# $B_s^0 \to \mu^+\mu^-$ at LHC

*CKM 2010 Warwick University*

*Nicola Serra*
*on behalf the LHCb/ATLAS/CMS collaborations*

# Menu':

- Introduction
- Signal Selection
- Normalization of the BR($B_s^0 \rightarrow \mu^+\mu^-$) and measurement of fd/fs at LHCb
- Studies with first data
- Conclusions

# Motivation

The CKM paradigm has been (until now) quite successful in describing all FCNC processes ($K^0$ mixing, $B^0$ mixing, CP violation in $B^0$,…).

$$A(decay) = \sum_i C_i O_i (V^i{}_{CKM})(\eta^i{}_{QCD})$$

NP can be classified in the following categories:

- ) MFV : In general new operators but CKM matrix describes the flavor structure
- ) Beyond MFV : In general new sources of CP are present

The Effective Hamiltonian for the ***BR($B_s \rightarrow \mu\mu$)*** can be written as:

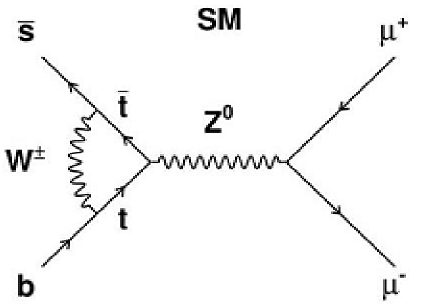
$$H = -2\sqrt{2} G_F \, |V_{tb}{}^* V_{tq}| \, (C_S O_S + C_P O_P + C_{10} O_{10})$$

***The factors $C_P$ and $C_S$ are negligible in the SM.***

This decay is very rare since it is not only FCNC but also helicity suppressed!

# SM and NP contribution

SM diagram for the $B_s^0 \rightarrow \mu^+\mu^-$ *decay.*




*SM predictions :*

$BR(\boldsymbol{B_s^0} \rightarrow \mu^+\mu^-) = (3.35 \pm 0.32)\cdot 10^{-9}$

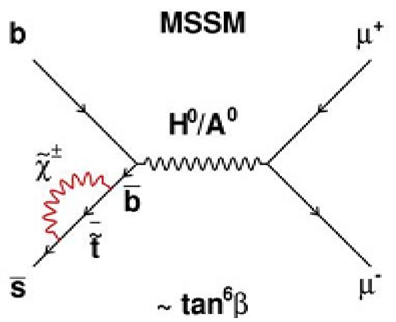
$BR(\boldsymbol{B_d^0} \rightarrow \mu^+\mu^-) = (1.03 \pm 0.09)\cdot 10^{-10}$

*A. Buras* ***arXiv:0910.1032v1***

***EPS-HEP2009 2009:024,2009***

They are *FCNC* and also *helicity* suppressed.

New scalar operators would allow to lift the helicity suppression enhancing the BR($\boldsymbol{B_{s,d}^0 \rightarrow \mu^+\mu^-}$)




In all MSSM the BR grows with ***tan⁶(β)*** ***,***

therefore very sensitive to models with high ***tan(β) :***

$$BR(B_s^0 \rightarrow \mu^+\mu^-) \propto \frac{\tan^6 \beta}{(M_A)^4}$$

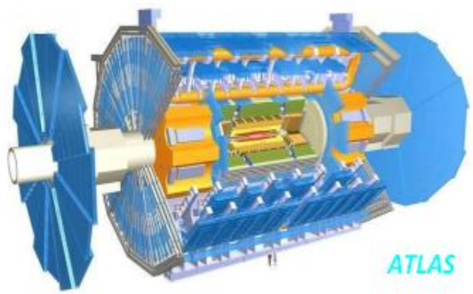
*Present limits:*

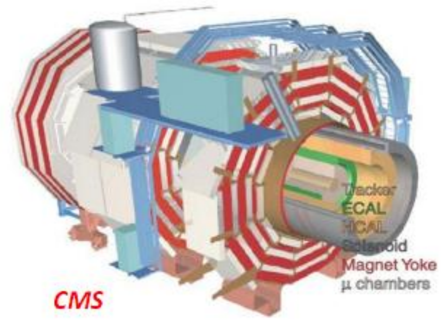
$BR(\boldsymbol{B_s^0} \rightarrow \mu^+\mu^-) < 4.3\cdot 10^{-8}$ , $BR(\boldsymbol{B_d^0} \rightarrow \mu^+\mu^-) < 7.9\cdot 10^{-9}$ *@95%CL*

***(CDF Public Note 9892)***

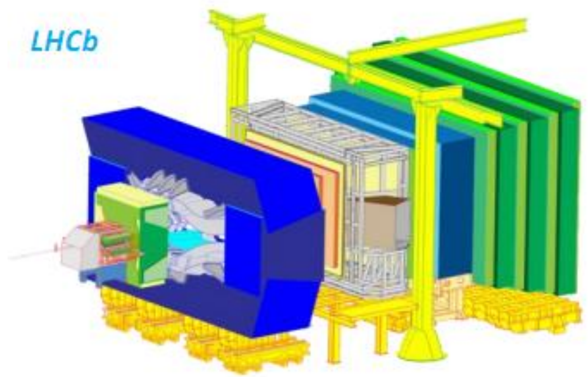
$BR(\boldsymbol{B_s^0} \rightarrow \mu^+\mu^-) < 5.1\cdot 10^{-8}$ *@95%CL* ***(D0 Coll.* arXiv:1006.3469v1*)***

# LHC experiments

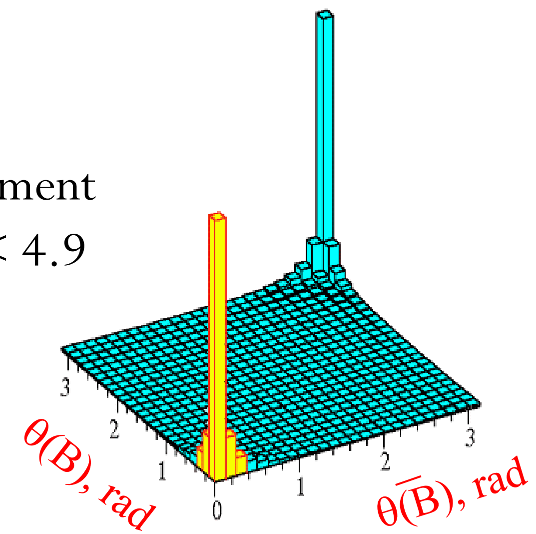



- General purpose experiment
- Central detactors $|\eta|<2.5$
- Hight Pt muon triggers




- B-physics dedicated experiment
- Forward detector $1.9<\eta<4.9$
- Low Pt muon triggers



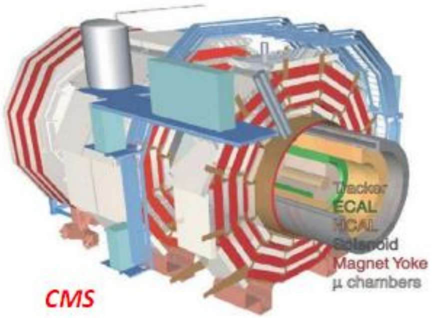

$b\bar{b}$ pairs are produced correlated and predominan tly forward and backward

# Sources of background

- For all the three experiments the main sources of backgrounds are:
  - b-bbar $\rightarrow \mu\mu$ combinatoric background due to muons coming from b-hadrons (BR($b \rightarrow \mu X$)≈10% )
  - B$\rightarrow$hh with double misidentification: (e.g. BR($B_d \rightarrow K\pi$ ) , BR($B_d \rightarrow \pi\,\pi$) , BR($B_s \rightarrow KK$ ) )
  - B$\rightarrow$J/ψ (μμ)h with h "misidentified" as a muon: (e.g. BR($B \rightarrow J/\psi\mu\nu$) ≈$5 \cdot 10^{-5}$ , BR($B_u \rightarrow J/\psi K^+$) ≈$10^{-3}$)

*Negligible for LHCb* (applies to the last two items)

# CMS /ATLAS selection




Muons :

$$p_{\perp}^{\mu} > 4GeV, |\eta| < 2.4$$

Bs - mesons :

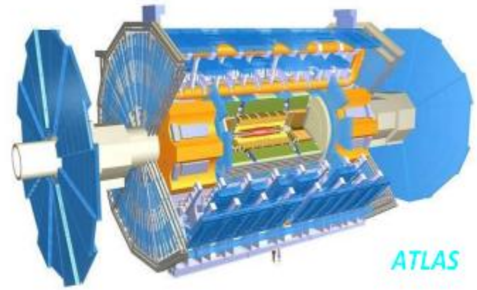
$$p_{\perp}^{B_s} > 5GeV, \alpha_{\text{pointing}} > 3.1 \text{ degrees}$$

Flight distance significance $\dfrac{L_{3D}}{\sigma_{3D}} > 17.0$

Global Event Cuts :

$$Iso = \frac{P_{\perp}^{B_s}}{P_{\perp}^{B_s} + \sum_i p_{\perp}^{i}(\Delta R < 1)} > 0.850$$

***ATLAS Coll. CERN-OPEN-2008-020***




Muons :

$$p_{\perp}^{\mu} > 6GeV, |\eta| < 2.5$$

Bs - mesons :

$$p_{\perp}^{B_s} > 5GeV, \alpha_{\text{pointing}} > 1.9 \text{ degrees}$$

Transverse flight distance $L_{XY} > 0.5mm$

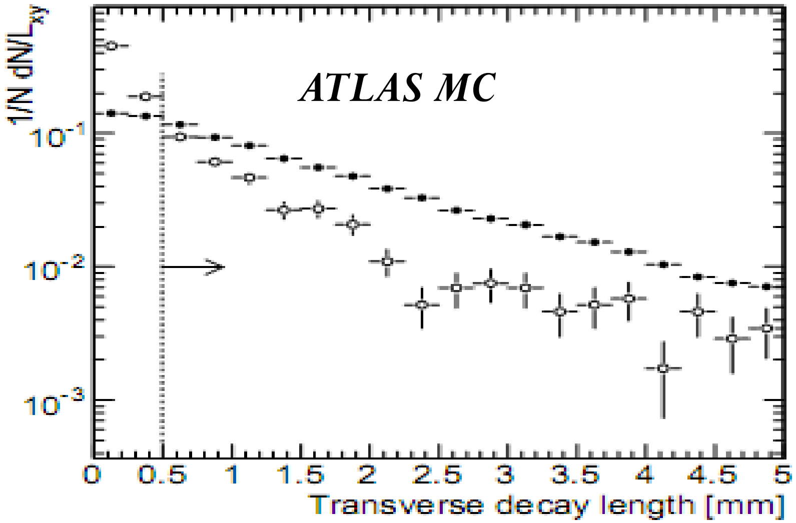
Global Event Cuts :

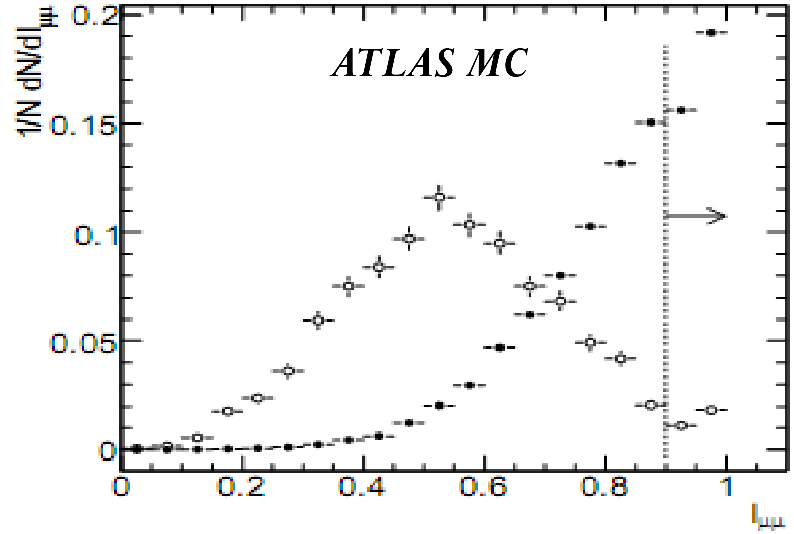
$$Iso = \frac{P_{\perp}^{B_s}}{P_{\perp}^{B_s} + \sum_i p_{\perp}^{i}(\Delta R < 1)} > 0.9$$

***CMS Coll. CMS PAS BPH-07-001***

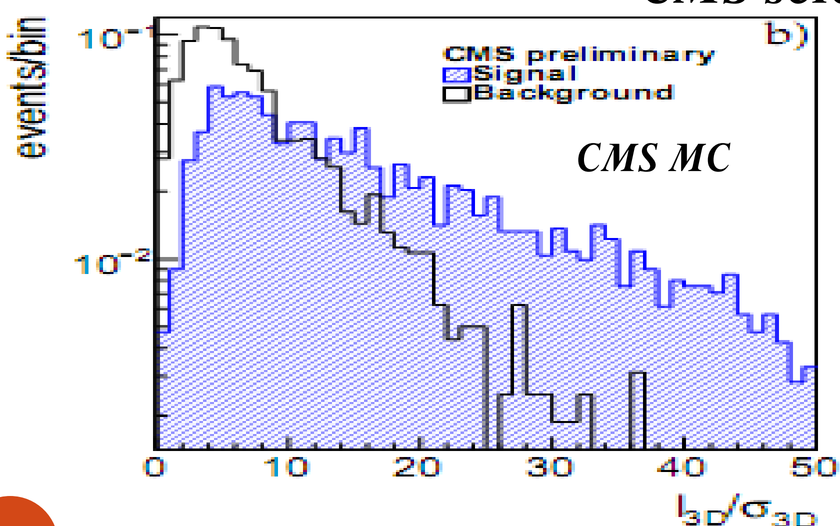
# Selection variables

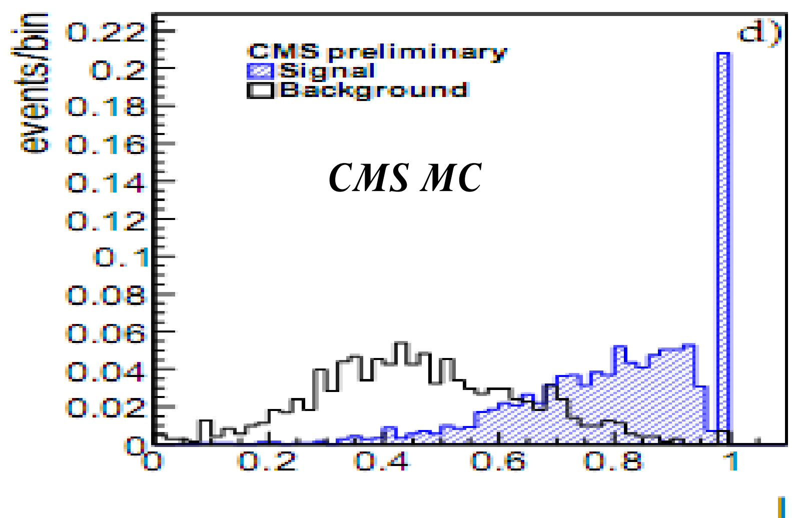
## *ATLAS selection variables*




## *CMS selection variables*



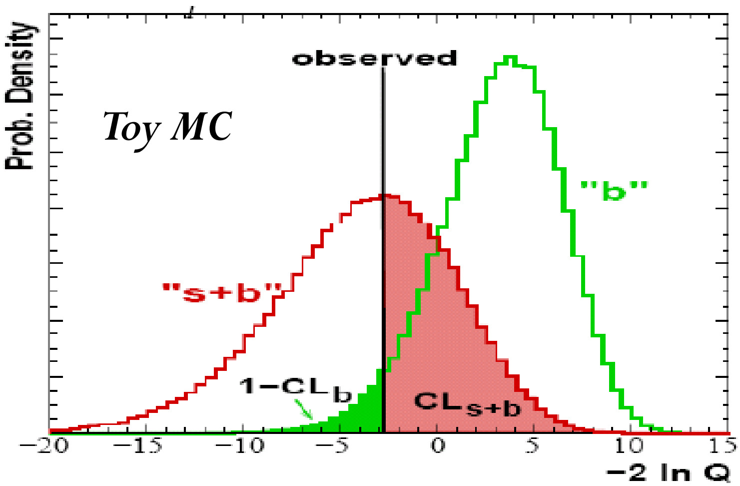



# LHCb analysis strategy

- Low Pt di-muon trigger allows for a loose pre-selection, as common as possible with the control channels:

  $B^+ \to J/\psi\ K^+,\ B \to J/\psi\ K^*,\ B_{s,d} \to h^+h^-,\ B_s \to J/\psi\ \varphi$

- "Binned likelihood fit" (MFA) in a 3D space:
  - Geometrical likelihood
  - Invariant mass likelihood
  - Muon identification likelihood




- The 3D space is divided into bins:

$s_i$ = exp. signal events in bin$_i$

$b_i$ = exp. bkg events in bin$_i$

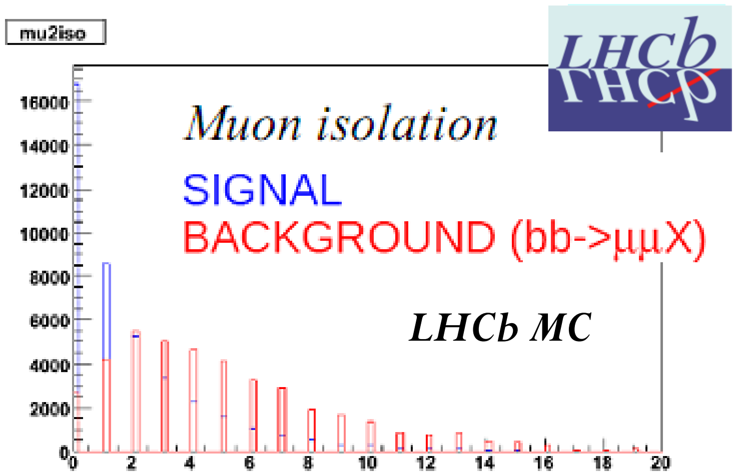
$d_i$ = measured events in bin$_i$

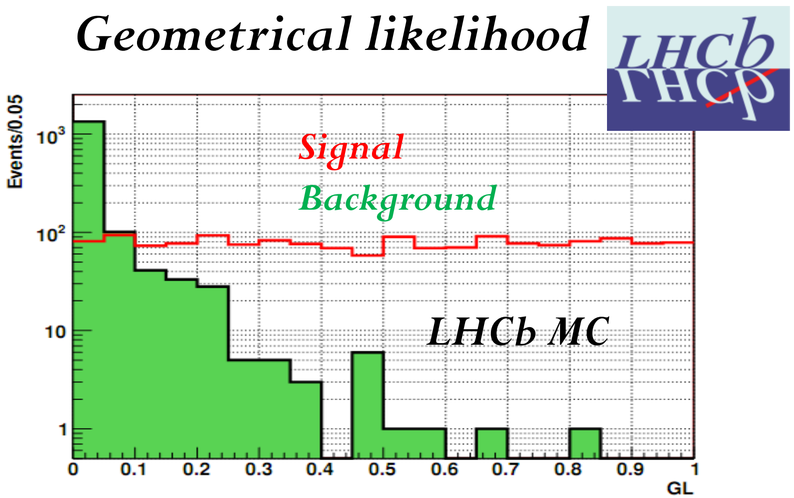
$$\Delta Q^2 = -2\ln\left(\frac{\prod_{i=1}^{n} P_i(d_i, <d_i> = b_i + s_i)}{\prod_{i=1}^{n} P_i(d_i, <d_i> = b_i)}\right)$$

# LHCb selection variables

*Selection Variables:*
*DOCA, Bs-lifetime, Bs IP, muon IP, Isolation*

*The definition of isolation used in ATLAS/CMS is not suitable for LHCb (forward exp).*
*In LHCb iso = number of tracks that make a good vertex with the one of the muons .*



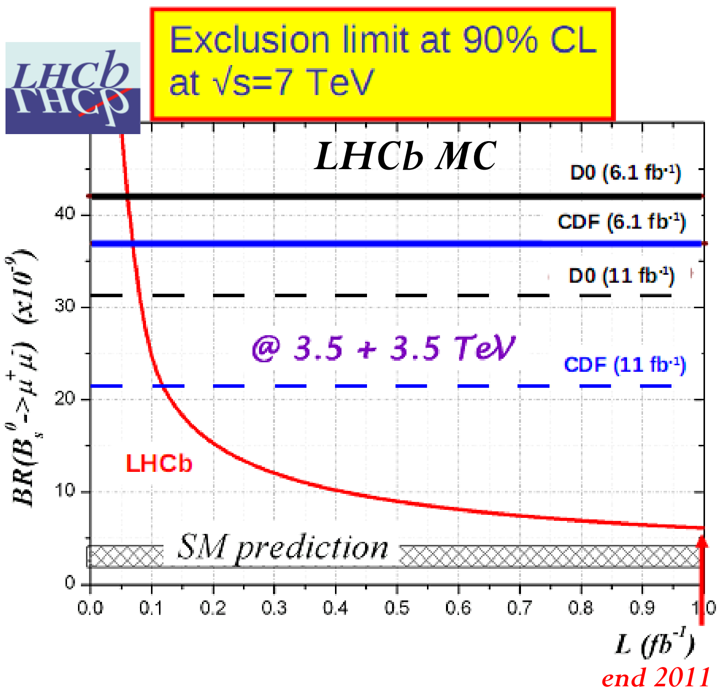




- *The input variables are transformed to Gaussian (cumulative and inverse error function)*
- *De-correlate with a linear rotation*

*LHCb Coll. arXiv:0912.4179v2*

# MonteCarlo expectations

| Experiment | Nsg | Nbg | Upper Limit 90%CL |
|---|---|---|---|
| ATLAS ( 10 $fb^{-1}$ 14TeV) | 5.6 events | $14^{+13}_{-10}$ events (only bb→μμ) | ----------- |
| CMS ( 1$fb^{-1}$ 7TeV ) | 1.4 | 4.0 (1.25 only bb→μμ ) | $15.8 \cdot 10^{-9}$ *private calculation* |
| LHCb ( 1$fb^{-1}$ 7TeV ) | 6.3 (in the most significant region) | 32.4 (in the most significant region) | $7 \cdot 10^{-9}$ |




The limit in the table are compute for σ(bbar)=292ub and using the Modified Frequentist Approach (no syst).

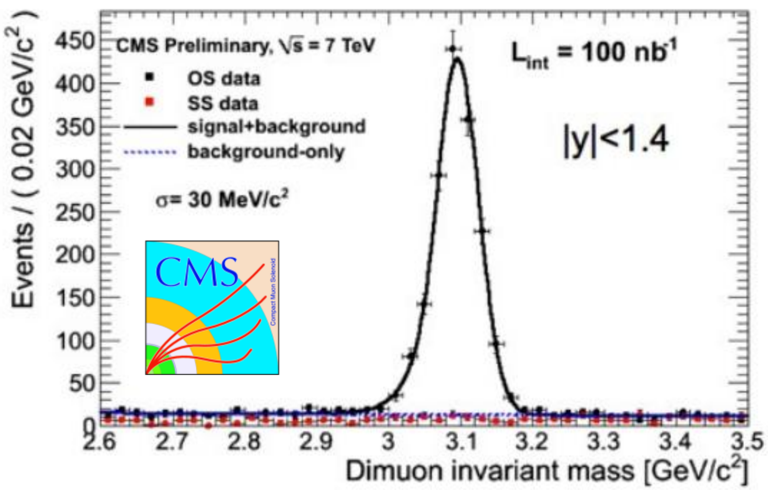
***Nucl.Instrum.Meth.A434:435-443,1999***

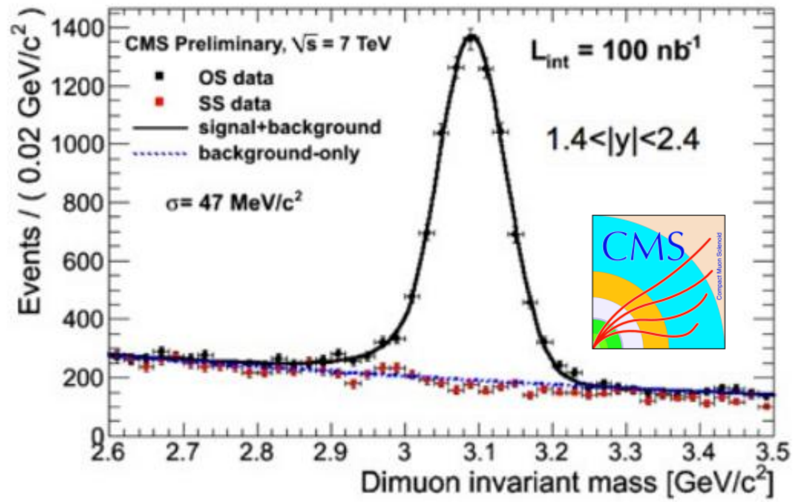
CMS official limit at σ(bbar)=500ub

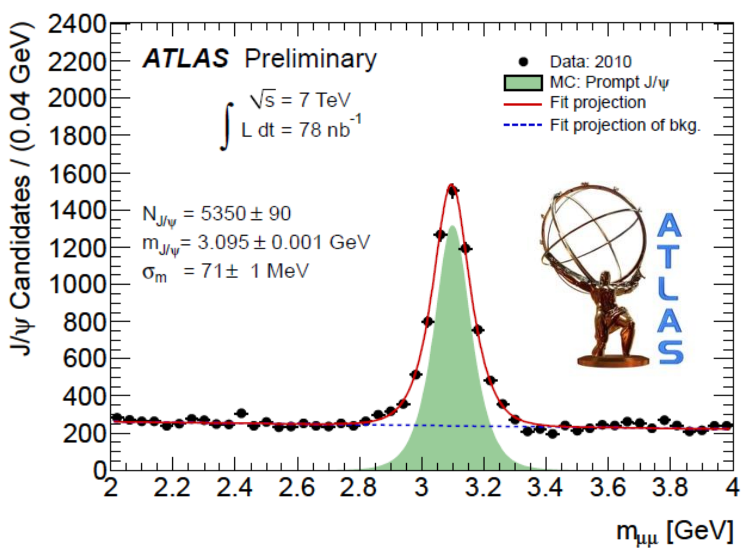
BR($B_s$→μμ)<$16 \cdot 10^{-9}$ @90% CL

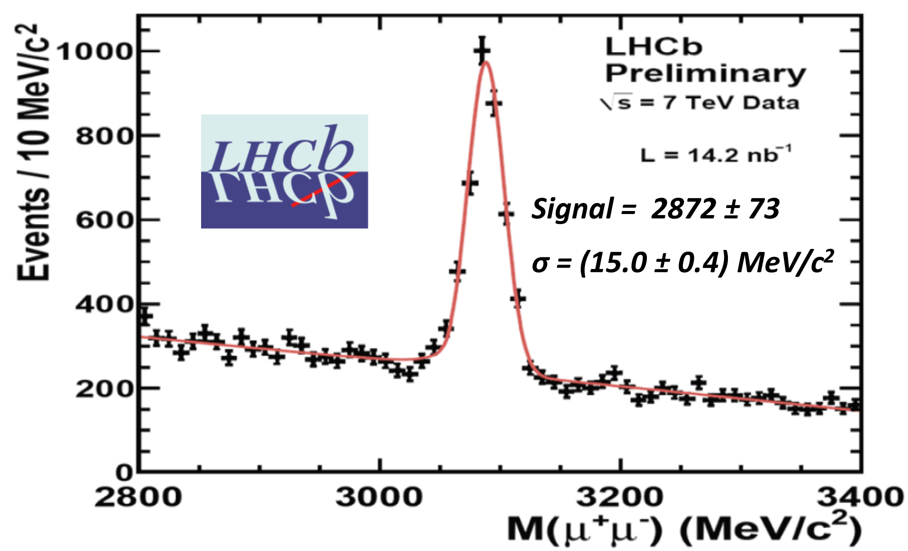
***Mass resolution one of the key variables.***

# $J/\psi$ resolution with first data



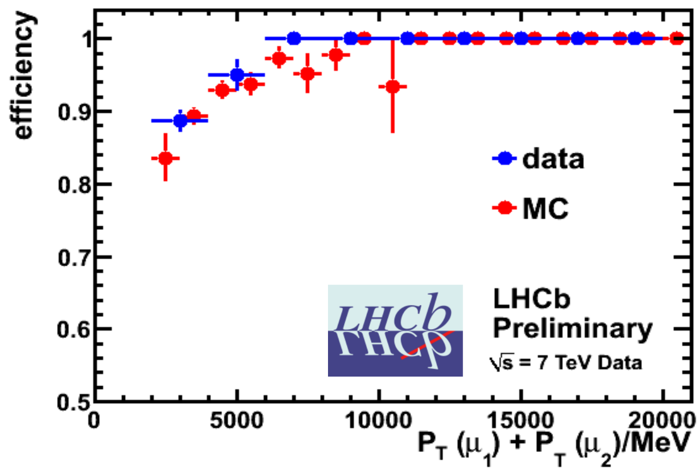



# Efficiency studies in LHCb

*Trigger efficiency using $J/\Psi$*

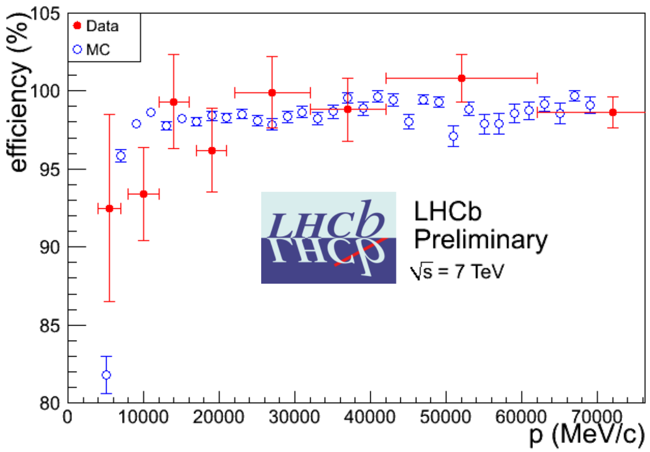



*Trigger and muon identification:*

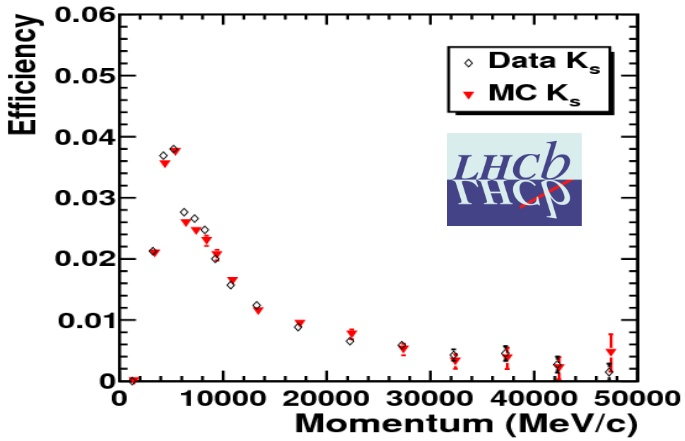
1) *High efficiency*
2) *Good agreement between data and MC*

*The Pion misidentification is well described by the MC.*

*Muon ID Efficiency, tag and probe using $J/\Psi$*

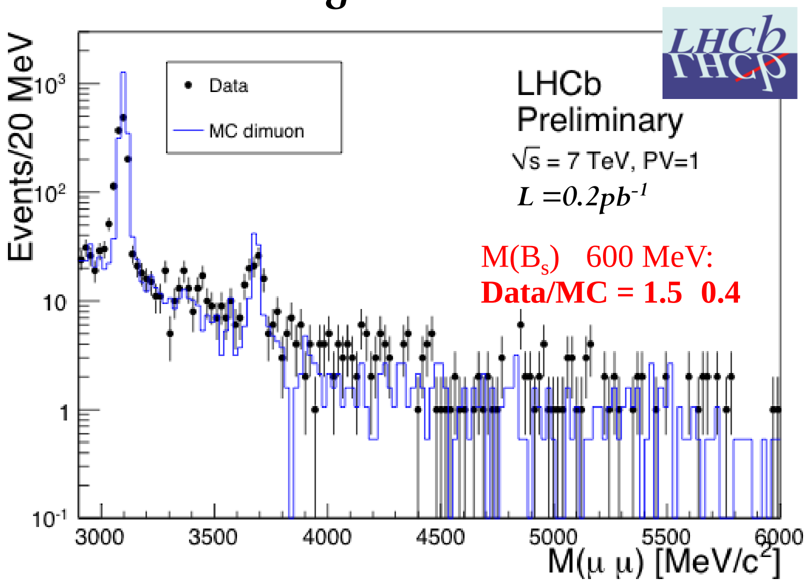



*Pion misidentification using $K_s$*

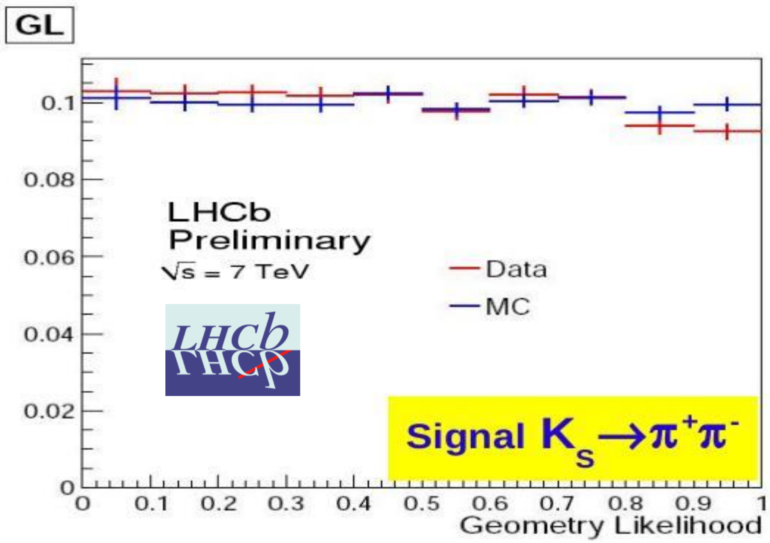


# Background

*Di-muon background invariant mass(data)*




*Comparison Data / Montecarlo computing the Geometrical Likelihood for Kshort analysis.*




*Variables:*

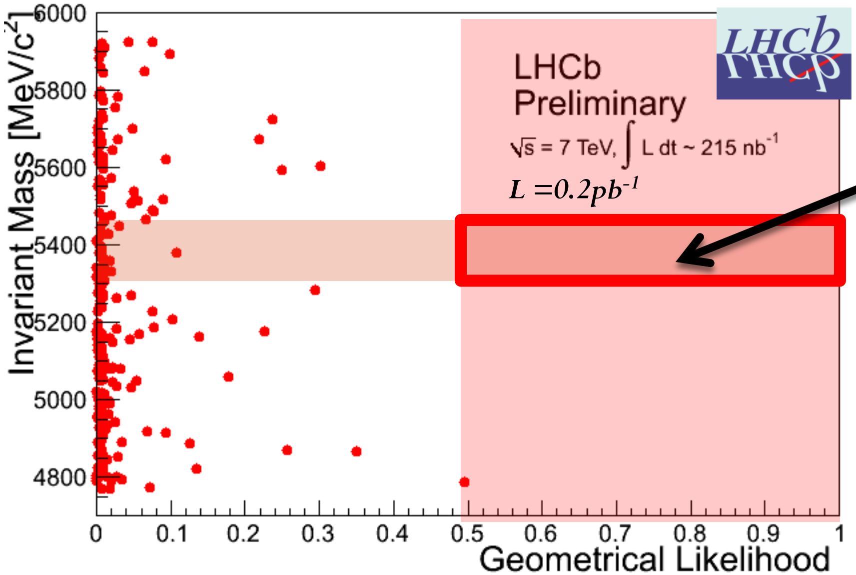
*Impact Parameter, Mother Lifetime and Vertex Chi2.*

*<u>Not yet appropriate control channel to test isolation criteria.</u>*

*The control sample which we will use in the experiment to calibrate the Geometrical Likelihood is the $B \rightarrow hh$.*

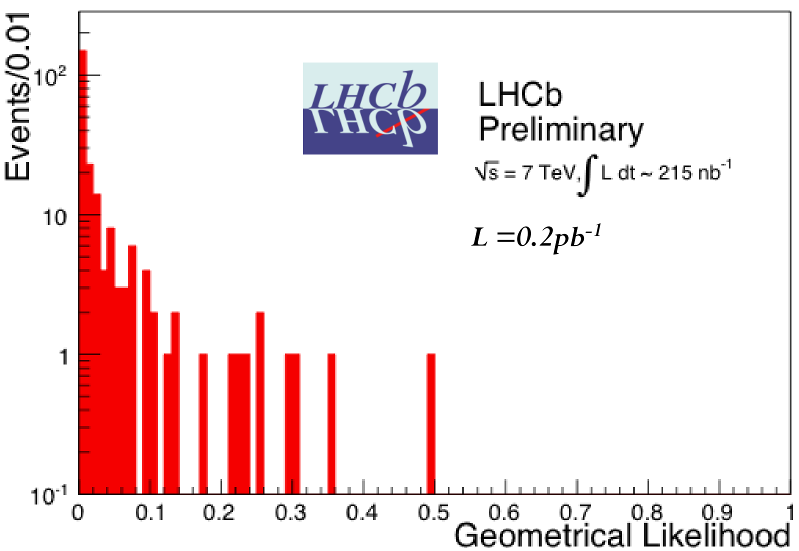
# Background (II)

*Di-muon background after selection (data)*




*Sensitive region*
*expected ~6 Signal events and ~30 background events in 2011 data*

*Di-muon Geometrical Likelihood (data)*




*First data indicate that MC estimation is reasonable!*

# Normalization

At LHC we will measure relative branching ratios,
the $B_s$→$\mu\mu$ branching ratio can be measured according to the formula

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon_{\mathrm{cal}}^{\mathrm{REC}} \epsilon_{\mathrm{cal}}^{\mathrm{SEL|REC}} \epsilon_{\mathrm{cal}}^{\mathrm{TRIG|SEL}}}{\epsilon_{\mathrm{sig}}^{\mathrm{REC}} \epsilon_{\mathrm{sig}}^{\mathrm{SEL|REC}} \epsilon_{\mathrm{sig}}^{\mathrm{TRIG|SEL}}} \times \frac{f_{\mathrm{cal}}}{f_{B_s^0}} \times \frac{N_{B_s^0 \to \mu^+ \mu^-}}{N_{\mathrm{cal}}}$$

All the experiments plan to normalize with
$B^+$→$J/\psi K^+$ or $B_d$→$J/\psi K^*$, in this case the dominant uncertainty would be fd/fs (~15% uncertainty).
***Moreover the fragmentation functions are not just numbers but they could depend on Pt, pseudo-rapidity, environment!***

***Another approach is to normalize to $B_s$→$J/\psi$ $\varphi$, directly measured at the Y(5S) .***

***<u>In this case the fragmentation function do not enter in the normalization</u>.***
***Present Measurement BR($B_s$→$J/\psi$ $\varphi$)*** = (1.18    0.25 $^{+0.22}_{-0.25}$(syst))   $10^{-3}$ *($23.6fb^{-1}$ )*
*(20% stat error + 20% systematic)*   ***arXiv:0905.2959v1***
***Expected ~10% <u>statistical</u> uncertainty with the full statistics of ~$120fb^{-1}$ .***

# Measuring fd/fs

*R.Fleischer, N.Serra, N.Tuning (PhysRevD.82.034038)*

*We can use the same formula to measure fd/fs if we knew from theory the ratio of two branching ratios:*

$$\frac{N_s}{N_d} = \frac{f_s}{f_d}\frac{\varepsilon(B_s \rightarrow \text{something})}{\varepsilon(B_d \rightarrow \text{something else})}\frac{BR(B_s \rightarrow \text{something})}{BR(B_d \rightarrow \text{something else})}$$

*Requiring :*

1) *Robust against NP contribution*
2) *The ratio can be calculated theoretically (factorization and $SU(3)_F$ )*
3) *$SU(3)_F$ breaking effects can be computed with non perturbative QCD*
4) *Assumptions are under control or can be probed experimentally*
5) *The ratio is easy to measure*

*The best decays are $B_d \rightarrow D^- K^+$ and $B_s \rightarrow D_s^- \pi^+$*

# Measuring fd/fs at LHCb

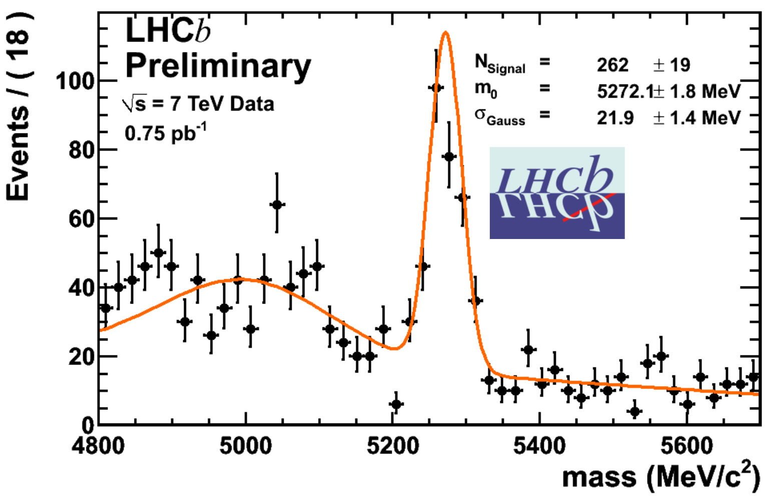
This two channel are very similar :

$B_d \rightarrow Dk \rightarrow (2\pi)^- K^+K^+$ and $B_s \rightarrow D_s\pi^+ \rightarrow K^+K^- \pi^-\pi^+$

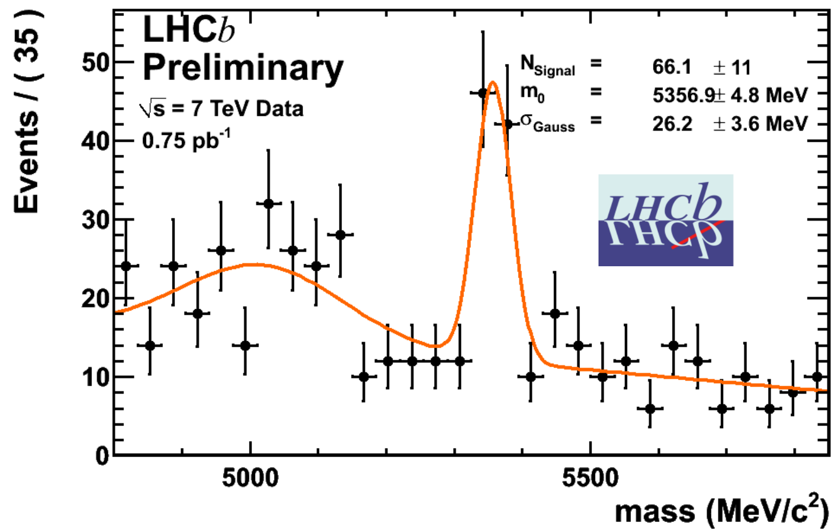
*the ratio of the efficiency deviates from 1 to few ‰ level according with full MC.*

*Expected precision on fd/fs is (5-7%)*

*Real data* $B_d \rightarrow D^-\pi^+$ *(data)*




*Real data* $B_s \rightarrow D_s^-\pi^+$ *(data)*




*NP discovery potential (at 5*$\sigma$*) with 1fb (end 2011) is* $\sim 17 \cdot 10^{-9}$

*ATLAS and CMS can use LHCb value once the dependence of* $\eta$ *is also measured.*

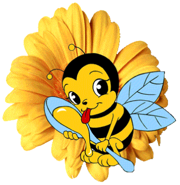
# Normalization

- ATLAS/CMS/LHCb:

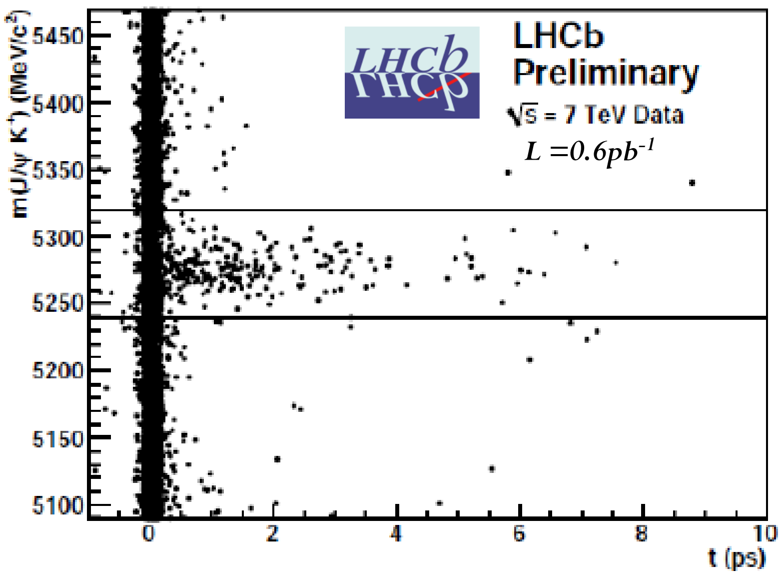
$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon^{\mathrm{REC}}_{\mathrm{cal}} \epsilon^{\mathrm{SEL|REC}}_{\mathrm{cal}} \epsilon^{\mathrm{TRIG|SEL}}_{\mathrm{cal}}}{\epsilon^{\mathrm{REC}}_{\mathrm{sig}} \epsilon^{\mathrm{SEL|REC}}_{\mathrm{sig}} \epsilon^{\mathrm{TRIG|SEL}}_{\mathrm{sig}}} \times \frac{f_{\mathrm{cal}}}{f_{B^0_s}} \times \frac{N_{B^0_s \to \mu^+\mu^-}}{N_{\mathrm{cal}}}$$

  - Plan to normlize to $B^+ \to J/\psi K^+$ (assuming fd/fs = fu/fs) or $B_d \to J/\psi K^*$ (or to $B_s \to J/\psi\varphi$ , in this case fd/fs doesn't enter)
  - Same trigger and same muon ID
  - Selection can be made similar
  - Use $B_d \to J/\psi K^*$ or other similar ratios allows for extracting the efficiency of the extra track(s)

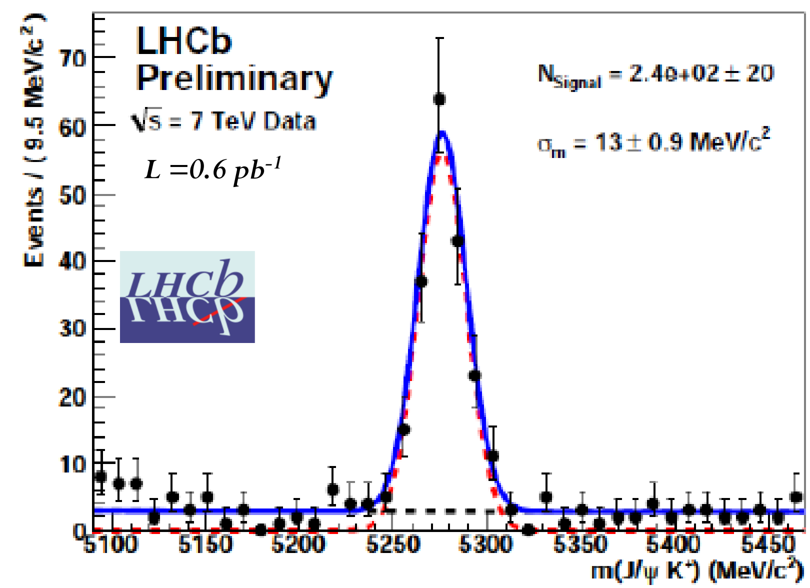
# *Some of the first Bees at LHCb*



*$B^+ \rightarrow J/\psi K^+$ candidates*
*Invariant mass VS lifetime*



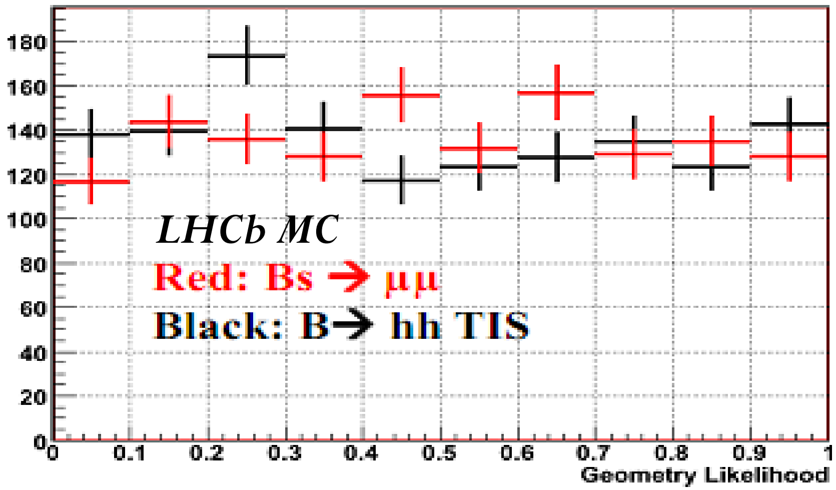

*$B^+ \rightarrow J/\psi K^+$ candidates*
*Invariant mass*



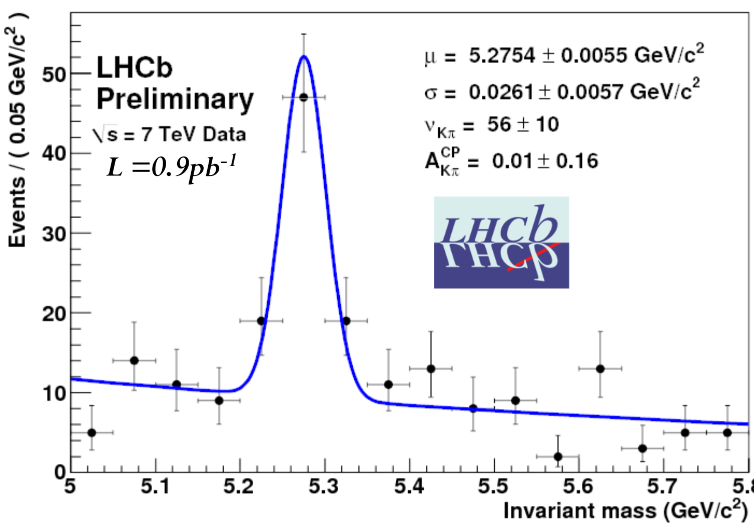
# $B_d \rightarrow h^+h^-$ as a control channel

- LHCb is also studying $B_d \rightarrow h^+h^-$ as control channel
  - This would allow to calibrate the Geometrical Likelihood since they have the same topology
  - Calibrate the invariant mass resolution

*Geometrical Likelihood distribution (MC)*




*Invariant Mass for $B_d \rightarrow K^+\pi^-$ (data)*



# Conclusions

- The $BR(B_s^0 \rightarrow \mu^+\mu^-)$ is a very sensitive probe to NP, in particular to theories with extending Higgs sector, such as the MSSM
- LHCb will profit of the low Pt muon trigger and the good invariant mass resolution (better sensitivity for a given luminosity)
- All the experiments plan to normalize to either $B_d \rightarrow J/\psi K^*$ or $B^+ \rightarrow J/\psi K^+$ ,

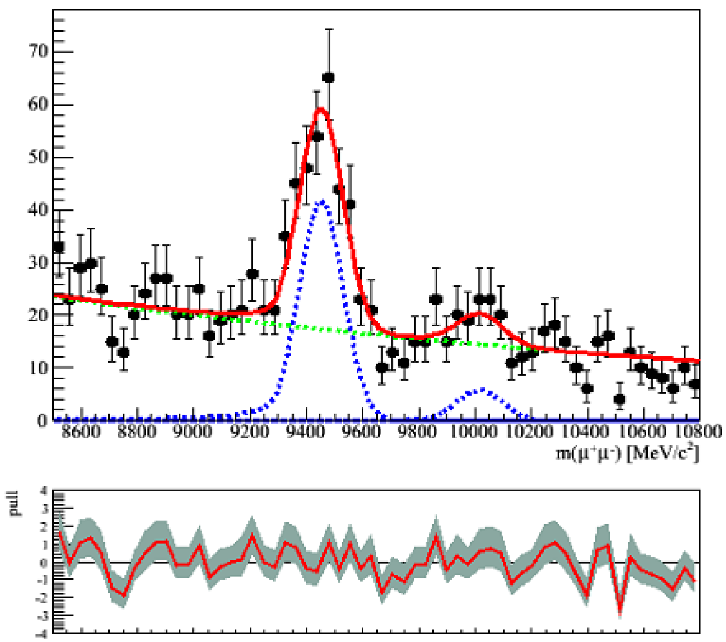
  LHCb is also studying the possibility to normalize to $B_s \rightarrow J/\psi\varphi$
- $B_d$ BR are well known the need the measurement of fd/fs , LHCb plans to measure this parameter with the ratio $B \rightarrow D^- K^+$ and $B_s \rightarrow D_s^- \pi^+$
- Expected limit on $BR(B_s^0 \rightarrow \mu^+\mu^-) < 7{\cdot}10^{-9}$ with LHCb with $1fb^{-1}$ (corresponding to what we will get by the end of next year)
- Possibility to discover NP for $BR(B_s^0 \rightarrow \mu^+\mu^-) > 17{\cdot}10^{-9}$ with $1fb^{-1}$ .

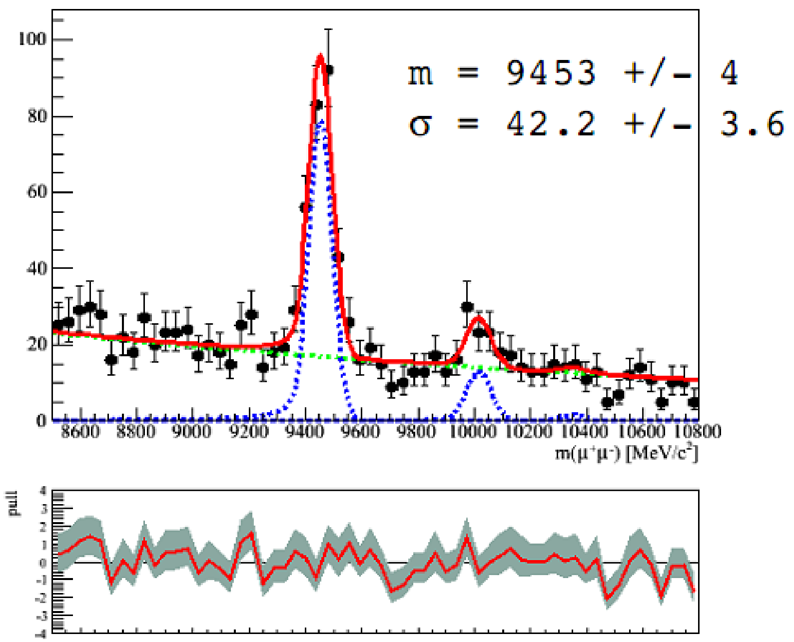
# We just started collecting bees

....we hope to discover some rare non-SM bees in 2010/2011

# Backup Slides

# Alignment



# Motivation

The SM is considered an incomplete description of fundamental interactions:

- Hierarchy, fine-tuning problems
- Unsatisfactory description
- Cosmological related observation

However the CKM paradigm has been (until now) quite successful in describing all FCNC processes ($K^0$ mixing, $B^0$ mixing, CP violation in $B^0$,…).

$$A(decay) = \sum_i C_i O_i (V^i{}_{CKM})(\eta^i{}_{QCD})$$

NP can be classified in the following categories:

|  | *New Operators* | |
|---|---|---|
|  | **CMFV** | **MFV** |
| ***New CPV*** | Beyond CMFV | Beyond MFV |

A.J. Buras (arxiv:0910.1032v1)

$$Br(B_q{}^0 \to \mu^+\mu^-) \propto \left| \langle B_q | H | \mu\mu \rangle \right|^2$$

$$H = -2\sqrt{2} G_F \, |V_{tb}{}^* V_{tq}| (C_S O_S + C_P O_P + C_{10} O_{10})$$

***The factors $C_P$ and $C_S$ are negligible in the SM.***

# Normalization

At LHCb we will measure a relative branching ratio.

$$BR = BR_{cal} \times \frac{\epsilon_{cal}^{REC}\,\epsilon_{cal}^{SEL|REC}\,\epsilon_{cal}^{TRIG|SEL}}{\epsilon_{sig}^{REC}\,\epsilon_{sig}^{SEL|REC}\,\epsilon_{sig}^{TRIG|SEL}} \times \frac{f_{cal}}{f_{B_s^0}} \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{cal}}$$

- Main normalization channels so far considered:
  - $B^+ \to J/\psi K^+$
  - $B^0 \to J/\psi K^*$
  - $B^0 \to K^- \pi^+$

  Better known BR, involve $f_d/f_s$

  - $B_s \to J/\psi\ \Phi$
  - $B_s \to D_s^- \pi^+$
  - $B_s \to K^- K^+$

  Direct measurement from Belle Y(5S), larger error

# Normalization

At LHCb we will measure a relative branching ratio.

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon^{\mathrm{REC}}_{\mathrm{cal}} \epsilon^{\mathrm{SEL|REC}}_{\mathrm{cal}} \epsilon^{\mathrm{TRIG|SEL}}_{\mathrm{cal}}}{\epsilon^{\mathrm{REC}}_{\mathrm{sig}} \epsilon^{\mathrm{SEL|REC}}_{\mathrm{sig}} \epsilon^{\mathrm{TRIG|SEL}}_{\mathrm{sig}}} \times \frac{f_{\mathrm{cal}}}{f_{B^0_s}} \times \frac{N_{B^0_s \to \mu^+\mu^-}}{N_{\mathrm{cal}}}$$

- Main normalization channels so far considered:
  - $B^+ \to J/\psi K^+$
  - $B^0 \to J/\psi K^*$
  - $B^0 \to K^- \pi^+$
  - $B_s \to J/\psi \Phi$
  - $B_s \to D_s^- \pi^+$
  - $B_s \to K^- K^+$

These channels are experimentally nice for the normalization:

✓ Triggered by the same (di)-muon trigger.

✓ There are methods for accounting for the extra tracks.

# Normalization

At LHCb we will measure a relative branching ratio.

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon_{\mathrm{cal}}^{\mathrm{REC}}\,\epsilon_{\mathrm{cal}}^{\mathrm{SEL|REC}}\,\epsilon_{\mathrm{cal}}^{\mathrm{TRIG|SEL}}}{\epsilon_{\mathrm{sig}}^{\mathrm{REC}}\,\epsilon_{\mathrm{sig}}^{\mathrm{SEL|REC}}\,\epsilon_{\mathrm{sig}}^{\mathrm{TRIG|SEL}}} \times \frac{f_{\mathrm{cal}}}{f_{B_s^0}} \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{\mathrm{cal}}}$$

- Main normalization channels so far considered:
  - $B^+ \to J/\psi K^+$
  - $B^0 \to J/\psi K^*$
  - $B^0 \to K^- \pi^+$
  - $B_s \to J/\psi\ \Phi$
  - $B_s \to D_s^- \pi^+$
  - $B_s \to K^- K^+$

These are less nice:

➢ No muons in the final state.

✓ However they have the same topology as $B_s \to \mu^- \mu^+$ .

# Normalization

At LHCb we will measure a relative branching ratio.

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon_{\mathrm{cal}}^{\mathrm{REC}} \epsilon_{\mathrm{cal}}^{\mathrm{SEL|REC}} \epsilon_{\mathrm{cal}}^{\mathrm{TRIG|SEL}}}{\epsilon_{\mathrm{sig}}^{\mathrm{REC}} \epsilon_{\mathrm{sig}}^{\mathrm{SEL|REC}} \epsilon_{\mathrm{sig}}^{\mathrm{TRIG|SEL}}} \times \frac{f_{\mathrm{cal}}}{f_{B_s^0}} \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{\mathrm{cal}}}$$

- Main normalization channels so far considered:
  - $B^+ \to J/\psi K^+$
  - $B^0 \to J/\psi K^*$
  - $B^0 \to K^- \pi^+$
  - $B_s \to J/\psi\ \Phi$
  - $B_s \to D_s^- \pi^+$
  - $B_s \to K^- K^+$

This channel is not nice for normalizing the $B_s \to \mu^- \mu^+$ :

- No muons in the final state.
- Very different topology (the D-meson decays in a separate vertex)

# Normalization with $B_s$ channels

- Bs-normalization channels (with 23.6 $fb^{-1}$ )
  - $BR(B_s \to J/\psi\ \Phi) = (1.18\quad 0.25\ ^{+0.22}_{-0.25}(syst))\ \ 10^{-3}$
    (stat err ~21%, syst ~13%, fs ~13%)
  - $BR(B_s \to K^- K^+) = (3.8^{+1.0}_{-0.9}\quad 0.5(syst)\quad 0.5(fs))\ \ 10^{-5}$
    (stat err ~26%, syst ~13%, fs~13%)
  - $BR(B_s \to D_s^- \pi^+) = (3.68^{+0.35}_{-0.33}\quad 0.42(syst)\ \ 0.49(fs))\ \ 10^{-3}$
    (stat err ~9.5%, syst ~11%, fs~13%)

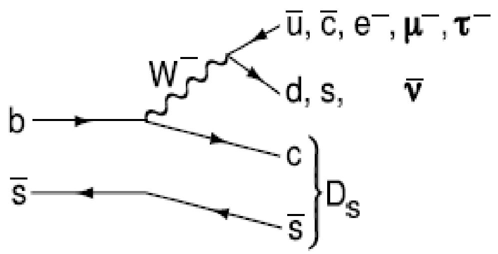
  Full statistics ~ 120$fb^{-1}$

All these channels have about 13% error from syst and 13% error from fs in addition to the statistical error.
A model-dependent determination of fs was used.
*The error on fs could be reduced(?)*

# Measurement of $f_s$ at $\Upsilon$(5S)

model-dependent

$$\mathrm{BR}(\Upsilon(5S) \to D_s X, \phi X) = 2 f_s \mathrm{BR}(B_s^0 \to D_s X, \phi X) + (1 - f_s)\mathrm{BR}(\Upsilon(4S) \to D_s X, \phi X)$$




Belle, Phys.Rev.Lett.98:052001,2007

$$f_s = (18.0 \pm 1.3 \pm 3.2)\%$$

- BR($B_s \to D_s X$)=92  11% from CLEO: "nearly 100% probability"

CLEO, Phys.Rev.Lett.95:261801,2005

Based on some model-dependent assumptions

However there are studies on how to measure fs in a model-independent way at Y(5S) (see R.Sia and S.Stone Phys. Rev. D74 031501)

# Normalization with $B^0$ channels

- $B^0$ normalization channels:
  - $BR(B^+ \to J/\psi K^+) = (1.007 \ \ 0.035) \ \ 10^{-3}$
    total error 3.4%
  - $BR(B^0 \to J/\psi K^*) = (1.33 \ \ 0.06) \ \ 10^{-3}$
    total error 4.5%
  - $BR(B^0 \to K^- \pi^+) = (1.94 \ \ 0.06) \ \ 10^{-5}$
    total error 3%

We need fd,u/fs!

•Tevatron average from PDG : fs/(fd+fu)= 0.142±0.019 (~13%)

•This is not just a number but it can depend on:
**Momentum, environment, pseudo-rapidity**
(see for instance arxiv:0808.1297v3 )

→ ***If we want to use $B^0$ for normalization we need to measure fd/fs.***

# Measurement of fd/fs at Tevatron

CDF measured fs/(fd+fu) using the semi-exclusive decays
B → $D^{(*,*)}$ lνX and $B_s$ → $D_s^{(*,*)}$ lνX .
Assuming the following conditions:

CDF, Phys.Rev.D77:072003,2008

SU(3) invariance:

$$\Gamma(\bar{B}^0 \to \ell^- \bar{\nu}_\ell D^+) = \Gamma(B^- \to \ell^- \bar{\nu}_\ell D^0) = \Gamma(\bar{B}_s^0 \to \ell^- \bar{\nu}_\ell D_s^+) = \Gamma(\bar{B} \to \ell^- \bar{\nu}_\ell D)$$

And similar conditions for $D^{*,*}$

They also assume that:

$$\Gamma(\bar{B} \to \ell^- \bar{\nu}_\ell D) + \Gamma^*(\bar{B} \to \ell^- \bar{\nu}_\ell D^*) + \Gamma^{**}(\bar{B} \to \ell^- \bar{\nu}_\ell D^{**}) = \Gamma(\bar{B} \to \ell^- \bar{\nu}_\ell X)$$

$$\frac{f_s}{f_u + f_d} = 0.160 \pm 0.005\,(\text{stat})\,^{+0.011}_{-0.010}\,(\text{sys})\,^{+0.057}_{-0.034}\,(\mathcal{B})$$

No systematic error considered for the two assumptions

# How to measure fd/fs

$$\frac{N_s}{N_d} = \frac{f_s}{f_d} \frac{\varepsilon(B_s \to \text{something})}{\varepsilon(B_d \to \text{something else})} \frac{BR(B_s \to \text{something})}{BR(B_d \to \text{something else})}$$

You just need to invert this formula! ☺

# Proposed new Method

$$\frac{N_s}{N_d} = \frac{f_s}{f_d} \frac{\varepsilon(B_s \to \text{something })}{\varepsilon(B_d \to \text{something else})} \frac{BR(B_s \to \text{something })}{BR(B_d \to \text{something else})}$$

Our aim is to find a ratio (Bs→something)/(Bd→something else) of two exclusive channels such that:

1) Robust against NP contribution
2) The ratio can be calculated theoretically (factorization and $SU(3)_F$ )
3) $SU(3)_F$ breaking effects can be computed with non perturbative QCD
4) Assumptions are under control and can be probed experimentally
5) The ratio is easy to measure (for LHCb)

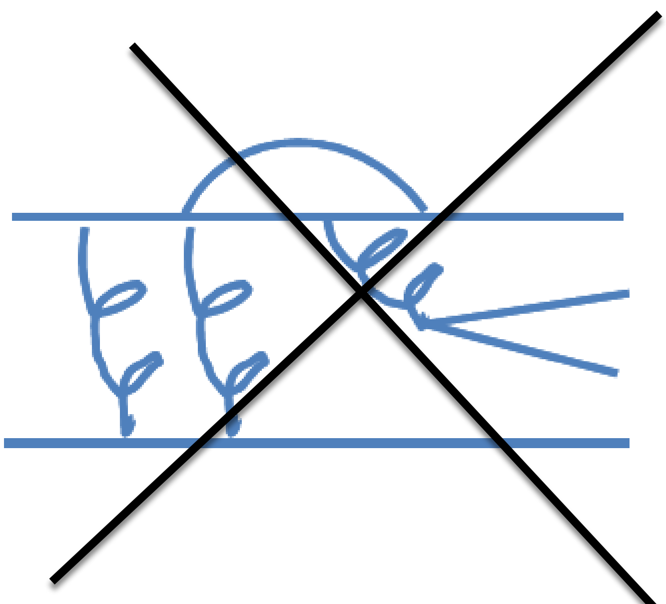
1)→ Rules out penguin decays (tree diagram only);
5) →Rules out all decays with neutrinos;
2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed and exchange topology).

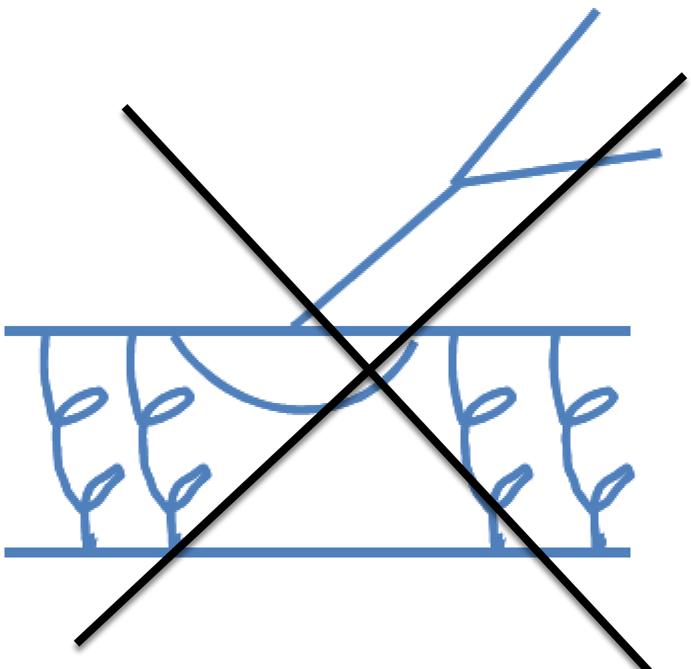
# Proposed Method

***1) → Rules out  penguin decays (tree diagram only);***

5) →Rules out all decays with neutrinos***;***

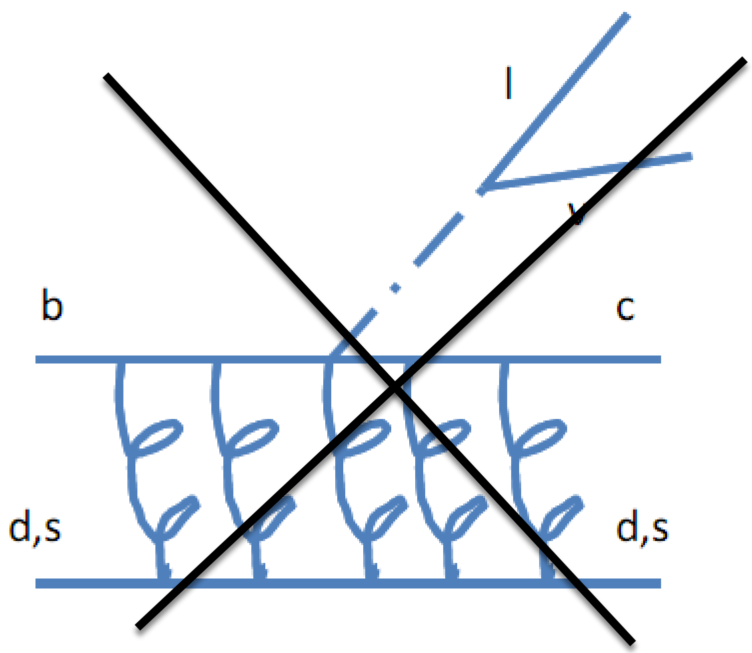
2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed  and exchange topology).





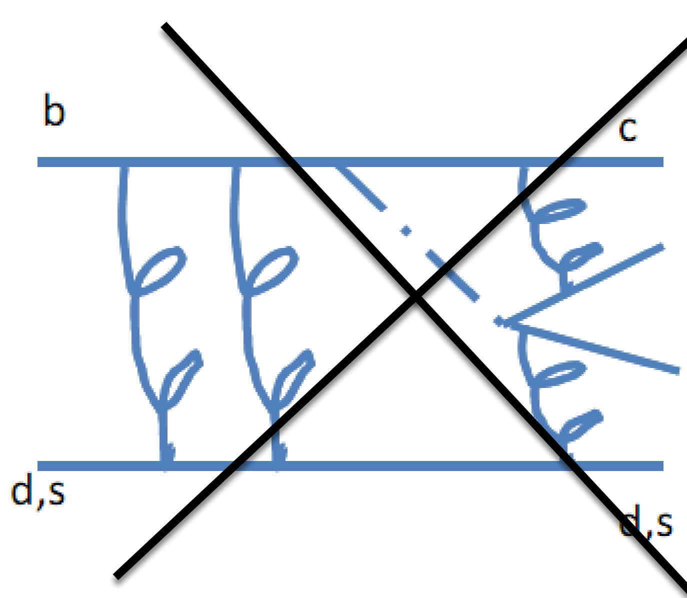
# Proposed Method

***1) → Rules out penguin decays (tree diagram only);***
***5) →Rules out all decays with neutrinos;***
2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed and exchange topology).



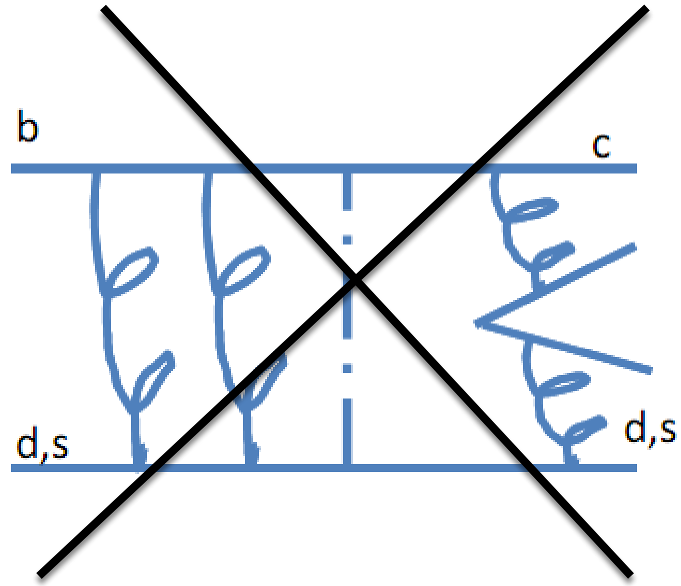
# Proposed Method

***1) → Rules out penguin decays (tree diagram only);***
***5) → Rules out all decays with neutrinos;***
***2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed*** *and exchange topology* ***).***



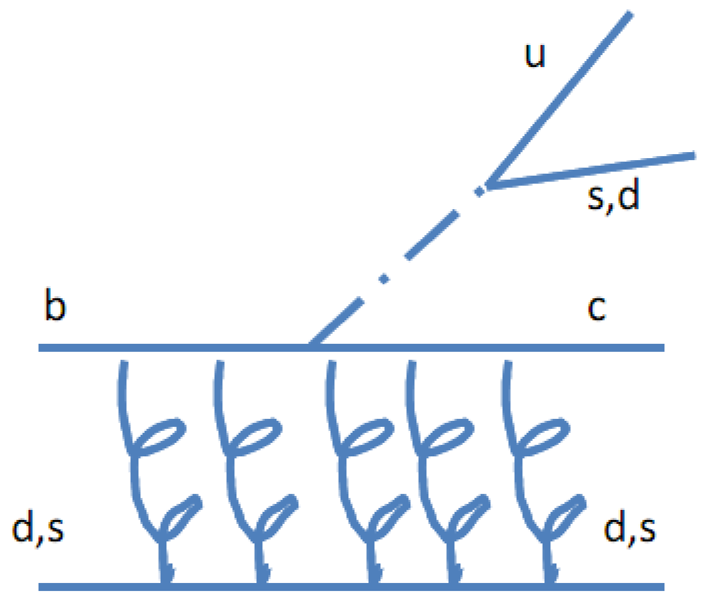
# Proposed Method

*1) → Rules out penguin decays (tree diagram only);*
*5) → Rules out all decays with neutrinos;*
*2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed and exchange topology).*



# Proposed Method

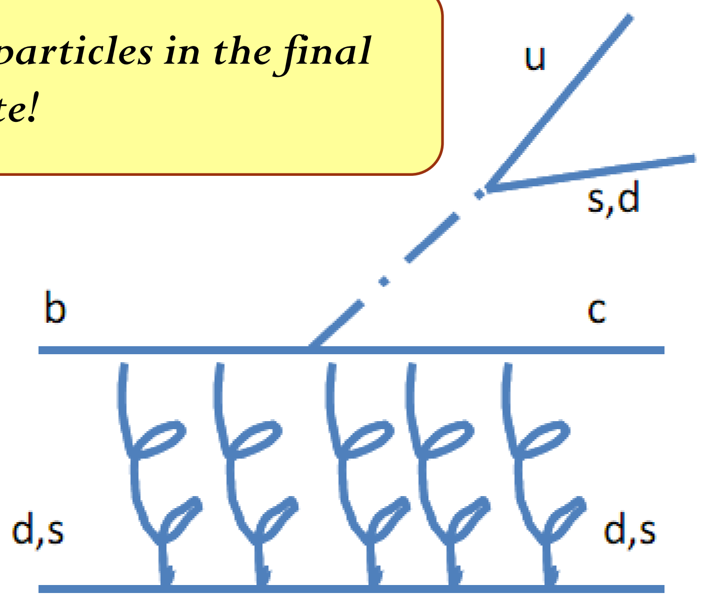
*1) → Rules out penguin decays (tree diagram only);*
*5) → Rules out all decays with neutrinos;*
*2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed and exchange topology).*



# Proposed Method

*1) → Rules out  penguin decays (tree diagram only);*
*5) → Rules out all decays with neutrinos;*
*2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed  and exchange topology).*

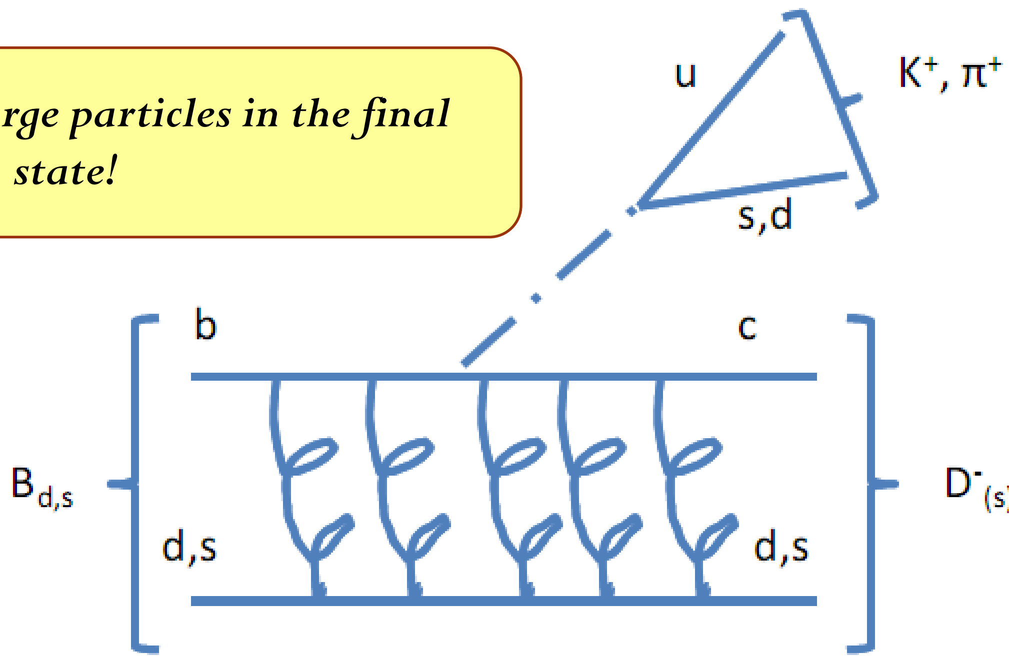
*We also want charge particles in the final state!*



# Proposed Method

*1) → Rules out penguin decays (tree diagram only);*
*5) → Rules out all decays with neutrinos;*
*2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed and exchange topology).*

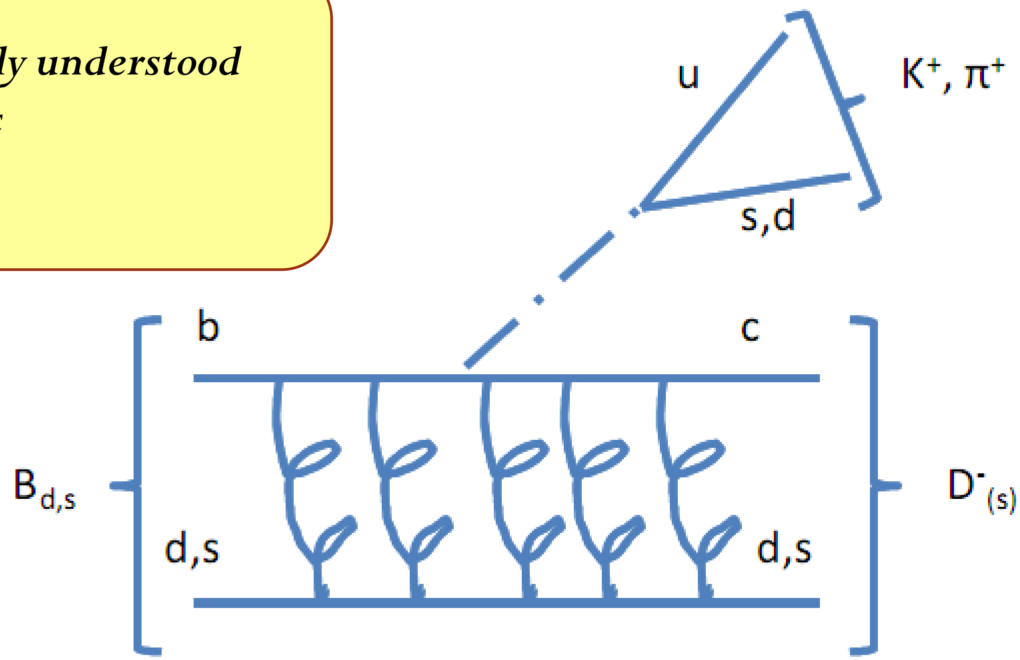
*We also want charge particles in the final state!*



# Proposed Method

*1) → Rules out penguin decays (tree diagram only);*
*5) → Rules out all decays with neutrinos;*
*2,3,4) → Implies that there must be 4 different quarks in the final state (no color suppressed and exchange topology).*

*These are the best theoretically understood*
*non-semileptonic*
*B-decays*



# Fragmentation extraction

We have:

$$\frac{N_{D_s\pi}}{N_{D_dK}} = \frac{f_s}{f_d}\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)}$$

We can compute the ratio of the BR as:

$$\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)} \sim \frac{\tau_{B_s}}{\tau_{B_d}}\left|\frac{V_{ud}}{V_{us}}\right|^2 \times \left(\frac{f_\pi}{f_K}\right)^2 \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2 \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2$$

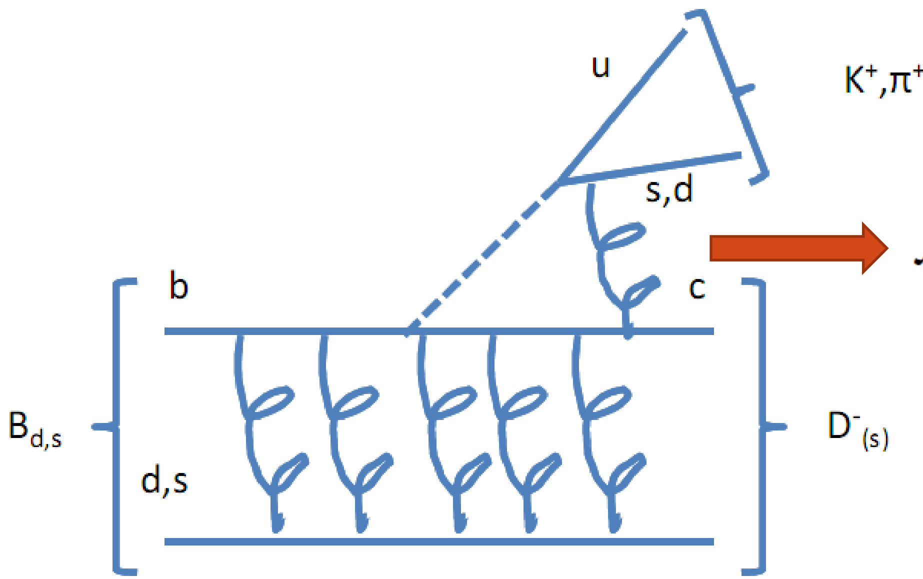
Combining the two we have:

$$\frac{f_d}{f_s} = 12.88 \times \frac{\tau_{B_s}}{\tau_{B_d}} \times \left[\mathcal{N}_a\mathcal{N}_F\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{N_{D_dK}}{N_{D_s\pi}}\right]$$

The theoretical uncertainty (due to SU(3) breaking) are:

$$\mathcal{N}_a \equiv \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2 \qquad \mathcal{N}_F \equiv \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2$$

# Theory uncertainty (I): Non factorizable part




$$\mathcal{N}_a \equiv \left| \frac{a_1(D_s\pi)}{a_1(D_d K)} \right|^2$$

***We can measure this factor, see backup slides!***

The factor "a1" is the deviation from naïve factorization.

$$|a_1| \simeq 1.05$$

Beneke et al. Nucl.Phys. B591: 313-418,2000

Moreover we are just sensitive to the SU(3) breaking part (at most of the order of 1% → negligible).

$$\mathcal{N}_a \approx 1 + 2\Re(a_1^{\mathrm{NF}}(D_s\pi) - a_1^{\mathrm{NF}}(D_d K))$$

# Factorization (1)

- Q: How large is the effect of non-factorization?
- A: Suppressed by $(\Lambda_{QCD}/m_b)$ M.Beneke et al Nucl.Phys.B591:313-418,2000,

However… we are just interested in the ratio! ☺

- Q: How large is the s↔d difference (ie. "non-factorizable SU(3) breaking")?
- A: Add at least another suppression by $(m_s/\Lambda_{QCD})$

$$\mathcal{N}_a \approx 1 + 2\Re(a_1^{NF}(D_s\pi) - a_1^{NF}(D_dK))$$

$$\mathcal{N}_a \in [0.97, 1.03]$$

Simple dimensional counting argument:

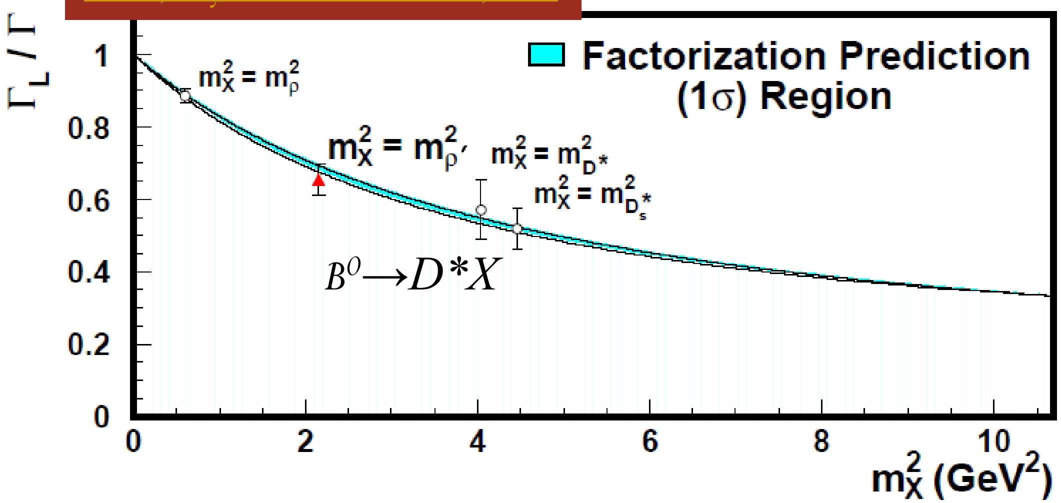
- ***We have corrections suppressed by $(\Lambda_{QCD}/m_b)$***
- ***They are also SU(3) breaking, which means a factor $(m_s/\Lambda_{QCD})$***
- ***They are also non factorizable which means a factor $1/N_C$***

***This means $m_s/m_b * 1/N_C \sim 0.01$!***

# Some test of Factorization

- These decays are the best known examples where factorization seems to work
- Factorization were tested in a similar cntext at B-factories

Babar, Phys.Rev.D74:012001,2006




Belle Phys.Rev.Lett 104, 231801 (2010)

Here factorization is tested with measuring the polarization of $\rho$ in the decays $B_s \to D_s^{(*)} \rho$

# Test of factorization at LHCb

- Can even *measure* | $a_1$ | experimentally, comparing to $B_d \to D\mu\nu_\mu$ from BaBar to $B_d \to DK$ at LHCb.

M.Beneke et al Nucl.Phys.B591:313-418,2000,

$$\frac{\mathrm{BR}(\bar{B}_q^0 \to D_q^+ P^-)\tau_{B_q}}{d\Gamma(\bar{B}_q^0 \to D_q^+ \ell^- \bar{\nu}_\ell)/dq^2|_{q^2=m_P^2}} = 6\pi^2 |V_q|^2 f_P^2 |a_1(D_q P)|^2 X_P$$

At LHCb we can normalize $B_d \to DK$ to $B_d \to D\pi$, Therefore we can compare this value to to $B_d \to D\mu\nu_\mu$ *and hence extract* |*a1*|

$a_1$ = non factorizab le part

$X_P$ = 1 for vector s and deviates from 1 less then 1% for pseudoscal ar mesons

$f_P$ = P meson decay constant

# Factorization summary

- We have theoretical hints that factorization works for these two decays ();
- We have some experimental hint (factorization was tested in a similar context: Babar: Belle: )
- We can probe |a| experimentally
- The total uncertainty is NOT $|a_1|$ but the ratio $R = |a_1(B_s \rightarrow D_s \pi)| / |a_1(B_d \rightarrow DK)|$, i.e. further SU(3) breaking suppressed.

# Form factor ratio

The main theory uncertainty is the ratio of the form factors:

$$\mathcal{N}_F \equiv \left[ \frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)} \right]^2$$

This can be calculated reliably with LQCD.
In order to match an experimental precision of ~5%,
20% accuracy on the SU(3) breaking part (corresponding to ~5% error on $\boldsymbol{N_F}$ ) is sufficient.

In CDF case they also have a ratio of form factors, but they ignore it.

***If we make the same assumption as CDF we would simply have*** $\boldsymbol{N_F = 1.0}$

# Bound on $N_f$

$$\mathcal{N}_F \equiv \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2$$

$$BR(B_s \to \mu\mu)_0 = \left(\frac{f_d}{f_s}\right)_{N_F=1} \frac{\varepsilon_{sig} N_{sig}}{\varepsilon_{cal} N_{cal}} BR_{cal}$$

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathcal{N}_F \mathrm{BR}(B_s^0 \to \mu^+\mu^-)_0$$

$N_F > 1$ , supported by:

1) ***Naïve expectation: radius of $B_s$ < radius $B_d$***
2) ***Chiral logarithms*** — E.E.Jenkins et al., Phys.Lett. B 281, 331
3) ***QCD sum-rules calculations*** — P. Blasi, G.Nardulli et al., Phys.Rev. D 49, 238

Now, assuming $N_F = 1$ is a conservative estimate!

If we measure NP evidence at n σ, using our ***bound*** $N_f = 1$,
then $SU(3)_F$ breaking effects can only ***enhance*** the deviation from SM:

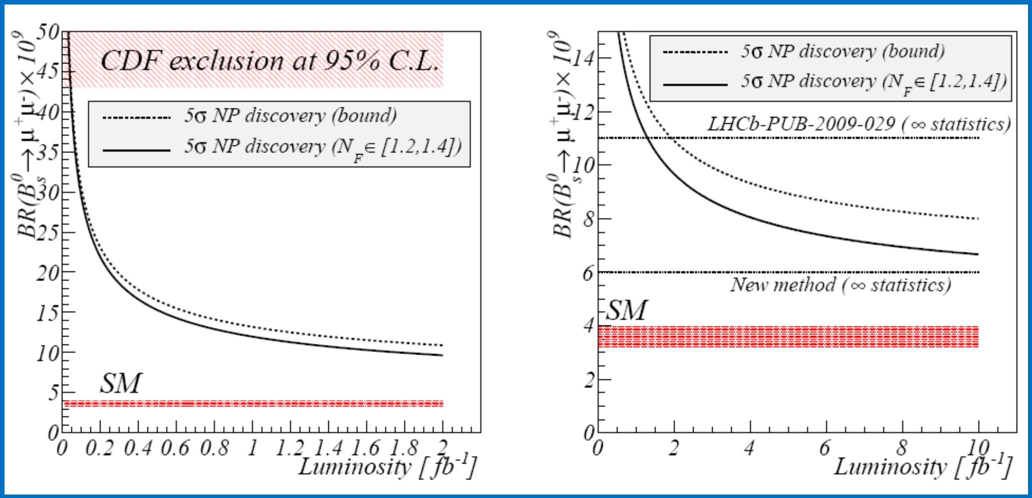
$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) > \mathrm{BR}(B_s^0 \to \mu^+\mu^-)_0$$

➔ Powerful tool to probe NP even without SU(3) breaking calculations.

# Result

- Assuming an uncertainty on $N_F$ of 5% we expect an uncertainty of 7% on fs/fd (for 1fb$^{-1}$ in 2011)!

Moreover we proposed a ***bound*** independent on SU(3) breaking effects.




Solid line assuming $N_F \in [1.2, 1.4]$ ,
dashed line using the ***bound*** for $N_F = 1.3$

P. Blasi , G. Nardulli et al., Phys.Rev. D 49, 238

# Bound for $N_F$

$N_F > 1$ , supported by:

1) *Naïve expectation: radius of $B_s$ > radius $B_d$*

2) *Chiral logarithms* E.E.Jenkins et al., Phys.Lett. B 281, 331

*The sign of the Chiral logarithmic correction to the SU(3)-breaking ratio of the decay constant of $D_{(s)}$ and $B_{(s)}$ agrees with experiment (for $D_{(s)}$ ) and LQCD calculation.*
*Also the numerical values are found of similar size.*

3) *QCD sum-rule calculations* P. Blasi et al., Phys.Rev. D 49, 238

Belle, Phys.Rev.Lett.98:052001,2007

# Measurement of $f_s$ @ Belle Υ(5S)

- Consider inclusive decays:

$$\Upsilon(5S) \to D_s X$$

- Use:

$$\mathcal{B}(\Upsilon(5S) \to D_s X)/2 = f_s \cdot \mathcal{B}(B_s \to D_s X) + (1 - f_s) \cdot \mathcal{B}(B \to D_s X) \;,$$

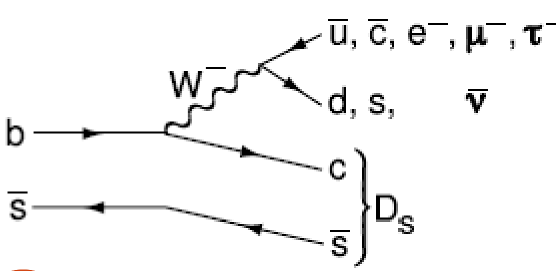
$$f_s = (18.0 \pm 1.3 \pm 3.2)\%$$

BR($B \to D_s X$)=8.7 1.2% (Belle)

BR($B_s \to D_s X$)=92 11% (CLEO)

- BR($B_s \to D_s X$)=92 11% from CLEO: "nearly 100% probability"

CLEO, Phys.Rev.Lett.95:261801,2005




**The nearly 100% probability** that this process will produce $D_s$ mesons is reduced if the cs pair fragments into a kaon plus a D instead of a $D_s$ by producing an additional uu or dd pair. **We don't actually know** the size of this fragmentation, though it's clear that producing a light quark-antiquark pair (dd or uu) **is easier** than ss. **We estimate** that the reduction in $D_s$ yield due to this fragmentation is a $(-15 \pm 10)\%$ effect.
Next **we estimate** the size of … $B \to DD_s$ modes have branching fractions that sum to about 5%. There are some additional decays … We add these and estimate an extra $(7 \pm 3)\%$ of $D_s$ mesons in $B_s$ decays produced by diagram Fig. 4(b). Taking into account all these contributions, we derive a **model dependent estimate** of $(100 + 7 - 15)\% = 92\%$. Therefore, we use $B(B_s \to D_s X) = (92 \pm 11)\%$.

# Future Measurement of $f_s$ @ Belle ?

R.Sia, S.Stone, Phys.Rev.D74:031501,2006

**Model Independent Methods for Determining $\mathcal{B}\left(\Upsilon(5S) \to B_S^{(*)}\overline{B}_S^{(*)}\right)$**

Radia Sia and Sheldon Stone
*Department of Physics, Syracuse University, Syracuse, New York 13244-1130*

Our first method for determining $f_s$ requires the measurement of like-sign versus opposite-sign dileptons. … We will assume here that the minimum lepton momentum requirement is large enough so that contamination from the decay sequence $B \to DX$, $D \to Y \ell\nu$ is negligible, or suitable corrections can be applied [6].

This technique relies on the fact that $B_s$ mixing oscillations are very rapid compared to $B_d$.

… we estimate that an error of $\pm 4\%$ on $f_s$ can be achieved with 30 $fb^{-1}$ of data.

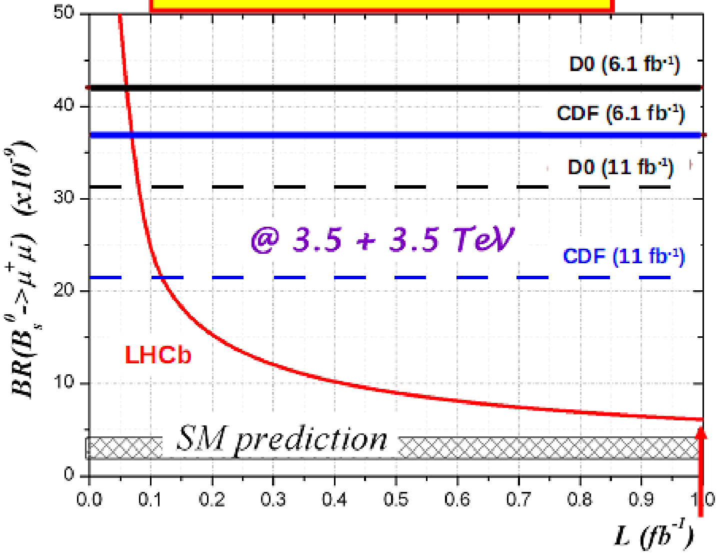
# MonteCarlo expectations

| Experiment | N sig | N bg |
|---|---|---|
| ATLAS ( 10 $fb^{-1}$ ) | 5.6 events | $14^{+13}_{-10}$ events (only bb→μμ) |
| CMS ( 1$fb^{-1}$ ) | 2.36 events | 6.53 events (2.5 bb→μμ) |

***Multivariate method to improve the sensitivity under study.***

***CMS Limit with 1$fb^{-1}$ (end 2011):***
***$BR(B_s^0 \rightarrow \mu^+\mu^-) < 1.6\cdot10^{-8}$***

Exclusion limit at 90% CL at √s=7 TeV




***LHCb for 2$fb^{-1}$***

| | $0.5 < GL < 0.65$ | $0.65 < GL < 1$ |
|---|---|---|
| $m_{\mu\mu} \in [5406.6, 5429.6]$ MeV/$c^2$ | $S = 0.23\,,\ B = 25^{+25}_{-14}$ | $S = 0.59\,,\ B = 8^{+24}_{-7}$ |
| $m_{\mu\mu} \in [5384.1, 5406.6]$ MeV/$c^2$ | $S = 1.14\,,\ B = 25^{+25}_{-14}$ | $S = 2.61\,,\ B = 8^{+24}_{-7}$ |
| $m_{\mu\mu} \in [5353.4, 5384.1]$ MeV/$c^2$ | $S = 3.45\,,\ B = 35^{+34}_{-19}$ | $S = 7.70\,,\ B = 12^{+23}_{-10}$ |
| $m_{\mu\mu} \in [5331.5, 5353.4]$ MeV/$c^2$ | $S = 1.35\,,\ B = 26^{+25}_{-14}$ | $S = 2.87\,,\ B = 9^{+24}_{-7}$ |
| $m_{\mu\mu} \in [5309.6, 5331.5]$ MeV/$c^2$ | $S = 0.41\,,\ B = 26^{+25}_{-14}$ | $S = 0.81\,,\ B = 9^{+24}_{-7}$ |

***LHCb result with 1$fb^{-1}$ (end 2011):***
***exclusion @90% CL***
BR($B_s^0 \rightarrow \mu^+\mu^-$)<7·10-9