# Rare decays at the LHC

## V Workshop Italiano sulla Fisica p-p a LHC

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on behalf of CMS, ATLAS and LHCb collaborations

# Outline

Antonio Policicchio (ATLAS)

- B-Physics at the LHC
- Experiment overview
  - ATLAS and CMS muon trigger for B-Physics
- Rare semileptonic decays

Nicola Serra (LHCb)

- $B_s \to \mu^+\mu^-$
- $B \to e\mu$

Roberto Covarelli (CMS)

- Inclusive cross section measurements
- LFV in $\tau$ decays
- Conclusions

# Rare decays at the LHC

Part I

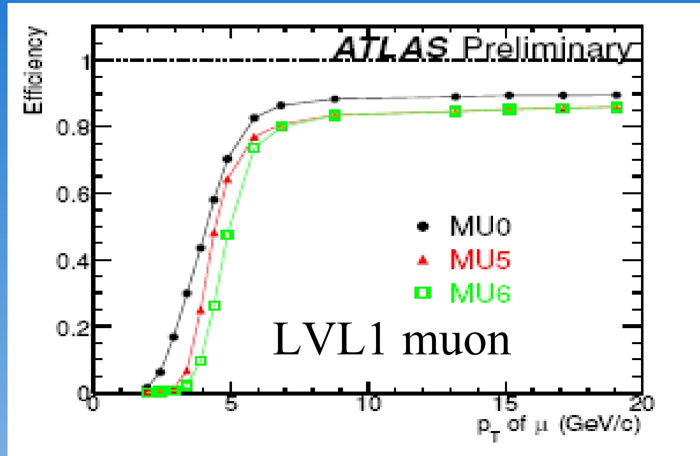
B-Physics at the LHC
Experiment overview
Rare semileptonic decays

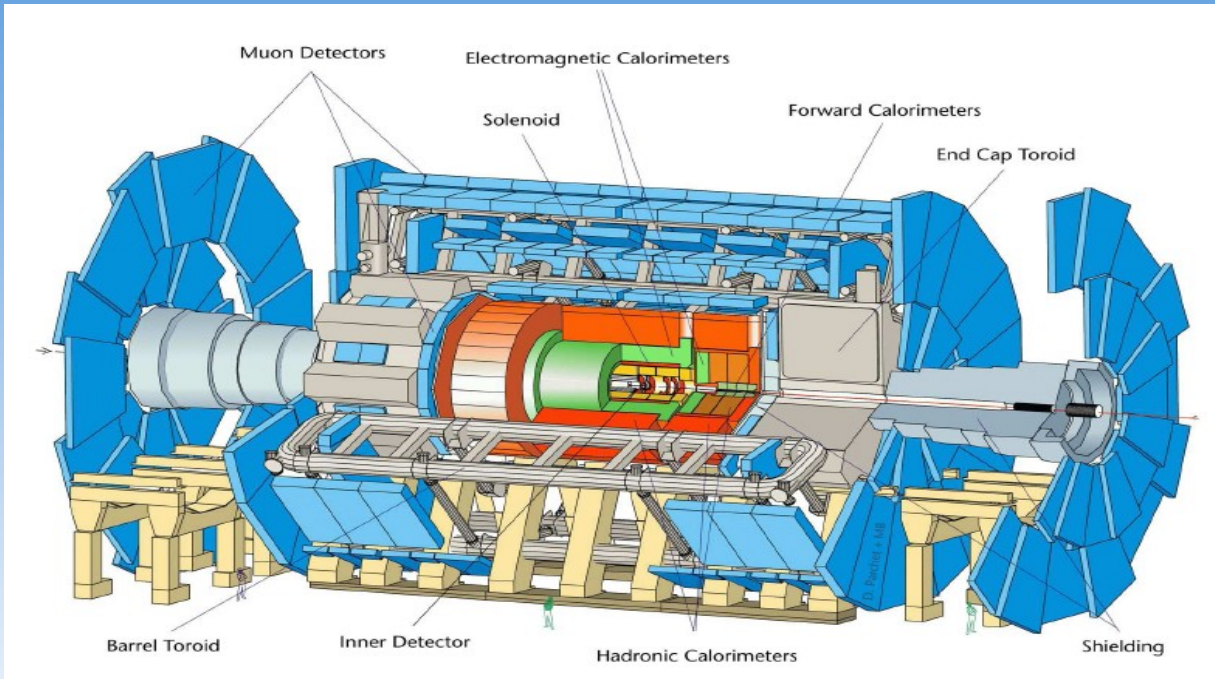
# B-Physics at the LHC

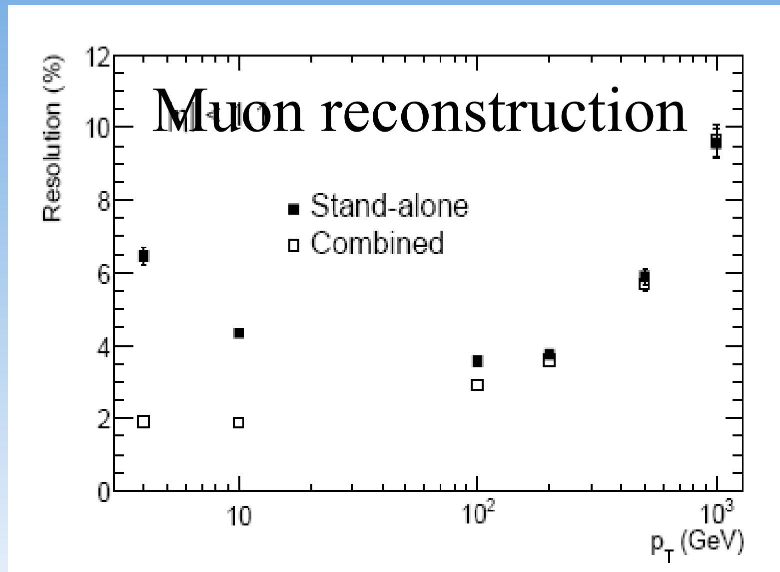
- LHC: proton-proton collisions at $\sqrt{s}$=14TeV and bunch crossing rate 40MHz
- High b-bbar production cross section: σ(bb)~500μb
  - $B_s$ system can be fully explored at the LHC
  - B-baryons accessible at the LHC
- LHCb designed to B-physics studies
- ATLAS and CMS design dedicated to high-$p_T$ physics
  - B-events trigger and analysis are a challenge due to low b mass
  - B-decays with muons in the final state are the most promising
- B-Physics programme
  - b-bbar inclusive cross-section (first day physics)
  - angles of the UT
  - $B_q$ mixing
  - rare decays
  - LFV

# ATLAS detector

- ATLAS is a general purpose detector
  - $|\eta|<2.5$ and full $\phi$
  - B-physics using trigger with relatively high $p_T$ muons
  - good muon resolution in tracker and spectrometer

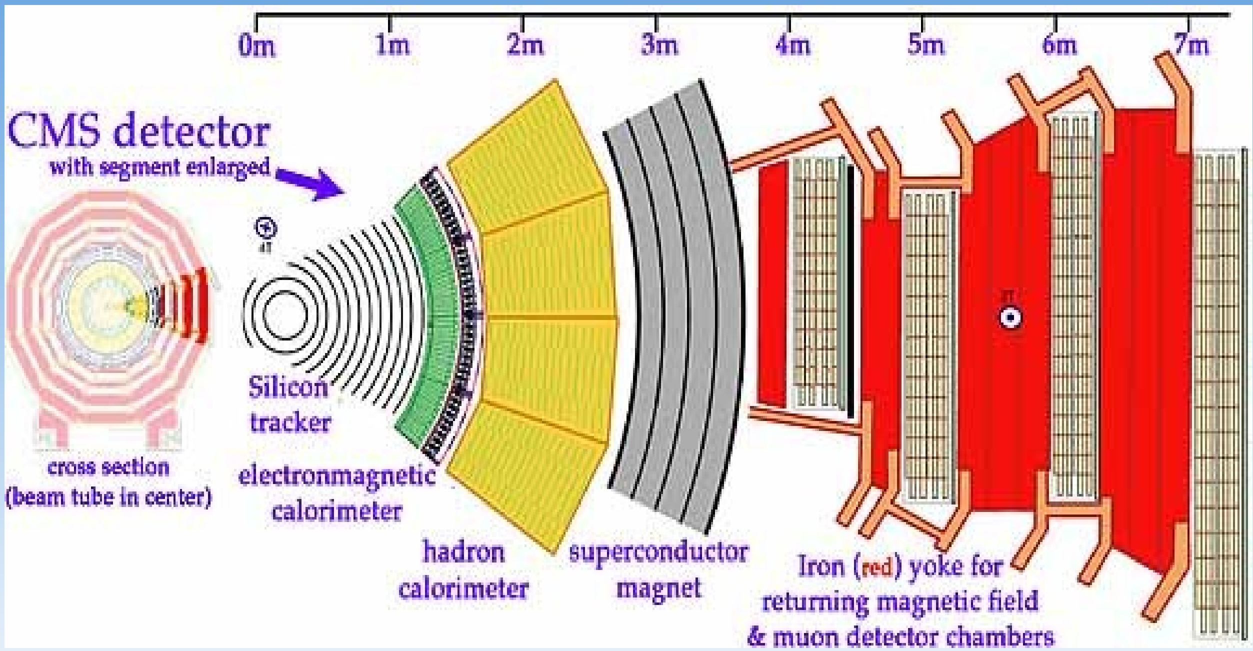


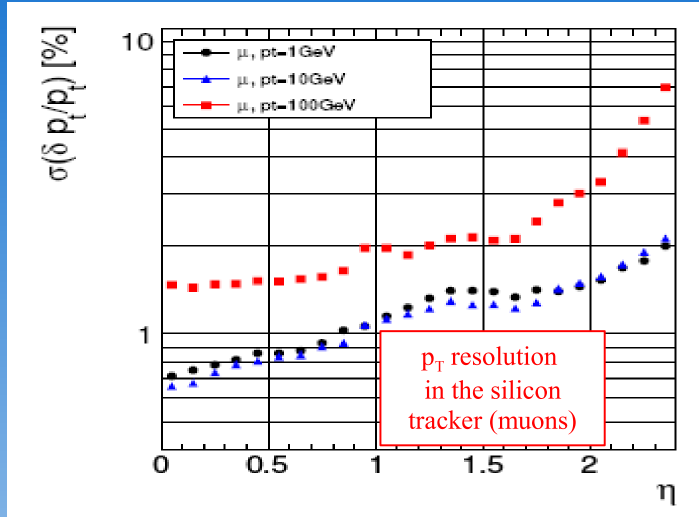



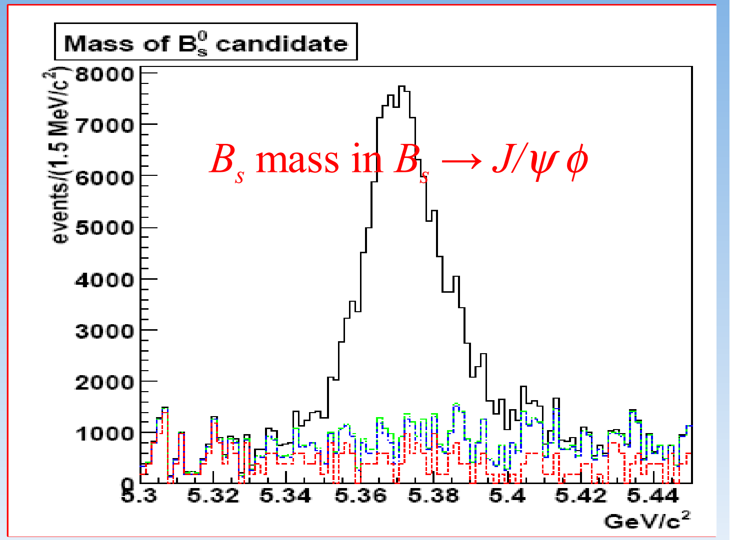



# CMS detector

- CMS is a general purpose detector
  - ~4π acceptance
  - B-physics focusing on muon/di-muon triggered event
  - good muon resolution in tracker and muon system
    - high magnetic field



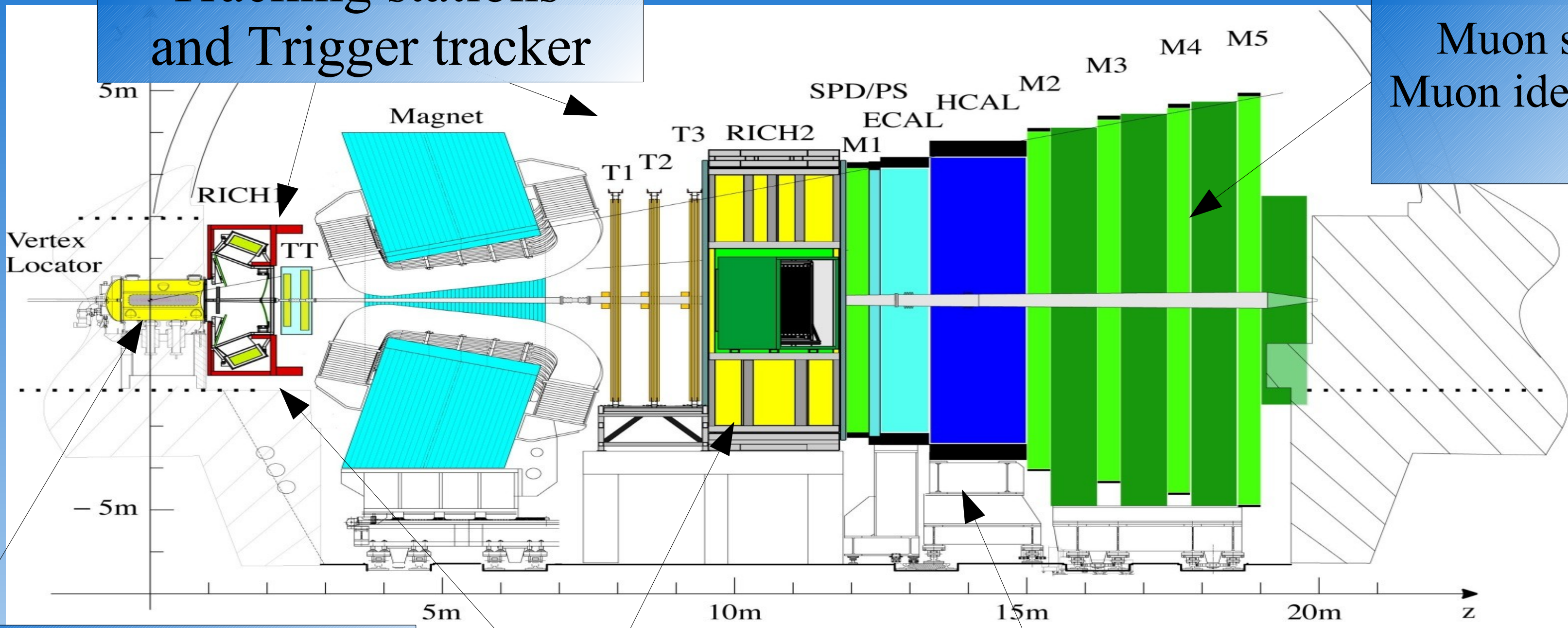



# LHCb detector

Tracking stations and Trigger tracker

Muon stations: Muon identification




**VELO: PV and IP reconstruction, track measurement close to the interaction point.**

RICH1 and RICH2: very good π/K separation

**ECAL and HCAL: e, $\pi^0$,γ identification and energy measurement**

- Cross section of b-bbar production in LHCb acceptance ~ 230 μb
- Luminosity is limited to $2*10^{32}cm^{-2}s^{-1}$ by not focusing the beams

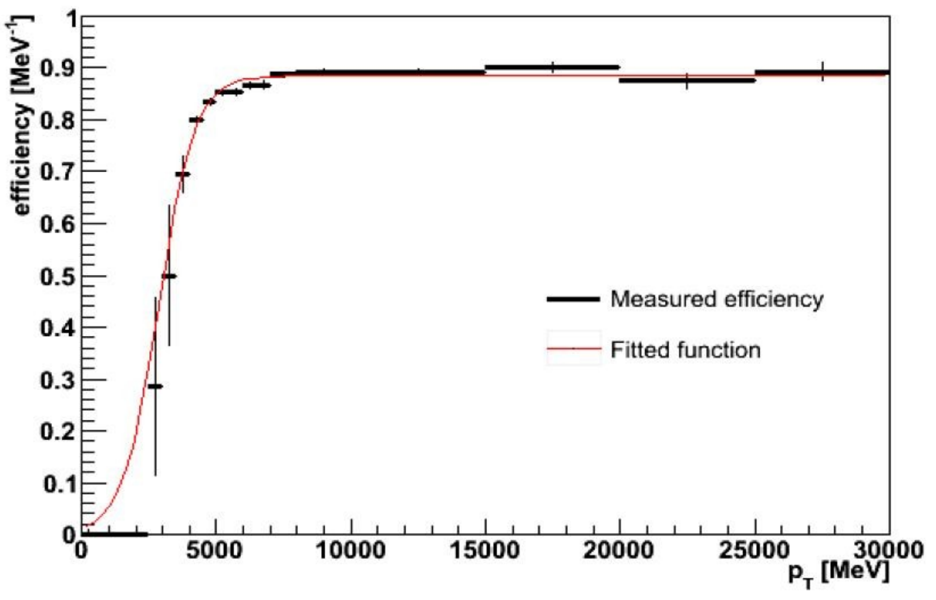
# ATLAS trigger for B-decays with 2μ in the final state

- LVL1
  - 2μ RoI with $p_T(\mu)$>6(4)GeV
- LVL2
  - confirm each μ RoI with precision muon chamber and inner detector measurements
  - dimuon vertex reconstruction and cuts on invariant mass
- EF
  - refit inner detector tracks
  - decay vertex reconstruction
  - proper time cut
  - angular distribution cuts
- Output rate <10Hz

| | Efficiency [%] | |
|---|---|---|
| Process | $B_s^0 \to \mu^+\mu^-$ | $B^+ \to J/\psi(\mu^+\mu^-)K^+$ |
| Trigger Menu | generated events | |
| MU0 | 97.0±0.1 | 96.8±0.1 |
| MU6 | 93.0±0.1 | 92.9±0.1 |
| 2MU0 | 67.9±0.2 | 68.8±0.2 |
| 2MU6 | 51.6±0.2 | 52.9±0.2 |

| Trigger Menu | Efficiency (%) $B_s^0 \to \mu^+\mu^-\phi$ |
|---|---|
| | generated events |
| MU0 | 97.0±0.1 |
| MU6 | 93.1±0.1 |
| 2MU0 | 69.0±0.2 |
| 2MU6 | 53.2±0.2 |

LVL2 di-muon trigger seeded by 2 LVL1 RoIs



# CMS muon and di-muon trigger

- Level 1 trigger (hardware – muon stations only):

| Trigger *(low luminosity)* | Threshold (GeV or GeV/c) | Rate (kHz) |
|---|---|---|
| Inclusive isolated muon | 14 | 2.7 |
| Di-muons | 3 | 0.9 |

| Trigger *(high luminosity)* | Threshold (GeV or GeV/c) | Rate (kHz) |
|---|---|---|
| Inclusive isolated muon | 20 | 6.2 |
| Di-muons | 5 | 1.7 |

- High-level trigger (software – muon and tracker):
    - tighter $p_T$ cut
    - pixel track seeds
    - partial track reconstruction up to 6 tracker hits or $\Delta p_T/p_T < 0.02$
  - for di-muon trigger:
    - opposite charge
    - possibility to add an invariant mass cut
  - "displaced" di-muon
    - add requirements on secondary vertex $\chi^2$ and flight length

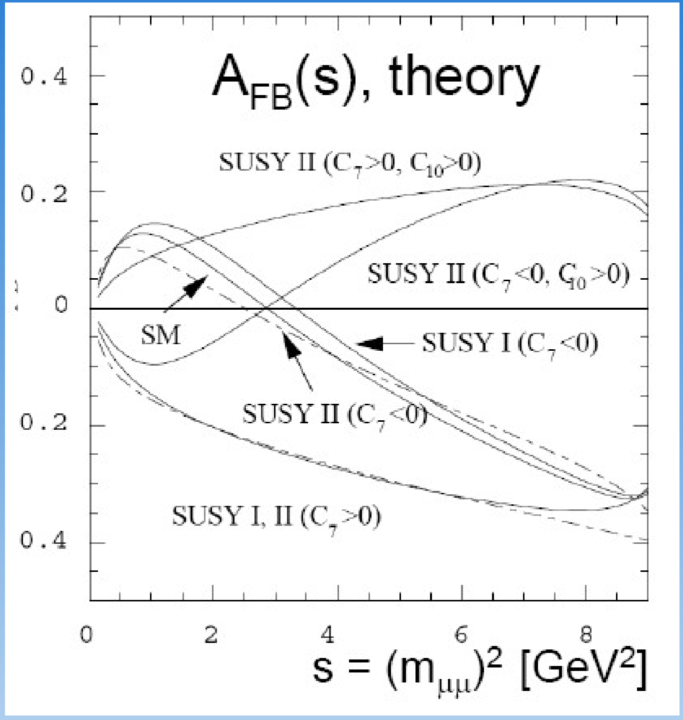
Di-muon background rate:
4 Hz

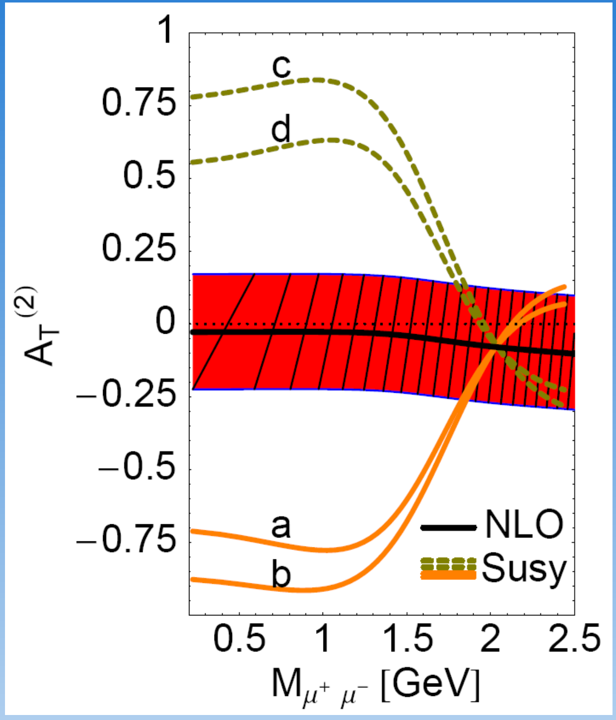
Requiring e.g.:
- displaced
- $|m(\mu\mu) - m(B_s)| < 150$ MeV/$c^2$

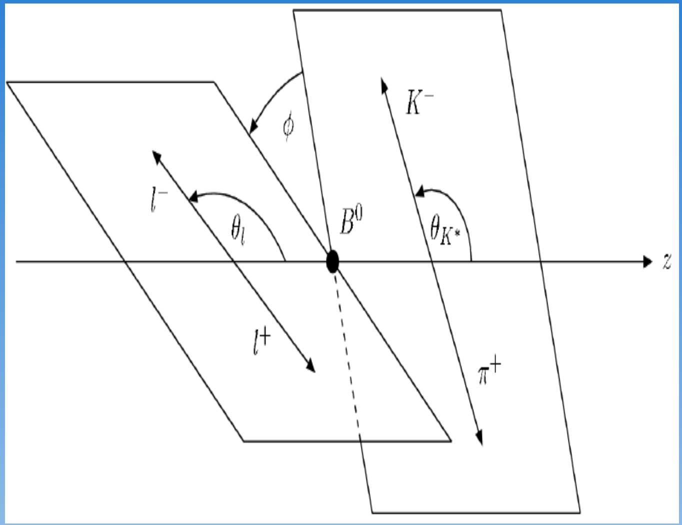
< 1.7 Hz

# Semileptonic rare decays

- Indirect effects of new physics mainly in forward-backward and transverse asymmetries




Forward-Backward Asymmetry in $\theta_l$:

$$A_{FB}(s) = \frac{\int_0^1 \frac{d^2\Gamma}{dsdcos\theta} dcos\theta - \int_{-1}^0 \frac{d^2\Gamma}{dsdcos\theta} dcos\theta}{\int_0^1 \frac{d^2\Gamma}{dsdcos\theta} dcos\theta + \int_{-1}^0 \frac{d^2\Gamma}{dsdcos\theta} dcos\theta}$$

Transverse Asymmetry:
(asymmetry in the spin amplitude of the K*). This asymmetry can be extracted by fitting:

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

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

# Semileptonic rare decays in ATLAS (1)

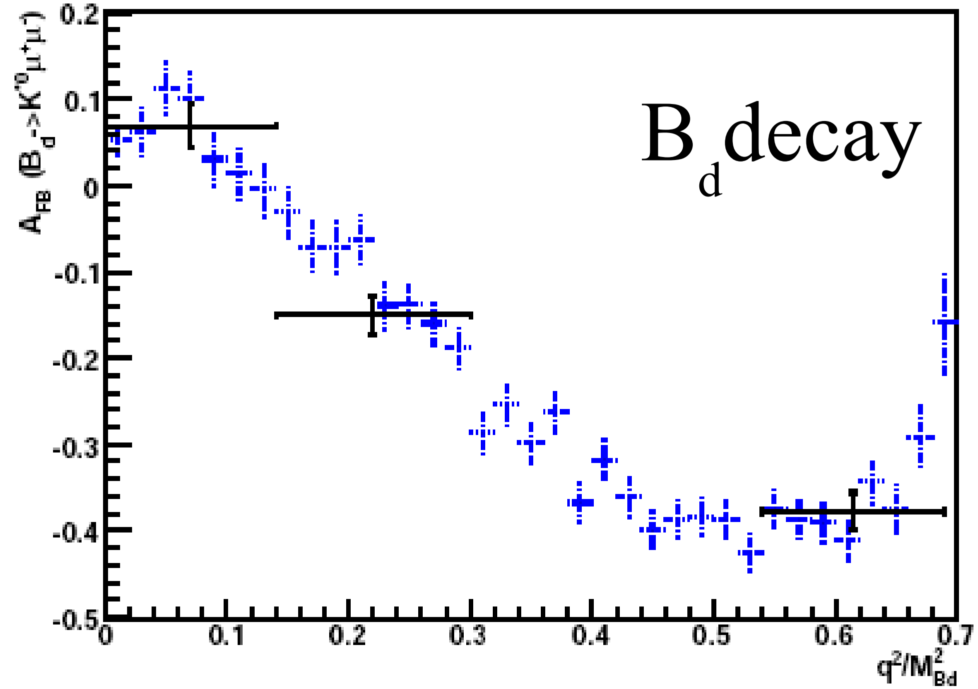
- $B^+ \to K^+\mu^+\mu^-$ , $B^+ \to K^{*+}\mu^+\mu^-$ , $B_d \to K^{0*}\mu^+\mu^-$, $B_s \to \phi\, \mu^+\mu^-$, $\Lambda_b \to \Lambda^0\mu^+\mu^-$
- Background sources
  - channels with $J/\Psi$ and $\Psi(2S)$ resonances: irreducible background, cut on dimuon invariant mass
  - combinatorial background
    - Semileptonic decays of both b and b-bar quarks
    - Double semileptonic decay of b quark ( $b \to c\mu\nu$, $c \to s\mu\nu$ )
      - topological and vertex requirements to eliminate this background
  - kaons and pions misidentification as muons: their contribution is expected poor with respect to combinatorial background
- Analysis variables
  - dimuon vertex with $\chi^2/NDF<3$
  - dimuon mass in kinematical allowed window excluding $J/\Psi$s areas $m_{\mu\mu} \notin [m_\Psi \pm 3\sigma]$
  - s-hadron reconstruction with vertex $\chi^2/NDF<3$, $p_T$ and decay length (for long-lived particles) and mass in $m_h \pm 3\sigma$
  - b-hadron vertex with $\chi^2/NDF<3$
  - b-hadron mass in $m_B \pm 3\sigma$ and proper time > 0.5ps

# Semileptonic rare decays in ATLAS (2)

- Signal after $30fb^{-1}$

| Decay Channel | Signal | Background |
|---|---|---|
| $B^+ \to K^+\mu^+\mu^-$ | 4000 | <10000 |
| $B^+ \to K^{*+}\mu^+\mu^-$ | 2300 | <10000 |
| $B_d \to K^{0*}\mu^+\mu^-$ | 2500 | <10000 |
| $B_s \to \phi\ \mu^+\mu^-$ | 900 | <10000 |
| $\Lambda_b \to \Lambda^0\mu^+\mu^-$ | 800 | <4000 |

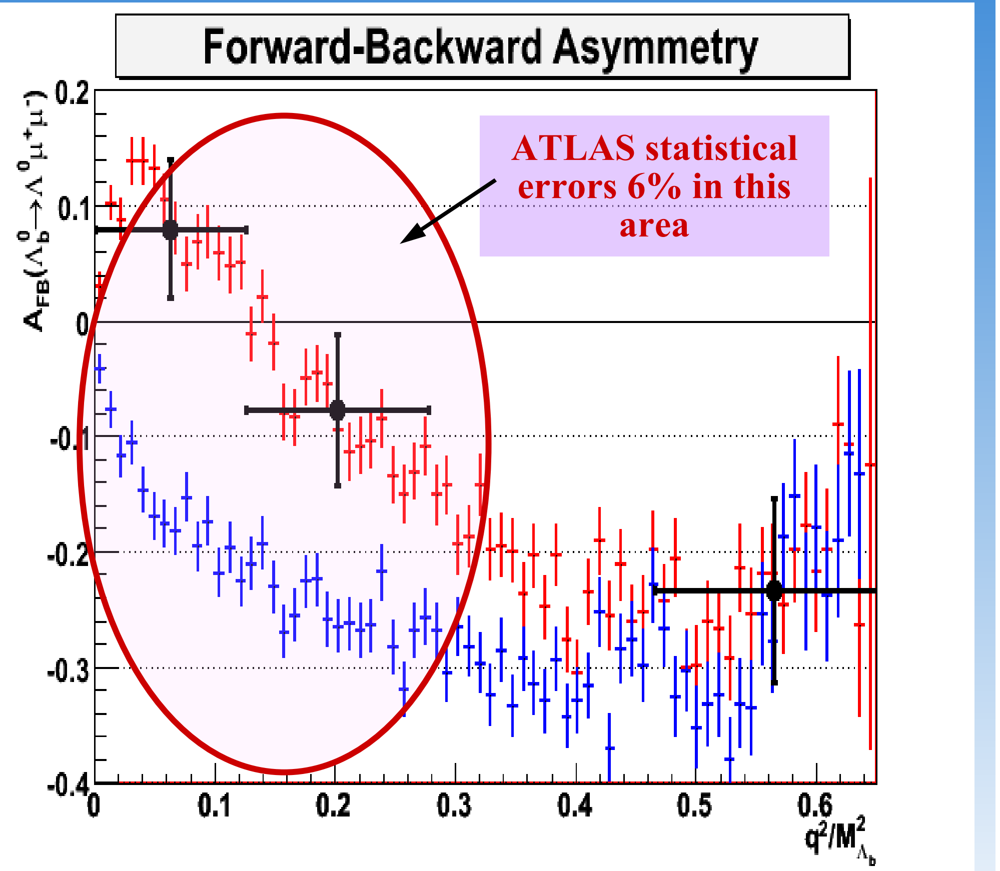
- Good sensitivity to forward-backward asymmetry measurements
- overall trigger efficiency ~40%




| Interval of $q^2/M_B^2$ | $0.00-0.14$ | $0.14-0.33$ | $0.55-0.71$ |
|---|---|---|---|
| Number of events | 570 | 540 | 990 |
| Statistical error | 4.2% | 4.3% | 3.2% |
| $A_{FB}$ SM prediction | 10% | $-14\%$ | $-29\%$ |

# Semileptonic rare decays in ATLAS (3)

- $\Lambda_b \rightarrow \Lambda^0\mu^+\mu^-$ decay: after 3 years @ $10^{33}cm^{-2}s^{-1}$ ATLAS can distinguish MSSM ($C_{7eff}$>0) from SM in the region with low values of dimuon mass
- The study on semileptonic rare decays is yet limited by the size of the background MC sample
- Further BG and HLT efficiency studies are ongoing




•ATLAS expected events after 3 years @ $10^{33}cm^{-2}s^{-1}$
•ATLAS MC events generated with SM
•ATLAS MC events generated with MSSM ($C_{7eff}$>0)

# Semileptonic rare decays in CMS

- $B_d \to K_s\mu^+\mu^-$, $B_s \to \phi\,\mu^+\mu^-$, $\Lambda_b \to \Lambda^0\mu^+\mu^-$
- Studies just started
- No $V^0$ particle: $B_s \to \phi\mu^+\mu^-$
  - Preliminary efficiency estimation after reconstruction and L1 trigger emulator: $\varepsilon = 0.27\%$
  - ~2700 events/year expected with Standard Model BR
- With $V^0$ particles: $B_d \to K_S\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$:
  - Preliminary study on $B_d \to K_S\mu^+\mu^-$
  - ~800 events/year expected with Standard Model BR
  - $K_S$ vertex reconstruction
    - x-y position > $4\sigma$ and < 4.0 cm from beamline
    - $|M(K_S) - M_{PDG}(K_S)| < 15$ MeV/$c^2$
    - No pion track hits inside $K_S$ vertex
    - Large benefit from iterative tracking. $\varepsilon_{track}$: 16% → 61%

# Semileptonic rare decays in LHCb (1)

## $B_d \to K^{*0} \mu^+ \mu^-$

| Cut Variable | Preselection cut value | Selection cut value |
|---|---|---|
| $B_d^0$ mass window | $\pm 500 MeV/c^2$ | $\pm 50 MeV/c^2$ |
| $B_d^0$ $P_t$ | $> 250 MeV/c$ | $> 250 MeV/c$ |
| $B_d^0$ vertex $\chi^2$ | $< 50$ | $< 20$ |
| $B_d^0$ Pointing angle | $< 141 mrad$ | $< 22 mrad$ |
| $B_d^0$ FS | – | $> 6$ |
| $B_d^0$ sIPS | $< 8$ | $< 5$ |
| $B_d^0$ Vertex Isolation | – | 11 |
| $K^{*0}(892)$ mass window | $\pm 300 MeV/c^2$ | $\pm 100 MeV/c^2$ |
| $K^{*0}(892)$ $P_t$ | $> 300 MeV/c$ | $> 300 MeV/c$ |
| $K^{*0}(892)$ vertex $\chi^2$ | $< 30$ | $< 30$ |
| $K^{*0}(892)$ FS | – | $> 1$ |
| $K^{*0}(892)$ sIPS | $> 1.5$ | $> 1.5$ |
| $K^{\pm}$ $P$ | $> 2000 MeV/c$ | $2000 MeV/c$ |
| $K^{\pm}$ $P_t$ | $250 MeV/c$ | $400 MeV/c$ |
| $K^{\pm}$ sIPS | $> 1.5$ | $> 3$ |
| $\mu\mu$ excluded mass window | – | $J/\psi(1S, 2S)$ mass rejection $2900 - 3200 MeV/c^2$ and $3650 - 3725 MeV/c^2$ |
| $\mu\mu$ vertex $\chi^2$ | – | $< 15$ |
| $\mu\mu$ flight-distance | – | $> 1mm$ |
| $\mu^{\pm}$ $P$ | $> 4000 MeV/c$ | $4000 MeV/c$ |
| $\mu^{\pm}$ $P_t$ | $300 MeV/c$ | $500 MeV/c$ |
| $\mu^{\pm}$ sIPS | $> 0.5$ | $> 2.0$ |

### Background

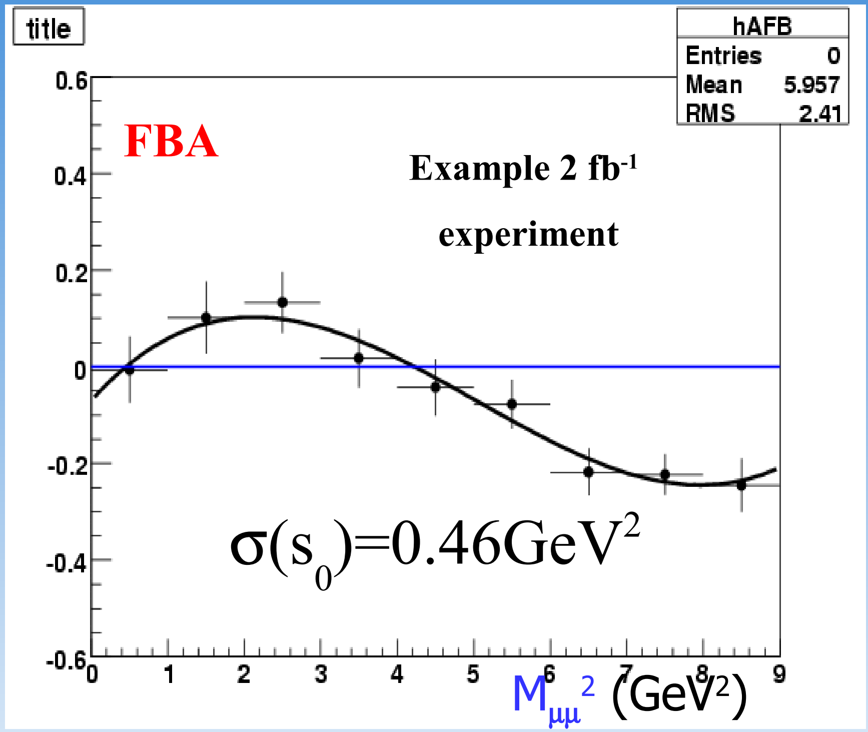
| MC sample | No. of events per $2fb^{-1}$ |
|---|---|
| $B_{d,u} \to s\mu\mu$ (no K*) | $9 \pm 3$ |
| $b\to\mu$, $b\to\mu$ | $1050\pm250$ |
| $b\to\mu$, $c\to\mu$ | $690\pm180$ |
| **Total** | **$1770\pm310$** |

Expected signal yield for $2fb^{-1}$
$7200 \pm 180(\text{stat.}) \pm 2200$ (BR)

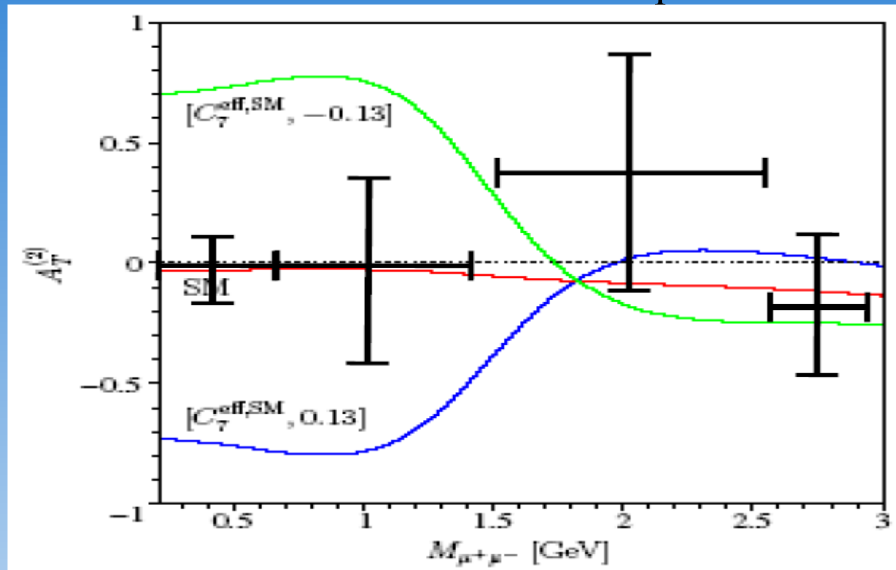
# Semileptonic rare decays in LHCb (2)

## $B_d \rightarrow K^{*0} \mu^+ \mu^-$

Expected FBA as a function of the di-muon in $2fb^{-1}$ .




Possible measurement of $A_T^2$ in $2fb^{-1}$

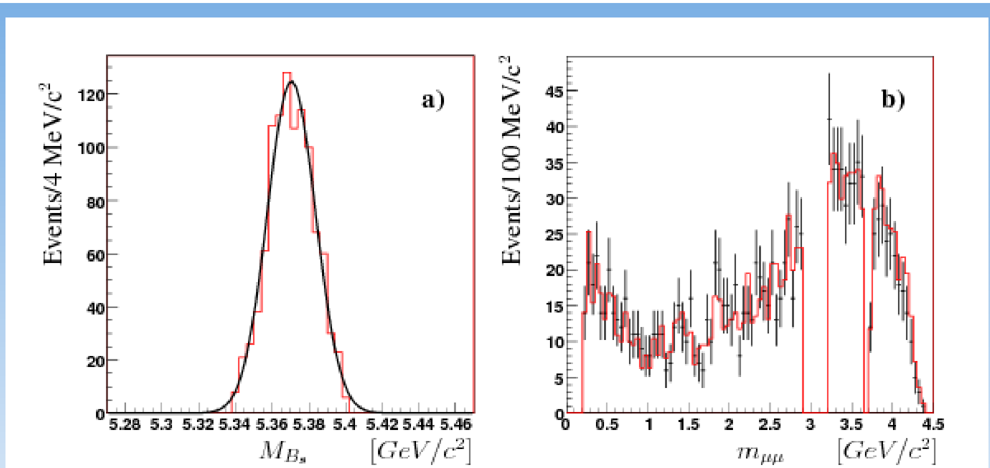



Sensitivity

| | $2fb^{-1}$ | $10fb^{-1}$ |
|---|---|---|
| $A_T^2$ | ±0.42 | ±0.16 |
| $A_{FB}$ | ±0.020 | ±0.008 |

# Semileptonic rare decays in LHCb (3)

| Cut variable | Preselection cut value | Selection cut value | Efficiency, % |
|---|---|---|---|
| $\chi^2_{IP}$ of kaons | $> 4$ | $> 25$ | 82 |
| $\chi^2_{IP}$ of muons | $> 4$ | $> 25$ | 89 |
| $\chi^2_{IP}$ of $B_s$-candidate | $< 50$ | $< 9$ | 95 |
| $\chi^2$ of $B_s$ decay vertex | $< 25$ | $< 12$ | 88 |
| $\theta_B$ | $< 50$ mrad | $< 10$ mrad | 98 |
| Mass region for $\phi$-candidate | $< 1.06$ GeV/c$^2$ | $\pm 10$ MeV/c$^2$ | 89 |
| Mass region for $B_s$-candidate | [4.0-8.0] GeV/c$^2$ | $\pm 30$ MeV/c$^2$ | 95 |
| $J/\psi$, $\psi(2S)$ mass rejection | | [2.9-3.2] GeV/c$^2$, [3.65-3.73] GeV/c$^2$ | 86 |




## $B_s \to \phi\, \mu^+ \mu^-$

1340±250 signal events/2fb$^{-1}$ with B/S<0.7 at 90%

Asymmetry sensitive to NP in this channel are still under study at present.

$\Lambda_b \to \Lambda^0 \mu^+ \mu^-$ channel under study

# Semileptonic rare decays in LHCb (4)

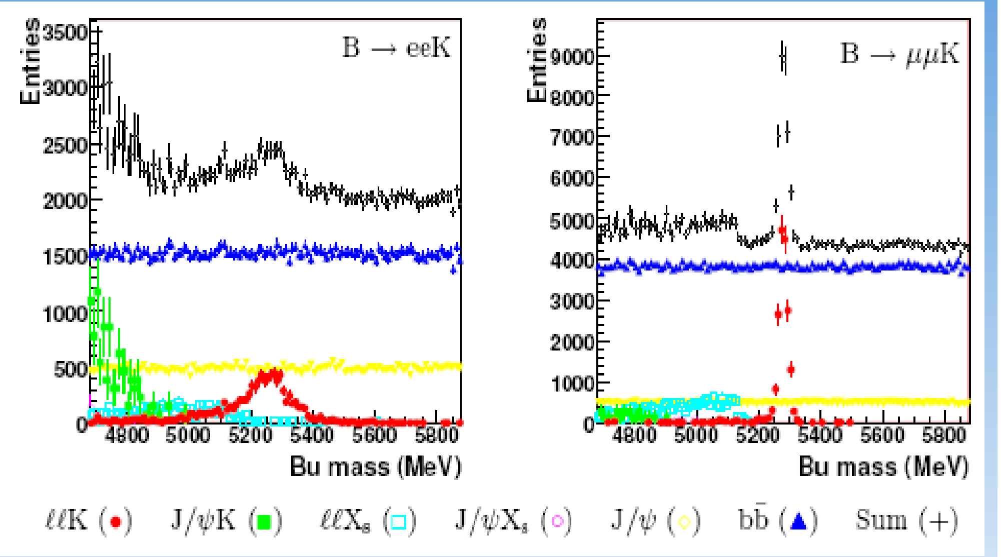
## BR(B→Xμ⁺μ⁻)/BR(B→Xe⁺e⁻) ratio

$$R_{\mathbf{X}} = \frac{\int_{4m_\mu^2}^{q^2_{\max}} ds \frac{d\Gamma(\mathbf{B}\to\mathbf{X}\mu^+\mu^-)}{ds}}{\int_{4m_\mu^2}^{q^2_{\max}} ds \frac{d\Gamma(\mathbf{B}\to\mathbf{X}e^+e^-)}{ds}} \stackrel{\text{SM}}{=} \begin{cases} 1.000 \pm 0.001 & \mathbf{X} = \mathbf{K} \\ 0.991 \pm 0.002 & \mathbf{X} = \mathbf{K}^* \end{cases}$$

SM prediction can get corrections of ~10% due to Higgs boson exchange
(Hiller & Krüger, PRD69 (2004) 074020)

| | Signal | Mean | Sigma |
|---|---|---|---|
| eeK | 349±34 | 5245 MeV | 74 MeV |
| μμK | 1550±5 | 5279 MeV | 15 MeV |

$\sigma_{Rk}(2fb^{-1}) \approx 10\%$
$\sigma_{Rk}(10fb^{-1}) \approx 4\text{-}6\%$




$R_{K^*}$ under study

# Rare decays at the LHC

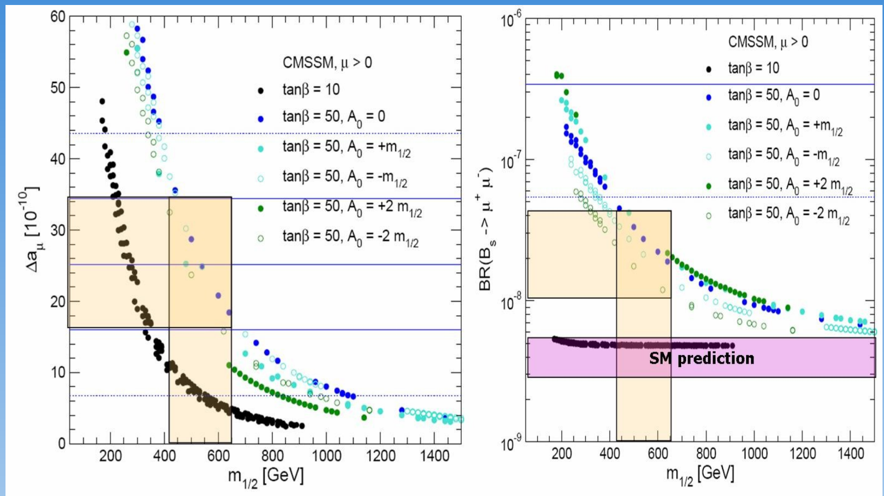
Part II

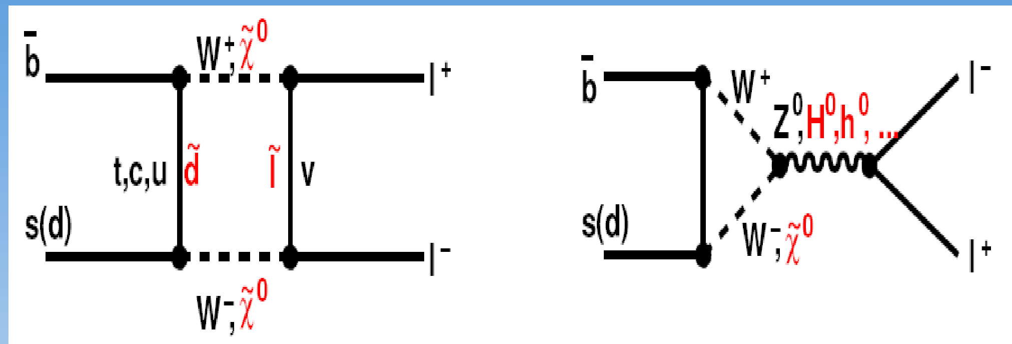
$B_s \rightarrow \mu^+\mu^-$

$B \rightarrow e\mu$

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

SM Prediction: $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \cdot 10^{-9}$
Sensitive to SUSY models at large tang(Beta) (see Cecilia's talk)




(*) A.Buras et. al. Phys.Lett.B. 566 (2003) 115

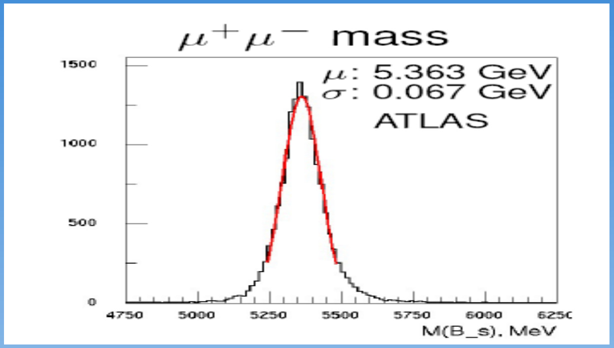
- CDF - DØ combined measurement
  $BR(B_s \to \mu^+\mu^-) < 4.5 \cdot 10^{-8}$ @ 95% CL

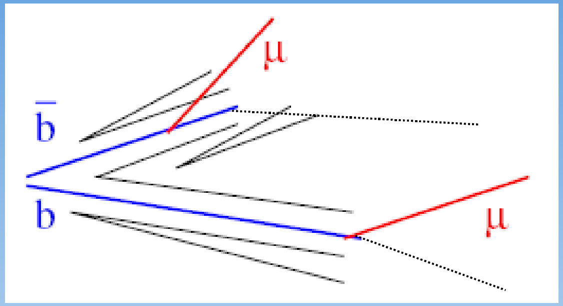
# $B_s^0 \to \mu^+\mu^-$: Signal and Background

Signal and background:

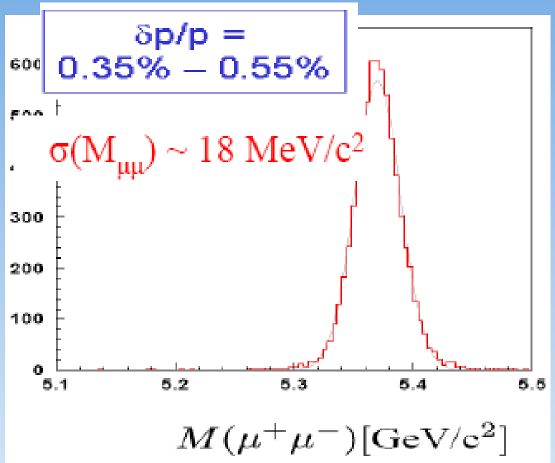
- b-bbar decaying semileptonically;
- B->hh decay modes (h = π, K );
- Specific decay modes (i.e. $B_c^{\pm} \to J/\Psi(\mu\mu)\mu^{\pm}\nu$ )

ATLAS: σ(Inv Mass)~67MeV

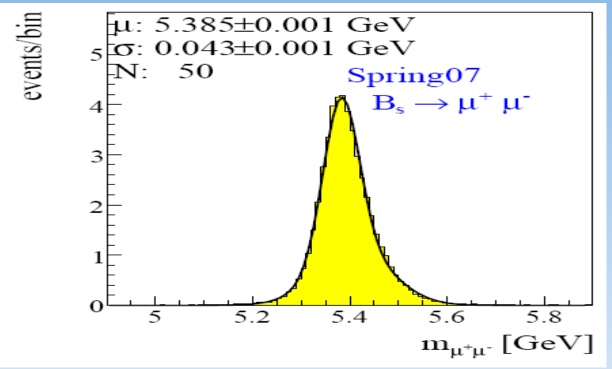


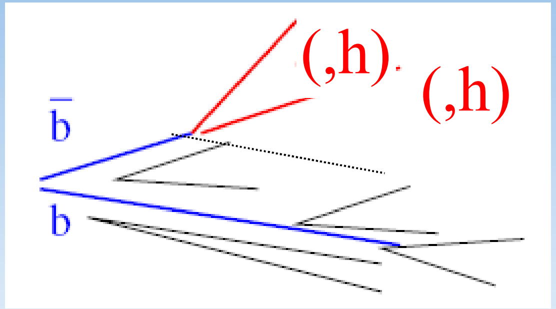




LHCb: σ(Inv Mass)~18MeV




CMS: σ(Inv Mass)~47MeV

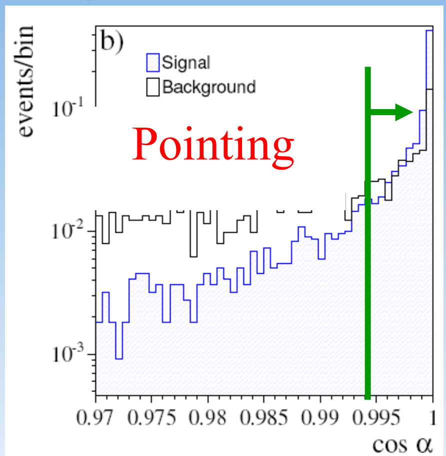


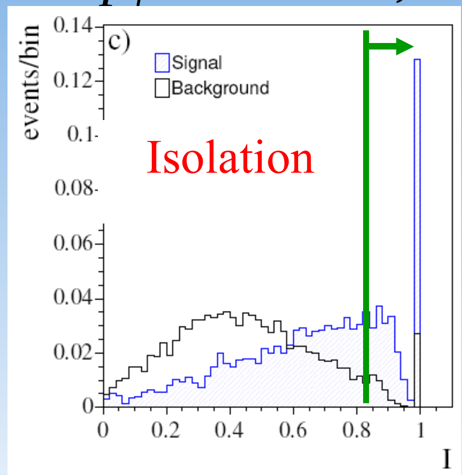



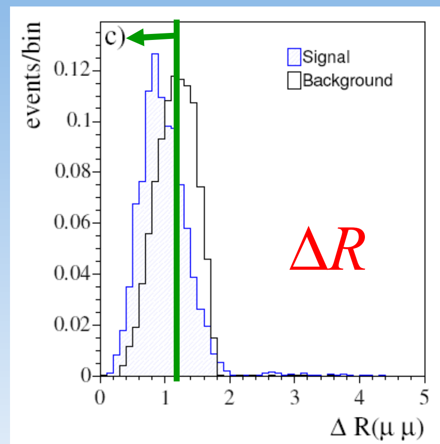
# $B_s^0 \to \mu^+\mu^-$ at CMS

CMS Variables:

- Di muon separation: $\Delta R = (\sqrt{\Delta\phi^2 + \Delta\eta^2})_{\mu\mu}$
- Pointing Angle: $\cos(\alpha)$
  (angle between the B_s momentum and the vector from PV to SV)
- Flight length significance
- $X^2$ of secondary vertex fit
- Isolation of B_s flight direction: $I = \frac{P_t(B_s^0)}{P_t(B_s^0) + \sum p_t}$
  (sum over all tracks with $p_t > 0.9\text{GeV}$, in a cone of $R = 1.0$)



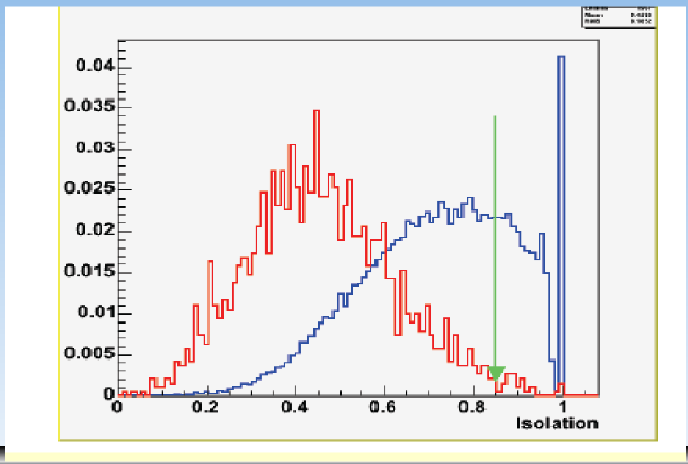



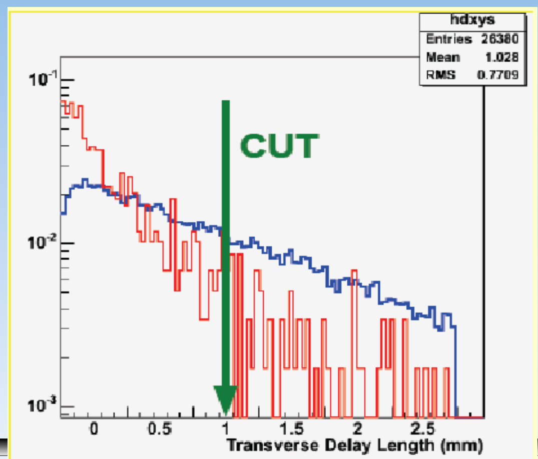



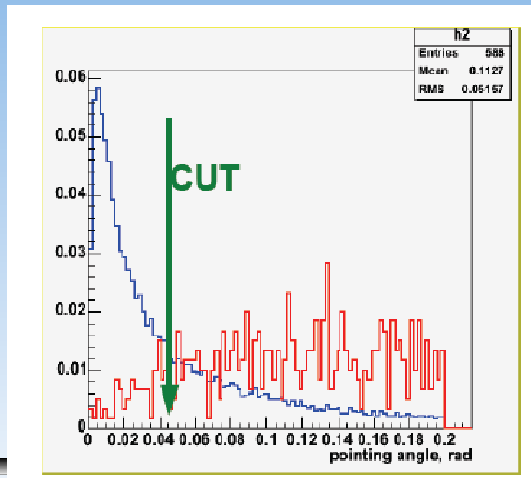
# $B_s^0 \rightarrow \mu^+\mu^-$ at ATLAS

ATLAS Variables:

- Pointing Angle: $\alpha < 1^o$
  (angle between the B_s momentum and the vector from PV to SV)
- Flight length distance on the transverse plane $> 0.5$mm
- $X^2 < 10$ of secondary vertex fit
- Isolation of B_s flight direction: $I = \dfrac{P_t(B_s^0)}{P_t(B_s^0) + \sum p_t} > 0.9$
  (sum over all tracks within a cone of $R = 1.0$)
- Invariant Mass window: $Mass(\mu, \mu) = Mass(B_s^0)^{+90\text{MeV}}_{-180\text{MeV}}$



# $B_s^0 \to \mu^+\mu^-$ : Atlas and CMS

Expected signal and background in 10fb$^{-1}$

CMS

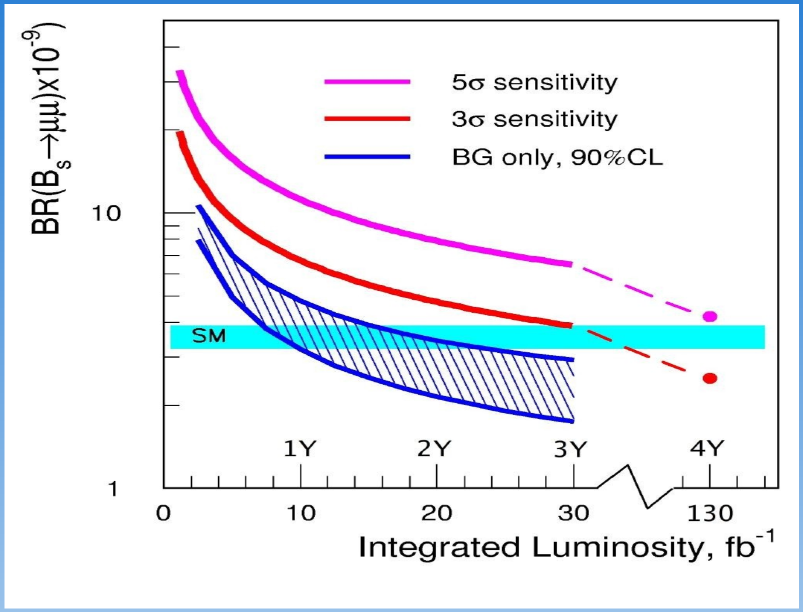
- Signal and background yields:

  $n_S = 6.1 \pm 0.6_{(syst).}$ $n_B = 13.8\ ^{+22.0}_{-12.8\ (syst).}$

ATLAS

- Signal and background yields:

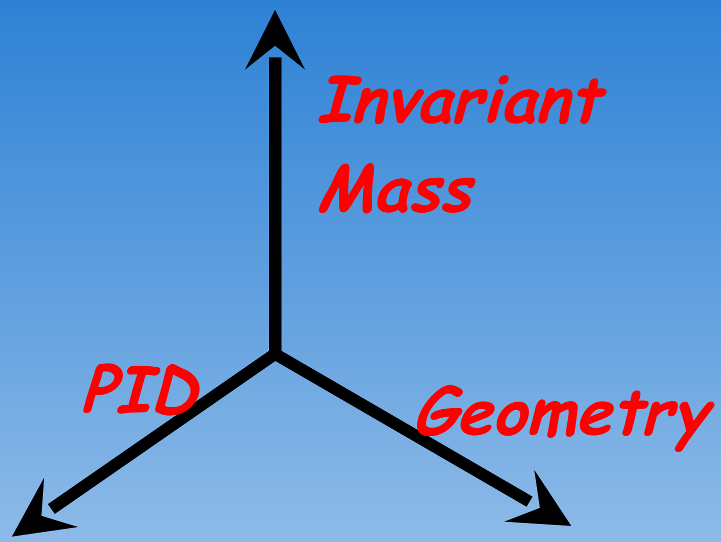
  $n_S = 5.7_{.}$ $n_B = 14 \pm 10_{.}$




Same level of signal and background after the off-line selection.

# LHCb Analysis Strategy

- Soft Preselection
- Selection:
  - combine the discriminant variables in a Geometrical Likelihood
  - PID
  - Invariant Mass



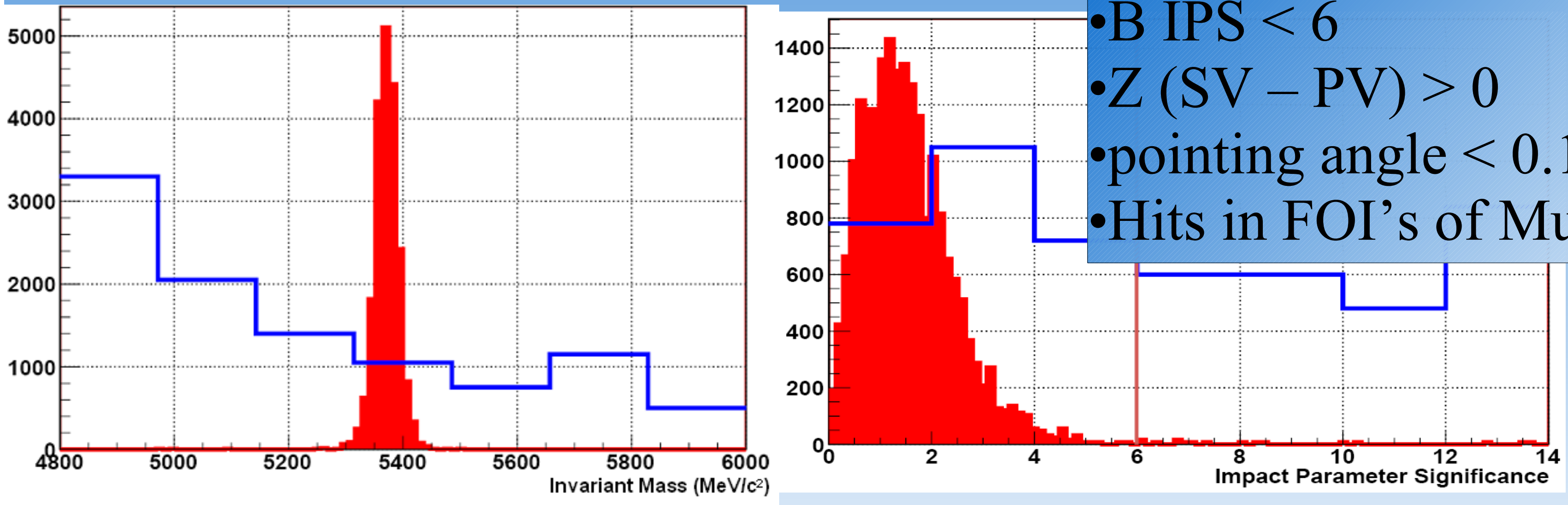

- N counting experiment:
  - Evaluate the expected numbers of events in each bin of the three dimensional space
  - compute CL for exclusion and observation in 3D

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

Very good invariant mass resolution ($\sigma$(InvMass)~18MeV) and particle identification performances (95% efficiency for 0.6% of missID pions).

After a preselection with soft cuts, a multidimensional analysis where applied.
~400k background events/fb$^{-1}$ .
35.4 signal events/fb$^{-1}$.

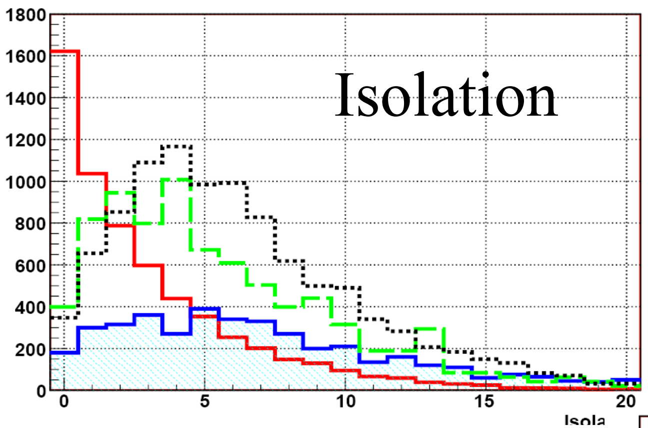
- Mass window: 60 MeV
- Vertex Chi2 < 14
- B IPS < 6
- Z (SV – PV) > 0
- pointing angle < 0.1 rad
- Hits in FOI's of Muon Chambers

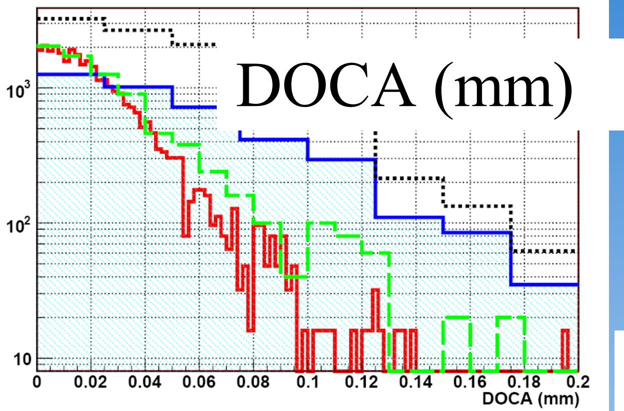


# $B_s^0 \to \mu^+\mu^-$ at LHCb: Selection

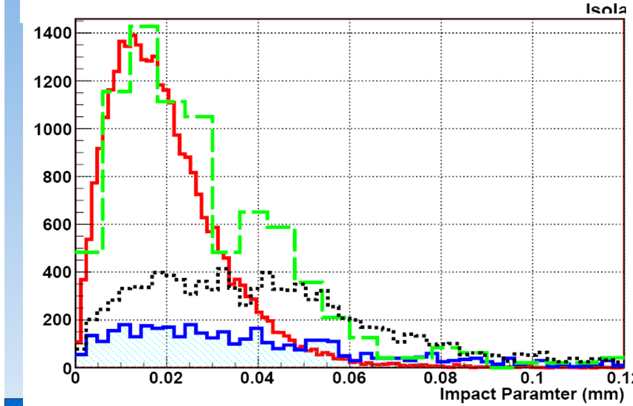
- **Geometrical likelihood**: [0,1]
- **PID Likelihood**: [0,1] (Combines DLL(μπ) DLL(μK) of both 'muons')
- **Invariant Mass**: [-60, +60] around Bs peak

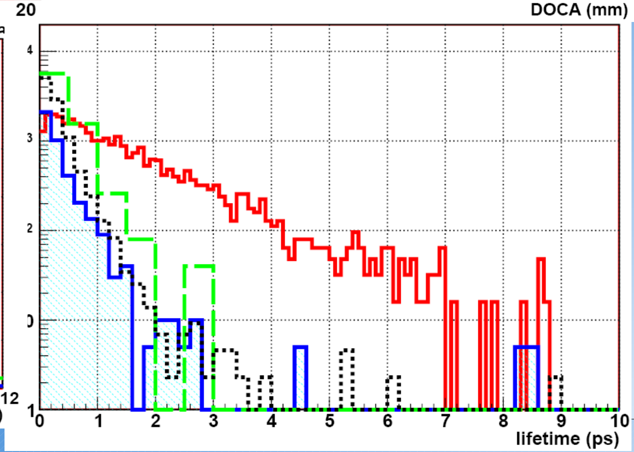
*Red*: signal
*Blue*: bb inc.
*Black*: b→μ
b→μ
*Green*:
Bc+ → J/Ψμν

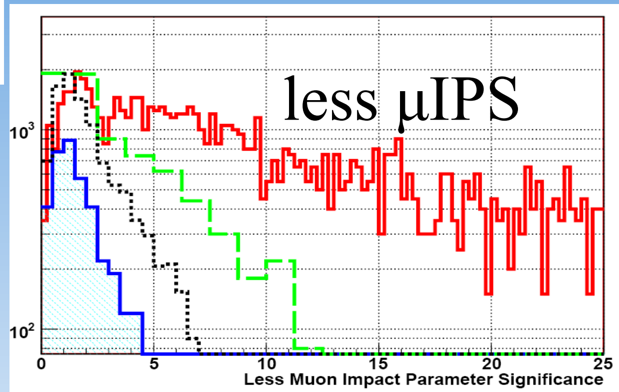



The variables are '*gaussianized*' and de-correlated, then $\chi^2_S - \chi^2_b$ is used to separate signal and background



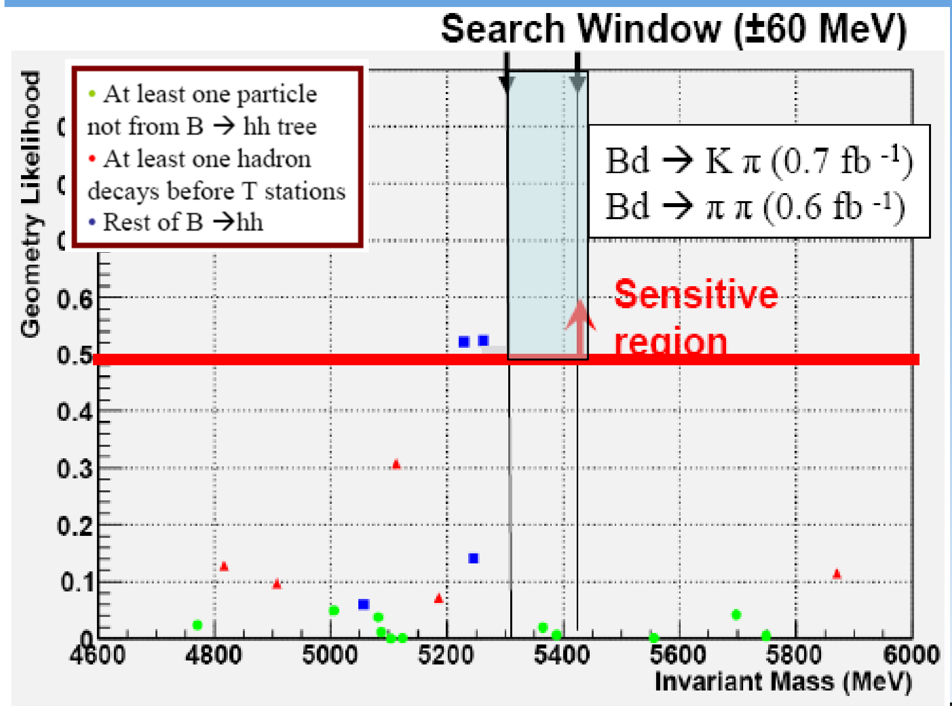

A similar method is described by Dean Karlen, *Computers in Physics Vol 12, N.4, Jul/Aug 1998*

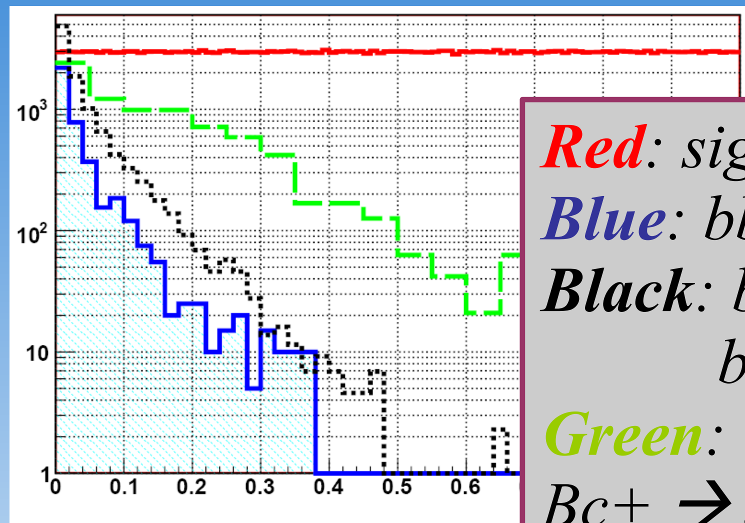
# $B_s^0 \to \mu^+\mu^-$ at LHCb: Background

***B→hh <u>NEGLIGIBLE</u> (~ 2 evts) in comparison to ~210 evtents/fb-1 from b→μ b→μ)***

-Missid from B → ππ is ~ 0.6%

-'Survivors' still fall in low PIDL values



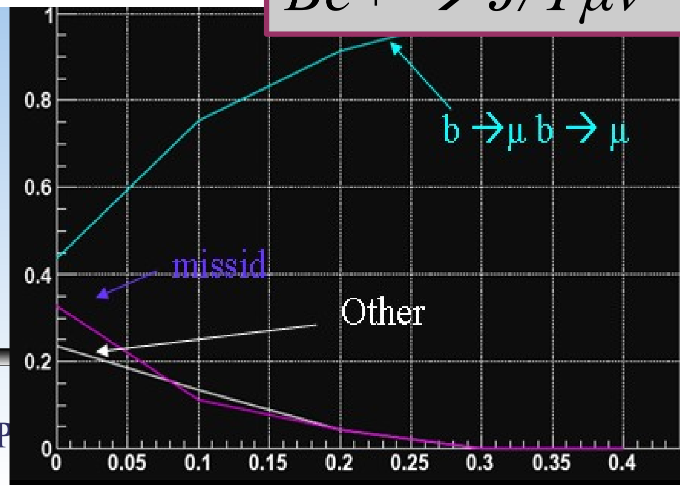



*Red: signal*

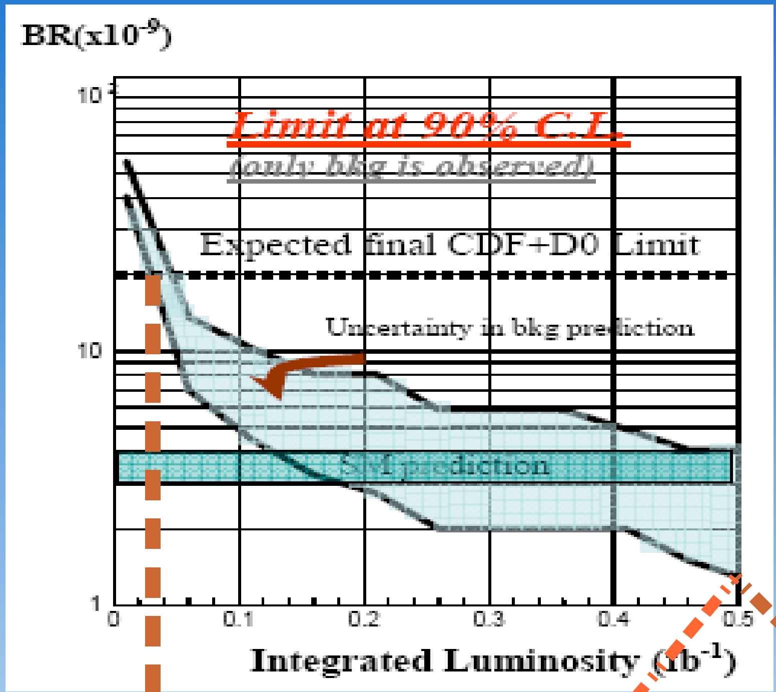
*Blue: bb inc.*

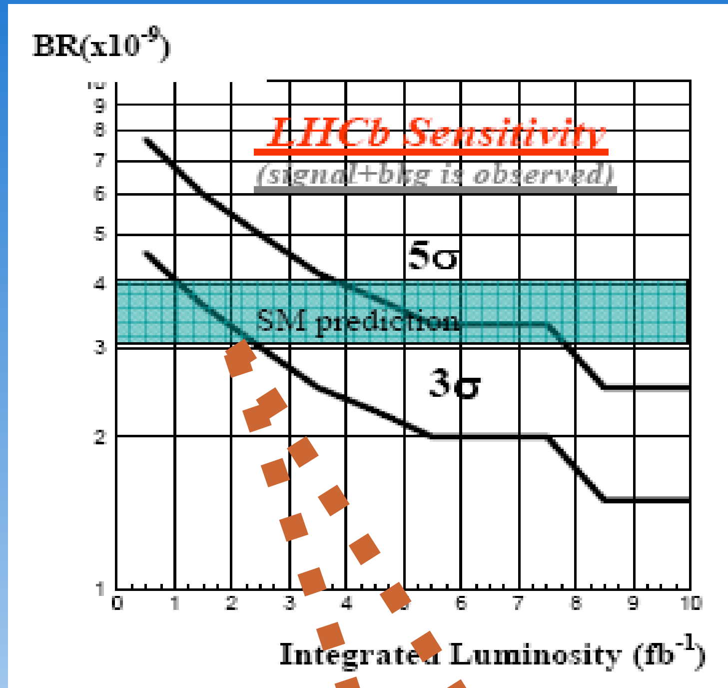
*Black: b→μ b→μ*

*Green: Bc+ → J/Ψμν*



# LHCb perspective for $B_s \rightarrow \mu\mu$




~ end 2008

~ end 2009

0.5 $fb^{-1}$ exclusion @ 90% CL down to the SM

3 σ observation if SM value!

0.05 $fb^{-1}$ overtake D0+CDF

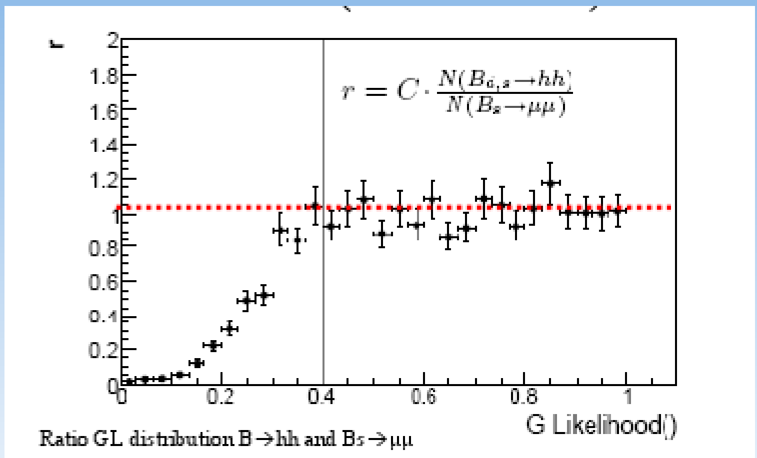
# Normalization and control channels

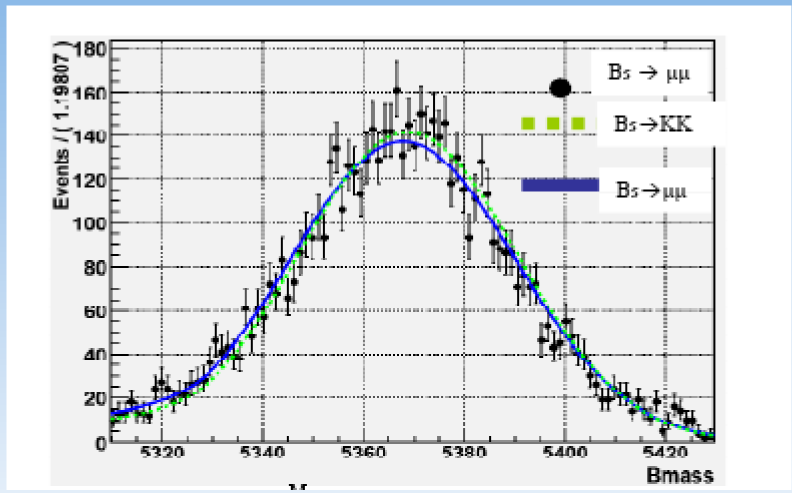
- $B^+ \to J/\psi K^+$ normalization mode
  - Large, well-measured BR
  - Similar selection: uncertainties on efficiencies cancel at first order

$$BR = \frac{BR_n \cdot \epsilon_n^{REC} \cdot \epsilon_n^{SEL} \cdot \epsilon_n^{TRIG}}{\epsilon_s^{REC} \cdot \epsilon_s^{SEL} \cdot \epsilon_s^{TRIG}} \cdot \frac{f_n}{f_{B_s}} \cdot \frac{N_n}{N_s}$$

LHCb is also studying the possibility to use $B_s \to KK$

In addition LHCb in thinking to use B→hh for the training of the signal.

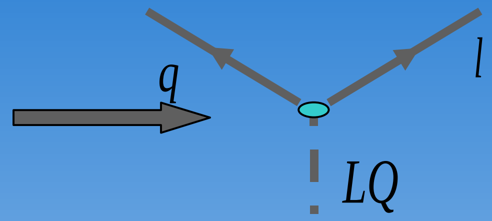


# $B_{s,d} \to e^{+/-}\mu^{-/+}$ and Pati Salam model

LFV decay forbidden by the SM, but is allowed by some extensions of the SM, as the Pati-Salam SU(4) model. It explain why quarks experience the strong force and lepton do not.

$$\begin{pmatrix} u_G \\ u_R \\ u_B \\ \nu \end{pmatrix} \begin{pmatrix} d_G \\ d_R \\ d_B \\ l \end{pmatrix}$$




Lepton number thought as the fourth color.

The branching ratio $B_{s,d} \to e\mu$ depends on LQ mass.

$$\begin{aligned}
BR(B^0_{d,s} \to e^+\mu^-) &= \Gamma(B^0_{d,s} \to e^+\mu^-) \cdot \frac{2\pi \cdot \tau_{B(d,s)}}{h} \\
\Gamma(B^0_{d,s} \to e^+\mu^-) &= \pi\alpha_s^2(M_{PS}) \frac{F^2_{B(d,s)} m^3_{B(d,s)} R^2 F_{mix}}{M^4_{PS}} \\
R &= \frac{m_{B(d,s)}}{m_b} \left(\frac{\alpha_s(M_{PS})}{\alpha_s(m_t)}\right)^{-4/7} \left(\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right)^{-12/23}
\end{aligned}$$

# *LHCb analysis for $B_{s,d} \rightarrow e^{+/-} \mu^{-/+}$*

Multidimensional analysis based on Geometrical Likelihood, PID and Invariant Mass.

background:
b-bbar→$e^{\pm}\mu^{\pm}$,
B→hh with misidentification
Other specific channels

These 5 variables are combined in the Likelihood:

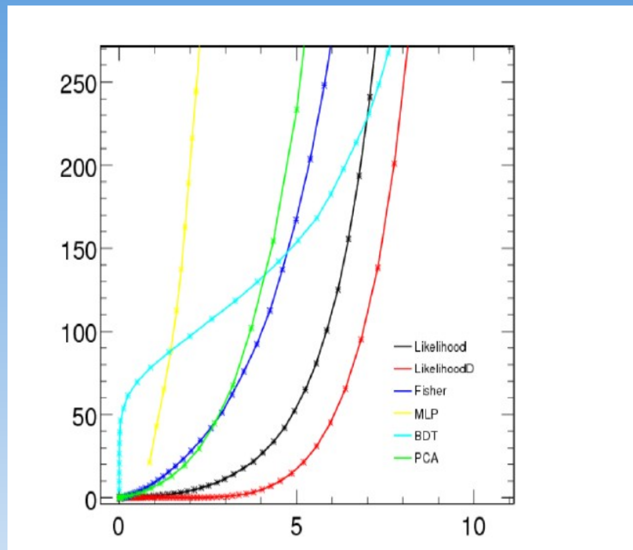
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

$$Isolation \quad : \quad Iso = \frac{P_T(B_s)}{P_T(B_s) + \sum_i p_{Ti}}$$

$$P_T(B_s)$$

$$\text{Flight Distance Significance} \quad = \frac{|\vec{r}_{PV} - \vec{r}_{BV}|}{\sigma}$$

$$IP(B_s \ \text{w.r.t.} \ \text{PV})/\sigma$$




signal efficiency VS number of b-bbar→$e^{\pm}\mu^{\pm}$ bg events

# LHCb perspective for $B_{s,d} \to e^{+/-} \mu^{-/+}$

| Channel | Branching ratio | events in $1 fb^{-1}$ | Analyzed events | L ($pb^{-1}$) |
|---|---|---|---|---|
| $B^0_d$ | | $6.8 \cdot 10^{10}$ | | |
| $B^0_s$ | | $1.73 \cdot 10^{9}$ | | |
| $b\bar{b} \to e^- \mu^+$ | $1.1 \cdot 10^{-2}$ | $6.8 \cdot 10^{10}$ | $5M$ | 2.1 |
| $b\bar{b} \to e^+ \mu^-$ | $1.1 \cdot 10^{-2}$ | $6.8 \cdot 10^{10}$ | $5M$ | 2.1 |
| $B^0_d \to \pi^+ \pi^-$ | $5.2 \cdot 10^{-6}$ | $3.5 \cdot 10^{5}$ | $40k$ | 113 |
| $B^0_d \to K^+ \pi^-$ | $2 \cdot 10^{-5}$ | $1.4 \cdot 10^{6}$ | $8k$ | 5.8 |
| $B^0_s \to K^+ K^-$ | $2.5 \cdot 10^{-5}$ | $4.3 \cdot 10^{5}$ | $8k$ | 18 |
| $\Lambda_b \to p\pi^-$ | $2.1 \cdot 10^{-5}$ | $1.3 \cdot 10^{6}$ | $8k$ | 5.9 |
| $\Lambda_b \to pK^-$ | $7.8 \cdot 10^{-5}$ | $3.6 \cdot 10^{6}$ | $8k$ | 2 |
| $B_c \to J/\psi \mu\nu$ | $2 \cdot 10^{-5}$ | $2 \cdot 10^{6}$ | $101k$ | 48 |
| $B^+ \to J/\psi K^+$ | $1 \cdot 10^{-3}$ | $9.7 \cdot 10^{4}$ | $200k$ | 1023 |
| $B^0_s \to e^\pm \mu^\mp$ | | | $102k$ | |

*Belle*:

$Br(B_s \to e^\pm \mu^\mp) < 1.7 \cdot 10^{-7}$ at 90% CL

*CDF*:

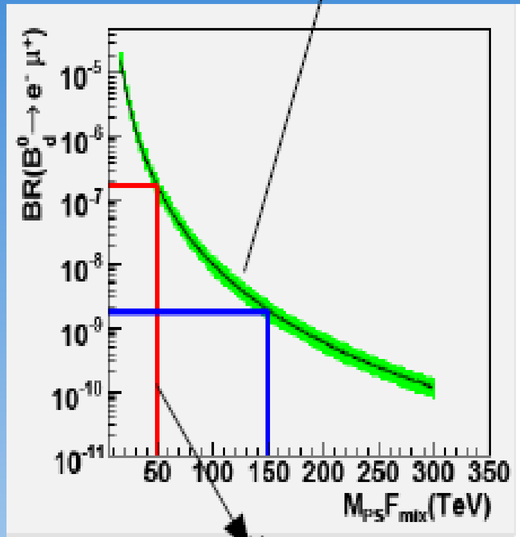
$Br(B_s \to e^\pm \mu^\mp) < 6.1 \cdot 10^{-6}$ at 90% CL

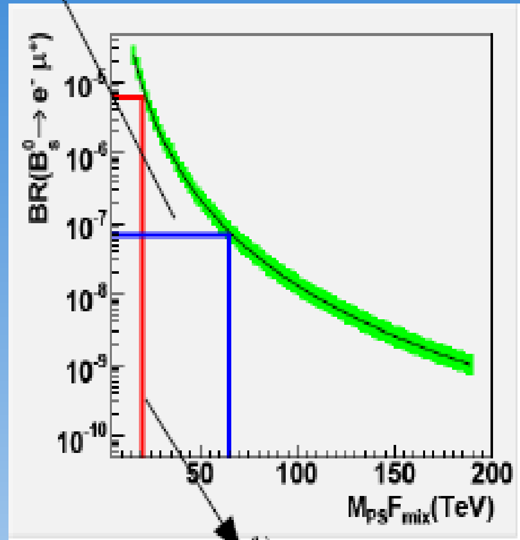
*LHCb*:

$Br(B_s \to e^\pm \mu^\mp) < 1.3 \cdot 10^{-8}$ in 2 fb$^{-1}$ at 90% CL

$Br(B_d \to e^\pm \mu^\mp) < 3.2 \cdot 10^{-9}$ in 2 fb$^{-1}$ at 90% CL

Limits in 1 year of data taking at LHCb




Belle Phys. Rev. D 68 (2003)111101

CDF Phys. Rev. Lett. 81 (1998) 5742

# Rare decays at the LHC

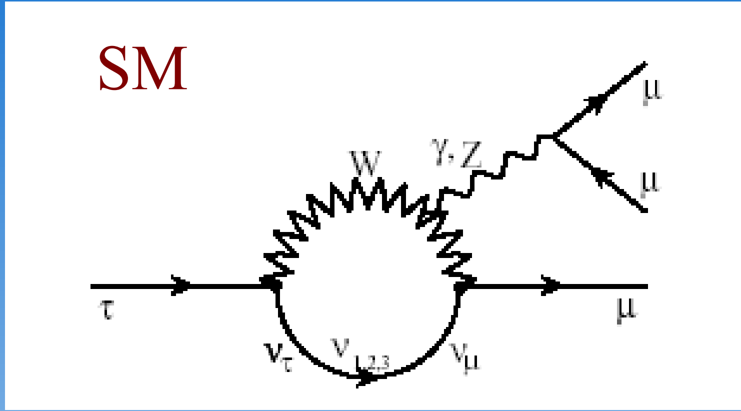
Part III

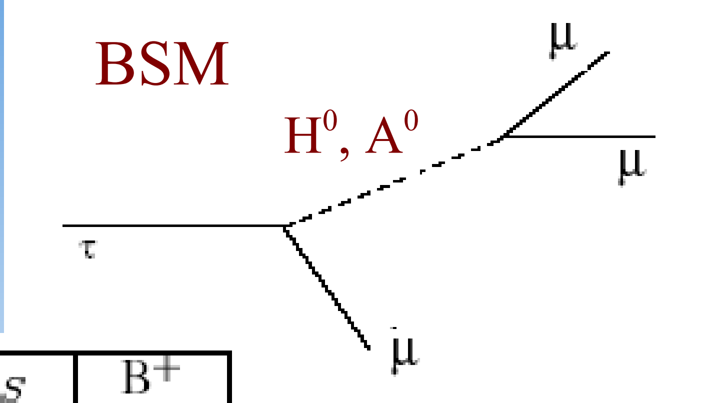
LFV in $\tau$ decays

Heavy flavor production measurements

# LFV in $\tau$ decays

- $\tau^+ \to \mu^+\mu^-\mu^+$
  - BR ~ $10^{-40}$ in Standard Model
  - Significant enhancement in several NP models (see discussion later), like $\tau^+ \to \mu^+\gamma$ ... etc.
  - Only one easily triggerable at LHC experiments via di-muon streams



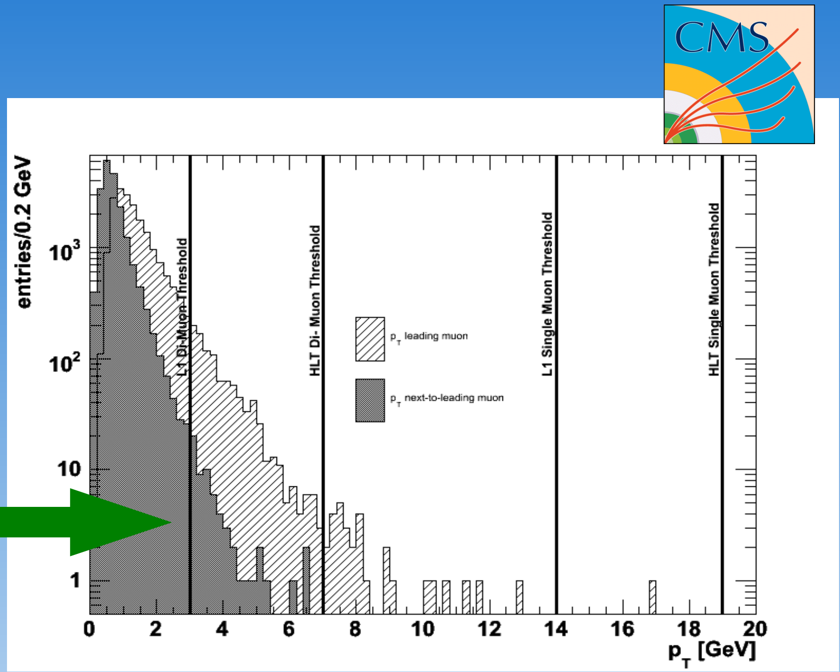

- $\tau$ cross sections: $\boxed{\sigma(pp \to \tau + X) \simeq 120\mu b.}$
  - From heavy-flavored mesons

| Meson (M) | $D_S$ | $D^+$ | $B^0$ | $B_S$ | $B^+$ |
|---|---|---|---|---|---|
| $\sigma(M \to \tau + X)/\sigma(pp \to \tau + X)$ | 77% | 3% | 9% | 2% | 9% |

  - From heavy bosons $\boxed{\sigma(pp \to W \to \tau + \nu_\tau) = 19nb}$ $\boxed{\sigma(pp \to Z^0 \to \tau\overline{\tau}) = 3nb}$

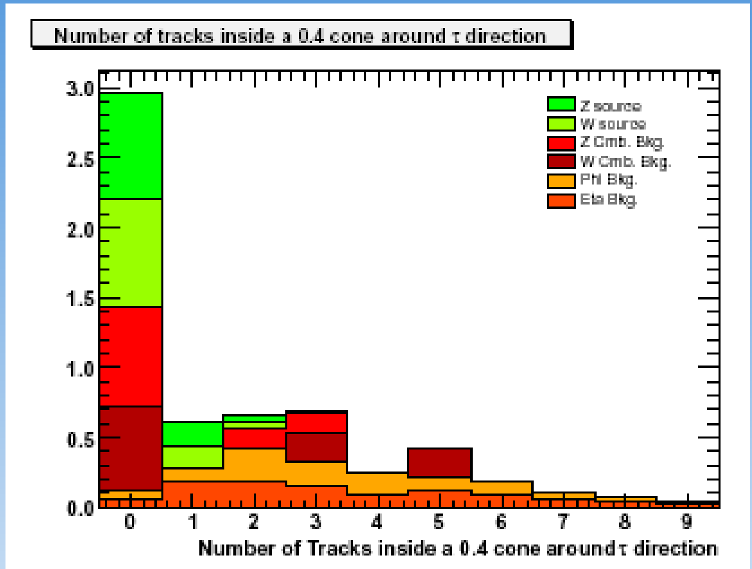
# $\tau \to 3\mu$: Trigger performances

- ATLAS:
  - Only $\tau$'s from W decays exploited
- CMS:
  - Use of combined inclusive muon / di-muon triggers
  - Very efficient for W and Z decays
    - 37.7% / 44.7% after HLT for W / Z source
  - Very low efficiency for B and D sources
- LHCb:
  - Lower $p_T$ thresholds allow for B-produced $\tau$'s
    - Initial statistics is larger by a factor $\sim 10^3$ - no Drell-Yan contribution estimated yet
  - Attempt of using also inclusive $D_s$ is in progress...



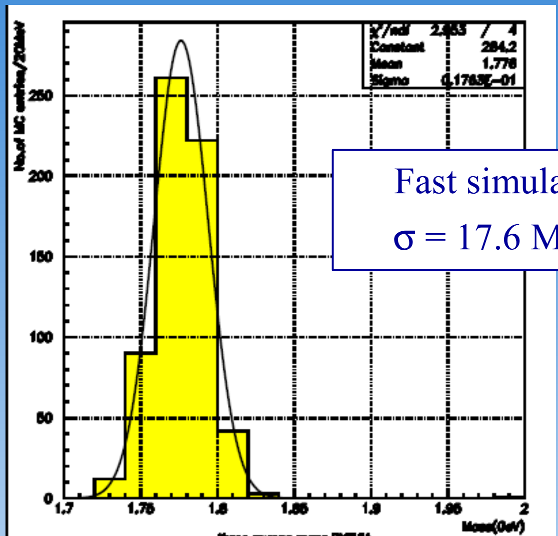
# $\tau \to 3\mu$: Selection in CMS

- Main backgrounds:
  - Combinatorial background in W and Z samples
  - *cc*bar $\to \mu^+ \phi X$, $\phi \to \mu^+\mu^-$ and *cc*bar $\to \mu^+ \eta X$, $\eta \to \mu^+\mu^-\gamma$
- Offline selection:
  - $\chi^2$ probability of vertex fit
  - Number of tracks around $\tau$ direction
  - Di-muon invariant mass vetoes
  - Sum over $\Delta R$
  - Additional muon-ID likelihood
    - Uses HCAL and ECAL energies, number of muon segments

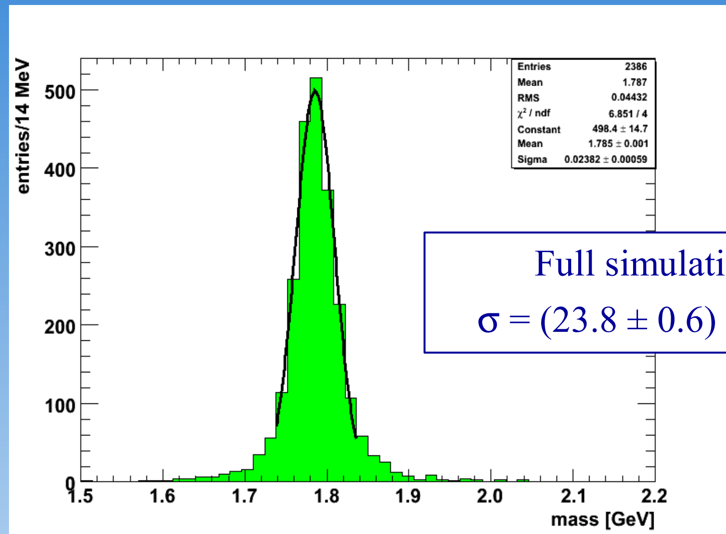


# $\tau \rightarrow 3\mu$: Results in CMS

- $3\mu$ invariant mass resolution:
  - Fast detector simulation compared to full simulation:




Fast simulation:
$\sigma$ = 17.6 MeV/$c^2$




Full simulation:
$\sigma$ = (23.8 ± 0.6) MeV/$c^2$

- Result expected (with fast simulation, to be established with full):

$$BR(\tau^+ \rightarrow \mu^+\mu^-\mu^+) < 3.0 \cdot 10^{-8} \text{ @ } 95\% \text{ CL}$$

MC equivalent luminosity: 30 fb$^{-1}$

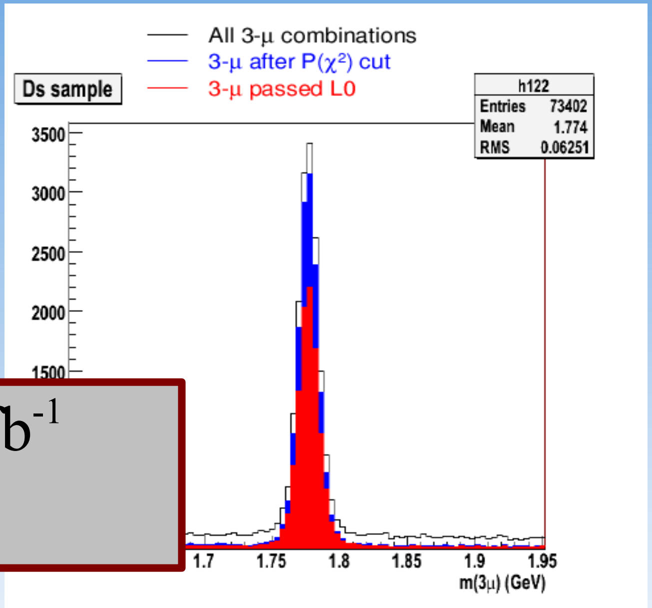
BaBar: $BR(\tau \rightarrow 3\mu) < 5.3 \times 10^{-8}$ @ 90% CL (2007)

# $\tau \rightarrow 3\mu$: ATLAS and LHCb

- ATLAS:
  - Selection of $\tau$ from W (isolated, high $p_T$, $E_{TMiss}$ signature)
  - With BR($\tau \rightarrow 3\mu$) = 5 x $10^{-8}$, 10 events $\tau \rightarrow 3\mu$ from W expected in 10 $fb^{-1}$
  - background: D and B mesons which decay in light resonances
- LHCb:
  - Very early study

**ATLAS upper limit:**
**BR($\tau \rightarrow 3\mu$) < 8.7 x $10^{-8}$ 90% C.L.**

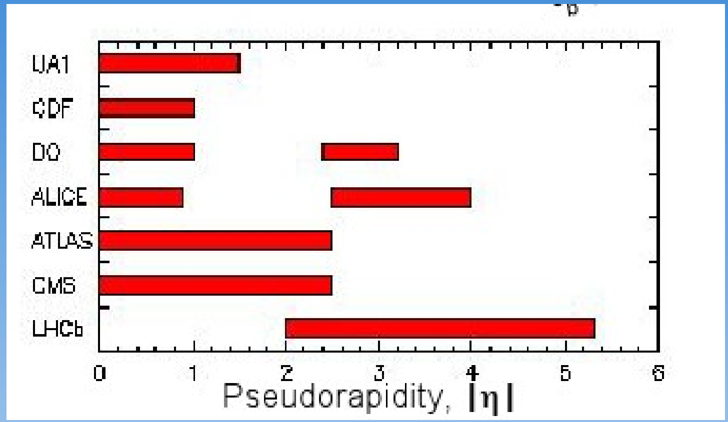
- Preselection (3μ, P($\chi^2$)>0.002)
- Impact parameter significance $IP/\sigma_{IP}$ > 3 for all muons
- ( Distance between 3μ Vtx and primary Vtx ) / Error > 3
- Z(3μ)-Z(Pvtx) > 4 mm
- Rxy(between 3μ & Pvtx) > 0.1 mm



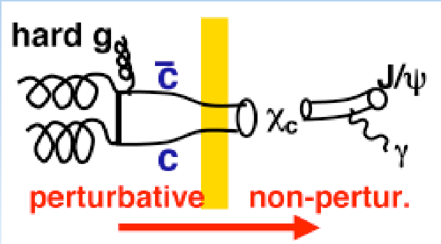

BR($\tau \rightarrow 3\mu$) < 7.2 x $10^{-7}$ @ 90% CL with 2 $fb^{-1}$
could reach 1.8 x $10^{-7}$ adding $D_s$

# HF production measurements: motivations

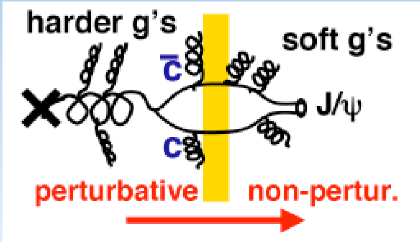
- *bb*bar production cross section (measurements with muons in the final state)
  - very large cross section expected σ(*bb*bar) ~ 500μb, but with large uncertainty originating from the extrapolation of the parton density function up the LHC energies
  - crucial initial measurement: input for theoretical description and for experimental calibrations and trigger optimization
  - Different phase-space regions for ATLAS/CMS and LHCb




- Charmonium production measurements:
  - Cross-section and polarization measurements
  - Production rate observed at Tevatron not in agreement with Color Singlet mechanism of NRQCD → disentangling Color Octet contribution is essential




Color singlet




Color octet

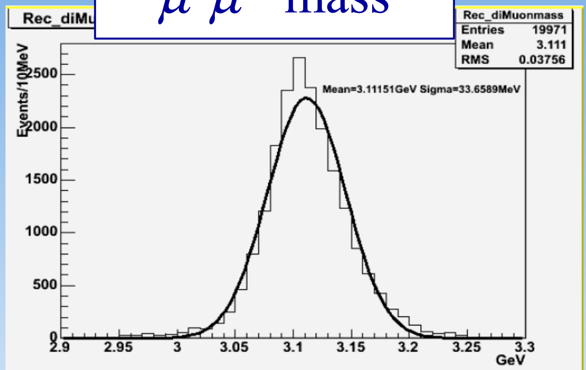
# J/ψ reconstruction performances (CMS)

- Detailed studies performed on $B_s \to J/\psi\,\phi$ MonteCarlo samples to determine single muon / di-muon efficiencies as functions of:
  - $p_T$ / $|\eta|$ / separation angle between the two muons

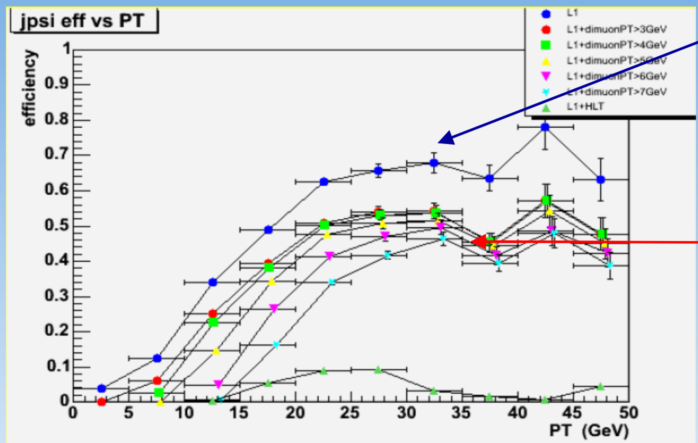
after:

  - Reconstruction only / level-1 (L1) / high-level trigger (HLT) decisions

$\mu^+\mu^-$ mass




$\sigma = 34$ MeV/$c^2$



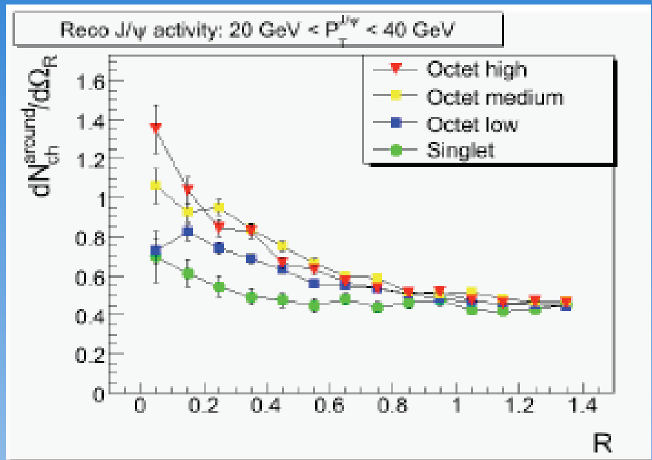

Efficiency after L1

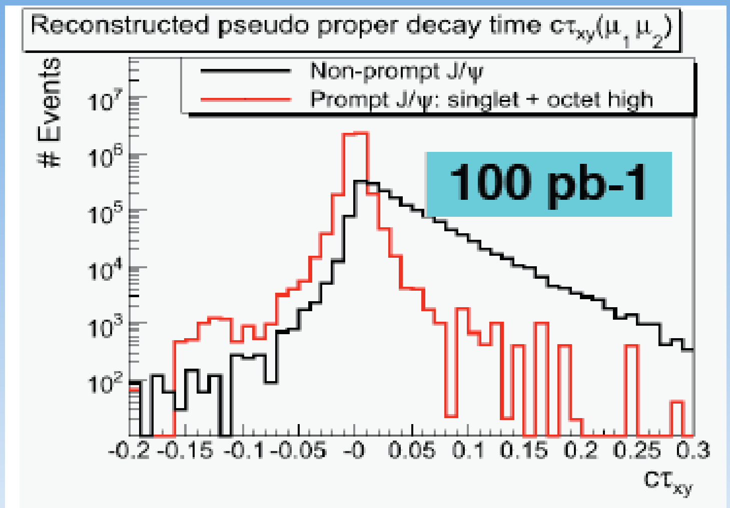
Efficiency after HLT at different muon $p_T$ thresholds, (up to 3 GeV, affordable at startup luminosity)

# J/ψ production mechanisms (CMS)

- Finding new observables besides J/ψ cross-section and polarization to distinguish charmonium production mechanisms:
  - e.g. particle density in cone slices about the J/ψ direction

$$\frac{dN}{d\Omega_R} = \frac{N(R+dR/2)-N(R-dR/2)}{\pi[(R+dR/2)^2-(R-dR/2)^2]}$$



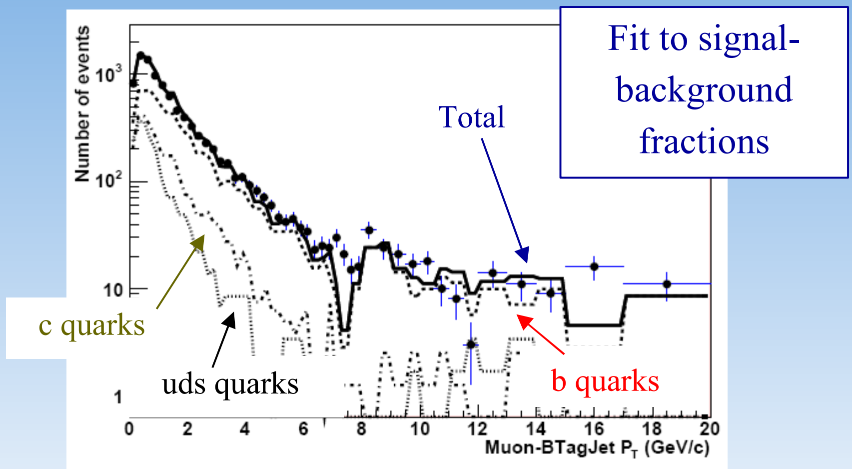

- Fit of prompt-non prompt J/ψ fractions using e.g. transverse decay length, in bins of $P_T^{J/\psi}$
  - OK for low $P_T^{J/\psi}$
  - Still limited by MonteCarlo background statistic for high $P_T^{J/\psi}$

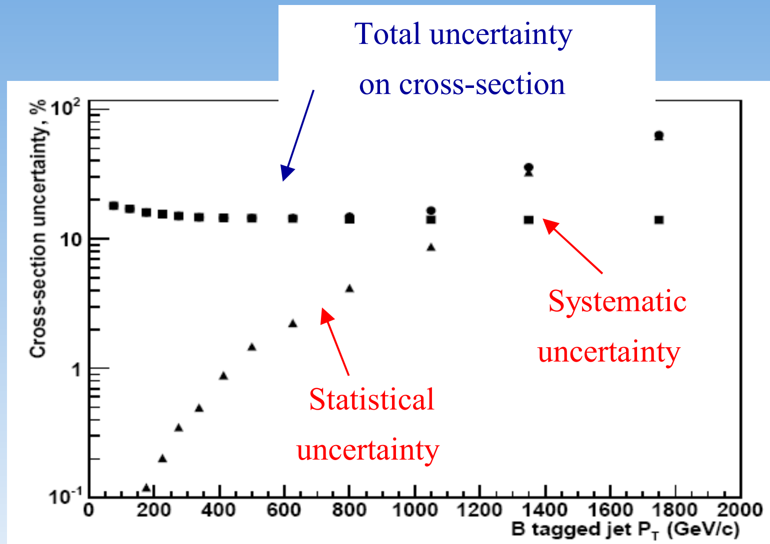
# b-bbar inclusive cross section at ATLAS

- Strategy 1 based on bottom decays into a $J/\psi \to \mu\mu$
  - 2 muons ($p_T$> 6 (4) GeV/c) at LVL1 and compute vertex and invariant mass at HLT: ~ 27 Hz total rate
  - with offline analysis, apply cuts on $J/\psi$ vertex quality and impact parameter of muons to remove prompt signals: good S/B ~ 1.6 ratio
- Strategy 2 based on the association between LVL1 muon and jet (semileptonic decays)
  - 1 muon ($p_T$> 6 GeV/c) at LVL1 and look at HLT for an associated jet ($E_T$ > 30 GeV) within a cone around the muon: total rate ~1.4 kHz
  - compute the relative transverse momentum of the muon track to the associated jet axis: the fraction of b events within the triggered sample is well reproduced (check with MC truth)
- Both strategies lead to good results:
  - inclusive b selections based on $J/\psi$ and based on semileptonic decays are possible
  - a measurement of the inclusive b-bbar cross section is possible with early ATLAS data

# b-bbar inclusive cross section at CMS

- Strategy: measurement of *b*-jet production rate, tagged by *b*-hadron semileptonic decay
- Trigger: muon + *b*-tagged jet HLT stream
- Very good efficiency for $p_T^{\text{b-hadron}} > 50$ GeV/*c*
  - L1 + HLT + *b*-tagging + muon-jet association = 4.0% (including semileptonic BR)
- Signal effectively discriminated by the muon transverse momentum w.r.t. to the *b*-tagged jet direction



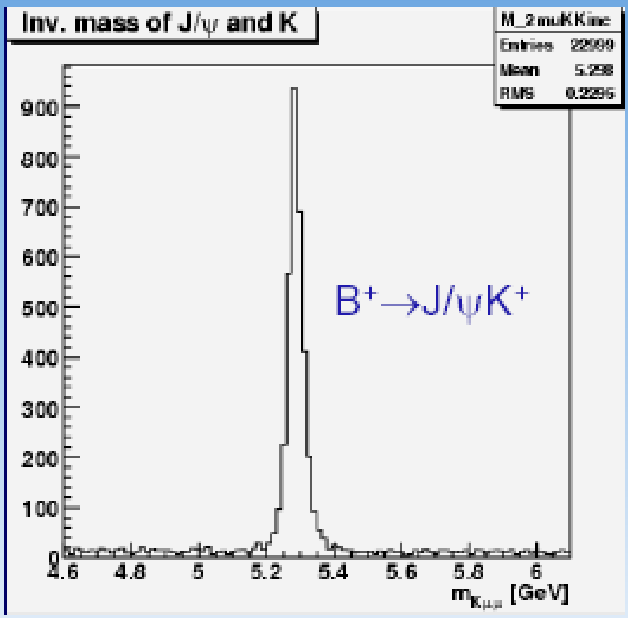



# b-bbar exclusive x-section at CMS ($B^+ \rightarrow J/\psi K^+$)

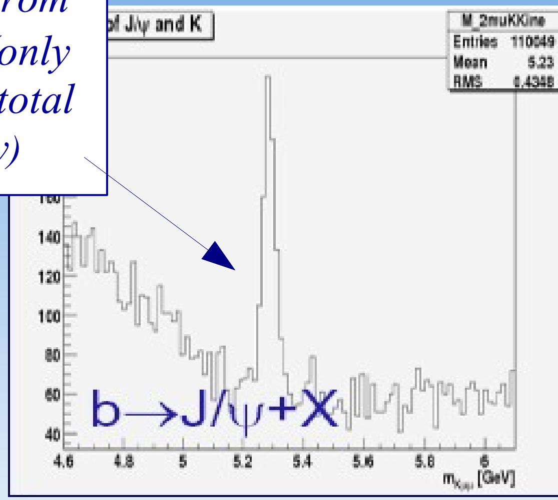
*Very preliminary*

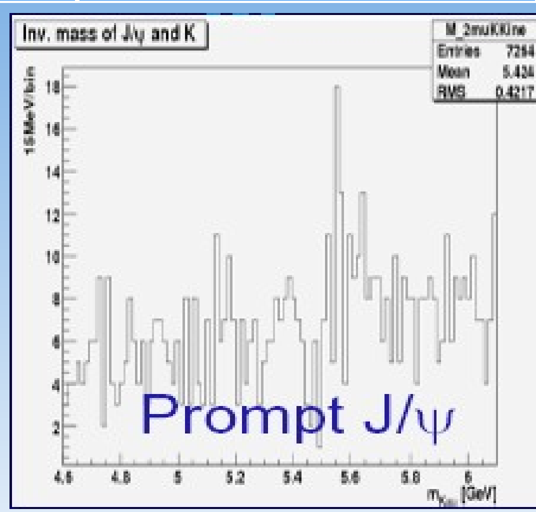
- Triggered by di-muons
- Vertex kinematic fit improves significantly $B^+$ mass resolution ($\sigma$ = 23.4 MeV/$c^2$)
- Due to high yields, differential cross-section is still possible (6 $p_T$ bins)

| Luminosity | Observed $N^{B+}$ |
|---|---|
| 500pb$^{-1}$ | 30.3K |
| 100pb$^{-1}$ | 6.1K |




*Irreducible contribution from $B^+ \rightarrow J/\psi\, \pi^+$ (only adds 0.6% to total uncertainty)*

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# b-bbar inclusive cross section at LHCb

- Study at an early stage: here discussing only general strategies
  - 
- 3 Strategies under study:
  - Identify J/ψ coming from b (cutting on $P_T$ and IP)
  - Identify D mesons coming from b (cutting on $P_T$ and IP)
  - Using exclusive channels with very well known branching ratio:

    $B^+ \rightarrow J/\psi\, K^+$ (uncertainty ~3.5%)

    $B^0 \rightarrow J/\psi\, K^0$ (uncertainty ~3.8%)

Expected ~100K reconstructed per year

# Conclusions

- Rare B decays will be extensively studied at LHC:
  - Part of main physics program for LHCb
  - ATLAS/CMS can be competitive mostly in channels involving muons / di-muons
- In the first years of data-taking
  - Standard Model BR($B_s \to \mu\mu$) can be observed by LHCb
  - Asymmetries in rare semileptonic decays can be measured
- Other interesting limits concerning LFV ($B \to e\mu$, $\tau \to 3\mu$) can be established
- b-bbar inclusive cross section will be measured by the three experiments in different $\eta$ regions