Rare decays of beauty and charm hadrons at LHCb

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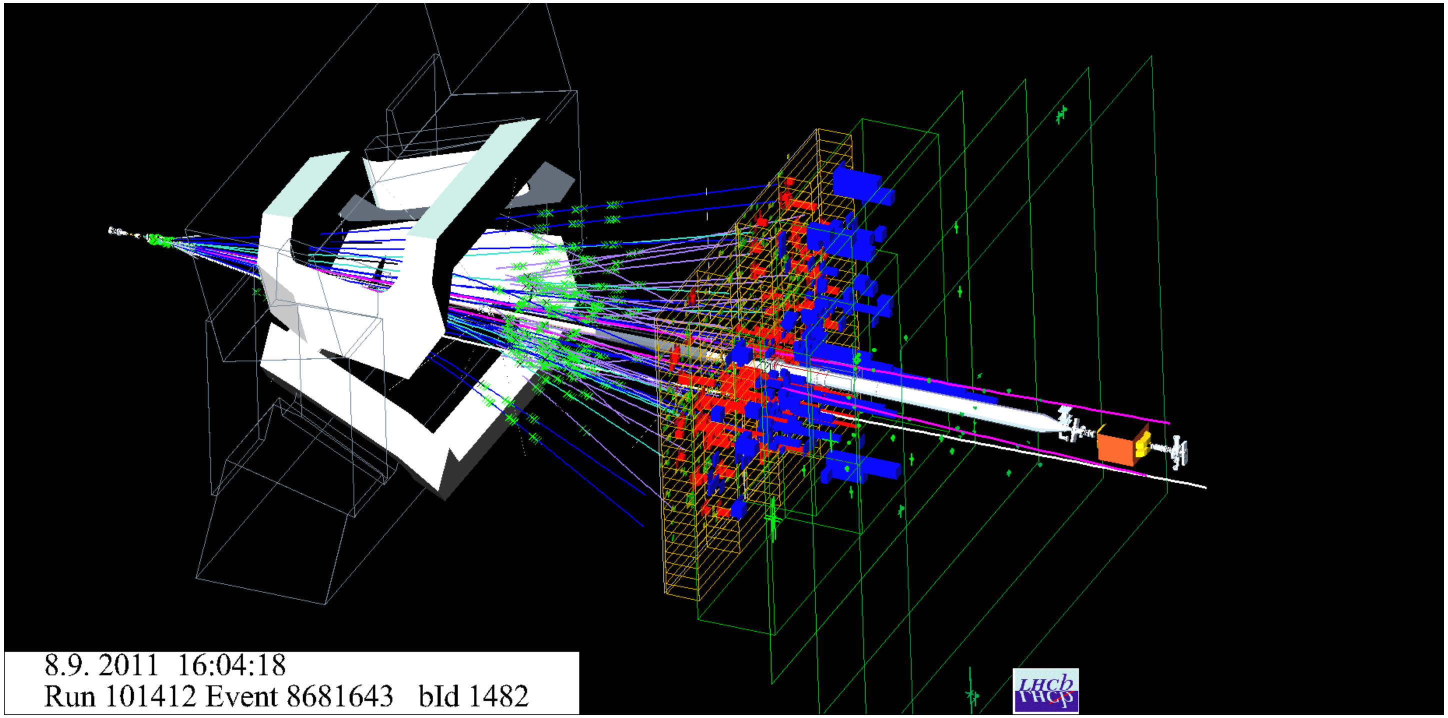
Centre de Physique des Particules de Marseille



Windows on the Universe, Quy Nhon, August 2013

Outline

- Rare B leptonic decays
  - BR($B_{s/d} \to \mu^+\mu^-$) *new at EPS!*
  - BR($B_{s/d} \to e^+\mu^-$) *new at LP!*

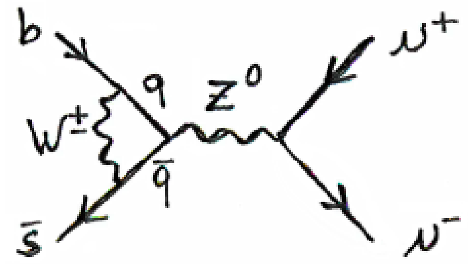
- Rare B semileptonic decays
  - $B_d \to K^{*0}\mu^+\mu^-$ standard observables
  - $B_d \to K^{*0}\mu^+\mu^-$ new observables *new at EPS!*
  - New resonance in $B^+ \to K^+\mu^+\mu^-$ *new at EPS!*

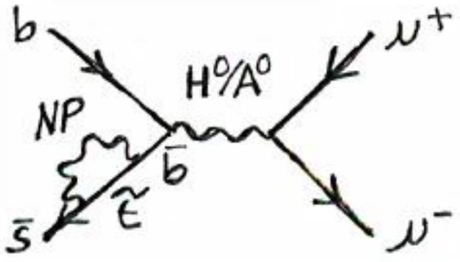
- Rare charm decays
  - BR($D^0 \to \mu^+\mu^-$) *new at LHCP!*
  - BR($D^+ \to \pi^+\mu^+\mu^-$)

The indirect search for new physics

- Up to now, no sign of new physics from direct searches... But flavour physics can help !

- Flavour changing neutral currents are forbidden at the tree level in the SM
They can only proceed through loop diagrams
  $\Rightarrow$ Suppressed by the GIM mechanism



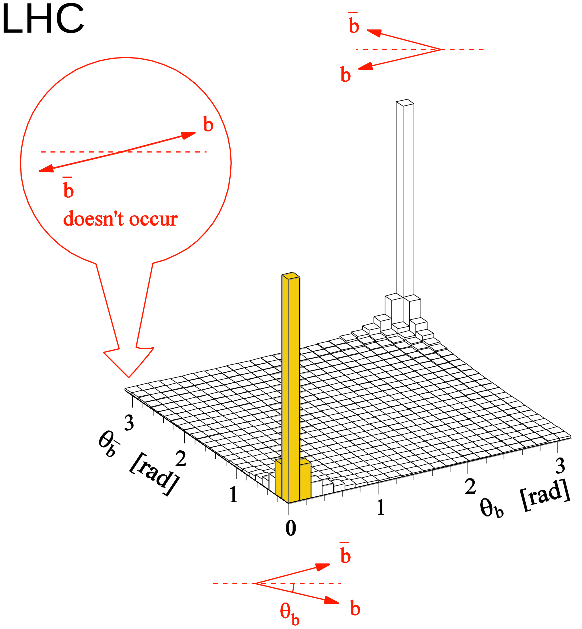


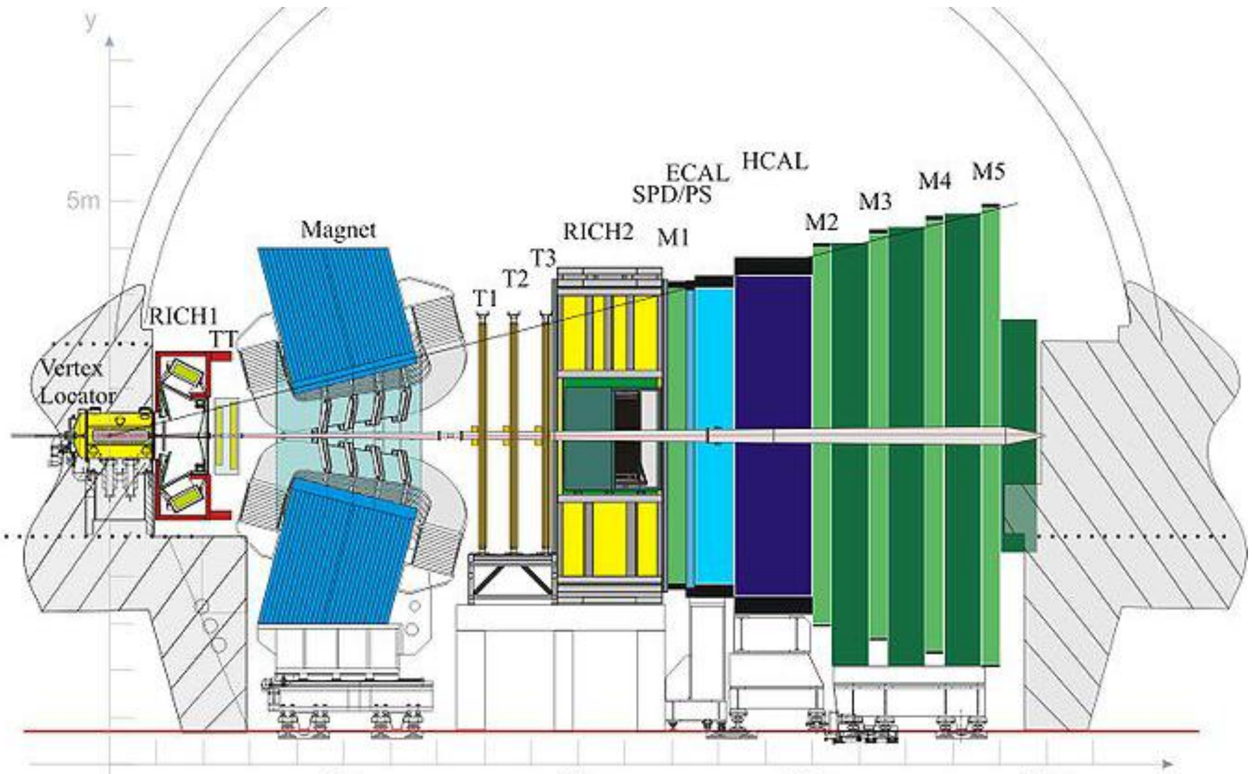
- NP virtual particles can enter the loop and modify observables as branching ratio, CP asymetry, angular distributions,…

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

LHCb

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





Data taking conditions

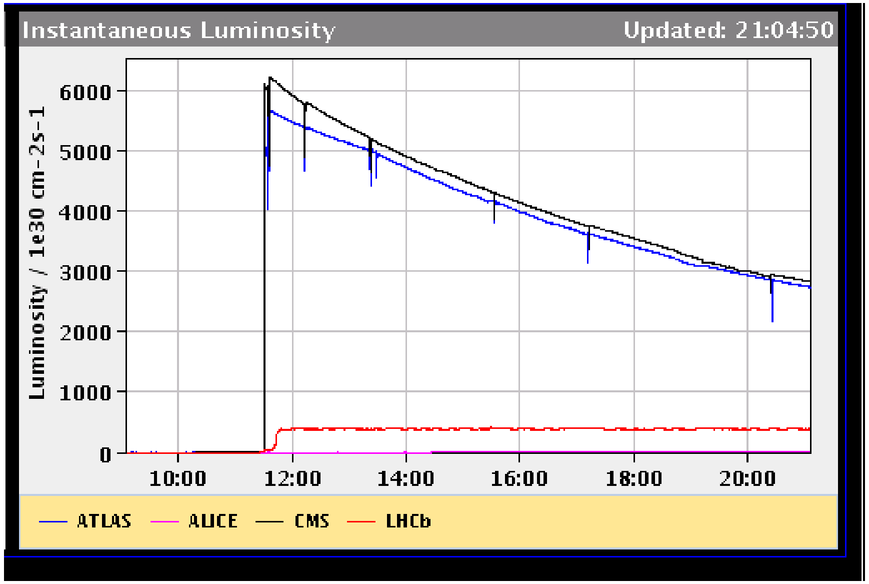
- Running at a constant luminosity of 4.10^{32} cm^{-2} s^{-1} thanks to the luminosity leveling

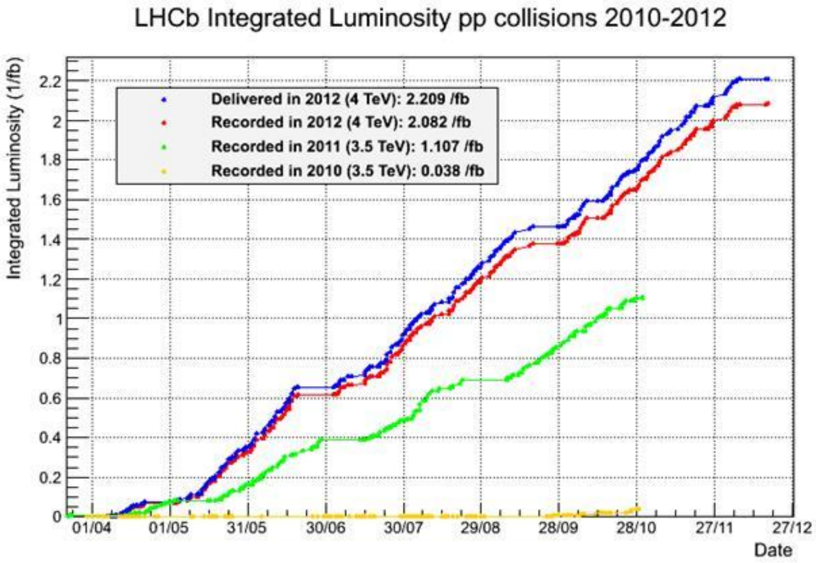
  This is twice the design luminosity!

- Interactions per crossing

  $\langle\mu\rangle \sim 1.7$

  This is four times more than design!





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

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

Theoretical status:

- Precise SM prediction:
  - $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}$
  - $BR(B_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

Updated from A.J.Buras arXiv:1208.0934

  - Taking B_s oscillation into account, the measured BR should be compare to: $B(B_s^0 \to \mu^+\mu^-)^{SM}_{exp} = (3.56 \pm 0.30) \times 10^{-9}$

Experimental status (before EPS 2013):

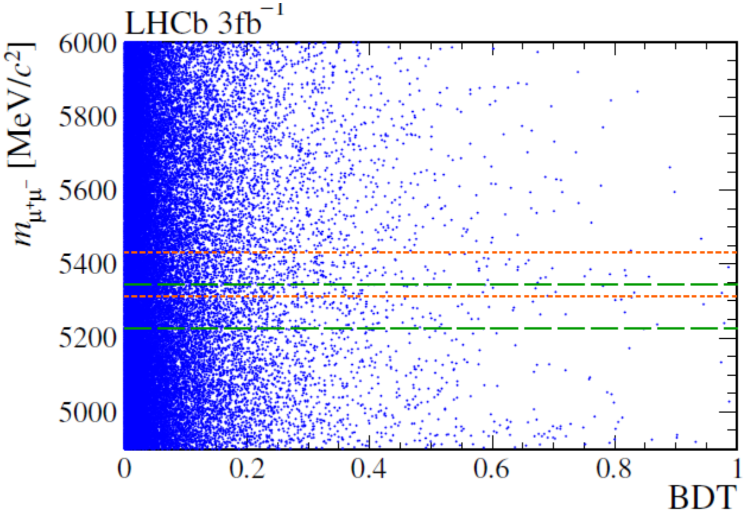
- First evidence of $B_s \to \mu^+\mu^-$ by LHCb, last november:

$$B(B_s^0 \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

3.5σ!! Phys. Rev. Lett. 110, 021801 (2013)

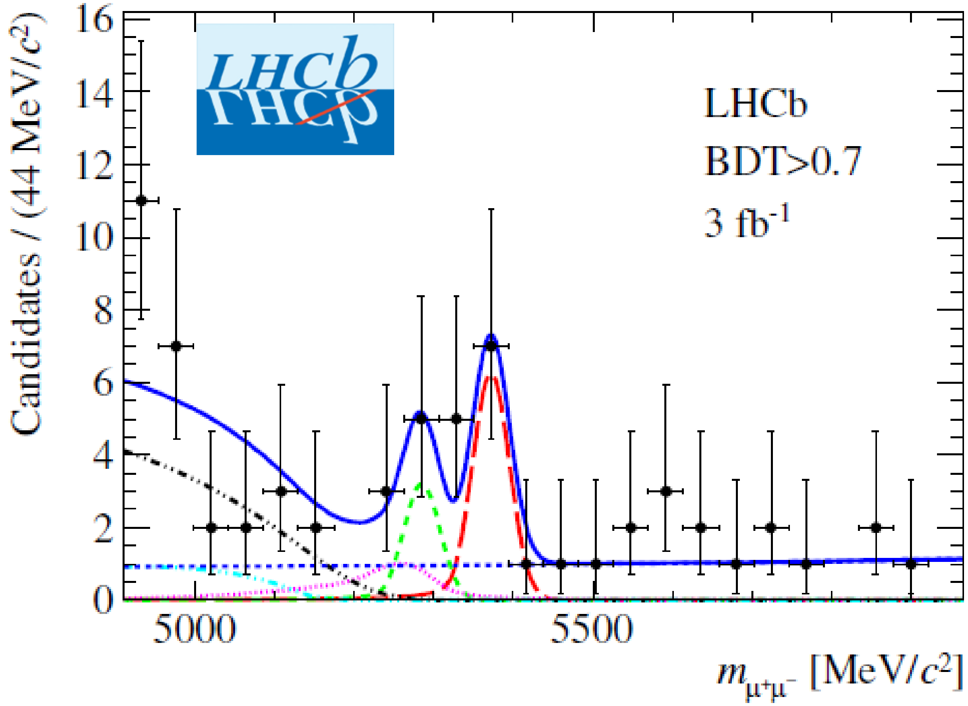
- Best upper limit for $B_d \to \mu^+\mu^-$: $B(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% CL
- CMS and ATLAS are in the game too

Analysis strategy



- Selection
  - muon-based trigger
  - Soft selection
  - Similar to control channels
  - Blind signal region (M_{Bd}-60MeV, M_{Bs}+60MeV)
- Signal and background discrimination:
  - Invariant mass
  - boosted decision tree combining kinematic and geometrical properties
  - Data driven calibration through control channels
- Normalization with channels of known BR: $B^+ \to J/\Psi K^+$ and $B_d \to K\pi$
- Background estimation
  - combinatorial from $m_{\mu\mu}$ sidebands
  - detailed study on various exclusive backgrounds
- BR measurement using a maximum likelihood fit in bins of BDT
- Limit measurement using the modified frequentist CLs method in bins of mass and BDT

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



arXiv:1307.5024
Accepted by PRL

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

LHCb + CMS

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

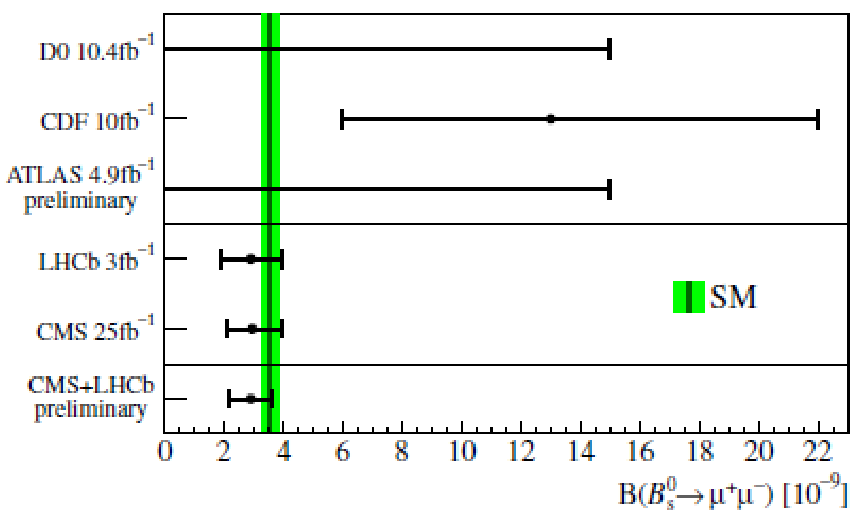
- CMS also showed un update using the full statistics at EPS
- Combining CMS and LHCb:

preliminary

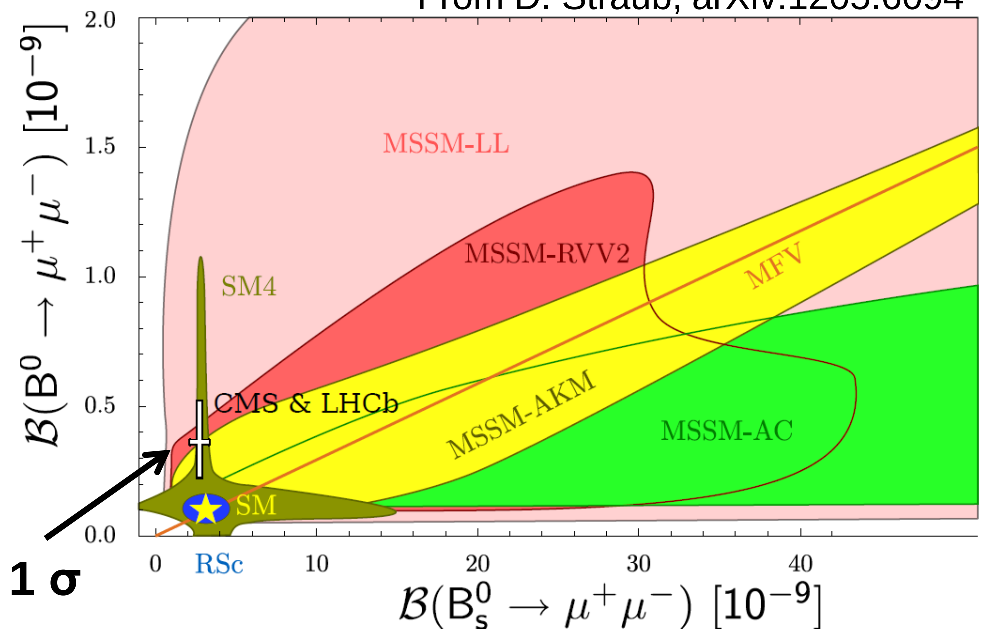
$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

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

First observation !!



From D. Straub, arXiv:1205.6094



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

arXiv:1307.4889

- Lepton flavour violating mode, forbidden in the SM
- Similar analysis strategy as $B_s \rightarrow \mu^+\mu^-$

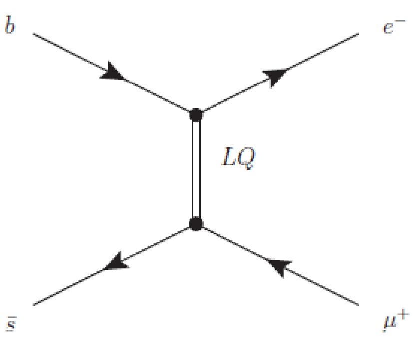
	$B^0_s \rightarrow e^+\mu^-$ at 90%(95%) CL	$B^0 \rightarrow e^+\mu^-$ at 90%(95%) CL
Expected (LHCb 1fb^{-1})	**1.5 (1.8) 10^{-8}**	**3.8 (4.8) 10^{-9}**
Observed (LHCb 1fb^{-1})	**1.1 (1.4) 10^{-8}**	**2.8 (3.7) 10^{-9}**
Current (CDF 2fb^{-1})	20.0 (20.6) 10^{-8}	64.0 (79.0) 10^{-9}

New world best limits!

Constraint on Pati-Salam leptoquark :

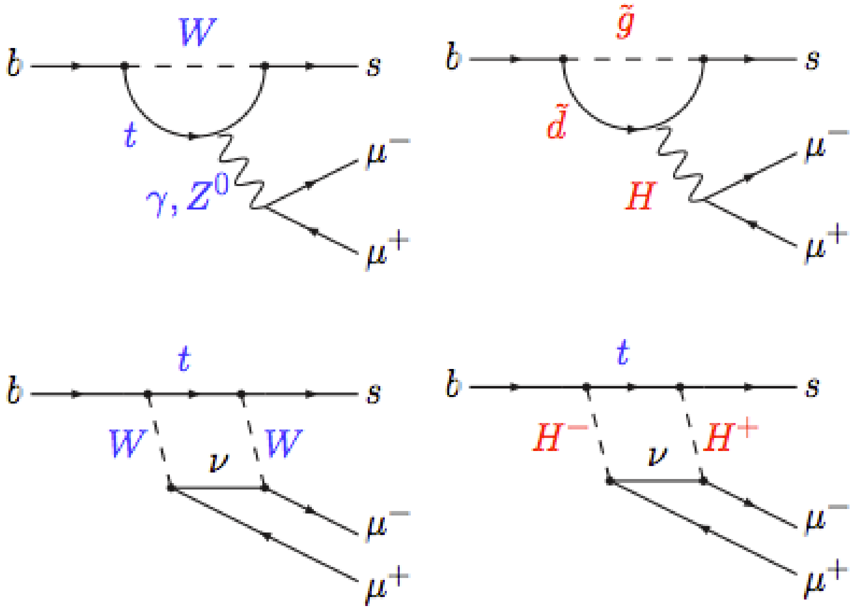
CDF
$$m_{LQ}(B_s \rightarrow e^+\mu^-) > 47.8(44.9)\ TeV/c^2 \text{ @ } 90(95)\%CL,$$
$$m_{LQ}(B_d \rightarrow e^+\mu^-) > 59.3(56.3)\ TeV/c^2 \text{ @ } 90(95)\%CL$$

LHCb
$$m_{LQ}(B_s \rightarrow e^+\mu^-) > 107(101)\ TeV/c^2 \text{ @ } 90(95)\%CL,$$
$$m_{LQ}(B_d \rightarrow e^+\mu^-) > 135(126)\ TeV/c^2 \text{ @ } 90(95)\%CL$$



Rare semileptonic decays

- b →sl⁺l⁻ FCNC processes represent a very rich environment: angular observables, rates, asymmetries sensitive to NP

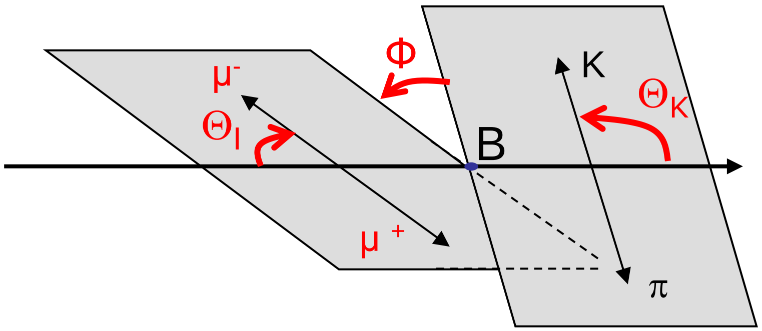


- A lot of different channels can be studied:

$B_d \to K^{*0}\mu^+\mu^-$, $B_d \to K^{*0}e^+e^-$, $B^+ \to K^+\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\ \mu^+\mu^-$, …

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

- 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:

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} = \frac{9}{16\pi}\Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell-1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$

$$S_3 = (1-F_L)A_T^2$$

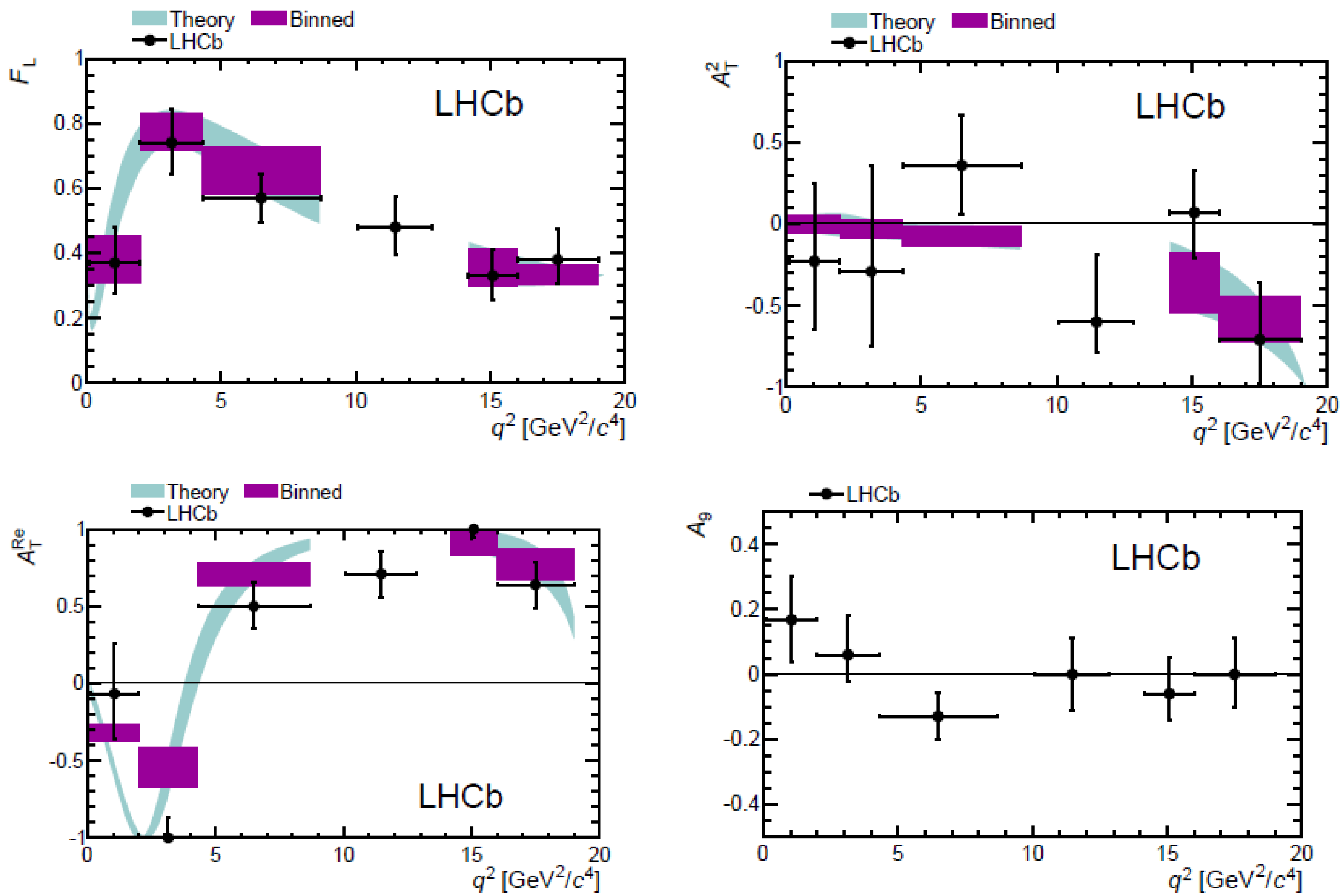
$$A_{FB} = \frac{3}{4}(1-F_L)A_T^{\mathrm{Re}}$$

A_{FB}
forward-backward asymmetry
F_L
fraction of K^{*0} longitudinally polarized
S_3
asymmetry in K^{*0} transverse polarization
A_9
T-odd CP

A_{FB} zero crossing point precisely predicted in SM: **$q^2 = 4.36^{+0.33}_{-0.31}$ $(\mathrm{GeV}/c^2)^2$**

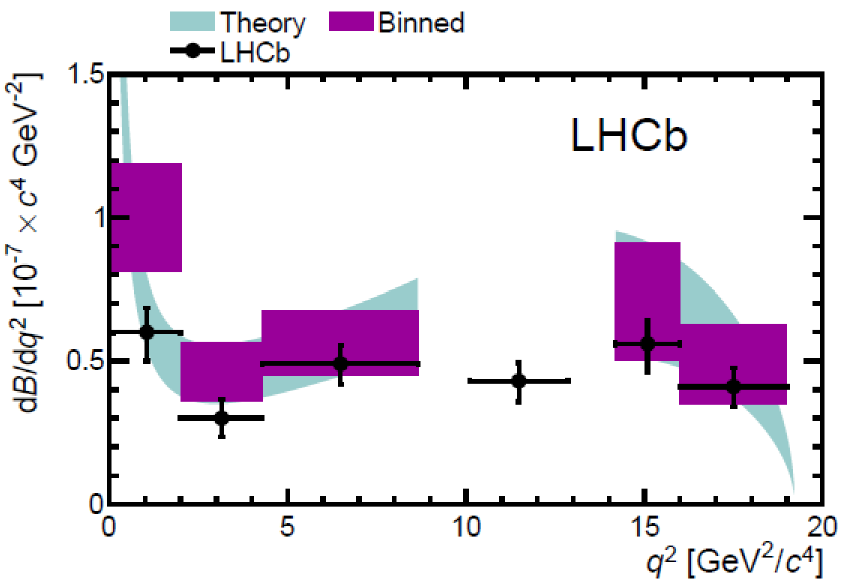
- Analysis based on 1 fb^{-1}, ~900 events
- Observables measured in 6 q^2 bins

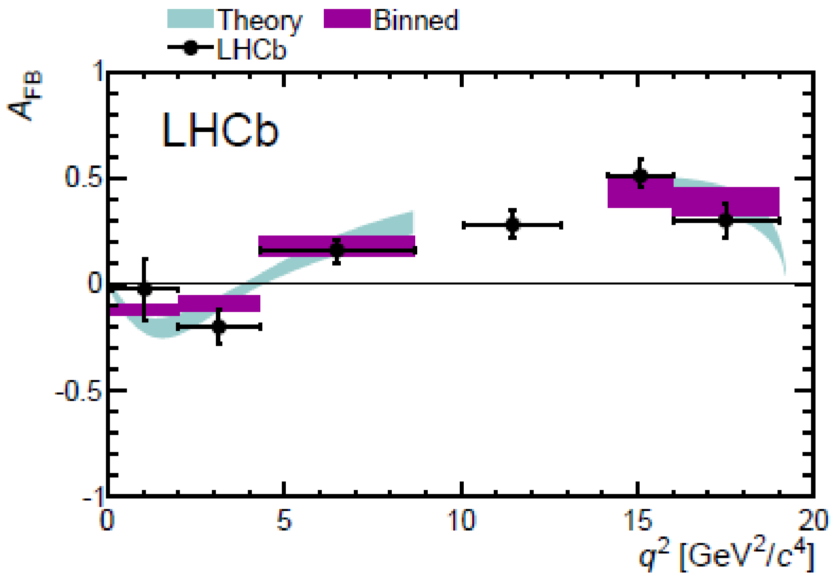
arXiv:1304.6325
Accepted by JHEP



Results

arXiv:1304.6325





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 ⇒ complementarity!
- Use different folding to measure each P'_i

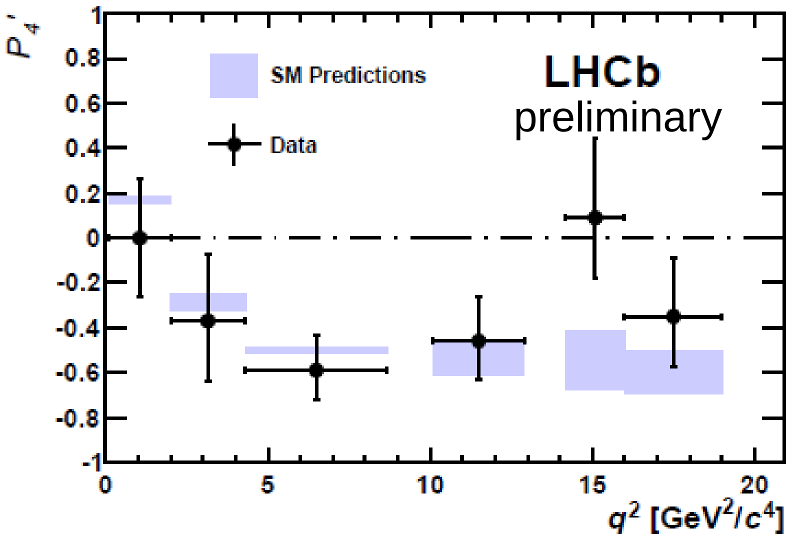
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

$$A_\mathrm{T}^{(2)} = \frac{2S_3}{(1-F_L)} \qquad P'_5 = \frac{S_5}{\sqrt{(1-F_L)F_L}}$$

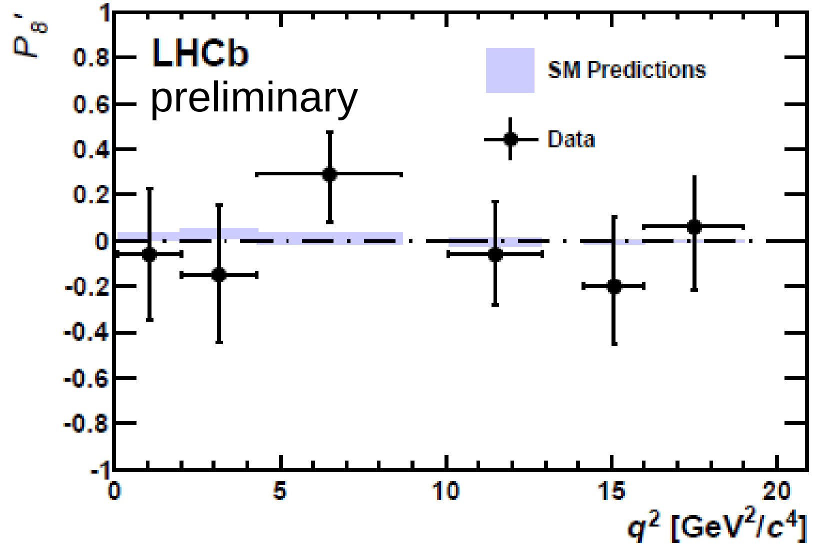
$$A_\mathrm{T}^{Re} = \frac{S_6}{(1-F_L)} \qquad P'_6 = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

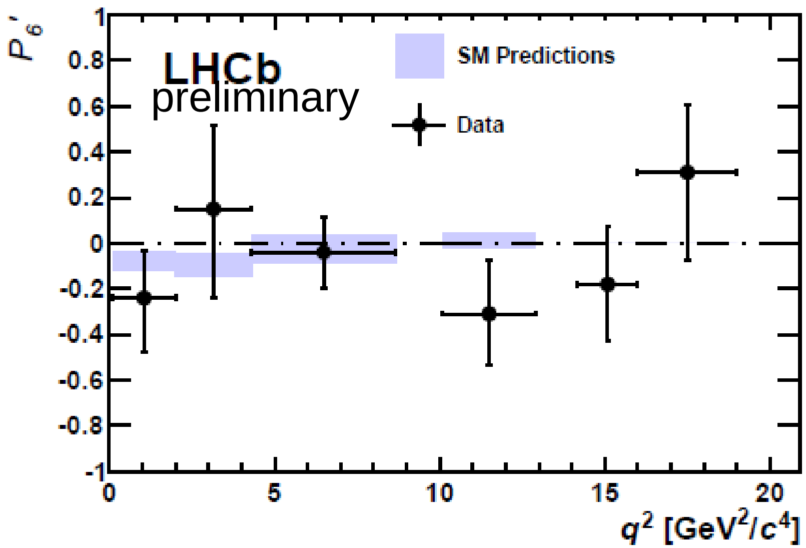
$$P'_4 = \frac{S_4}{\sqrt{(1-F_L)F_L}} \qquad P'_8 = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

Results for new observables



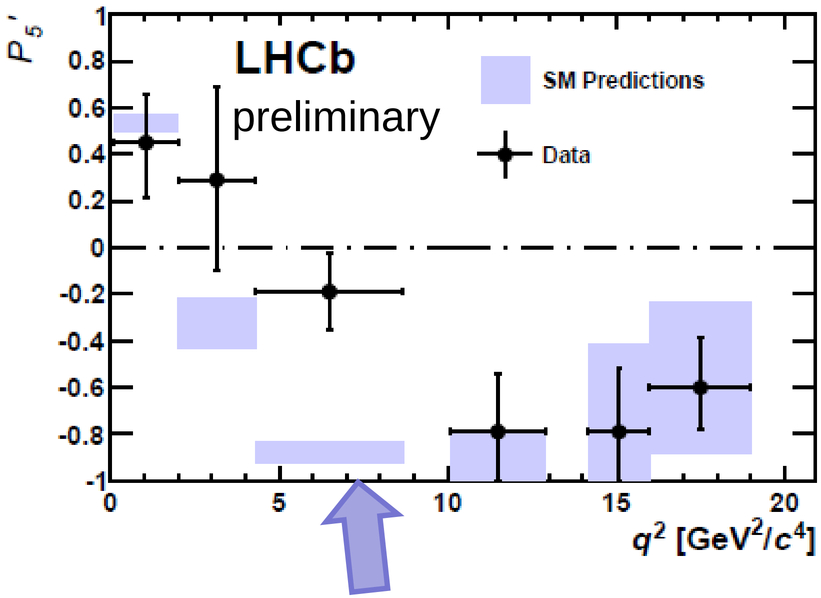
arXiv:1308.1707

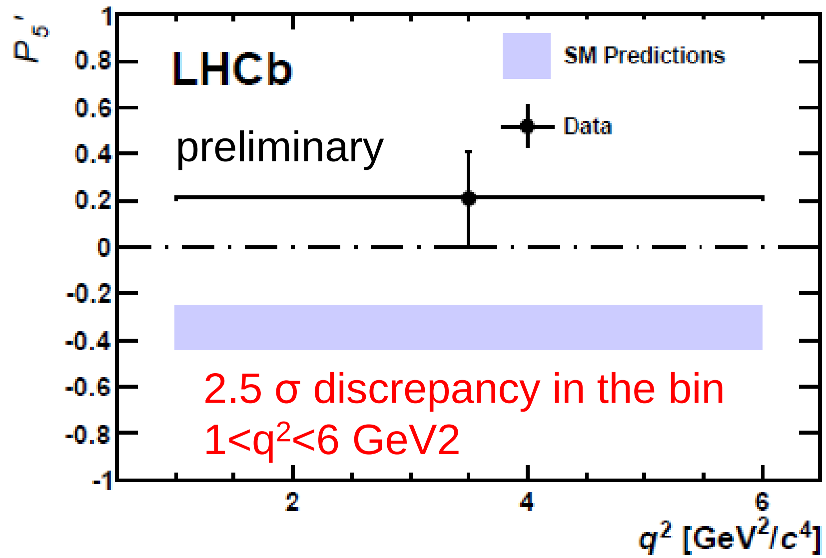




Good agreement with SM predictions from J. Matias et al, arXiv:1303.5794

Results for new observables

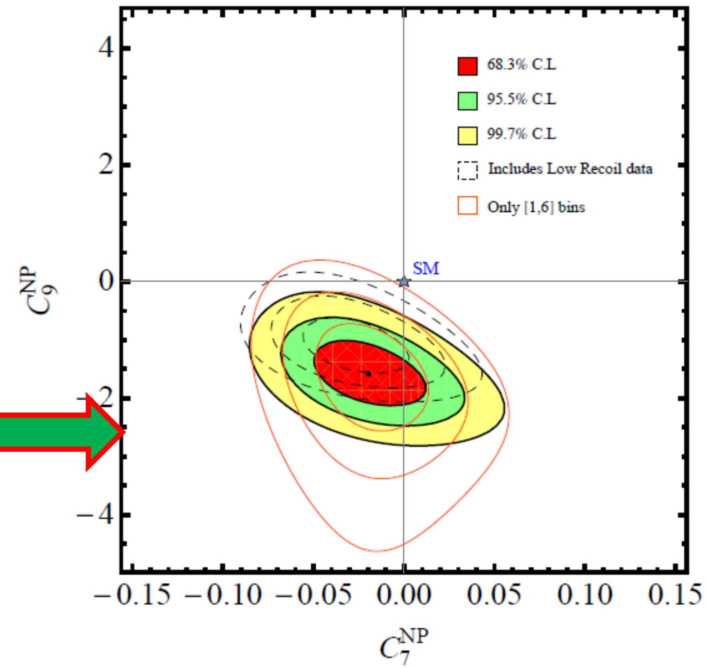




3.7 σ discrepancy in the bin $4.3<q^2<8.68$ GeV^2

Could be interpreted as NP contribution in Wilson coefficients C_9 and C_7 (arXiv:1308.101, arXiv:1307.5683)

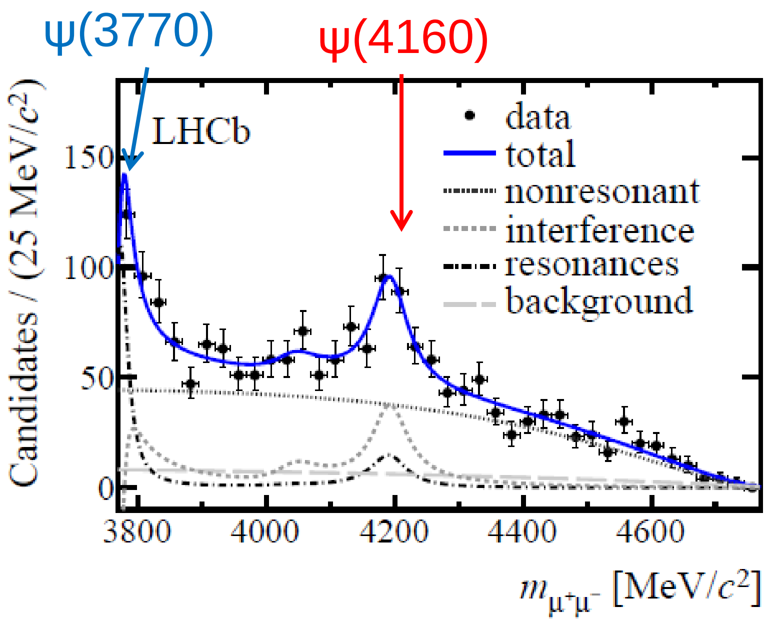
Several b → s measurements used in this fit



New resonance in $B^+ \to K^+\mu^+\mu^-$

arXiv:1307.7595

- Analysis based on 3 fb^{-1}



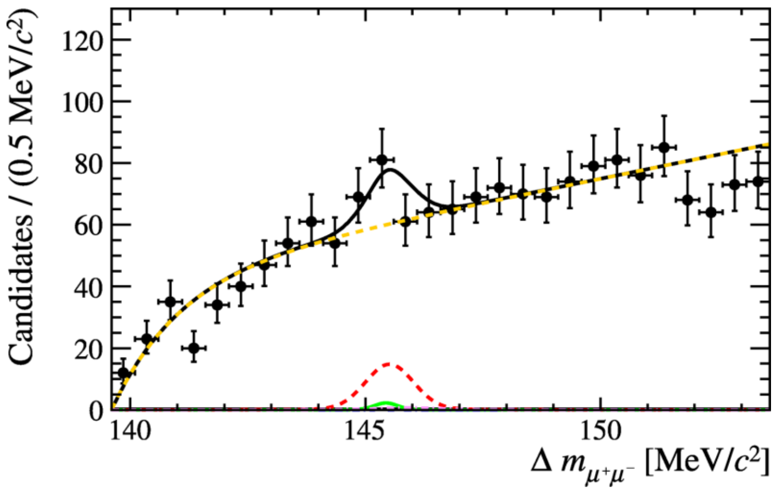
ψ(4160) parameters:

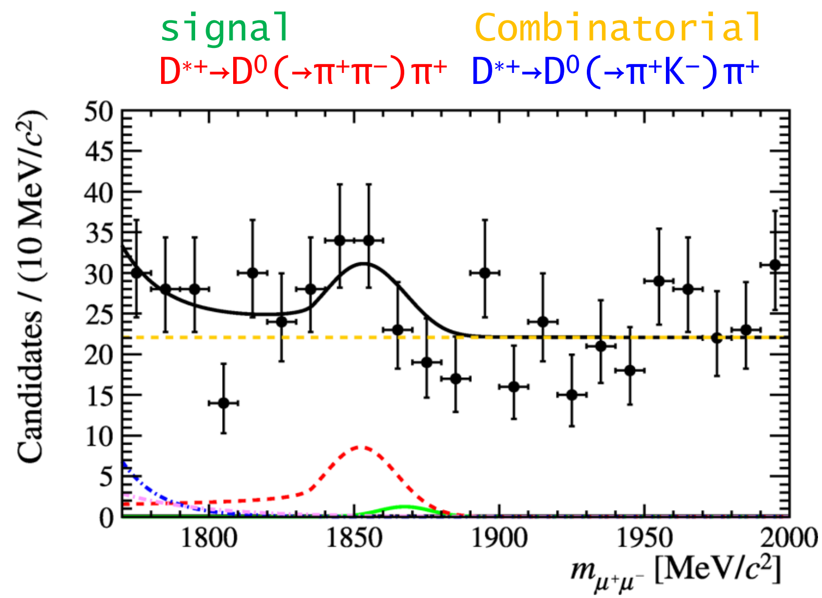
$\mathcal{B} [\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$
Mass [MeV/c^2]	$4191\,^{+9}_{-8}$
Width [MeV/c^2]	$65\,^{+22}_{-16}$
Phase [rad]	-1.7 ± 0.3

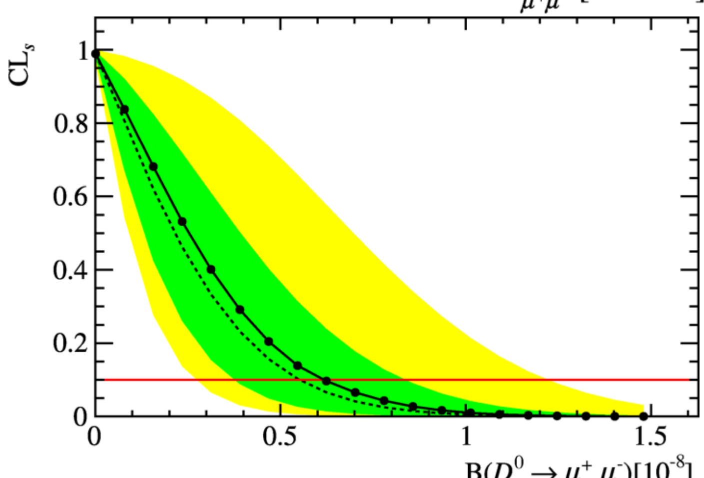
- Observation of a resonant structure at high q^2
- Consistent with Ψ(4160). Confirm BES mass and width.
- Contribute to ~20% of total signal at high q^2 >> OPE estimate

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

- SM prediction : 10^{-13}–10^{-11}
- 0.9 fb^{-1} analysed, using $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+_{slow}$
- Yields from 2D fit: $m(D^0)$ vs $\Delta m(D^{*+}-D^0)$





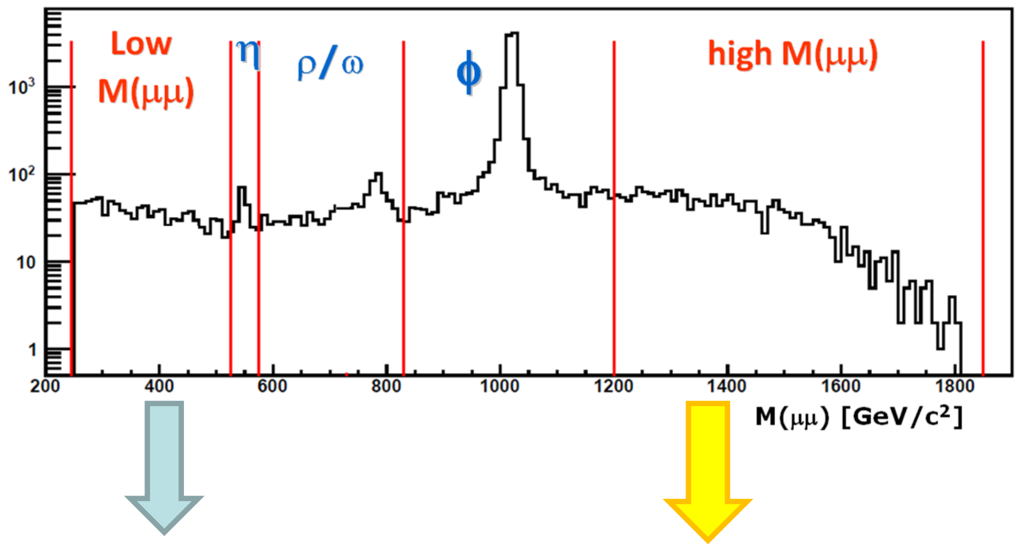


$B(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$ @ 95% CL

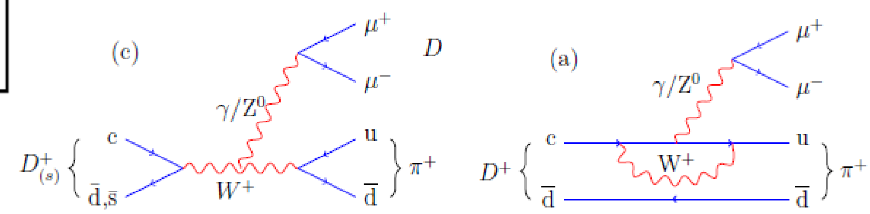
(20 times better than previous limit)

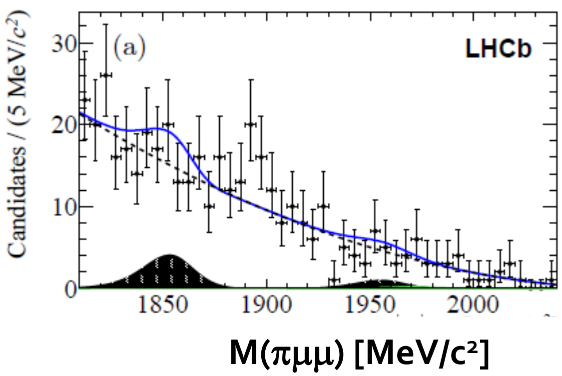
Phys. Lett. B725 (2013) 16

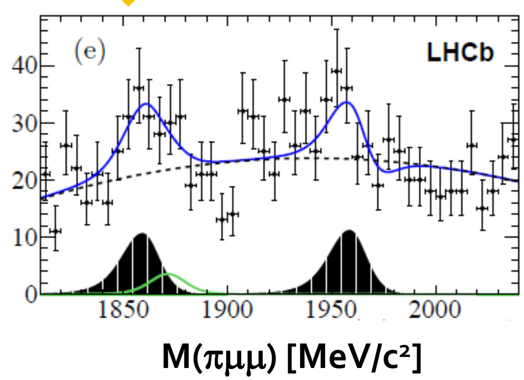
Rare charm decay: $D_{(s)}^+ \to \pi^+\mu^+\mu^-$



- In SM, FCNC's BR could reach 10^{-9}
- Probe of NP in regions not clouded by resonances
- 1 fb^{-1} analysed







Signal

Comb. background:

Peaking backgrounds: $D^+_s \to \pi^+\pi^+\pi^-$

PLB 724 (2013) 203-212

Upper limits x10^{-8} @90(95)%CL

			Total
$BR(D^+ \to \pi^+\mu^+\mu^-)$	2.0 (2.5)	2.6 (2.9)	7.3 (8.3)
$BR(D_s^+ \to \pi^+\mu^+\mu^-)$	6.9 (7.7)	16.0 (18.6)	41 (48)

New world best limits!

Conclusion

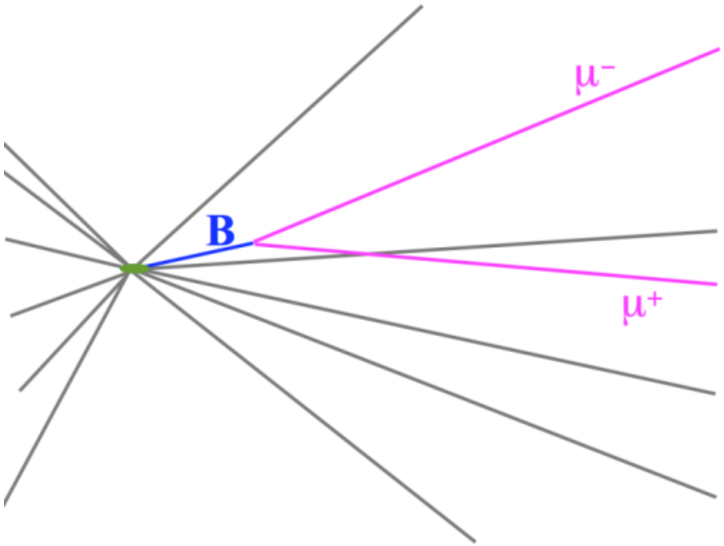
- LHCb has plenty of new results on rare decays!
  - New BR measurement for $B_s \to \mu^+\mu^-$ with 4 σ significance
  - New observables measurement in $B_d \to K^{*0}\mu^+\mu^-$
  - New resonance found in $B^+ \to K^+\mu^+\mu^-$
  - World best limits on $B_{s/d} \to e^+\mu^-$, $D^0(\to \mu^+\mu^-)$, $D_{(s)}^+ \to \pi^+\mu^+\mu^-$
  - Not covered in this talk : CP asymetry in $B^+ \to K^+\mu^+\mu^-$, $BR(B_d \to K^{*0}e^+e^-)$, angular analysis of $B_s \to \phi\mu^+\mu^-$, $BR(\Lambda_b \to \Lambda\, \mu^+\mu^-)$, asymetries in $B_d \to K\pi\pi\gamma$

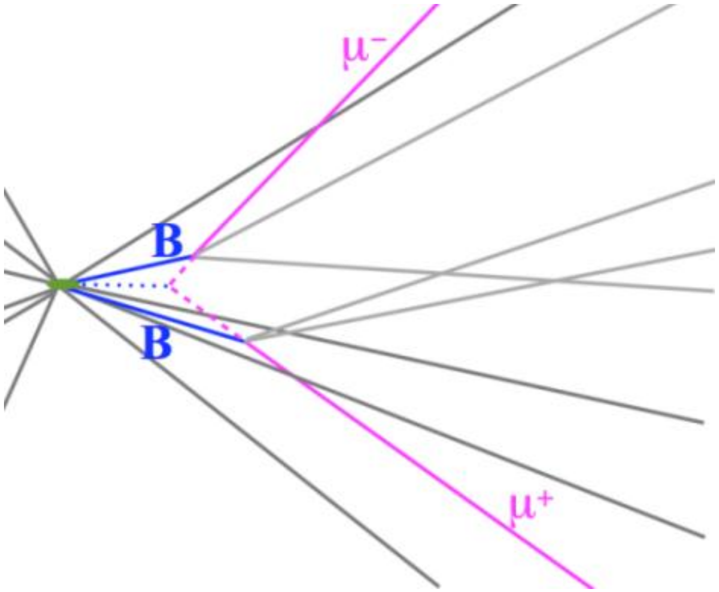
- Overall good agreement with SM, except for a local discrepancy in the low q^2 region for P_5' in the $B_d \to K^{*0}\mu^+\mu^-$ decay

- Most of analyses done with 1 fb^{-1}, 2 other fb^{-1} to be analysed!

backup

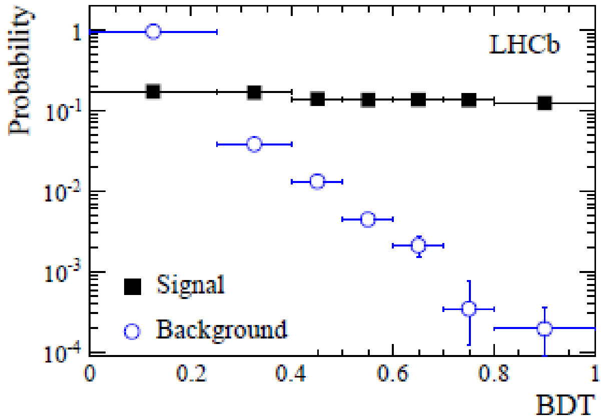
Spot the differences





- Geometrical variables: Impact Parameters, Distance of Closest Approach, isolation
- Kinematic variables: Transverse momentum

Boosted decision tree



Fit projections

$B^0 \to \pi^- \mu^+ \nu$

$B_s \to K^- \mu^+ \nu$

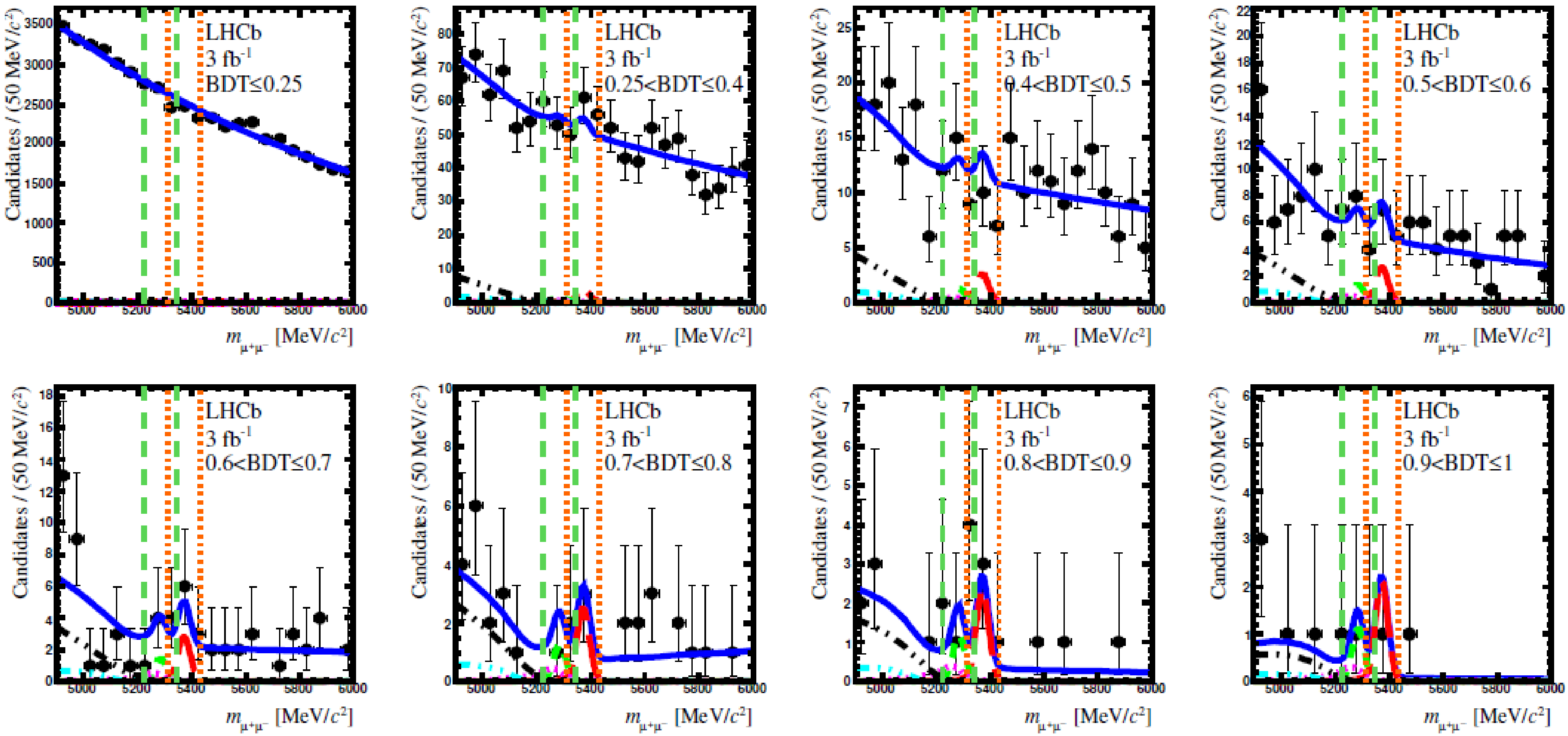
$B^{0/+} \to \pi^{0/+} \mu\mu$

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

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

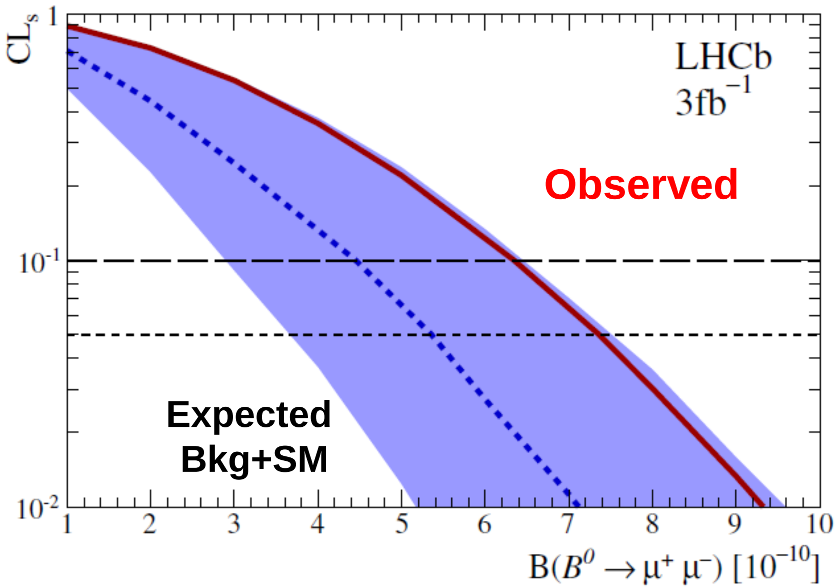
$B^0 \to \mu^+ \mu^-$

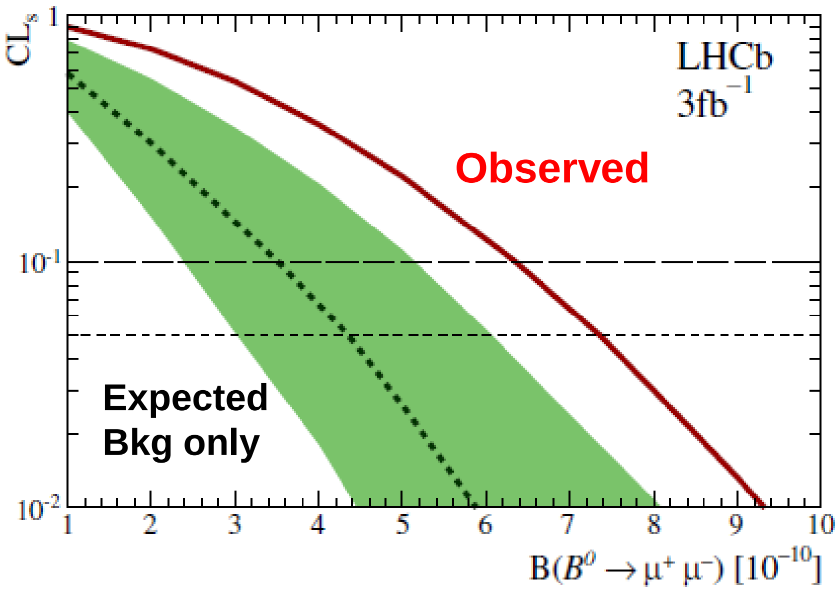
Total



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

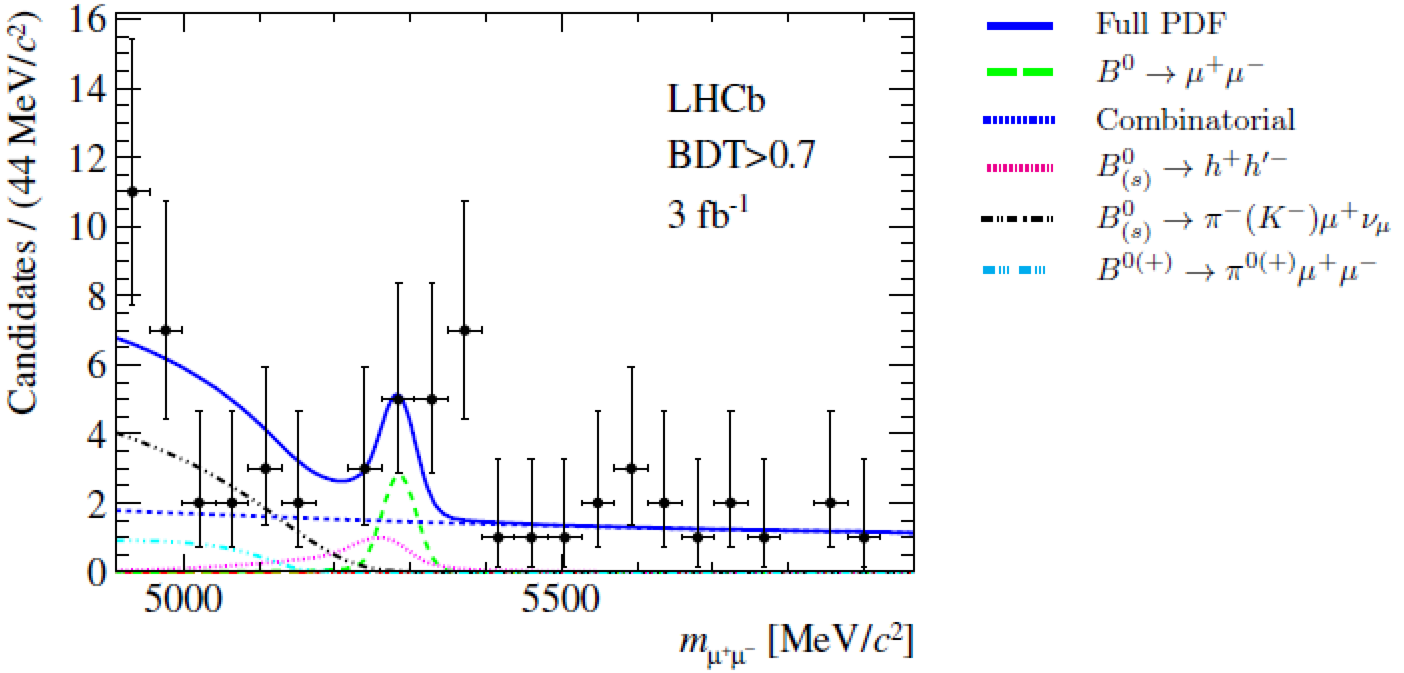
- Use CLs method: evaluate compatibility with bkg only (CL_b) and signal+bkg (CL_{s+b}) hypothesis
- The 95%CL upper limit is defined at $CL_s = CL_{s+b}/CL_b = 0.05$





	Limit at 95%CL
Expected bkg only	4.4×10^{-10}
Expected bkg + SM	5.4×10^{-10}
observed	7.4×10^{-10}

- Fit without Bs signal



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

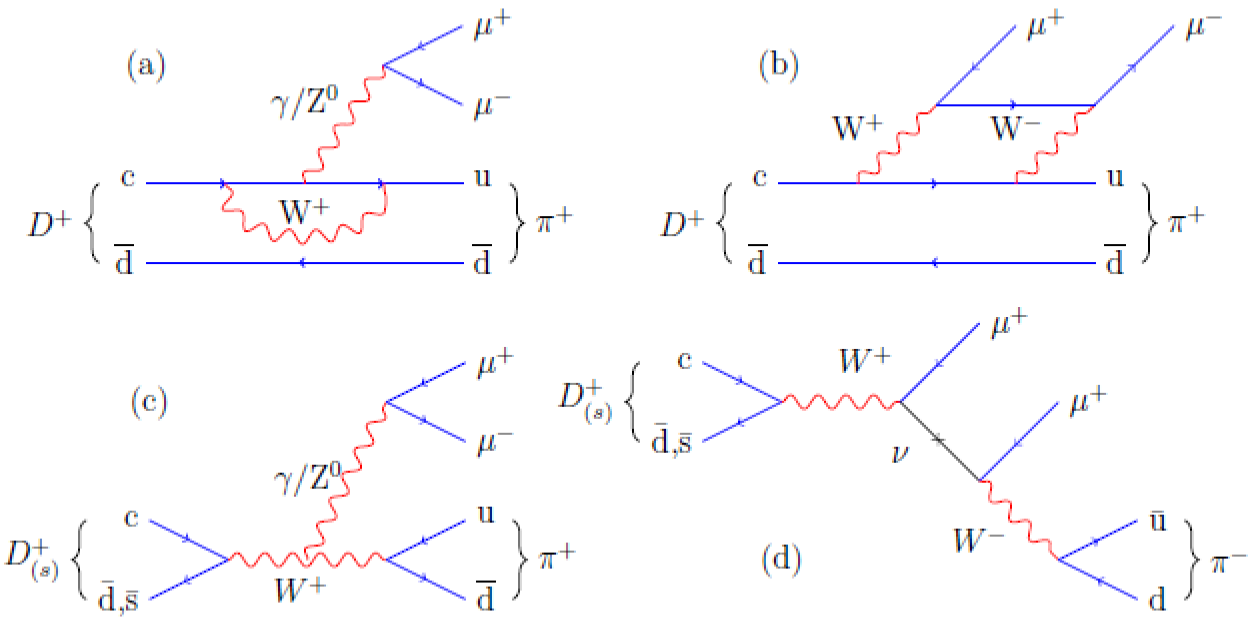


Table 1: Signal yields for the $D^+_{(s)} \to \pi^+\mu^+\mu^-$ fits. The ϕ region yields differ due to the different trigger conditions.

Trigger conditions	Bin description	$m(\mu^+\mu^-)$ range [MeV/c^2]	D^+ yield	D_s^+ yield
Triggers without $m(\mu^+\mu^-) > 1.0$ GeV/c^2	low-$m(\mu^+\mu^-)$	250 – 525	-3 ± 11	1 ± 6
	η	525 – 565	29 ± 7	22 ± 5
	ρ/ω	565 – 850	96 ± 15	87 ± 12
	ϕ	850 – 1250	2745 ± 67	3855 ± 86
All triggers	ϕ	850 – 1250	3683 ± 90	4857 ± 90
	high-$m(\mu^+\mu^-)$	1250 – 2000	16 ± 16	-17 ± 16

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\,(8.3) \times 10^{-8},$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1\,(4.8) \times 10^{-7},$$
$$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2\,(2.5) \times 10^{-8},$$
$$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2\,(1.4) \times 10^{-7}.$$