \to \mu\mu$
  - discrimination using BDT, mass and PID
  - combinatorial background $bb \to \mu\mu X$, $cc \to \mu\mu X$, $D^-_s \to \eta(\mu\mu\gamma)\mu\nu$
  - normalization and control channel: $D^-_s \to \phi(\mu\mu)\pi^-$



expected 90(95) % C.L:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) \;<\; 8.3\ (10.2) \times 10^{-8},$$

observed:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) \;<\; 8.0\ (9.8) \times 10^{-8},$$

approachs best limit from Belle!

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8} \text{ at } 90\%$$

[1fb^{-1}/arXiv:1308.1340] [1fb^{-1}/PRL 110 (2013) 031801]

CP $B^+ \to K^+\mu\mu$, $B \to K^*\mu\mu$

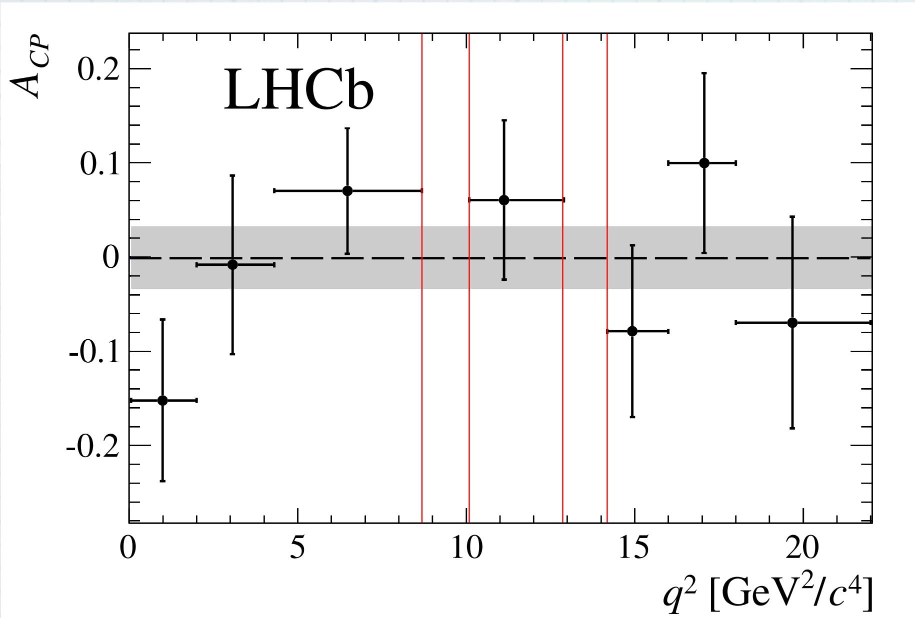
- CP Asymmetry predicted to be small SM
- Use control channels to eliminate production and detection asymmetries

$$\mathcal{A}_{CP} = \frac{\Gamma(B^- \to K^-\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)},$$

$$\mathcal{A}_{\rm RAW}(B^+ \to K^+\mu^+\mu^-) = \mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) + \mathcal{A}_{\rm P} + \mathcal{A}_{\rm D},$$

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

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



$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)},$$

$$\mathcal{A}_{\rm RAW} = \mathcal{A}_{CP} + \kappa\mathcal{A}_P + \mathcal{A}_D,$$

$$\mathcal{A}_{CP} = \mathcal{A}_{\rm RAW}(B^0 \to K^{*0}\mu^+\mu^-) - \mathcal{A}_{\rm RAW}(B^0 \to J/\psi K^{*0}).$$

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040 \pm 0.005.$$