Indirect searches for Physics beyond the Standard Model with the LHCb experiment

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B-Physik Seminar München, 07. Oktober 2011

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

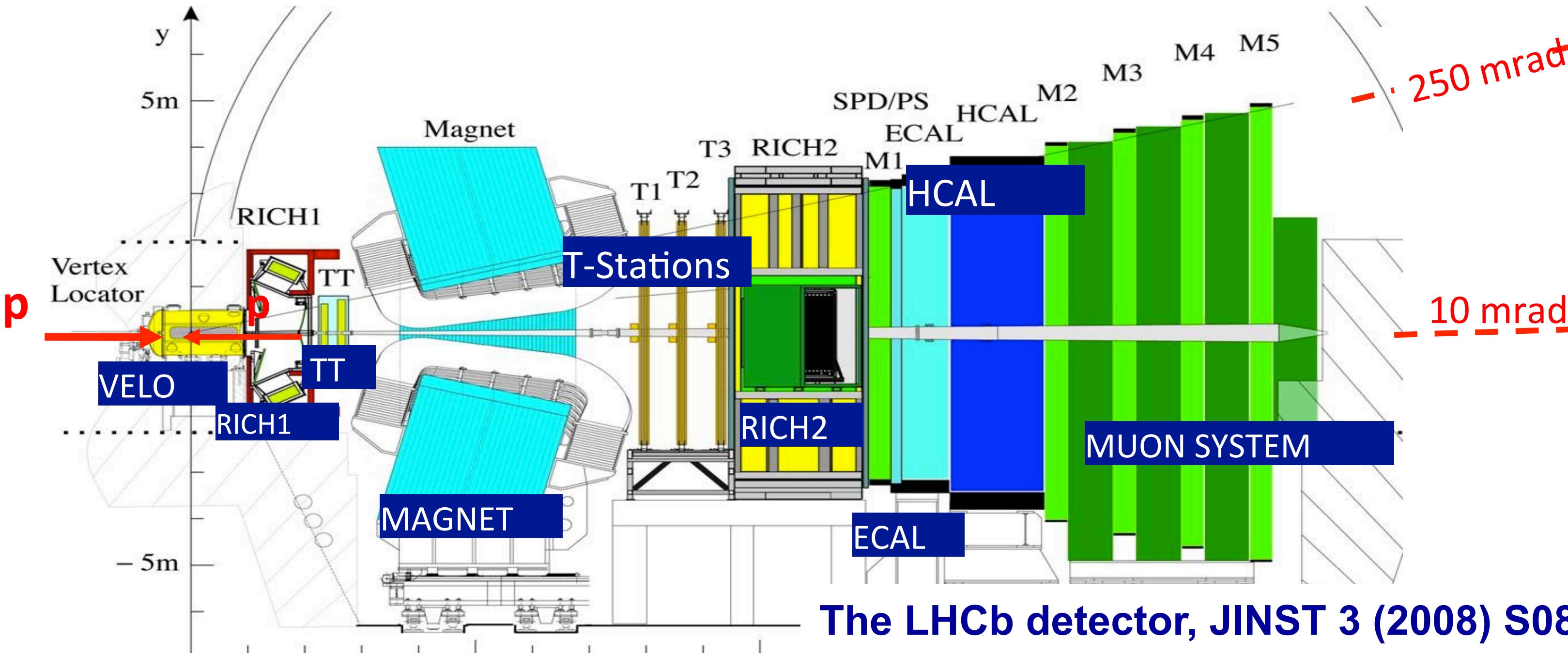
Charm physics

Outline

- The LHCb experiment
  - Overview of the experiment and performance
- **Focus here on most promising searches:**
  - **Probe of Lorentz structure in $B_d \to K^* \mu^+\mu^-$ decays**
  - **Measurement of CP violation in B_s mixing: $B_s \to J/\psi\ \phi$, $J/\psi\ f_0$**
  - **Probe an extended scalar sector: $B_{s,d} \to \mu^+\mu^-$**
- Many interesting LHCb measurements not covered here
  - search for CPV in charm
  - Bs mixing in $B_s \to \phi\phi$
  - radiative decays $B_s \to K^* \gamma$, $\phi\gamma$
  - Progress towards the CKM phase γ
  - Search for new penguin decays, for majorana neutrinos
  - production measurements, excited B's

The LHCb Experiment: Overview of the experiment and performance

The LHCb detector



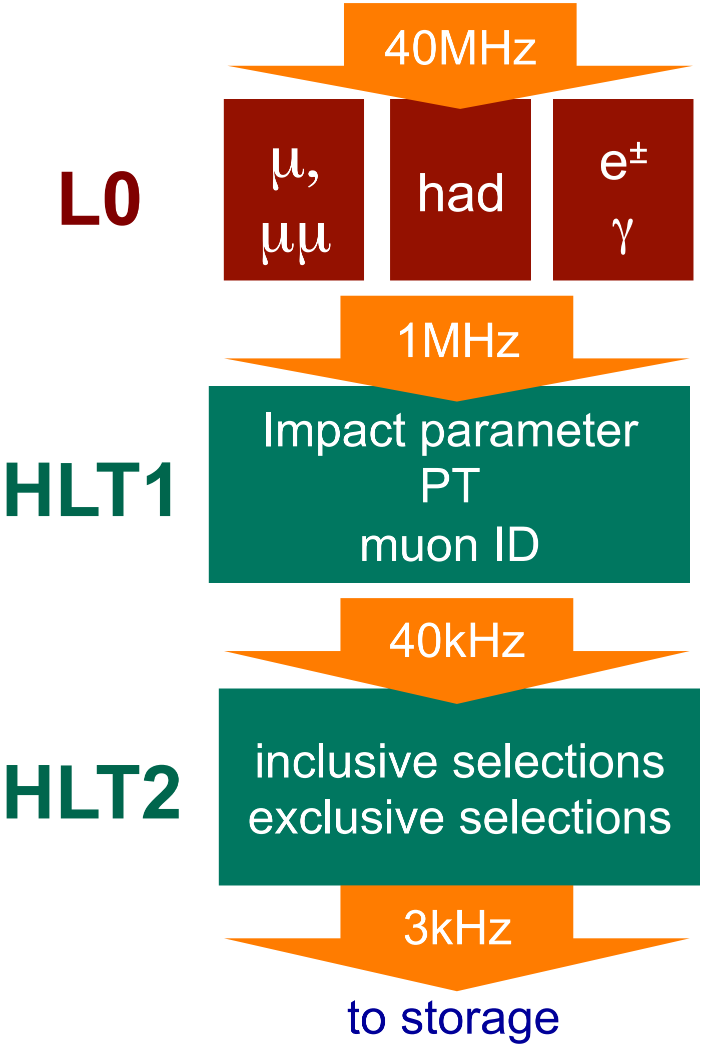
The LHCb detector, JINST 3 (2008) S08005

- Huge cross sections: **σ(pp→bbX) @ 7 TeV ~ 300 μb***
  - But only 1/200 events contain b quark → Trigger
- Large acceptance **1.9<η<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

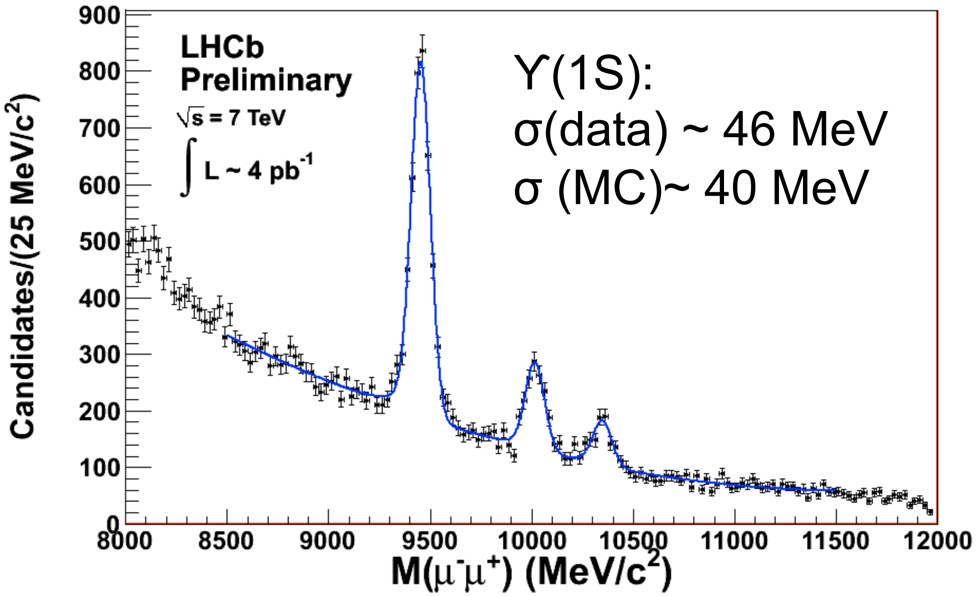
L0 hardware	**"high p_T" signals in calorimeter and muon systems**
HLT1 software	Partial reconstruction selection based on one or two tracks (dimuon) displaced in the VELO, muon ID (offline like)
HLT2 software	Global reconstruction (very close to offline) dominantly inclusive signatures

+ Global event cuts rejecting busy events

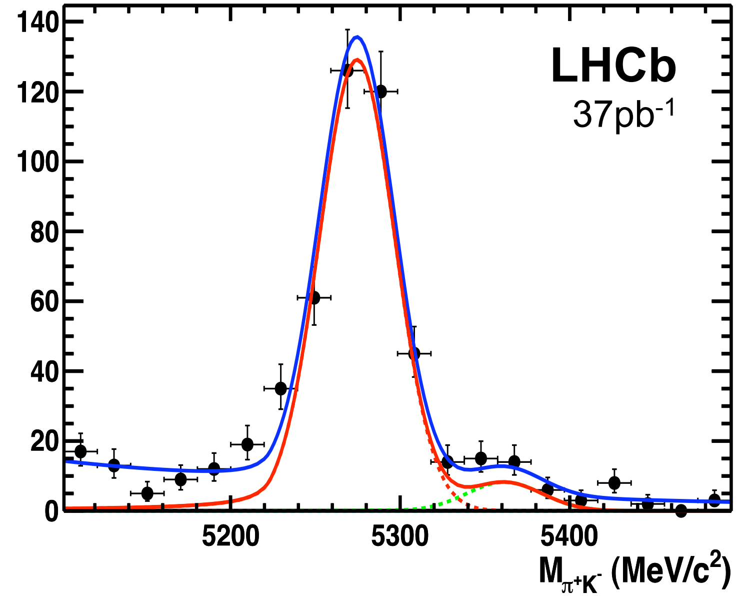
	Charm	**Hadr. B**	**Lept. B**
Global efficiency	~10%	~40%	75-90%

Keys for b-physics II: mass resolution

Υ(1S), Υ(2S), Υ(3S)



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



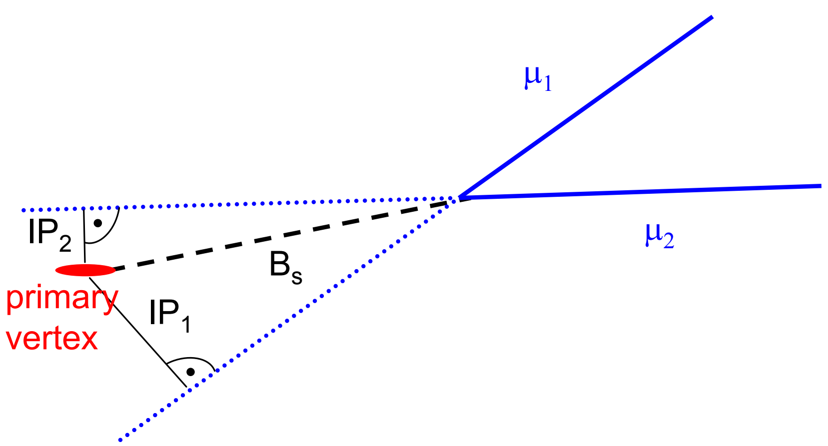
	momentum resolution	mass resolution $J/\psi \rightarrow \mu\mu$
LHCb	$\delta p/p$ = 0.4-0.6 %	13 MeV
CMS	$\delta pt/pt$ = 1-3 %	40 MeV
ATLAS	$\delta pt/pt$ = 5-6 %	71 MeV

Keys for b-physics III: IP and vertex resolution

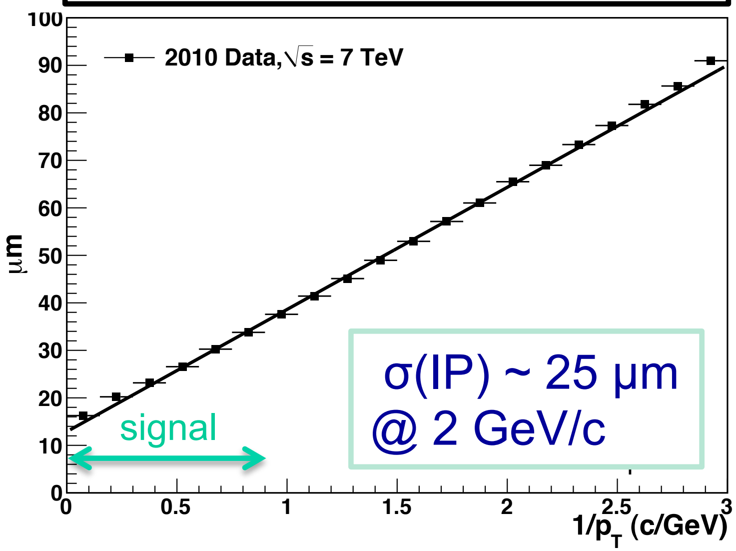
Primary vertex resolutions (25 tracks):

	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

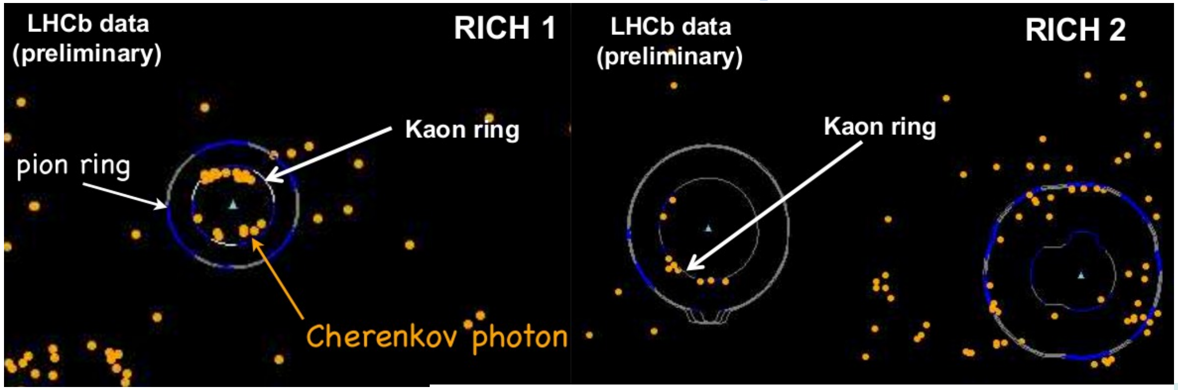
Impact parameter (IP):

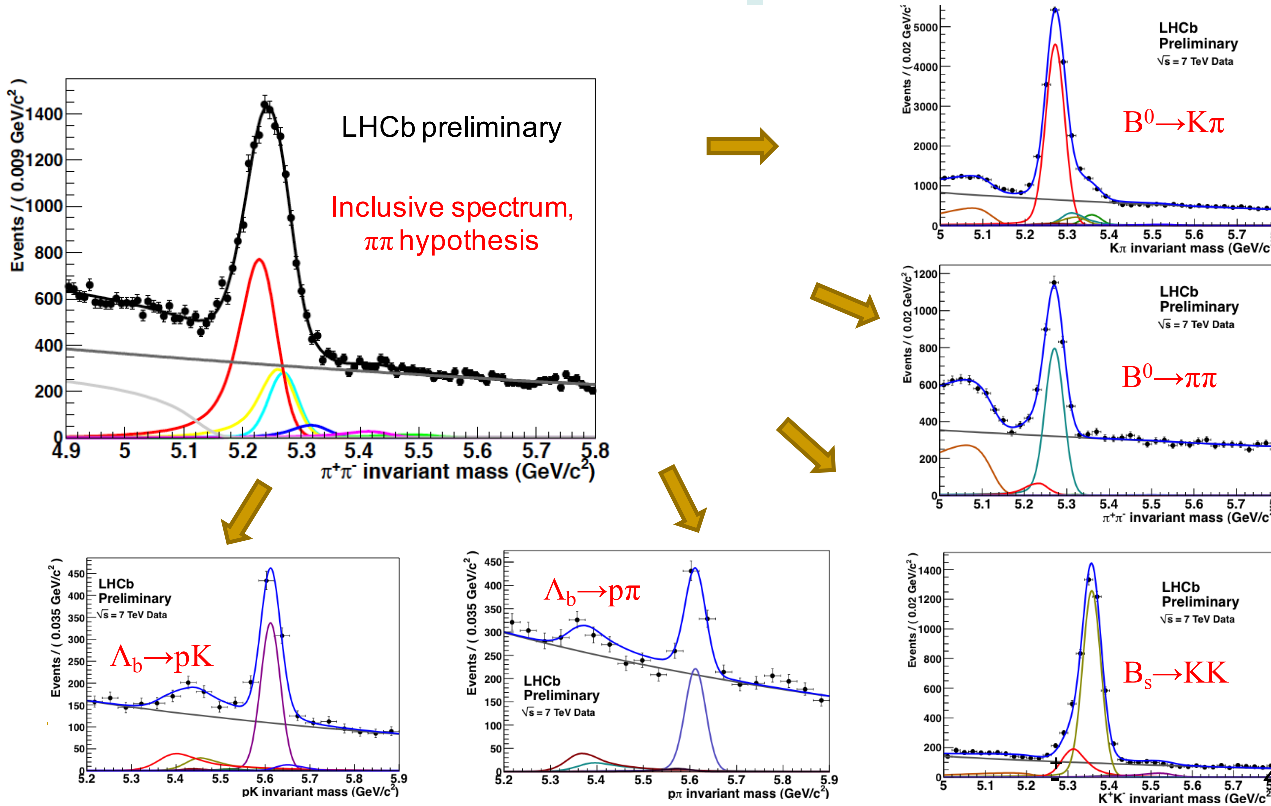


IP resolution vs 1/pT



Keys for b-physics IV: Muon ID





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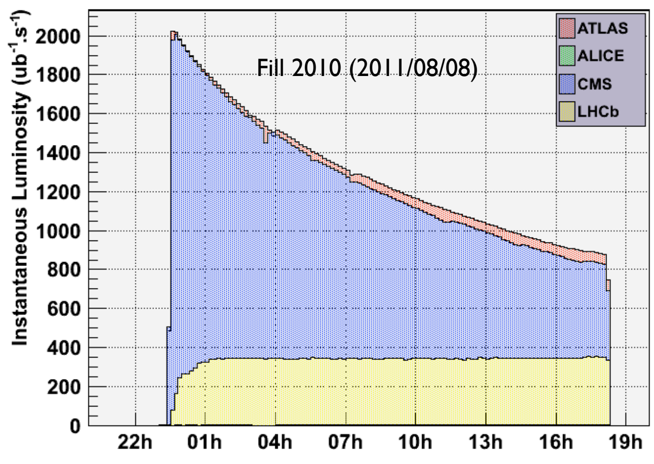
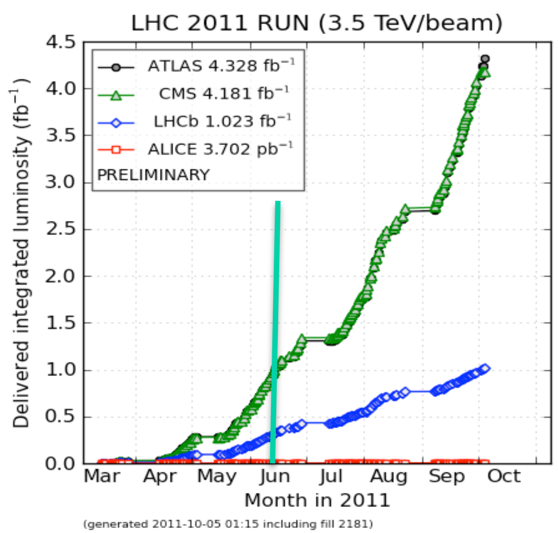
LHCb operation

- Most of 2011, LHCb ran at $3.5 \times 10^{32} cm^{-2}s^{-1}$
  - LHCb design luminosity: $2 \times 10^{32} cm^{-2}s^{-1}$

	L_{inst} [Hz/cm^2]	L0 output rate	μ	Efficiency	L_{int} [pb^{-1}]
April-June	3.0×10^{32}	620 kHz	1.8-2.0	90 %	~350
July-Sept	**3.5×10^{32}**	**850 kHz**	**<1.5**	**90 %**	**~650**



- Analyses presented here use ~340pb^{-1}
  - Dataset available for summer conferences
  - ~ three times on tape now



B-production at the LHC

Detached J/ψ

CMS: [Eur.Phys.J. C71 (2011) 1575],
Atlas: [Nucl.Phys. B850 (2011) 387-444]
LHCb: [Eur. Phys. J. C 71 (2011) 1645]

$$\sigma^{4\pi}_{b\bar{b}} = (288 \pm 4 \pm 48)\ \mu\text{b}$$

Dilepton tags

CMS: [CMS-PAS-BPH-10-015]

$D\mu$ tags

LHCb: [Physics Letters B 698 (2011) 14]

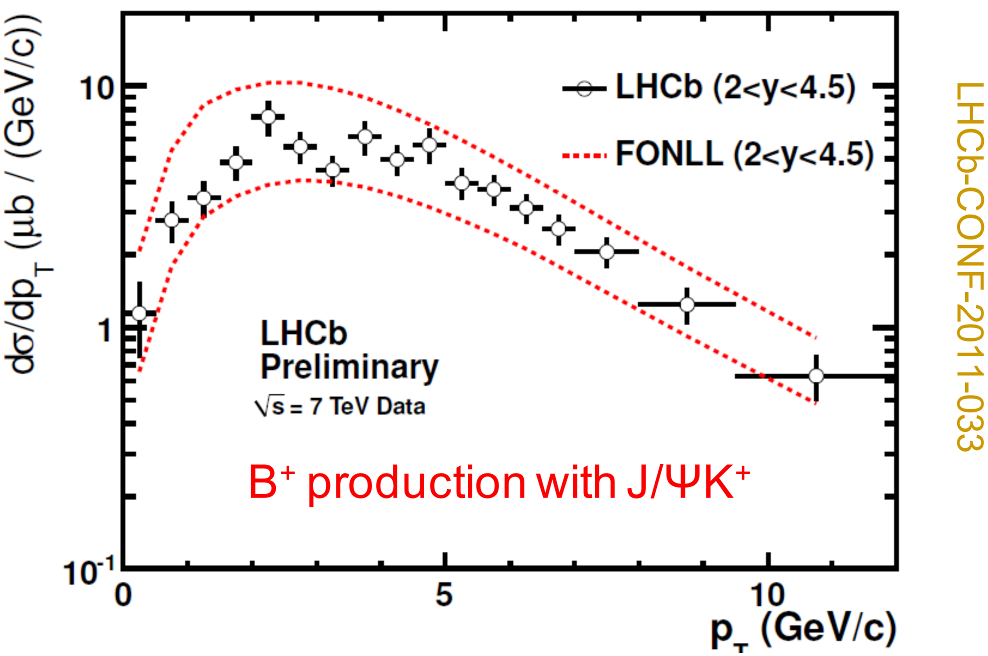
$$\sigma^{(2<\eta<6)}_{b\bar{b}} = (75 \pm 5 \pm 13)\ \mu\text{b}$$

$$\sigma^{4\pi}_{b\bar{b}} = (284 \pm 20 \pm 49)\ \mu\text{b}$$

Fully reconstructed

$B \to J/\psi X$

LHCb [CONF-2011-033]
CMS: [Phys.Rev.Lett.106:112001,2011]
[Phys. Rev. Lett. 106, 252001 (2011)]
[arXiv:1106.4048]



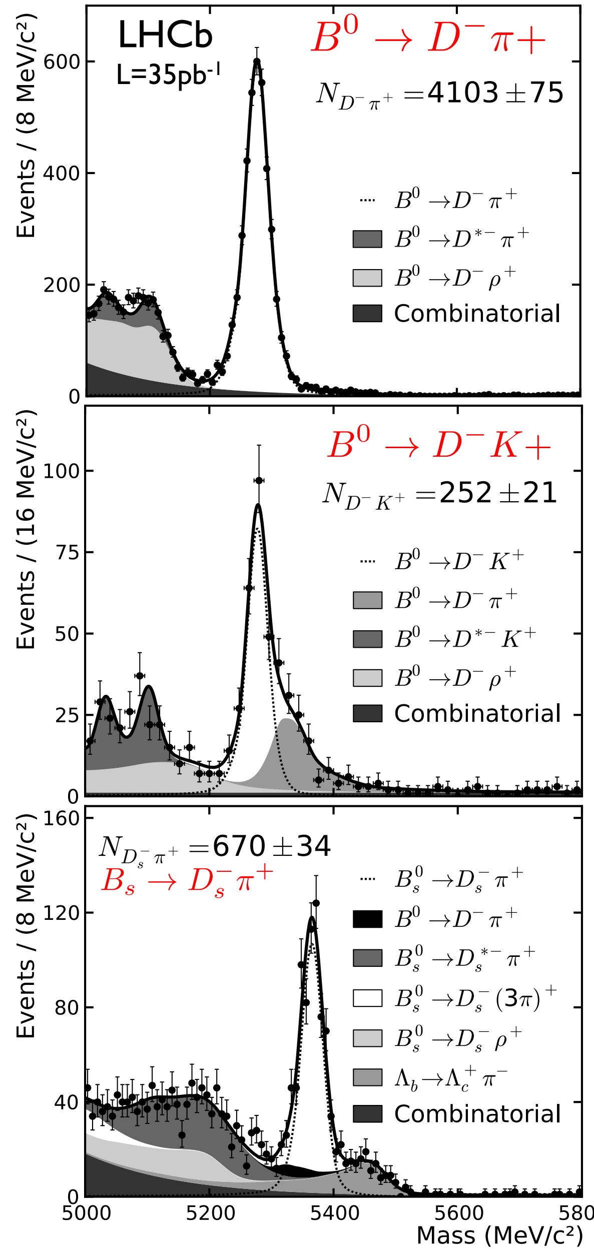
	L(fb^{-1})	σ_{acc}(μb)	bb / 10^9
ATLAS / CMS	4.1	75	304
LHCb	1	75	74
CDF / D0	9.5	2.8	26
Belle + BaBar	832+426	0.0011	1.4

b fragmentation f_d/f_s

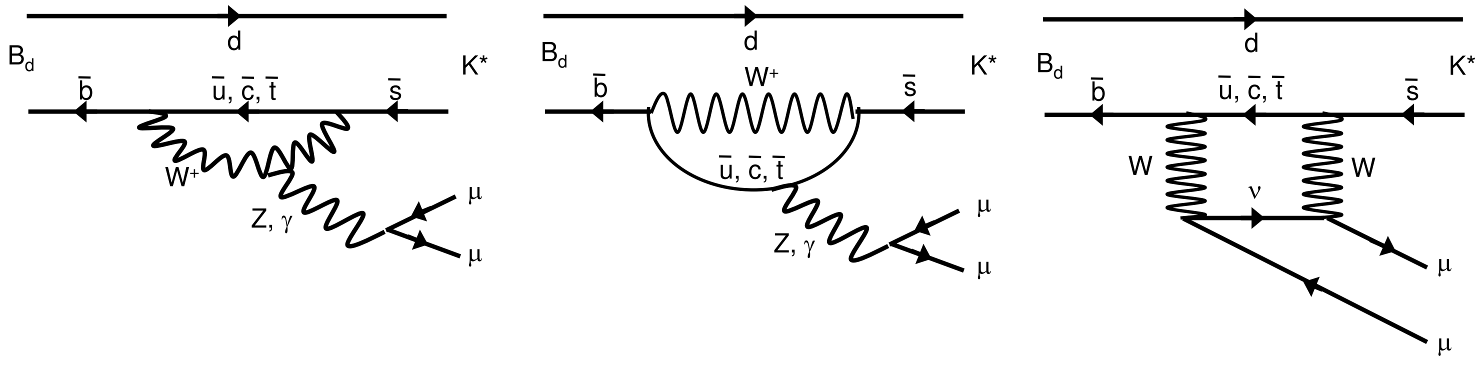
- Fraction of b→B_s is an essential ingredient to B_s→μμ and other searches
- LHCb has measured it in two ways:
  - Ratio of $B \to D_s \mu X$ to $B \to D^+ \mu X$ modes
    [LHCb-CONF-2011-028]
  - Ratio of $B_d \to DK$ and $B_s \to D_s \pi$ modes
    [Accepted by PRL]
- Combination **[LHCb-CONF-2011-034]**

$$\left(\frac{f_s}{f_d}\right)_{\text{LHCb}} = 0.267 \,{}^{+0.021}_{-0.020}$$

- Found to be independent of PT
  - Also similar to LEP and Tevatron fractions



New Lorentz structure:
Angular analysis of $B^0 \rightarrow K^* \mu^+\mu^-$



New Lorentz structure: $B^0 \rightarrow K^* \mu^+\mu^-$

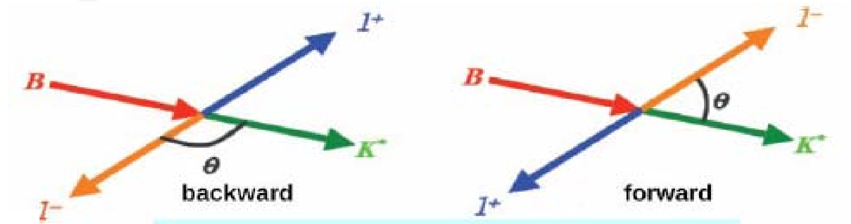
- Angular distribution mostly sensitive to magnetic (O_7) and (axial-) vector (O_9, O_{10}) operators

- Measurement of angular distributions as function of $q^2 = m_{\mu\mu}^2$

$$\frac{1}{\Gamma}\frac{\partial\Gamma}{\partial\cos\theta\,\partial q^2} = \frac{3}{4}F_L\sin^2\theta + \frac{3}{8}(1-F_L)(1+\cos^2\theta) + A_{FB}\cos\theta$$

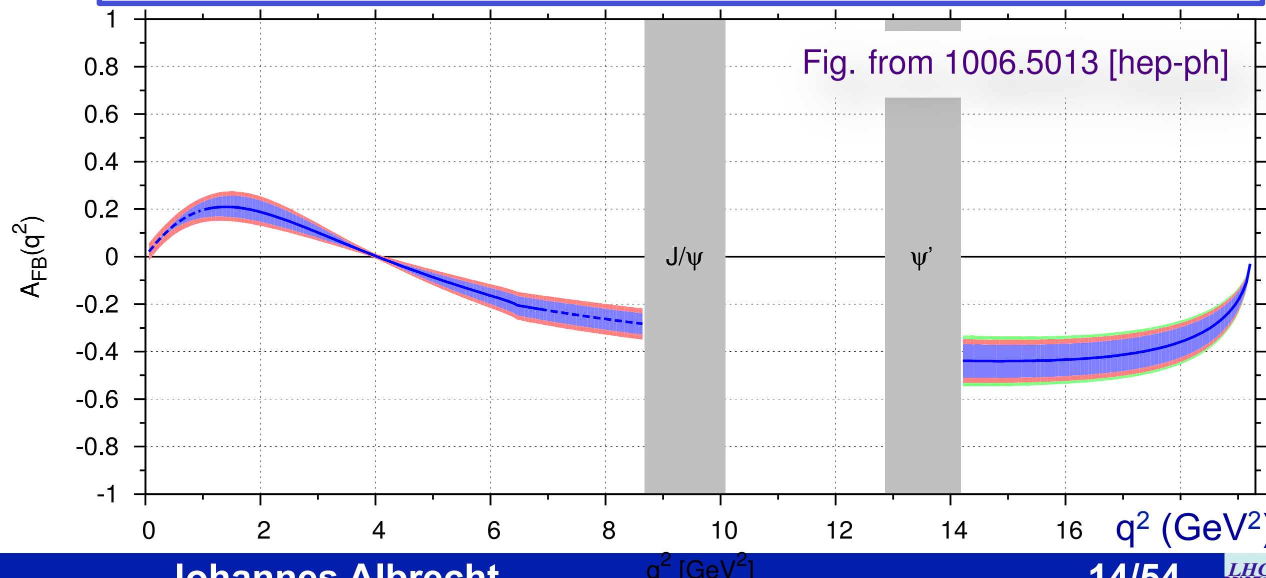
forward-backward asymmetry A_{FB},
Longitudinal polarization F_L

Forward-backward asymmetry A_{FB}:



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

Standard Model prediction



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forward-backward asymmetry A_{FB},
Longitudinal polarization F_L

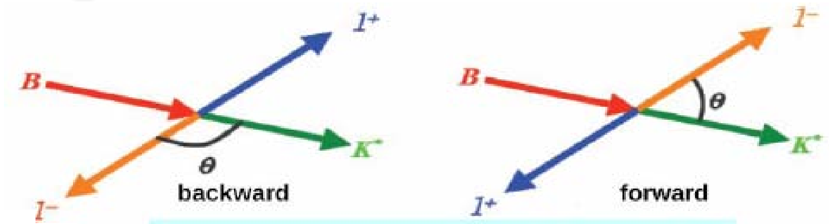
- Data at B-factories and CDF might hint a non-SM contribution

230 events, B/S = 0.3

70 events, B/S = 0.25

100 events, B/S = 0.4

Forward-backward asymmetry A_{FB}:



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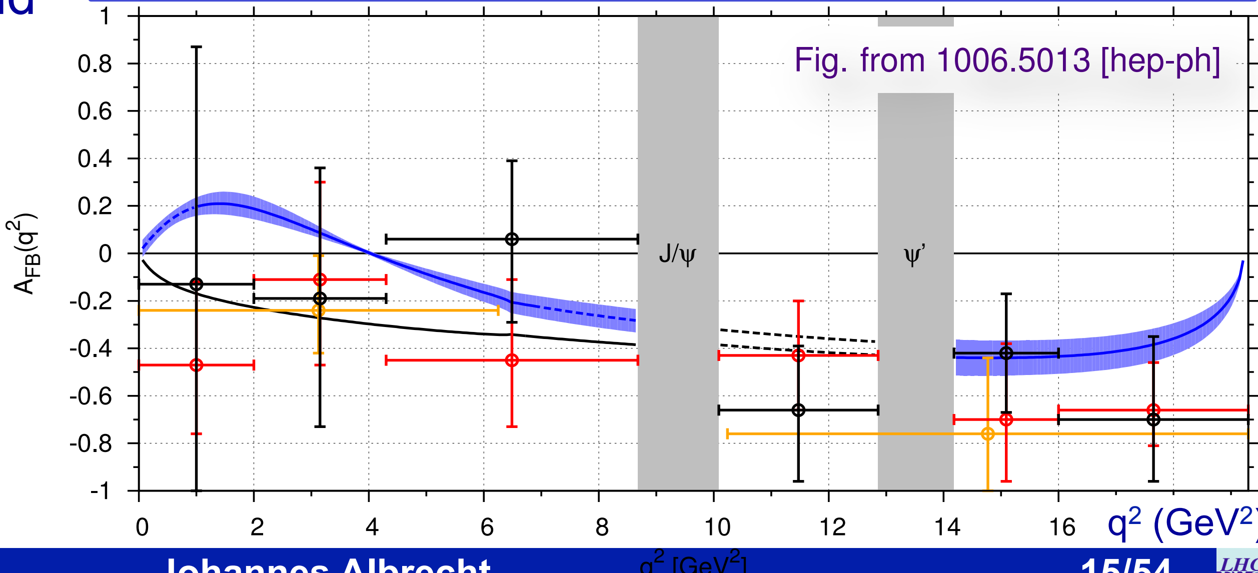
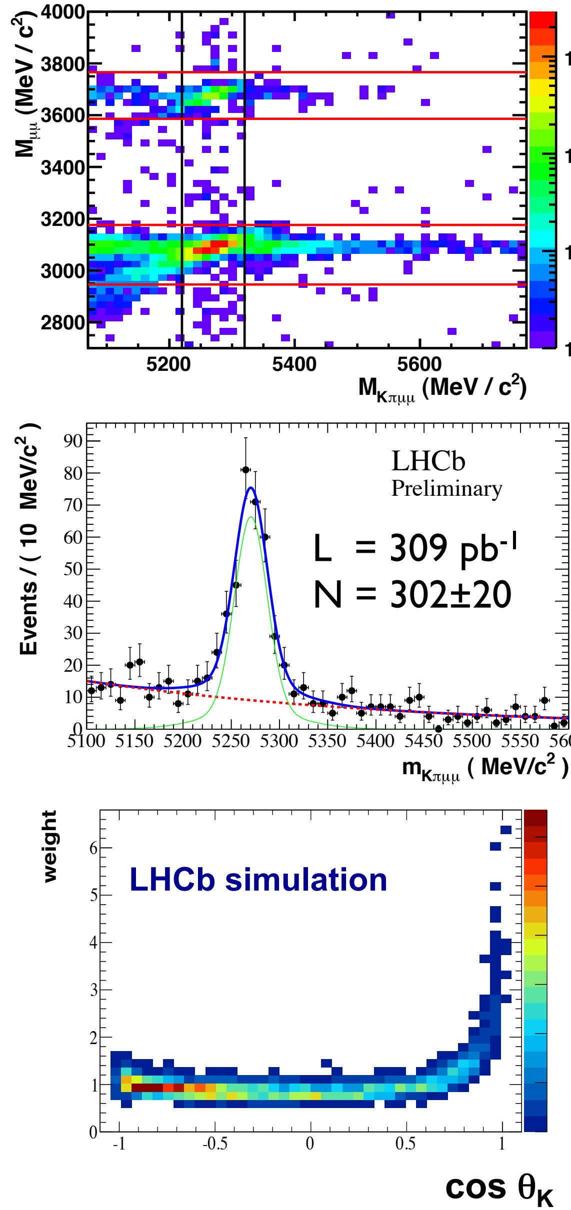
Experimental situation before summer 2011



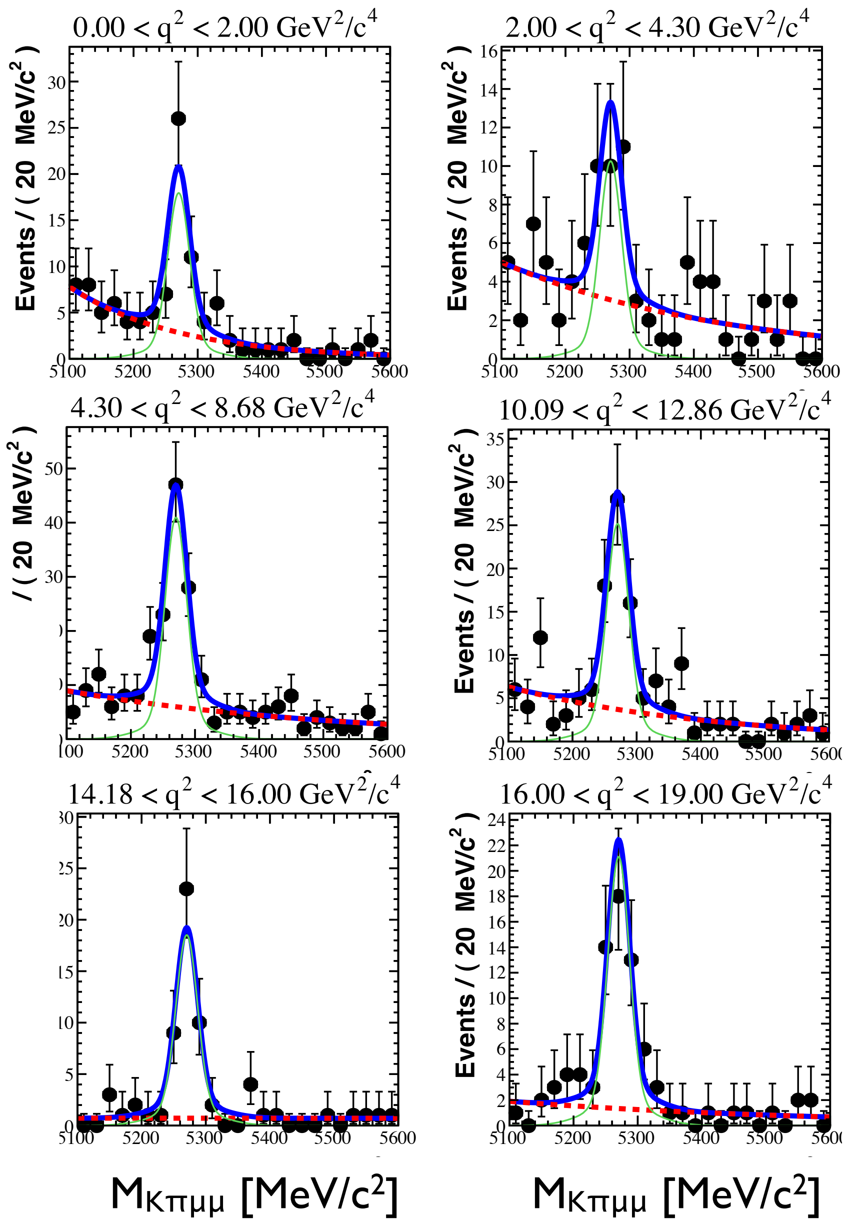
- Select events with Boosted Decision Tree
  - Veto J/ψ and $\psi(2S)$
- Weight events according to ε^{-1}
  - As function of (θ_l, θ_k, q^2)
  - Procedure verified on $B_d \rightarrow J/\psi K^*$ data and MC



LHCb-CONF-2011-038

$B^0 \to K^* \mu^+\mu^-$ in LHCb

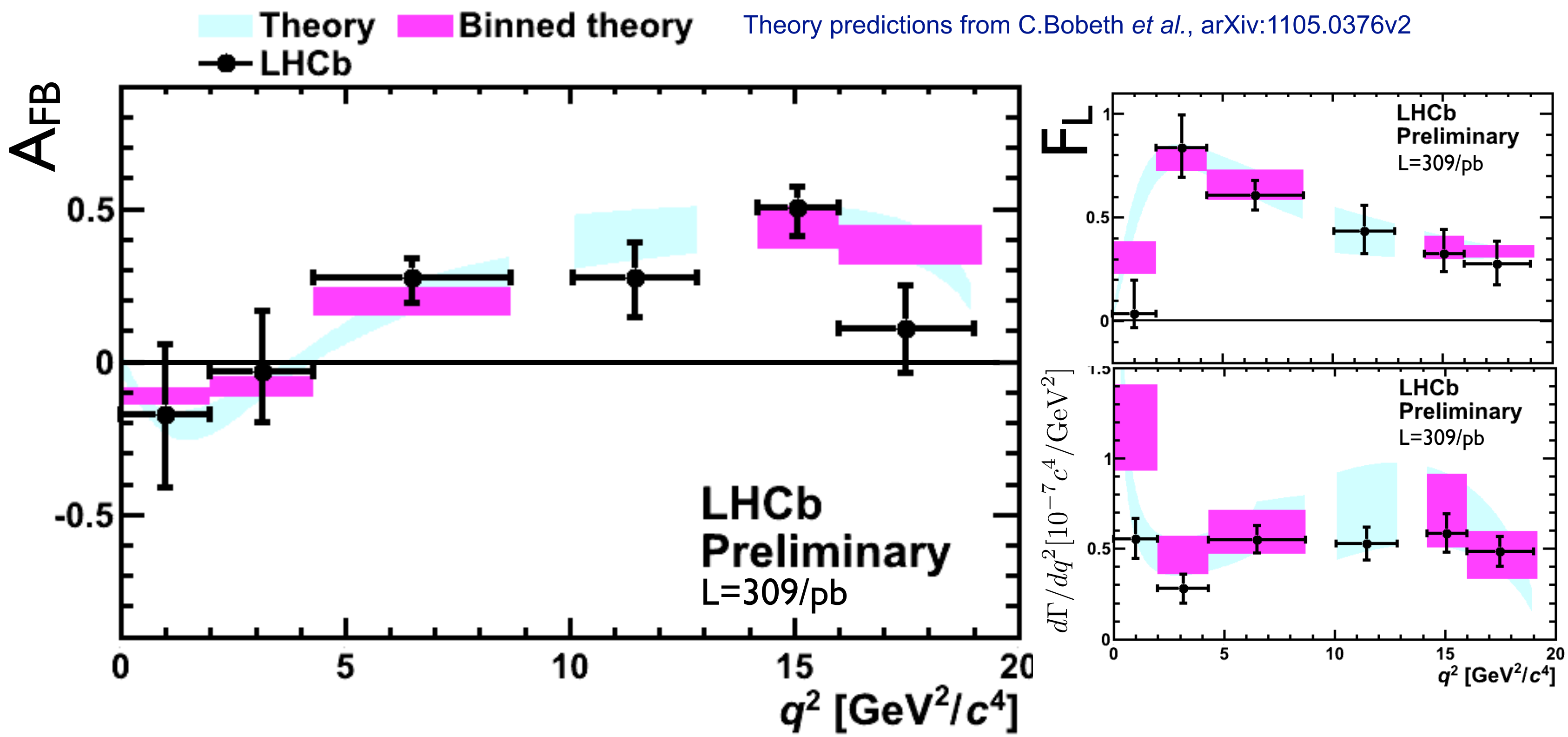
- Select events with Boosted Decision T
  - Veto J/ψ and $\psi(2S)$
- Weight events according to ε^{-1}
  - As function of $(\theta_l, \theta_k, q^2)$
  - Procedure verified on $B_d \rightarrow J/\psi K^*$ data a
- Perform measurement in 6 q^2 bins using simultaneous fit of mass, θ_l and θ_k
  - Differential BR $d\Gamma/dq^2$
  - Longitudinal polarization F_L
  - Forward backward assymmetry A_{FB}
- [Likelihood scan for F_L and A_{FB} due to correlations]



LHCb-CONF-2011-038

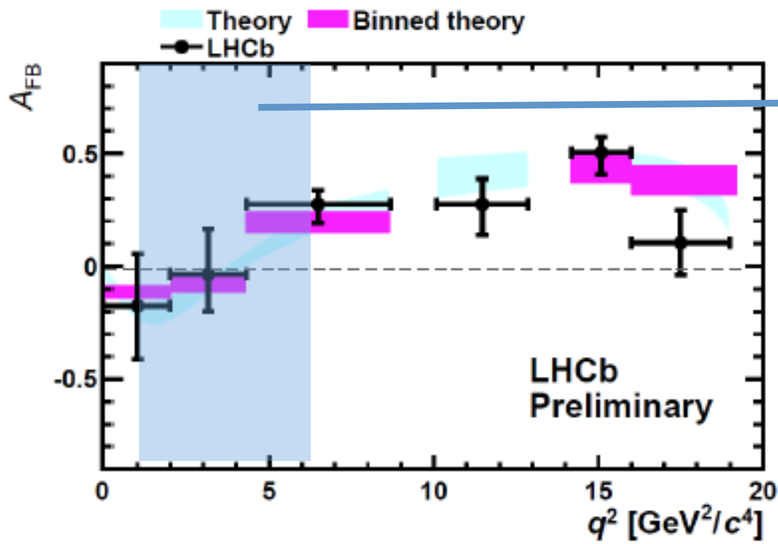
$B^0 \to K^* \mu^+\mu^-$ in LHCb

Theory predictions from C.Bobeth *et al.*, arXiv:1105.0376v2

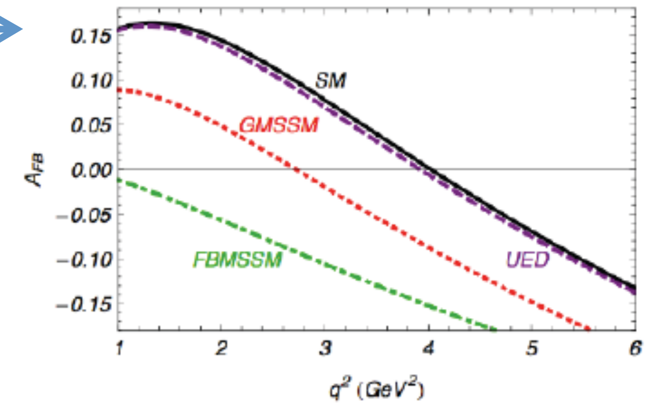


- Measurement based on 300 candidates (largest sample)
  - Purity comparable to B-factories
  - Generally statistics limited, systematic uncertainties small
- Data in excellent agreement with theory (☺ or ☹ ?)

$B^0 \to K^* \mu^+\mu^-$ in LHCb: next steps



A_{FB} with flipped sign for $1<q^2<6$:
zero crossing point in different models



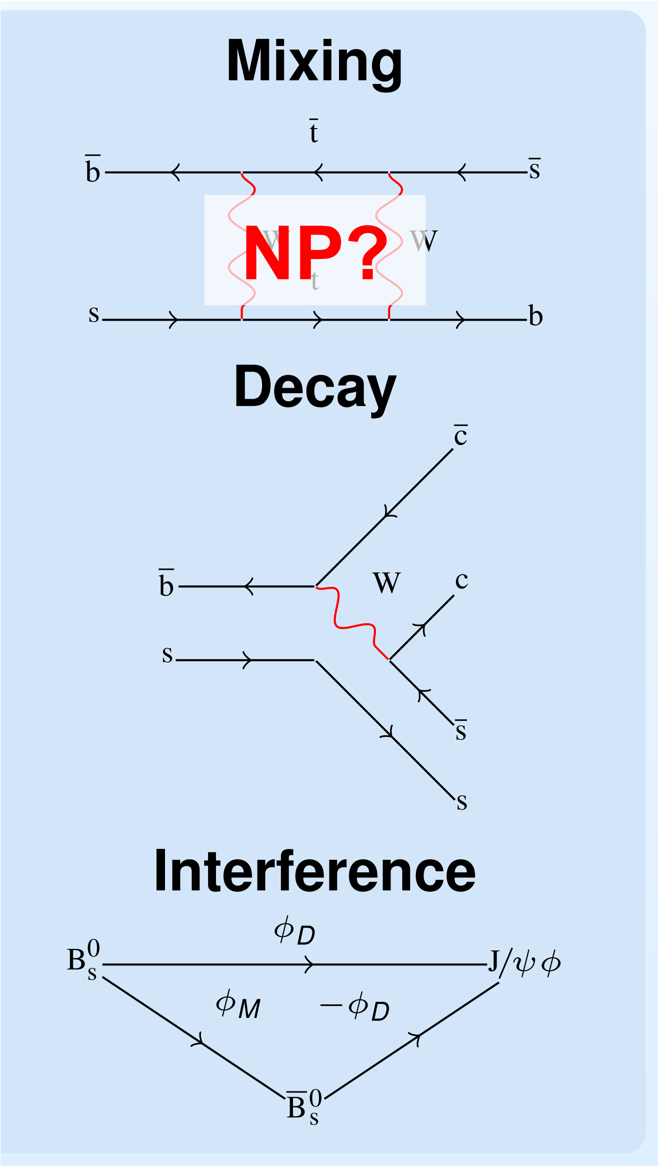
W. Altmannshofer et al. [JHEP 0901:019 (2009)]

- Precisely determine the zero crossing point of A_{FB}
- Measure $A_t^{(2)}$, partial angular analysis
  - 2/fb → full angular analysis

- Many anaogue channels in preparation
  - $B_s \to \phi\mu^+\mu^-$, $B^0 \to K^* e^+e^-$, $\Lambda_B \to \Lambda \mu^+\mu^-$
  - Isospin analyses

Search for NP in the Bs mixing phase: $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow J/\psi f_0$

CP violation in B_s mixing



- Interference between mixing and decay leads to CPV phase $\phi_s=\phi_M-2\phi_D$
- Precise SM calculation for f_s possible (small penguin contribution)

  $$\phi_s^{SM} = -0.0363\pm0.0016\text{rad}$$

  CKMFitter, hep-ph:0406184

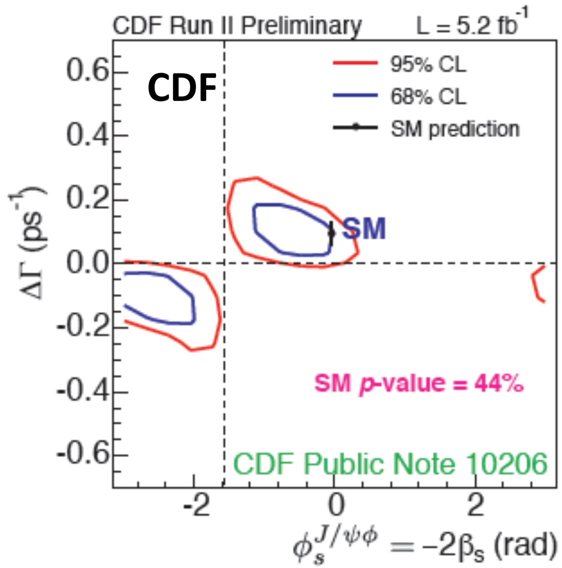
- Additional contributions from New Physics possible

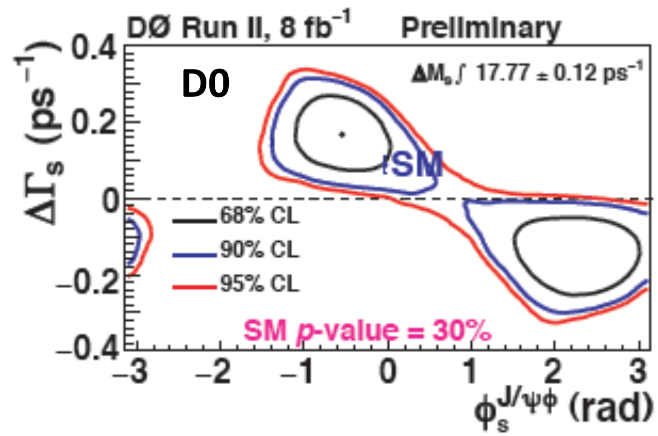
  $$\phi_s=\phi_s^{SM}+\phi_s^{NP}$$

- Requires time dependent, flavour tagged angular analysis

Experimental situation (before summer 2011)

Results presented before summer 2011 showed compatibility with SM at ~1σ but all experiments with the same trend….





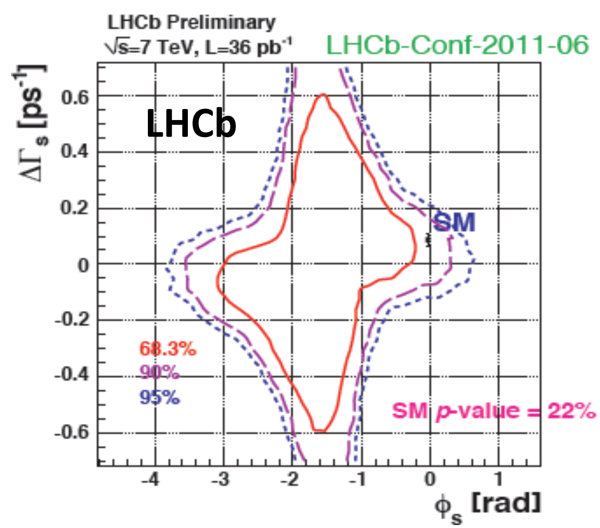
$$\phi_s \in [-3.10, -2.16] \cup [-1.04, -0.04]$$ CDF, 5.2 fb^{-1}

68% CL

$$\phi_s = -0.55^{+0.38}_{-0.36}$$ D0, 8 fb^{-1}

$$\phi_s \in [-2.7, -0.5]$$ LHCb, 0.035 fb^{-1}

68% CL



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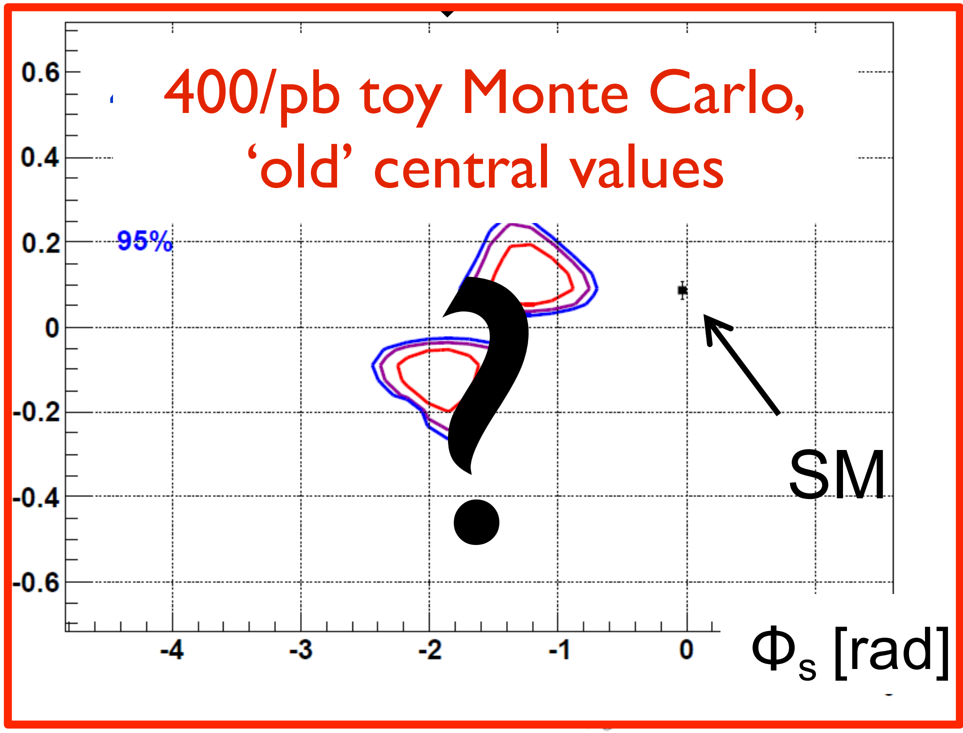

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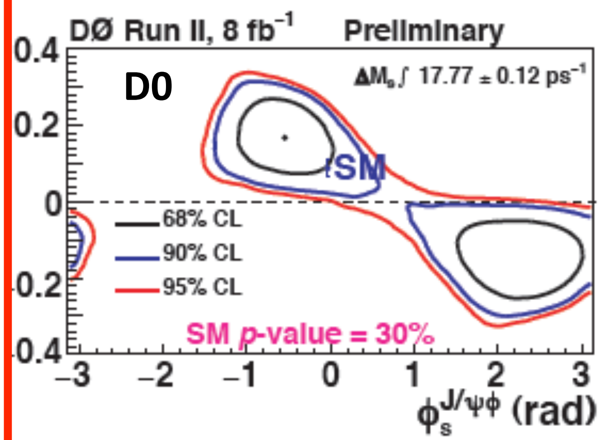

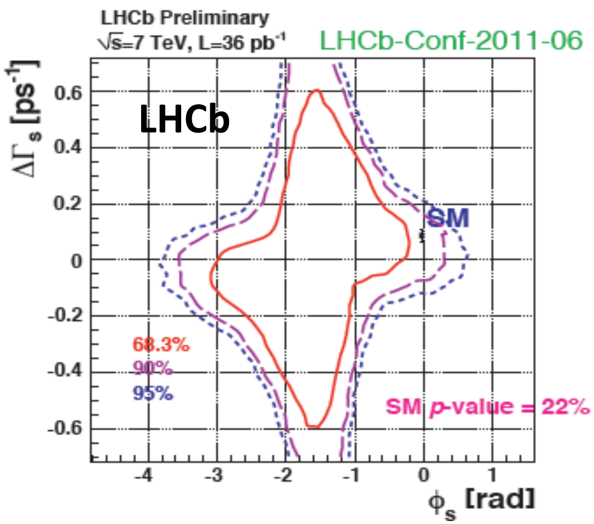

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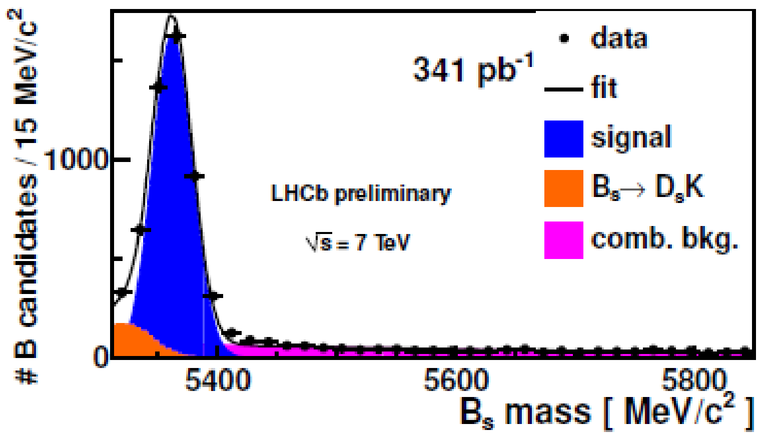
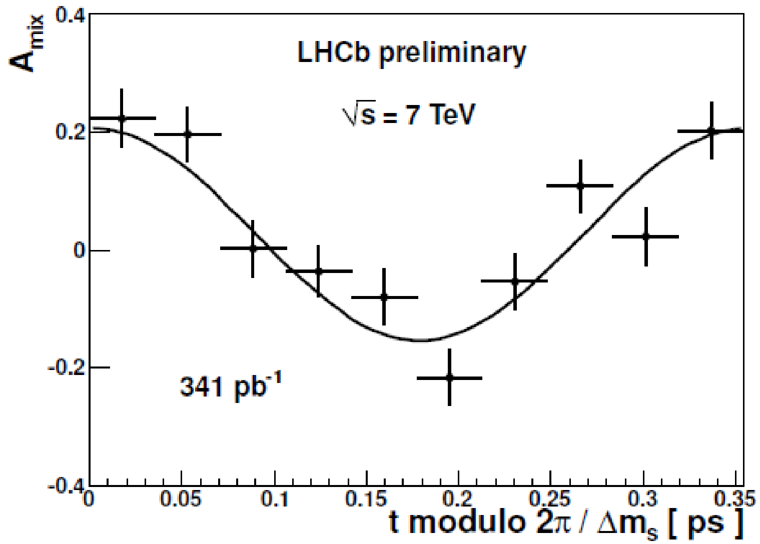
$\phi_s \in [-2.7, -0.5]$ 68% CL — LHCb, 0.035 fb^{-1}

B_s mixing measurement

LHCb has measured the Bs mixing frequency in $B_s \to D_s^- \pi^+$ decays





decay mode	# signal candidates
$B_s^0 \to D_s^-(\phi\pi^-)\pi^+$	4371 ± 91
$B_s^0 \to D_s^-(K^*K^-)\pi^+$	2910 ± 89
$B_s^0 \to D_s^-\pi^+$ non-resonant	1908 ± 74

$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026\, ps^{-1}$$

LHCb preliminary, 341/pb
LHCb-CONF-2011-050

(R. v. Kooten, LP11)

- compare older results

CDF (2006) $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1} (PRL97,242003 (2006)))

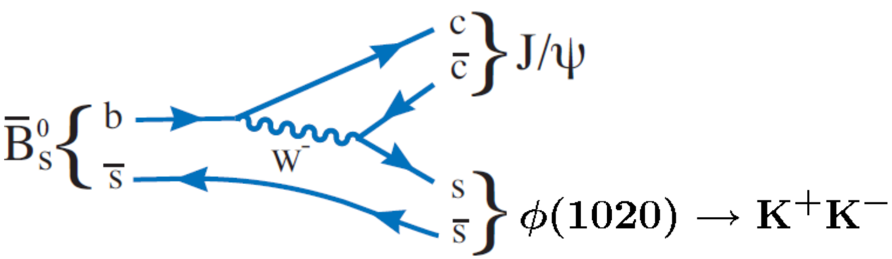
LHCb, 37/pb: $\Delta m_s = 17.63 \pm 0.11 \pm 0.03$ ps^{-1} (LHCb-CONF-2011-005)

- new WA: $\Delta m_s^{\rm WA} = 17.731 \pm 0.045$ ps^{-1}

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2090 \pm 0.0009 \pm 0.0046$$

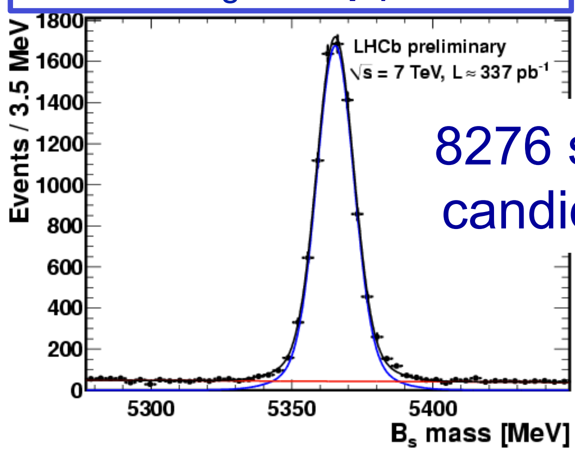
exp lattice

Time dependent CPV in Bs

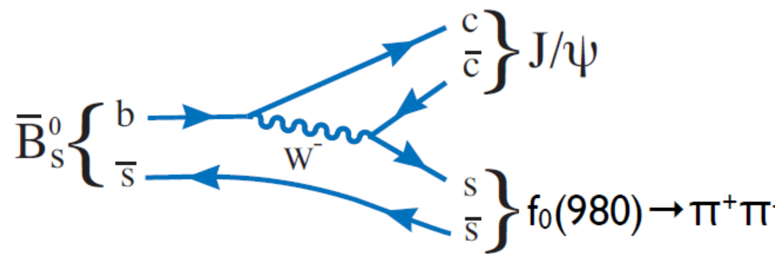


- Narrow resonance → clean
- Vector-vector final state
  - Requires time dependent angular analysis to separate CP even and CP odd
  - Measure also $\Delta\Gamma$ directly

$B_s \to J/\psi\phi$

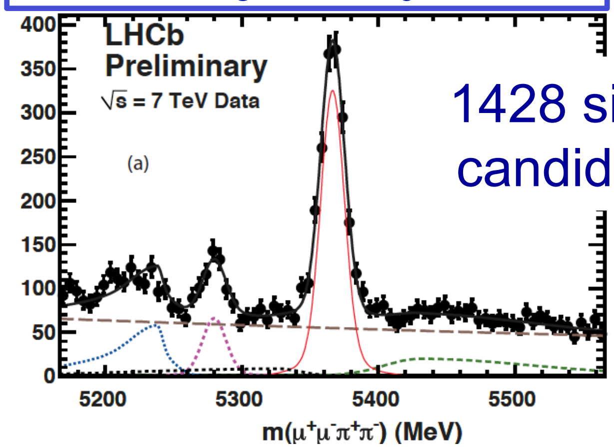


8276 signal candidates



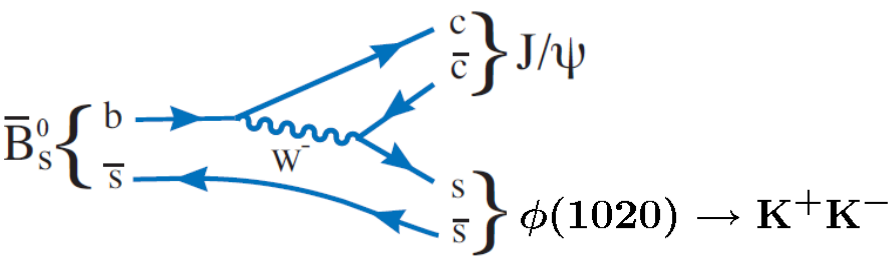
- Lower branching fraction (~1/4)
  - Higher background level
- Vector-pseudoscalar final state
  - No angular analysis needed
  - Needs $\Delta\Gamma$ as input

$B_s \to J/\psi f_0$



1428 signal candidates

Time dependent CPV in Bs



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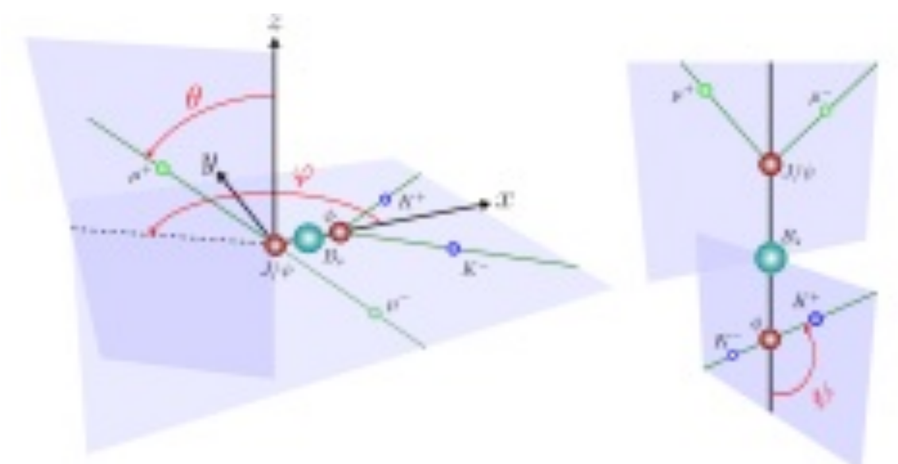

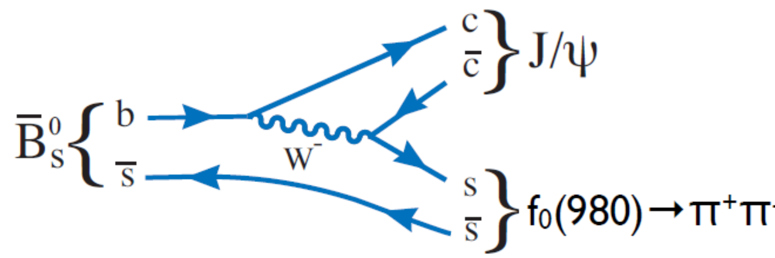

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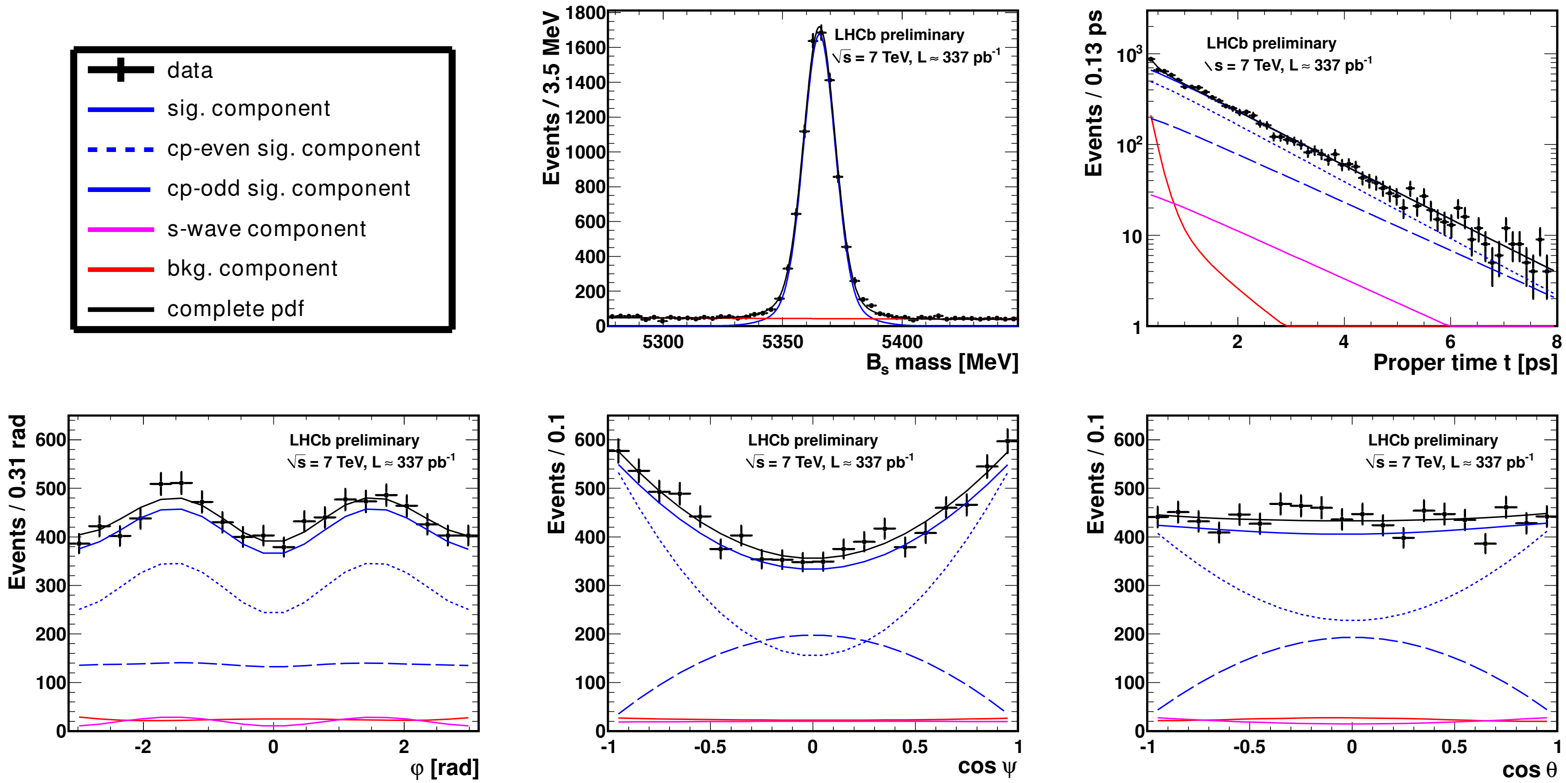
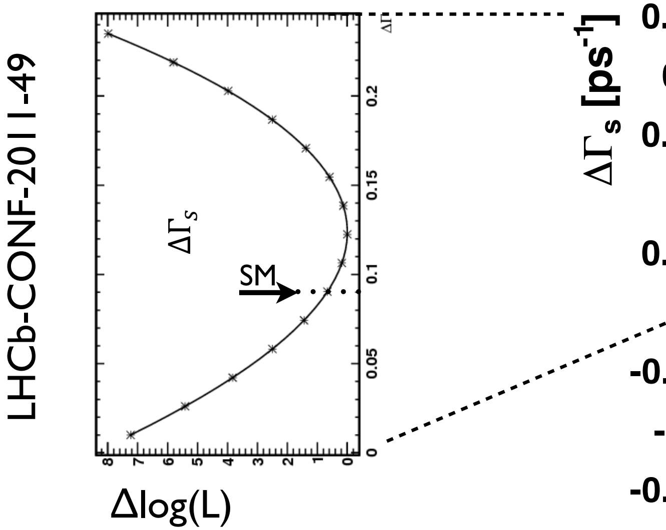
$B_s \rightarrow J/\psi\phi$: Angular analysis ML fit

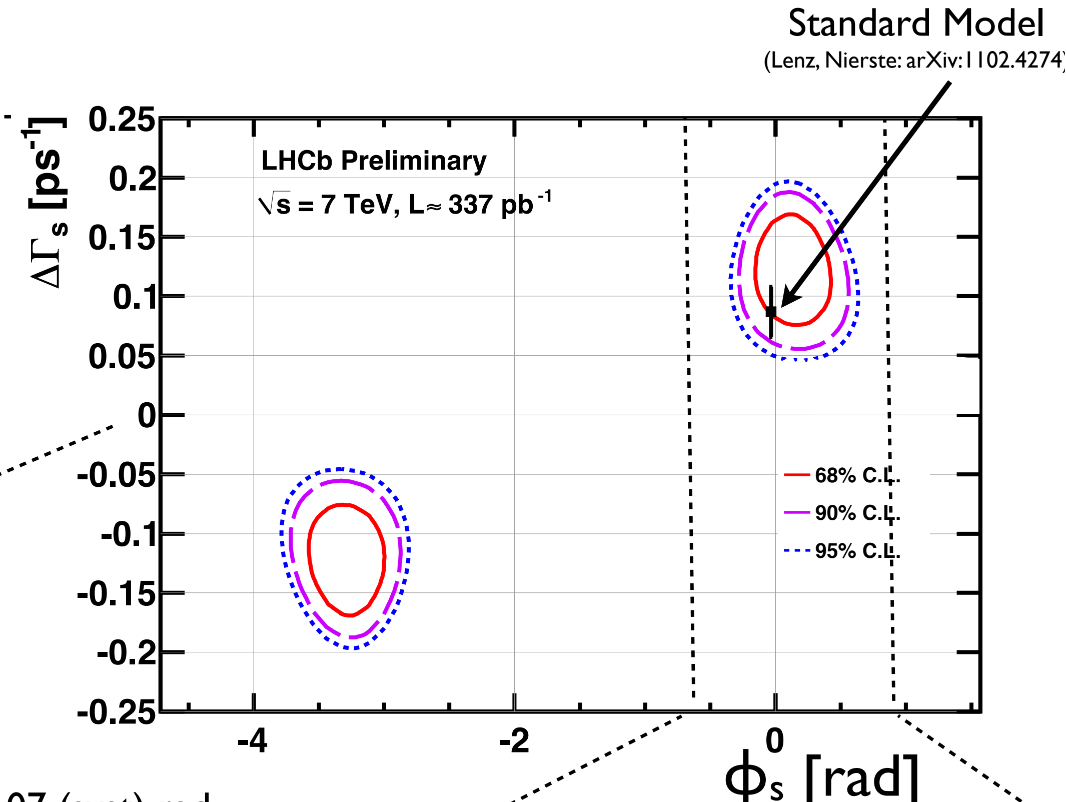
- Maximum likelihood fit with 10 physics parameters
  - 7 angular amplitudes and phases
  - Γ_s , $\Delta\Gamma_s$, ϕ_s
- Proper time calibrated with prompt J/ψ: $\sigma(t)$~50ps
- Used Opposite sign flavour tagging, εD^2=(2.08±0.41)%



Goodness of fit: p-value=44%

$B_s \rightarrow J/\psi\phi$: $\Delta\Gamma$ and ϕ_s



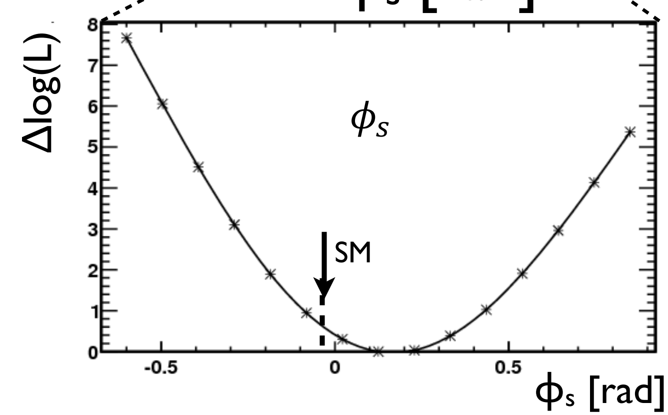


Most precise measurement of ϕ_s

- ϕ_s = 0.13 ± 0.18 (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma s$ = 0.123 ± 0.029 (stat) ± 0.008 (syst) ps^{-1}
- Γ_s = 0.656 ± 0.009 (stat) ± 0.008 (syst) ps^{-1}



$B_s \to J/\psi f_0$: ϕ_s

- LHCb made first observation of the decay $B_s \to J/\psi f_0$
- Nice channel to measure ϕ_s (CP odd eigenstate)
  - No need for angular analysis
  - But need to export Γ_s, $\Delta\Gamma_s$ & correlation matrix from $B_s \to J/\psi\phi$

2010 data
arXiv:1102:0206

$$\phi_s = -0.44 \pm 0.44(stat) \pm 0.02(syst)$$

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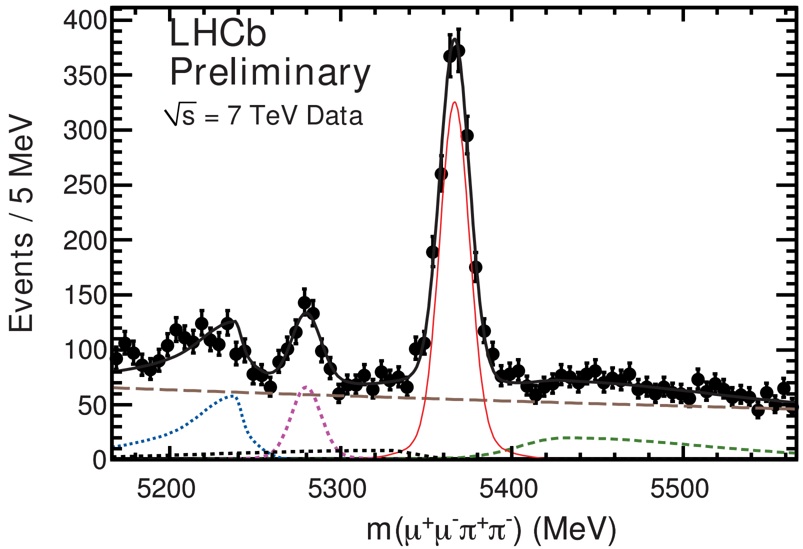
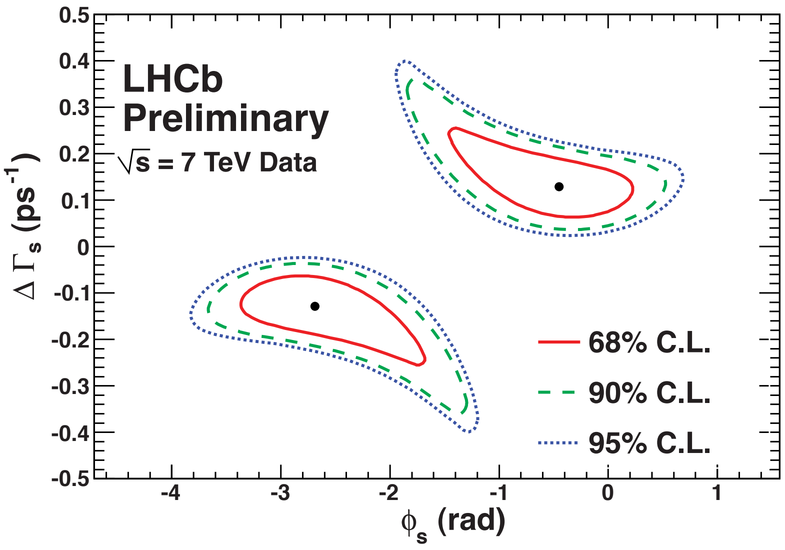
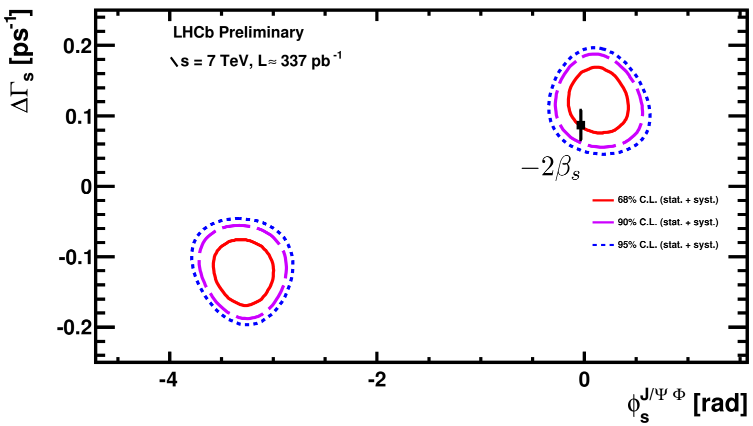


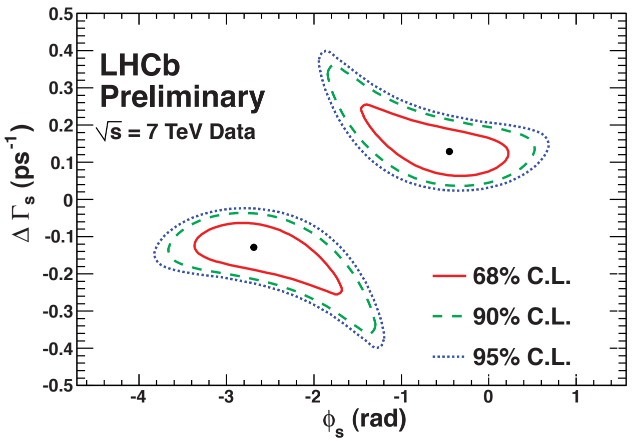


Combination of ϕ_s results

$J/\psi\phi$



$J/\psi f_0(980)$



- Combine both results, simultaneous fit using joint likelihood

$$\phi_s = 0.03 \pm 0.16(stat) \pm 0.07(syst)$$

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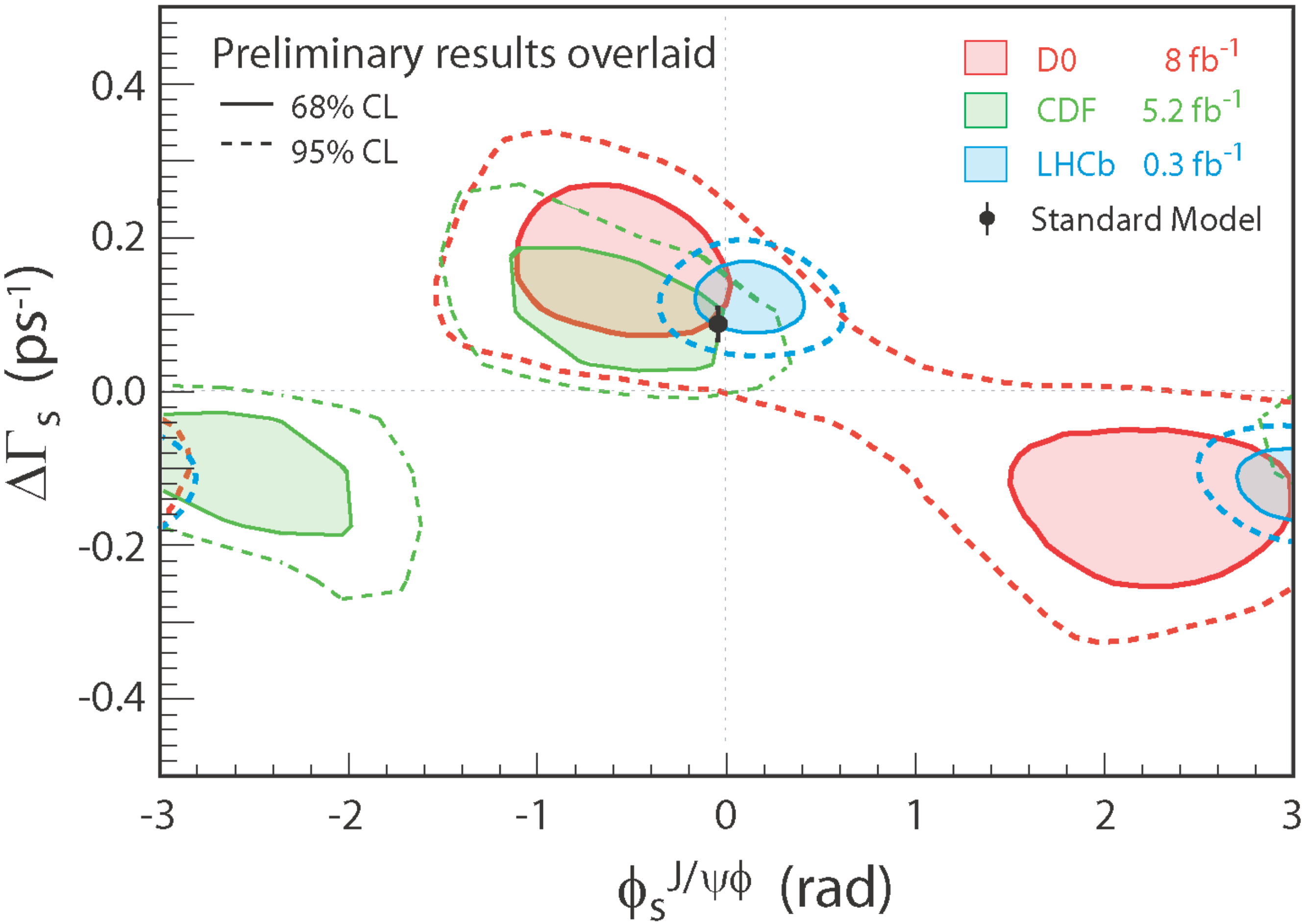
$\phi_s^{SM} = -0.0363 \pm 0.0016$rad

- Outlook:
  - ½ statistical uncertainty with 2011 data
  - Resolve ambiguity in $\Delta\Gamma_s$, ϕ_s
  - Evaluate penguin contributions
  - Measurable with ~1/fb: A_{sl} and $B_s \rightarrow \phi\phi$

Artists impression: ϕ_s from LHC & Tevatron



P. Clarke, LHC Implications workshop

This is NOT an official accurate overlay – the experiments have not done this yet !

This is just flipping and scaling the PDFs taken from talks to give impression

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

arXiv:1103.2465
Phys. Lett. B 699 (2011) 330-340

37pb^{-1}

LHCb-CONF-2011-047
will be submitted to PLB

370pb^{-1}

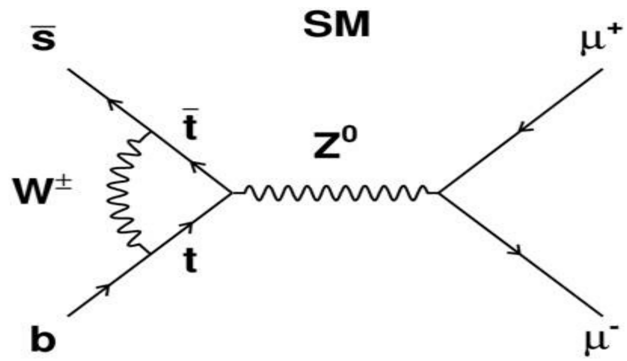
$B_{s,d} \to \mu^+\mu^-$ in the Standard Model

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

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

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

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



BR expressed in Wilson coefficients:

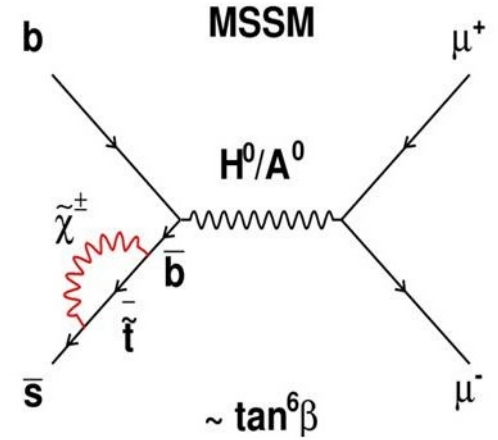
$$BR(B_q \to l^+l^-) \approx \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 \tau_{B_q}}{64\pi^3 \sin^4\theta_W} |V_{tb}V_{tq}^*|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_q}^2}}$$
$$\left\{ M_{B_q}^2 \left(1 - \frac{4m_l^2}{M_{B_q}^2}\right) c_S^2 + \left[M_{B_q} c_P + \frac{2m_l}{M_{B_q}}(c_A - c_A')\right]^2 \right\}.$$

→ 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

- Example: MSSM
  (with R-parity conservation)

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

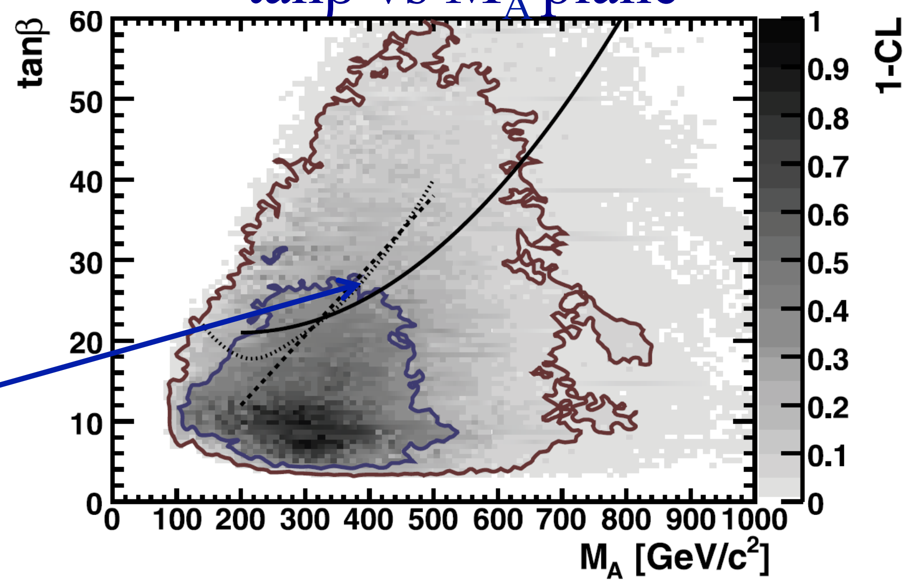


➔ limit or measurement of $B_{s,d} \to \mu\mu$ will strongly constrain $\tan\beta$ vs M_A plane

- NUHM1

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

$\tan\beta$ vs M_A plane

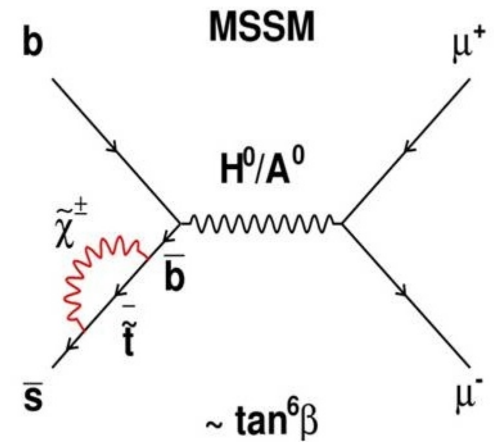


CMS direct search 30-60fb^{-1}: 5σ discovery $H/A \to \tau\tau$
(2007 analysis: arXiv:0704.0619)

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

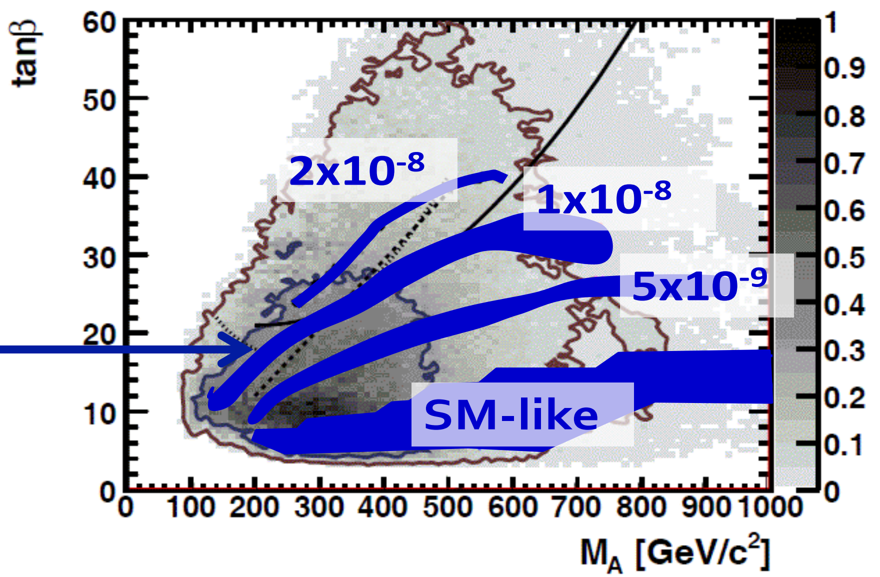
- <u>NUHM1</u>

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

Regions compatible with
$BR(B_s \to \mu\mu) = 2\text{x}10^{-8}, 1\text{x}10^{-8}, 5\text{x}10^{-9}$ and SM

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

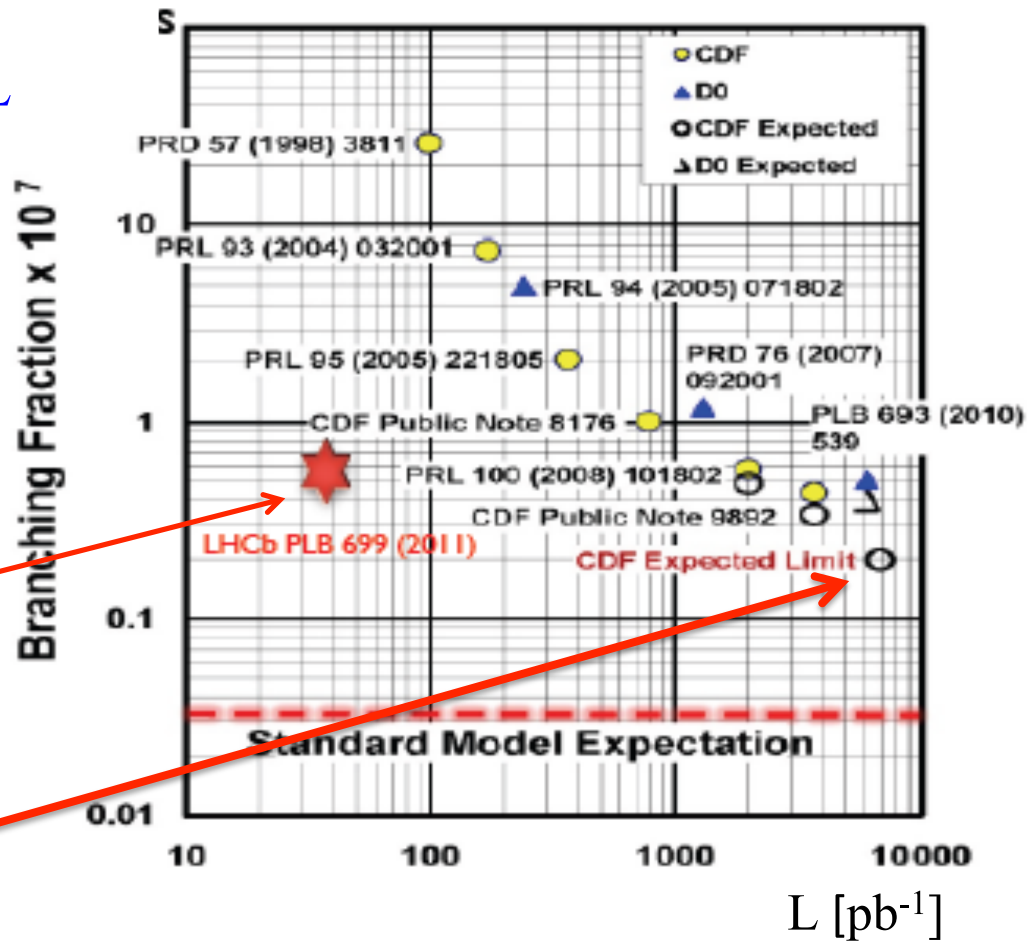
tanβ vs M_A plane



Published $B_s \to \mu\mu$ limits @ 95% CL

Experiment	Data set	Limit
CDF	3.7 fb^{-1}	4.3 x 10^{-8}
D0	6.1 fb^{-1}	5.1 x 10^{-8}
LHCb	0.036 fb^{-1}	5.6 x 10^{-8}

LHCb equivalent to CDF with ~100 times less luminosity



But also an anomaly:

long-staying (since La Thuile)
expected-only limit from CDF:
BR($B_s \to \mu\mu$) < 2 x 10^{-8} @ 95% CL

CDF "evidence"

Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays with CDF II

A search has been performed for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays using 7 fb^{-1} of integrated luminosity collected by the CDF II detector at the Fermilab Tevatron collider. The observed number of B^0 candidates is consistent with background-only expectations and yields an upper limit on the branching fraction of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% confidence level. We observe an excess of B_s^0 candidates. The probability that the background processes alone could produce such an excess or larger is 0.27%. The probability that the combination of background and the expected standard model rate of $B_s^0 \to \mu^+\mu^-$ could produce such an excess or larger is 1.9%. These data are used to determine $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ and provide an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% confidence level.

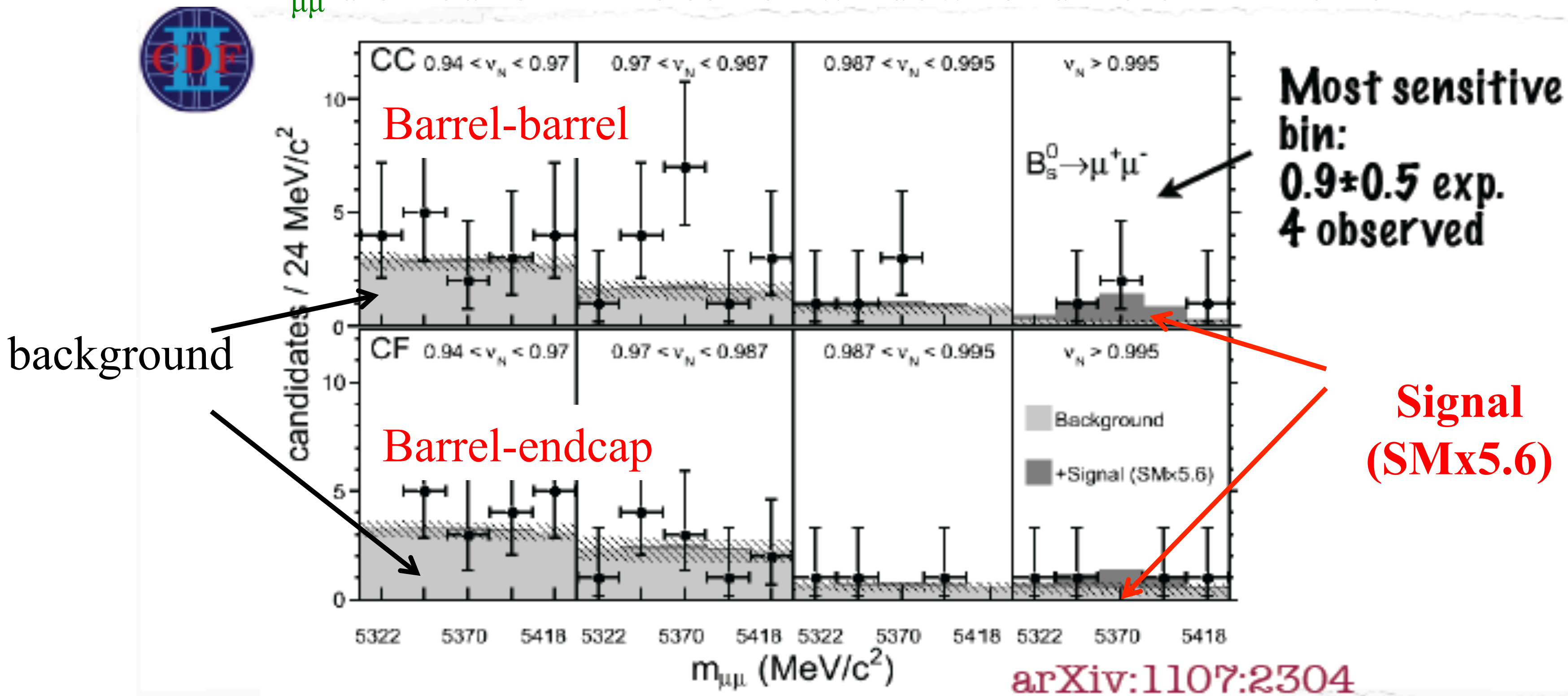
arXiv: 1107.2304 [hep-ex]

12. July 2011

CDF “evidence”

Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays with CDF II

$M_{\mu\mu}$ distribution in Bs search window for different NN bins



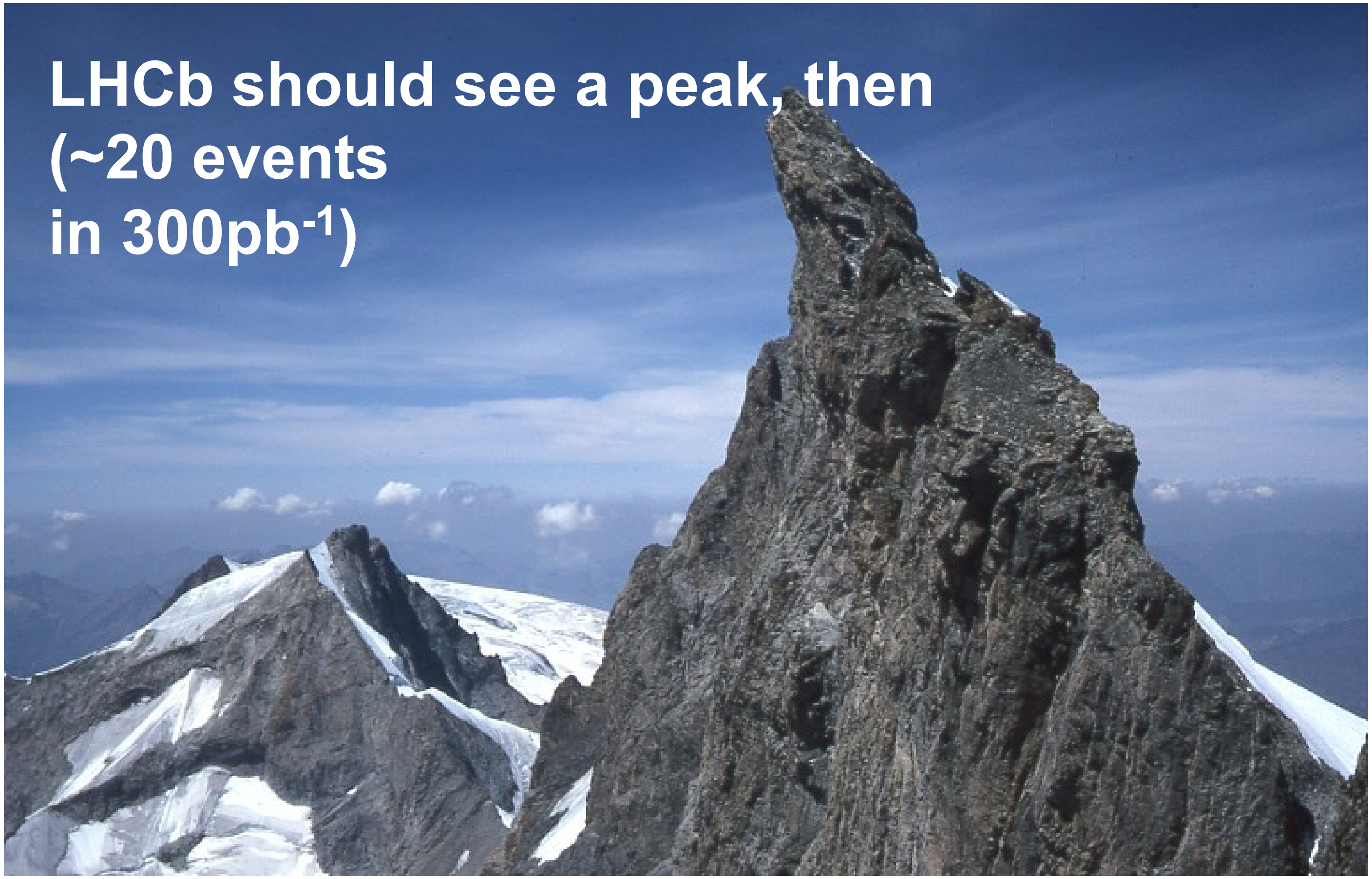
2.8 σ assuming bkg-only hypothesis

1.9% compatibility with bkg+SM hypothesis

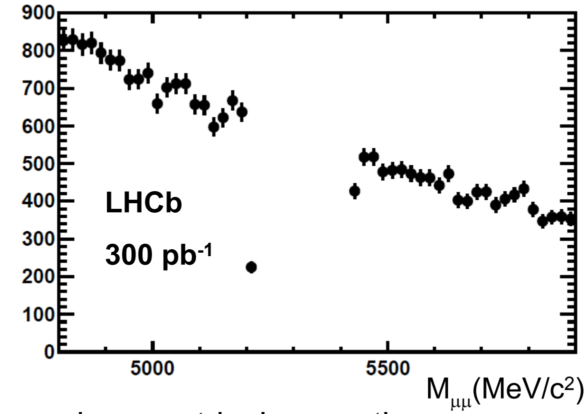
$0.46 \times 10^{-8} < BR < 3.9 \times 10^{-8}$ @ 90% CL ($BR = 1.8^{+1.1}_{-0.9}$) $\times 10^{-8}$

$B_{s,d} \rightarrow \mu^+\mu^-$ peak hunting I

Search for $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ Decays with CDF II



LHCb analysis strategy



- **Selection**
  - Muon based triggers
  - Soft selection to reduce size of dataset
  - Similar to control channels
- **Signal and background likelihoods**
  - Geometrical Likelihood (BDT)
    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

Signal likelihood definition

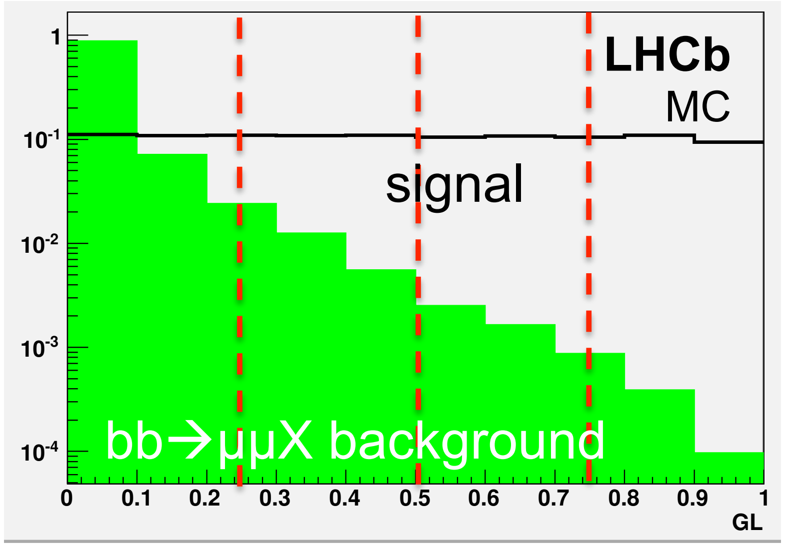
- Use 9 input variables:
  - B impact parameter, B lifetime, muon isolation, DOCA, B Pt, minimum impact parameter of the muons
  - B isolation
  - Polarization variable
  - Minimum Pt of the muons

Already in previous analysis

New

- Choice of variables to avoid correlation with invariant mass
- Optimization and training on MC, using $B_s \to \mu^+\mu^-$ and $bb \to \mu\mu X$ background

BDT shape of signal and bkg



→ flat for signal
→ peaked at zero for background

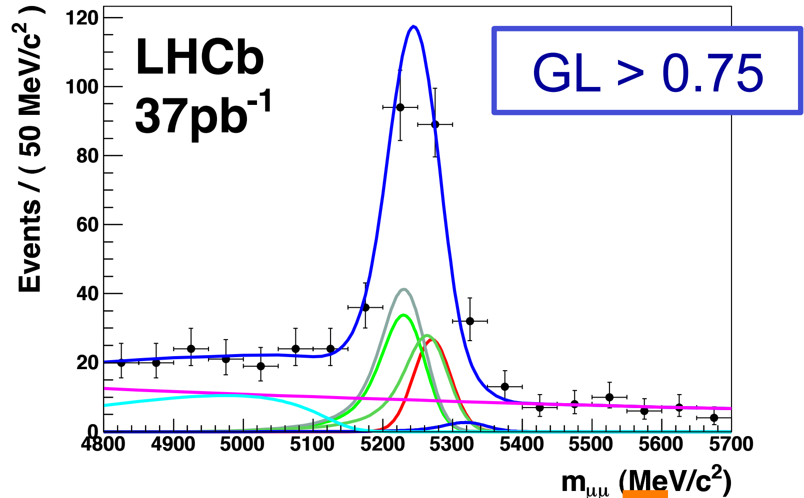
Analysis is done in 4 bins of GL

Signal likelihood calibration

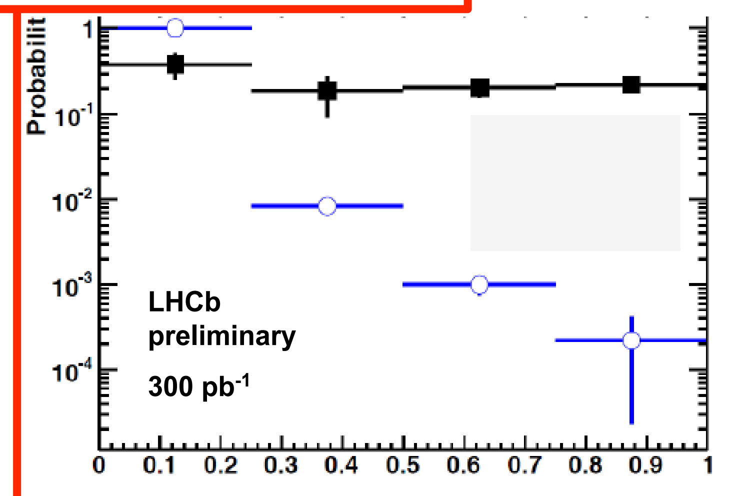
- BDT calibration:
  - $B \rightarrow h^+h'^-$ ideal sample: identical decay topology
  - Use events triggered independent of signal (TIS) to avoid trigger bias

- **Signal distribution in GL flat as expected from simulation**

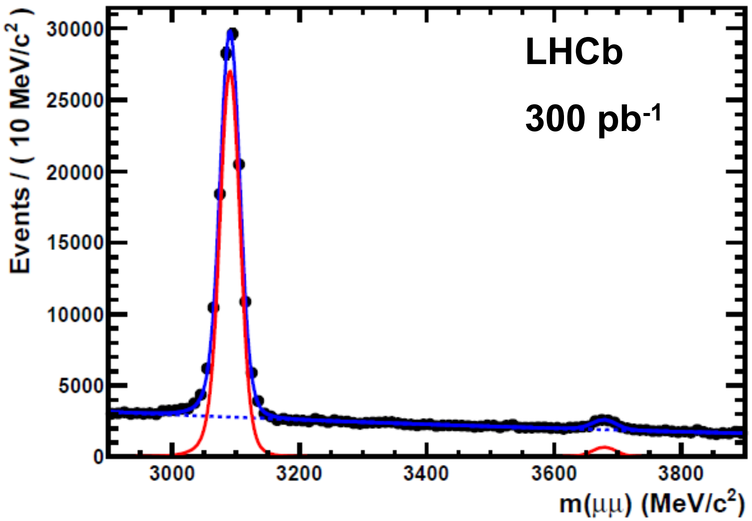
TIS $B \rightarrow h^+h'^-$

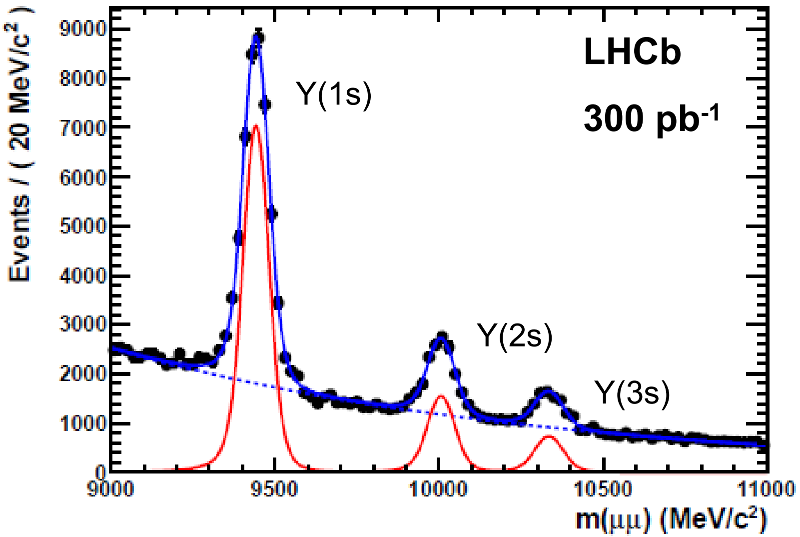


Calibrated GL



- Signal invariant mass modelled with a crystal ball
  - Resolution obtained from data:
    - Interpolation between dilepton resonances (J/ψ, $\psi(2S)$ and Υ)
    - Cross checked with inclusive $B \rightarrow h^+h'^-$
  - Mean from exclusive $B^0 \rightarrow K^+\pi^-$ and $B_s \rightarrow K^+K^-$





$\sigma(B_s) = (24.6 \pm 0.2 \pm 1.0)$ MeV/c^2

$\sigma(B_d) = (24.3 \pm 0.2 \pm 1.0)$ MeV/c^2

Calibration of the background shape

- Combinatorial background expectation extracted from a fit to the mass sidebands in bins of BDT
- Systematics evaluated using different fit functions and ranges

B_s=2968±69

B_d=3175±72

B_s=25.0±2.5

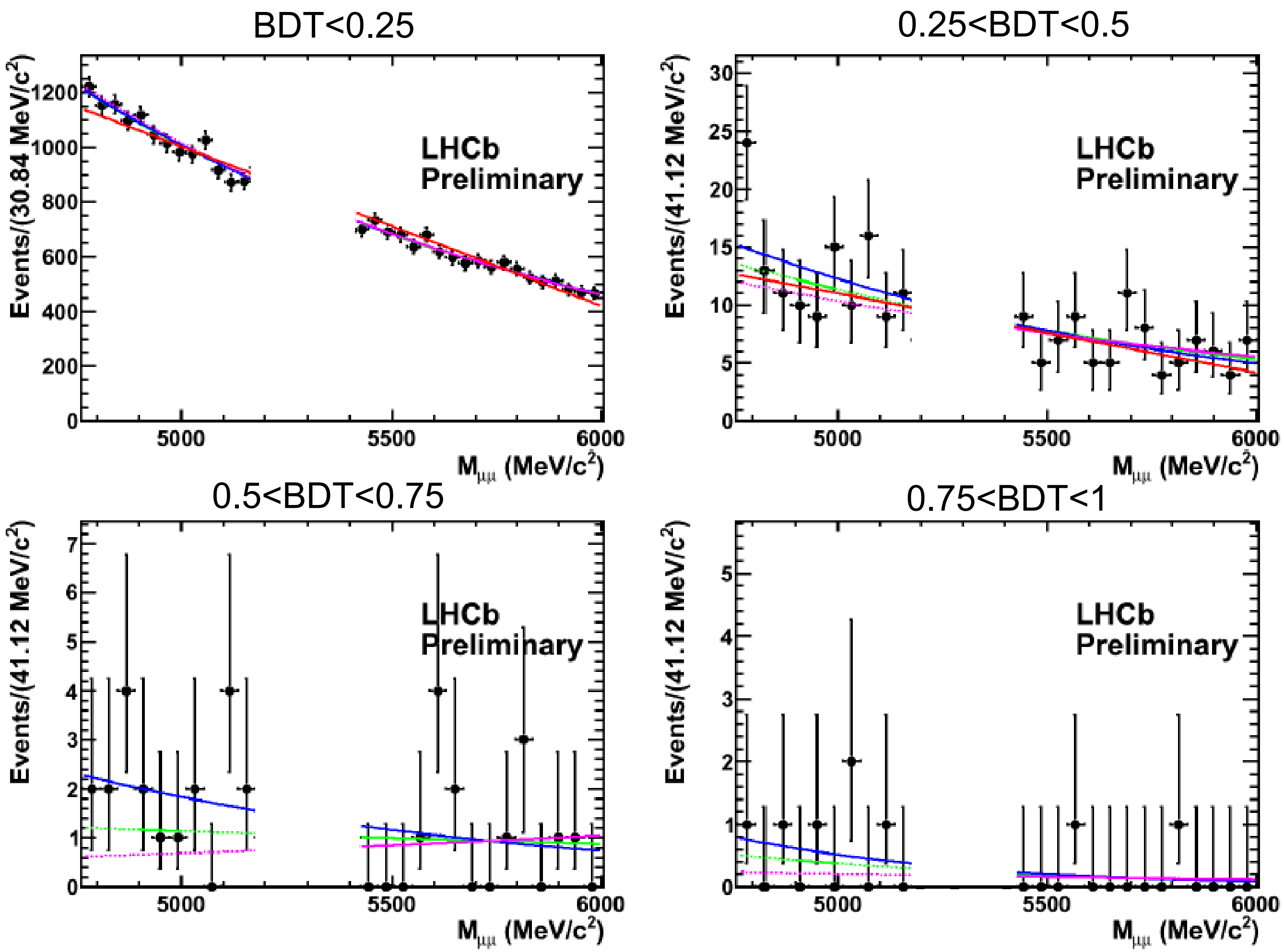
B_d=26.6±2.5

B_s=3.0±0.9

B_d=3.1±0.8

B_s=0.7±0.4

B_d=0.7±0.4



Normalization to channels with known BR

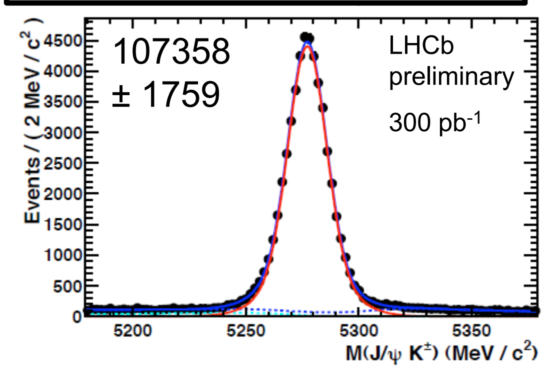
$$BR = BR_{cal} \cdot \frac{\varepsilon^{Rec}_{cal} \cdot \varepsilon^{Sel}_{cal}}{\varepsilon^{Rec}_{Bs} \cdot \varepsilon^{Sel}_{Bs}} \cdot \frac{\varepsilon^{Trig}_{cal}}{\varepsilon^{Trig}_{Bs}} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

Evaluated from MC, cross checked with data

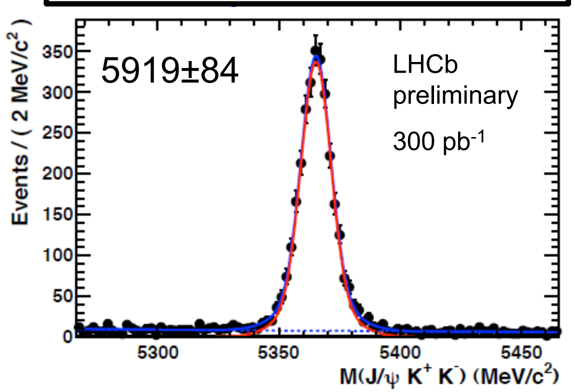
Measured in data

Ratio of probability for a b-quark to hadronize into a given meson

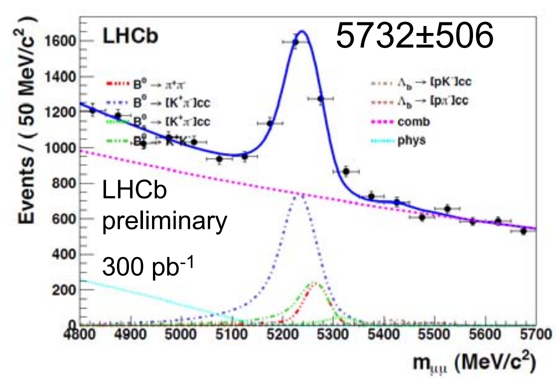
$B^\pm \to J/\psi K^\pm$



$B_S \to J/\psi\phi$



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

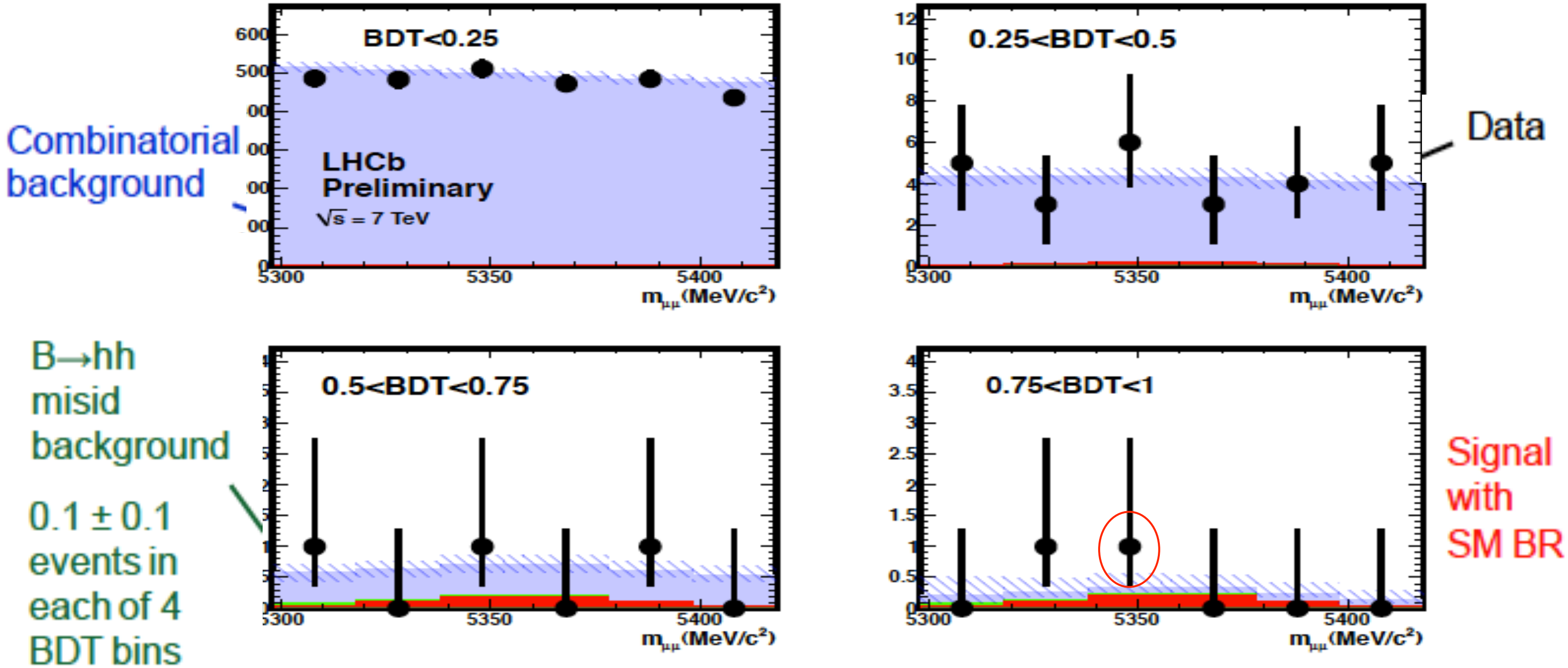


Average:

$\alpha(B_s \to \mu^+\mu^-) = 9.84 \pm 0.91 \times 10^{-10}$

$\alpha(B_d \to \mu^+\mu^-) = 2.89 \pm 0.15 \times 10^{-10}$

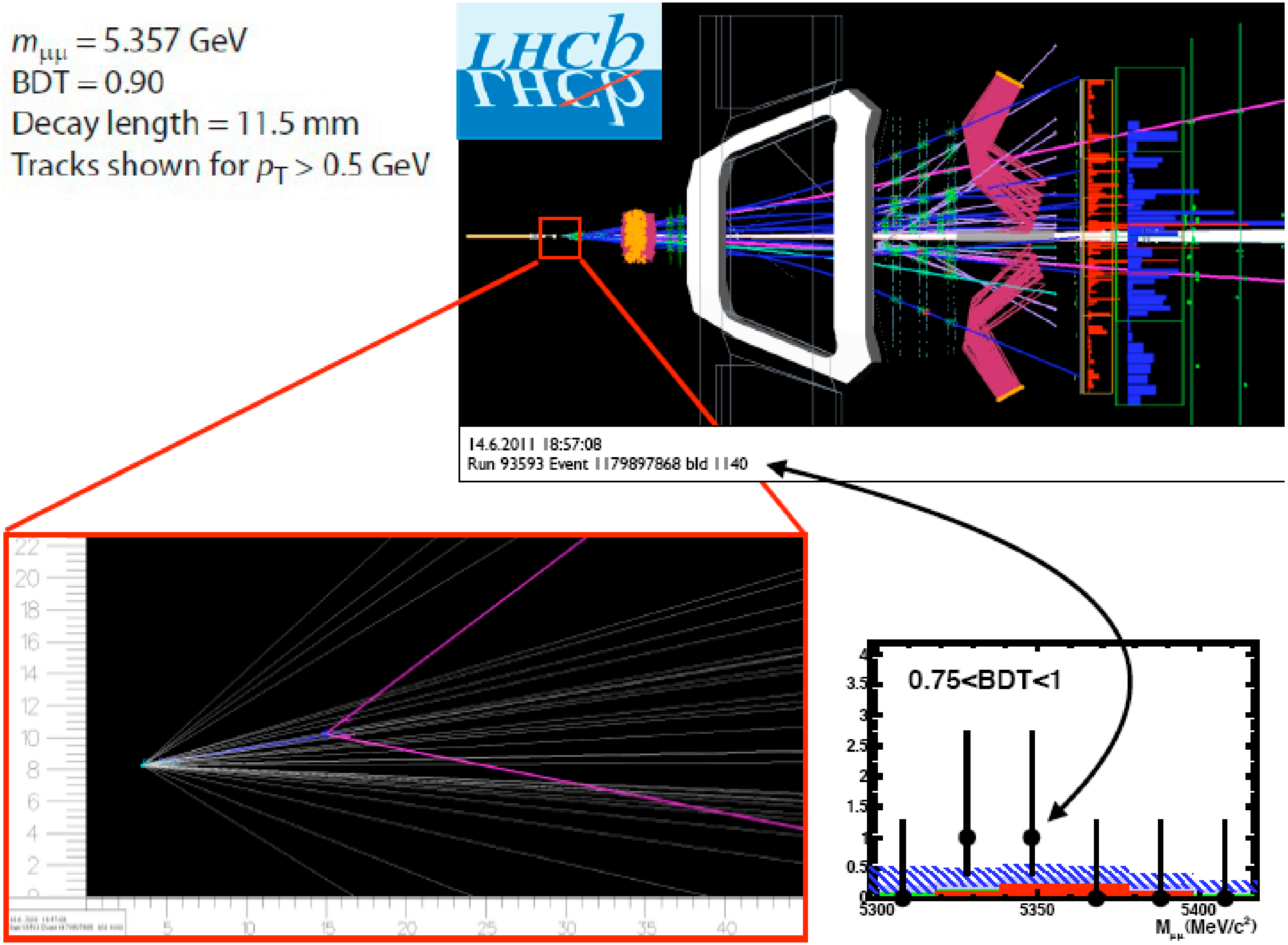
LHCb result in the B_s mass window with 300 pb^{-1} (preliminary)



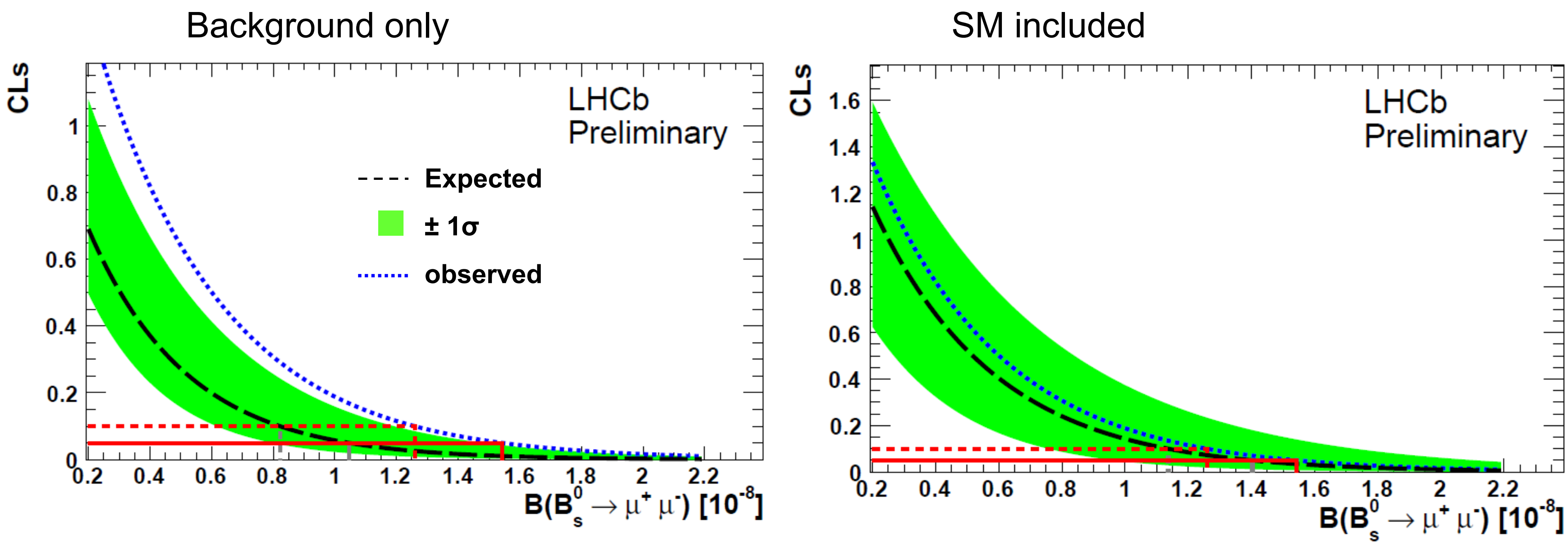
	BDT<0.25	0.25<BDT<0.5	0.5<BDT<0.75	0.75<BDT
Exp.combinatorial	2968 ± 69	25 ± 2.5	2.99 ± 0.89	0.66 ± 0.40
Exp. SM signal	1.26 ± 0.13	0.61 ± 0.06	0.67 ± 0.07	0.72 ± 0.07
Observed	2872	26	3	2

"Perfect" $B_s \rightarrow \mu^+\mu^-$ candidate

$m_{\mu\mu} = 5.357$ GeV
BDT = 0.90
Decay length = 11.5 mm
Tracks shown for $p_T > 0.5$ GeV

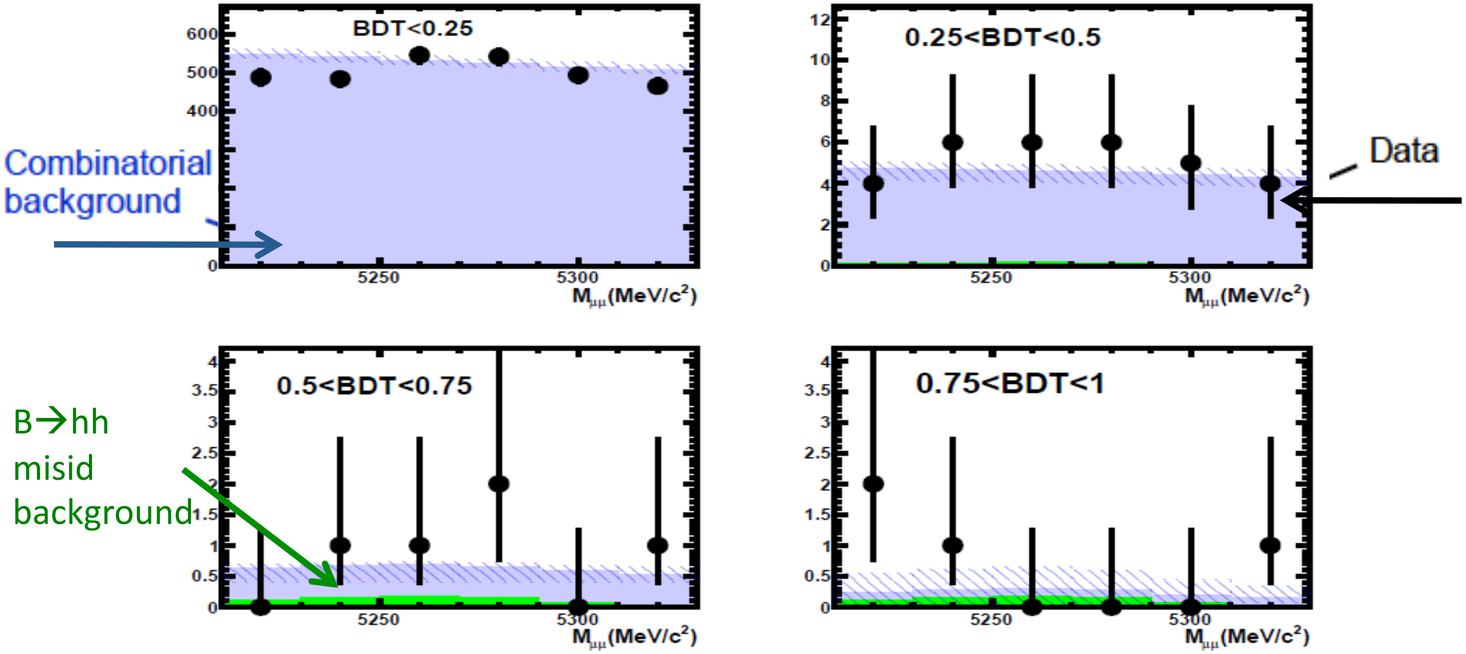


Limit on $B_s \to \mu^+\mu^-$



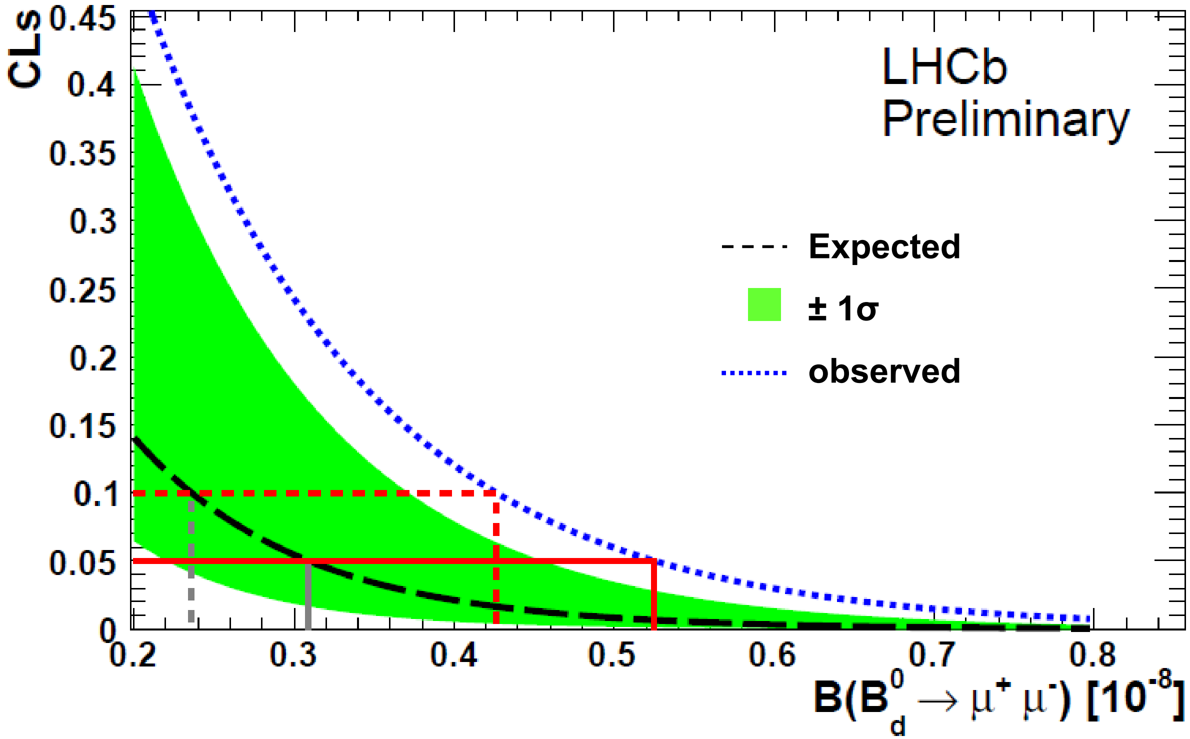
$B_s \to \mu^+\mu^-$	90% CL	95% CL
Expected limit (bkg only)	8×10^{-9}	10×10^{-9}
Expected limit(bkg+SM)	12×10^{-9}	15×10^{-9}
Observed limit	13×10^{-9}	16×10^{-9}
combination 2010+2011	12×10^{-9}	**15×10^{-9}**

LHCb result in the **B_d mass window** with 300 pb^{-1}
(preliminary)



	BDT<0.25	0.25<BDT<0.5	0.5<BDT<0.75	0.75<BDT
Exp.combinatorial	3175 ± 72	26.6 ± 2.5	3.1 ± 0.8	0.7 ± 0.4
Exp. MisID	0.6± 0.1	0.6± 0.1	0.6± 0.1	0.6± 0.1
Observed	3025	31	5	4

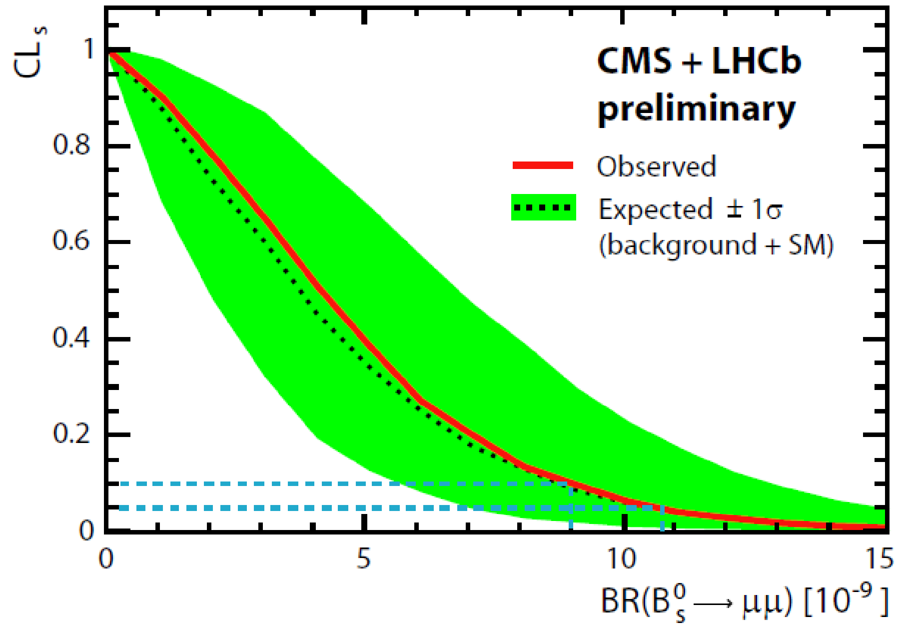
Observed limit on BR($B_d \to \mu^+\mu^-$)



$B_d \to \mu^+\mu^-$	90% CL	95% CL
Expected limit (bkg only)	2.4×10^{-9}	3.1×10^{-9}
Observed limit	4.2×10^{-9}	**5.2×10^{-9}**

Combined LHC limit on $B_s \rightarrow \mu^+\mu^-$

- CMS limit with 1.18/fb very competitive with LHCb
- Results combined using LHCbs f_d/f_s
- Observed distribution agrees very well with bkg+SM



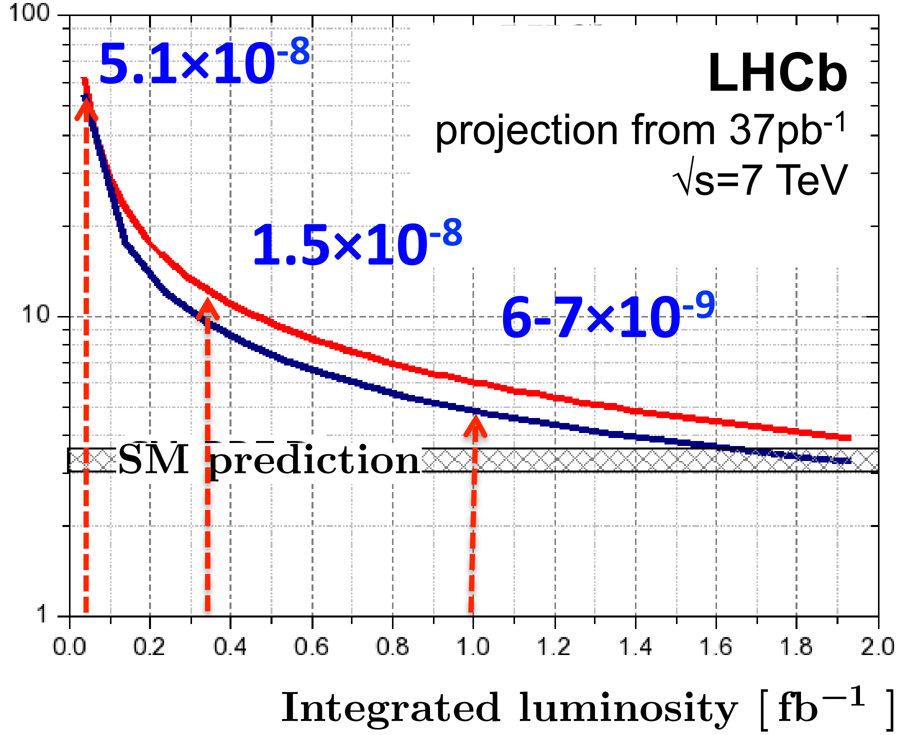
$B_s \rightarrow \mu^+\mu^-$, 95% CL	LHCb	CMS
Expected limit (bkg+SM)	15×10^{-9}	18×10^{-9}
Observed limit	15×10^{-9}	19×10^{-9}
Observed LHCb+CMS	11×10^{-9}	

CMS-PAS-BPH-11-019 and LHCb-CONF-2011-047


Maybe winter (conferences)
is a better time for mountaineering…

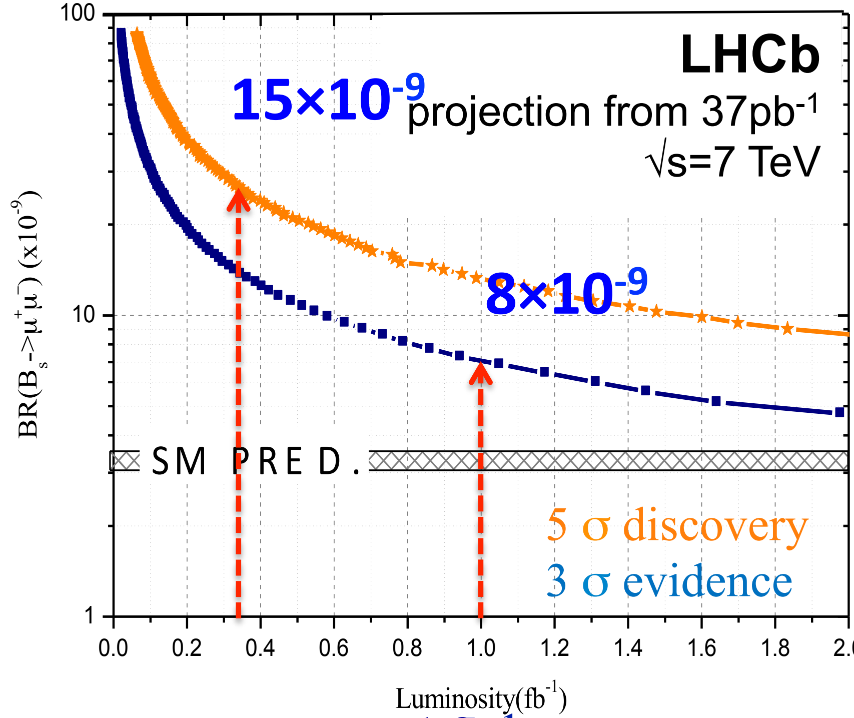
Prospects: $B_s \rightarrow \mu^+\mu^-$

$B_S \rightarrow \mu^+\mu^-$ exclusion @ 90% CL



37 pb^{-1} 340 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~ $6\text{-}8\times10^{-9}$ at 95% CL

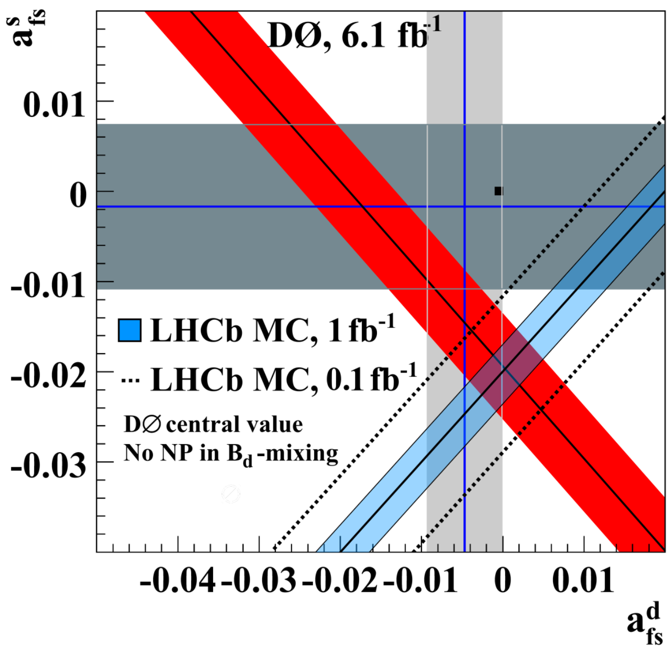
Conclusions

- LHC and LHCb are running extremely well
  - LHCb is taking data at higher than design luminosity
  - LHCb has >1fb^{-1} recorded, analyses shown with 0.3fb^{-1}
- LHCb has contributed the worlds most precise results on
  - Forward-backward asymmetry in $B^0 \rightarrow K^* \mu^+ \mu^-$
  - Measurements of the Bs mixing phase ϕ_s
  - Limits on the rare decay $B_s \rightarrow \mu^+ \mu^-$
  - And many more
- But no hint for New Physics yet…
  - .. we've just gotten started: plenty left on the shopping list
  - Increase precision over the next 5 years
  - New observables welcome


STOP

A_{SL} and the like-sign dimuon anomaly

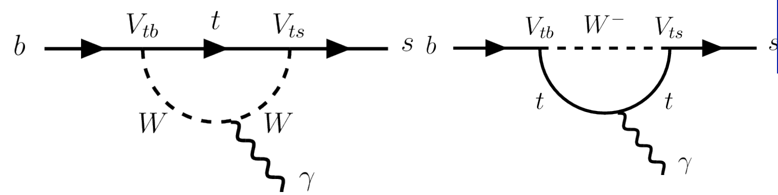
- Measuring A_{SL} on a pp collider is tough: Production asymmetries
- More so at LHCb because we're not symmetric
  - Can't count like-sign muons when one of them isn't in your acceptance



- LHCb has two independent analyses investigating this
- Time integrated A_{SL} in $\mathrm{B_s^0} \to \mathrm{D_s^-} X \mu^+ \nu_\mu$
  - Production asymmetry is washed out by fast $\mathrm{B_s^0}$-$\mathrm{\overline{B}{}_s^0}$ mixing
- Time dependent subtraction:
  - $\Delta A_{fs}^{s,d} = A_{fs}^s - A_{fs}^d$
  - $\mathrm{B_s^0} \to \mathrm{D_s^-} X \mu^+ \nu_\mu$ and $\mathrm{B} \to \mathrm{D^-} X \mu^+ \nu_\mu$ channels
  - Production asymmetries cancel out

- The time-dependent analysis benefits from fewer systematics and cancellation of cross-feed backgrounds, while the time-integrated analysis benefits from fewer parameters to constrain
- Both analyses are progressing and can expect preliminary results soon.

$B^0 \rightarrow K^*\gamma$ and $B_s \rightarrow \phi\gamma$



LHCb-CONF-2011-055

- Radiative b→s penguin decay, $B^0 \rightarrow K^*\gamma$ first seen by CLEO in 1993.

- Broader signal peak (compared to all-charged final states) implies more work on backgrounds ($B^0 \rightarrow K^+\pi^-\pi^0$, $B_s \rightarrow K^+\pi^-\pi^0$, $B^0 \rightarrow K^{*0}e^+e^-$, $B_s \rightarrow K^+\pi^-\gamma$) and cross-feed

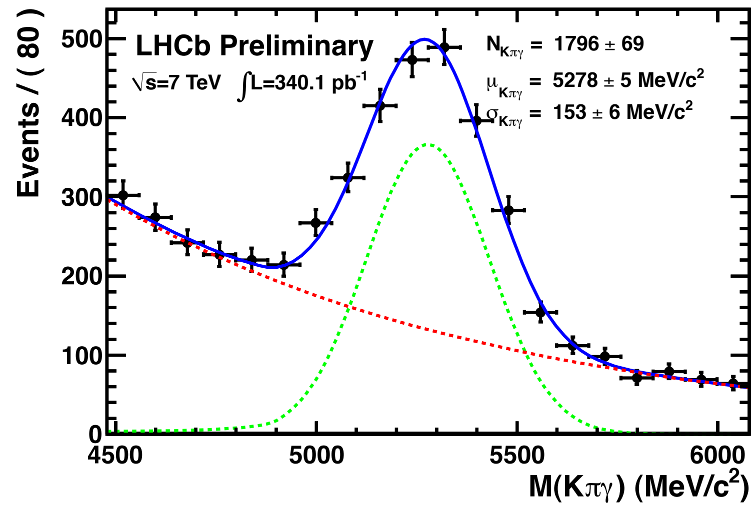
- Simultaneous fit to $B_s \rightarrow \phi\gamma$ and $B^0 \rightarrow K^*\gamma$;
  - mass difference fixed to PDG

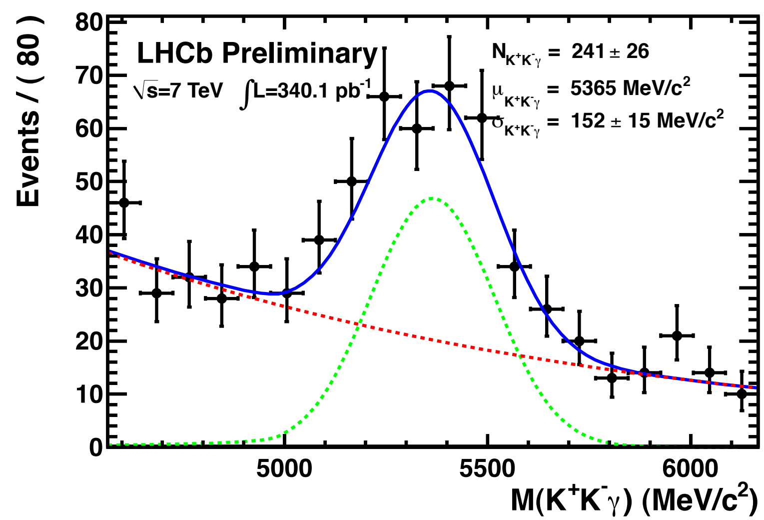
- Largest $B_s \rightarrow \phi\gamma$ signal, measure:

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.52 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}) \pm 0.12(f_s/f_d)$$

- SCET predicts 1.0 ± 0.2 for this ratio
  [Ali et al., EPJ C55:577 (2008)]

- Future steps: measure CP asymmetries





S-wave in Bs→J/ψφ

- including S-wave: from 6 to 10 terms in angular/time distributions

LHCb-CONF-2011-049

k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\|A_0\|^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\|A_\parallel(t)\|^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\|A_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin 2\theta\cos\phi$
7	$\|A_s(t)\|^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

The terms 7–10 are related to the description of the S-wave component, which has been added to this analysis. Expressed in terms of the size $|A_i(0)|$ and phase δ_i of the transversity and S-wave amplitudes at $t=0$, the time dependent amplitudes are given by

$$|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)], \quad (4)$$

$$|A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)], \quad (5)$$

$$|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)], \quad (6)$$

$$\Im(A_\parallel(t)A_\perp(t)) = |A_\parallel||A_\perp|e^{-\Gamma_s t}[-\cos(\delta_\perp-\delta_\parallel)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m t) + \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m t)], \quad (7)$$

$$\Re(A_0(t)A_\parallel(t)) = |A_0||A_\parallel|e^{-\Gamma_s t}\cos(\delta_\parallel-\delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)], \quad (8)$$

$$\Im(A_0(t)A_\perp(t)) = |A_0||A_\perp|e^{-\Gamma_s t}[-\cos(\delta_\perp-\delta_0)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp-\delta_0)\cos\phi_s\sin(\Delta m t) + \sin(\delta_\perp-\delta_0)\cos(\Delta m t)], \quad (9)$$

$$|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)], \quad (10)$$

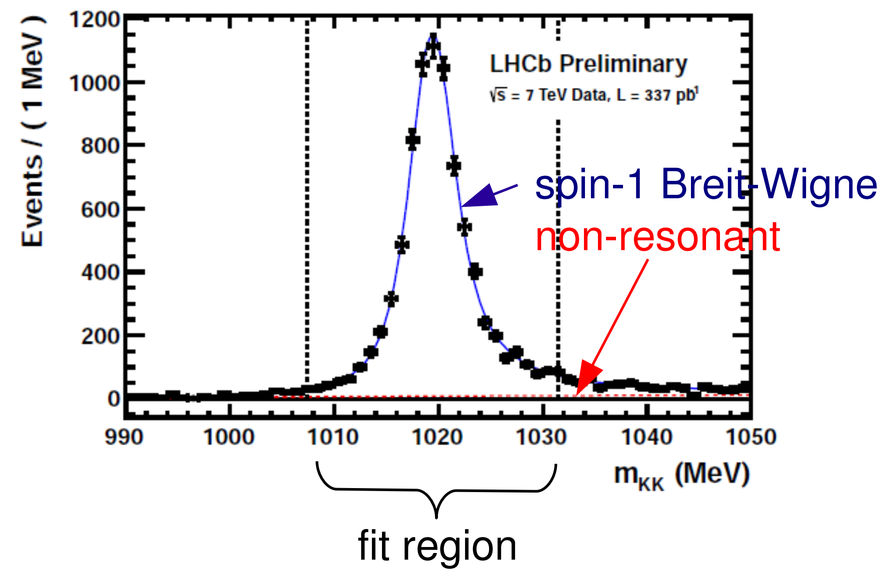
$$\Re(A_s^*(t)A_\parallel(t)) = |A_s||A_\parallel|e^{-\Gamma_s t}[-\sin(\delta_\parallel-\delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel-\delta_s)\cos\phi_s\sin(\Delta m t) + \cos(\delta_\parallel-\delta_s)\cos(\Delta m t)], \quad (11)$$

$$\Im(A_s^*(t)A_\perp(t)) = |A_s||A_\perp|e^{-\Gamma_s t}\sin(\delta_\perp-\delta_s)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)], \quad (12)$$

$$\Re(A_s^*(t)A_0(t)) = |A_s||A_0|e^{-\Gamma_s t}[-\sin(\delta_0-\delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0-\delta_s)\cos\phi_s\sin(\Delta m t) + \cos(\delta_0-\delta_s)\cos(\Delta m t)]. \quad (13)$$

where we have chosen a phase convention such that $\delta_0 = 0$. The decay time dependent decay rates for an initial $\overline{B}_s^0$ decaying to $J/\psi\phi$ can be obtained from those above by inserting a factor -1 in front of the terms involving mixing ($\sin(\Delta m_s t)$ and $\cos(\Delta m_s t)$).

accounts for ~4% "non-resonant" KK in 12 MeV mass window around phi



note: S-wave contribution identified by angular distribution, not by KK mass

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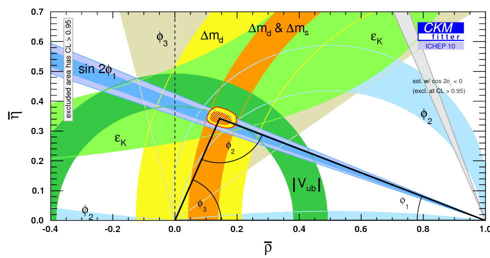
Controlling Penguins

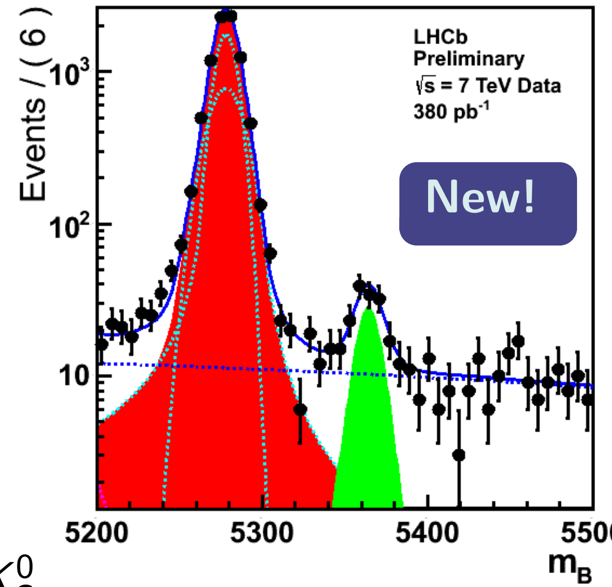
With LHCb's experimental precision, penguin contributions to e.g. $B_d \to J/\psi K_S^0$ will have to me taken into account



Is that the tension on $\sin 2\beta$?

➜ Study U-spin partners as $B_s \to J/\psi K_S^0$

De Bruyn, PK, Fleischer [Eur.Phys.J.C70:1025 (2010)], [arXiv:1012.0840]



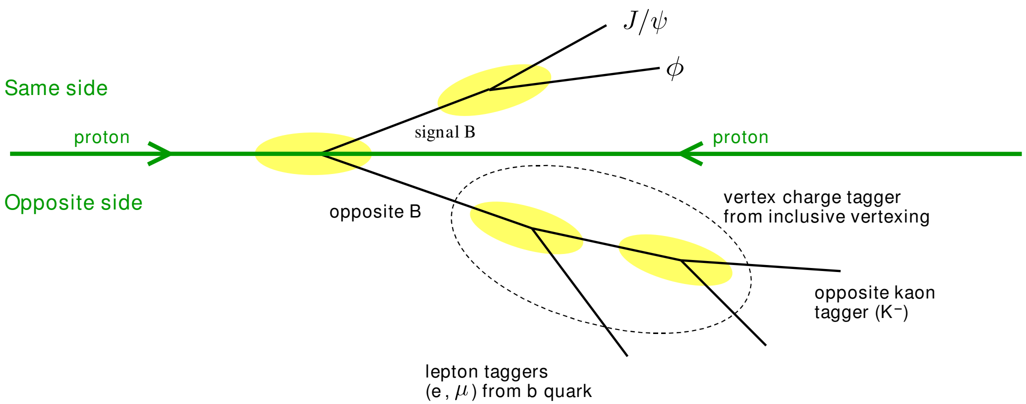
[LHCb-CONF-2011-048]

$$\frac{\mathcal{B}(B_s \to J/\psi K_S^0)}{\mathcal{B}(B_d \to J/\psi K_S^0)} = 0.0378 \pm 0.0058\,(\text{stat}) \pm 0.0020\,(\text{syst}) \pm 0.0030\,(\frac{f_s}{f_d})$$

CDF: $0.041 \pm 0.007 \pm 0.004 \pm 0.005$ [Note 10240]

Flavour tagging

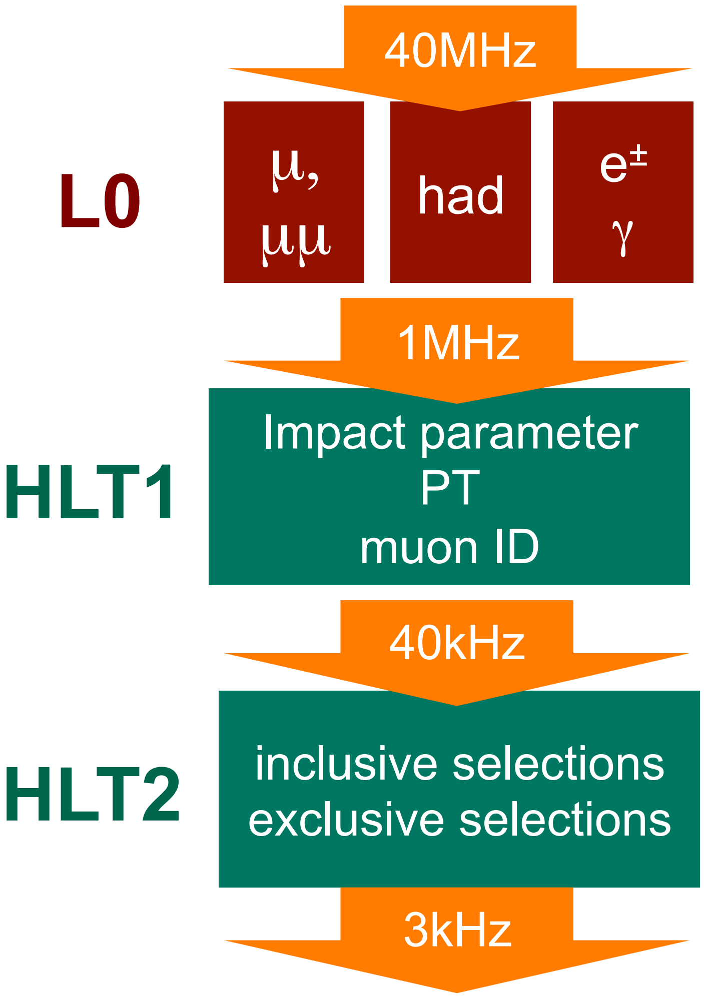
- To measure ϕ_s we need to know the B_s^0 flavour at the production vertex
- B_s^0 flavour is determined by **tagging** algorithms LHCb-CONF-2011-003:
  - Opposite Side **(OS)**: Decay products of the other b-meson
  - Same Side **(SS)**: particles produced in fragmentation alongside signal B



- Results shown here use OS tagging only. This is optimised and calibrated using the control channel $B^+ \to J/\psi K^+$
  $\epsilon_{eff}(J/\psi\phi) = \epsilon(1-2\omega)^2 = 2.08 \pm 0.41\%$
- Future analyses will also use the SS tagger.

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)

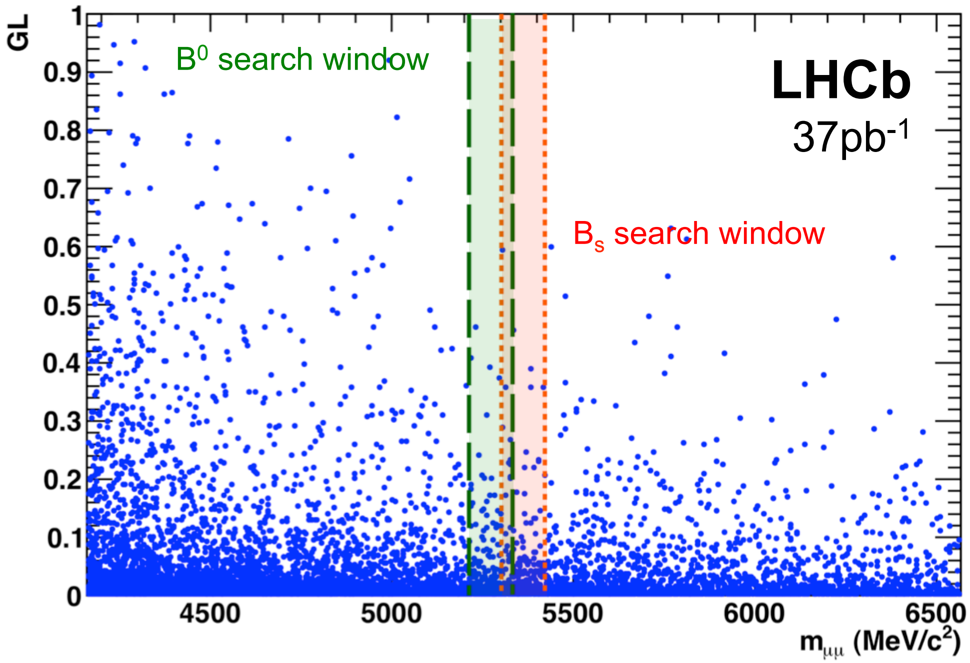


Muon lines:

L0 hardware	**Single-μ: p_T>1.4GeV/c** **Di – μ : 2 clean muons** **$p_{T1} x p_{T2}$>$(1.3 GeV/c)^2$**
HLT1 software	Single-μ: p_T>0.8GeV/c IP > 0.11mm, IPS > 5 Dimuon: $M_{\mu\mu}$ > 2.7GeV/c^2, $M_{\mu\mu}$ > 1GeV/c^2+detached
HLT2 software	Dimuon: $M_{\mu\mu}$ > 4.7GeV/c^2 $\Delta m(J/\psi)$ < 120 MeV/c^2 Several lines with p_T and vertex displacement cuts

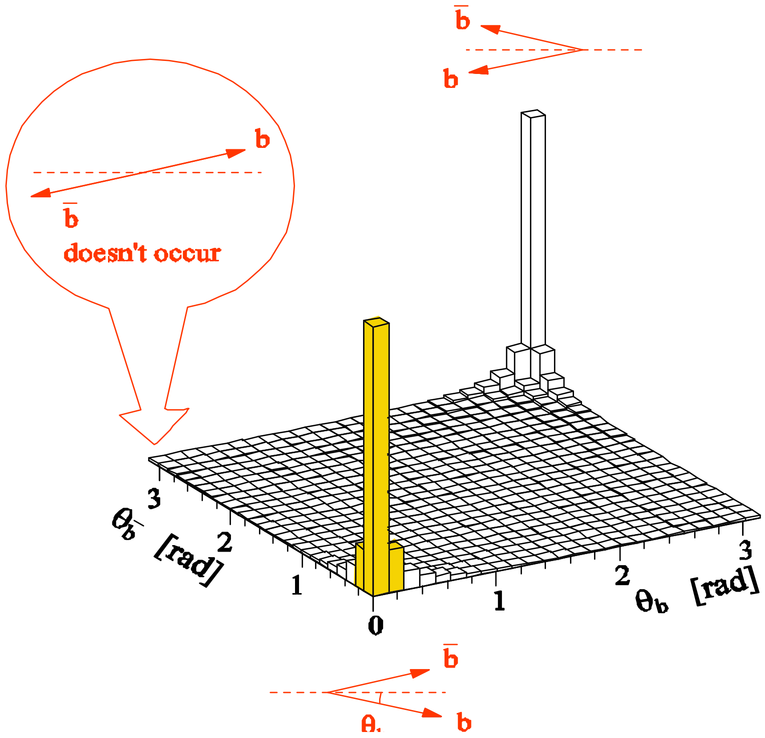
Signal and background likelihoods

- 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 [$CL_S = CL_{S+B}/CL_B$] → **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**

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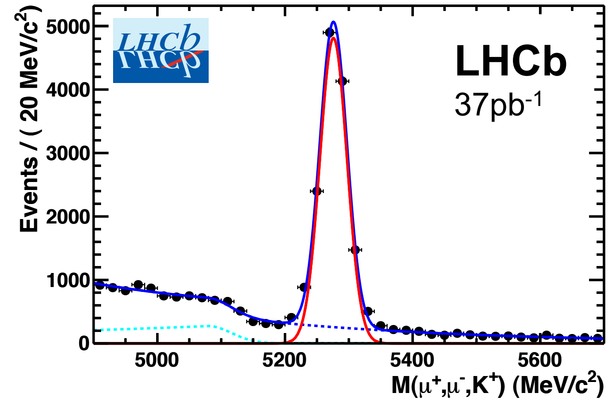
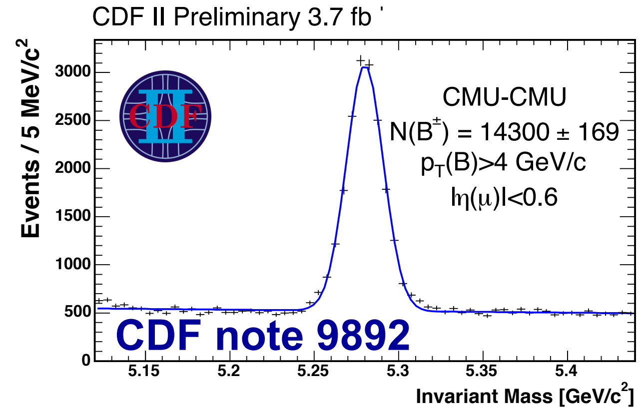
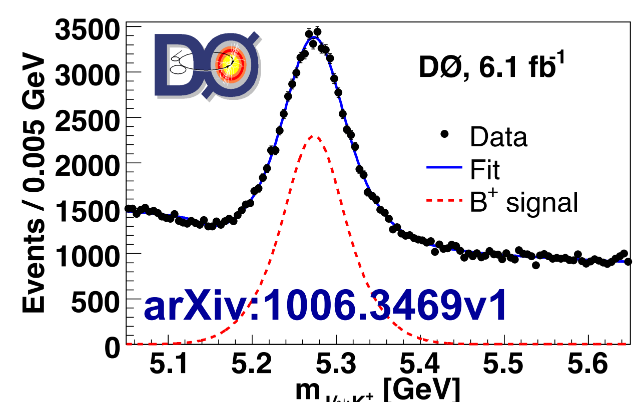
(CDF: $|\eta|<1$; D0: $|\eta|<2$; CMS/ATLAS: $|\eta|<2.4$)

- Rough estimate for B acceptance: compare $B^{\pm} \rightarrow J/\psi K^{\pm}$ 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

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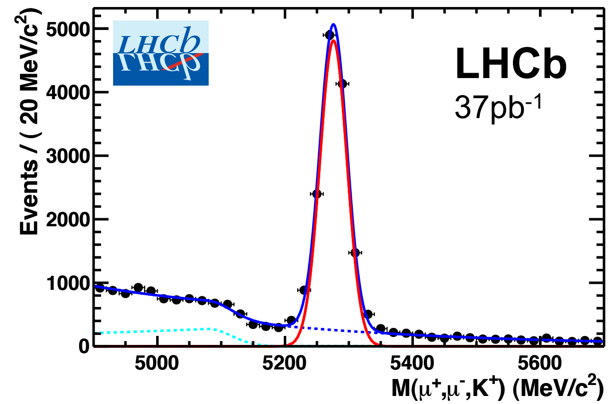
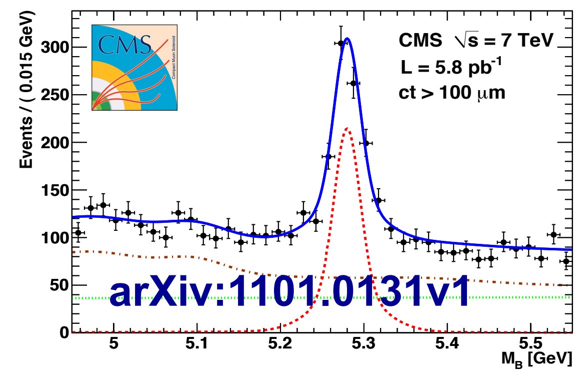
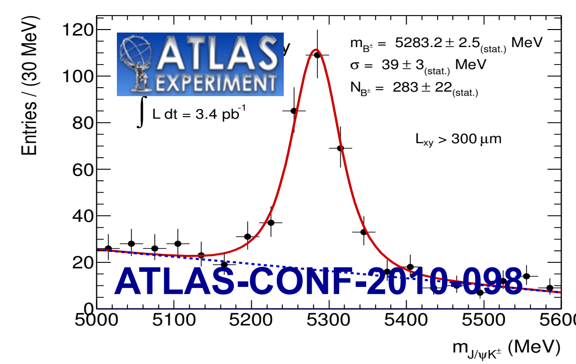
  - **LHCb**
    N^{signal}: $12{,}366 \pm 403^{stat+syst}$ ($0.037 fb^{-1}$)
  - **CMS (from 5.8pb-1)**
    N^{signal}: 5,818 scaled
  - **ATLAS (from 3.4pb-1)**
    N^{signal}: 3,080 scaled



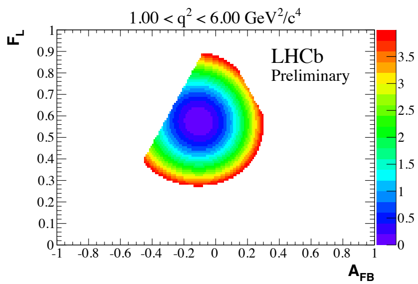




Likelihood scan in K*mm

K*μμ

LHCb-CONF-2011-038



(g) $1 < q^2 < 6\,\mathrm{GeV}^2$

Figure 6: Profile-likelihood contour (profiling the background parameters and the signal fraction) showing the difference in log-likelihood between the global minimum and the likelihood at each value of A_{FB} and F_L for the seven q^2 bins used in the analysis. Points outside the physical region are not included resulting in the triangular boundary visible in the figures.

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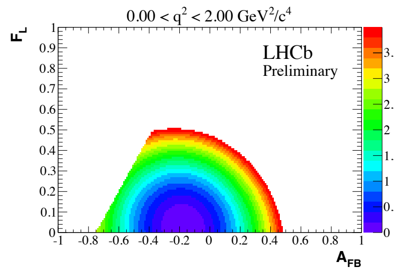
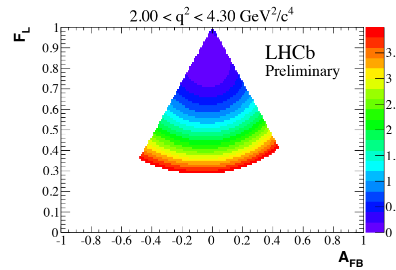
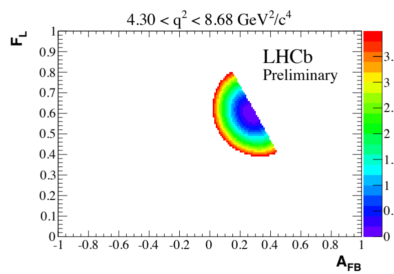


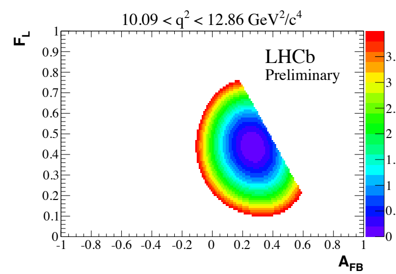
(a) $0 < q^2 < 2\,\mathrm{GeV}^2$



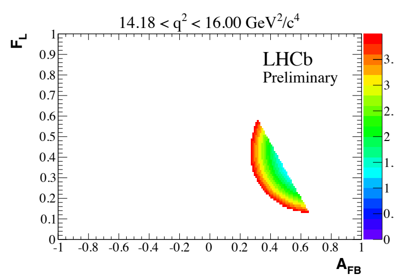
(b) $2 < q^2 < 4.3\,\mathrm{GeV}^2$



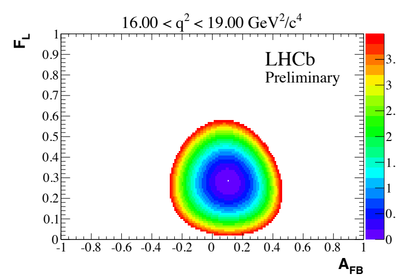
(c) $4.3 < q^2 < 8.68\,\mathrm{GeV}^2$



(d) $10.09 < q^2 < 12.86\,\mathrm{GeV}^2$



(e) $14.18 < q^2 < 16\,\mathrm{GeV}^2$



(f) $16 < q^2 < 19\,\mathrm{GeV}^2$

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