Les Rencontres de Physique
de la Vallée d'Aoste

Latest rare decay results from LHCb

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Rare decays

- Processes which are **suppressed in the SM** (FCNC, loops, GIM, helicity)

  $\Rightarrow$ NP particles in loops can produce sizeable distortions in phases, amplitudes, Lorentz structure

  $\Rightarrow$ **Many observables in rare decays probe NP**

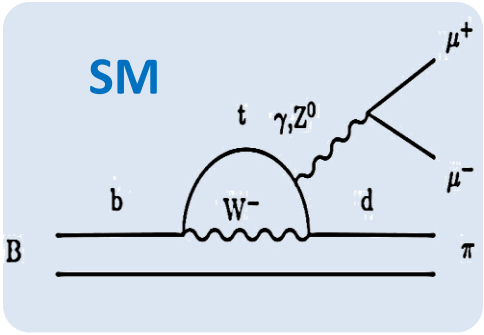
- **Today** showing results for:
  - **Branching ratios:**
    - First observation of $b \to d\ell^+\ell^-$ transition
    - Purely leptonic B, D, K decays
    - Lepton Flavour Violating B and τ decays
  - **CP violation observables**
    - $b \to s\gamma$
  - **Isospin asymmetries**

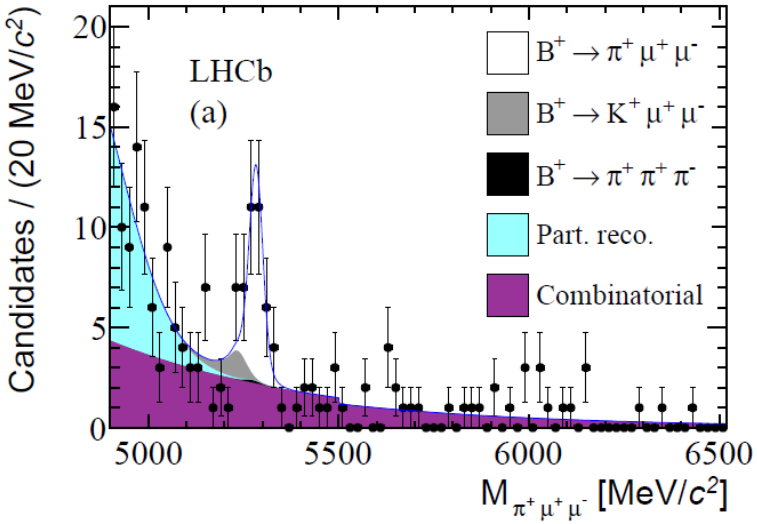
  } $b \to s\mu^+\mu^-$ transitions

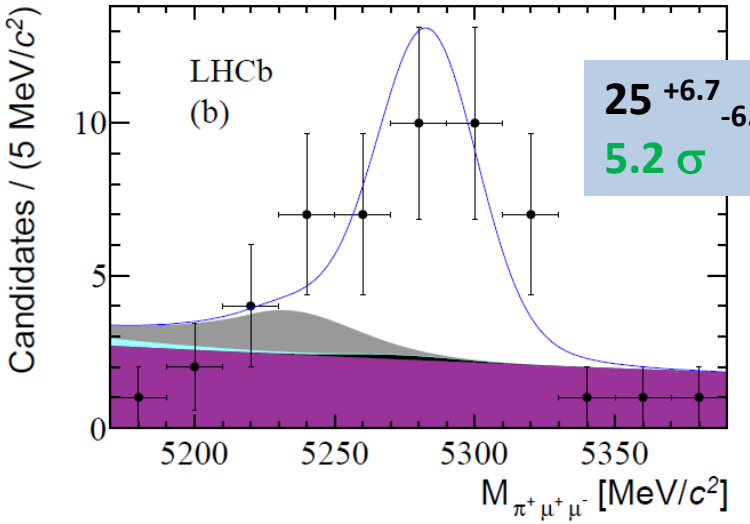
- All results shown for **$1fb^{-1}$ @ 7 TeV from 2011**, unless specified

First observation of $b \to d\ell^+\ell^-$

- SM: **BR($B^+ \to \pi^+\mu^+\mu^-$)=(2.0 ± 0.2) · 10^{-8}** [arXiv:0711.0321]
- Previous limit: < $6.9 \cdot 10^{-8}$ @ 90%CL (Belle) [arXiv:0804.3656]
- **LHCb:**
  - **Normalize based on $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+$**
  - Exclude candidates with m($\mu^+\mu^-$) consistent with J/ψ, ψ(2S)
  - Main source of systematics: limited sizes of MC samples







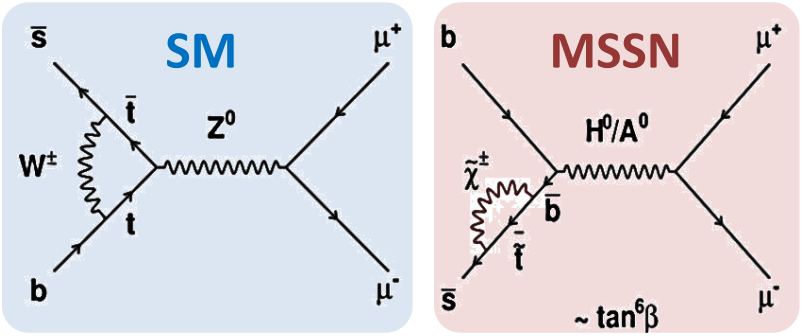
$25^{+6.7}_{-6.4}$ evts
5.2 σ

BR($B^+ \to \pi^+\mu^+\mu^-$)=[2.3±0.6(stat)± 0.1(syst)]· 10^{-8} ⇒rarest B decay seen until 11/2012

LHCB-PAPER-2012-020, subm. to JHEP

$B^0/B_s \to \mu^+\mu^-$ 2 fb^{-1}

- Double suppression: FCNC & helicity



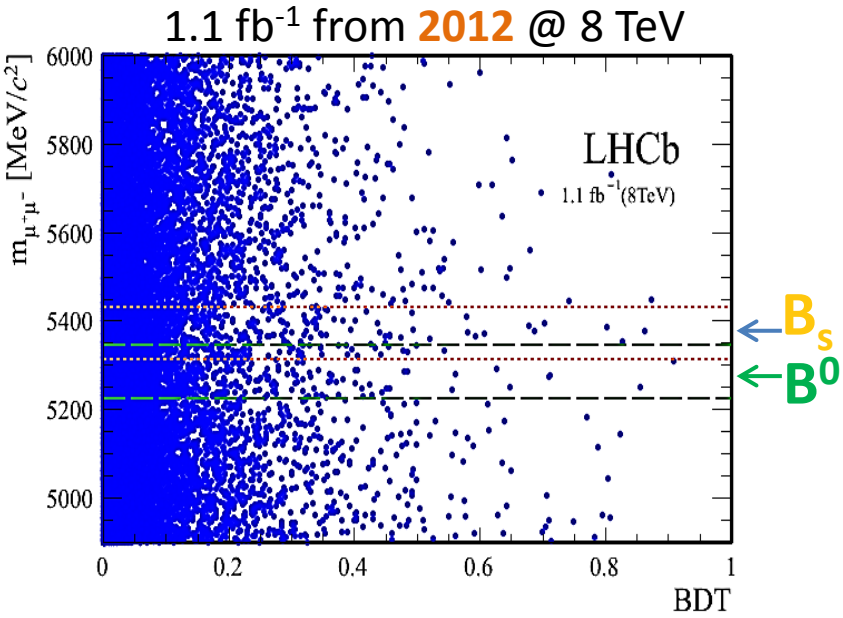
- **SM:**
  - $B_s \to \mu^+\mu^- = (3.54 \pm 0.30) \times 10^{-9}$
  - $B^0 \to \mu^+\mu^- = (0.107 \pm 0.01) \times 10^{-9}$

  Buras, Isidori: arXiv:1208.0934

- Sensitive to extended Higgs sector models: MSSM, large tanβ approximation

  $$BR(B_{s,d} \to \mu^+\mu^-) \propto \tan^6\beta / M^4_A$$

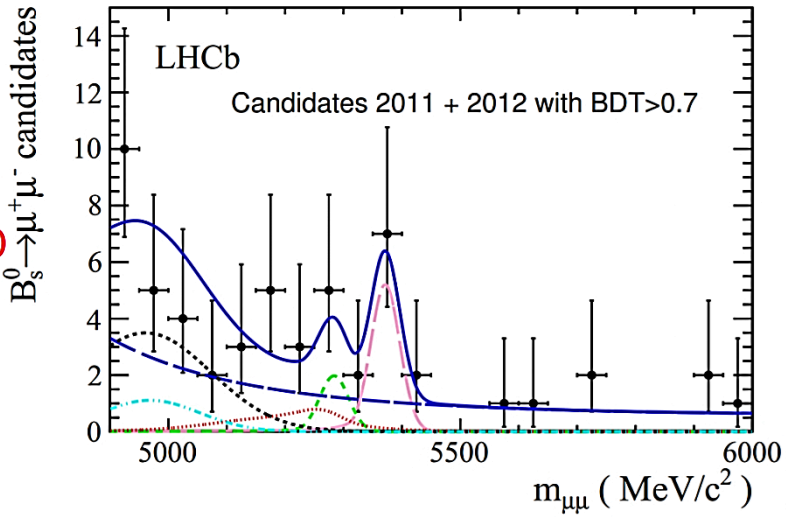
- **LHCb:**
  - maximize sensitivity by classifying events according to two variables:
    - $m_{\mu\mu}$
    - Boosted Decision Tree (BDT) combining geometrical and kinematic information
  - Use $B^0/B_s \to h^+h^-$ as calibration of BDT



$B^0/B_s \to \mu^+\mu^-$ 2 fb^{-1}

- Excess $\Rightarrow$ extract BR from a simultaneous fit to different BDT, mass bins
- BR normalized using $B_{(s)} \to h^+h^-$, $B^+ \to J/\psi K^+$

$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B_{(s)}^0 \to h^+h'^-$ mis-ID
$B^{\pm,0} \to \pi^{\pm,0}\mu^+\mu^-$
$B^0 \to \pi^-\mu^+\nu_\mu$
$b\bar{b} \to \mu^+\mu^- X$



$BR(B_s \to \mu^+\mu^-) = (3.17\ ^{+1.45}_{-1.18}\ (stat.) \pm 0.23\ (syst.)) \cdot 10^{-9}$

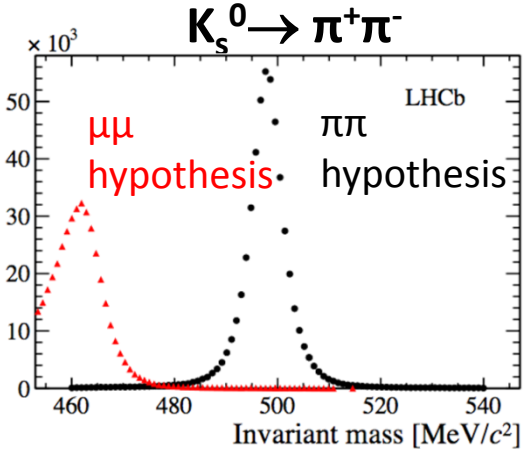
Probability of background-only fluctuation: $5 \times 10^{-4} \Leftrightarrow 3.5\ \sigma$

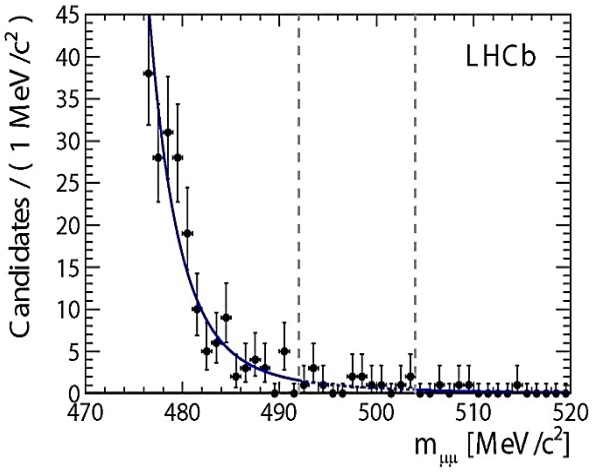
- **$BR(B^0 \to \mu^+\mu^-) < 9.4 \cdot 10^{-10}$ @ 95%C.L (World-best)**
  - Probability of background-only fluctuation: 11% $\Leftrightarrow$ 1.2 σ.

PRL 110, 021801 (2013)

$K^0_S \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$

- **SM: BR($K^0_S \to \mu^+\mu^-$) ~ $5 \cdot 10^{-12}$** [JHEP 0401(2004)009], sensitive to new light scalars
- **LHCb:** main background is misidentified $K^0_S \to \pi^+\pi^-$, with a shifted mass





- **Result: BR($K^0_S \to \mu^+\mu^-$) < $9 \cdot 10^{-9}$ at 90% CL**
  - x 30 improvement wrt previous limit (from 1973!)

PLB44 (1973) 217

JHEP 01 (2013) 090

- **SM: BR($D^0 \to \mu^+\mu^-$) ~ $6 \cdot 10^{-11}$** [PRD 66 (2992)]
- **Result: BR($D^0 \to \mu^+\mu^-$) < 1.3×10^{-8} at 95% C.L.**
  - O(10) improvement wrt previous limit fromBelle

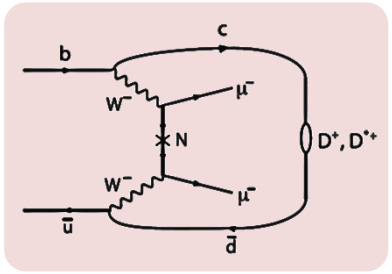
Previous talk by Benoit Viaud

LHCb-CONF-2012-005

Search for Majorana ν

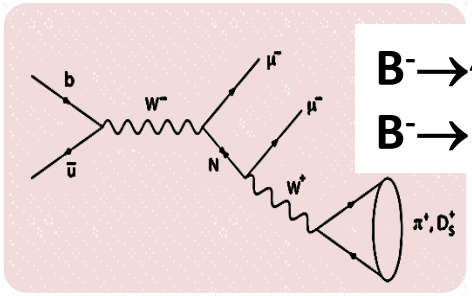
0.4fb^{-1}

- **SM:** $B^- \to (h^0)h^+\mu^-\mu^-$ are ($\Delta L=2$) strictly forbidden
- Can happen if Majorana neutrinos (N) enter in the diagrams:
- **Virtual:**

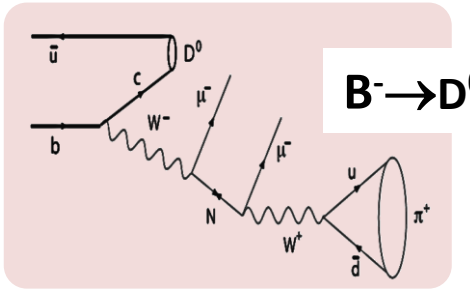


$B^- \to D^{(*)+}\mu^-\mu^-$
sensitive to any N mass

- **On-shell:**



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



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

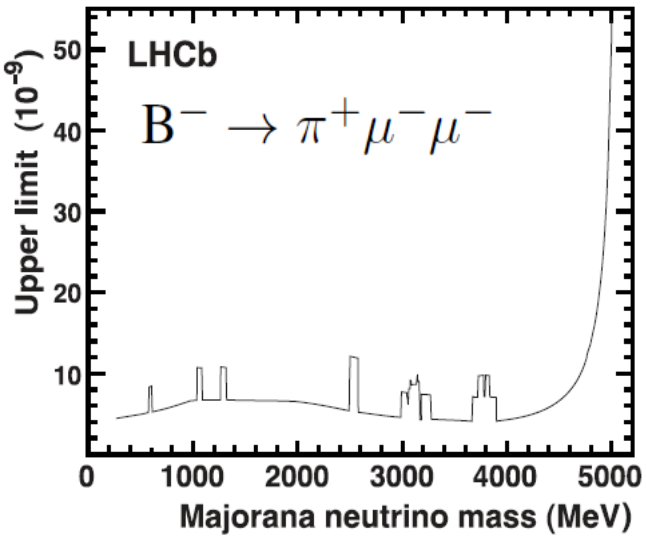
  - Additional constrain for reconstruction: $m_N = m(h^+\mu^-)$
  - Restricts the searches to the mass ranges kinematicaly accessible

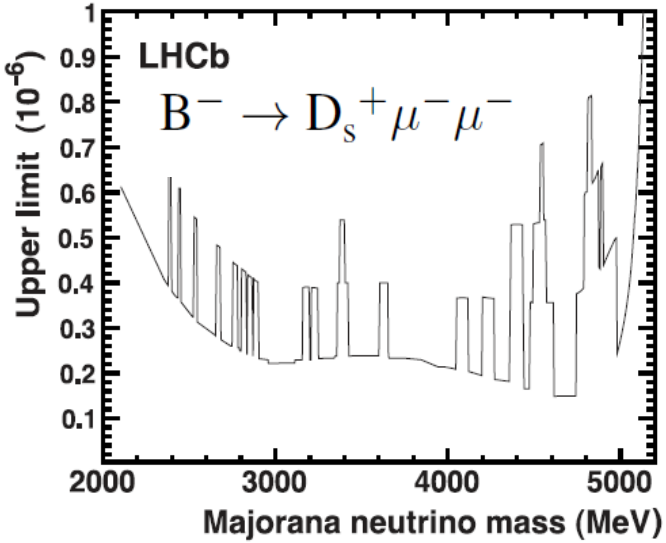
(*) : unexplored

- **LHCb:**
  - Normalize to $B^- \to J/\psi K^- \to \mu^+\mu^- K^-$ or $B^- \to \psi(2S)K^- \to \pi^+\pi^- J/\psi K^- \to \pi^+\pi^-\mu^+\mu^- K^-$
  - Assume N is narrow but has negligible flight distance

Search for Majorana ν

- Results in terms of 95% CL limits:



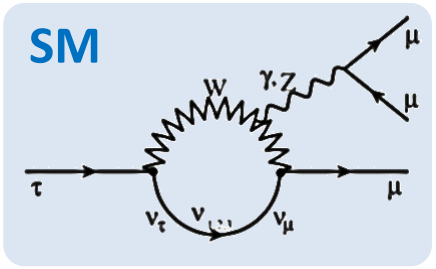


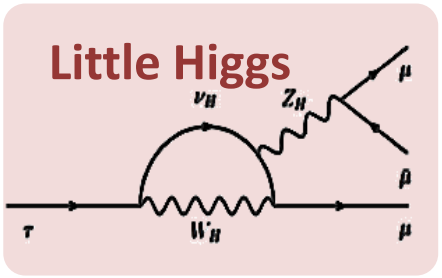
Mode	$\mathcal{B}$ upper limit	Approximate limits as function of M_N
$D^+ \mu^- \mu^-$	6.9×10^{-7}	
$D^{*+} \mu^- \mu^-$	2.4×10^{-6}	
$\pi^+ \mu^- \mu^-$	1.3×10^{-8}	$(0.4 - 1.0) \times 10^{-8}$
$D_s^+ \mu^- \mu^-$	5.8×10^{-7}	$(1.5 - 8.0) \times 10^{-7}$
$D^0 \pi^+ \mu^- \mu^-$	1.5×10^{-6}	$(0.3 - 1.5) \times 10^{-6}$

PRD85 (2012) 112004

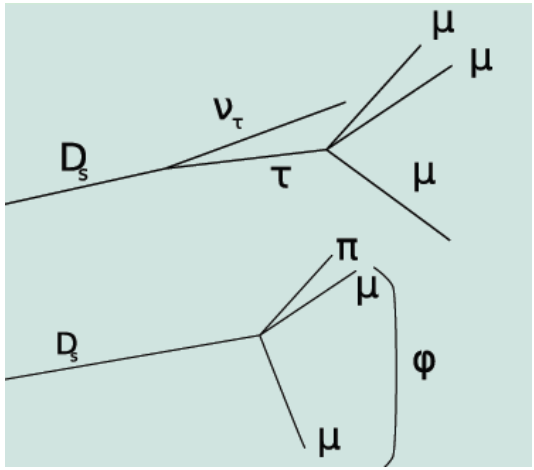
LFV decays: $\tau^- \to \mu^+\mu^-\mu^-$

- **SM: BR($\tau^- \to \mu^+\mu^-\mu^-$) <$10^{-40}$**
- **NP:** huge increases, e.g.:
  - Little Higgs: <10^{-7} [Acta Phys Pol B41 (2010) 657)]
  - Doubly charged Higgs (e.g. PLB 99 411)
- PDG: BR($\tau^- \to \mu^+\mu^-\mu^-$)< $2.1 \cdot 10^{-8}$ @90%CL, B factories



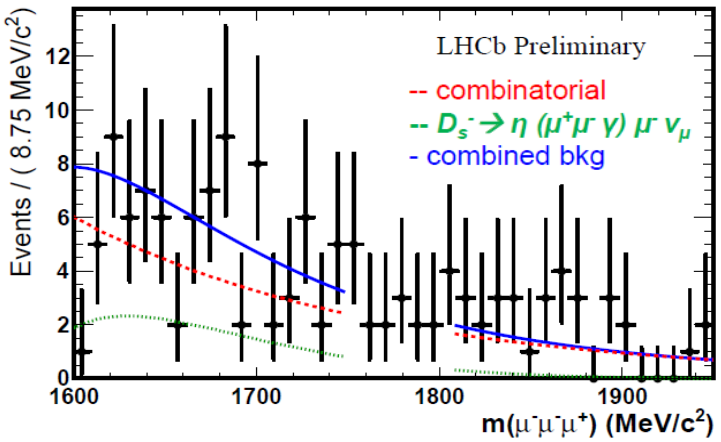


- **LHCb: ~10^{11} τ^- per year** (~80% from D^+_s)
  - Normalization and calibration on $D_s^+ \to \varphi(\mu^+\mu^-)\pi^+$
  - Maximize sensitivity by classifying à la $B_s \to \mu^+\mu^-$:
    - $m_{\mu\mu\mu}$
    - Geometric and kinematic BDT
    - Muon PID BDT with info from muon, RICH and CALO systems
  - Extract BR from global fit to all bins



LFV decays: $\tau^- \to \mu^+\mu^-\mu^-$

- For illustration: in the 5 highest-purity bins (out of 150):



- **BR($\tau^- \to \mu^+\mu^-\mu^-$) < 6.3 ·$10^{-8}$ @ 90% CL**
  - Approaching B-factory sensitivity with only 1fb^{-1}
  - Proof of principle at a hadron collider

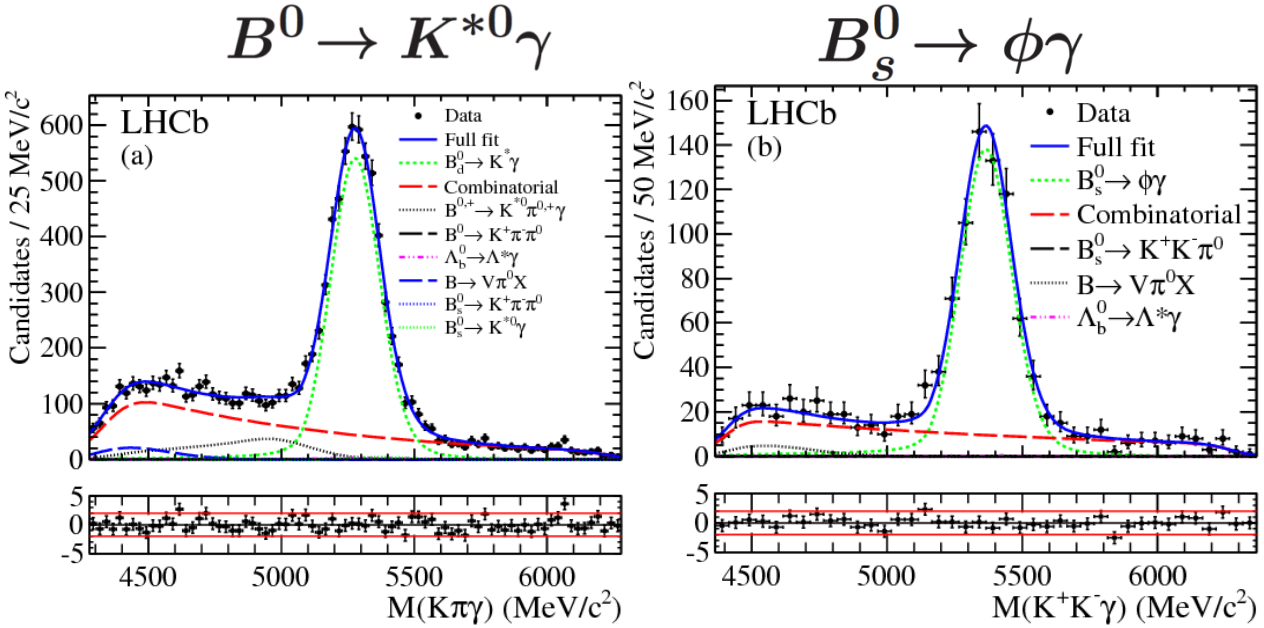
LHCb-CONF-2012-015

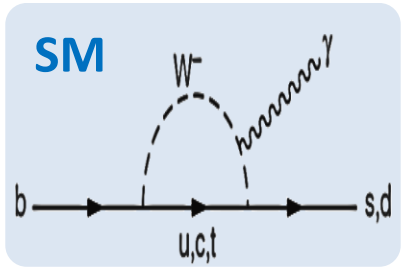
- In a very similar analysis, LHCb puts first limits on:
  - **BR($\tau^- \to \bar{p}\mu^+\mu^-$) < 4.5 · 10^{-7}**
  - **BR($\tau^- \to p\mu^-\mu^-$) < 4.5 · 10^{-7}**

LHCb-CONF-2012-018

Radiative decays: b→(d,s)γ

- Many observables: BR (10^{-5}), A_{CP}, isospin asym., γ polarization
- Two channels studied to date:





Sensitive to chromo-magnetic operator (C_{8g})

σ_m ~100 MeV, dominated by ECAL

- **World-best measurements** produced to date:

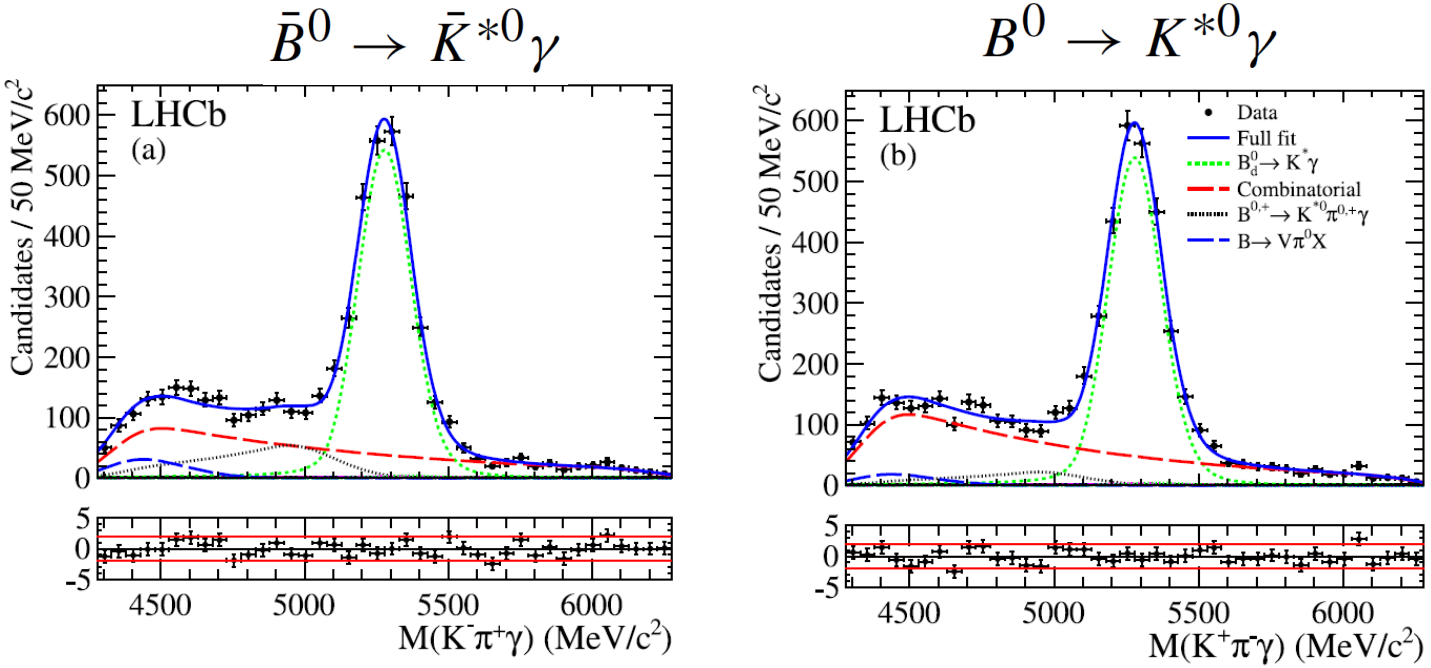
1) $$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$ **SM:** 1.0±0.2 [EPJC 55 (2008) 577]

2) By using World average of BR($B^0 \to K^*\gamma$): BR($B_s \to \phi\gamma$) = (3.9 ± 0.5) 10^{-5}

PRD 85, 112013 (2012)
NPB 867 (2013) 1-18

$A_{CP}(B^0 \to K^*\gamma)$

- **SM:** A_{CP}=(-0.61±0.43)%
- **NP: up to15%!** [PRD72 (2005) 014013, arXiv:0710.3819, PRD60 (1999) 035004, NPB554 (1999) 50,PRD58 (1998) 094012[



$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%$$

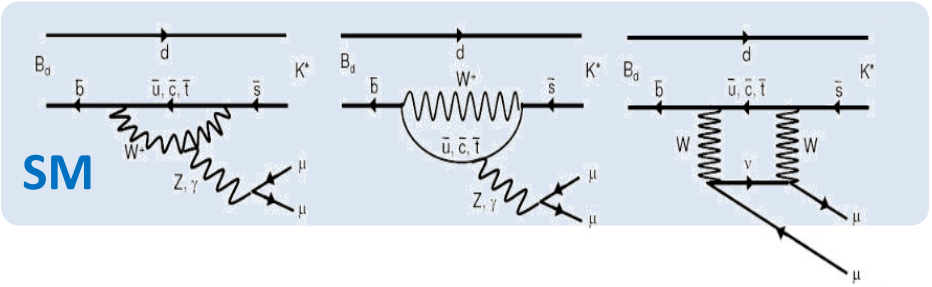
Most precise measurement to date

– New sources of systematics in CP measurements, see two previous talks

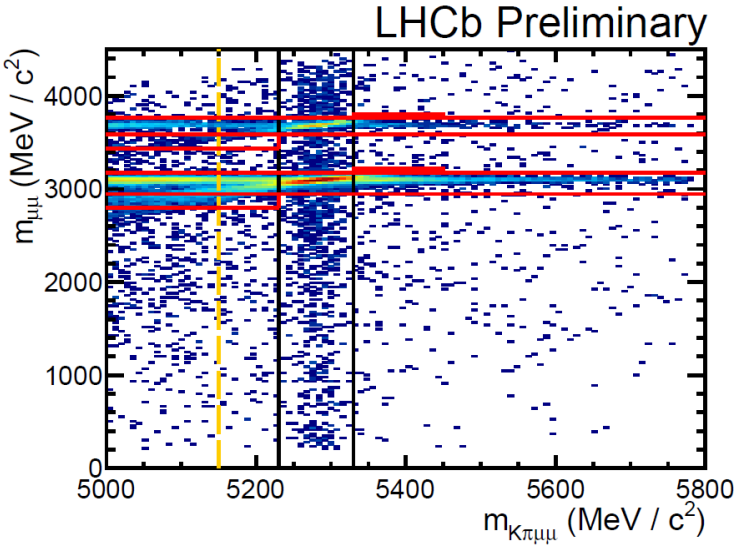
NPB 867 (2013) 1-18

$b \to s\mu^+\mu^-$: $B^0 \to K^* \mu^+\mu^-$

- BR ~ 10^{-6}
- Many **angular observables** sensitive to new operators



- **LHCb analysis:**
  - Selection based on BDT, then simultaneous fit to angles and m_B in bins of q^2 ($\equiv m_{\mu\mu}$)
  - Used $B^0 \to J/\psi K^{*0}$ for normalization, calibration of BDT, modeling angular acceptance
  - Residual angular acceptance uncertainties dominate systematics

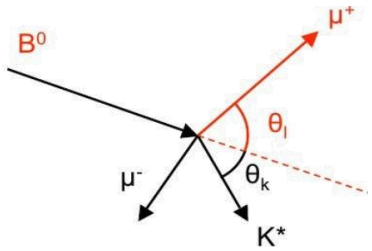


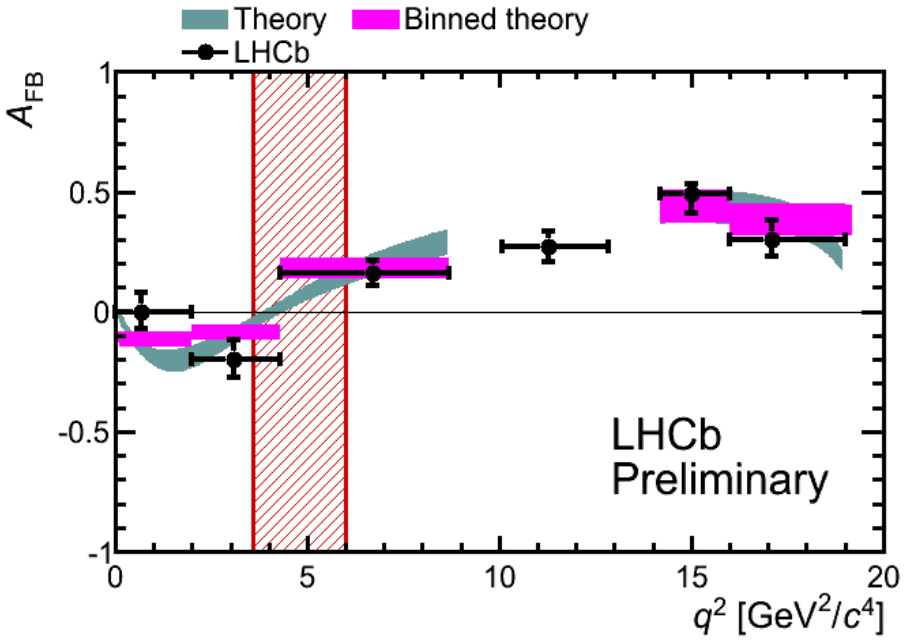
900 ± 34 signal events

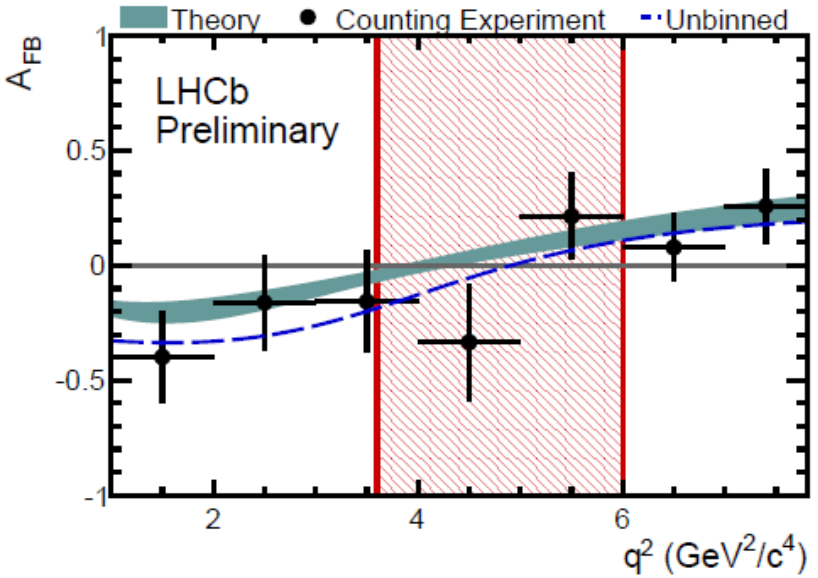
Removed to avoid cc resonances
Removed to avoid partially reco. backgr.

$B^0 \rightarrow K^* \mu^+ \mu^-$: A_{FB}

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





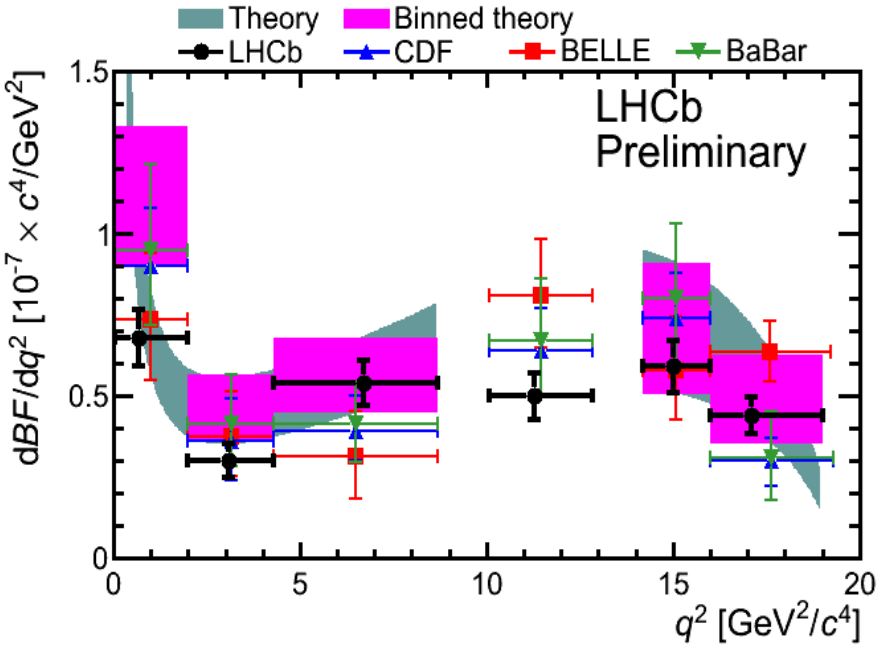


- In the SM, $A_{FB}(q^2)$ flips sign at a well predicted value of q^2
- Measured to be **$4.9^{+1.1}_{-1.3}$ GeV²** at LHCb, in agreement with SM

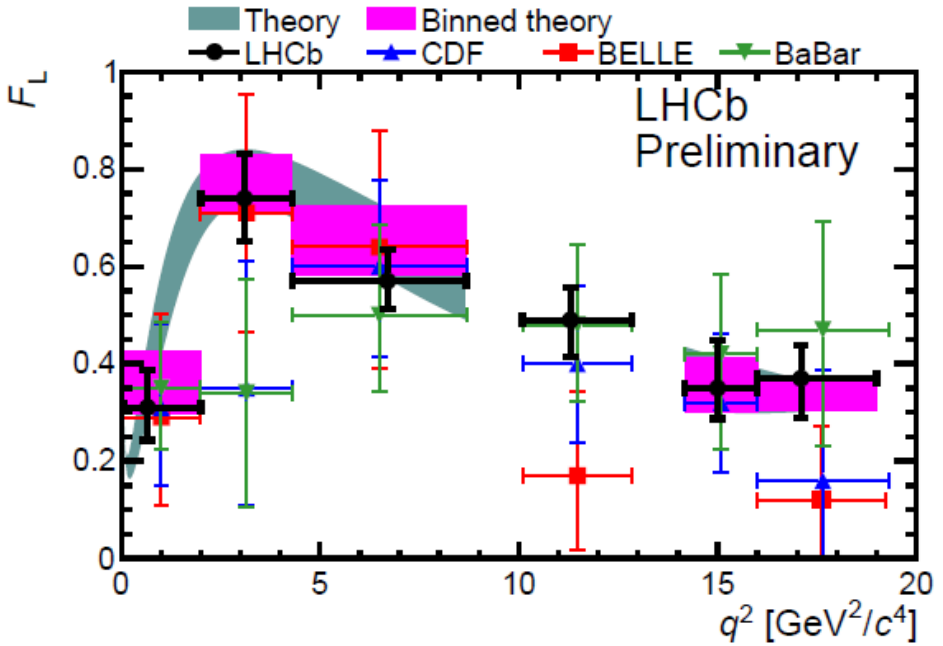
LHCB-CONF-2012-008

$B^0 \to K^* \mu^+ \mu^-$: more observables

- **Differential branching fraction**



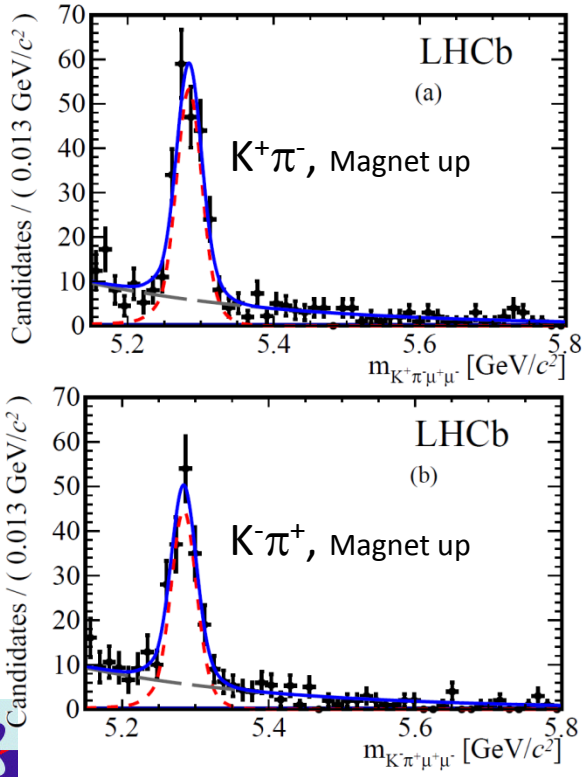
- **Fraction of longitudinally polarized K*:**

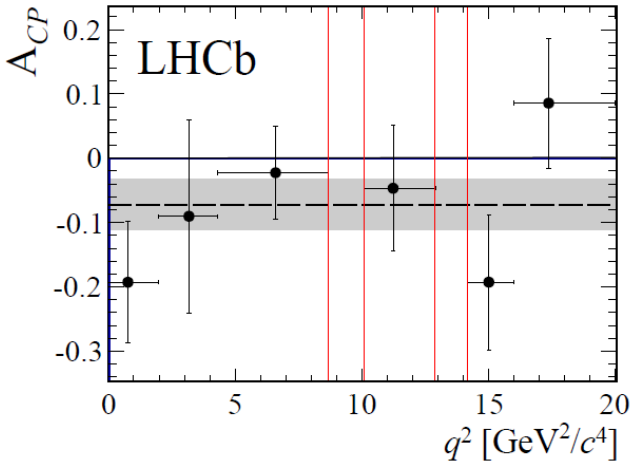


$B^0 \to K^* \mu^+ \mu^-$: CP asymmetry

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

- **SM:** $A_{CP} \sim 10^{-3}$ [JHEP 07(2008)106, JHEP 01(2009)019]
- **NP:** up to ±0.15 [JHEP 1111(2011)122]
- Dominant systematics: different kinematic of signal and control modes





$A_{CP}(B^0 \to K^* \mu^+ \mu^-) = -0.072 \pm 0.040(\text{stat}) \pm 0.005(\text{syst})$

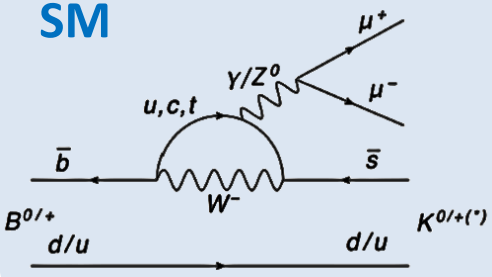
Halved uncertainties wrt B factories

PRL 110, 031801 (2013)

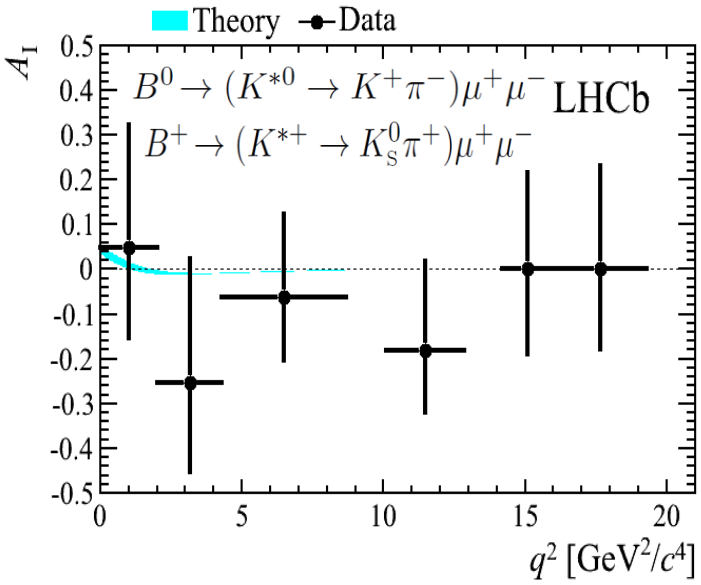
Isospin asymmetry in $B^{(+)} \to K^{(*)(+)} \mu^+\mu^-$

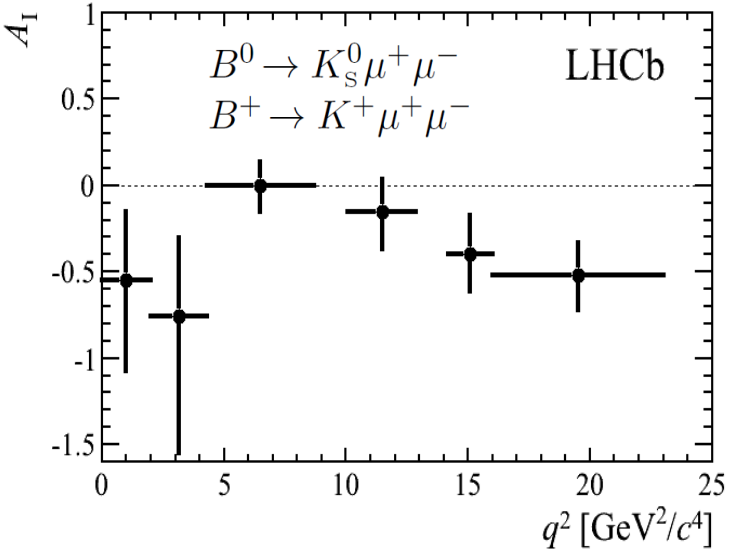
$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

SM



- **SM:**
  - *K*: A_I~-1% for $q^2 < m^2(J/\psi)$, A_I~O(10%) for $q^2 \to 0$*
  - *K:* no predictions, "expected" ~ 0
- **Results:**





- **$K\mu^+\mu^-$:** Integrating over **q^2**: **4.4σ from 0**
  - Consistent with "hints" from CDF, BaBar (3.9σ), Belle

JHEP 07 (2012) 133

Conclusions

- **Room for NP in many observables has been reduced**
  - BR($B_s \to \mu^+\mu^-$)
  - $B^0 \to K^* \mu^+\mu^-$

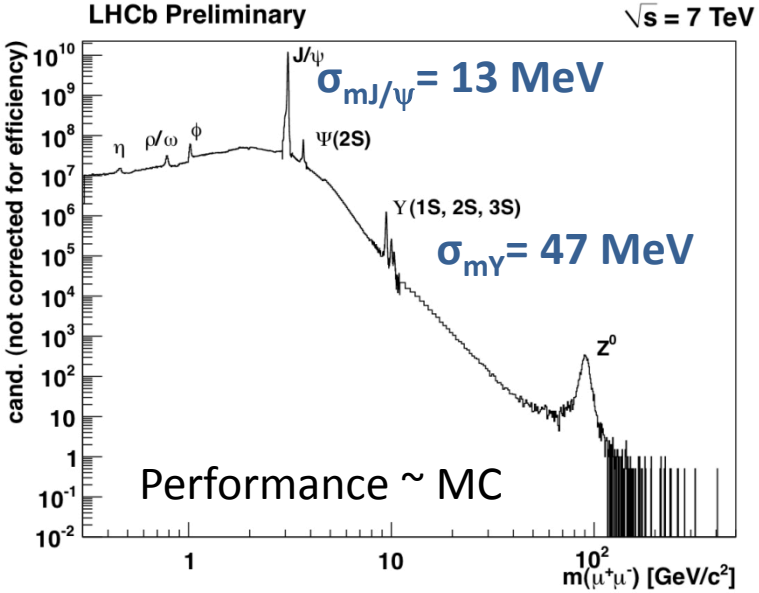
  …
- **Proof of principle** that LHCb can do challenging Physics in a hadronic environment
  - Radiative decays
  - LFV τ decays
  - Many-track decays

- **Much more to come:** 1fb^{-1} analyzed + 2 fb^{-1} on tape + 4 fb^{-1} by 2017 + 50 fb^{-1} by end of upgrade phase…

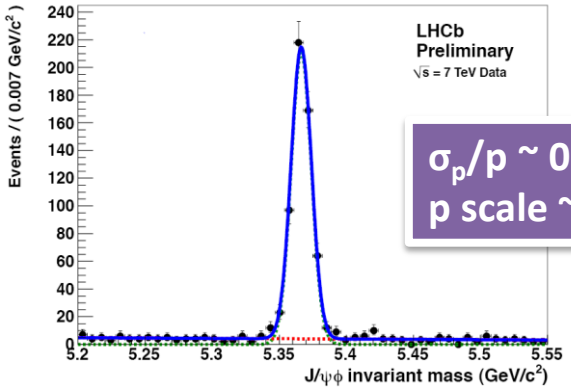
Back-up

Performance

- **Mass resolution**



$B_s \to J/\psi\phi$ (σ_{Bs}= 7 MeV)

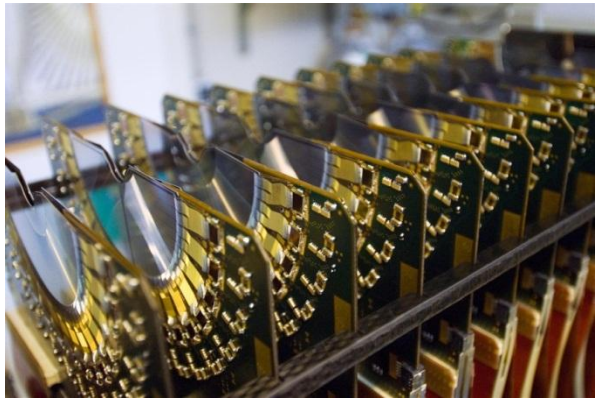


σ_p/p ~ 0.4 – 0.6 %
p scale ~ $2 \cdot 10^{-4}$ MeV

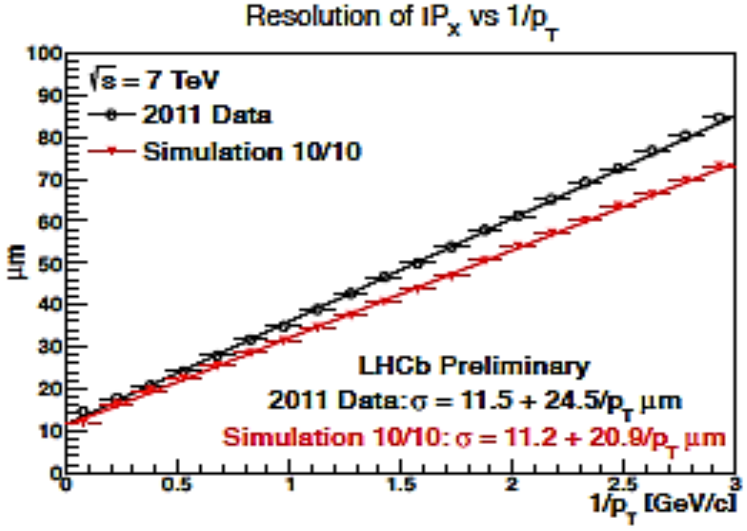
Produced World-best b-hadron masses

PLB 708 (2012) 241-248

Vertexing



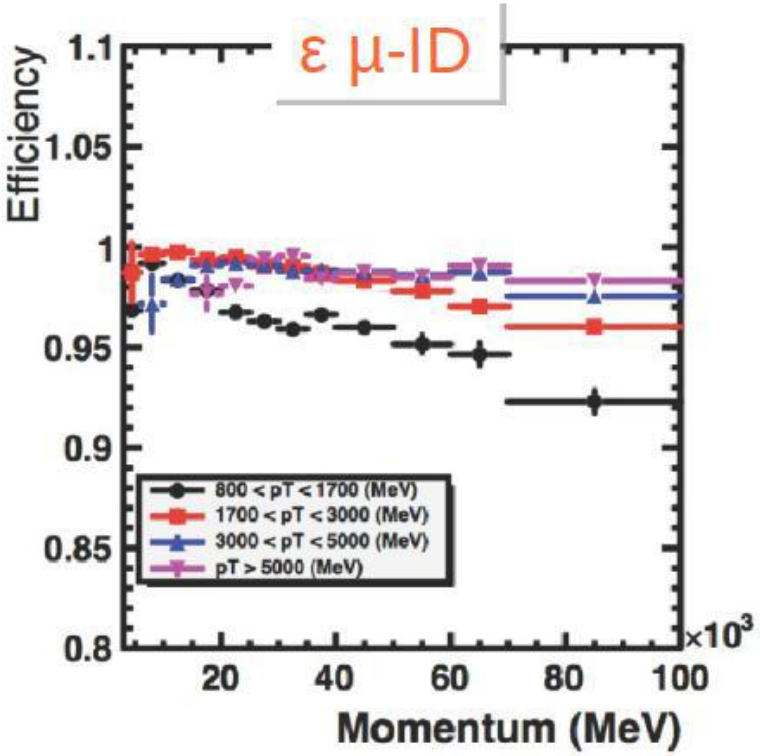
VELO: @1cm from beam!

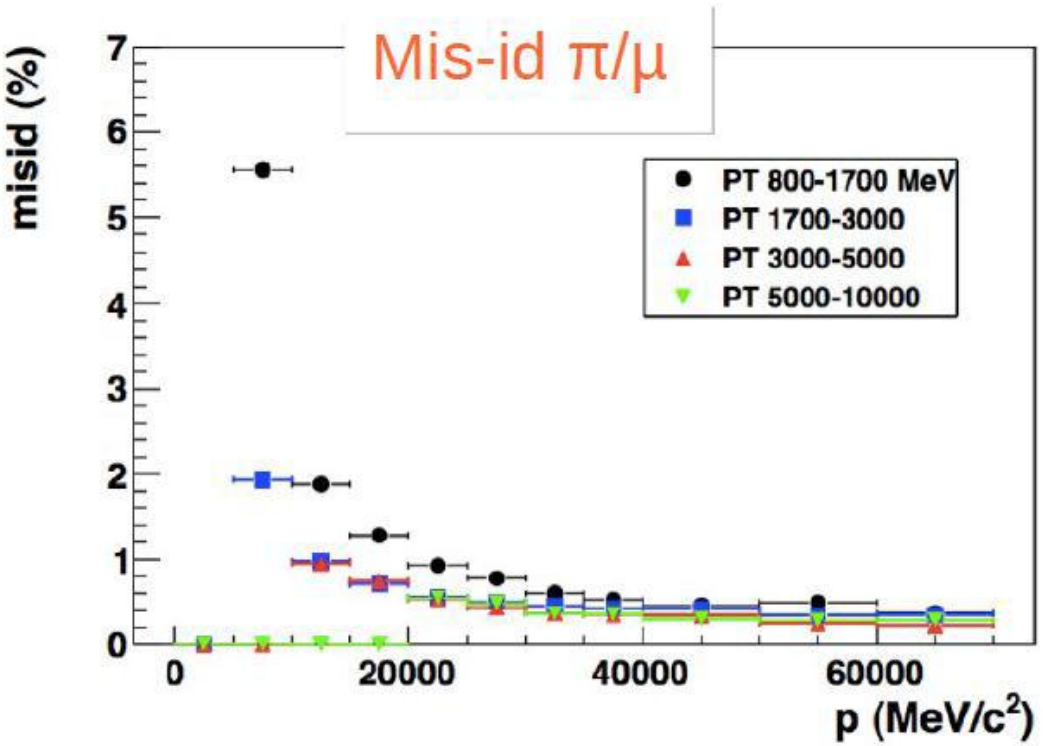


$\sigma_{\tau B}$ ~ 50 fs

period $B_d(B_s)$ ~12500(350) fs

Muon ID


ε μ-ID
Efficiency
1.1
1.05
1
0.95
0.9
0.85
0.8
800 < pT < 1700 (MeV)
1700 < pT < 3000 (MeV)
3000 < pT < 5000 (MeV)
pT > 5000 (MeV)
20
40
60
80
100
×10³
Momentum (MeV)


Mis-id π/μ
misid (%)
7
6
5
4
3
2
1
0
PT 800-1700 MeV
PT 1700-3000
PT 3000-5000
PT 5000-10000
0
20000
40000
60000
p (MeV/c²)

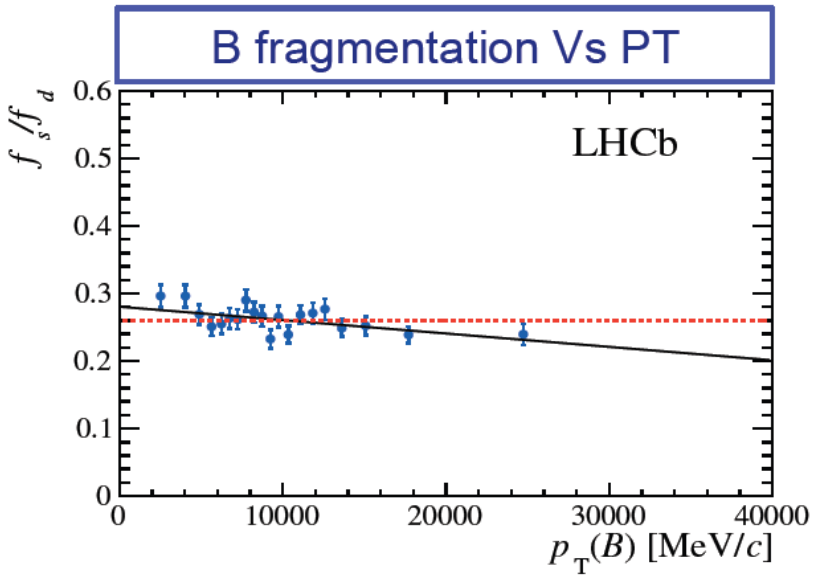
b fragmentation functions

- LHCb has measured the fraction of $b \to B_s$ in two ways:
  - Ratio of $B_s \to D_s \mu X$ to $B \to D^+ \mu X$ [PRD85 (2012) 032008]
  - Ratio of $B_s \to D_s \pi^+$ to $B \to D^+ K$ and $B^0 \to D^+ \pi^+$ (**newly updated: 1fb^{-1} @ 7 TeV**

- Combined result $\frac{f_s}{f_d} = 0.256 \pm 0.020$ [LHCb-Paper-2012-037] to appear shortly

- Found to be dependent of p_T
  - For the p_T values involved: effect smaller than 0.02 → negligible

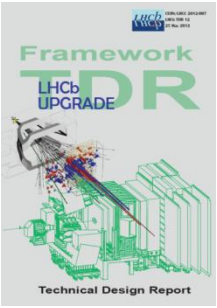
- Stability 7 vs 8 TeV checked
  - $B^+ \to J/\psi K^+ / B_s \to J/\psi \phi$ ratio stable



Upgrade

- **LHCb:** 5 fb^{-1} in coming 5 years. **Upgrade:** 50 fb^{-1}
- **Aim:** forward physics + match ~ theory precision in key observables:

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

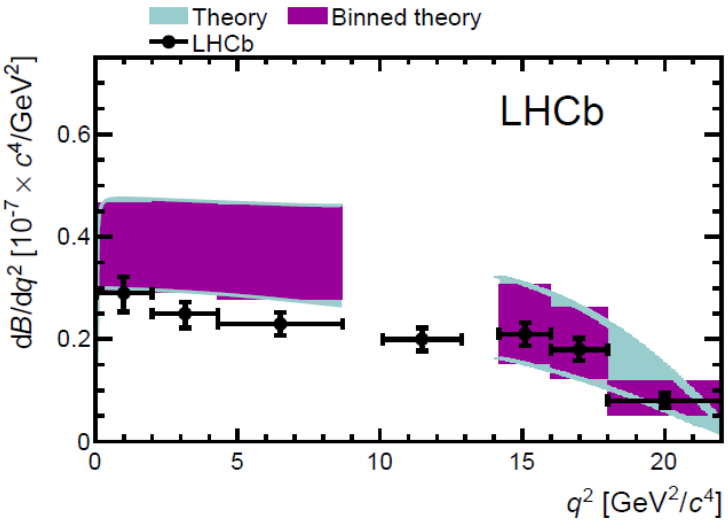


*** Statistical sensitivities,** assume measured (or SM) central values

- **How:**
  - CPU-trigger, upgrade all detectors for read-out @40 MHz
  - Increase inst. lumi. x 2.5 to 10^{33} (25ns bunch spacing)
- **Yield increase:** x 10 (20) in channels with (out) muons

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

- Normalization from $B^+ \to K^+ J/\psi \to K^+ \mu^+ \mu^-$



LHCb-PAPER-2012-024, submitted to JHEP