Search for the rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ with the LHCb Experiment

Johannes Albrecht (CERN)
for the LHCb Collaboration

Joint EP/PP/LPCC seminar, 22.March 2011

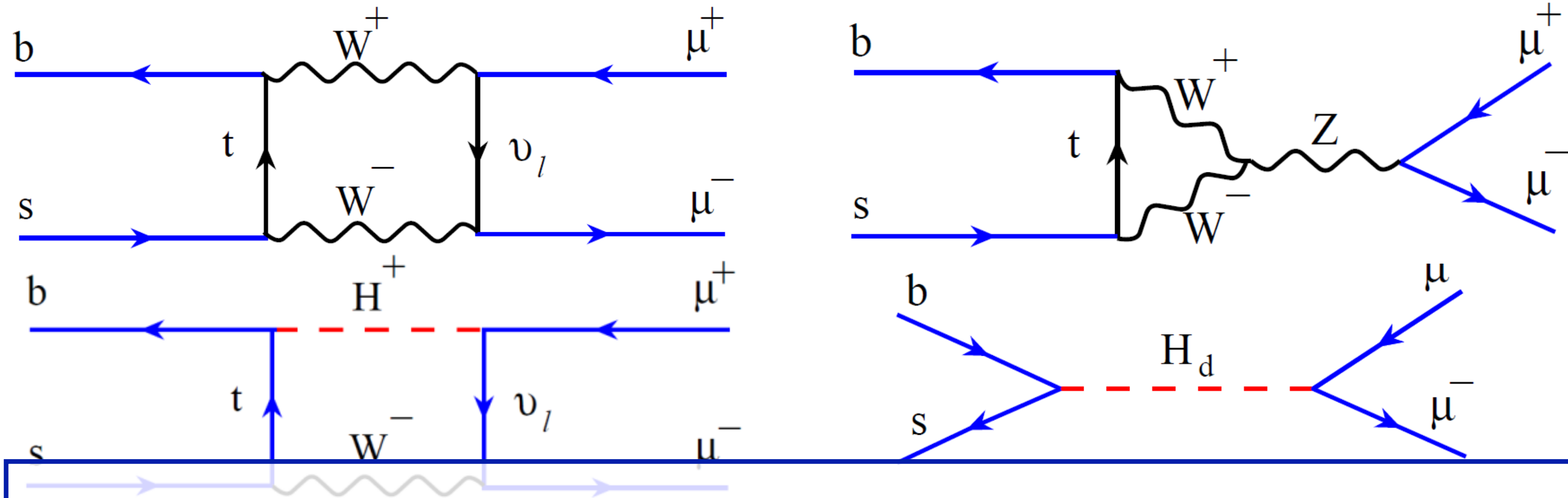
Outline

- Introduction: $B_{s,d} \rightarrow \mu^+\mu^-$ as probe for New Physics

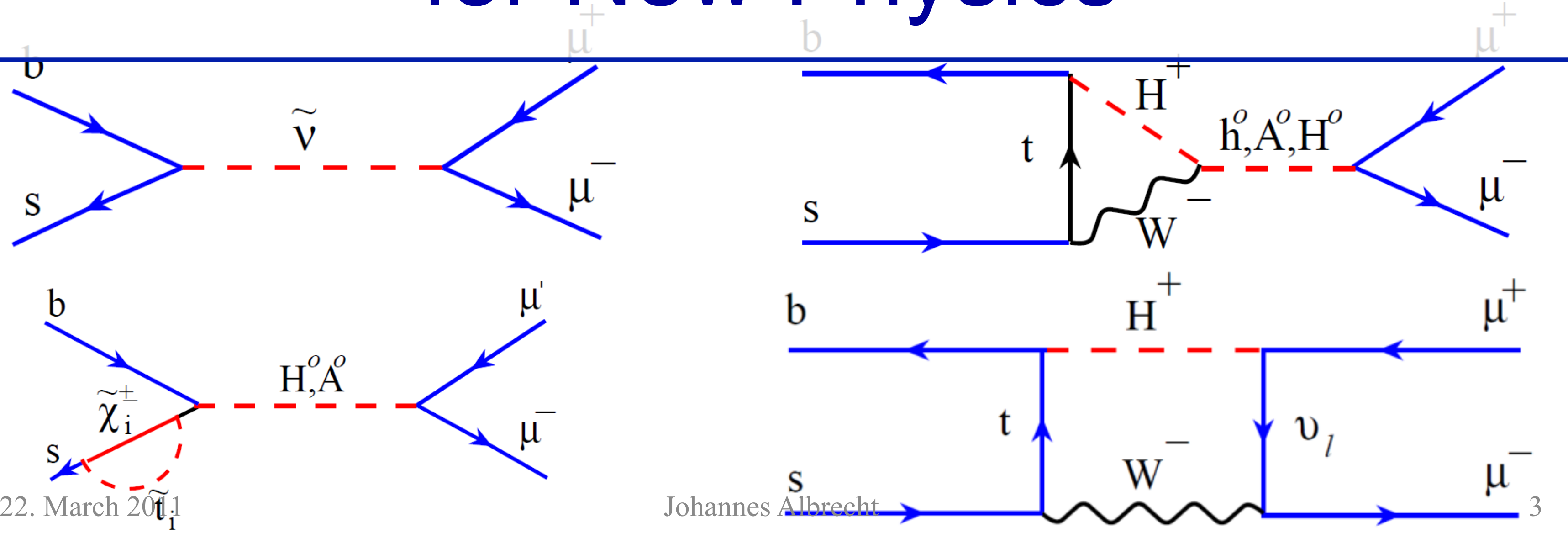
- The LHCb experiment
  - Overview of the experiment and performance

- Search for $B_{s,d} \rightarrow \mu^+\mu^-$ decays
  - Selection
  - Signal and background likelihoods
  - Normalization
  - Extraction of the limit

- Summary & Outlook



Introduction: $B_{s,d} \rightarrow \mu^+\mu^-$ as probe for New Physics



Indirect approach to New Physics

- ***Flavour physics in the LHC era***

ATLAS / CMS

A *unique* effort toward the high-energy frontier

Coutesy of G. Isidori, LP07

LHCb

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV

Universality tests in B

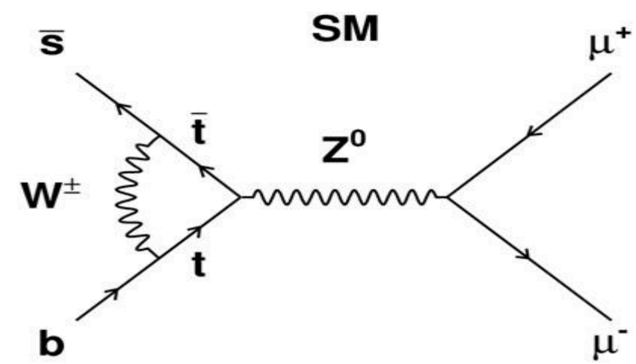
$B_{s,d} \rightarrow \mu^+\mu^-$ in the Standard Model

Double suppressed decay: **FCNC process** and **helicity suppressed**:

➔ **very small in the Standard Model but well predicted:**

Mode	SM
$B_s \rightarrow \mu^+\mu^-$	$3.2 \pm 0.2\ 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$0.10 \pm 0.01\ 10^{-9}$

A.J.Buras: arXiv:1012.1447
E. Gamiz et al: Phys.Rev.D 80 (2009) 014503



BR expressed Wilson coefficients:

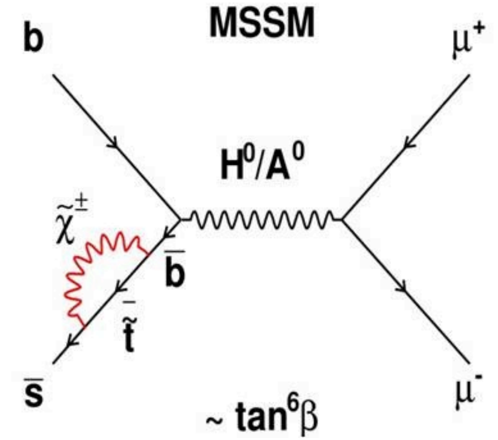
$$BR(B_q \to l^+l^-) \approx \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 \tau_{B_q}}{64\pi^3 \sin^4\theta_W} |V_{tb}V_{tq}^*|^2 \sqrt{1-\frac{4m_l^2}{M_{B_q}^2}}$$
$$\left\{ M_{B_q}^2 \left(1-\frac{4m_l^2}{M_{B_q}^2}\right) c_S^2 + \left[M_{B_q} c_P + \frac{2m_l}{M_{B_q}}(c_A - c_A')\right]^2 \right\}.$$

→ sensitive to contributions in the **scalar/pseudo-scalar sector**
→ highly interesting to probe **extended Higgs** models

$B_{s,d} \to \mu^+\mu^-$ as probe for New Physics

- <u>Example: MSSM</u>
  (with R-parity conservation)

$$BR(B_s \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{m_A^4}$$



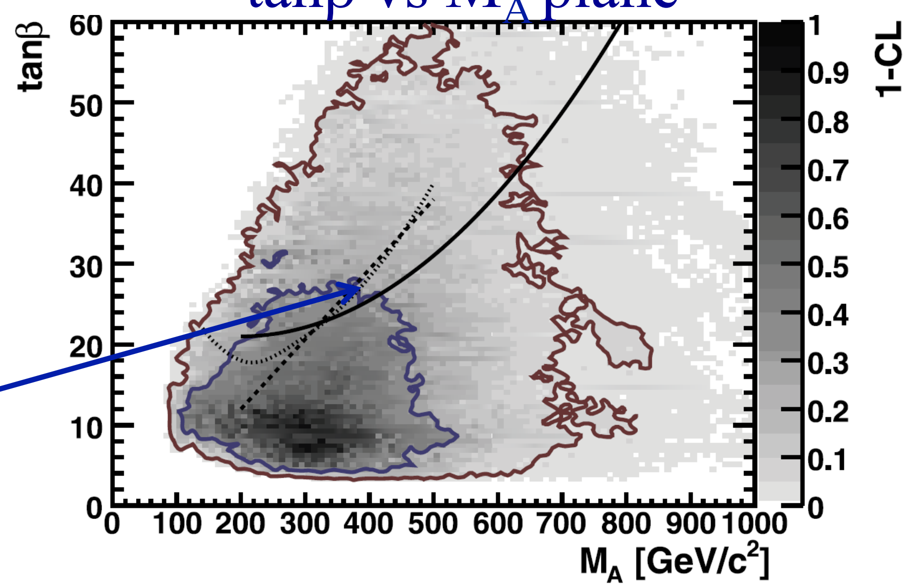
➔ limit or measurement of $B_{s,d} \to \mu\mu$ will strongly constrain $\tan\beta$ vs M_A plane

- <u>NUHM1</u>

  Best fit contours in $\tan\beta$ vs M_A plane in the NUHM1 model
  [O. Buchmuller et al, arxiv:0907.5568]

  CMS direct search 30-60fb^{-1}: 5σ discovery $H/A \to \tau\tau$
  (2007 analysis: arXiv:0704.0619)

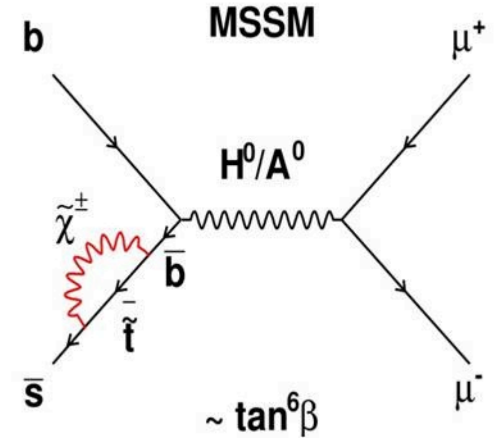
$\tan\beta$ vs M_A plane



$B_{s,d} \to \mu^+\mu^-$ as probe for New Physics

- Example: MSSM
  (with R-parity conservation)

$$BR(B_S \to \mu^+\mu^-) \propto \frac{\tan^6 \beta}{m_A^4}$$



➔ limit or measurement of $B_{s,d} \to \mu\mu$ will strongly constrain $\tan\beta$ vs M_A plane

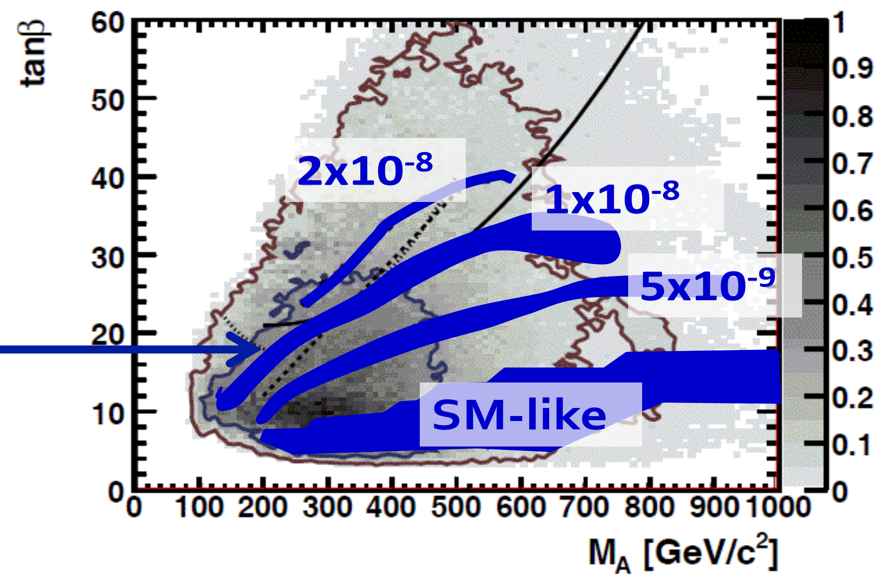
- NUHM1

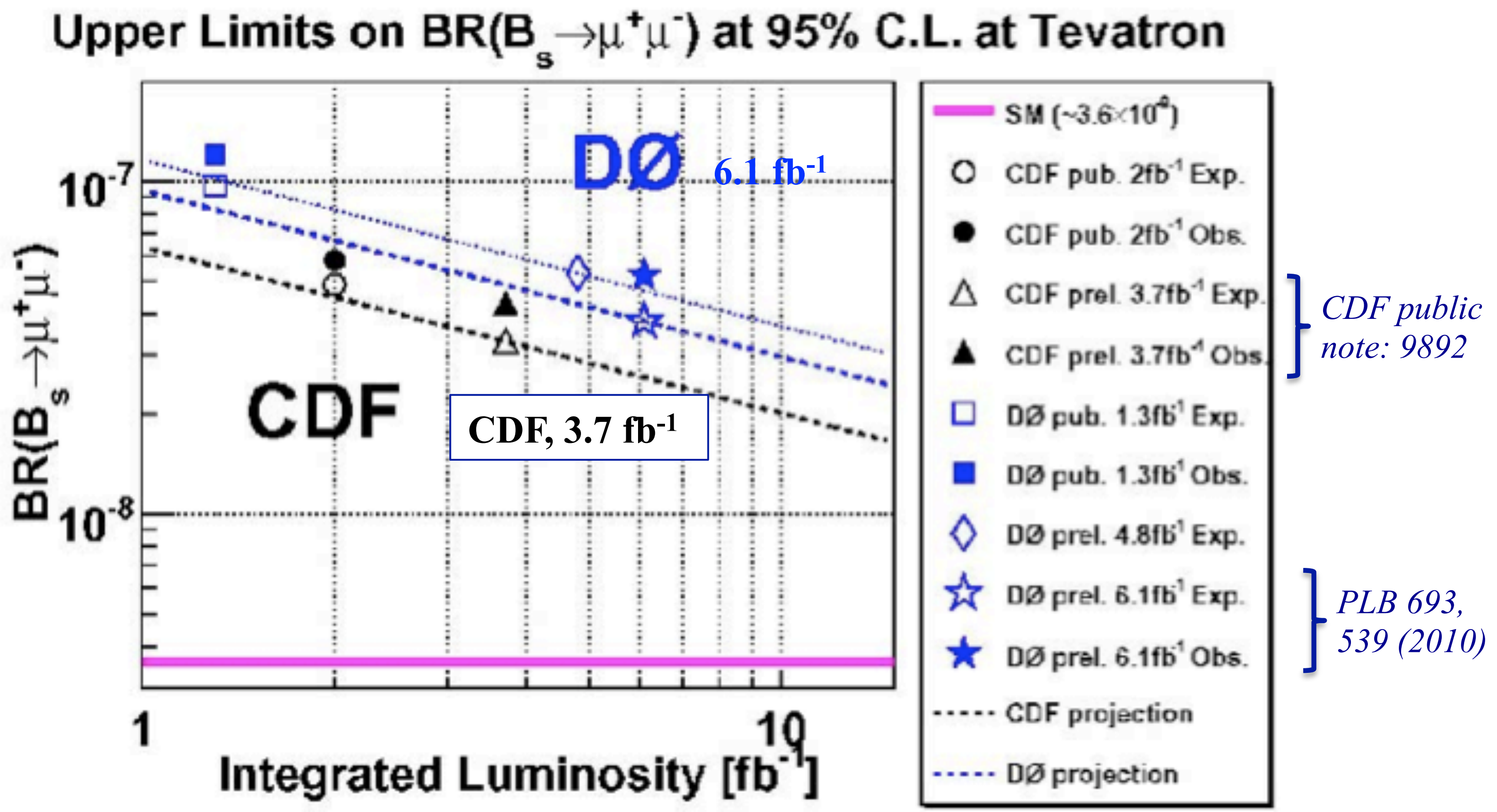
Best fit contours in $\tan\beta$ vs M_A plane in the NUHM1 model
[O. Buchmuller et al, arxiv:0907.5568]

Regions compatible with
$BR(B_s \to \mu\mu) = 2x10^{-8}, 1x10^{-8}, 5x10^{-9}$ and SM

LHCb calculation using
F. Mahmoudi, SuperIso, arXiv: 08083144

$\tan\beta$ vs M_A plane



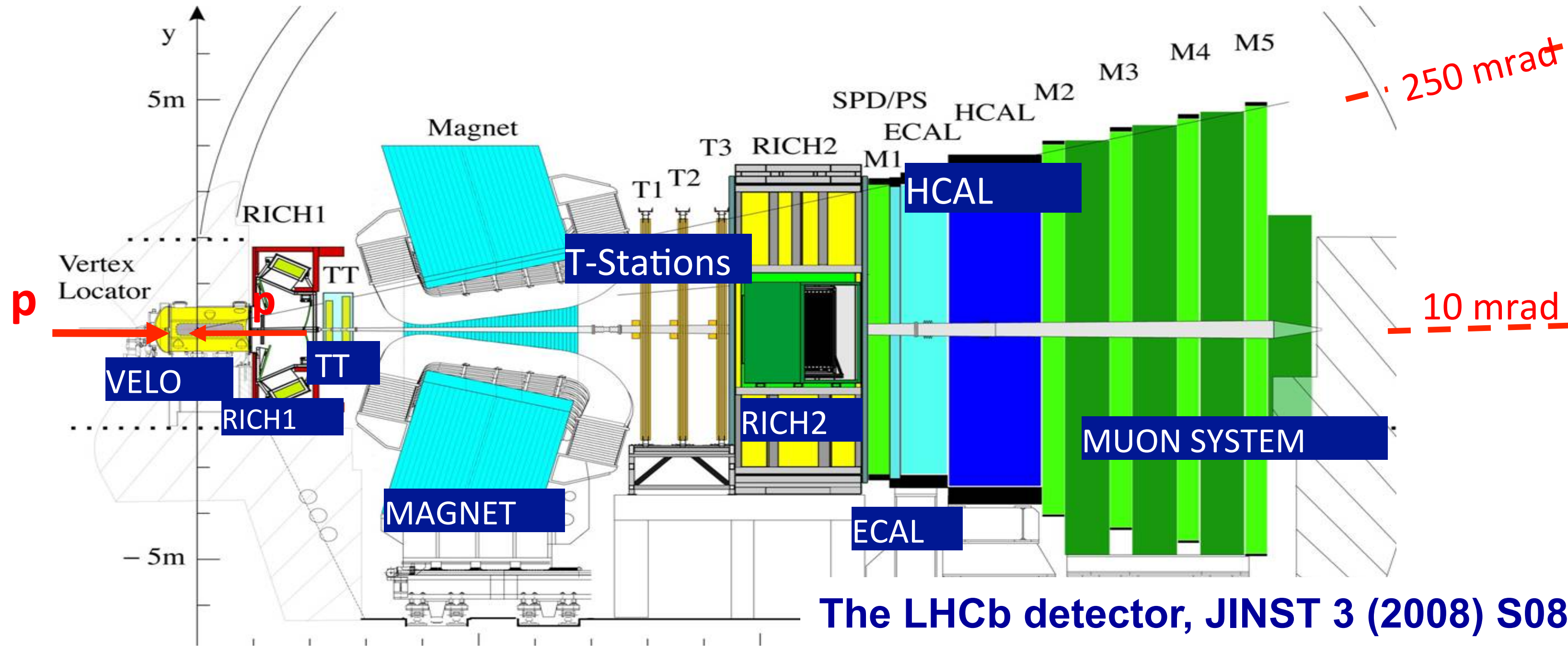


Limits from Tevatron @ 95% CL:

- CDF (~3.7 fb^{-1}): B_S (B_d) → μμ **< 43 (7.6) ×10^{-9}** **factor ~13 from SM**
- D0 (~6.1 fb^{-1}): B_S→μμ **< 51×10^{-9}**

The LHCb Experiment: Overview of the experiment and performance

The LHCb detector



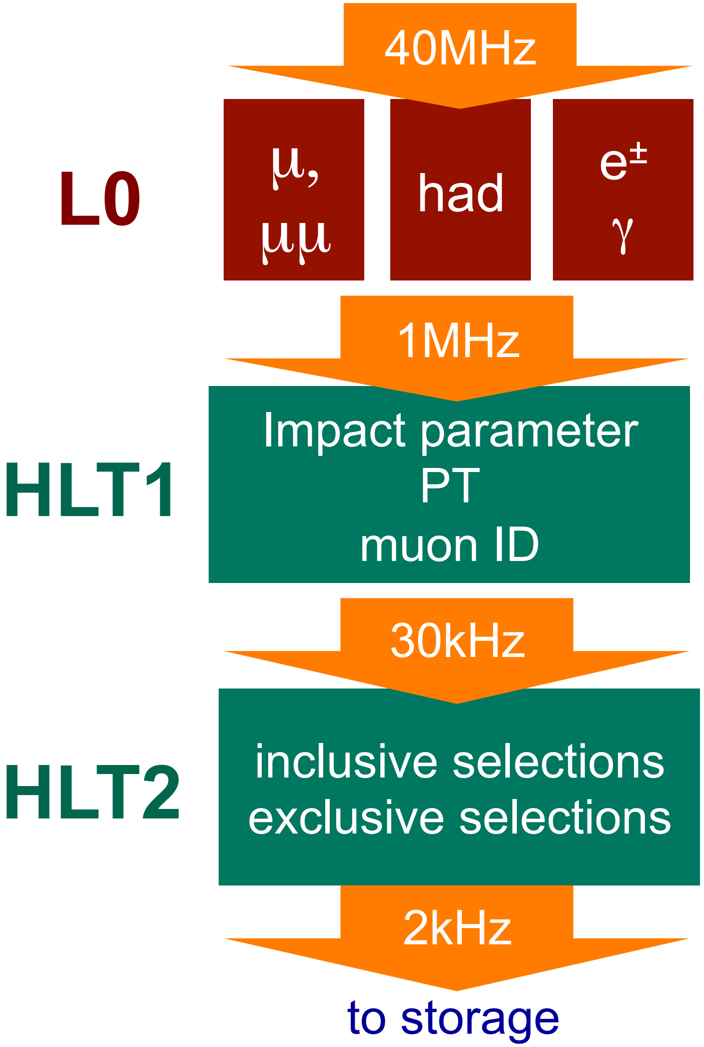
The LHCb detector, JINST 3 (2008) S08005

- Huge cross sections: **$\sigma(pp \rightarrow bbX)$ @ 7 TeV ~ 300 μb***
  - But only 1/200 events contain b quark → Trigger
- Large acceptance **$1.9<\eta<4.9$**
- Large boost:
  - **average flight distance of B mesons ~ 10mm**

→ A huge amount of very displaced b's

(*) LHCb, Phys.Lett.B 694 (2010) 209

Keys for b-physics I: Trigger



Small event size (60kB)
→ large bandwidth
→ allows low trigger thresholds

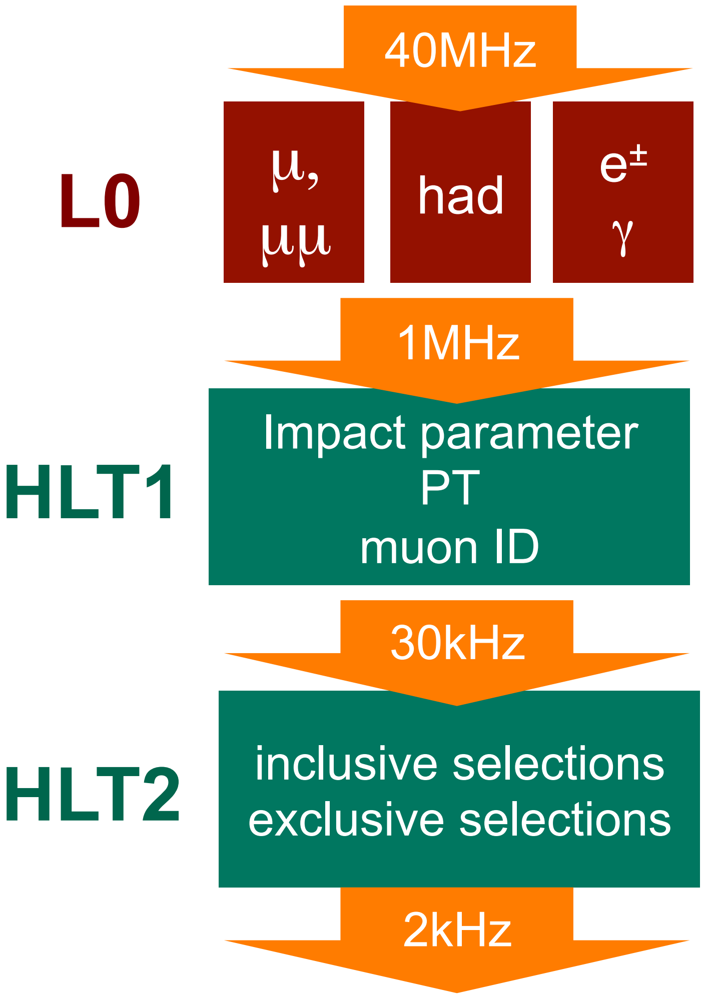
L0 hardware	**"high p_T" signals in calorimeter and muon systems**
HLT1 software	Partial reconstruction selection based on one or two tracks (dimuon) displaced in the VELO, muon ID (offline like)
HLT2 software	Global reconstruction (very close to offline) dominantly inclusive signatures

+ Global event cuts rejecting busy events

	Charm	**Hadr. B**	**Lept. B**
Global efficiency	~10%	~40%	75-90%

Keys for b-physics I: Muon trigger

Half of the bandwidth (~1 kHz) given to the muon lines
p_T cuts on muon lines kept very low → trigger efficiency very high
Trigger rather stable during the whole period (despite L increased by ~10^5)

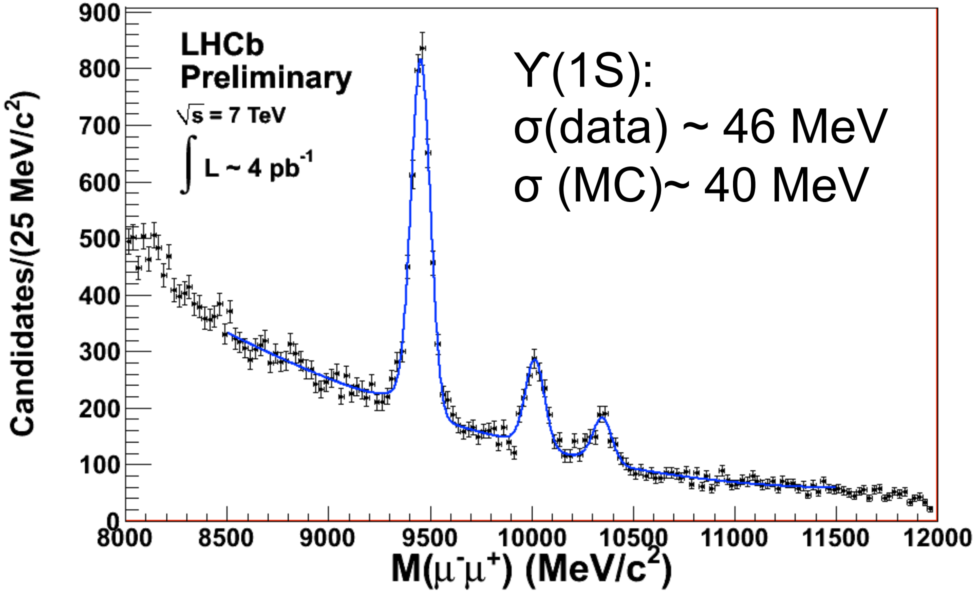


Muon lines:

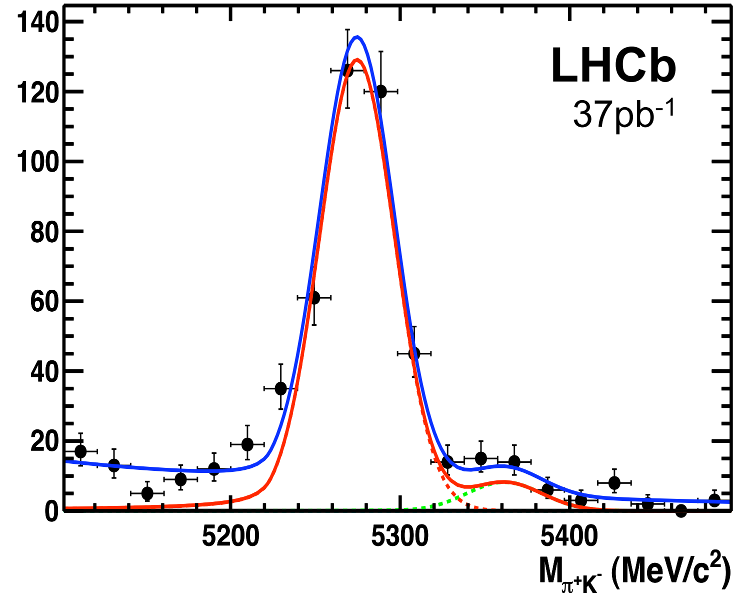
L0 hardware	**Single-μ: p_T>1.4GeV/c** **Di – μ : 2 clean muons** **p_{T1}>0.56GeV/c** **p_{T2}>0.48GeV/c**
HLT1 software	Single-μ: p_T>0.8GeV/c IP > 0.11mm, IPS > 5 Single-μ: p_T>1.8GeV/c (no IP)
HLT2 software	Dimuon: $M_{\mu\mu}$ > 4.7GeV/c² Δm(J/ψ) < 120 MeV/c² Several lines with p_T and vertex displacement cuts

Keys for b-physics II: mass resolution

Υ(1S), Υ(2S), Υ(3S)



$B^0 \rightarrow K^{\pm}\pi^{\pm}$

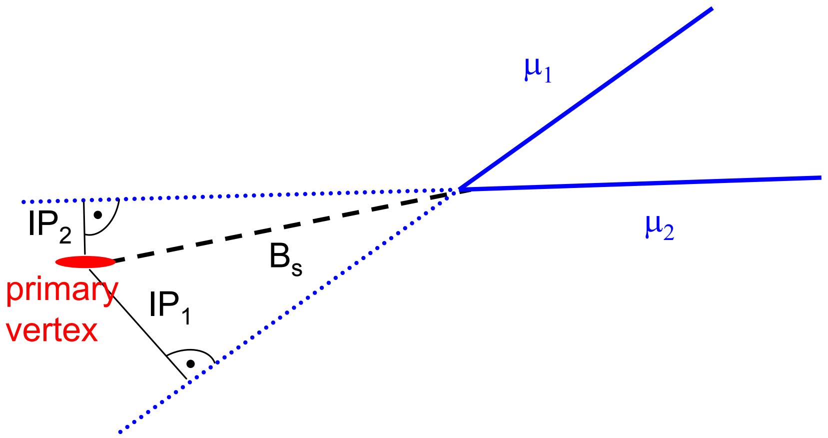


	momentum resolution	mass resolution $J/\psi \rightarrow \mu\mu$
LHCb	$\delta p/p$ = 0.4-0.6 %	13 MeV
CMS	$\delta pt/pt$ = 1-3 %	40 MeV
ATLAS	$\delta pt/pt$ = 5-6 %	71 MeV

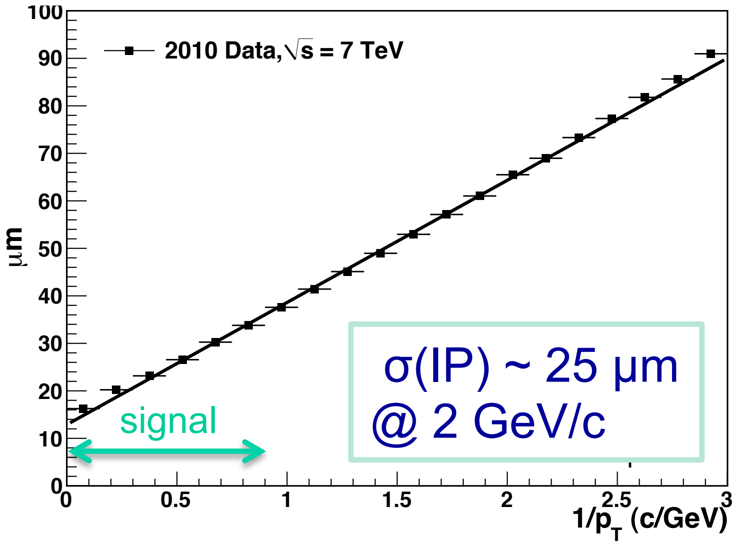
Primary vertex resolutions (25 tracks):

	LHCb [μm]	ATLAS [μm]	CMS [μm]
σ(x)	15.8	60	20-40
σ(y)	15.2	60	20-40
σ(z)	76	100	40-60

Impact parameter (IP):

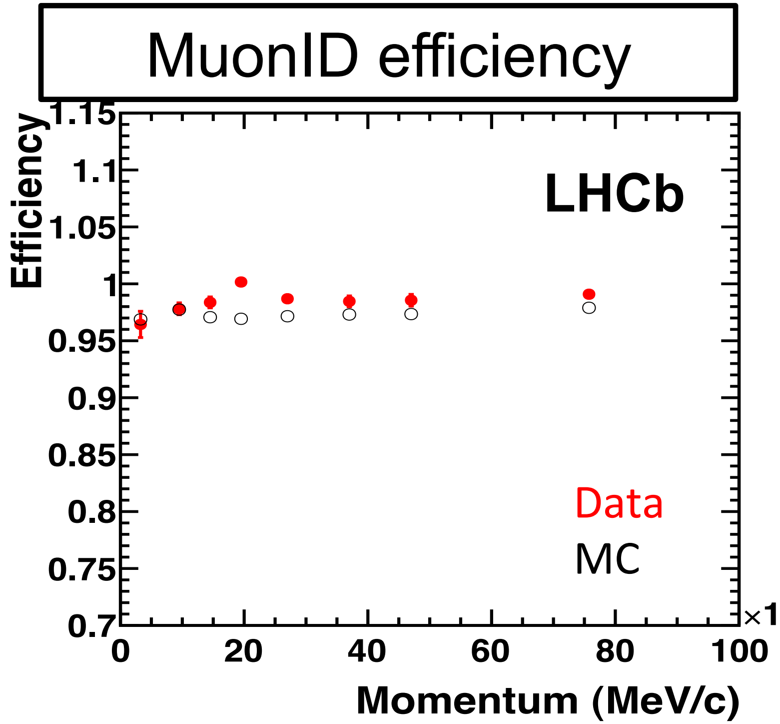


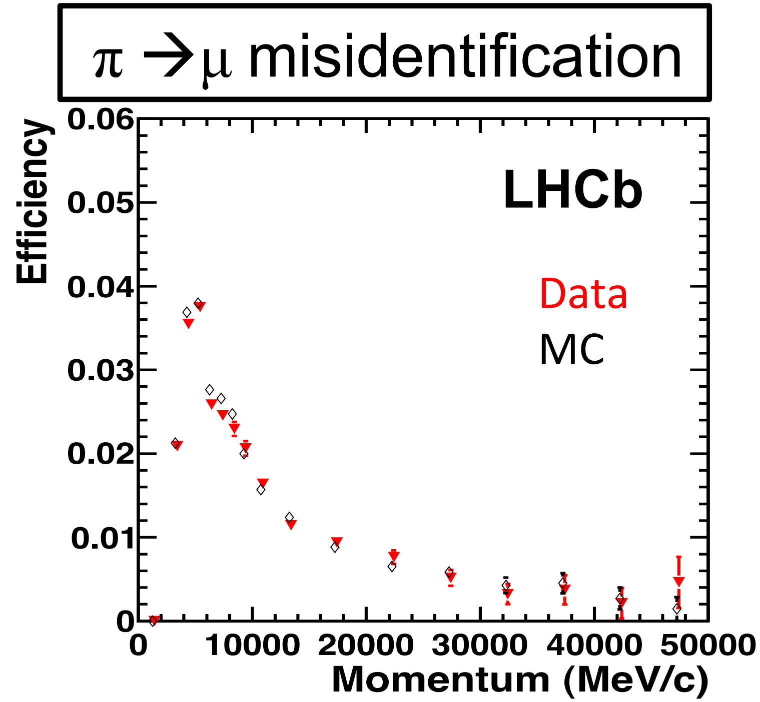
IP resolution vs 1/pT



Keys for b-physics IV: Muon ID

- Performance measured with pure samples of $J/\psi \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$, $\phi \rightarrow KK$, $\Lambda \rightarrow p\,\pi$





- Performance in the kinematic range of $B_s \rightarrow \mu\mu$:

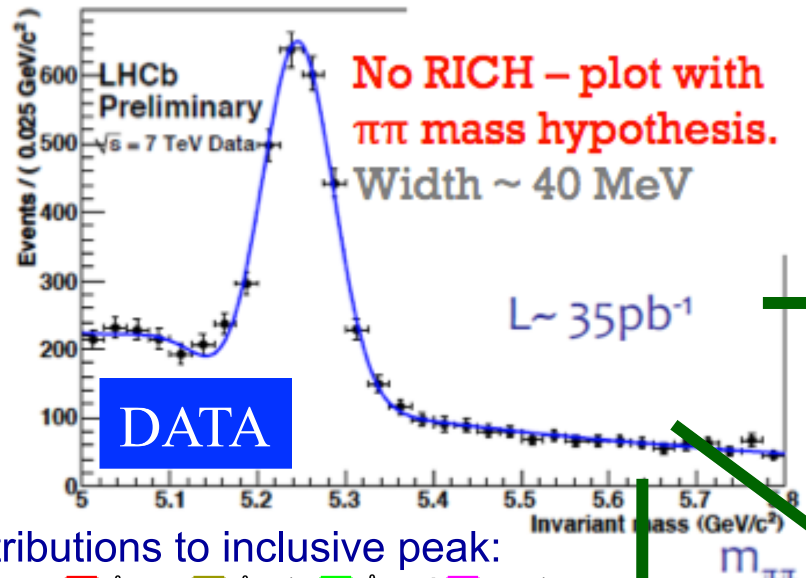
$\varepsilon(\mu \rightarrow \mu) \sim (97.1 \pm 1.3)\%$

$\varepsilon(h \rightarrow \mu) \sim (7.1 \pm 0.5)\, 10^{-3}$

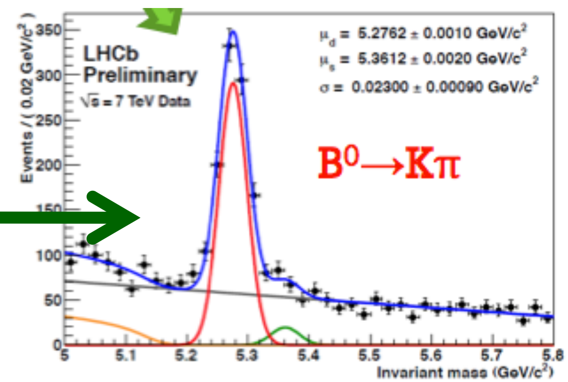
$\varepsilon(hh \rightarrow \mu\mu) \sim (3.5 \pm 0.9)\, 10^{-5}$

LHCb capabilities for hadronic physics

Inclusive $B_{(s,d)} \rightarrow hh'$

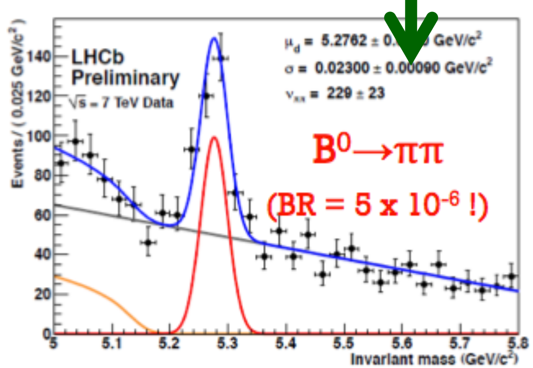


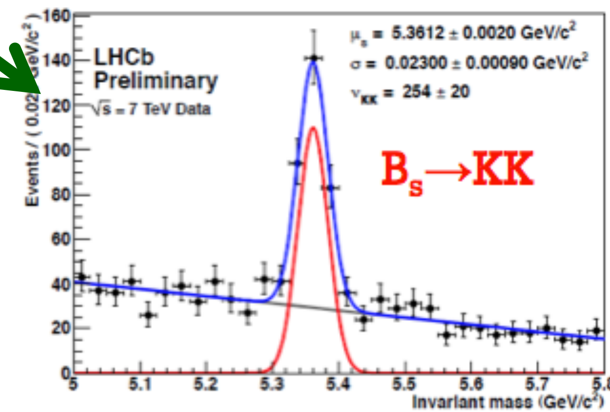
$B_{(s,d)} \rightarrow hh'$ WITH RICH



Contributions to inclusive peak:

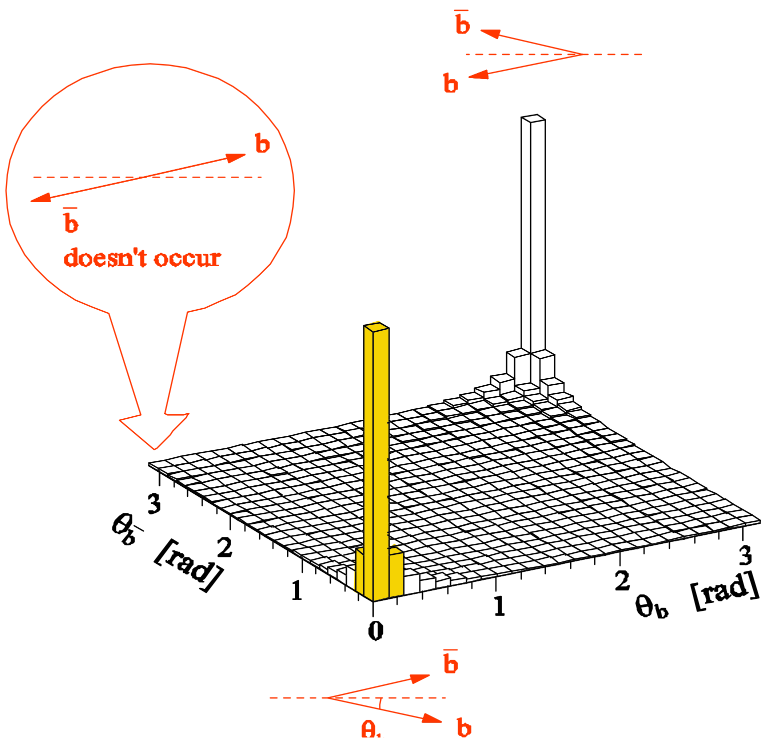
$B^0 \to \pi^+\pi^-$	$B^0 \to K^+K^-$	$B_s^0 \to \pi^+K^-$	$\Lambda_b \to \pi^+\bar{p}$
$B^0 \to K^+\pi^-$	$B_s^0 \to \pi^+\pi^-$	$B_s^0 \to K^+K^-$	$\Lambda_b \to pK^-$
$B^0 \to \pi^+K^-$	$B_s^0 \to K^+\pi^-$	$\Lambda_b \to p\pi^-$	$\Lambda_b \to K^+\bar{p}$





LHCb acceptance

- LHCb: maximize B acceptance @ LHC
  → forward spectrometer, 1.9<η<4.9
  - B hadrons produced at low angle
  - B pairs are produced in same forward or backward cone → single arm ok

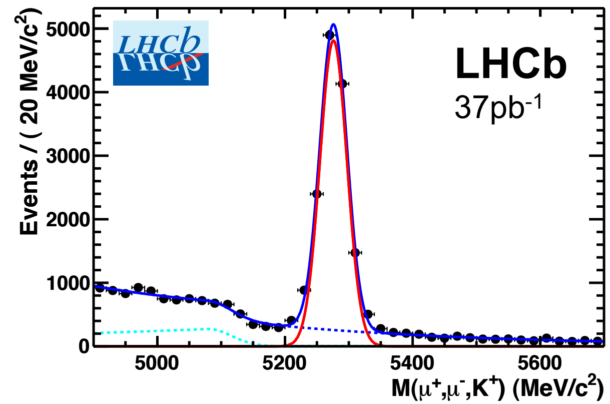


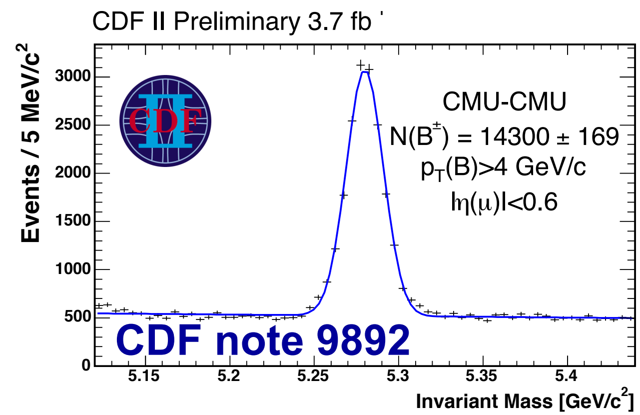
LHCb acceptance

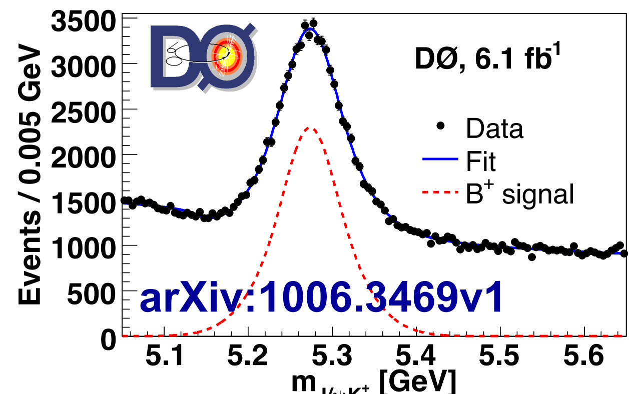
- LHCb: maximize B acceptance @ LHC
  → forward spectrometer, $1.9<\eta<4.9$
  - B hadrons produced at low angle
  - B pairs are produced in same forward or backward cone → single arm ok

(CDF: $|\eta|<1$; D0: $|\eta|<2$; CMS/ATLAS: $|\eta|<2.4$)

- Rough estimate for B acceptance: compare $B^{\pm}\to J/\psi K^{\pm}$ yield with CDF / D0
  - **LHCb**
    N^{signal}: $12,366 \pm 403^{stat+syst}$ ($0.037 fb^{-1}$)
  - **CDF**$_{(CMU-CM(U+X))}$
    N^{signal}: $19,762 \pm 203^{stat+syst}$ ($3.7 fb^{-1}$)
    D0$_{(RunIIa+b)}$
    N^{signal}: $46,803 \pm 1099^{stat+syst}$ ($6.1 fb^{-1}$)



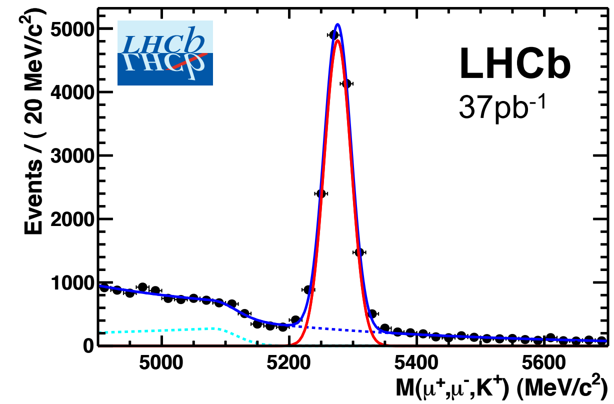


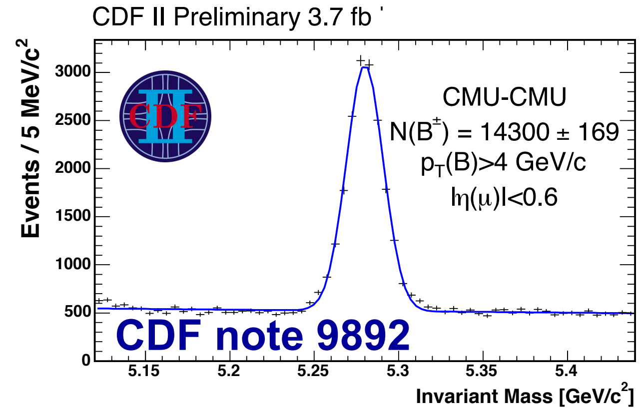


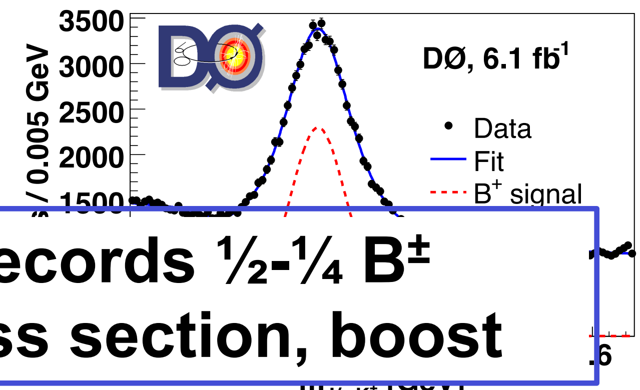
LHCb acceptance

- LHCb: maximize B acceptance @ LHC
  → forward spectrometer, $1.9<\eta<4.9$
  - B hadrons produced at low angle
  - B pairs are produced in same forward or backward cone → single arm ok

- Rough estimate for B acceptance: compare $B^{\pm}\to J/\psi K^{\pm}$ yield with CDF / D0
  - **LHCb**
    N^{signal}: $12{,}366 \pm 403^{stat+syst}$ ($0.037 fb^{-1}$)
  - **CDF**$_{(CMU\text{-}CMU+X)}$
    N^{signal}: $19{,}762 \pm 203^{stat+syst}$ ($3.7 fb^{-1}$)
    D0$_{(RunIIa+b)}$
    N^{signal}: $46{,}803 \pm 1099^{stat+syst}$ ($6.1 fb^{-1}$)

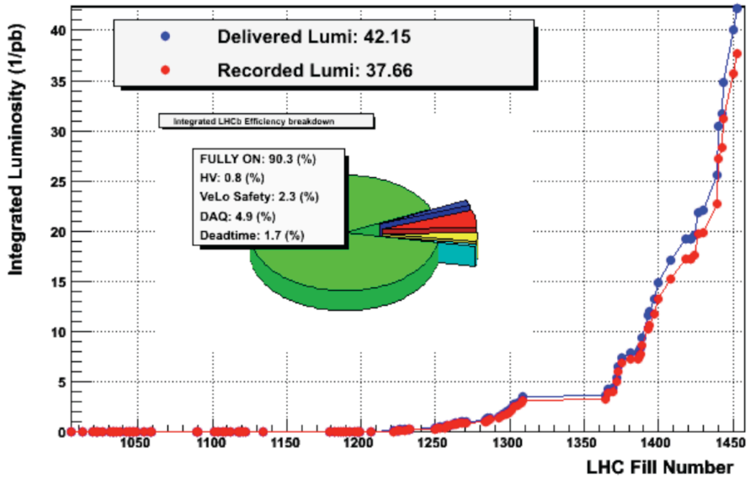






With 1/100-1/200 of $\int L\,dt$, LHCb records ½-¼ B$^{\pm}$ thanks to acceptance & trigger, cross section, boost

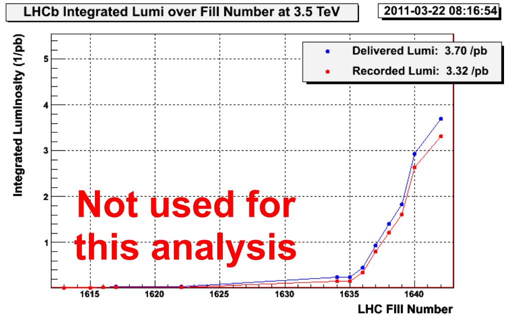
LHCb operation in 2010

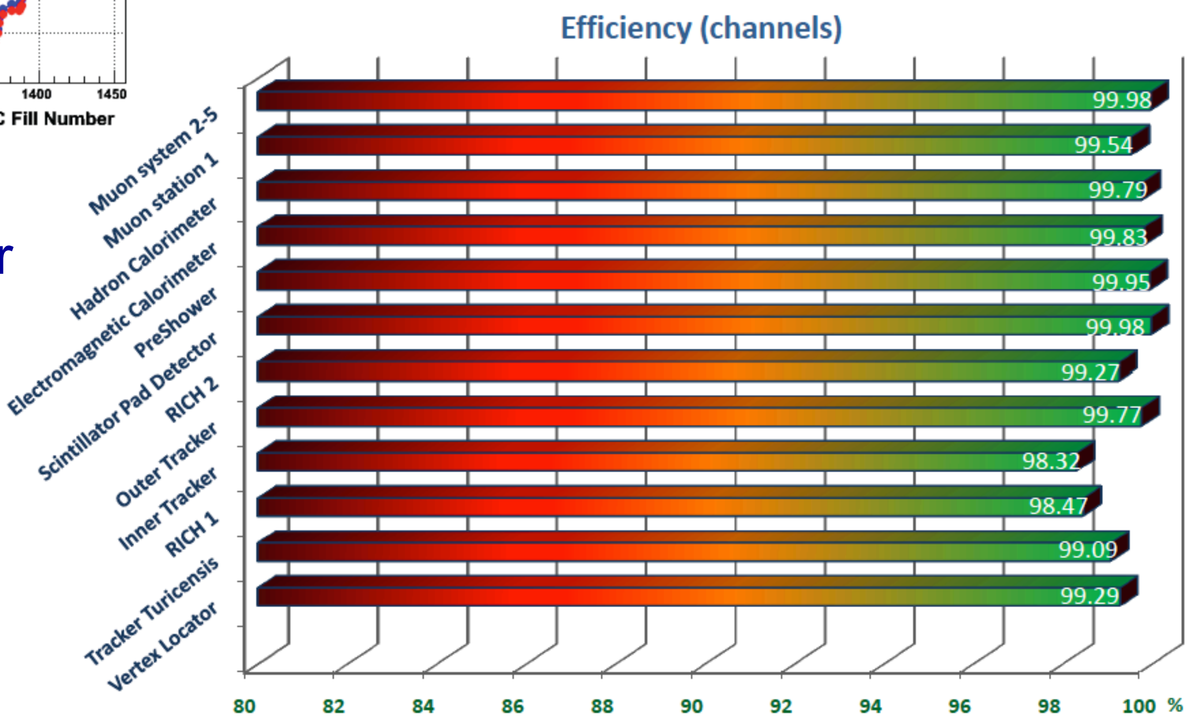


LHCb recorded 37pb^{-1} of high quality physics data in 2010
→ dataset for this analysis

Data taking efficiency around 90% over the year

3.3pb^{-1} recorded in 2011

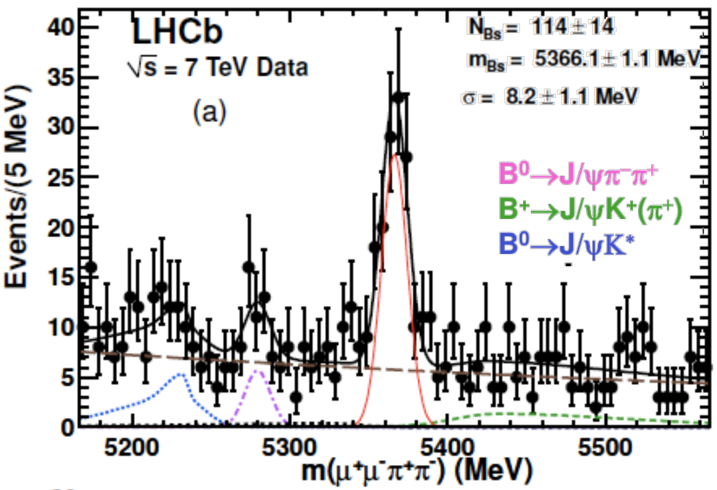




All sub-detectors >99% efficient

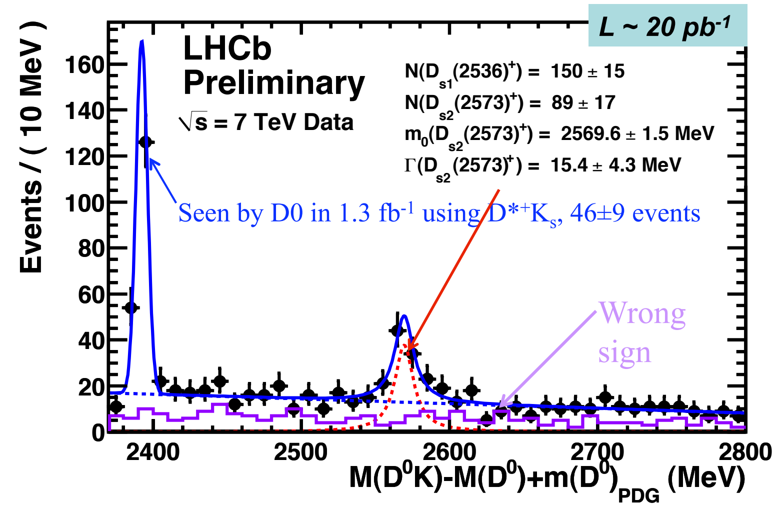
First observations by LHCb

First observation of $B_s \to J/\psi\ f^0(980)$:



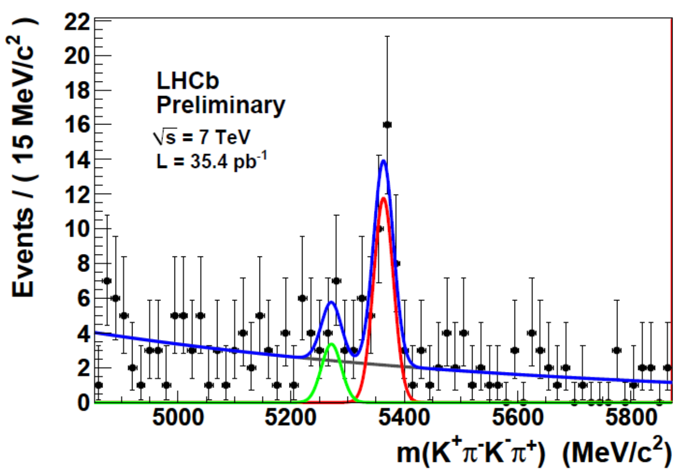
arXiv:1102.0206
Phys.Lett.B **698** (2011)

First observation of $B_s \to D_{s2}^{*+} X \mu \nu$



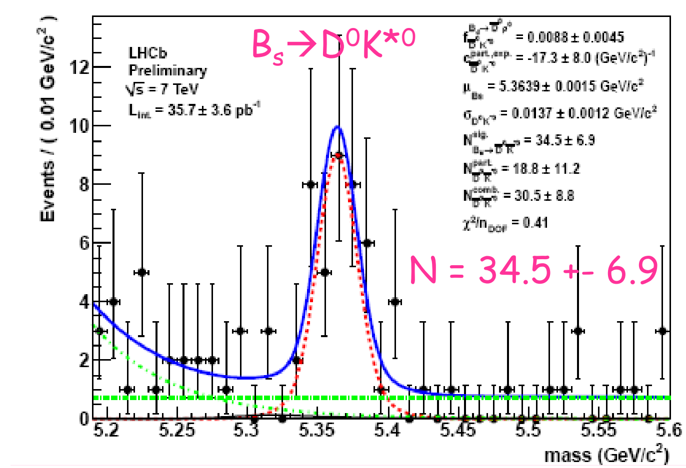
arXiv:1102.0348

First observation of $B_s \to K^* K^*$

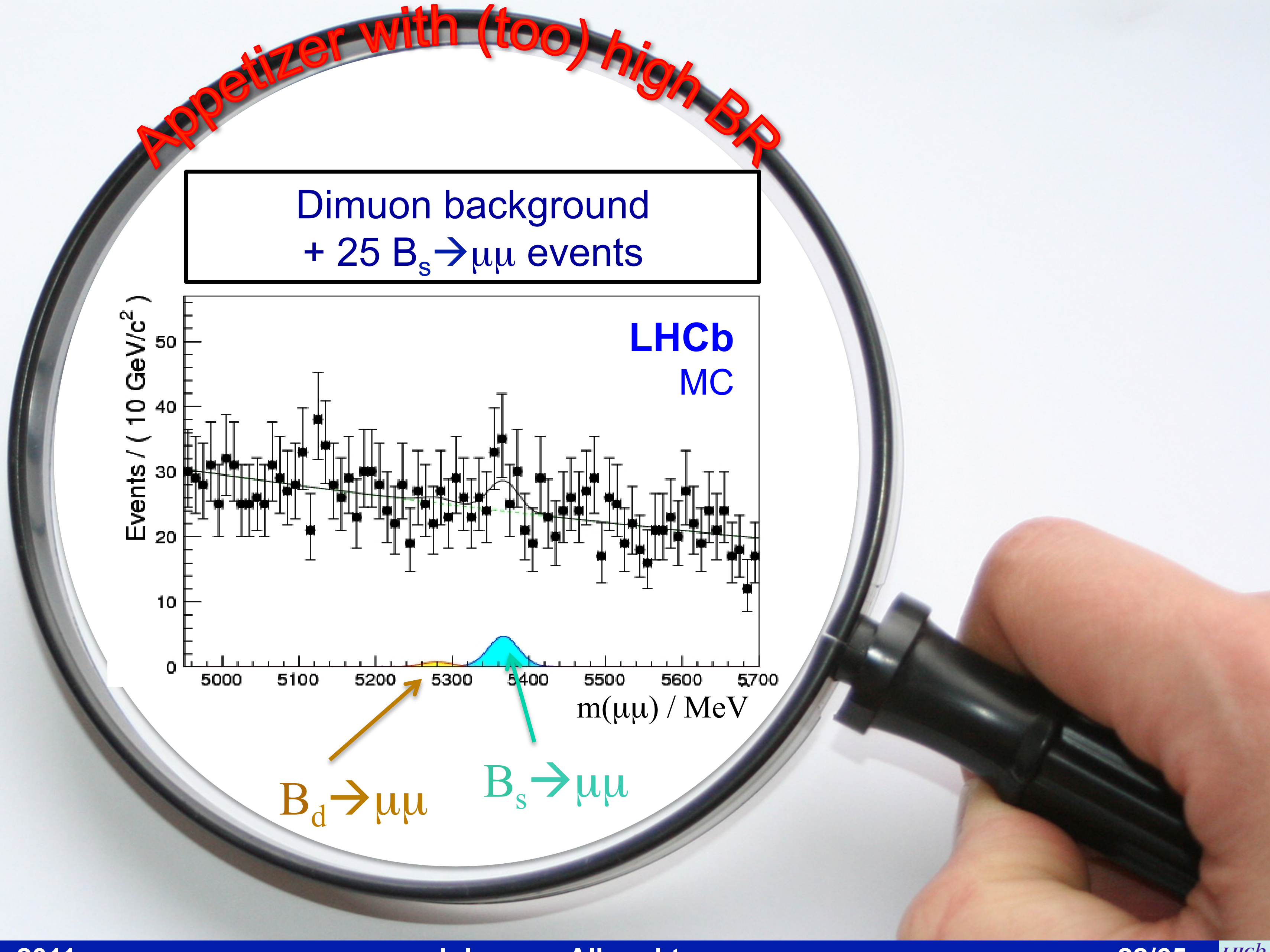


LHCb-CONF-2011-019

First observation of $B_s \to D^0 K^*$



LHCb-CONF-2011-008


Appetizer with (too) high BR
Dimuon background
+ 25 Bs→μμ events
LHCb
MC
Events / (10 GeV/c²)
50
40
30
20
10
0
5000
5100
5200
5300
5400
5500
5600
5700
m(μμ) / MeV
Bd→μμ
Bs→μμ

Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

arXiv:1103.2465
submitted to Phys. Lett. B

Analysis strategy

- **Selection**
  - Soft selection to reduce size of dataset
- **Signal and background likelihoods**
  - Geometrical Likelihood (GL)
    Multivariate classifier combining topological and kinematic information
  - Invariant mass
- **Normalization**
  - Convert number of observed events in branching fraction by normalizing with channels of known BR
- **Extraction of the limit**
  - Extract observation / exclusion measurement using the CL_S method

Search for $B_{d,s} \rightarrow \mu^+\mu^-$

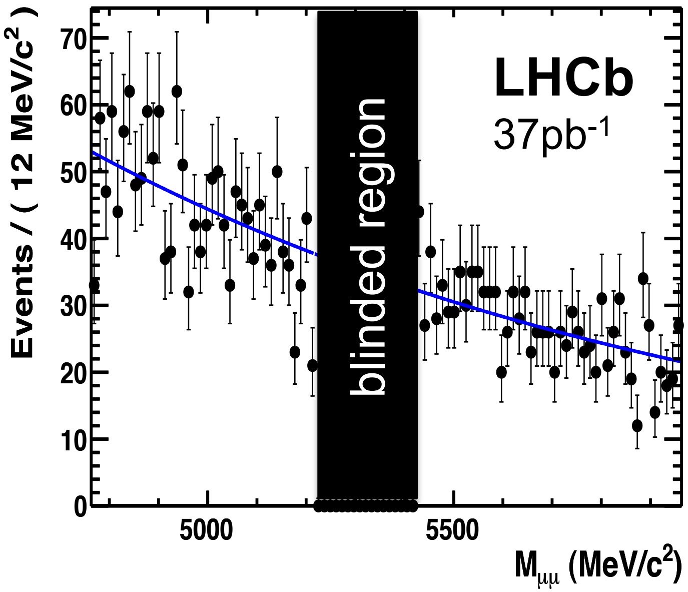
- Selection
- Signal and background likelihood
- Normalization
- Extraction of the limit

Selection

- Soft selection:
  - pairs of opposite charged muons with high quality tracks, making a common vertex very displaced with respect to the PV and $M_{\mu\mu}$ ±600 MeV/c^2

- Keeps high signal efficiency:
  - Expected after selection (BR=BR^{SM}): **$B_S(B^0) \to \mu\mu$: 0.3 (0.04) events**

- Rejects most of the background
  - ~ **300 background events** in the signal windows m($B_{d,s}$) ±60 MeV/c^2
  - ~ 3000 background events ($M_{\mu\mu}$ ±600 MeV/c^2)



Signal regions were blinded up to analysis approval

Background composition

Background composition after selection:

$bb \rightarrow \mu\mu X$	fake + muon	peaking background
90%	10%	negligible
Double semileptonics and cascade decays	~0.3% from double fake	• Double misID from $B \rightarrow hh'$: < 0.1 events in signal region • misID well described by MC $\varepsilon(hh \rightarrow \mu\mu) \sim (3.5 \pm 0.9)\ 10^{-5}$

- Remaining background consists of real muons
  ➔ further signal discrimination from topology of event and invariant mass in likelihoods

- **Remark: precise knowledge of background not necessary for analysis: background estimate taken from sidebands**

Search for $B_{d,s} \rightarrow \mu^+\mu^-$

- Selection
- Signal and background likelihoods
- Normalization
- Extraction of the limit

Signal and background likelihoods

- After selection:
  - ~0.3 $B_s \rightarrow \mu\mu$ signal events expected
  - ~300 background events
    → Background consists dominantly of real muons

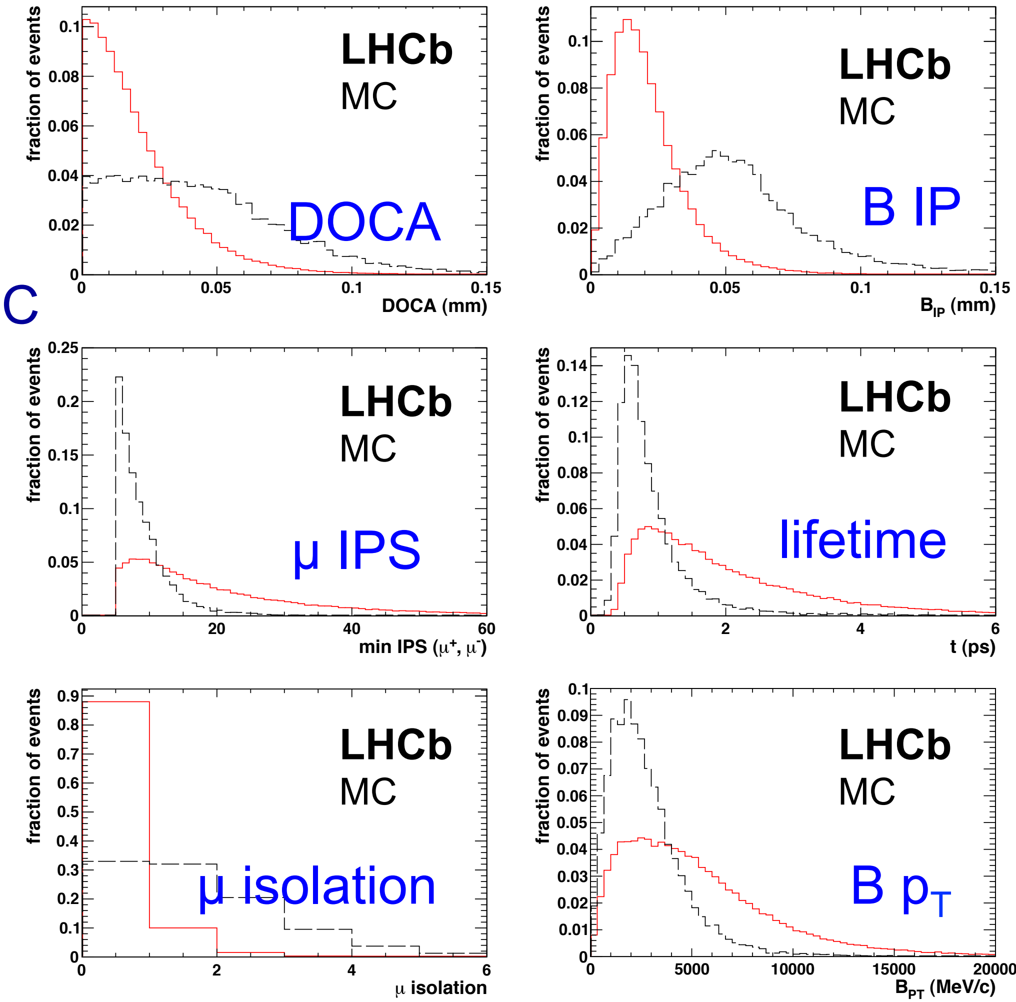
- Create 2D likelihood to classify events:
  - **Geometrical likelihood (GL)**:
    combines topological and kinematic information
  - **Invariant mass**

- Geometrical likelihood is *defined* on simulation and *calibrated* on data
  - Analysis does not rely critically on simulation
    → fast analysis possible

Geometrical likelihood definition

- Combination of kinematic and topological variables
- Variables are decorrelated and a discriminant variable is built
- Optimization and training using MC
  - Signal $B_s \rightarrow \mu\mu$
  - Background $bb \rightarrow \mu\mu X$

GL input variables



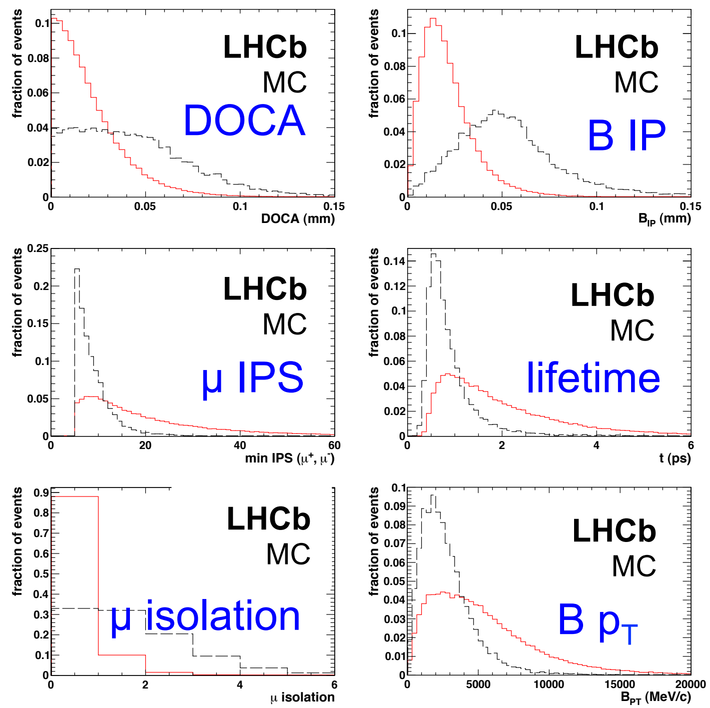
MC $B_s \rightarrow \mu\mu$

MC $bb \rightarrow \mu\mu X$

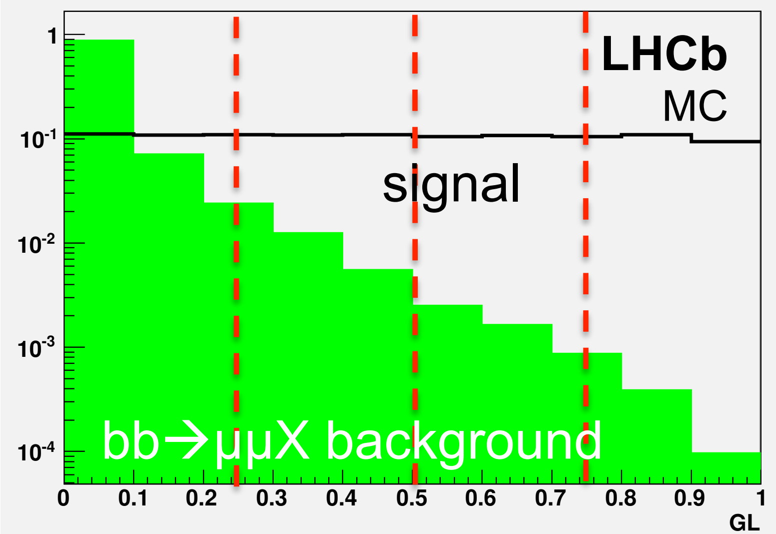
Geometrical likelihood definition

- Combination of kinematic and topological variables
- Variables are decorrelated and a discriminant variable is built
- Optimization and training using MC
  - Signal $B_s \rightarrow \mu\mu$
  - Background $bb \rightarrow \mu\mu X$

GL input variables



GL shape of signal and bkg



→ flat for signal
→ peaked at zero for background

Analysis is done in 4 bins of GL

Calibration of likelihoods

- Calibration of likelihoods from data:

1. Background
   – Both GL and invariant mass are calibrated simultaneously from mass sidebands

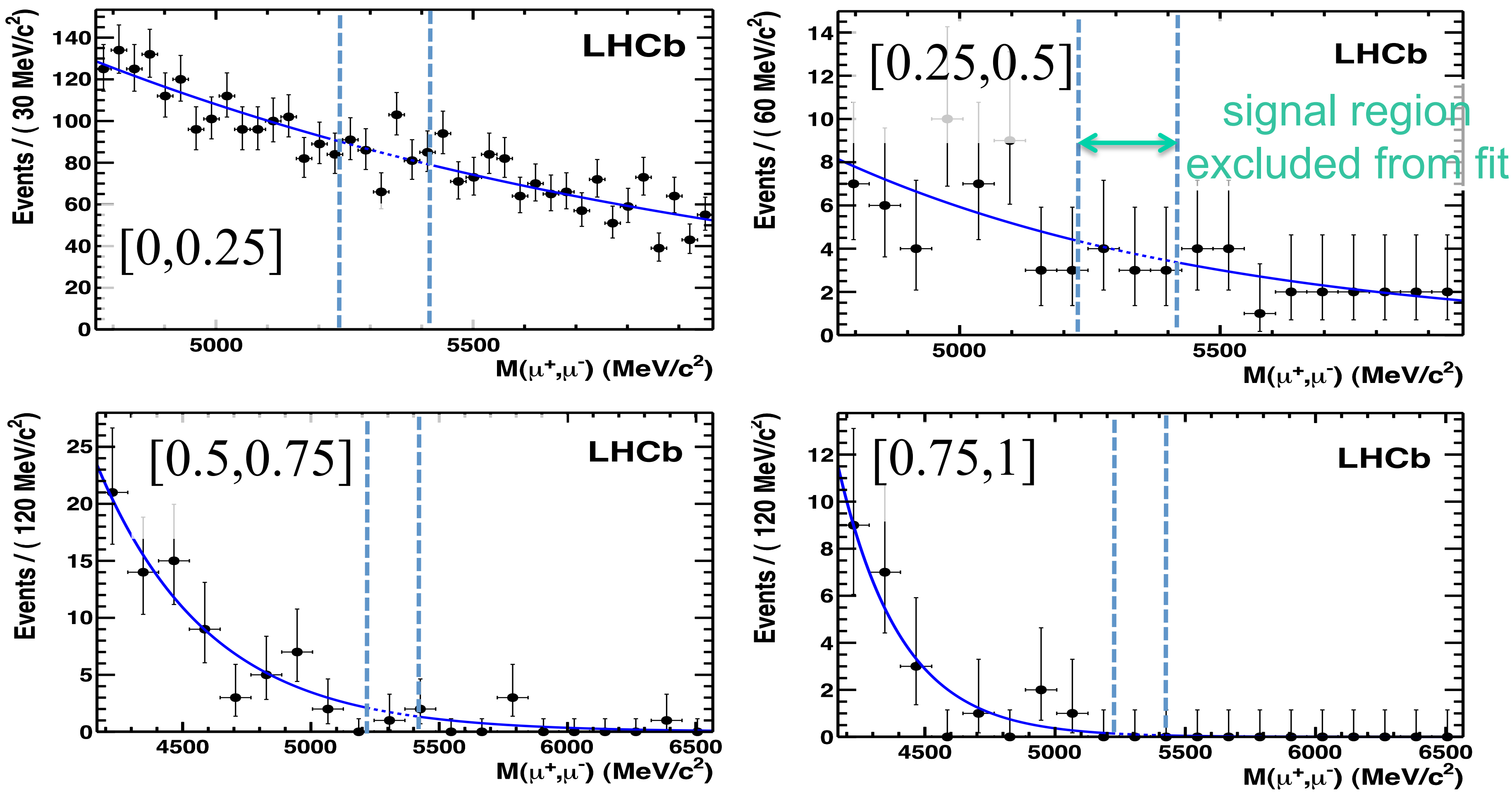
2. Signal:
   a) GL calibrated with $B \rightarrow h^+h'^-$
   b) Invariant mass shape from $B \rightarrow h^+h'^-$ and dimuon resonances

Background likelihood shape in mass and GL

Expected background in signal region is extracted from a fit to mass sidebands divided in GL bins

±600 MeV/c^2

±1200 MeV/c^2

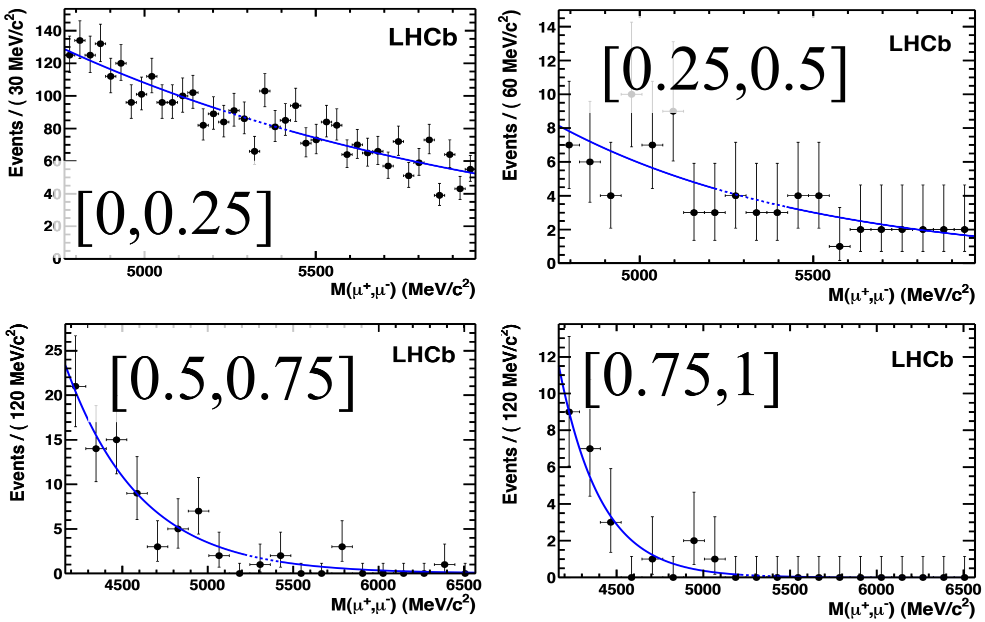


Very low background in regions of high sensitivity

Background likelihood shape in mass and GL

Expected background in signal region is extracted from a fit to mass sidebands divided in GL bins

Invariant mass in GL bins



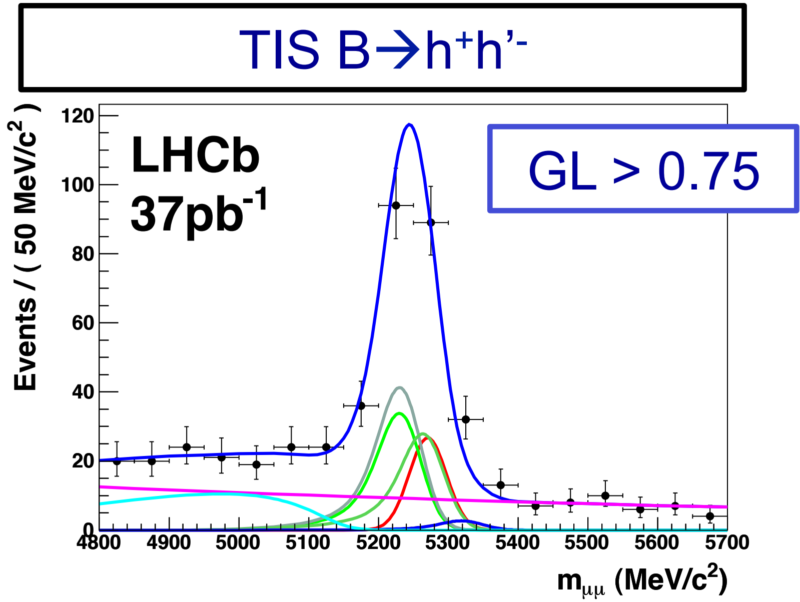
Expected background events in $B_{s,d}$ mass regions

GL	$B_s \rightarrow \mu\mu$	$B^0 \rightarrow \mu\mu$
[0, 0.25]	329.1±6.4	351.6±6.6
[0.25, 0.5]	7.4 ± 1	$8.3^{+1.1}_{-1.0}$
[0.5, 0.75]	$1.51^{+0.41}_{-0.35}$	$1.85^{+0.45}_{-0.39}$
[0.75, 1]	$0.08^{+0.10}_{-0.05}$	$0.13^{+0.13}_{-0.07}$

Very low background in sensitive region

Signal GL calibration

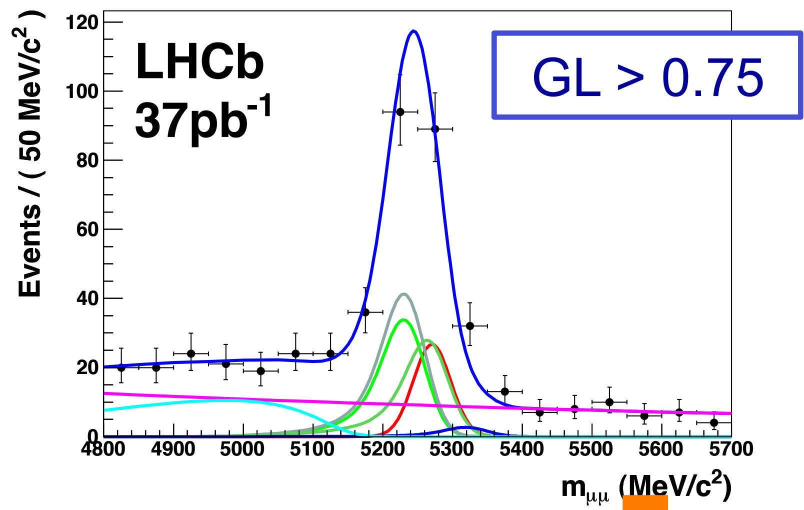
- $B \rightarrow h^+h'^-$ ideal sample for GL calibration
  - Identical decay topology
  - Use events triggered independent of signal (TIS) to avoid trigger bias
- Inclusive $B \rightarrow h^+h'^-$ fit
  - Fit all $B \rightarrow h^+h'^-$ channels simultaneously
  - uses constrained BR (PDG)



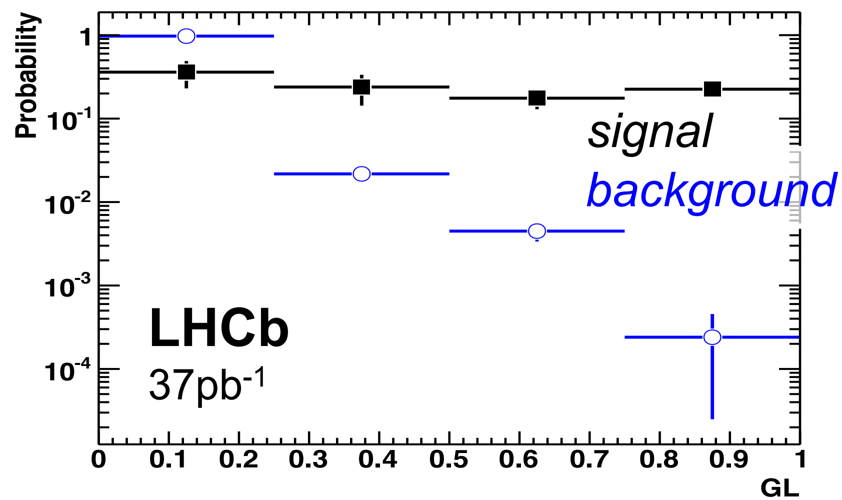
Signal GL calibration

- $B \rightarrow h^+h'^-$ ideal sample for GL calibration
  - Identical decay topology
  - Use events triggered independent of signal (TIS) to avoid trigger bias
- Inclusive $B \rightarrow h^+h'^-$ fit
  - Fit all $B \rightarrow h^+h'^-$ channels simultaneously
  - uses constrained BR (PDG)
- **Signal distribution in GL flat as expected from simulation**

TIS $B \rightarrow h^+h'^-$



Calibrated GL



Signal invariant mass calibration

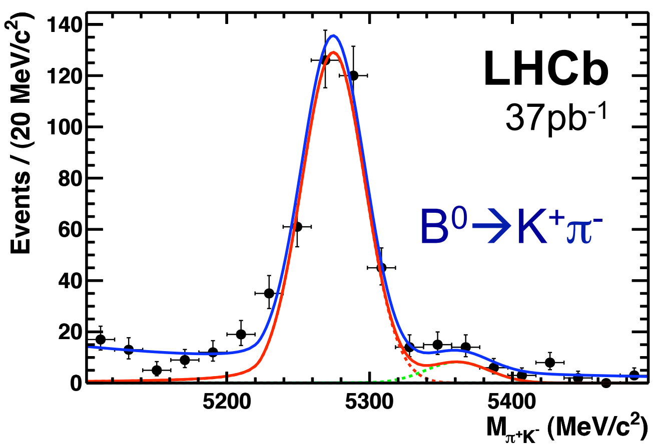
- Parameters of crystal ball (mean, resolution) from data
  - **Central value**: fit to exclusive B^0 and B_s decays
  - **Resolution**: average from
    - Inclusive B→hh' (identical topology)
    - dimuon resonances

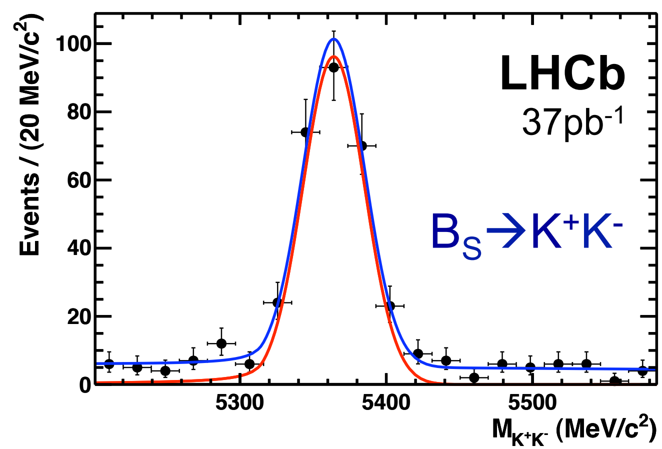
Signal invariant mass calibration: Mean

- Parameters of crystal ball (mean, resolution) from data
  - **Central value**: fit to exclusive B^0 and B_s decays
  - **Resolution**: average from
    - Inclusive B→hh' (identical topology)
    - dimuon resonances

Central value of invariant mass:

Select exclusive $B^0 \to K^+\pi^-$ and $B_s \to K^+K^-$ by using RICH particle ID



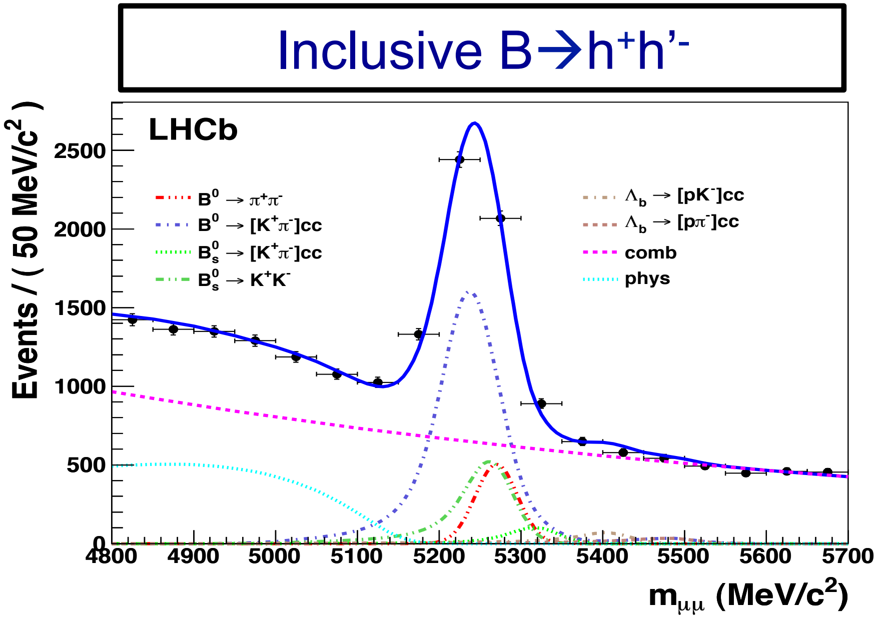


$m(B^0) = 5275.0 \pm 1.0$ MeV/c^2 $m(B_s) = 5363.1 \pm 1.5$ MeV/c^2

Signal invariant mass calibration: Sigma

- Mass resolution from $B \rightarrow h^+h'^-$
  - No use of PID info
    $\rightarrow$ would bias σ
  - BR fixed to PDG values

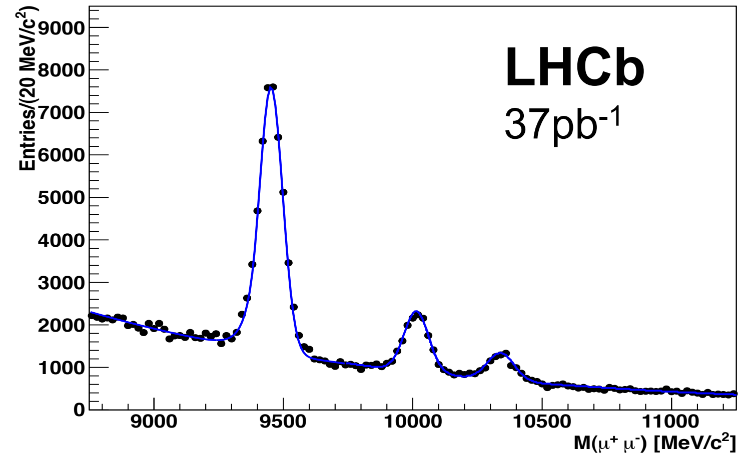
- Signal resolution from $B \rightarrow h^+h'^-$:
  $\sigma = 25.8 \pm 1.0^{stat} \pm 2.7^{syst}$ MeV/c^2



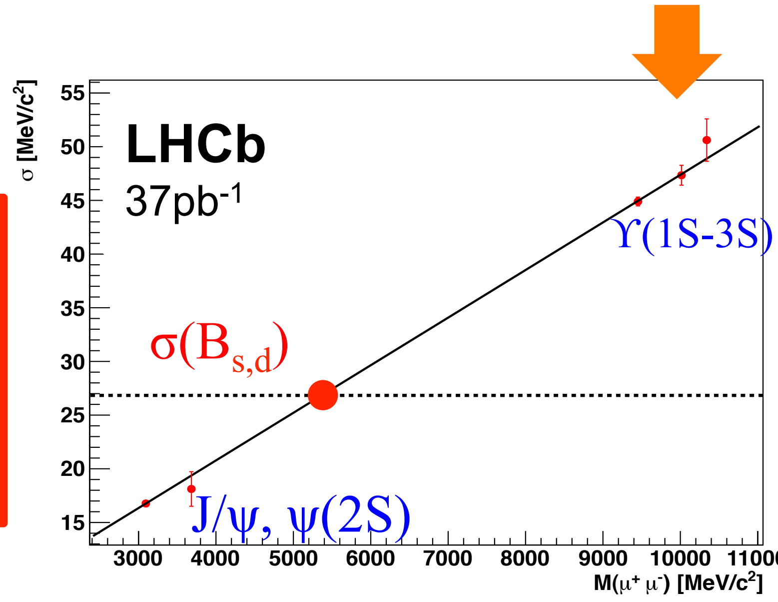
Mass resolution from dimuon resonances

- Mass resolution of resonances depends linearly on the mass
  - interpolate between J/ψ, $\psi(2S)$ and $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
  - momentum spectrum of resonances reweighted to the $B_s \to \mu\mu$ one

The Υ family: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$



- Resolution from interpolation: $\sigma(B_{S,d}) = 26.8 \pm 0.1^{stat} \pm 1^{syst}$ MeV/c^2



Weighted average of signal resolution:

$\sigma(B_{S,d}) = 26.7 \pm 0.9^{stat+syst}$ MeV/c^2

CDF (D0) : $\sigma(M) \sim 24$ (120) MeV/c^2

Search for $B_{d,s} \rightarrow \mu^+\mu^-$

- Selection
- Signal and background likelihoods
- Normalization
    - Extraction of the limit

Normalization channels

Normalize measured events to a channel with known BR

→ many uncertainties cancel

→ no knowledge of luminosity or cross section needed

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{\mathrm{Rec}} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{\mathrm{Rec}} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B \to \mu\mu}}{N_{cal}} = \alpha \cdot N_{B \to \mu\mu}$$

Normalization channels

Normalize measured events to a channel with known BR

→ many uncertainties cancel

→ no knowledge of luminosity or cross section needed

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

Three independent normalization channels used:

$B^{\pm}\to J/\psi(\mu\mu)\, K^{\pm}$	$B_s\to J/\psi(\mu\mu)\, \phi(KK)$	$B^0\to K^+\pi^-$
BR = 5.98×10^{-5} (±3.7%)	BR = 3.35×10^{-5} (±26%)	BR = 1.94×10^{-5} (±3.1%)
• Similar trigger and PID • Tracking efficiency (+1track) dominates error on efficiency ratio • f_d/f_s dominates overall uncertainty	• Similar trigger and PID • Tracking efficiency (+2tracks) dominates error on efficiency ratio • BR dominates overall uncertainty	• Different trigger → **use events triggered independent of signal** • Identical topology • Uncertainty from f_d/f_s, trigger, mass fit

f_d/f_s at LHCb

NEW

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon^{Rec}_{cal} \cdot \varepsilon^{Sel}_{cal} \cdot \varepsilon^{Trig}_{cal}}{\varepsilon^{Rec}_{Bs} \cdot \varepsilon^{Sel}_{Bs} \cdot \varepsilon^{Trig}_{Bs}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

Currently use HFAG average of LEP/Tevatron value: **f_d/f_s=3.71±0.47**

<u>LHCb already provides (preliminary) results</u>

- Measure f_d/f_s in the relative yields of $B^0 \to D^\pm K^\pm$ or $B^0 \to D^\pm \pi^\pm$ to $B_S \to D_S^\pm \pi^\pm$

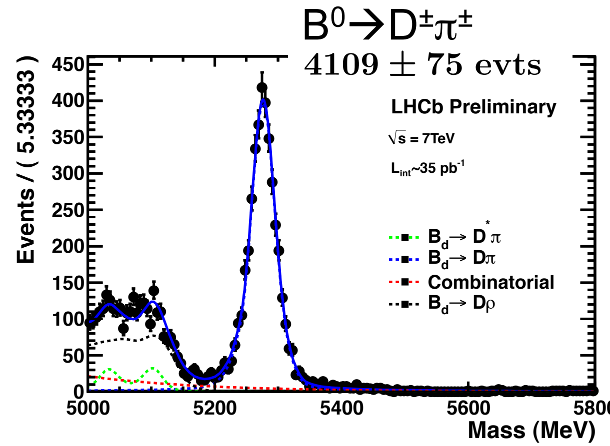
Fleischer et al, Phys.Rev.D83,014017 (2011)

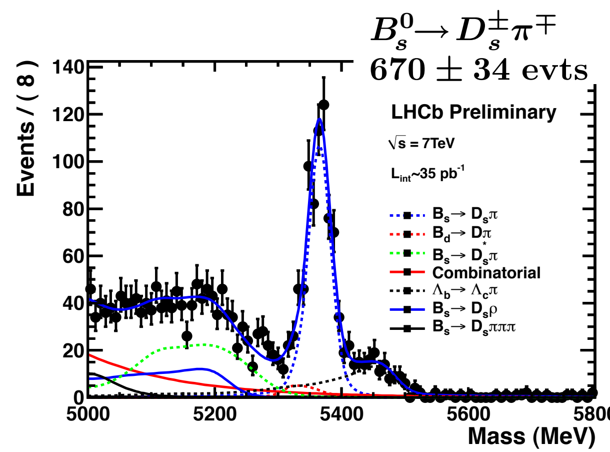
NEW: with 35pb^{-1} LHCb measures

$$\frac{f_{B^0_d}}{f_{B_s}} = 4.02 \pm 0.52$$

(using $B^0 \to D^\pm \pi^\pm$)

LHCb-CONF-2011-013





- Also preliminary result from semileptonics:

$$\frac{f_{B^0_d}}{f_{B_s}} = 3.84 \pm 0.34$$

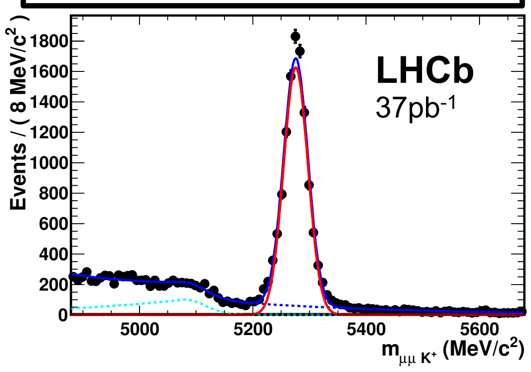
preliminary

Ratio of reconstruction and selection efficiencies

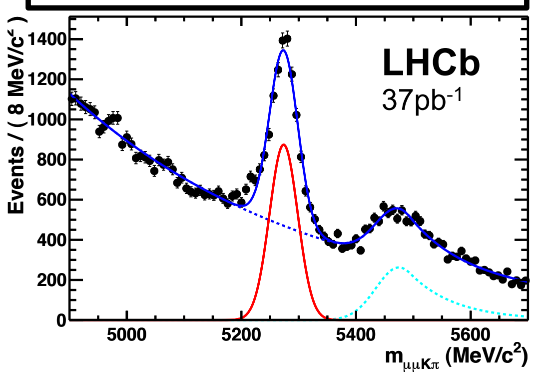
$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon^{Rec}_{cal} \cdot \varepsilon^{Sel}_{cal} \cdot \varepsilon^{Trig}_{cal}}{\varepsilon^{Rec}_{Bs} \cdot \varepsilon^{Sel}_{Bs} \cdot \varepsilon^{Trig}_{Bs}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

- Ratio of reconstruction / acceptance and selection efficiencies from simulation, dominated by
  - **$B^\pm \to J/\psi K^\pm$, $B_s \to J/\psi\phi$**: acceptance and cuts for extra track(s)
  - **$B \to hh'$**: material interactions, no muon ID
- X-check: Yield ratio 4-body / 3-body B decays in data
  - Gives reconstruction efficiency / acceptance for extra track

$B^\pm \to J/\psi K^\pm$



$B^0 \to J/\psi K^*$



$$\frac{\varepsilon^{Rec}_{B^0\to J/\psi K^*}}{\varepsilon^{Rec}_{B^\pm\to J/\psi K^\pm}} \propto \frac{\varepsilon^{Rec}_{B^\pm\to J/\psi K^\pm}}{\varepsilon^{Rec}_{B_S\to\mu\mu}}$$

Good data / MC agreement

Ratio of reconstruction and selection efficiencies

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel}} \cdot \frac{\varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

- Ratio of reconstruction / acceptance and selection efficiencies from simulation, dominated by
  - **$B^{\pm}\rightarrow J/\psi K^{\pm}$, $B_s\rightarrow J/\psi\phi$**: acceptance and cuts for extra track(s)
  - **B→hh'**: material interactions, no muon ID

<u>Ratio of reconstruction, selection efficiencies & acceptance:</u>

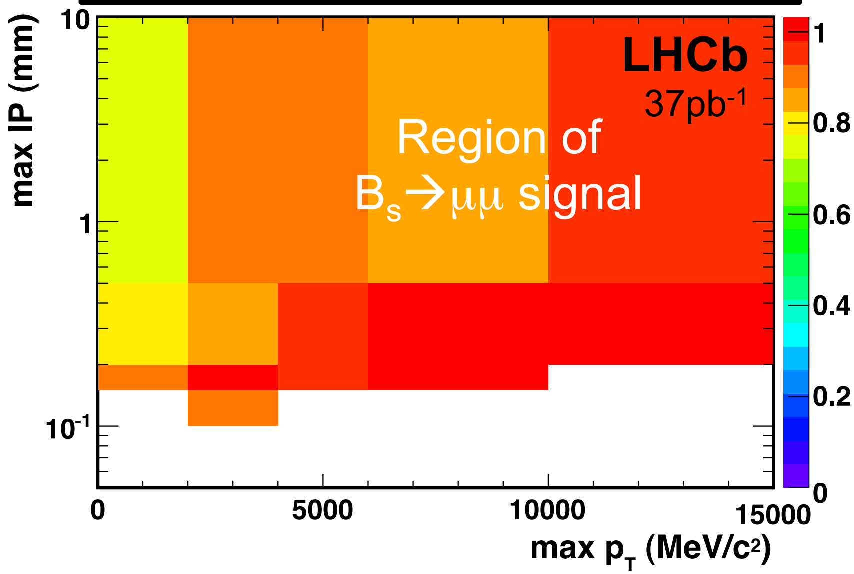
$B^{\pm}\rightarrow J/\psi K^{\pm}$	$B_s\rightarrow J/\psi\phi$	B→hh'
0.49±0.02	0.25±0.02	0.82±0.06

Trigger efficiency ratio: J/ψ channels

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

- Trigger efficiency determined purely from data
  - use independent trigger decisions to measure efficiency
- Efficiency for $B_s \to \mu\mu$ signal:
  - parameterize trigger efficiency with inclusive detached J/ψ sample
  - apply harder $B_s \to \mu\mu$ spectra: trigger efficiency: $\varepsilon^{Bs\to\mu\mu}$ **= 90±4%**

J/ψ trigger efficiency map



Ratio of trigger efficiencies:

$B_{S,d} \to J/\psi X$
0.96±0.05

Trigger efficiency ratio: B→hh'

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

- $B^0 \to K^+\pi^-$: normalize to trigger independent sample (TIS)
- Efficiency to trigger independent of the signal is **independent of the signal**
  - Measure from $B^\pm \to J/\psi K^\pm$ candidates
    → higher yield allows more precise efficiency determination

Ratio of trigger efficiencies:

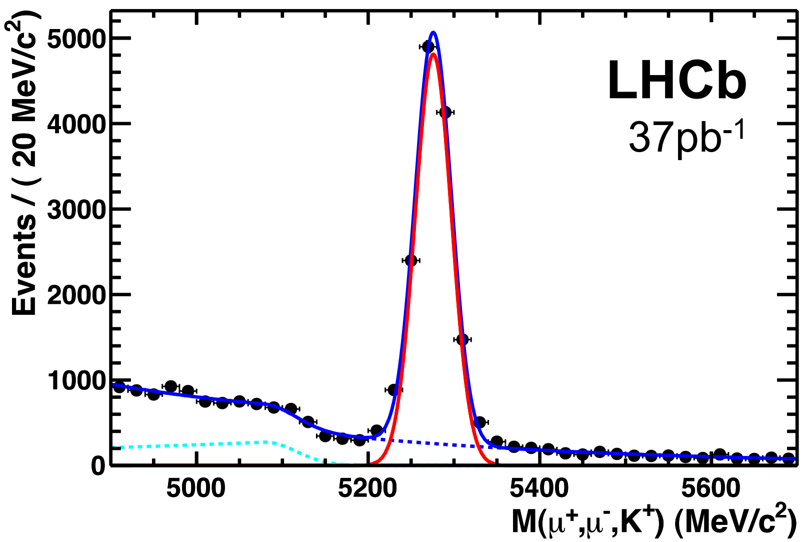
B→hh' (TIS)
7.2±1.0 %

First normalization factor : $B^\pm \rightarrow J/\psi K^\pm$

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B\rightarrow\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\rightarrow\mu\mu}$$

- $B^\pm \rightarrow J/\psi K^\pm$: $12{,}366 \pm 403^{stat+syst}$
  - 3% systematics from fit model and duplicated candidates
  - No RICH PID used
- **Normalization factor:**
  $\alpha(B_S \rightarrow \mu\mu) = 8.4 \pm 1.3 \times 10^{-9}$
  $\alpha(B^0 \rightarrow \mu\mu) = 2.27 \pm 0.18 \times 10^{-9}$

$B^\pm \rightarrow J/\psi K^\pm$ normalization



Summary of uncertainties

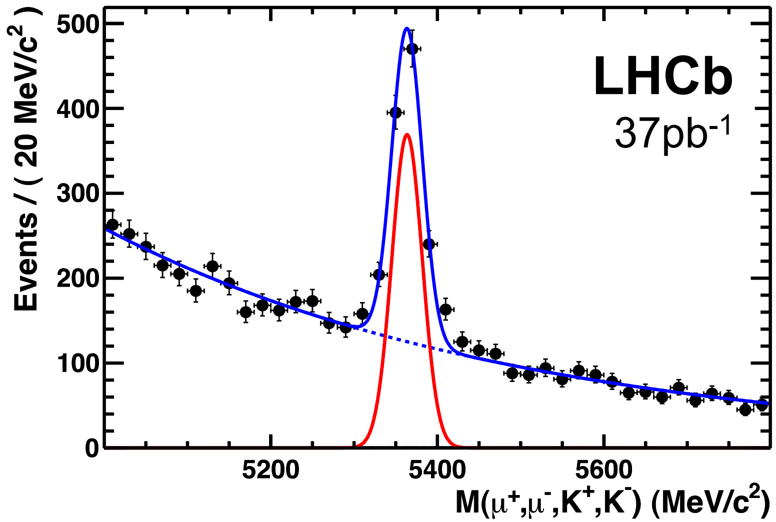
	BR	sel* rec	Trigger	f_d/f_s	N	total B_S	total B^0
$B^\pm \rightarrow J/\psi K^\pm$	4%	4%	5%	13%/-	3%	15%	8%

Second normalization factor: $B_S \rightarrow J/\psi\phi$

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon^{Rec}_{cal} \cdot \varepsilon^{Sel}_{cal} \cdot \varepsilon^{Trig}_{cal}}{\varepsilon^{Rec}_{Bs} \cdot \varepsilon^{Sel}_{Bs} \cdot \varepsilon^{Trig}_{Bs}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

- $B_S \rightarrow J/\psi\phi$: $760 \pm 71^{\text{stat+syst}}$
  - 9% systematics from fit model and duplicated candidates
  - No RICH PID used
- **Normalization factor:**
  $\alpha(B_S \rightarrow \mu\mu) = 10.5 \pm 2.9 \times 10^{-9}$
  $\alpha(B^0 \rightarrow \mu\mu) = 2.83 \pm 0.86 \times 10^{-9}$

$B_S \rightarrow J/\psi\phi$ normalization



Summary of uncertainties:

	BR	sel* rec	Trigger	f_d/f_s	N	total B_S	total B^0
$B_S \rightarrow J/\psi\phi$	26%*	8%	5%	-/13%	9%	28%	30%

(*) from Belle @ $\Upsilon(5S)$: arXiv:0905.4345

Third Normalization factor: $B^0 \to K^+\pi^-$

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{N_{B\to\mu\mu}}{f_{K\pi} \cdot N_{B\to hh}} = \alpha \cdot N_{B\to\mu\mu}$$

- Strategy: measure yield from inclusive $B \to hh'$ sample
  - B_s modes in $B \to hh'$ have poorly known BR
  - Calibration of absolute PID efficiency non-trivial
    → determine fraction of $B^0 \to K^+\pi^-$ directly from data:

$$f_{B^0 \to K^+\pi^-} = 0.605 \pm 0.027$$

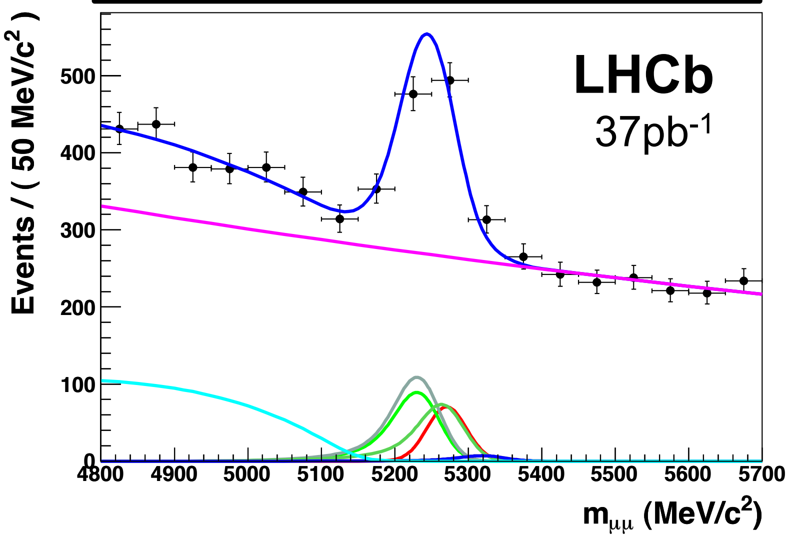
without relying on absolute PID efficiencies

Third Normalization factor: $B^0 \rightarrow K^+\pi^-$

$$BR = BR_{cal} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{\varepsilon^{Rec}_{cal} \cdot \varepsilon^{Sel}_{cal} \cdot \varepsilon^{Trig}_{cal}}{\varepsilon^{Rec}_{Bs} \cdot \varepsilon^{Sel}_{Bs} \cdot \varepsilon^{Trig}_{Bs}} \cdot \frac{N_{B\rightarrow\mu\mu}}{f_{K\pi} \cdot N_{B\rightarrow hh}} = \alpha \cdot N_{B\rightarrow\mu\mu}$$

- $B^0 \rightarrow K^+\pi^-$: $578 \pm 74^{stat+syst}$
  - 8% systematics from fit model
  - 4% from $B^0 \rightarrow K^+\pi^-$ fraction
- **Normalization factor:**
  $\alpha(B_S \rightarrow \mu\mu) = 7.3 \pm 1.8 \times 10^{-9}$
  $\alpha(B^0 \rightarrow \mu\mu) = 1.99 \pm 0.40 \times 10^{-9}$

Trigger unbiased $B \rightarrow h^+h'^-$



Summary of uncertainties:

	BR	sel* rec	Trigger	f_d/f_s	N	total B_S	total B^0
$B^0 \rightarrow K^+\pi^-$	3%	7%	14%	13%/-	13%	25%	20%

Summary of normalization factors

- Normalization factors from three channels consistent
  → take the **weighted average**

$$\alpha_{B_S \to \mu\mu} = 8.6 \pm 1.1 \times 10^{-9}$$
$$\alpha_{B^0 \to \mu\mu} = 2.24 \pm 0.16 \times 10^{-9}$$

(dominated by $B^{\pm} \to J/\psi K^{\pm}$)

- The three normalization channels bring very different systematic uncertainties

	BR 10^{-5}	sel * rec	Trigger	N_{cal}	$\alpha(B_s \to \mu\mu)$ 10^{-9}	$\alpha(B^0 \to \mu\mu)$ 10^{-9}
$B^{\pm} \to J/\psi K^{\pm}$	5.98±0.22	0.49±0.02	0.96±0.05	12,366±403	8.4±1.3	2.27±0.18
$B_S \to J/\psi\phi$	3.4±0.9	0.25±0.02	0.96±0.05	760±71	10.5±2.9	2.83±0.86
$B^0 \to K^+\pi^-$	1.94±0.06	0.82±0.06	0.072±0.01*	578±74*	7.3±1.8	1.99±0.40

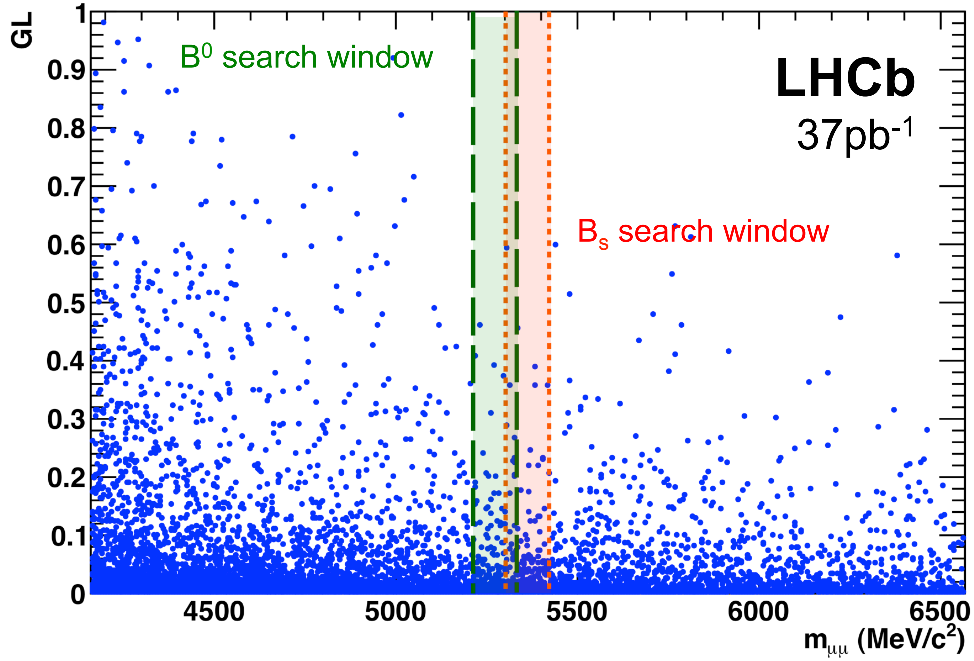
(*) trigger independent B→hh' sample used

Search for $B_{d,s} \rightarrow \mu^+\mu^-$

- Selection
- Signal and background likelihoods
- Normalization
- Extraction of the limit

Signal and background likelihoods

- Events are classified in 2D plane: invariant mass, GL
- Evaluate the compatibility of measurement with
  - B only hypothesis [CL_B]
    → quote observation
  - S+B hypothesis
    [$\mathbf{CL_S}$$=CL_{S+B}/CL_B$]
    → **quote exclusion limit**



- Calculate **expected limit** using toy MC techniques
  - Shows reach of the measurement, independent of stat. fluctuations
  - Errors of normalization factors and PDF parameters are included as nuisance parameters in limit calculation
- Use pattern of events to calculate **observed limit**

Expected number of background (signal) events

Invariant mass (Δm, MeV/c2)

Δm \ GL	[0-0.25]	[0.25-0.5]	[0.5-0.75]	[0.75-1]
[-60, -40]	57 (0.01)	1.3 (0.01)	0.3 (0.00)	0.0 (0.00)
[-40,-20]	56 (0.02)	1.3 (0.01)	0.3 (0.01)	0.0 (0.01)
[-20,0]	55 (0.04)	1.2 (0.03)	0.3 (0.02)	0.0 (0.02)
[0,20]	54 (0.04)	1.2 (0.03)	0.3 (0.03)	0.0 (0.02)
[20,40]	54 (0.02)	1.2 (0.01)	0.2 (0.01)	0.0 (0.01)
[40,60]	53 (0.01)	1.1 (0.01)	0.2 (0.00)	0.0 (0.00)
(bkgexp.)	*329*	*7.36*	*1.51*	*0.081*

$B_s \to \mu^+\mu^-$: Expected Limit

Expected number of background (signal) events

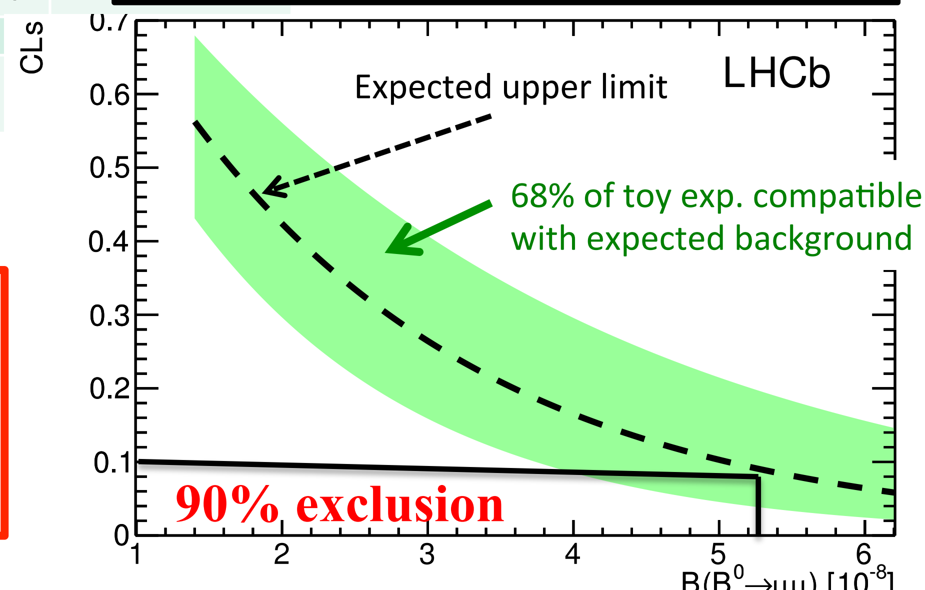
Invariant mass (Δm, MeV/c2)

Δm \ GL	[0-0.25]	[0.25-0.5]	[0.5-0.75]	[0.75-1]
[-60, -40]	57 (0.01)	1.3 (0.01)	0.3 (0.00)	0.0 (0.00)
[-40,-20]	56 (0.02)	1.3 (0.01)	0.3 (0.01)	0.0 (0.01)
[-20,0]	55 (0.04)	1.2 (0.03)	0.3 (0.02)	0.0 (0.02)
[0,20]	54 (0.04)	1.2 (0.03)	0.3 (0.03)	0.0 (0.02)
[20,40]	54 (0.02)	1.2 (0.01)	0.2 (0.01)	0.0 (0.01)
[40,60]	53 (0.01)	1.1 (0.01)	0.2 (0.00)	0.[illegible]
(bkgexp.)	*329*	*7.36*	*1.51*	

Expected limit:

$BR(B_s \to \mu\mu) < 5.1\ (6.5)\ 10^{-8}$
@ 90 (95%) CL

CL_S vs $BR(B_S \to \mu\mu)$



$B_s \rightarrow \mu^+\mu^-$: Observed Limit

Observed number of events

Invariant mass (Δm, MeV/c2)

Δm \ GL	[0-0.25]	[0.25-0.5]	[0.5-0.75]	[0.75-1]
[-60, -40]	39	2	1	0
[-40,-20]	55	2	0	0
[-20,0]	73	0	0	0
[0,20]	60	0	0	0
[20,40]	53	2	0	0
[40,60]	55	1	0	0
(TOTAL)	*335*	*7*	*1*	*0*
(bkg exp.)	*329*	*7.36*	*1.51*	*0.081*

$B_s \rightarrow \mu^+\mu^-$: Observed Limit

Observed number of events

Invariant mass (Δm, MeV/c2)

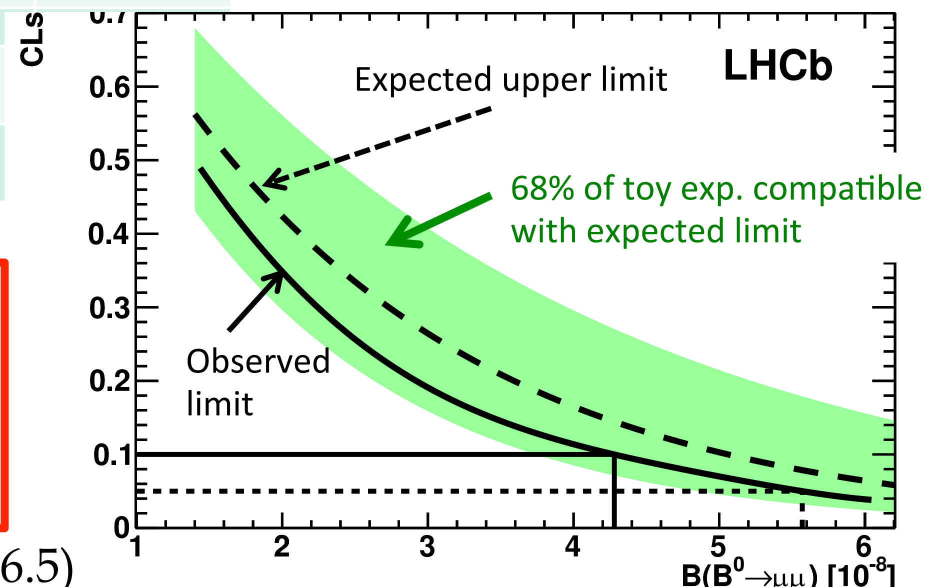
Δm \ GL	[0-0.25]	[0.25-0.5]	[0.5-0.75]	[0.75-1]
[-60, -40]	39	2	1	0
[-40,-20]	55	2	0	0
[-20,0]	73	0	0	0
[0,20]	60	0	0	0
[20,40]	53	2	0	0
[40,60]	55	1	0	0
(TOTAL)	*335*	*7*	*1*	
(bkg exp.)	*329*	*7.36*	*1.51*	

Observed limit:

$BR(B_s \rightarrow \mu\mu) < 4.3\ (5.6)\ 10^{-8}$ @ 90 (95%) CL

Expected are: 5.1 (6.5)

CL_S vs $BR(B_S \rightarrow \mu\mu)$



$B^0 \to \mu^+\mu^-$: Observed Limit

Observed number of events

Invariant mass (Δm, MeV/c2)

Δm \ GL	[0-0.25]	[0.25-0.5]	[0.5-0.75]	[0.75-1]
[-60, -40]	**59**	**2**	**0**	**0**
[-40,-20]	**67**	**0**	**0**	**0**
[-20,0]	**56**	**2**	**0**	**0**
[0,20]	**60**	**0**	**0**	**0**
[20,40]	**42**	**2**	**1**	**0**
[40,60]	**49**	**2**	**0**	**0**
(TOTAL)	*333*	*8*	*1*	*0*
(bkgexp.)	*352*	*8.29*	*1.85*	*0.118*

$B^0 \rightarrow \mu^+\mu^-$: Observed Limit

Observed number of events

Invariant mass (Δm, MeV/c2)

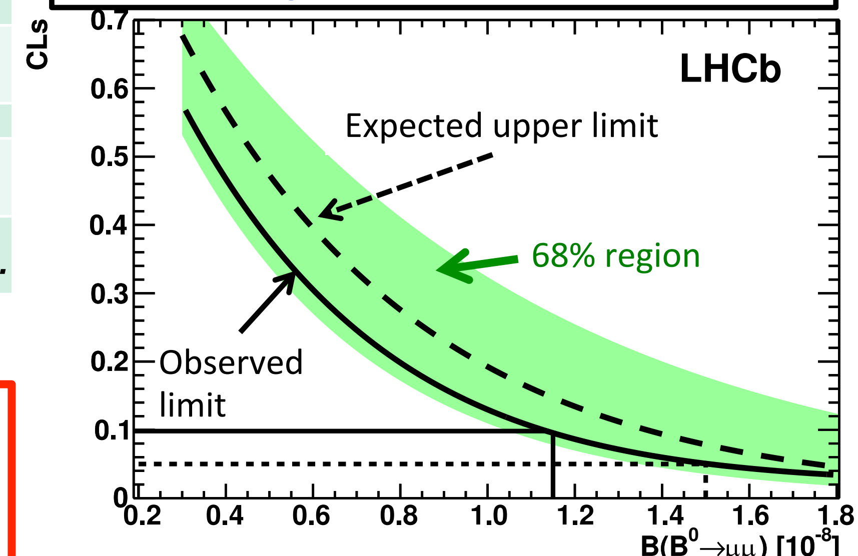
Δm \ GL	[0-0.25]	[0.25-0.5]	[0.5-0.75]	[0.75-1]
[-60, -40]	**59**	**2**	**0**	**0**
[-40,-20]	**67**	**0**	**0**	**0**
[-20,0]	**56**	**2**	**0**	**0**
[0,20]	**60**	**0**	**0**	**0**
[20,40]	**42**	**2**	**1**	**0**
[40,60]	**49**	**2**	**0**	**0**
(TOTAL)	*333*	*8*	*1*	*0*
(bkgexp.)	*352*	*8.29*	*1.85*	*0.*

Observed limit:

$BR(B^0 \rightarrow \mu^+\mu^-) < 1.2\ (1.5)\ \ 10^{-8}$

@ 90 (95% CL)

CL_S vs $BR(B^0 \rightarrow \mu\mu)$



Expected are: 1.4 (1.8)

Results

- First LHCb result (0.037 fb^{-1})

$BR(B_s \to \mu^+\mu^-) < 4.3\ (5.6)\ 10^{-8}$ @ 90 (95% CL)

$BR(B^0 \to \mu^+\mu^-) < 1.2\ (1.5)\ 10^{-8}$ @ 90 (95% CL)

arXiv 1103.2465, submitted to Phys. Lett. B

- Already now competitive to worlds best limit (not published, CDF 3.7 fb^{-1}):

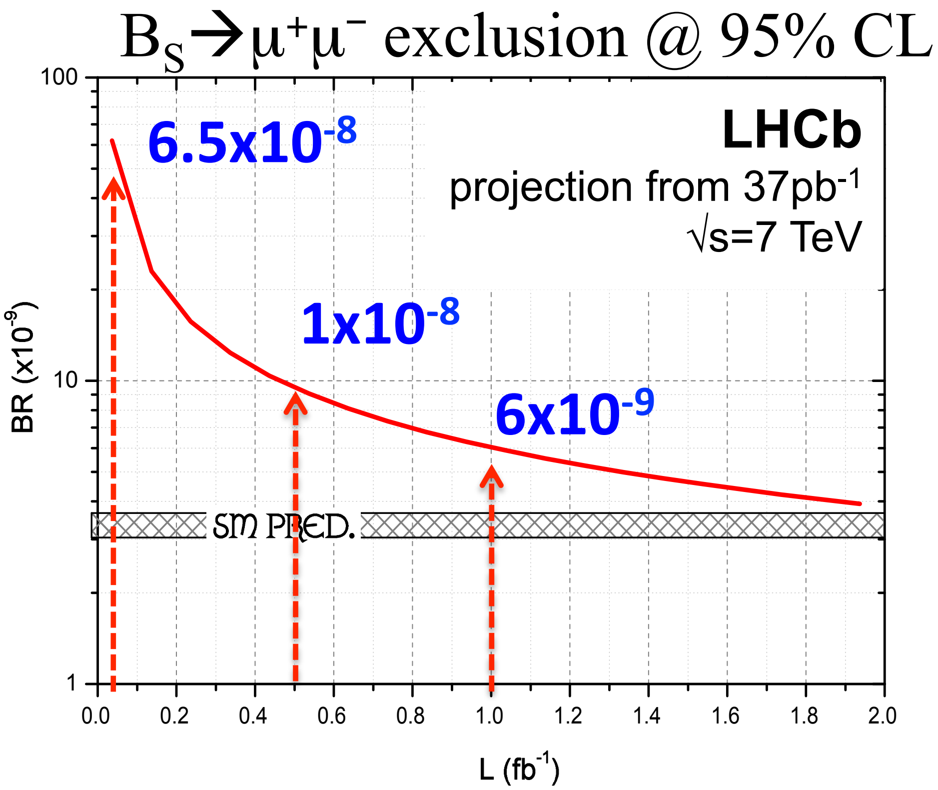
$BR(B_s \to \mu^+\mu^-) < 3.6\ (4.3)\ 10^{-8}$ @ 90 (95% CL)
$BR(B^0 \to \mu^+\mu^-) < 0.76\ (0.91)\ 10^{-8}$ @ 90 (95% CL)

Public CDF note 9892

- And to worlds best published (D0 6.1fb^{-1}):

BR$(B_S \to \mu\mu) < 5.1\times10^{-8}$ @ 95% CL

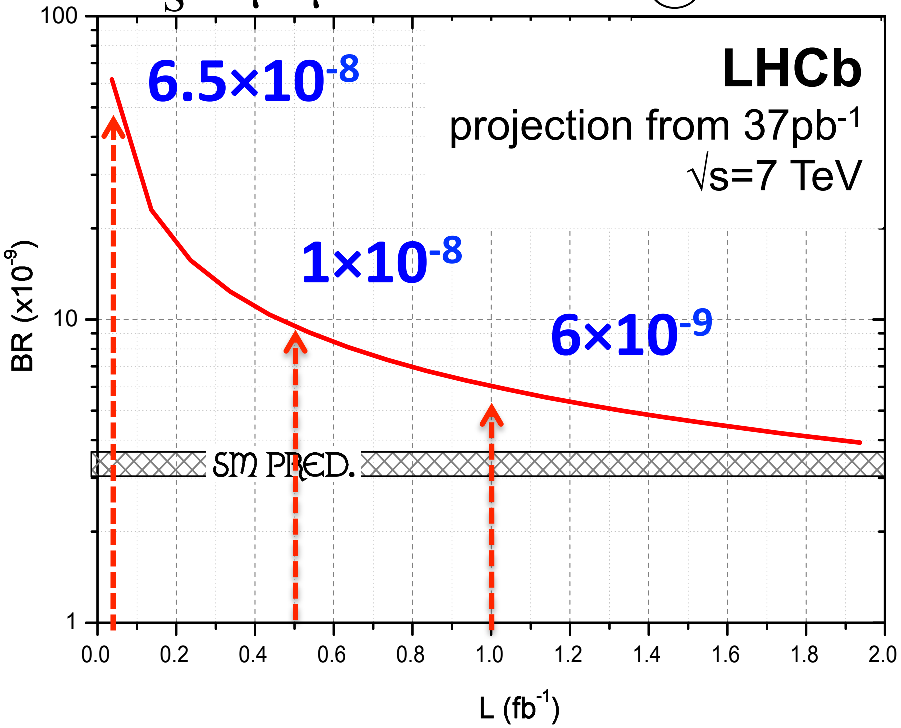
Phys. Lett B 693, 593 (2010)



37 pb^{-1} 500 pb^{-1} 1 fb^{-1}

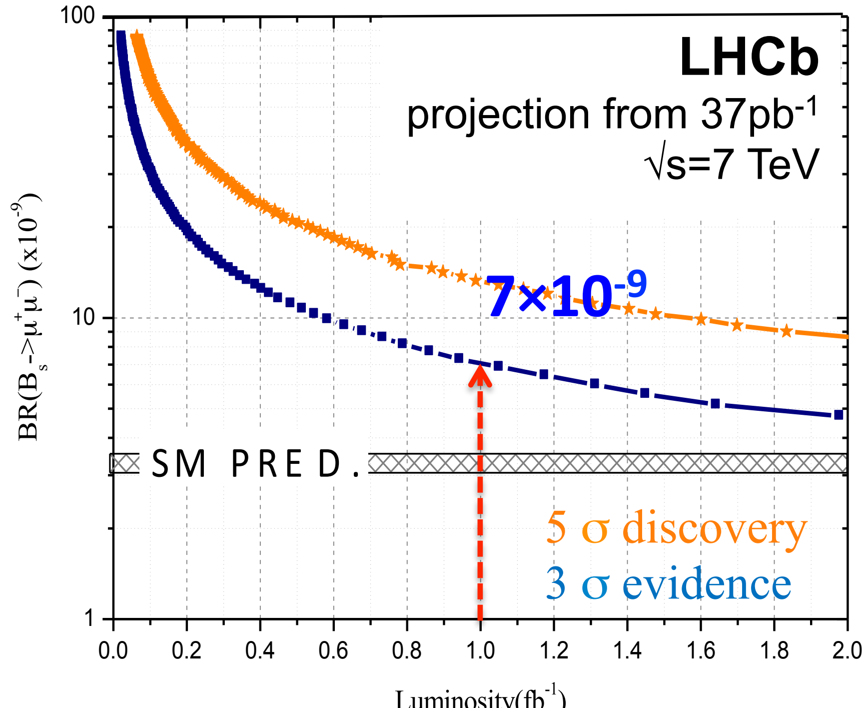
Prospects for 2011-2012

$B_s \rightarrow \mu^+\mu^-$ exclusion @ 95% CL



37 pb^{-1} **500 pb^{-1}** **1 fb^{-1}**

$B_s \rightarrow \mu^+\mu^-$ observation



1 fb^{-1}

With the data collected in 2011 we will be able to explore the region BR~ 6-10×10^{-9}

Conclusions

- With only $37pb^{-1}$ LHCb showed its amazing potential to search for New Physics in rare B decays

- The LHCb results…

$$BR(B_s \rightarrow \mu^+\mu^-) < 4.3\ (5.6) \times 10^{-8}\ @\ 90\ (95\%\ CL)$$

$$BR(B^0 \rightarrow \mu^+\mu^-) < 1.2\ (1.5) \times 10^{-8}\ @\ 90\ (95\%\ CL)$$

arXiv 1103.2465, submitted to Phys. Lett. B

… are very close to the worlds best results from Tevatron with ~100 (CDF) to ~200 (D0) less luminosity

- The 2011-12 LHC run will allow LHCb to explore the range of BR down to 4×10^{-9} and possibly discover New Physics


STOP
WRONG WAY
DO NOT ENTER
XA-XA.ORG

Comparison LHCb – CDF/D0

	LHCb	CDF	D0
Luminosity	$0.037fb^{-1}$	$3.7fb^{-1}$	$6.1fb^{-1}$
B+→ J/yK+	12366	19762	46803
Expected limit @ 95% CL	$6.5\ 10^{-8}$	$3.3\ 10^{-8}$	$4.0\ 10^{-8}$
Observed limit @ 95% CL	$5.6\ 10^{-8}$	$4.3\ 10^{-8}$	$5.1\ 10^{-8}$

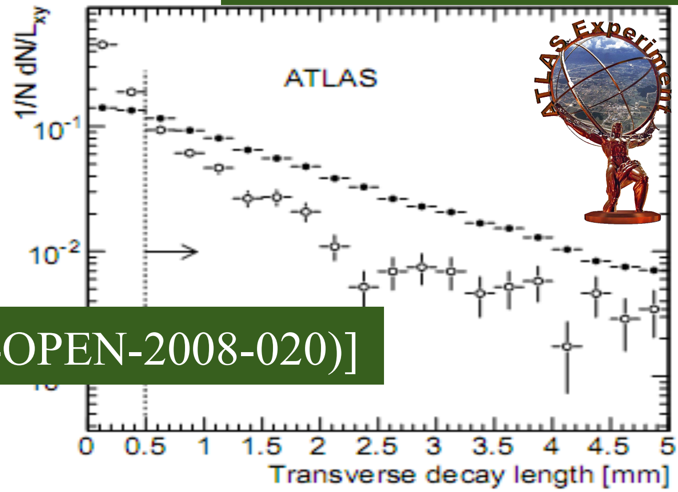
LHCb / CDF:

L : 1/100
nB^+: 0.63
expected limit: 1.97

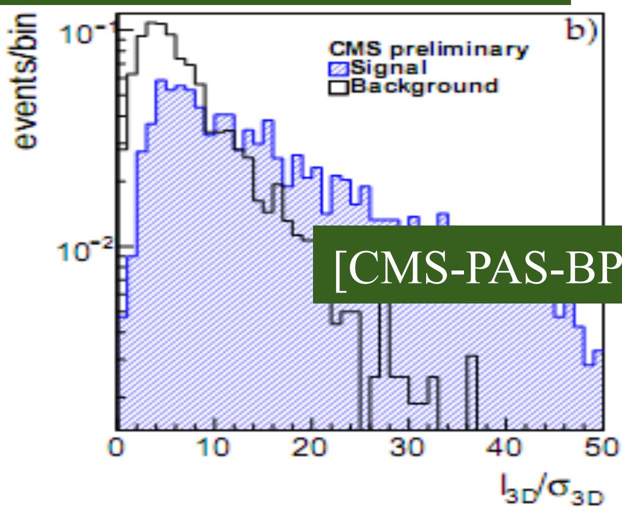
$B_s \to \mu^+\mu^-$ @ ATLAS / CMS

Cut based analysis: separate signal from background by using highly discriminant variables such as pointing, isolation and secondary vertex displacement:

Eg: Distance of flight and distance of flight significance:



[CERN-OPEN-2008-020)]

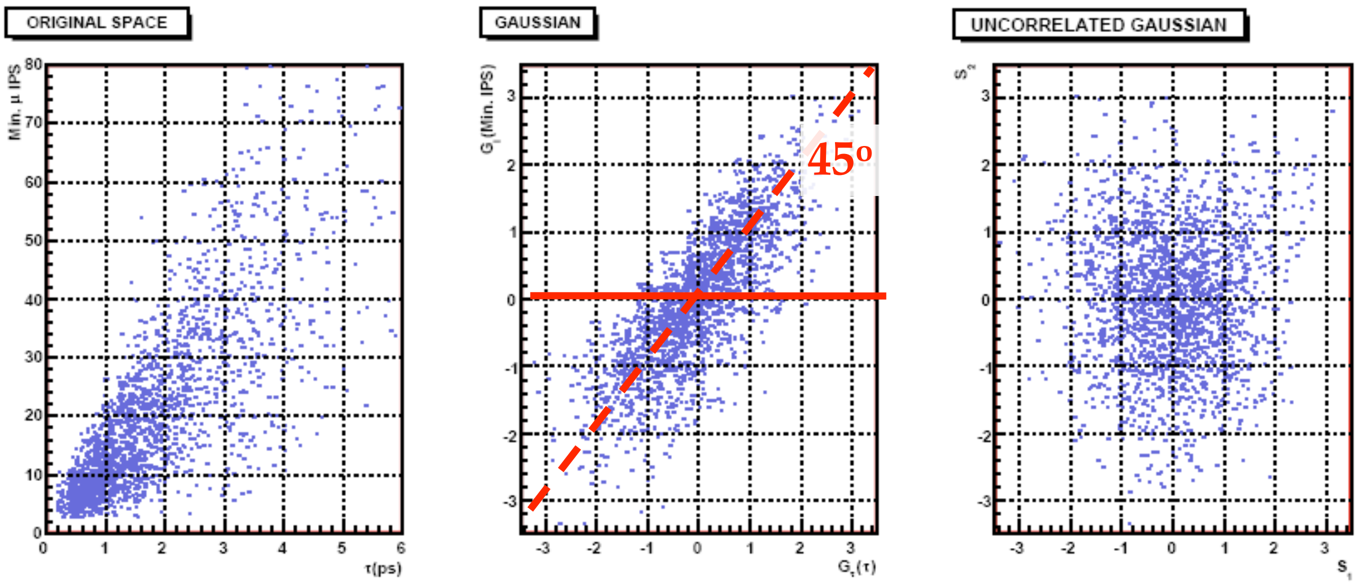


[CMS-PAS-BPH-07-001 (2009)]

Experiment	N sig	N bkg	90% CL limit in absence of signal
ATLAS (10 fb^{-1}) $\sigma(bb)$=500 ub	5.6 events	14^{+13}_{-10} events (only $bb \to \mu\mu$)	-------
CMS (1 fb^{-1}) $\sigma(bb)$=500 ub	2.36 events	6.53 events (2.5 $bb \to \mu\mu$)	$< 1.6 \times 10^{-8}$

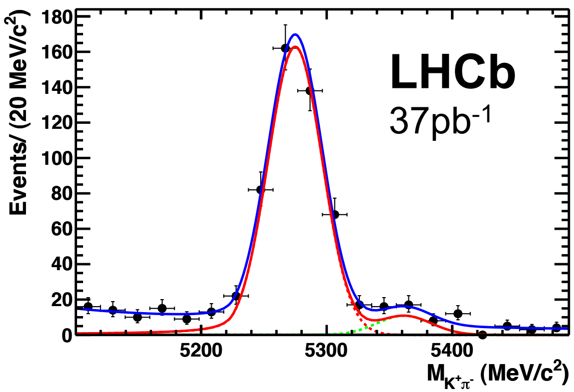
GL build procedure

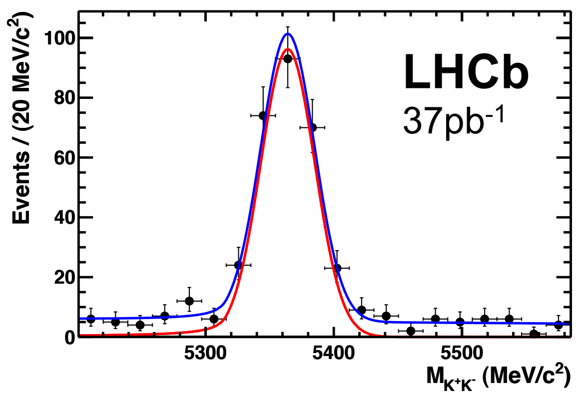
- The geometrical likelihood built from input variables, takes into account properly the correlations among the variables
  1. the input variables are transformed to Gaussian through cumulative and inverse error function
  2. In such space correlations are more linear-like → a rotation matrix, [inverse of correlation matrix] is applied and the 1st step is repeated
  3. Transformations under signal hyp. → χ^2_S, under bkg. → χ^2_B.
  4. Discriminating variable is $\chi^2_S - \chi^2_B$

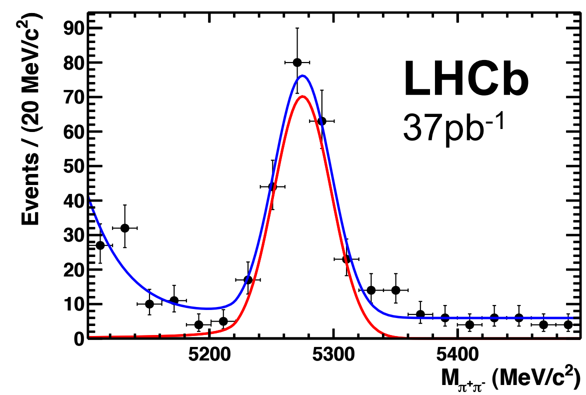


Normalization factor: fraction B2KPi

- Fraction of B→Kp events in inclusive B→hh' from data → use RICH PID and fit exclusive peaks
  - RICH efficiency cancels if well known BR(Bd→Kπ)/BR(Bd→ππ) are constrained
  - For clean selections, $f_{B\to Kp}$ is independent of PID cut



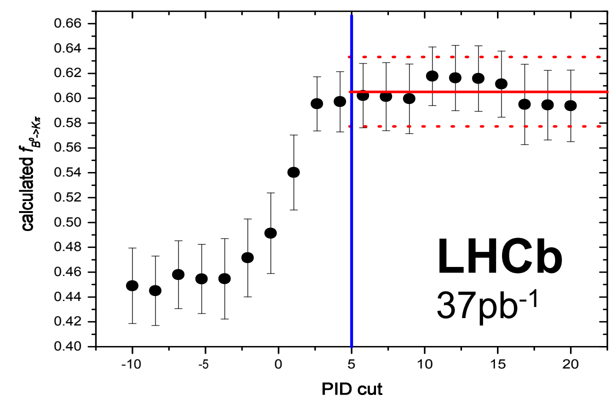




$f_{B\to Kp}$ as function of PID cut, plateau value:

$\mathbf{f_{B\to Kp}=0.605\pm0.027}$

(in agreement but more precise than PDG)



CL_S method

- For each bin (i) we need to know:
  - Number of expected signal events [for a given BR & L] : s_i
  - Number of expected background events [for a given L] : b_i
  - The number of observed events from data [after unblinding!]: d_i

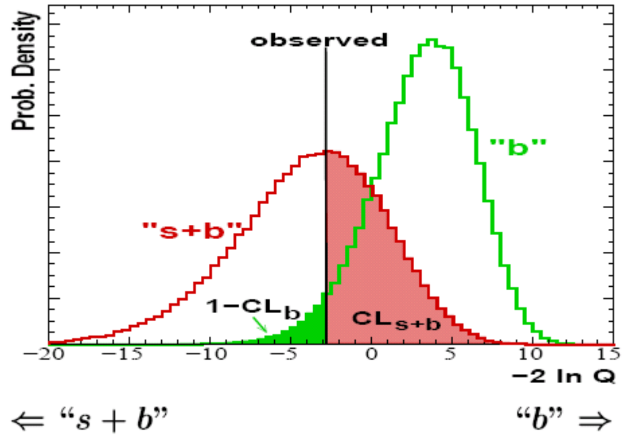
$$X_i = \frac{Poisson(d_i, <d_i>= s_i + b_i)}{Poisson(d_i, <d_i>= b_i)}$$

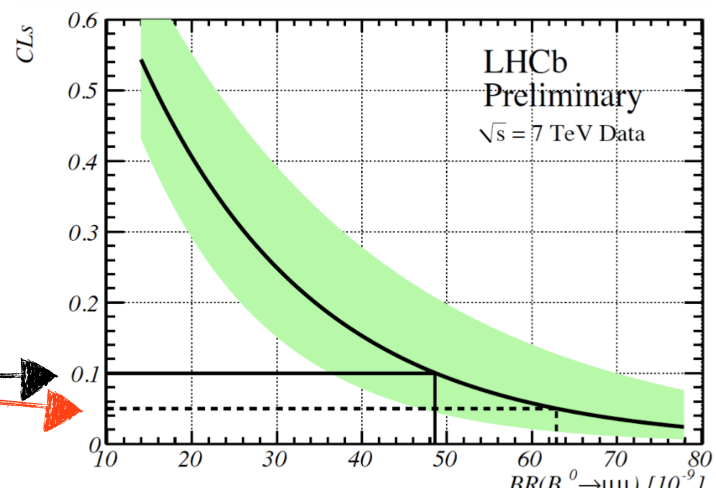
$$X = \prod_i^N X_i$$

$$CL_{s+b} = P_{s+b}(X \leq X^{OBSERVED})$$

$$CL_b = P_b(X \leq X^{OBSERVED})$$

Compute CL_s as CL_{s+b}/CL_b and evaluate the limits at 90 (95) % CL





$B_s \rightarrow \mu\mu$ search window

Invariant Mass bins (MeV/c^2)		Geometrical Likelihood Bins [0, 0.25]	[0.25, 0.5]	[0.5, 0.75]	[0.75, 1]
[−60, −40]	Exp. bkg.	$56.9^{+1.1}_{-1.1}$	$1.31^{+0.19}_{-0.17}$	$0.282^{+0.076}_{-0.065}$	$0.016^{+0.021}_{-0.010}$
	Exp. sig.	$0.0076^{+0.0034}_{-0.0030}$	$0.0050^{+0.0027}_{-0.0020}$	$0.0037^{+0.0015}_{-0.0011}$	$0.0047^{+0.0015}_{-0.0010}$
	Observed	39	2	1	0
[−40, −20]	Exp. bkg.	$56.1^{+1.1}_{-1.1}$	$1.28^{+0.18}_{-0.17}$	$0.269^{+0.072}_{-0.062}$	$0.015^{+0.020}_{-0.009}$
	Exp. sig.	$0.0220^{+0.0084}_{-0.0079}$	$0.0146^{+0.0066}_{-0.0053}$	$0.0107^{+0.0036}_{-0.0026}$	$0.0138^{+0.0034}_{-0.0024}$
	Observed	55	2	0	0
[−20, 0]	Exp. bkg.	$55.3^{+1.1}_{-1.1}$	$1.24^{+0.17}_{-0.16}$	$0.257^{+0.069}_{-0.059}$	$0.014^{+0.018}_{-0.009}$
	Exp. sig.	$0.038^{+0.015}_{-0.014}$	$0.025^{+0.012}_{-0.010}$	$0.0183^{+0.0063}_{-0.0047}$	$0.0235^{+0.0059}_{-0.0042}$
	Observed	73	0	0	0
[0, 20]	Exp. bkg.	$54.4^{+1.1}_{-1.1}$	$1.21^{+0.17}_{-0.16}$	$0.246^{+0.066}_{-0.057}$	$0.013^{+0.017}_{-0.008}$
	Exp. sig.	$0.03761^{+0.015}_{-0.015}$	$0.025^{+0.012}_{-0.010}$	$0.0183^{+0.0063}_{-0.0047}$	$0.0235^{+0.0060}_{-0.0044}$
	Observed	60	0	0	0
[20, 40]	Exp. bkg.	$53.6^{+1.1}_{-1.0}$	$1.18^{+0.17}_{-0.15}$	$0.235^{+0.063}_{-0.054}$	$0.012^{+0.015}_{-0.007}$
	Exp. sig.	$0.0220^{+0.0084}_{-0.0081}$	$0.0146^{+0.0067}_{-0.0054}$	$0.0107^{+0.0036}_{-0.0027}$	$0.0138^{+0.0035}_{-0.0025}$
	Observed	53	2	0	0
[40, 60]	Exp. bkg.	$52.8^{+1.0}_{-1.0}$	$1.15^{+0.16}_{-0.15}$	$0.224^{+0.060}_{-0.052}$	$0.011^{+0.014}_{-0.007}$
	Exp. sig.	$0.0076^{+0.0031}_{-0.0027}$	$0.0050^{+0.0025}_{-0.0019}$	$0.0037^{+0.0013}_{-0.0010}$	$0.0047^{+0.0013}_{-0.0010}$
	Observed	55	1	0	0

$B_d \rightarrow \mu\mu$ search window

Geometrical Likelihood Bins

Invariant Mass bins (MeV/c^2)		[0, 0.25]	[0.25, 0.5]	[0.5, 0.75]	[0.75, 1]
[−60, −40]	Exp. bkg.	$60.8^{+1.2}_{-1.1}$	$1.48^{+0.19}_{-0.18}$	$0.345^{+0.084}_{-0.073}$	$0.024^{+0.027}_{-0.014}$
	Exp. sig.	$0.0009^{+0.0004}_{-0.0003}$	$0.0006^{+0.0003}_{-0.0002}$	$0.0004^{+0.0002}_{-0.0001}$	$0.0006^{+0.0002}_{-0.0001}$
	Observed	59	2	0	0
[−40, −20]	Exp. bkg.	$59.9^{+1.1}_{-1.1}$	$1.44^{+0.19}_{-0.17}$	$0.329^{+0.080}_{-0.070}$	$0.022^{+0.024}_{-0.013}$
	Exp. sig.	$0.0026^{+0.009}_{-0.009}$	$0.0017^{+0.0008}_{-0.0006}$	$0.0013^{+0.0004}_{-0.0003}$	$0.0016^{+0.0004}_{-0.0002}$
	Observed	67	0	0	0
[−20, 0]	Exp. bkg.	$59.0^{+1.1}_{-1.1}$	$1.40^{+0.18}_{-0.17}$	$0.315^{+0.077}_{-0.067}$	$0.020^{+0.022}_{-0.012}$
	Exp. sig.	$0.0045^{+0.0017}_{-0.0017}$	$0.0030^{+0.0014}_{-0.0011}$	$0.00219^{+0.00067}_{-0.00054}$	$0.00280^{+0.00060}_{-0.00045}$
	Observed	56	2	0	0
[0, 20]	Exp. bkg.	$58.1^{+1.1}_{-1.1}$	$1.36^{+0.18}_{-0.16}$	$0.300^{+0.073}_{-0.064}$	$0.019^{+0.021}_{-0.011}$
	Exp. sig.	$0.0045^{+0.0017}_{-0.0017}$	$0.0030^{+0.0014}_{-0.0011}$	$0.00219^{+0.00067}_{-0.00054}$	$0.00280^{+0.00060}_{-0.00045}$
	Observed	60	0	0	0
[20, 40]	Exp. bkg.	$57.3^{+1.1}_{-1.1}$	$1.33^{+0.17}_{-0.16}$	$0.287^{+0.070}_{-0.061}$	$0.017^{+0.019}_{-0.010}$
	Exp. sig.	$0.0026^{+0.0009}_{-0.0009}$	$0.0017^{+0.0008}_{-0.0006}$	$0.0013^{+0.0004}_{-0.0003}$	$0.0016^{+0.0004}_{-0.0002}$
	Observed	42	2	1	0
[40, 60]	Exp. bkg.	$56.4^{+1.1}_{-1.1}$	$1.29^{+0.17}_{-0.16}$	$0.274^{+0.067}_{-0.058}$	$0.016^{+0.018}_{-0.009}$
	Exp. sig.	$0.0009^{+0.0003}_{-0.0003}$	$0.0006^{+0.0003}_{-0.0002}$	$0.0004^{+0.0001}_{-0.0001}$	$0.0006^{+0.0002}_{-0.0001}$
	Observed	49	2	0	0