Rare Decays at LHCb

- Introduction
- LHCb design, environment, detector
- 2010 data
- Rare Decays

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Universität Zürich Seminar

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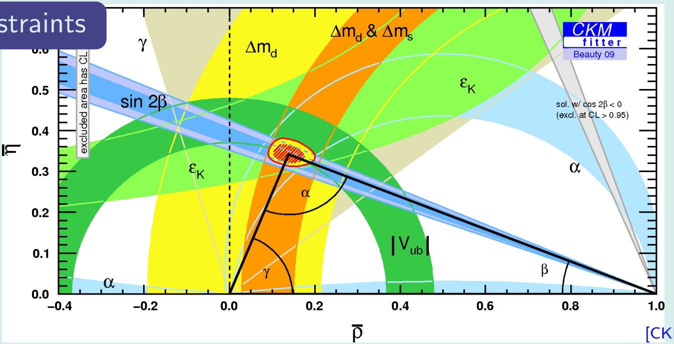
Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
  - ➜ Discrepancies in measurements or unitarity triangle

All constraints

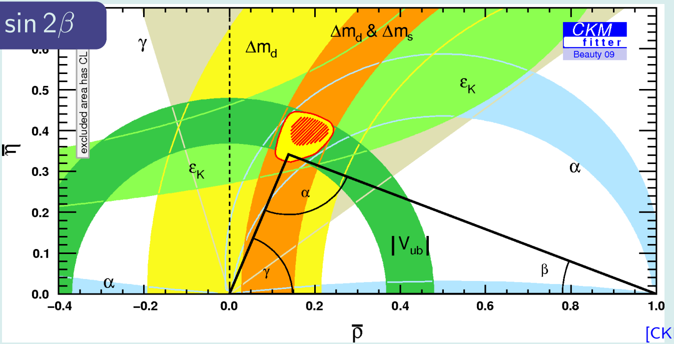


[CKMfitter 09/09]

Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
  - ➜ Discrepancies in measurements or unitarity triangle
- $(\bar\rho, \bar\eta)$ fit is dominated by $\sin 2\beta$

All but $\sin 2\beta$

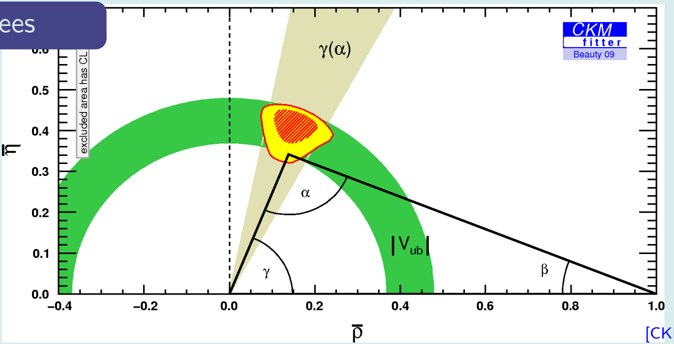


[CKMfitter 09/09]

Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
  - ➜ Discrepancies in measurements or unitarity triangle
- We don't know much about constraints from trees

Only trees



[CKMfitter 09/09]

Unitarity Triangle

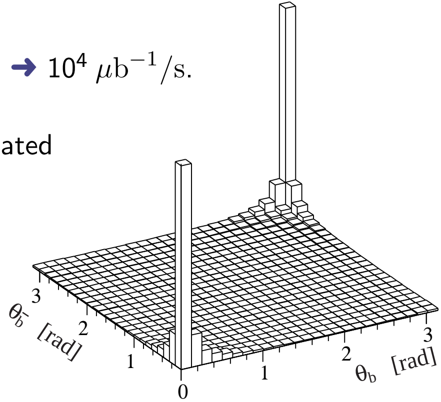
- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
  - ➜ Discrepancies in measurements or unitarity triangle
- ✔ Look for rare B & D decays (and K as well)
  - ➜ **Need a lot of data and a good precision**
- ✔ Need very good precision on all angles and sides.
  - ✔ Precise measurement of γ
- ✔ Need B_s as well ➜ β_s and more

The Large Hadron Collider beauty experiment for precise measurements of CP violation and rare decays

LHC

Nominal LHC Environment

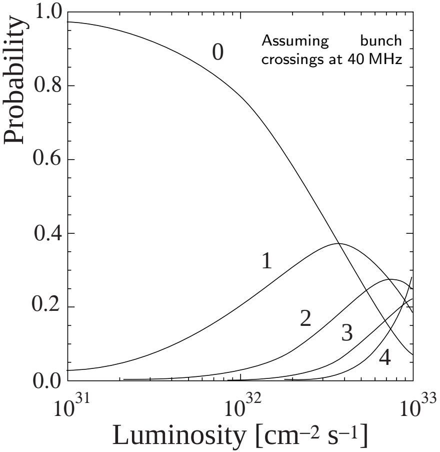
- *pp* collider at 14 TeV (7 TeV in 2010–12)
  - Inelastic cross-section about 60 mb
  - Assumed $b\bar{b}$ cross-section about 500 μb (one every 120)
  - Our `Pythia` tuning predits more than 1 mb at 14 TeV
- Bunch crossings at 40 MHz
- Luminosity up to $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ➜ $10^4\ \mu\mathrm{b}^{-1}/\mathrm{s}$.
  - ➜ $5 \cdot 10^6$ $b\bar{b}$ pairs per second
- Direction of b and $\bar{b}$ very correlated
  - ➜ A 4π coverage not optimal
  - ➜ Build a forward spectrometer
- The choice of the LHCb collaboration



b Physics at Hadron Colliders

- B mesons have a long lifetime $c\tau = 0.5\,\mathrm{mm}$ with $\gamma = \mathcal{O}(10\text{–}100)$
  - You want to make lifetime-dependent measurements
    - ✔ Good vertex resolution

✗ Not too many pp interactions per bunch crossing
➜ Control luminosity to avoid multiple pp collision events
  - We will reach baseline luminosity very early



b Physics at Hadron Colliders

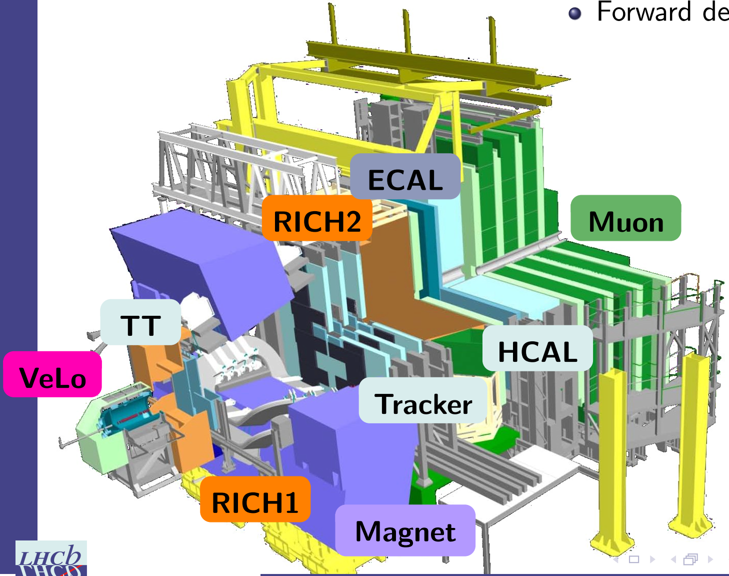
- B mesons have a long lifetime $c\tau = 0.5\,\mathrm{mm}$ with $\gamma = \mathcal{O}(10–100)$
  - You want to make lifetime-dependent measurements
    - ✔ Good vertex resolution
- They have a large mass ~ 5 GeV, but not very large.
  - Look for particles with a transverse momentum $p_T = \mathcal{O}(1)$ GeV
- $b \to c$ and $c \to s$. 20% B decay to leptons.
  - ✔ Use Kaon, muon and electron-ID

✔ Good particle ID to fight large background

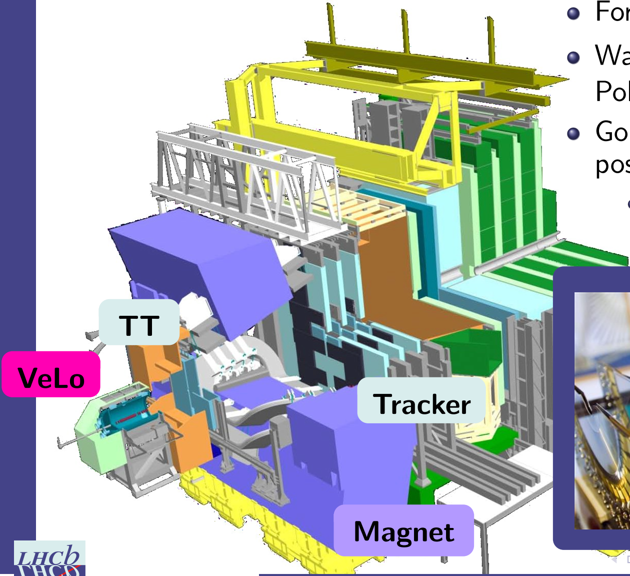
- There will still be a lot of background
  - ✔ Good mass, i.e. momentum resolution

LHCb

- Forward detector



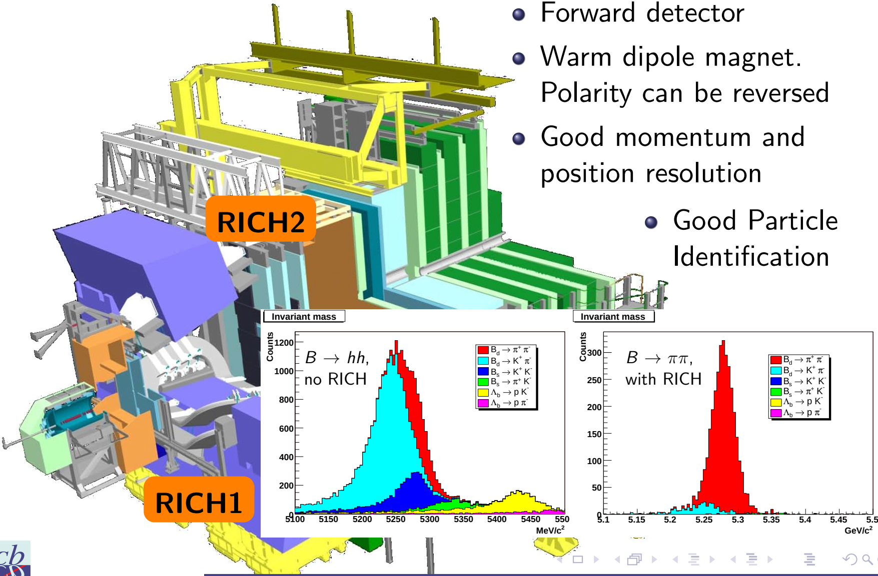
LHCb



- Forward detector
- Warm dipole magnet. Polarity can be reversed
- Good momentum and position resolution
  - Vertex detector gets 8mm to the beam

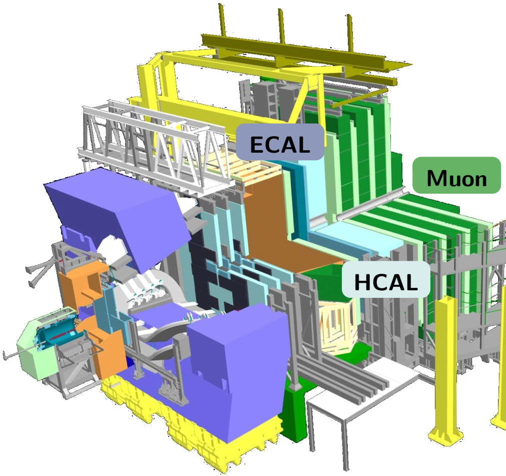
LHCb

- Forward detector
- Warm dipole magnet. Polarity can be reversed
- Good momentum and position resolution
  - Good Particle Identification



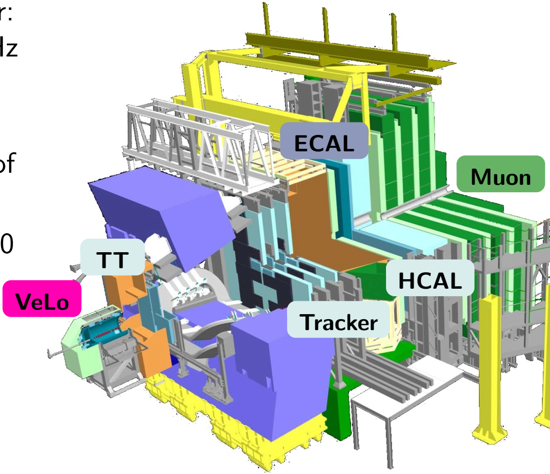
LHCb Trigger

- Hardware-based L0 trigger: moderate p_T cuts: 40 MHz ➜ 1 MHz



LHCb Trigger

- Hardware-based L0 trigger: moderate p_T cuts: 40 MHz ➜ 1 MHz
- The whole data is then sent at 1 MHz to a farm of $\mathcal{O}(2000)$ CPUs
- HLT1 tries to confirm a L0 decision by matching the L0 candidates to tracks. ➜ $\sim$ 30 kHz



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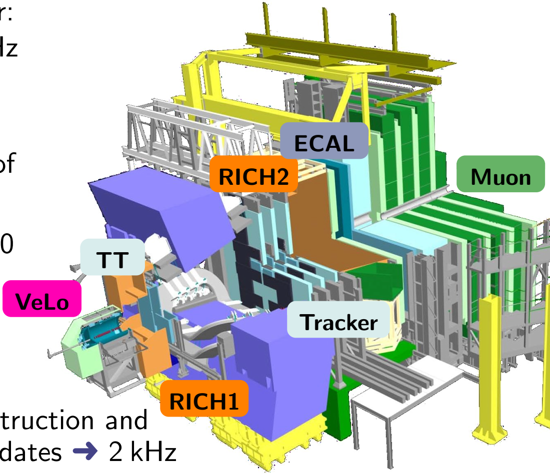
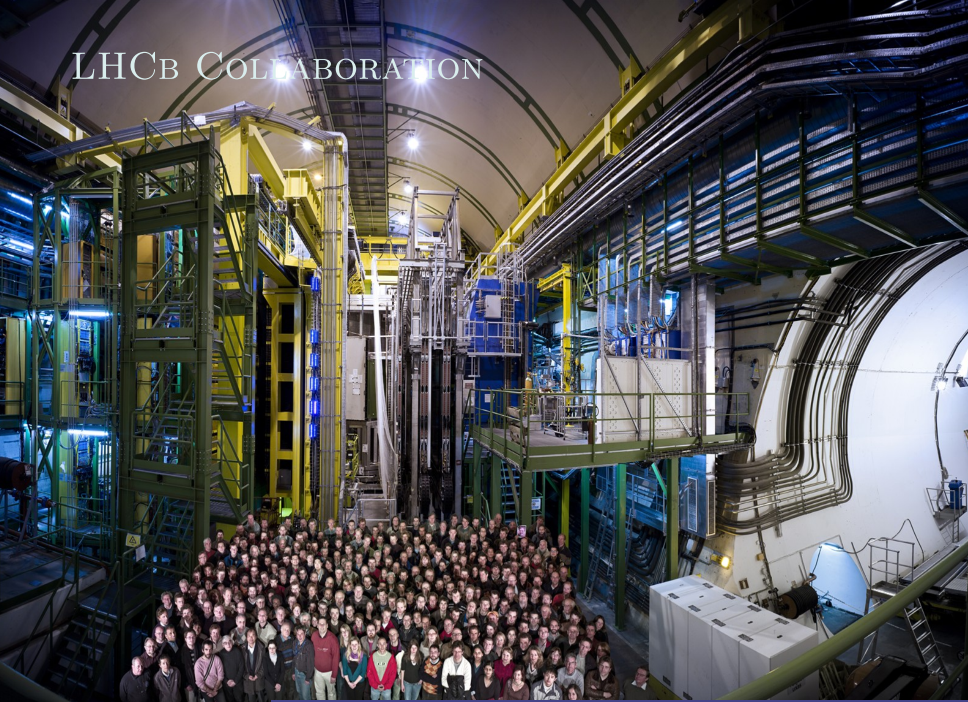


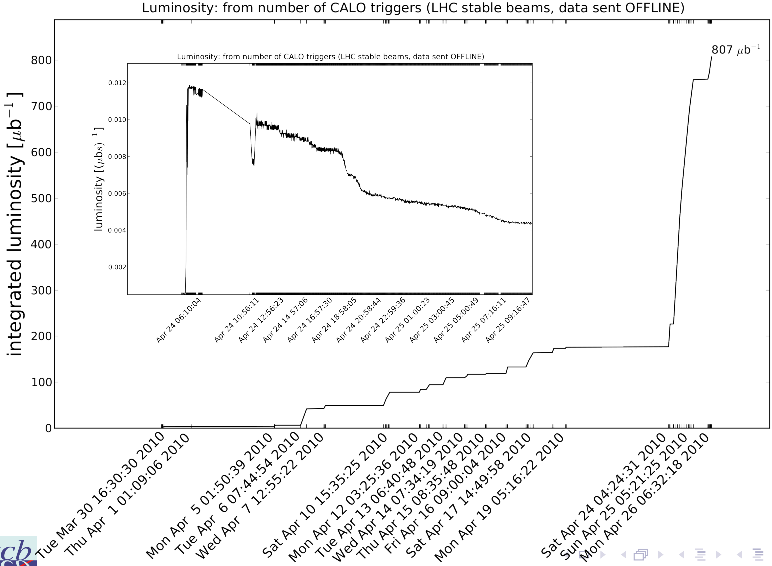
- HLT2 does the full reconstruction and loose selection of B candidates ➜ 2 kHz
  - This is much less than the 10^5 b events per second

LHCb Collaboration



2010 Data Taking

Luminosity at 3.5 TeV



Trigger Strategy

L0: Based on Calo, Muon and Pile-up

MB triggers: HCAL, SPD, CALO, MUON, Pile-Up . . .
c,*b* triggers: Electron, Photon, Hadron, Muon, Di-Muon, π^0
Luminosity: Muon, Di-Muon, Beam-Gas

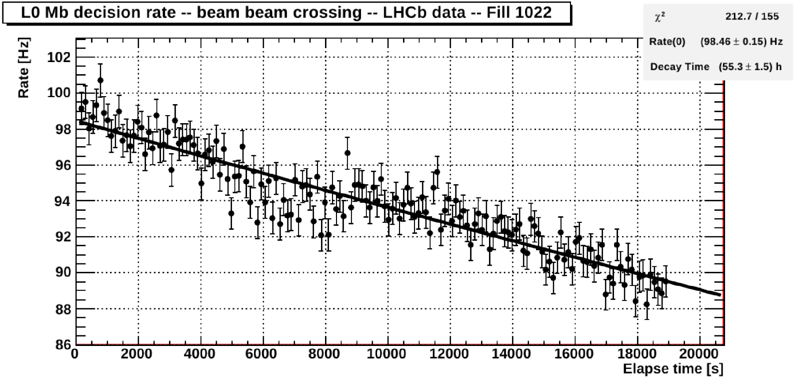
Readout Supervisor: Passes on L0 decision and adds random triggers

- Knows about bunch structure.

HLT: software based on "everything"

Micro-Bias: At least one track in velo (RZ), or T stations
No-Bias: 100 Hz of random

Trigger Operations



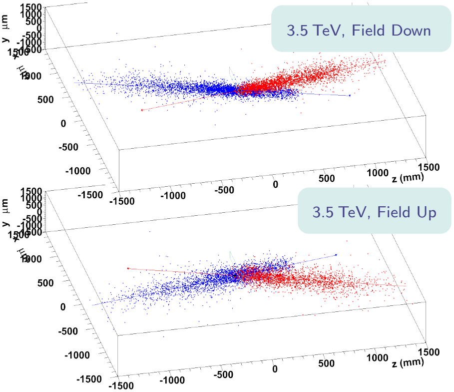
Minimum bias: We can take minimum bias at full rate at the moment

No bias: 100 Hz of no bias events (including 1 Hz beam-gas)

Hlt1: Standard selections in parallel with pass-all

Magnet Polarity

- We can swap the magnet polarity
  - ➜ Important for systematic studies of CP effects
  - So far have taken 10% data with field Up. Will catch up soon



- Primary vertex in Beam Gas events for Beam1 and Beam2
  - z coverage due to velo acceptance
  - Crossing angle due to B field
- Beam profiles used to determine luminous region
  - ➜ Luminosity

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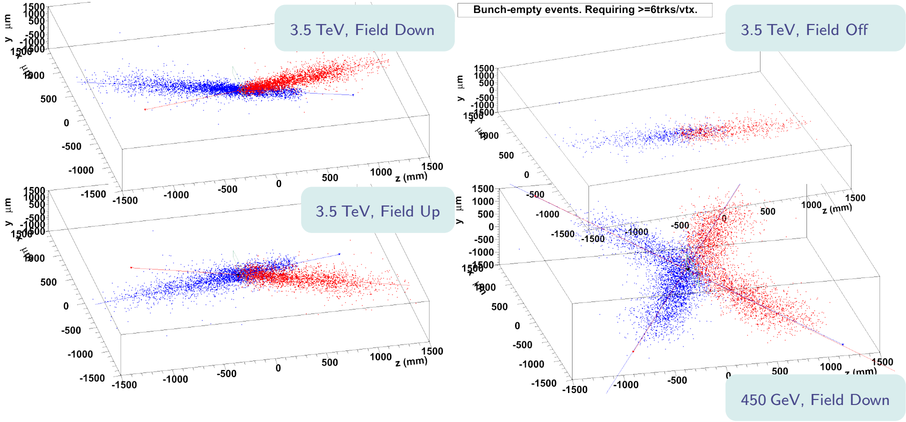
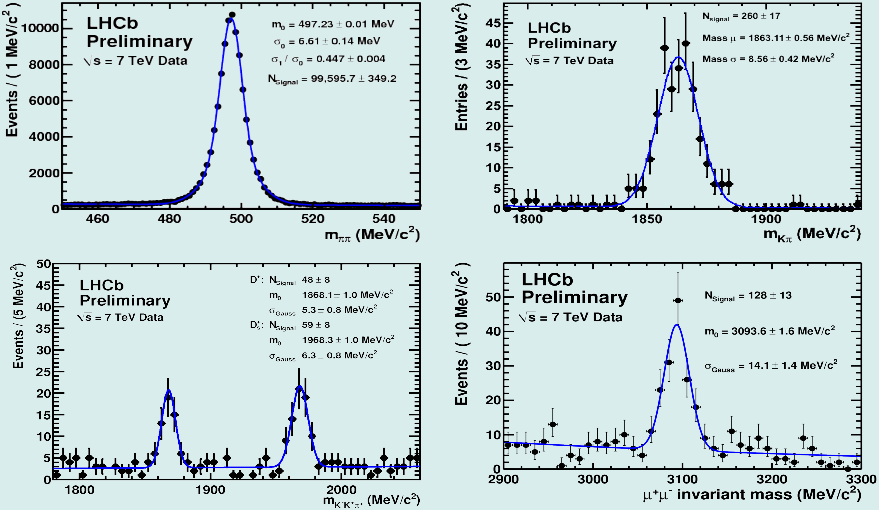
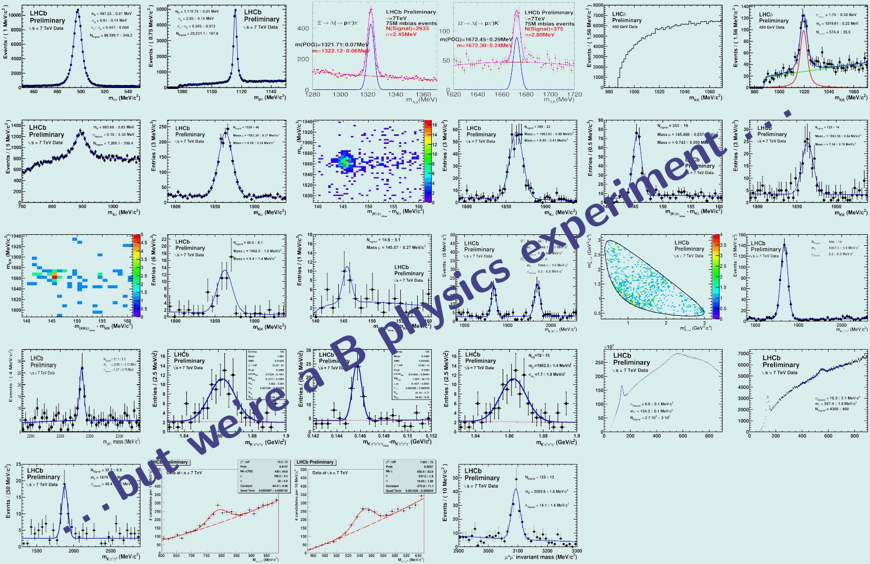


Higlights



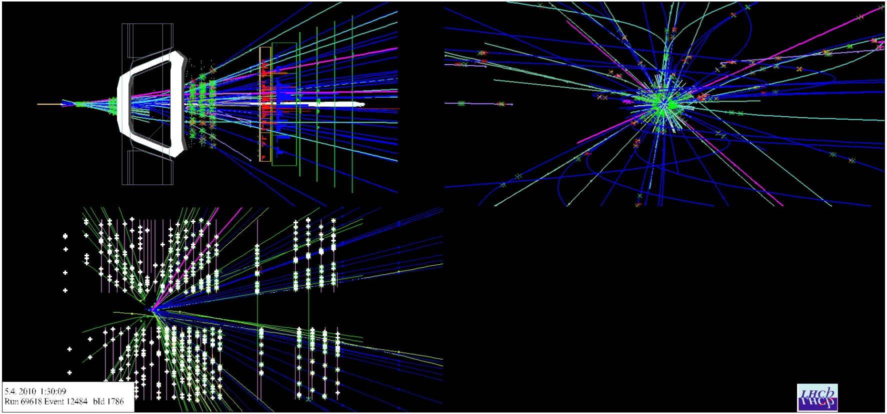
LHCb
Preliminary
√s = 7 TeV Data
m0 = 497.23 ± 0.01 MeV
σ0 = 6.61 ± 0.14 MeV
σ1 / σ0 = 0.447 ± 0.004
NSignal = 99,595.7 ± 349.2
Events / (1 MeV/c2)
mππ (MeV/c2)
LHCb
Preliminary
√s = 7 TeV Data
Nsignal = 260 ± 17
Mass μ = 1863.11 ± 0.56 MeV/c2
Mass σ = 8.56 ± 0.42 MeV/c2
Entries / (3 MeV/c2)
mKπ (MeV/c2)
LHCb
Preliminary
√s = 7 TeV Data
D+: NSignal 48 ± 8
m0 1868.1 ± 1.0 MeV/c2
σGauss 5.3 ± 0.8 MeV/c2
Ds+: NSignal 59 ± 8
m0 1968.3 ± 1.0 MeV/c2
σGauss 6.3 ± 0.8 MeV/c2
Events / (5 MeV/c2)
mK-K+π+ (MeV/c2)
LHCb
Preliminary
√s = 7 TeV Data
NSignal = 128 ± 13
m0 = 3093.6 ± 1.6 MeV/c2
σGauss = 14.1 ± 1.4 MeV/c2
Events / (10 MeV/c2)
μ+μ- invariant mass (MeV/c2)

VERY NICE PEAKS!

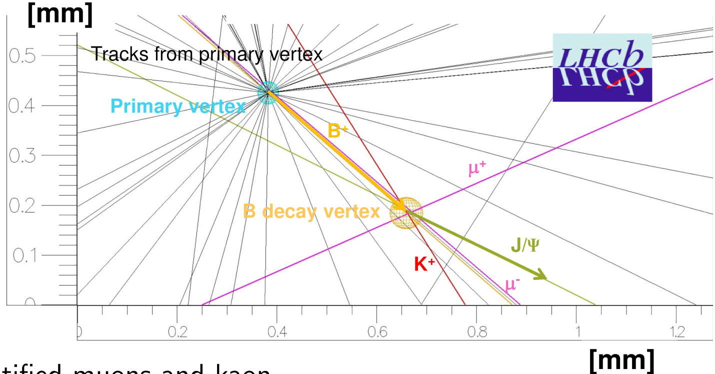


... but we're a B physics experiment ...

B^+ Candidate

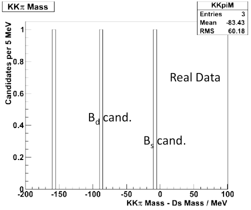


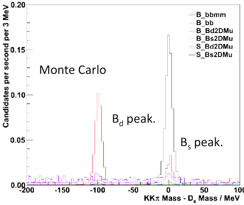
B^+ Candidate



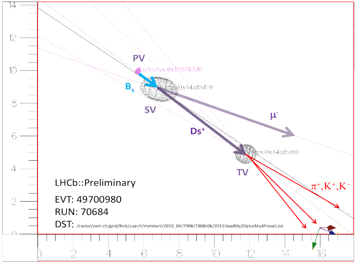
- Well identified muons and kaon.
- $m_{J/\psi} = 3097.90$ MeV, $m_{B^+} = 5319.90$ MeV
- Proper time $= 0.6\,\mathrm{ps}$ (26 σ from PV)
- Angle of flight and momentum of $B^+ = 0.7°$

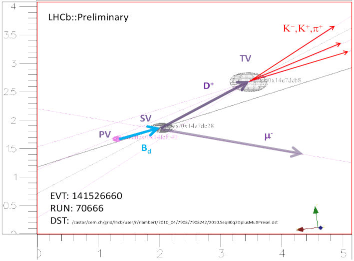
Semileptonic Candidates





LHCb::Preliminary





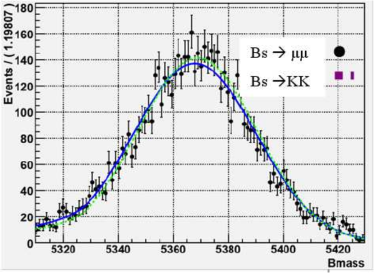
- Looking at $D \to KK\pi$ with a μ tag forming a secondary vertex
- Classify by $KK\pi$ mass
- 3 Candidates:
  - One background
  - One $B_d \to D^+ \mu\nu$
  - One $B_s \to D_s \mu\nu$

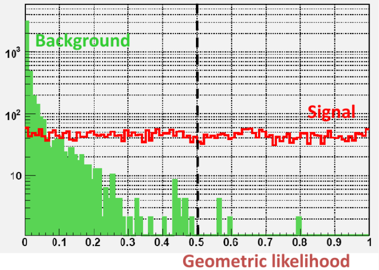
Some Sensitivities

- $B_s \to \mu\mu$
- $b \to s\gamma$
- A_{FB} in $B \to \mu\mu K^*$

$B_s \to \mu\mu$

- Very rare but SM BF well predicted $\mathcal{B} = (3.35 \pm 0.32) \cdot 10^{-9}$ [Blanke et al., JHEP0610:003,2006]
- Sensitive to (pseudo)scalar operators
  - MSSM: $\mathcal{B} \propto \frac{\tan^6 \beta}{M_A^4}$
- Present limit from CDF $\mathcal{B} < 4.3 \cdot 10^{-8}$ (95% CL)
- Select signal in a 3D-box of mass, geometrical likelihood, PID likelihood
  - Uncorrelated variables with different control samples
  - B mass resolution ~ 20 MeV





$B_s \to \mu\mu$

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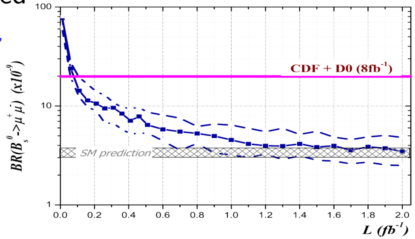
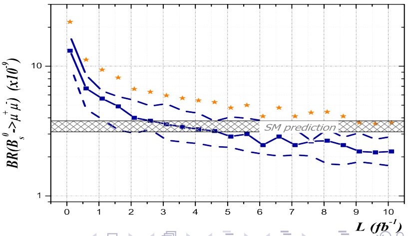
  - MSSM: $\mathcal{B} \propto \frac{\tan^6 \beta}{M_A^4}$
- Present limit from CDF $\mathcal{B} < 4.3 \cdot 10^{-8}$ (95% CL)
- With SM BF, expect 8 signal and 12 background events in most sensitive bin in 2 fb^{-1}
  - ➜ 3σ evidence with 2 fb^{-1}
  - ➜ 5σ observation with 6–10 fb^{-1}

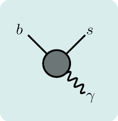




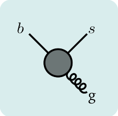
Operators

Operator

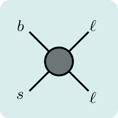
$\mathcal{O}_{7\gamma}$



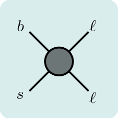
$\mathcal{O}_{8\mathrm{g}}$



$\mathcal{O}_{9\ell,10\ell}$



$\mathcal{O}_{\mathrm{S,P}}$



Effective Hamiltonian $\mathcal{H}$

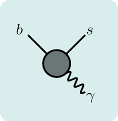
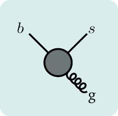
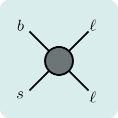
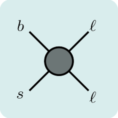
$$A(M \to F) = \langle F \,|\mathcal{H}_{\mathrm{eff}}|\, M \rangle$$

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}{}^{*} V_{tb} \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$

- Operators $\mathcal{O}_i$: Long-distance effects
- Wilson coefficients C_i: Short-distance effects(masses above μ are integrated out)

New physics can show up in new operators or modified Wilson coefficients

Operators

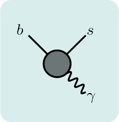
Operator		magnitude	phase	helicity flip $\mathcal{O}'_i$
$\mathcal{O}_{7\gamma}$		$b \to s\gamma$	$A_{CP}(b \to s\gamma)$	$\Lambda_b \to \Lambda\gamma$ $B \to K^{**}\gamma$ $B \to \ell\ell K^*$
$\mathcal{O}_{8g}$		$b \to s\gamma$ $b \to \{s, u, d\}$	$A_{CP}(b \to s\gamma)$ $B \to \phi K$	$\Lambda_b \to \Lambda\phi$ $B \to K^*\phi$
$\mathcal{O}_{9\ell,10\ell}$		$b \to \ell\ell s$	$A_{FB}(b \to \ell\ell s)$	$B \to \ell\ell K^*$
$\mathcal{O}_{S,P}$		$B \to \mu\mu$	$B \to \tau\tau$	$b \to s\tau\tau$

Adapted from [G.Hiller,hep-ph/0308180]

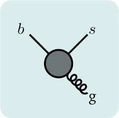
Operators

Operator

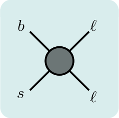
$\mathcal{O}_{7\gamma}$



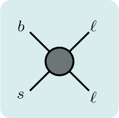
$\mathcal{O}_{8\mathrm{g}}$



$\mathcal{O}_{9\ell,10\ell}$

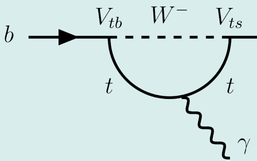


$\mathcal{O}_{\mathrm{S,P}}$

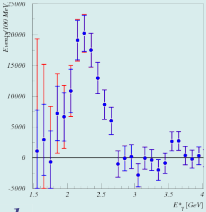


- All C_i calculated at NLO if not NNLO in SM
- We need to measure all coefficients
- Any discrepancy is a sign of New Physics

$b \to s\gamma$



$b \to s\gamma$



[Koppenburg et al., PRL93, 061803 (2004)]

BF sets strong constraints on New Physics

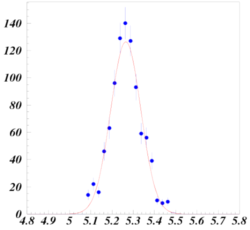
The photon polarisation is not well measured.

- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}} \overset{\text{SM}}{\simeq} \frac{m_s}{m_b}$
- Right-handed operators could contribute
- ✔ Mixing-induced CP violation in $B_s \to \phi\gamma$
- Λ_b baryons
- $B \to \gamma K^{**}(K\pi\pi)$
- ✔ Virtual photons ($b \to \ell\ell s$)
- Converted photons

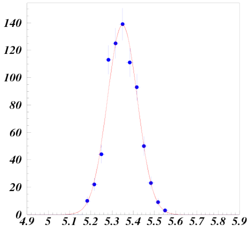
$B_d \to K^*\gamma$ AND $B_s \to \phi\gamma$ YIELDS FOR 2 FB^{-1}

	$B_d \to K^*\gamma$	$B_s \to \phi\gamma$
Visible BR	$2.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
η_{rec}	5.6%	5.4%
η_{sel}	13.3%	11.7%
η_{trg}	46%	44%
η_{tot}	0.34%	0.28%
Signal Yield	73 000	11 000
B/S	0.59 ± 0.26	< 0.55

The B mass resolution is 70 MeV.



$K^*\gamma$ mass [GeV/c^2]

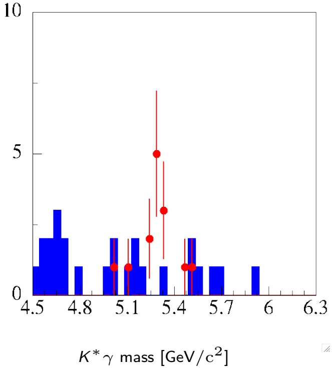


$\phi\gamma$ mass [GeV/c^2]

$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$ yields for 2 fb^{-1}

	$B_d \to K^*\gamma$	$B_s \to \phi\gamma$
Visible BR	$2.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
η_{rec}	5.6%	5.4%
η_{sel}	13.3%	11.7%
η_{trg}	46%	44%
η_{tot}	0.34%	0.28%
Signal Yield	73 000	11 000
B/S	0.59 ± 0.26	< 0.55

Running on 13 minutes equivalent of $b\bar{b}$ events one already gets a peak



The B mass resolution is 70 MeV.

$B_d \to K^*\gamma$ AND $B_s \to \phi\gamma$ YIELDS FOR 2 FB^{-1}

	$B_d \to K^*\gamma$	$B_s \to \phi\gamma$
Signal Yield	73 000	11 000
B/S	0.59 ± 0.26	< 0.55

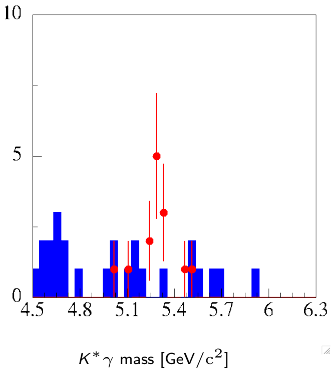
Expecting a *statistical* error on $A_{\mathrm{CP}}(B_d \to K^*\gamma)$ of 0.5%

➜ Will be dominated by systematics

- $K^\pm$ interaction with matter
- B_d, $\overline{B}_d$ production asymmetries ...

[LHCb note 2007-030]

Running on 13 minutes equivalent of $b\bar{b}$ events one already gets a peak

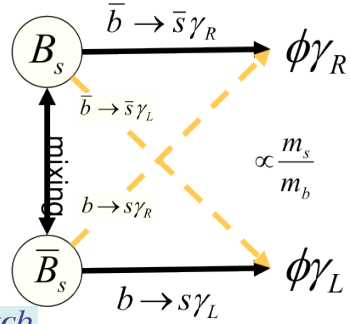


$B_s \to \phi\gamma$

In SM mainly $B_s \to \phi\gamma_R$ and $\overline{B}_s \to \phi\gamma_L$. Mixing only if wrong polarisation.

$\mathcal{A}^{\text{mix}}$ tiny $\quad$ $\mathcal{A}^{\text{dir}} = 0$ in MFV $\quad$ $\mathcal{A}^{\Delta\Gamma} \propto r$

$$\mathcal{A}_s(t) = \frac{\Gamma_{\overline{B}_s \to \phi\gamma} - \Gamma_{B_s \to \phi\gamma}}{\Gamma_{\overline{B}_s \to \phi\gamma} + \Gamma_{B_s \to \phi\gamma}} = \frac{\mathcal{A}^{\text{dir}} \cos \Delta m_s t + \mathcal{A}^{\text{mix}} \sin \Delta m_s t}{\cosh \frac{1}{2}\Delta\Gamma t - \mathcal{A}^{\Delta\Gamma} \sinh \frac{1}{2}\Delta\Gamma t}$$



Tagged approach (measure all $\mathcal{A}$):

- ➜ 12% on $\mathcal{A}^{\text{mix}}$ (2 fb^{-1})
- ➜ 23% error on $\mathcal{A}^{\Delta\Gamma}$ (2 fb^{-1})

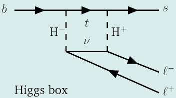
Untagged approach (only $\mathcal{A}^{\Delta\Gamma} \propto r$):

- ➜ 19% error (2 fb^{-1})
  - 9% with 10 fb^{-1}

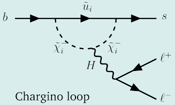
$B \to \mu\mu K^*$

- $B \to \mu\mu K^*$ very rare in the SM
  $\mathcal{B}(B \to \ell\ell K^*) = (1.2 \pm 1.0) \cdot 10^{-6}$
- Sensitive to
  - Supersymmetry,
  - Graviton exchanges,
  - Extra dimensions

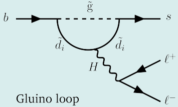
➜ Ideal place to look for new physics



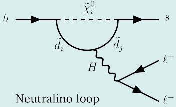
Higgs box



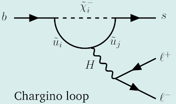
Chargino loop



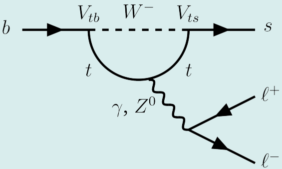
Gluino loop

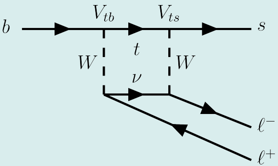


Neutralino loop



Chargino loop





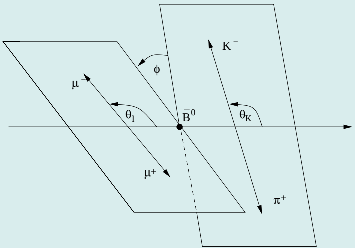
Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_l} = \Gamma'\left(\frac{3}{4}F_L\sin^2\theta_l + A_{\mathrm{FB}}\cos\theta_l + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l)\right)$$

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\phi} = \frac{\Gamma'}{2\pi}\left(\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{\mathrm{Im}}\sin 2\phi + 1\right)$$

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_K} = \frac{3\Gamma'}{4}\sin\theta_K\left(2F_L\cos^2\theta_K + (1-F_L)\sin^2\theta_K\right)$$



➜ **Many observables**

[Krüger & Matias]
[Egede, et. al.]

Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_l} = \Gamma'\left(\frac{3}{4}F_L\sin^2\theta_l + A_{\mathrm{FB}}\cos\theta_l + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l)\right)$$

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\phi} = \frac{\Gamma'}{2\pi}\left(\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{\mathrm{Im}}\sin 2\phi + 1\right)$$

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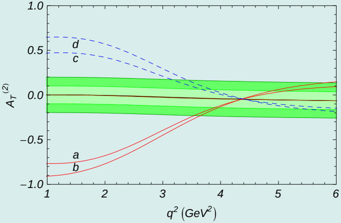


→ **Transverse asymmetry $A_T^{(2)}$ (RH)**

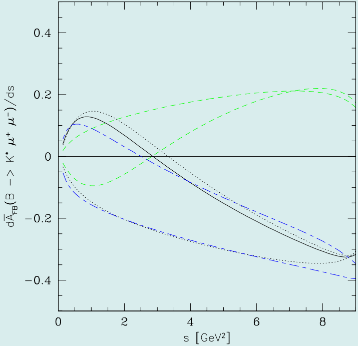
[Krüger & Matias]
[Egede, et. al.]

Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_l} = \Gamma' \left(\frac{3}{4} F_L \sin^2\theta_l + A_{\mathrm{FB}} \cos\theta_l + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l) \right)$$

$$A_{\mathrm{FB}} = \frac{\left(\int_0^1 - \int_{-1}^0 \right) \mathrm{d}\cos\theta_l \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_l}}{\int_{-1}^1 \mathrm{d}\cos\theta_l \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_l}}$$



➜ Zero point measures ratio of Wilson coeffs C_9/C_7.

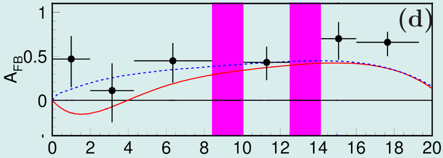
➜ Forward-backward asymmetry A_{FB}

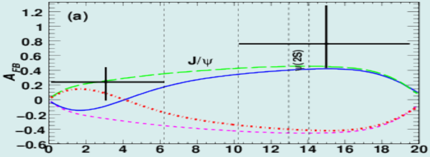
[Krüger & Matias]
[Egede, et. al.]

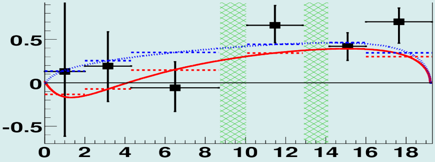
Messages from Other Experiments

- Belle: 230 $B \to \ell\ell K^*$ events in $657 \cdot 10^6$ $B\overline{B}$ [PRL103:171801,2009]
- Babar: 60 $B \to \ell\ell K^*$ events in $384 \cdot 10^6$ $B\overline{B}$ [PRD79:031102,2009]
- CDF: 100 $B \to \ell\ell K^*$ events in $4.4\ \mathrm{fb}^{-1}$ [CDF public note]
- FB asymmetry: All seem to favour $C_7 = -C_7^{\mathrm{SM}}$ case. Not conclusive yet...

➜ Need much more statistics



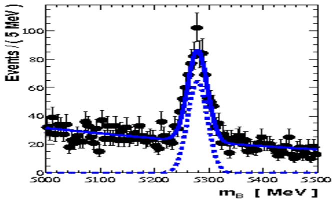


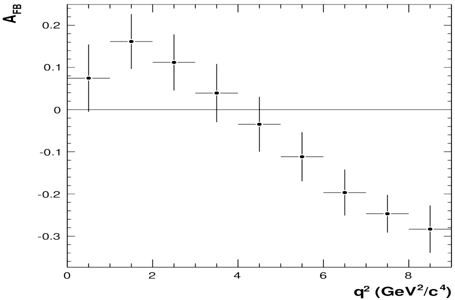


$B_d \to \mu\mu K^*$ YIELDS WITH $2\,\mathrm{fb}^{-1}$

Expected signal and background yields in $2\,\mathrm{fb}^{-1}$ of data (Assuming the SM BR of $\mathbf{12 \cdot 10^{-7}}$):

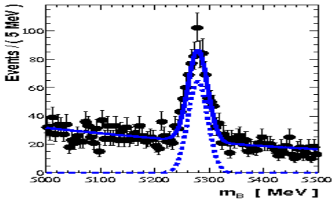
Sample	Yield
$\mathbf{B_d \to \mu\mu K^*}$	$\mathbf{7200 \pm 2100}$
$b \to \mu\mu s$	2000 ± 100
$2(b \to \mu)$	1050 ± 250
$b \to \mu c(\mu q)$	600 ± 200
Background	3700 ± 300
B/S	$\mathbf{0.5 \pm 0.2}$



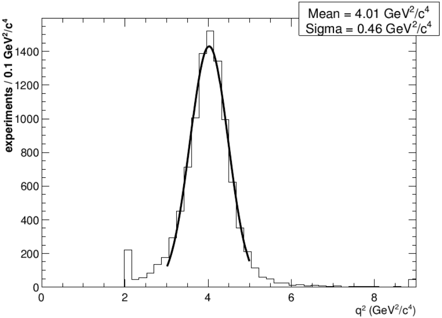


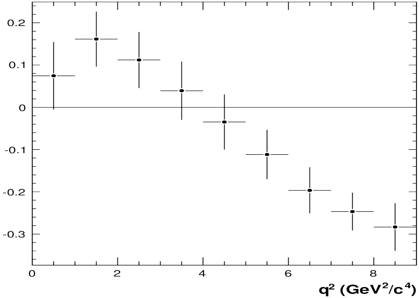
$B_d \to \mu\mu K^*$ yields with $2\,\text{fb}^{-1}$

Expected signal and background yields in $2\,\text{fb}^{-1}$ of data (Assuming the SM BR of $\mathbf{12 \cdot 10^{-7}}$):



➜ Resolution on A_{FB} zero : $\pm 0.46\,\text{GeV}^2$ (12%) in $2\,\text{fb}^{-1}$



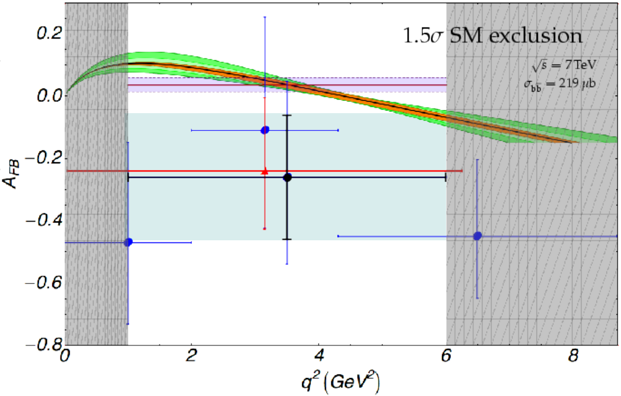


Scaling to Lower Luminosities

Assume Belle is right.

If we measure the mean A_{FB} in a bin 1–6 GeV^2. How well can we exclude the SM?

100 pb^{-1}: 1.5σ



SM prediction — Babar — Belle

LHCb at 100 pb^{-1}

Scaling to Lower Luminosities

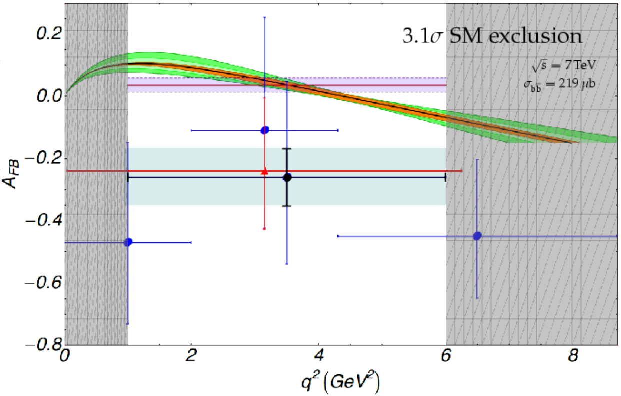
Assume Belle is right.

If we measure the mean $A_{\rm FB}$ in a bin 1–6 GeV^2. How well can we exclude the SM?

100 pb^{-1}: 1.5σ

300 pb^{-1}: 2.4σ

500 pb^{-1}: 3.1σ



SM prediction — Babar — Belle

LHCb at 500 pb^{-1}

Scaling to Lower Luminosities

Assume Belle is right.

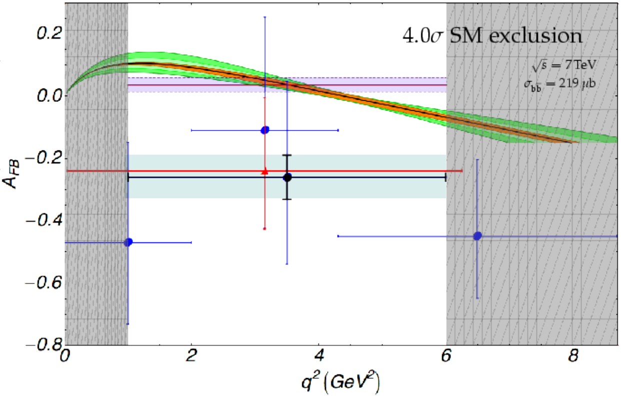
If we measure the mean A_{FB} in a bin 1–6 GeV^2. How well can we exclude the SM?

100 pb^{-1}: 1.5σ

300 pb^{-1}: 2.4σ

500 pb^{-1}: 3.1σ

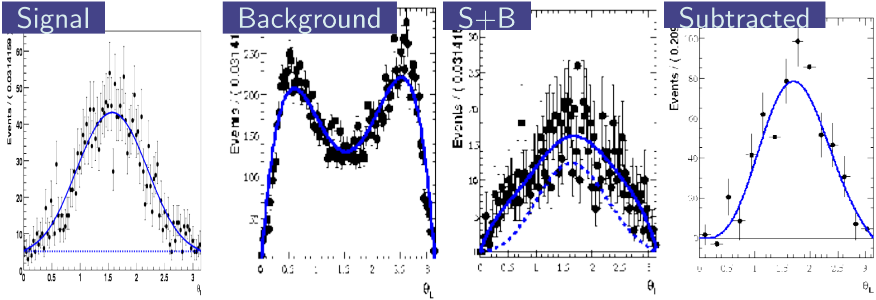
1 fb^{-1}: 4.0σ



SM prediction — Babar — Belle

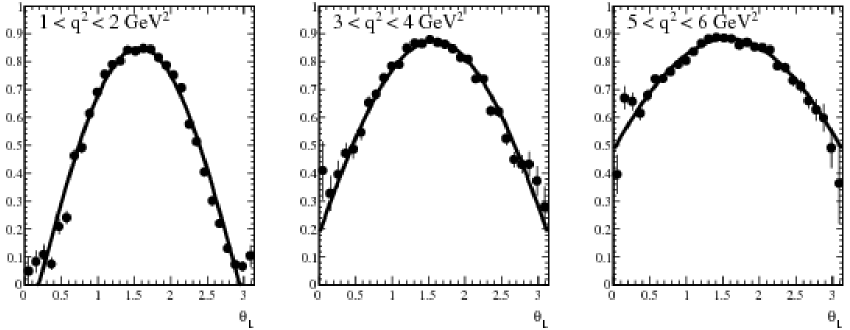
LHCb at 1 fb^{-1}

Understanding the θ_l distribution



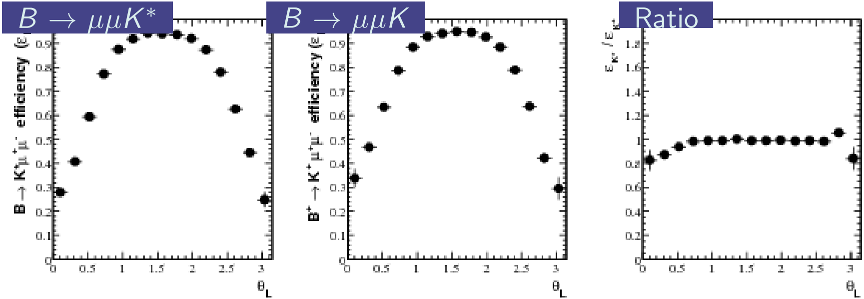
- Needs to know the θ_L distribution for background ➜ sidebands

Understanding the θ_l distribution



- Needs to know the θ_L distribution for background ➜ sidebands
- Need to understand the acceptance effects on θ_L ➜ MC?

Understanding the θ_l distribution



- Needs to know the θ_L distribution for background ➜ sidebands
- Need to understand the acceptance effects on θ_L ➜ MC?

➜ Using control samples like $B_d \to J/\psi K^*$ and $B \to \mu\mu K$

Conclusion

- Very good start in 2010
- We should be able to get new results in $B_s \to \mu\mu$ and $B \to \mu\mu K^*$ in 2011

A new era in flavour physics is starting