Physics Institute

Rare B decays at LHC

Current results and future prospects

Christian Elsasser [on behalf of the LHC*b* Collaboration]

SM@LHC 2011, Durham, April 13, 2011

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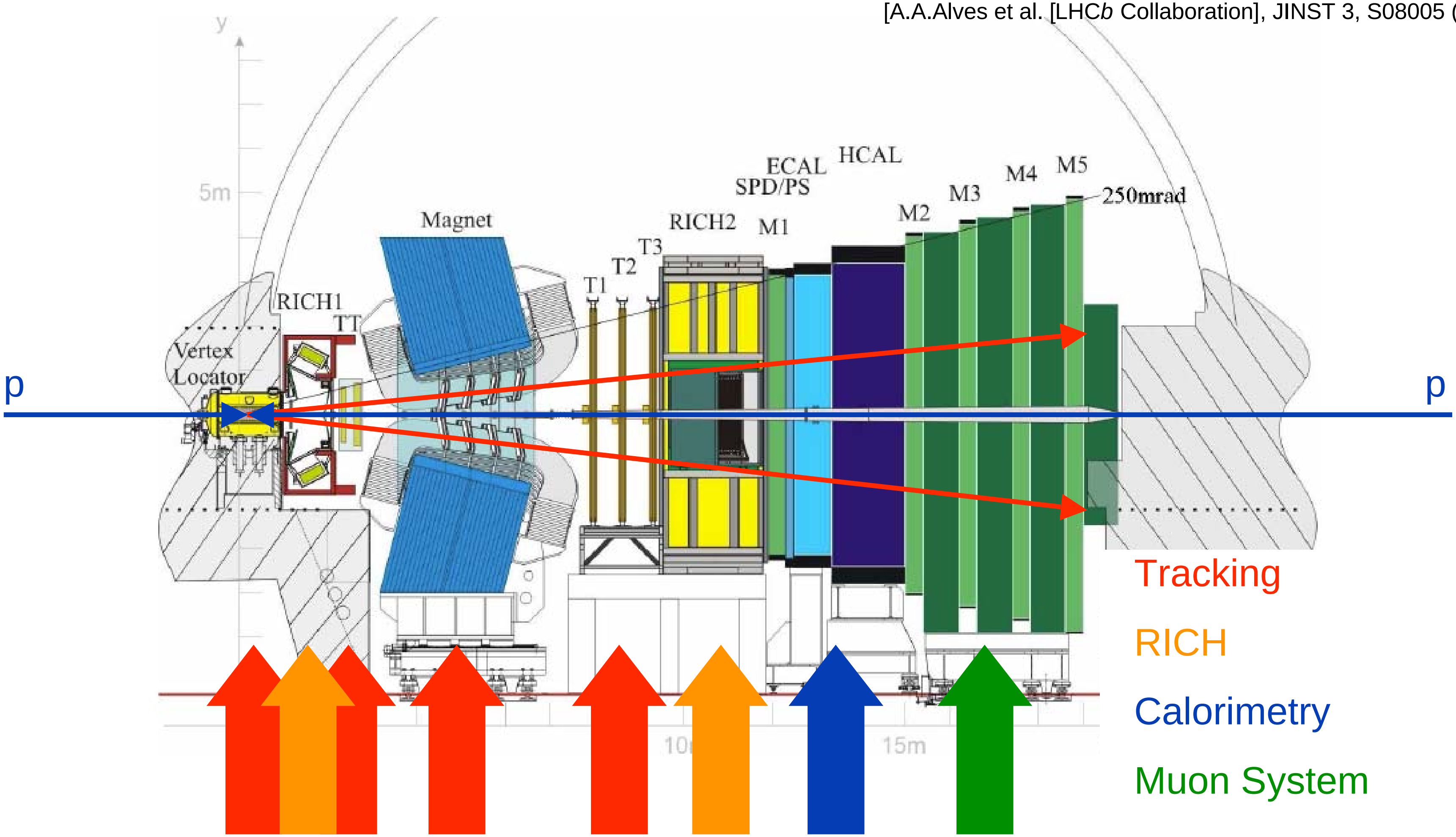
Search for the rare decays
$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The LHCb Collaboration[1]

arXiv:1103.2465

The LHCb detector

[A.A.Alves et al. [LHC*b* Collaboration], JINST 3, S08005 (2008)]



The LHC*b* experiment

- $\sigma(pp \rightarrow bbX) = (284 \pm 20_{stat} \pm 49_{syst})\ \mu b$ @ 7 TeV

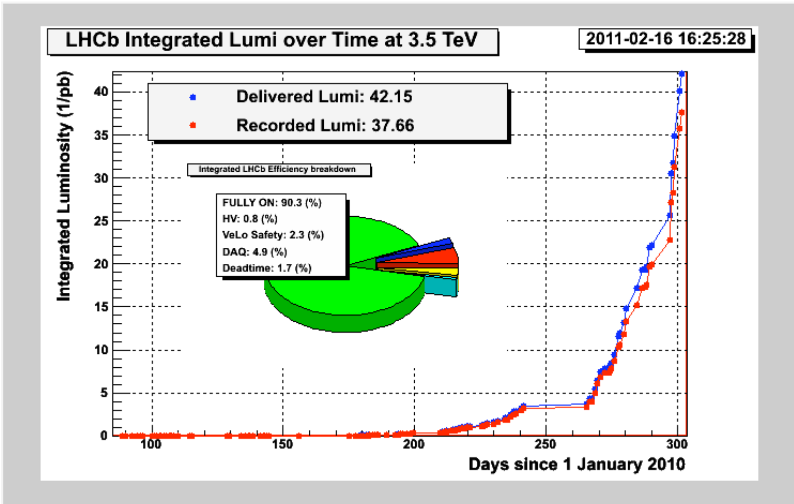
  [Physics Letters B 694 (2010) 209]

- Pseudo-rapidity: $1.9 < \eta < 4.9$

- Max. instantaneous luminosity 2010 $L = 1.7 \cdot 10^{32}\ cm^{-2}s^{-1}$

  (Design instantaneous luminosity $L = 2 \cdot 10^{32}\ cm^{-2}s^{-1}$)

- 2010 data: $L_{int} = 37\ pb^{-1}$



Goal:

Measurements of CP violation (see Tobias Brambach's talk) and

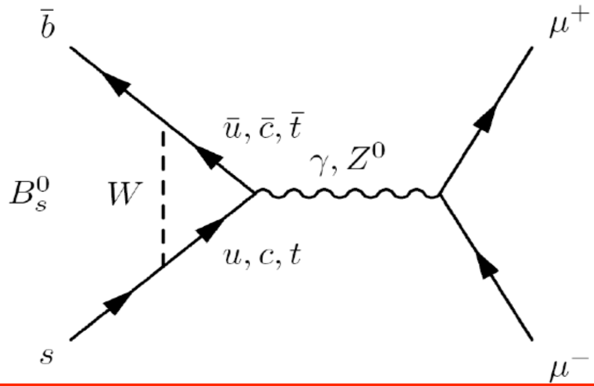
rare (B) decays (see this talk)

Results for $B_s \to \mu^+\mu^-$: Predictive Power (I)

- Decay is in the SM only allowed via FCNC.
- Helicity suppressed
- $BR(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \cdot 10^{-9}$

  $BR(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \cdot 10^{-10}$

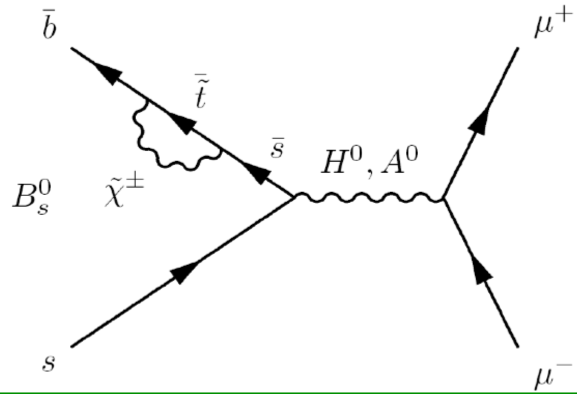
  [A.J.Buras,arXiv:1012.1447/Phys. Rev. D 80 (2009) 014503]



- Sensitive to New Physics (e.g. MSSM)

$$c_{S,P}^{MSSM} \propto \frac{m_b \cdot m_\mu \cdot \tan^3\beta}{M_A^2}$$

- Probing models with extended Higgs sector



Worlds best limit for $BR(B_s \to \mu^+\mu^-)$ @ 95% CL: CDF: $4.3 \cdot 10^{-8}$ with 3.7 fb^{-1}

DØ: $5.1 \cdot 10^{-8}$ with 6.1 fb^{-1}

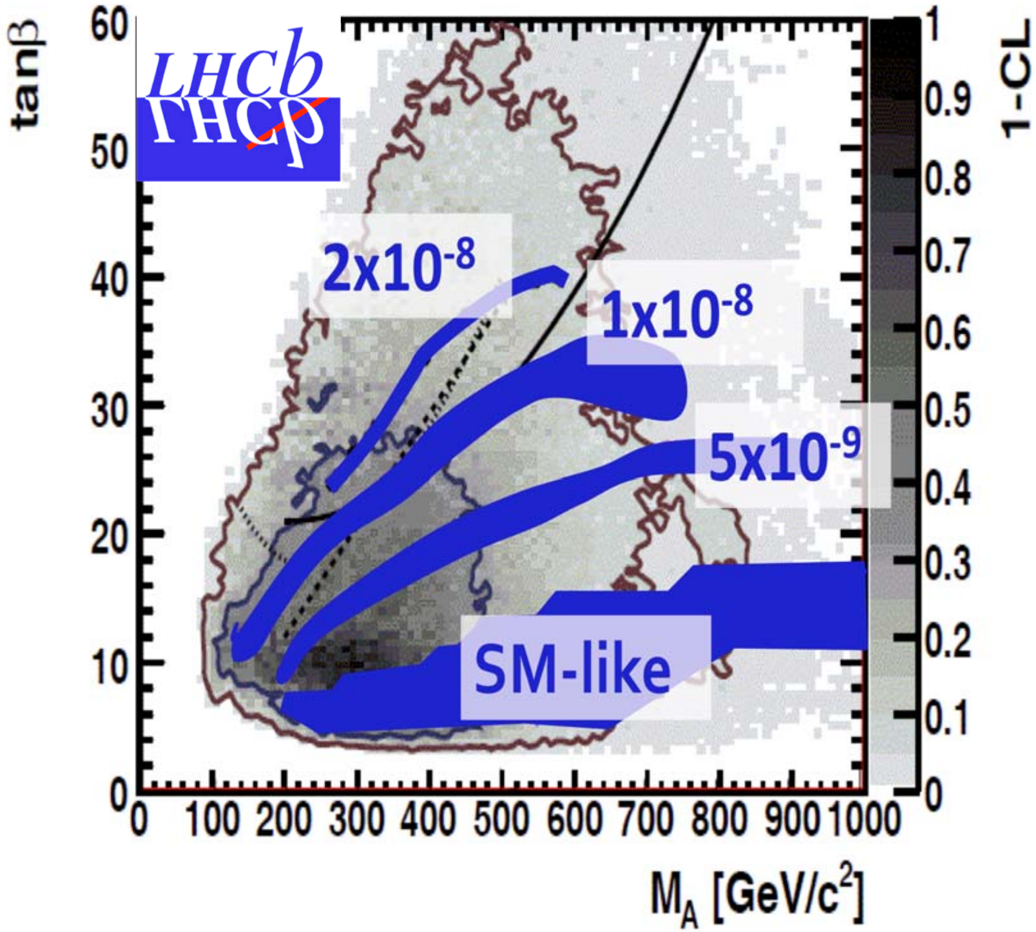
[Public CDF note 9892/Phys. Lett B 693, 593 (2010)]

Results for $B_s \to \mu^+\mu^-$: Predictive Power (II)

Constrains on tanβ and M_A in the NUHM1 model

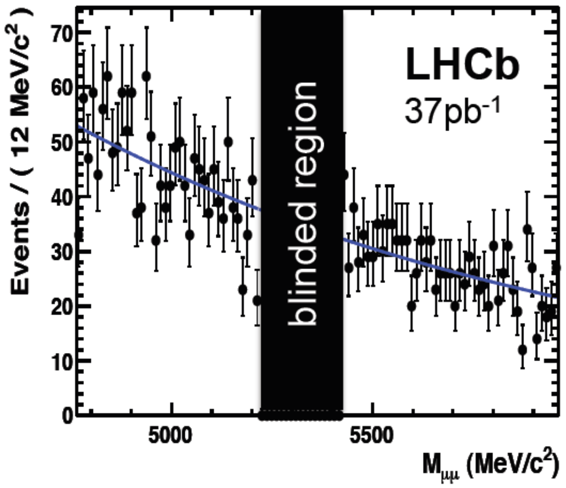
Regions compatible for different $B_s \to \mu^+\mu^-$ branching ratios

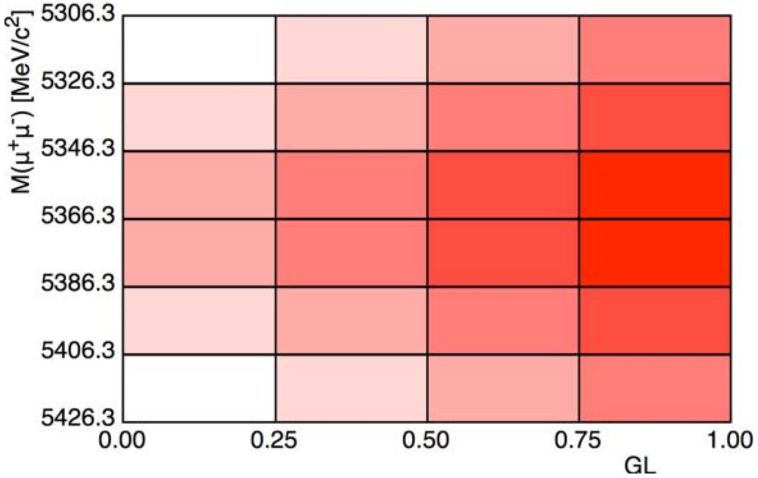
Calculation using SuperIso/SoftSUSY
[Comput. Phys. Comm. 143, 305 (2008)/180, 1718 (2009)]



Results for $B_s \to \mu^+\mu^-$: Analysis strategy

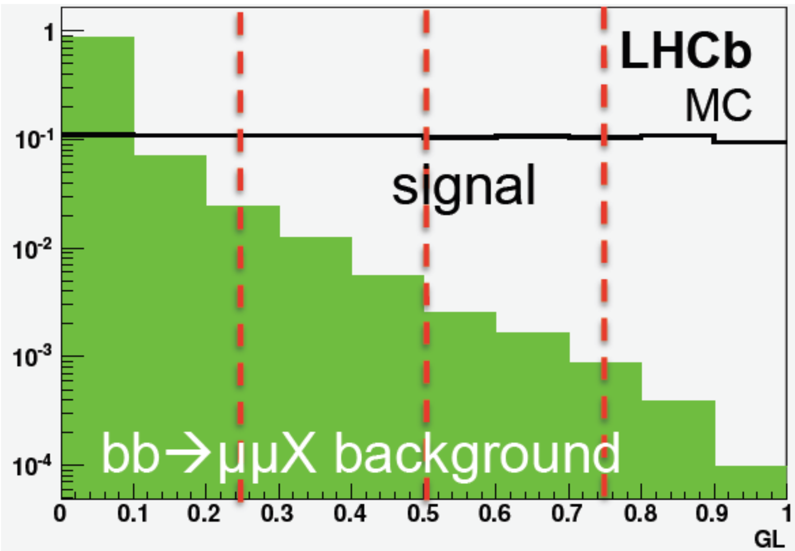
1. Reduce data set by soft selection and blind signal region of $m(B_{(s)}^0) \pm 60$ MeV/c^2
2. Discriminate signal and background by Geometrical Likelihood (GL) and Invariant Mass
3. Normalize to channels with known branching ratios to extract BR($B_s \to \mu^+\mu^-$)
4. Extraction of the limit with binned CL_s method in four equally distributed GL- and six equally distributed invariant mass bins

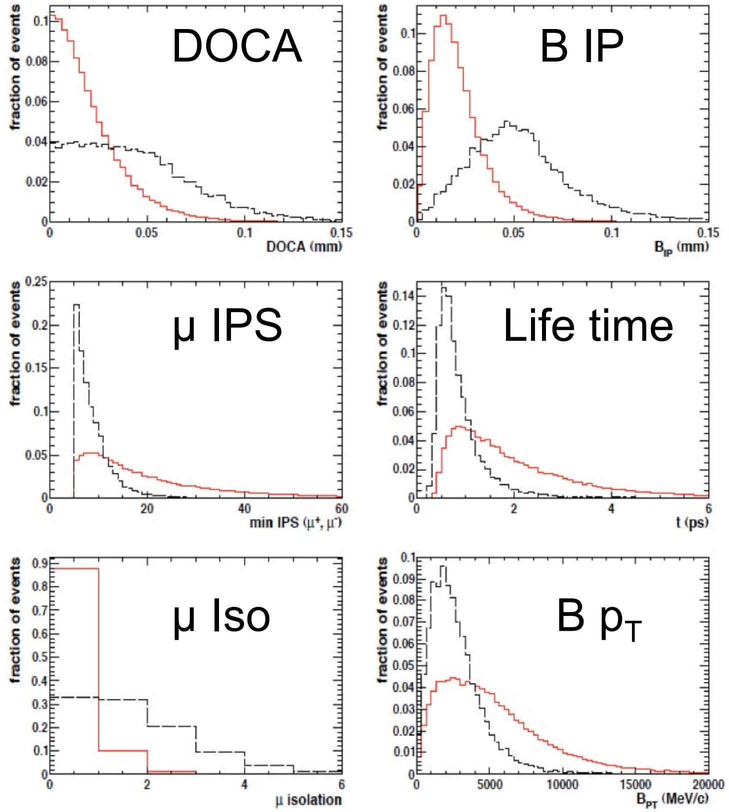




Results for $B_s \to \mu^+\mu^-$: Geometrical likelihood (I)

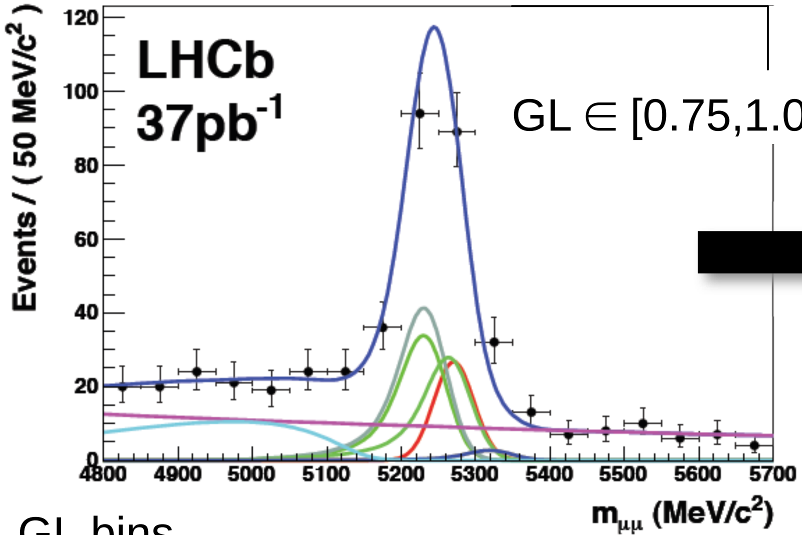
- Main background combinatorical from two muons $bb \to \mu\mu X$
- Select topological and kinematical variables to separate signal from **background**
- Decorrelate these variables and use them to build up a multi variate classifier: GL
- Train GL with Monte Carlo

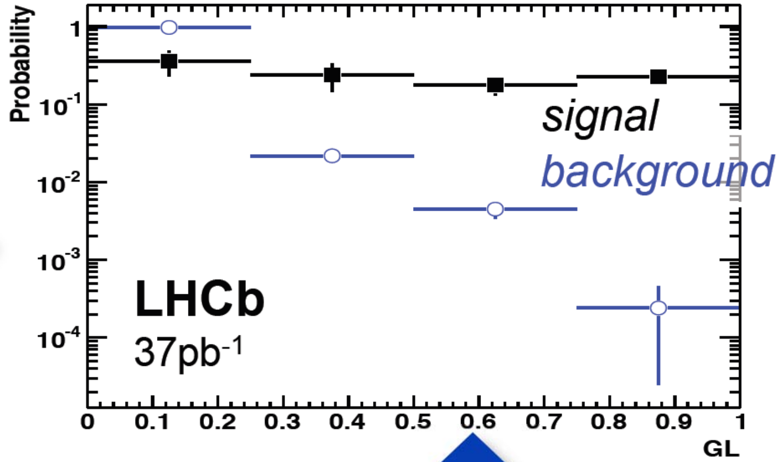




Results for $B_s \to \mu^+\mu^-$: Geometrical likelihood (II)

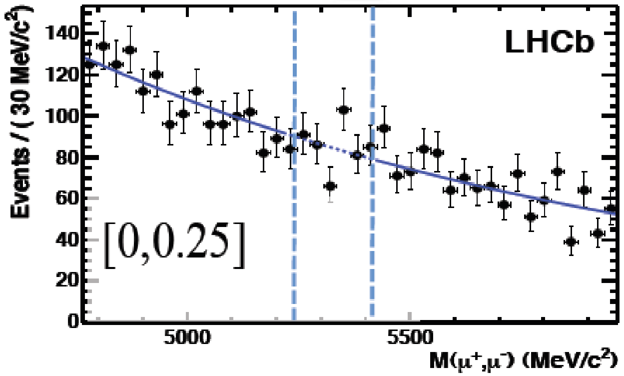
- Normalization for signal with data from $B \to KK/\pi\pi/K\pi$:





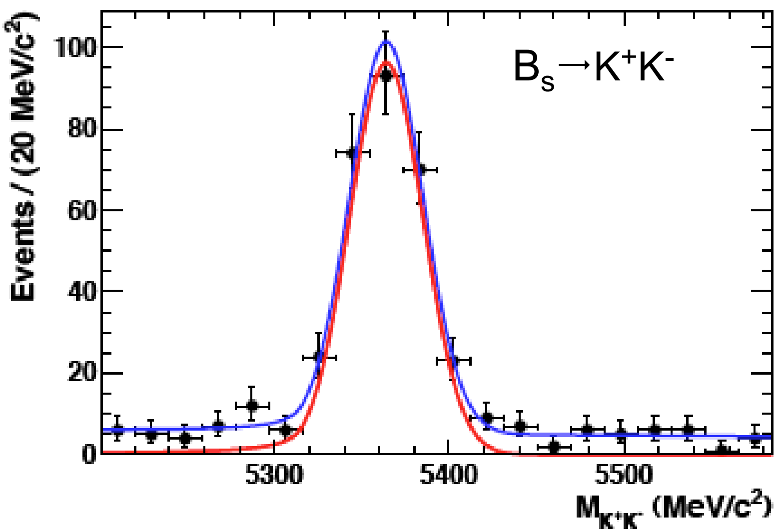
4 GL bins

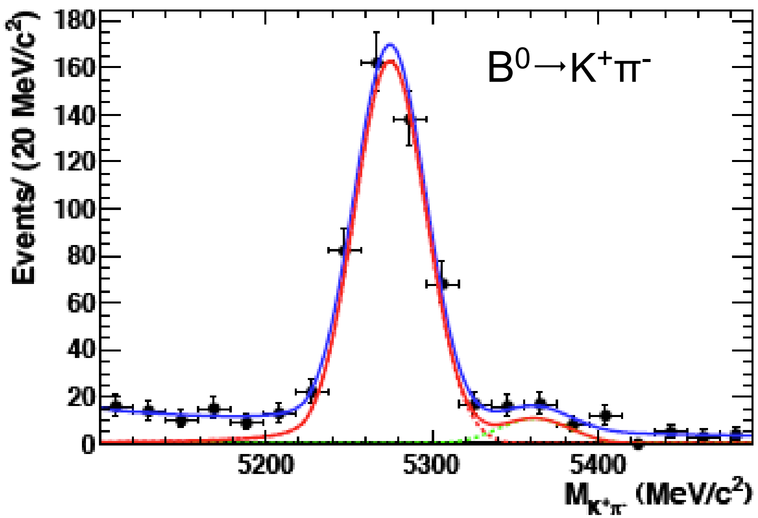
Simultaneous normalization of GL and invariant mass with side bands



Results for $B_s \to \mu^+\mu^-$: Invariant mass (I)

- Invariant mass distribution for signal described by Crystal Ball function (Gaussian with radiative tail)
  - ➔ transition point (α) and exponent (n) from Monte Carlo
  - ➔ mean (μ) and width (σ) of Gaussian from B→KK/ππ/Kπ and dimuon resonances

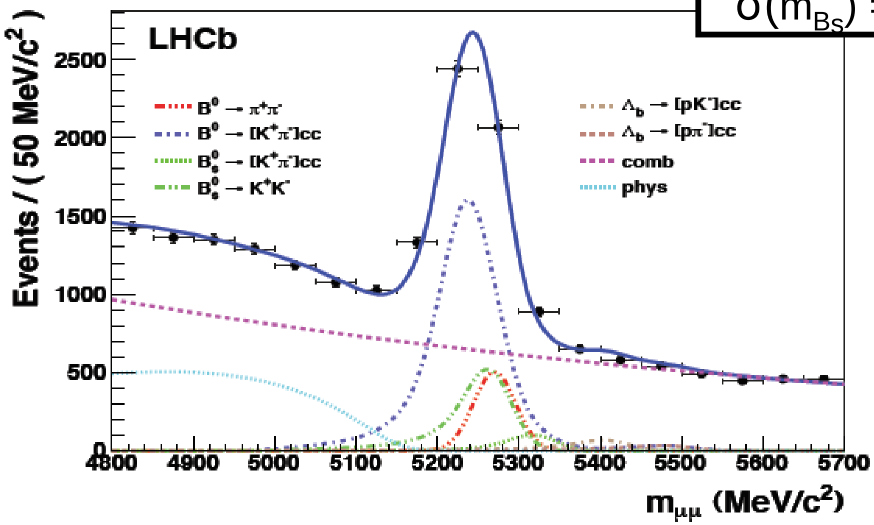




μ_{B0} = 5275.0±1.0 MeV/c^2
μ_{B_s} = 5363.1±1.5 MeV/c^2

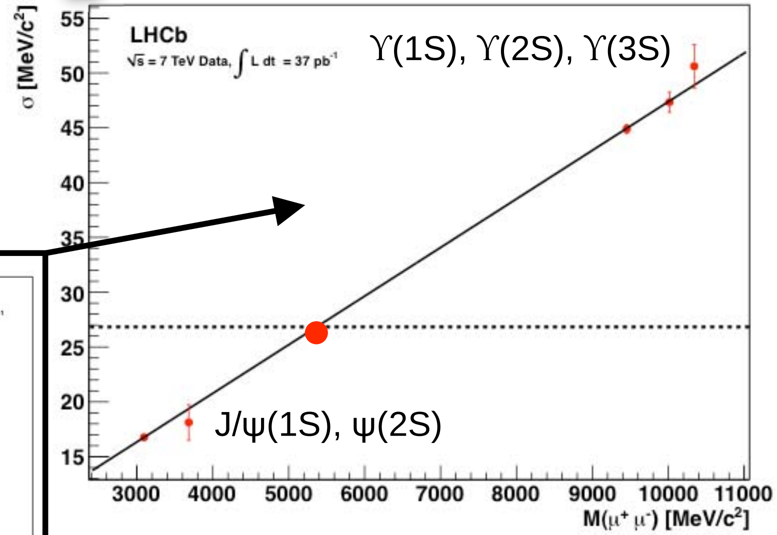
Results for $B_s \to \mu^+\mu^-$: Invariant mass (II)

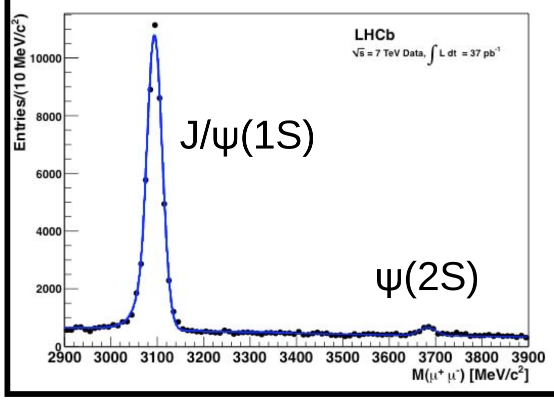
$\sigma(m_{Bs}) = 25.8 \pm 1.0_{stat} \pm 2.7_{syst} \mathrm{MeV}/c^2$

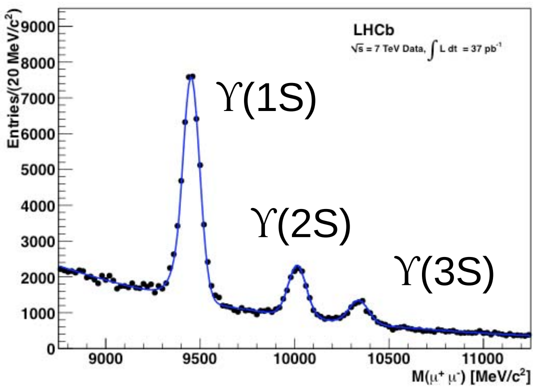


$\sigma(m_{Bs}) = 26.7 \pm 0.9 \mathrm{MeV}/c^2$

$\sigma(m_{Bs}) = 26.8 \pm 0.1_{stat} \pm 1.0_{syst} \mathrm{MeV}/c^2$







Results for $B_s \to \mu^+\mu^-$: Normalization

Normalization via:

$BR(B^+ \to J/\psi(\mu^+\mu^-)K^+)$ $= (5.98 \pm 0.22) \cdot 10^{-5}$

$BR(B^0 \to K^+\pi^-)$ $= (1.94 \pm 0.06) \cdot 10^{-5}$

$BR(B_s \to J/\psi(\mu^+\mu^-)\varphi(K^+K^-))$ $= (3.4 \pm 0.9) \cdot 10^{-5}$

$$\mathrm{BR}_{\mathrm{sig}} = \mathrm{BR}_{\mathrm{cal}} \cdot \frac{\varepsilon_{\mathrm{cal}}^{\mathrm{REC}} \varepsilon_{\mathrm{cal}}^{\mathrm{SEL|REC}}}{\varepsilon_{\mathrm{sig}}^{\mathrm{REC}} \varepsilon_{\mathrm{sig}}^{\mathrm{SEL|REC}}} \cdot \frac{\varepsilon_{\mathrm{cal}}^{\mathrm{TRIG|SEL}}}{\varepsilon_{\mathrm{sig}}^{\mathrm{TRIG|SEL}}} \cdot \frac{f_{\mathrm{cal}}}{f_s} \cdot \frac{N_{B_s \to \mu^+\mu^-}}{N_{\mathrm{cal}}} = \alpha \cdot N_{B_s \to \mu^+\mu^-}$$

$f_d/f_s = 3.71 \pm 0.47$ (HFAG; recent update, $f_u/f_d = 1$))

LHC*b* preliminary:

$f_d/f_s = 4.02 \pm 0.52$

from ratio $B^0 \to D^+\pi^-$ to $B_s \to D_s^+\pi^-$

$f_d/f_s = 3.84 \pm 0.34$

from semileptonic decays

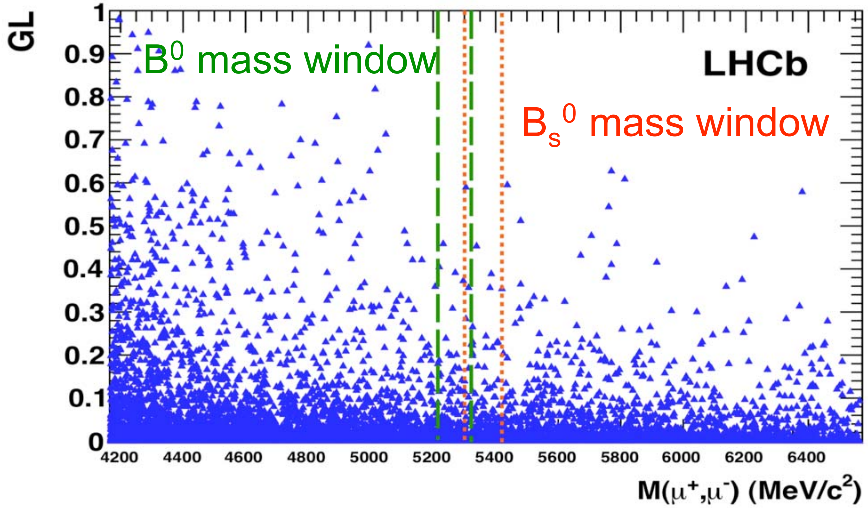
$\alpha =$ $(8.4 \pm 1.3) \cdot 10^{-9}$

$\alpha =$ $(7.3 \pm 1.8) \cdot 10^{-9}$

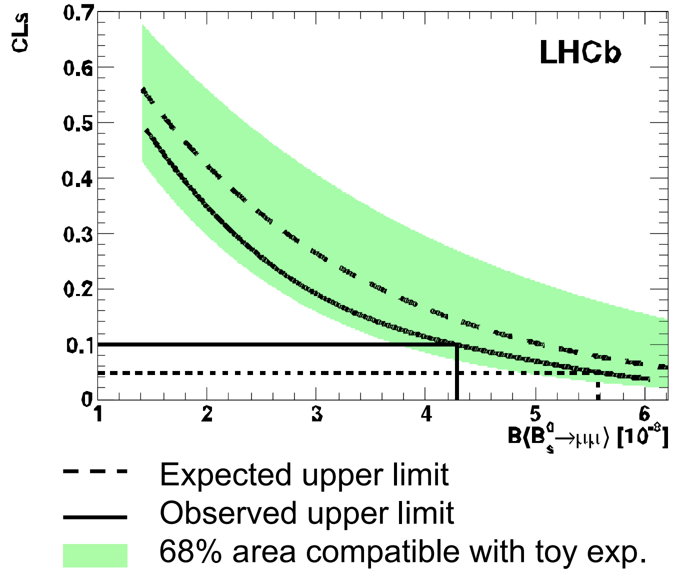
$\alpha = (10.5 \pm 2.9) \cdot 10^{-9}$

$B_s \to \mu^+\mu^-$: $\alpha =$ (8.6 ± 1.1) $\cdot 10^{-9}$

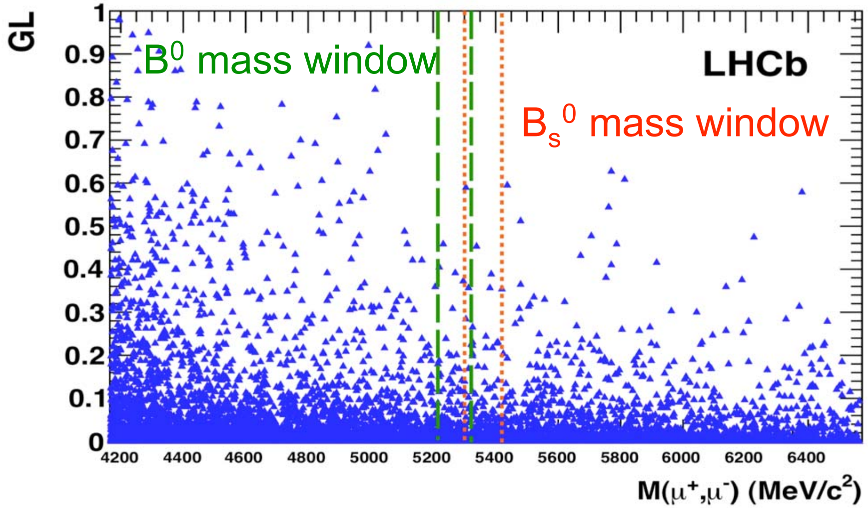
Limit for $B_s \to \mu^+\mu^-$



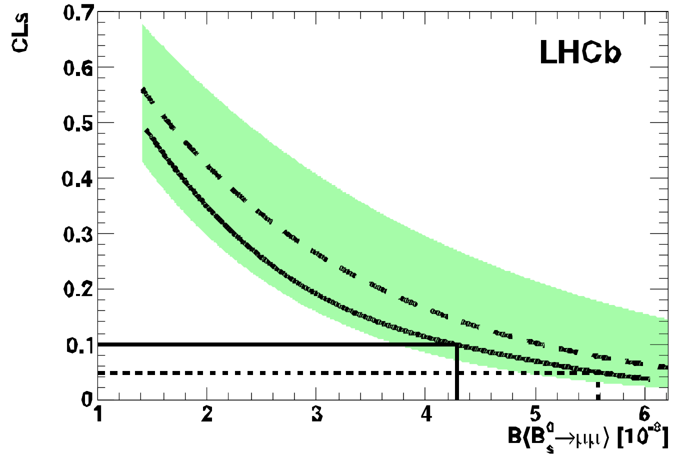
$M(\mu\mu)-M_{B_s}$ [MeV/c^2]	GL [0.00,0.25]	GL [0.25,0.50]	GL [0.50,0.75]	GL [0.75,1.00]
[-60,-40]	39	2	1	0
[-40,-20]	55	2	0	0
[-20,0]	73	0	0	0
[0,20]	60	0	0	0
[20,40]	53	2	0	0
[40,60]	55	1	0	0
Total	**335**	**7**	**1**	**0**
Total (Bkg exp)	329.1	7.4	1.53	0.080



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



$M(\mu\mu)-M_{B_s}$ [MeV/c²]	GL [0.00,0.25]	GL [0.25,0.50]	GL [0.50,0.75]	GL [0.75,1.00]
[-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**
Total (Bkg exp)	329.1	7.4	1.53	0.080



Expected upper limit
Observed upper limit
68% area compatible with toy exp.

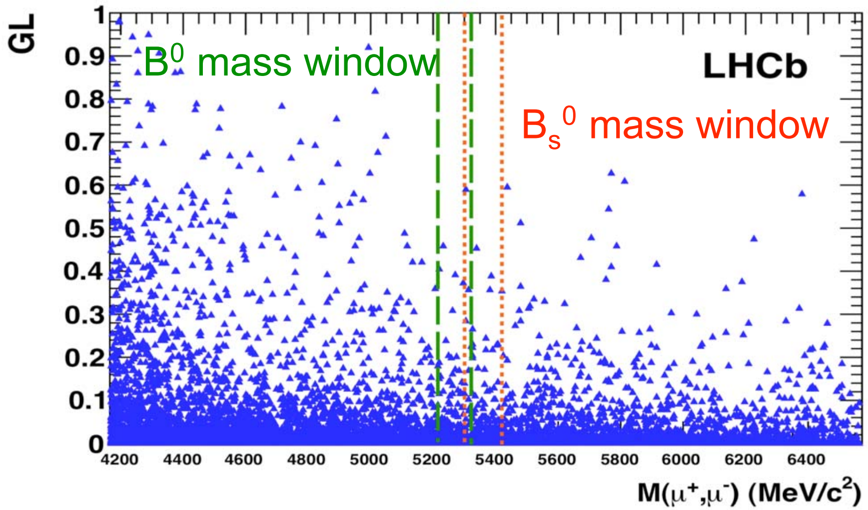
$BR(B_s \to \mu^+\mu^-) < 5.6 \cdot 10^{-8}$

@ 95% CL

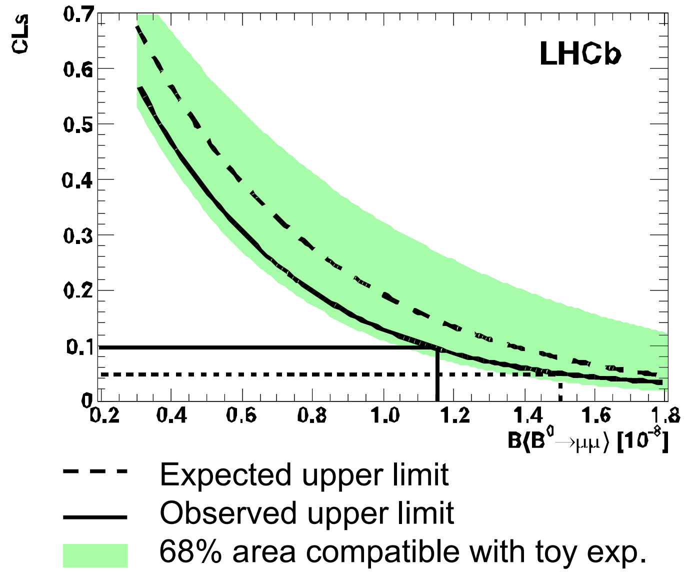
CDF: $4.3 \cdot 10^{-8}$ @ 95% CL with 3.7 fb^{-1}
[Public CDF note 9892]

DØ: $5.1 \cdot 10^{-8}$ @ 95% CL with 6.1 fb^{-1}
[Phys. Lett B 693, 593 (2010)]

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



M(μμ)-M_{B0} [MeV/c^2]	GL [0.00,0.25]	GL [0.25,0.50]	GL [0.50,0.75]	GL [0.75,1.00]
[-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**
Total (Bkg exp)	351.5	8.3	1.85	0.118



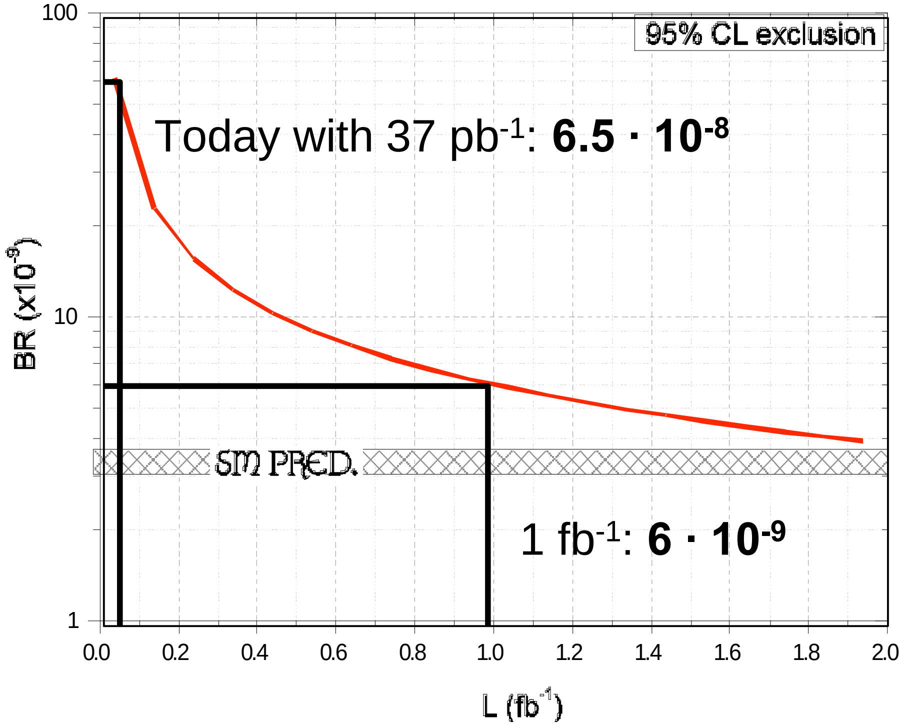
$BR(B^0 \to \mu^+\mu^-) < 1.5 \cdot 10^{-8}$

@ 95% CL

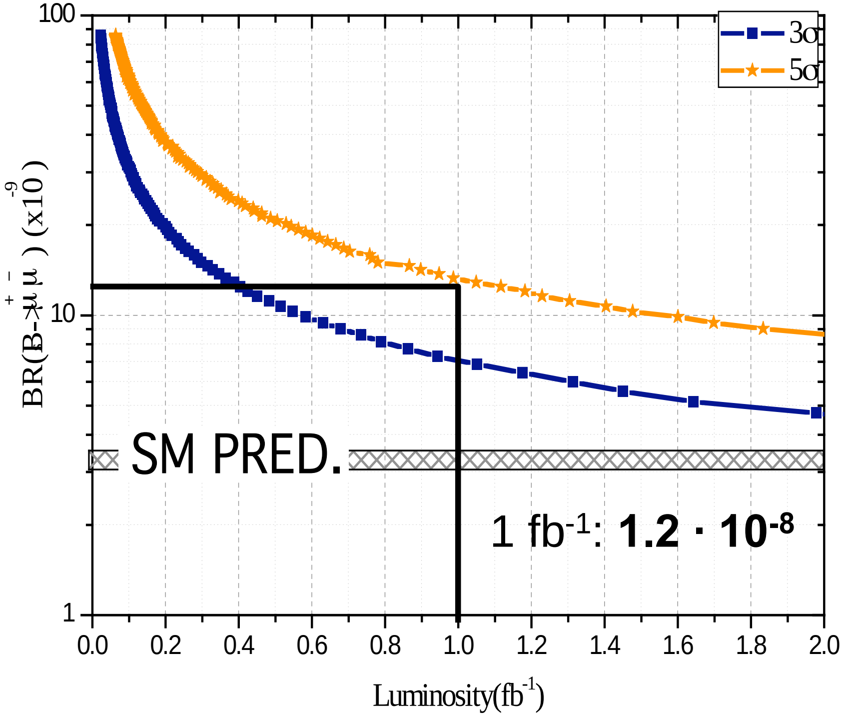
CDF: $0.76 \cdot 10^{-8}$ @ 95% CL with 3.7 fb^{-1}
[Public CDF note 9892]

Results for $B_s \to \mu^+\mu^-$: Prospects

95% exclusion



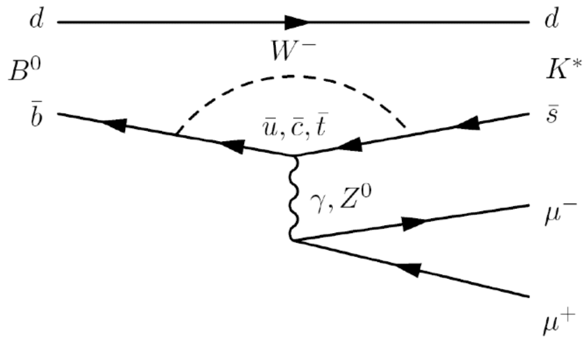
Discovery



Prospect for $B^0 \rightarrow K^* \mu^+ \mu^-$: Predictive Power (I)

- Decay is in the SM only allowed via FCNC.

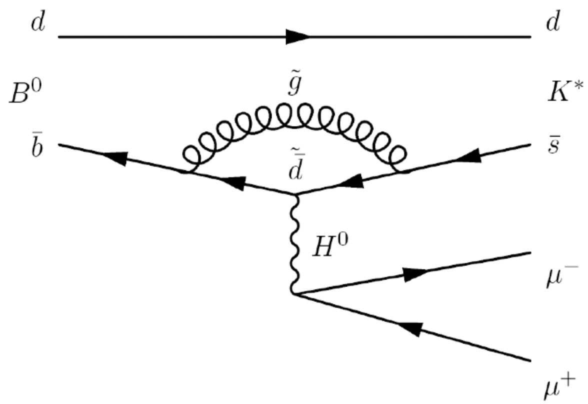
- $BR(B^0 \rightarrow K^* \mu^+ \mu^-) = (1.2 \pm 0.4) \cdot 10^{-6}$
  [Phys Rev D 69 (2004), 074020]



Measured $BR(B^0 \rightarrow K^* \mu^+ \mu^-)$: $(1.05^{+0.16}_{-0.13}) \cdot 10^{-6}$ [PDG]

- Sensitive to New Physics via angular observables

- Allows to constrain Wilson coefficients C_7, C_9, C_{10}

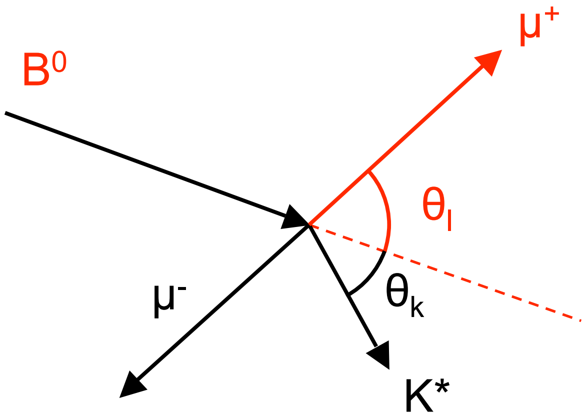


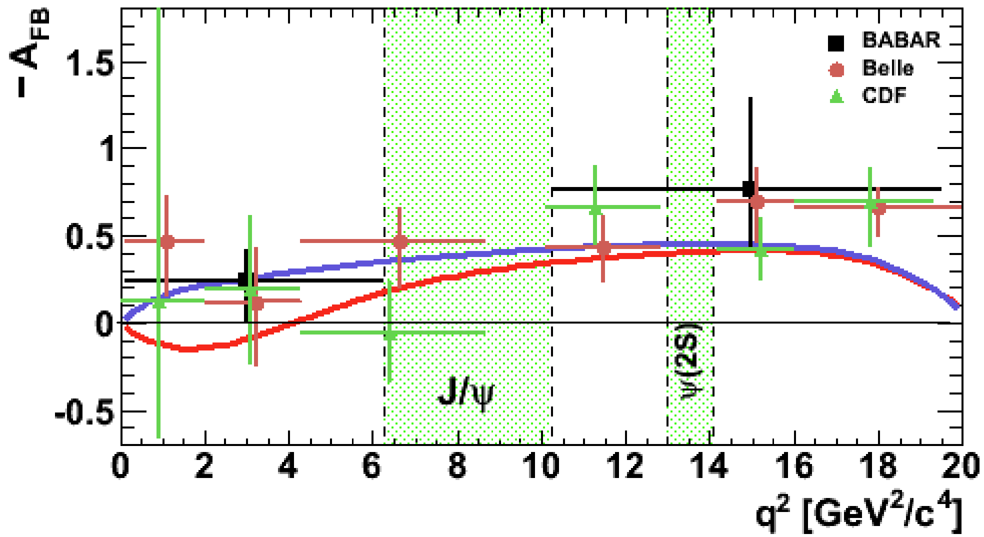
Prospect for $B^0 \rightarrow K^{*}\mu^{+}\mu^{-}$: Predictive Power (II)

Forward-backward asymmetry A_{FB}

$$A_{\mathrm{FB}}(q^2) = \frac{\left.\frac{\mathrm{d}N}{\mathrm{d}q^2}\right|_{\cos\theta_l>0} - \left.\frac{\mathrm{d}N}{\mathrm{d}q^2}\right|_{\cos\theta_l<0}}{\left.\frac{\mathrm{d}N}{\mathrm{d}q^2}\right|_{\cos\theta_l>0} + \left.\frac{\mathrm{d}N}{\mathrm{d}q^2}\right|_{\cos\theta_l<0}}$$

θ_l measured in dimuon rest-frame



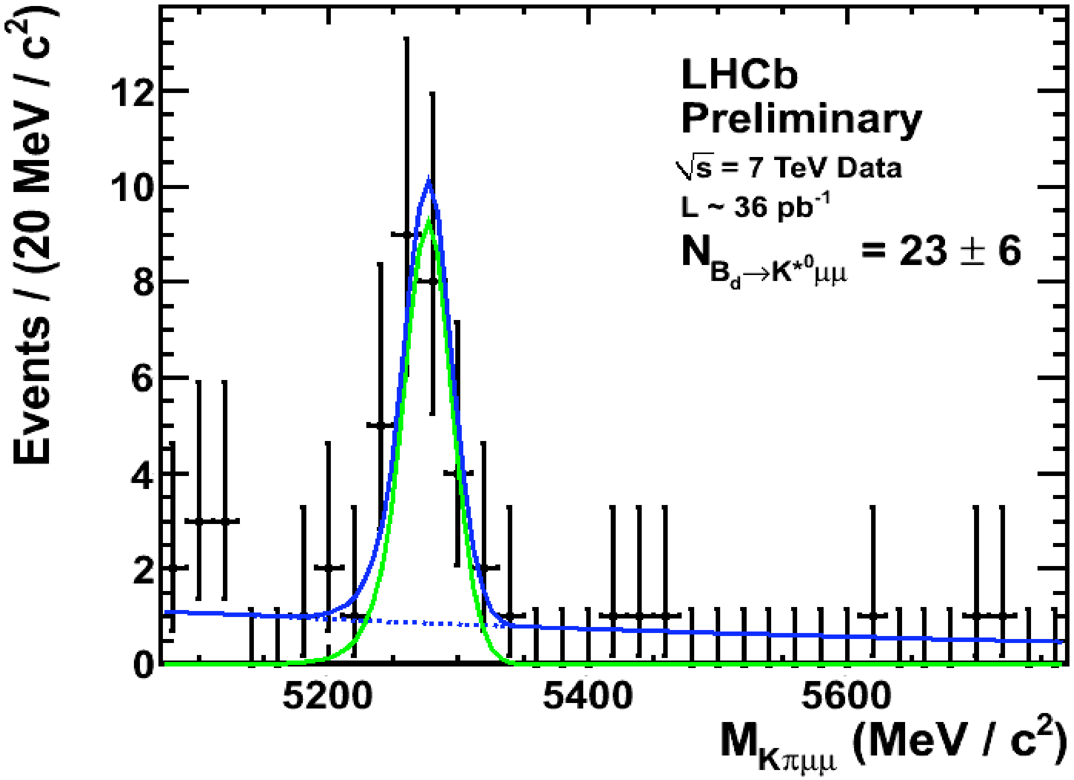


Zero crossing point (SM):

$s_0 = 4.36^{+0.33}_{-0.31}\ (\mathrm{GeV}/c^2)^2$ [Eur. Phys. J. C, 41, 2005, 173 - 188]

Prospect for $B^0 \to K^{*}\mu^{+}\mu^{-}$: Analysis strategy

- Blind A_{FB} of $B^0 \to K^{*}(K^{+}\pi^{-})\mu^{+}\mu^{-}$ and use control channels to calibrate selection
- BDT selection



Signal window:

[5230,5330] MeV/c^2

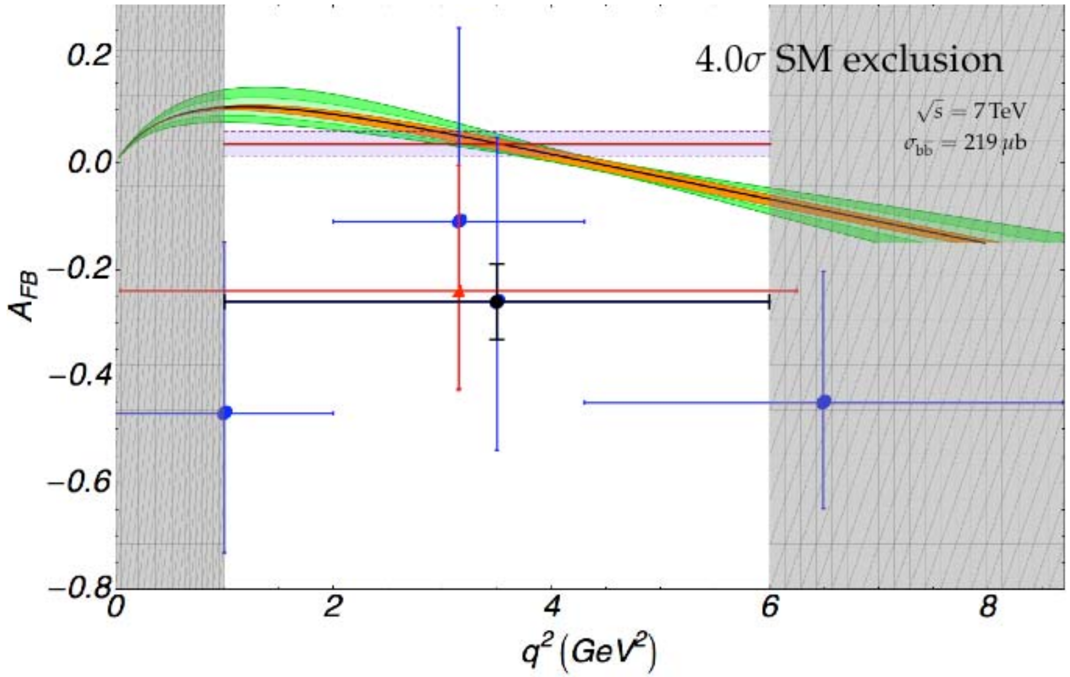
- Extraction of A_{FB} needs correction for trigger, selection and reconstruction efficiencies as well as acceptance
- $B^0 \to J/\psi(\mu^{+}\mu^{-})K^{*}$, $B^{+} \to J/\psi(\mu^{+}\mu^{-})K^{+}$ to check corrections for Monte Carlo
- Compare selected and generated Monte Carlo to get acceptance in phase space bins

Prospect for $B^0 \to K^* \mu^+ \mu^-$: Prospects

200 pb^{-1}: 127 ± 31 signal events

1 fb^{-1}: 635 ± 154 signal events

at B/S = 0.2±0.1



[BaBar:	60	at B/S = 0.3]
[Belle:	230	at B/S = 0.25]
CDF:	100	at B/S = 0.4

[BaBar: PRD79:031102, 2009
Belle: PRL103:171801, 2009
CDF: CDF note 10047]

4σ exclusion of SM assuming that LHC*b* sees with 1 fb^{-1} the same value at low q^2 than Belle

Red: BaBar, Blue: Belle, Black: LHC*b* (hypo.)

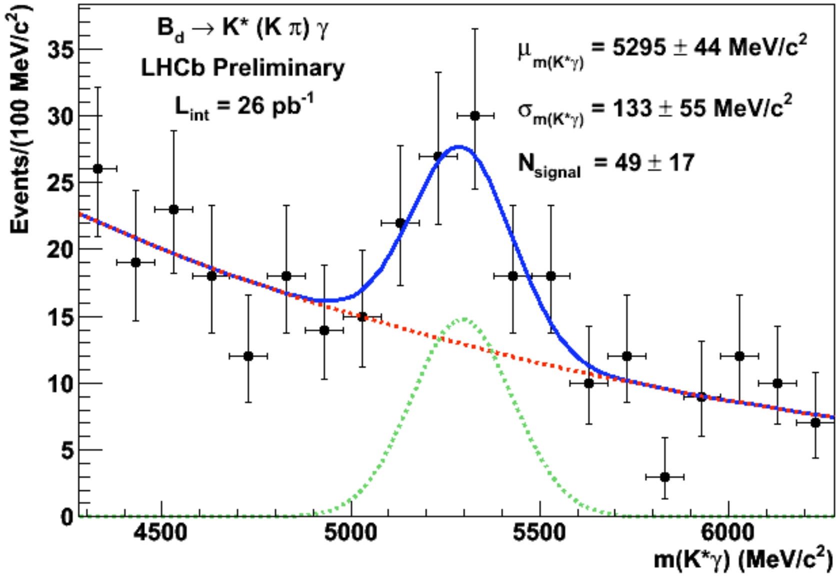
Prospect for radiative decays: $b \to s\gamma$

- Measurement of photon polarization as in SM right-handed is suppressed by $m_s/m_b \approx 10^{-2}$
- Probing via $B_s \to \varphi\gamma$ or $B^0 \to K^* e^+ e^-$
- Measurement of the time dependent *CP* asymmetries

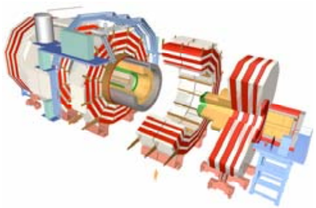
- Observation of $B^0 \to K^*\gamma$: Beacon for other radiative decays

  $B_s \to \varphi\gamma$ (BR ratio to $B^0 \to K^*\gamma$ ➔ NNLO QCD test)

  $B^0 \to \rho^0/\omega\ \gamma$ for $|V_{td}/V_{ts}|$ (with $B^0 \to K^*\gamma$)

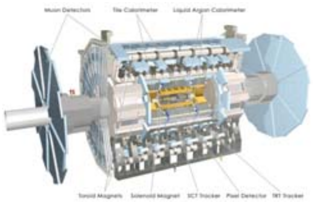


Rare B decays at CMS and ATLAS



- $B_s \to \mu^+\mu^-$: For 2010 not yet unblinded; Strategy: cut based (at the moment) with grid search ($p_T(\mu)$, $p_T(B_s)$, isolation and vertexing), relaying on Monte Carlo for signal calibrating with $B_s \to J/\psi\varphi$ (e.g. for invariant mass resolution), normalization via $B^+ \to J/\psi(\mu^+\mu^-)K^+$(later probably also $B_s \to J/\psi\varphi$); Systematics expected to be dominated by f_d/f_s
- Some work in progress on $B^0 \to K^*\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$ (and $D^0 \to \mu^+\mu^-$). Until 2011/12 no trigger problem for these channels expected

[CMS-PAS-BPH-07-001, PoS(HQL 2010)070]



- $B_s \to \mu^+\mu^-$: For 2010 not yet unblinded; Strategy: Similar to the one of CMS, cut based (isolation, pointing angle of dimuon momentum and connecting line PV-SV, transverse decay length), normalization via $B^+ \to J/\psi(\mu^+\mu^-)K^+$
- Consideration at ATLAS for for $B^0 \to K^*\mu^+\mu^-$, $B_s \to \varphi\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$ as well as $B^+ \to K^{+*}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$

[ATLAS-PHYS-PROC-2010-131]

Conclusion

LHC*b* has shown with its first 37 pb^{-1} a great potential for indirect search of New Physics.

The results for $B_{(s)}^0 \rightarrow \mu^+\mu^-$ of

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

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

are already close to the limits set up by the Tevatron experiments. With data collected in 2011 LHC*b* should be able to investigate the region of $BR(B_s \rightarrow \mu^+\mu^-) \sim 6\text{-}10 \cdot 10^{-9}$

First steps toward measurements of the angular structure of $B^0 \rightarrow K^*\mu^+\mu^-$ and toward measurements of $b \rightarrow s\gamma$

LHC*b* has in 2010 proven to be ready to make many interesting measurements in rare decay channels.

First results from CMS/ATLAS can be expected for 2011.

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LHC*b* has shown with its first 37 pb^{-1} a great potential for indirect search of New Physics.

The results for $B_{(s)}^0 \to \mu^+\mu^-$ of

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are already close to the limits set up by the Tevatron experiments. With data collected in 2011 LHC*b* should be able to investigate the region of $BR(B_s \to \mu^+\mu^-) \sim 6\text{-}10 \cdot 10^{-9}$

First steps toward measurements of the angular structure of $B^0 \to K^*\mu^+\mu^-$ and toward measurements of $b \to s\gamma$

LHC*b* has in 2010 proven to be ready to make many interesting measurements in rare decay channels.

First results from CMS/ATLAS can be expected for 2011.

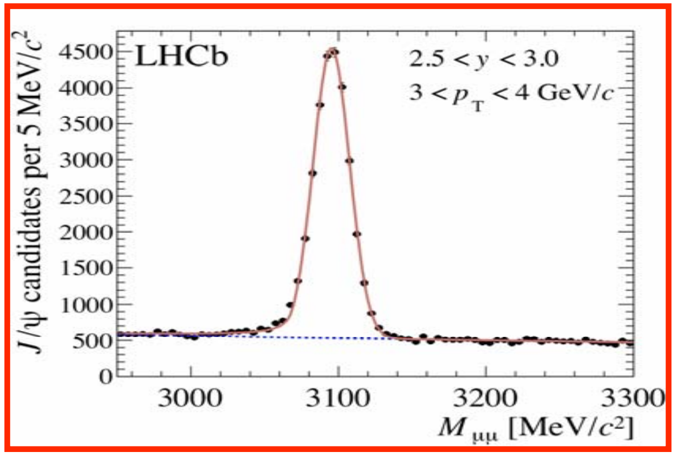
Stay tuned to future LHC(*b*) results

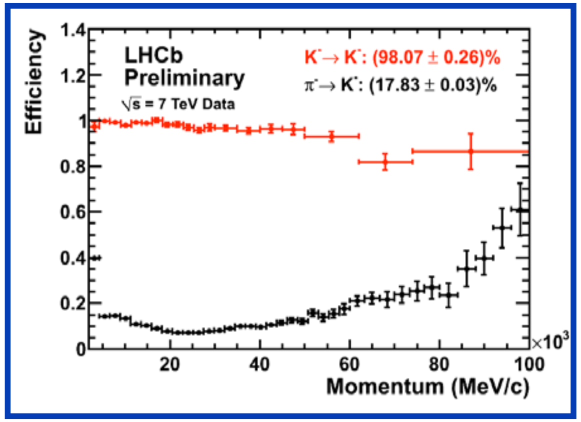
The end

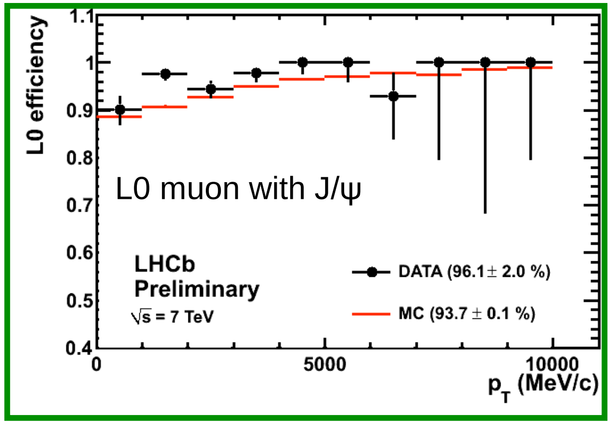
Backup: Detector performance

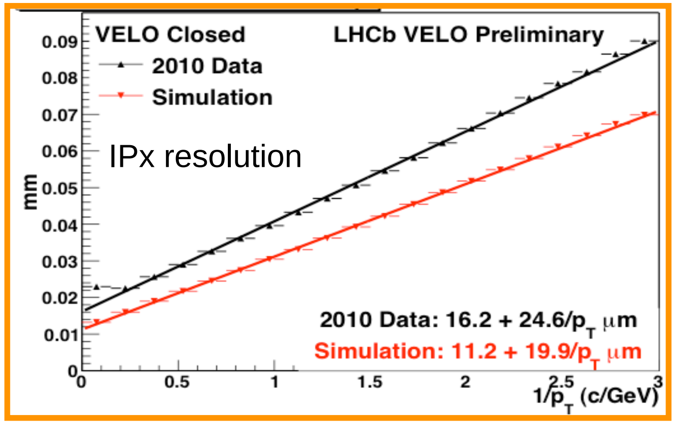
For searches after rare decays are necessary:

- a good invariant mass/momentum resolution
- a good vertex resolution
- an efficient trigger
- a good particle identification

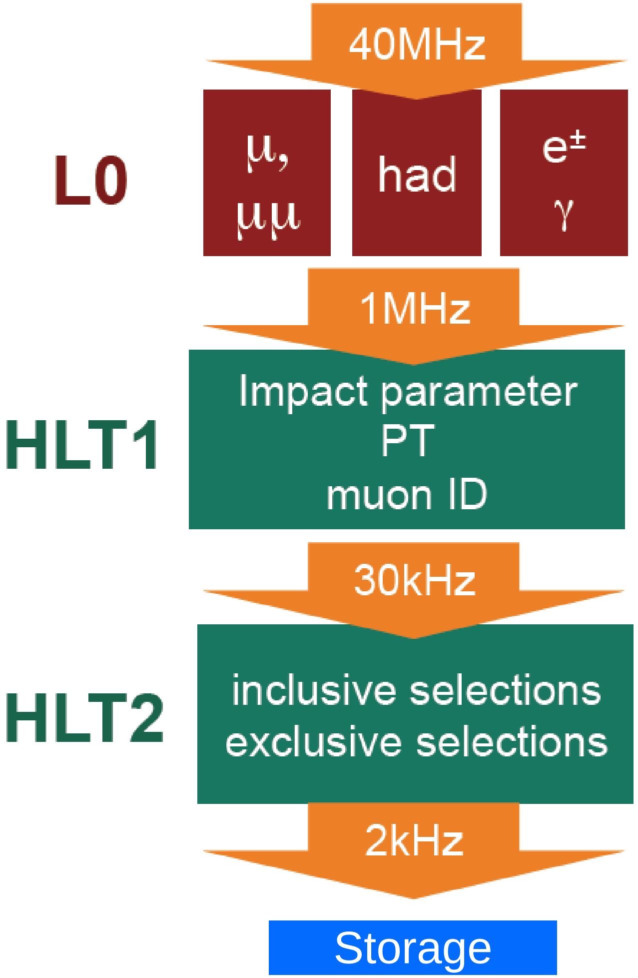








Backup: Trigger at LHC*b*



L0: Hardware, calorimeter and muon system information

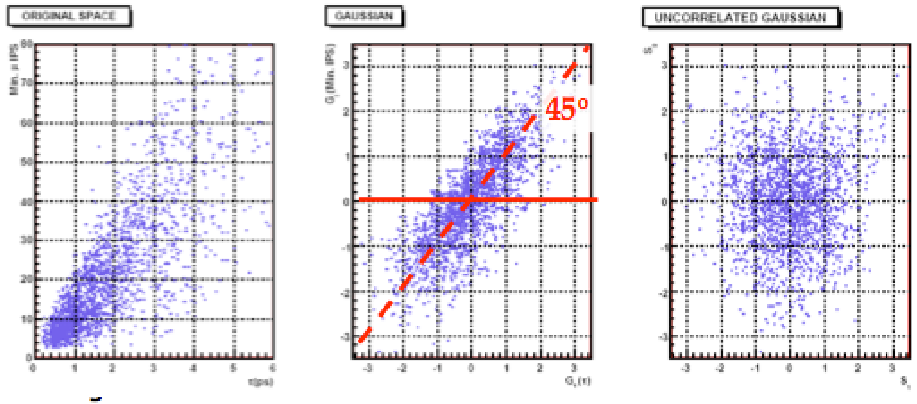
HLT1: Software, partial reconstruction based on one or two tracks with displacment in the vertex locator

HLT2: Software, global reconstruction

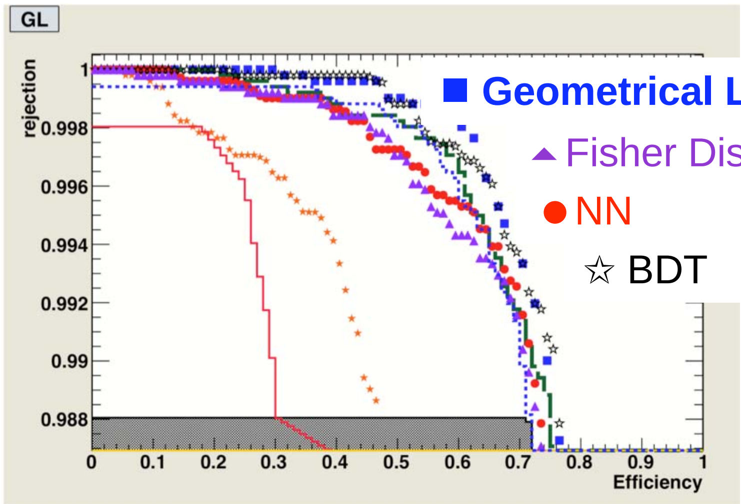
Backup: Geometrical likelihood

Handling of correlations among the topological and kinematical variables

1. Transformation to Gaussian by cumulative, inverse error function
2. Application of inverse correlation matrix (rotation in parameter space)



Efficiency/rejection plot



Backup: Normalization uncertainties

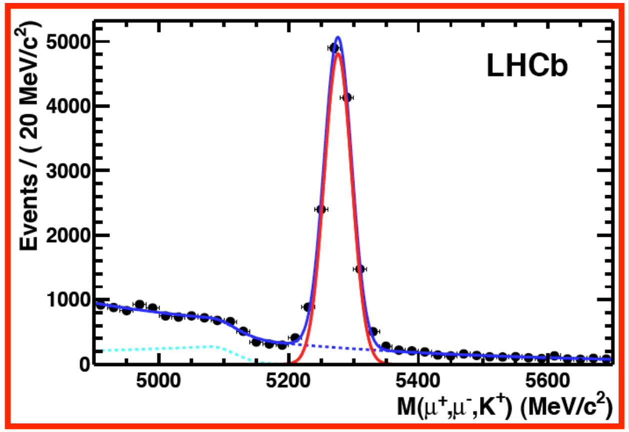
Channel	BR ($\cdot 10^{-5}$)	$\frac{\varepsilon^{REC}_{cal}\varepsilon^{SEL\|REC}_{cal}}{\varepsilon^{REC}_{sig}\varepsilon^{SEL\|REC}_{sig}}$	$\frac{\varepsilon^{TRIG\|SEL}_{cal}}{\varepsilon^{TRIG\|SEL}_{sig}}$	N_{norm}	$\alpha_{B_s\to\mu^+\mu^-}$ ($\cdot 10^{-9}$)	$\alpha_{B0\to\mu^+\mu^-}$ ($\cdot 10^{-9}$)
$B^+\to J/\psi(\mu^+\mu^-)K^+$	5.98±0.22	0.49±0.22	0.96 ±0.05	12'366±403	8.4±1.3	2.27±0.18
$B^0\to K^+\pi^-$	1.94±0.06	0.82±0.06	0.072±0.010	578± 74	7.3±1.8	1.99±0.40
$B_s\to J/\psi(\mu^+\mu^-)\varphi(K^+K^-)$	3.4 ±0.9	0.25±0.02	0.96 ±0.05	760± 71	10.5±2.9	2.83±0.86

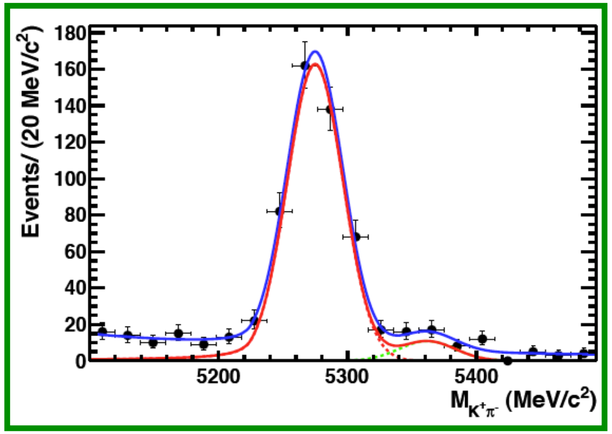
Systematic uncertainties

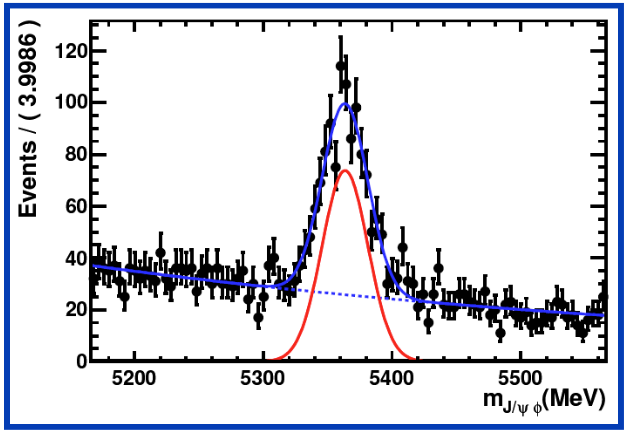
$B^+\to J/\psi(\mu^+\mu^-)K^+$	15%	dominated by f_u/f_s (13%)
$B^0\to K^+\pi^-$	23%	dominated by f_d/f_s (13%)
$B_s\to J/\psi(\mu^+\mu^-)\varphi(K^+K^-)$	28%	dominated by error on BR (26%)

Backup: Normalization channels

- $B^+ \to J/\psi(\mu^+\mu^-)K^+$: similar trigger, different reconstruction (3 tracks), f_u/f_s
- $B^0 \to K^+\pi^-$: different trigger, similar reconstruction (2 tracks), f_d/f_s
- $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$: similar trigger, different reconstruction (4 tracks)







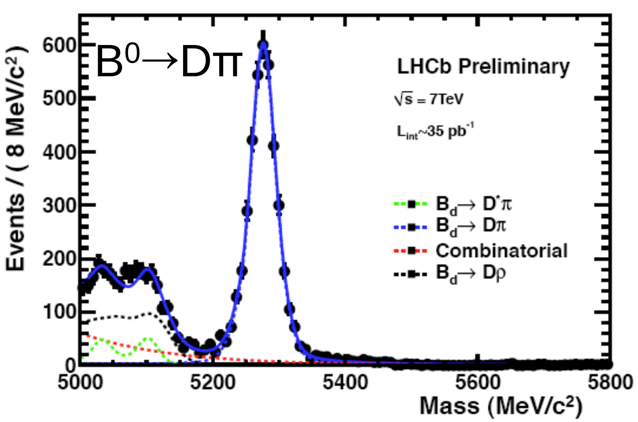
Backup: f_d/f_s at LHC*b*

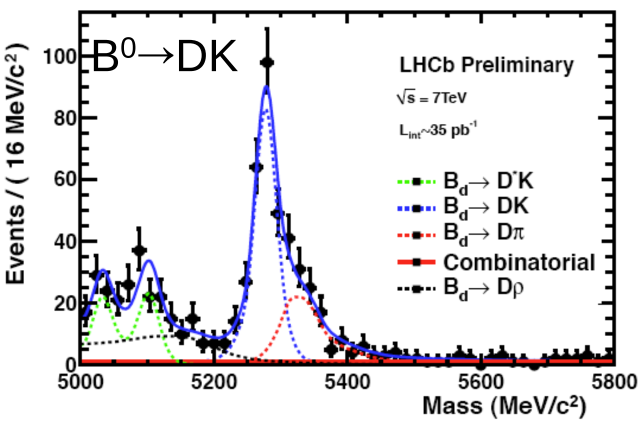
Preliminary results for f_s/f_d from LHC*b* [Moriond 2011 QCD, LHCb-CONF-2011-013]

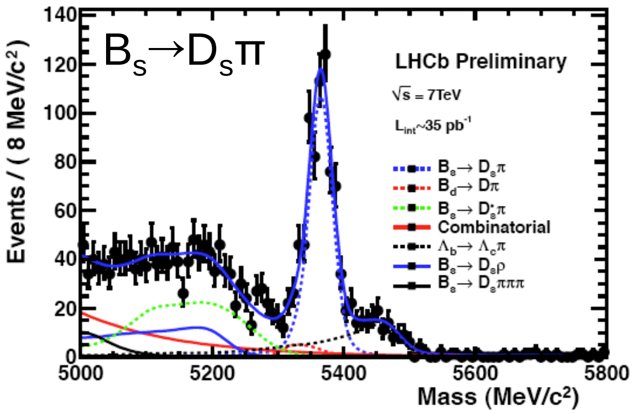
Using ratio of yields of $B_s \rightarrow D_s\pi$ to $B^0 \rightarrow D\pi$ and $B^0 \rightarrow DK$

$f_s/f_d = 0.242 \pm 0.024_{stat} \pm 0.018_{syst} \pm 0.016_{theo}$ with $B^0 \rightarrow DK$

$f_s/f_d = 0.249 \pm 0.013_{stat} \pm 0.020_{syst} \pm 0.022_{theo}$ with $B^0 \rightarrow D\pi$







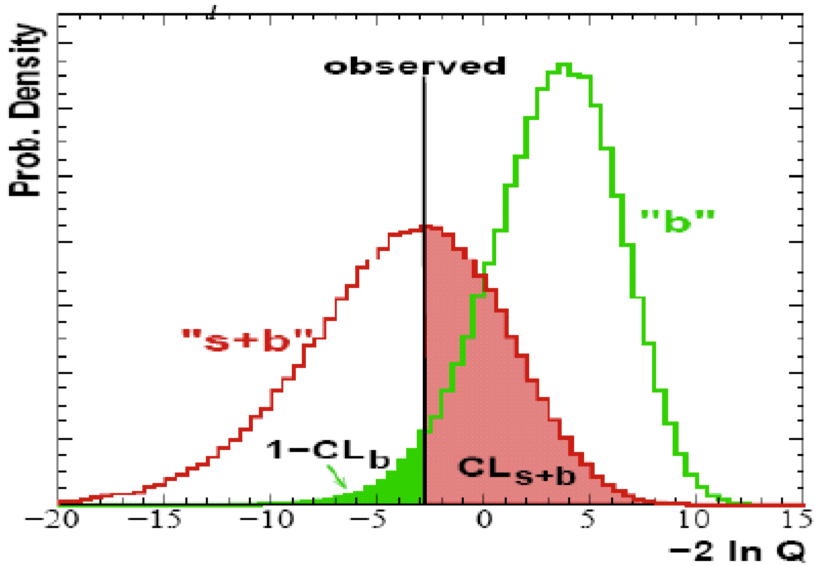
Backup: Binned CL$_s$ method

Modified frequentist approach

b_i = exp. number of background events

s_i = exp. number of signal events

d_i = observed number of events



$$CL_{s+b} = P(X \le X_{\mathrm{obs}}|s+b)$$
$$CL_b = P(X \le X_{\mathrm{obs}}|b)$$

$$CL_s = CL_{s+b}/CL_b$$

$$X = \prod_{i=1}^{n} \frac{P_{\mathrm{pois}}(d_i|\mathrm{E}(d_i) = b_i + s_i)}{P_{\mathrm{pois}}(d_i|\mathrm{E}(d_i) = b_i)}$$

Backup: Why are we already so close to Tevatron?

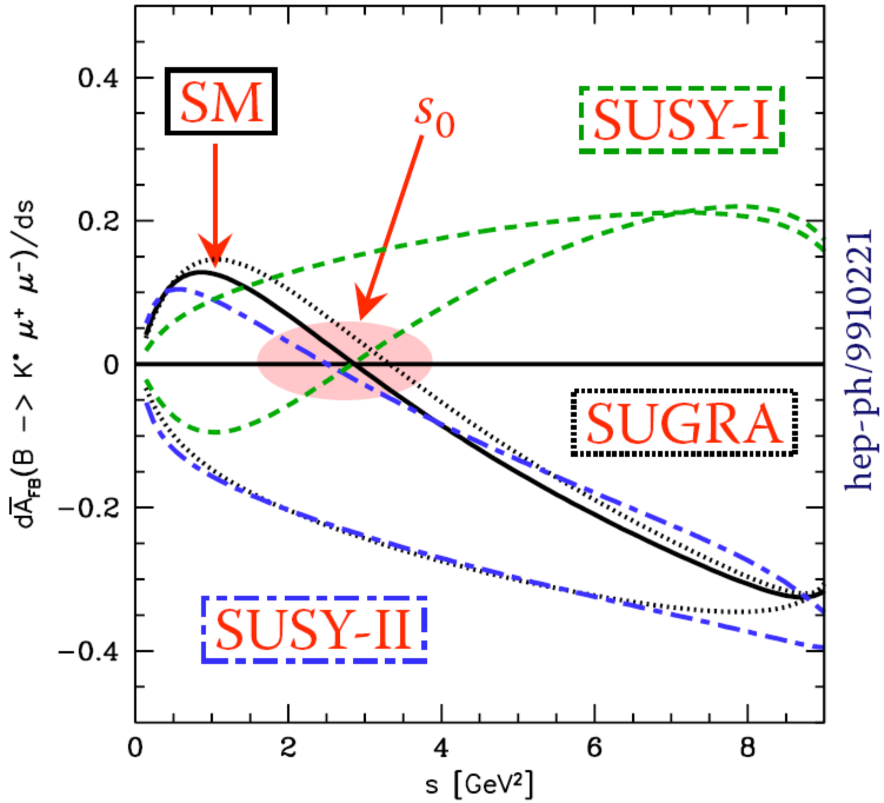
Although LHC*b* has collected 100 times less data than CDF, the result for $B_s \to \mu^+\mu^-$ is already compatible.

The reasons are:

- Combined acceptance and trigger efficiency is 10 times higher.
- $\sigma(pp \to bbX)$ is 3 times higher at 7 TeV compared to 1.96 TeV
- B mesons fly at LHC*b* approx. 1 cm ➔ handeling of trigger and background gets easier

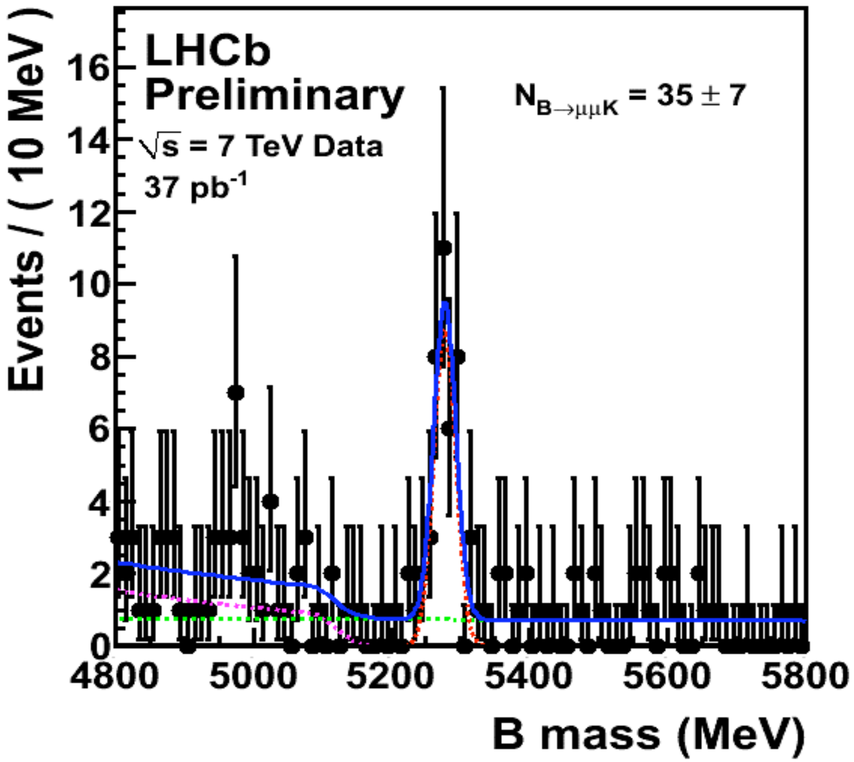
Backup: Theoretical models and $B^0 \to K^* \mu^+ \mu^-$

- Different NP models predict some shifts in s_0.
- or an absence of s_0 if there is a sign change in the C_7 coefficient of the effective Hamiltonian



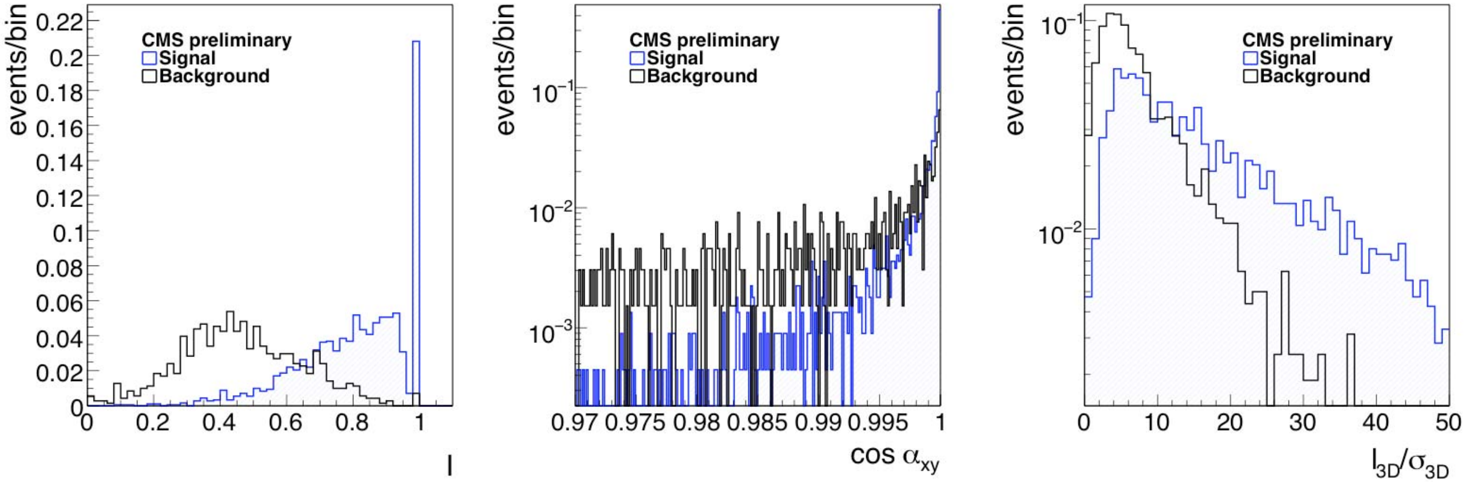
Backup: $B^+ \to K^+\mu^+\mu^-$

- Decay $B^+ \to K^+\mu^+\mu^-$ as reference for $B^0 \to K^*\mu^+\mu^-$ with no A_{FB} expected
- Rarest decay seen so far at LHC*b* (BR ≈ $5 \cdot 10^{-7}$)
- Interesting as SM prediction $BR(B^0 \to K^*e^+e^-)/ BR(B^0 \to K^*\mu^+\mu^-) = 1$



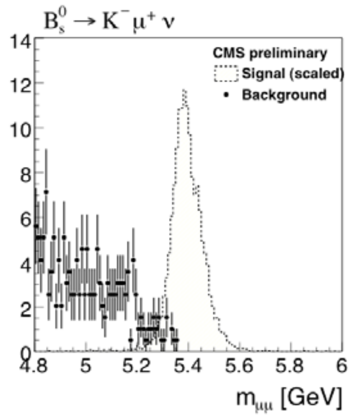
Backup: More about CMS …

Discriminating variables for $B_s \to \mu^+\mu^-$ (Isolation, pointing angle, flight length significance [l.t.r.]) from Monte Carlo



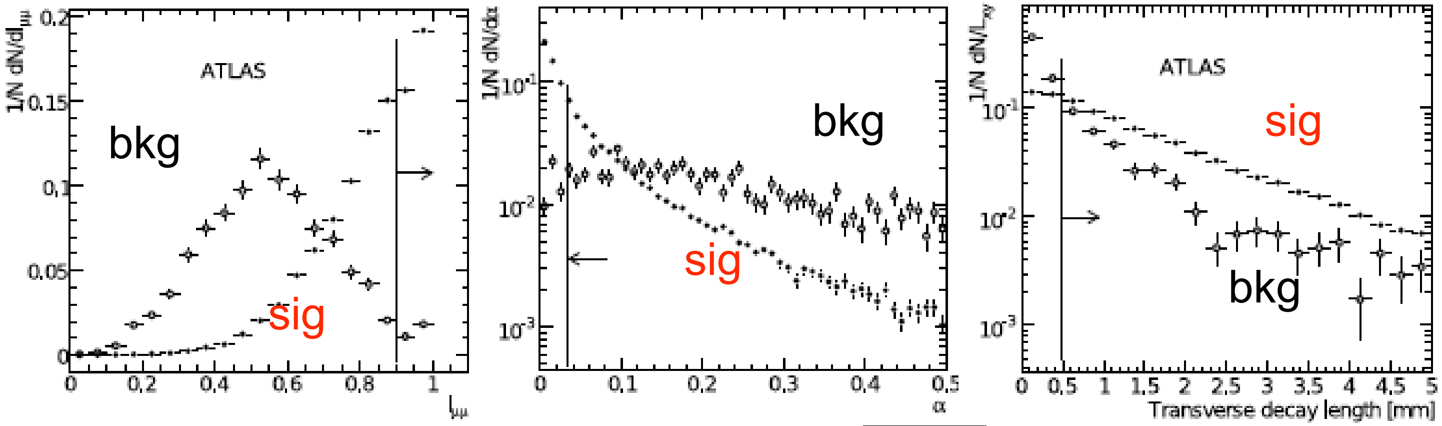
Signal efficiency: 0.023

Background reduction: $7.82 \cdot 10^{-9}$

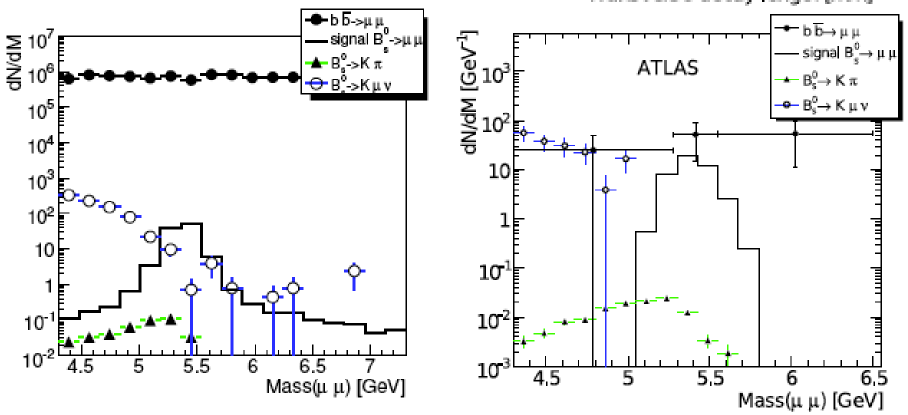


Backup: … and about ATLAS

Discriminating variables for $B_s \to \mu^+\mu^-$ (Isolation, pointing angle, Decay length [l.t.r.]) from Monte Carlo



Dimuon invariant mass spectrum before (left) and after (right) selection



Expect 5.7 signal and 14 background events for 10 fb^{-1}