# Probing new physics in $B_s \to \mu^+\mu^-$ at LHCb

II CPAN DAYS, Valencia
November 30th, 2010

Xabier Cid Vidal

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

LHCb

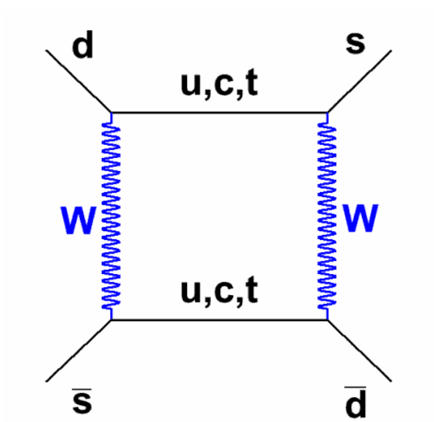
# Outline

- Motivation of $B_s \rightarrow \mu\mu$ as a probe of NP
- Analysis in LHCb
  - Overview
  - Calibration and normalization
- First results
- Conclusions

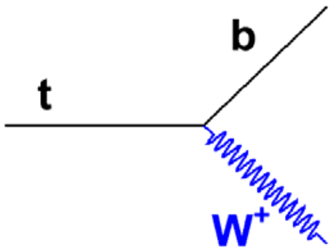
# Motivation of $B_s \to \mu\mu$ as a probe of NP

# Indirect approach

- $B_s \rightarrow \mu\mu$ can access NP through new virtual particles entering in the loop → indirect search of NP
- Indirect approach can access higher energy scales and see NP effects earlier:
  - Done before in the history of physics…
    - 3rd quark family inferred by Kobayashi and Maskawa (1973) to explain CPV in K mixing (1964). Directly observed in 1977 (b) and 1995 (t)
    - Neutral Currents discovered in 1973, $Z^0$ directly observed in 1983




*~30 years till the direct observation…*



# Decay Physics (SM)

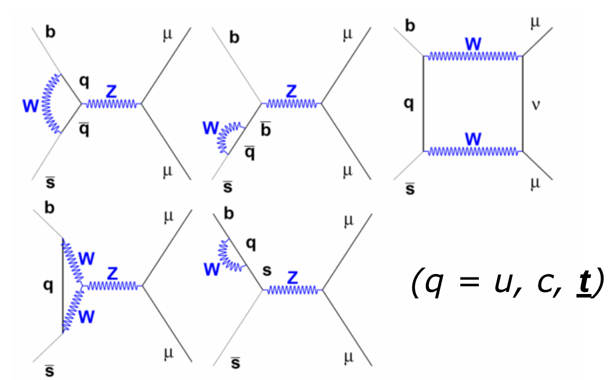
- Hadronic weak decays are often studied in terms of effective hamiltonians of local operators. Degrees of freedom of exchanged particles are integrated out giving rise to the **Wilson coefficients $C_i$**.

$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3}|V_{tb}^*V_{tq}|^2\,\tau_{Bq}M_{Bq}^3 f_{Bq}^2\sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}}\times$$

$$\times\left\{M_{Bq}^2\left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right)C_S^{\,2}+\left[M_{Bq}C_P+\frac{2m_\mu}{M_{Bq}}C_{10}\right]^2\right\}$$

$C_{P,S,10}$ (pseudoscalar, scalar and axial) depend on the underlying model (SM, SUSY…)

**Main SM diagrams**




- $C_{S,P}$ are negligible in **SM, $C_{10}$ gives the only relevant contribution**.

⟶ This decay is very suppressed in SM:

**BR($B_s \to \mu\mu$) = (3.35 ± 0.32)·10$^{-9}$** M.Blanke et al., JHEP 10 003,2006

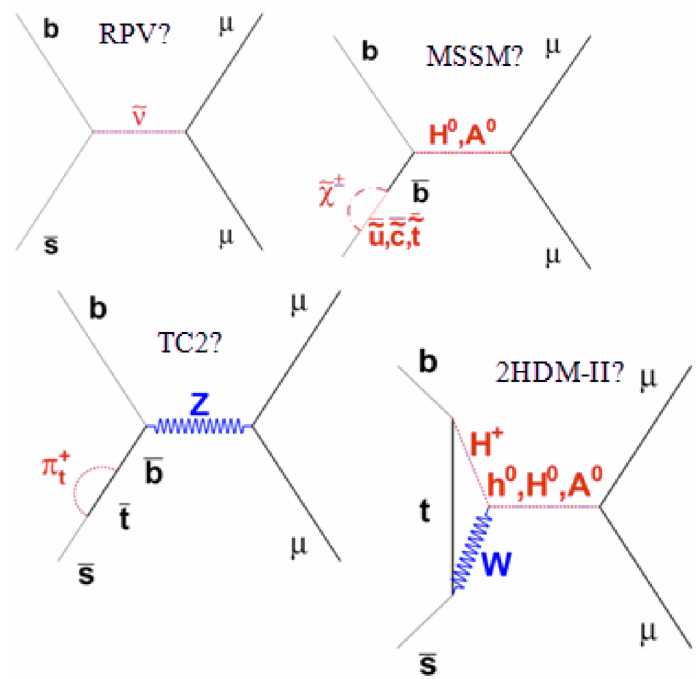
- Current experimental upper limit (CDF, 2fb$^{-1}$) still one order of magnitude above these values. @ 90% CL:

**BR($B_s \to \mu\mu$) < 3.6·10$^{-8}$** CDF collab., CDF Public Note 9892

* BR (Bd → μμ) = (1.03 ± 0.09)·10$^{-10}$

# New Physics effects

- NP can contribute to this decay rate (specially SUSY at high tanβ (*tanβ = $v_u/v_d$*)):
- More than one Higgs → contributions to $\mathbf{C_{S,P}}$
  - 2HDM-II : BR proportional to $\tan^4\beta$
  - SUSY (MSSM): above + extra $\tan^6\beta$ +…
- RPV SUSY: tree level diagrams
- Technicolor (TC2), Little Higgs (LHT) … modify $\mathbf{C_{10}}$.

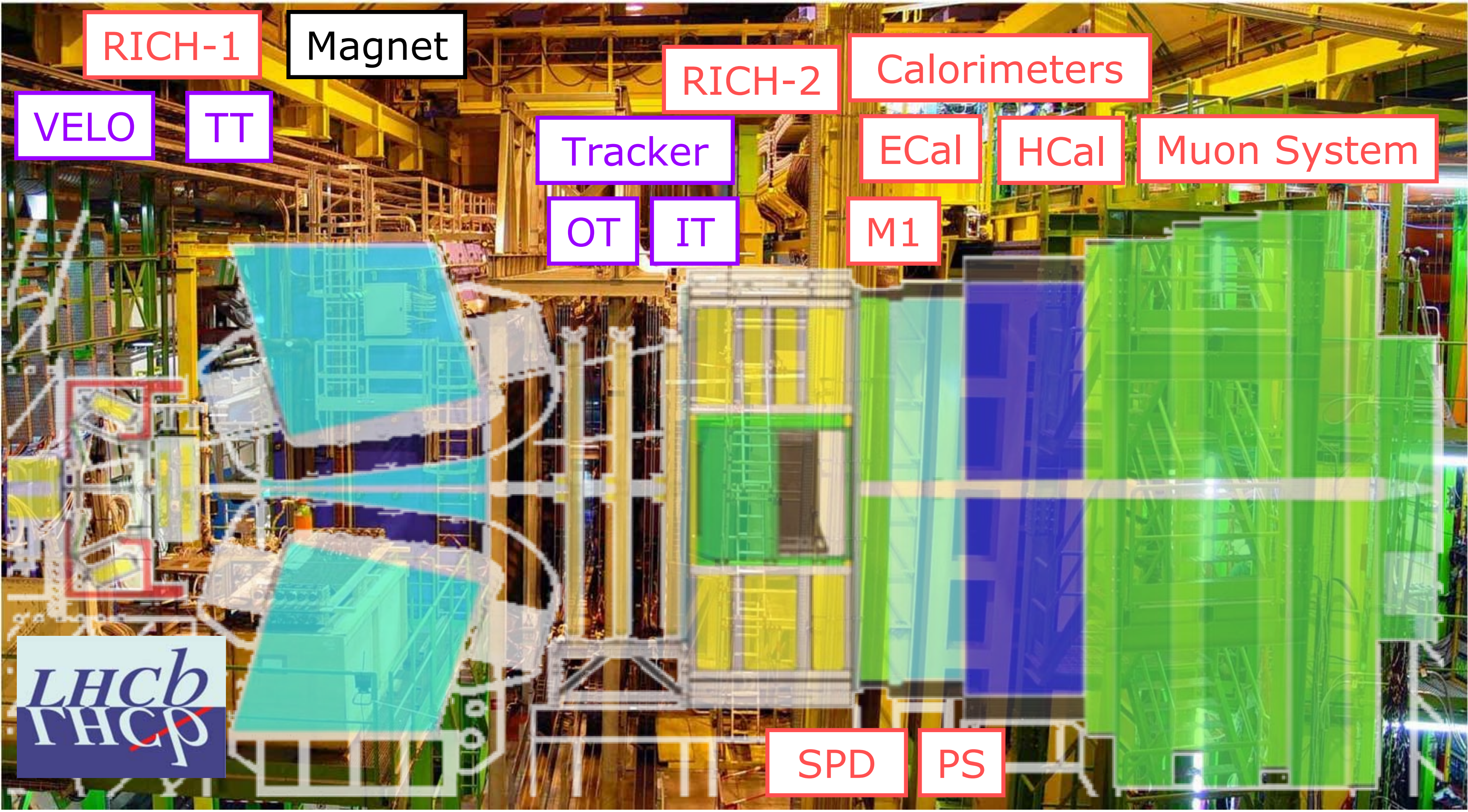



NP can modify the BR from smaller SM up to current experimental upper limit → **Any measured value will affect NP searches!**

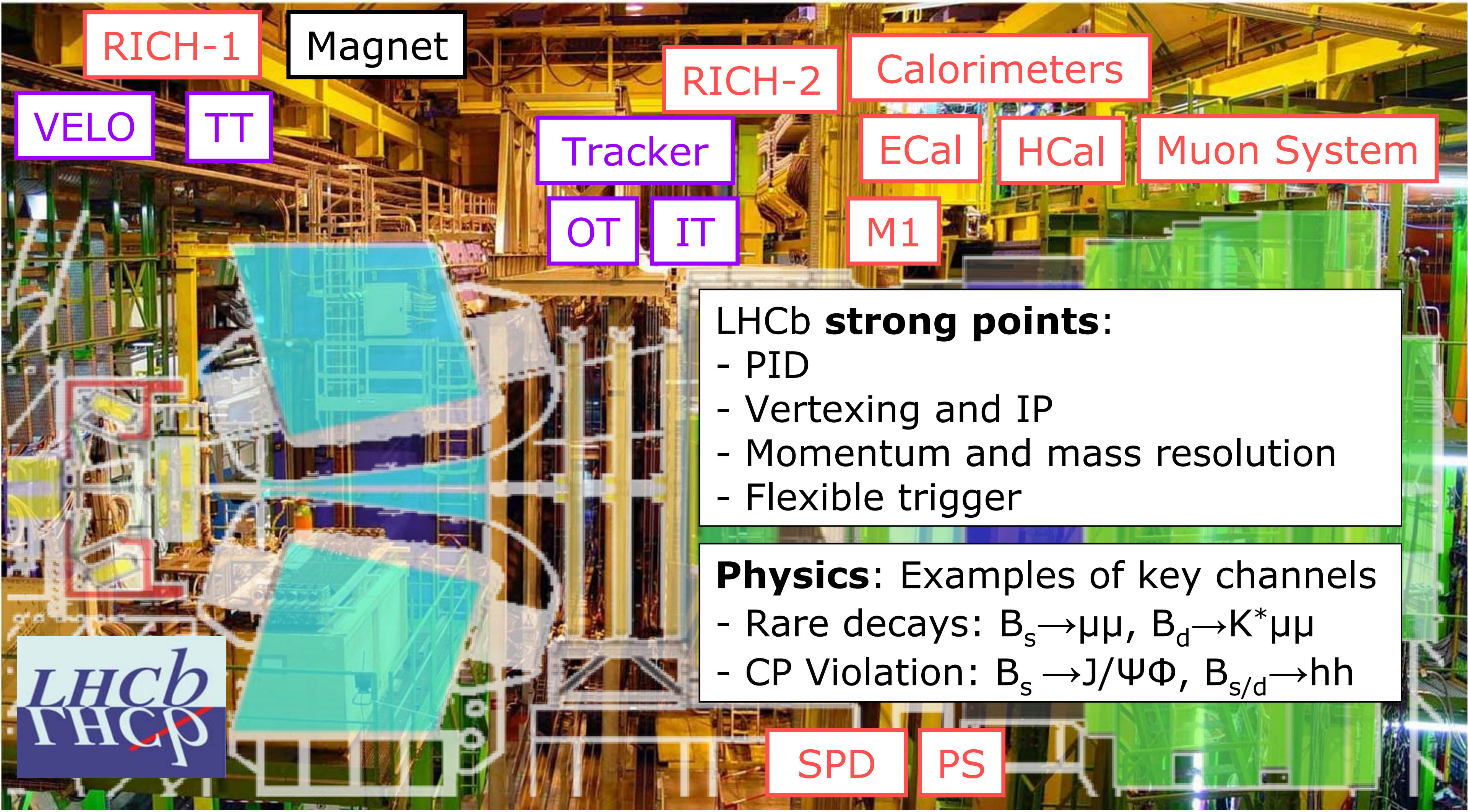
# Analysis in LHCb

⟶ Overview

# LHCb overview

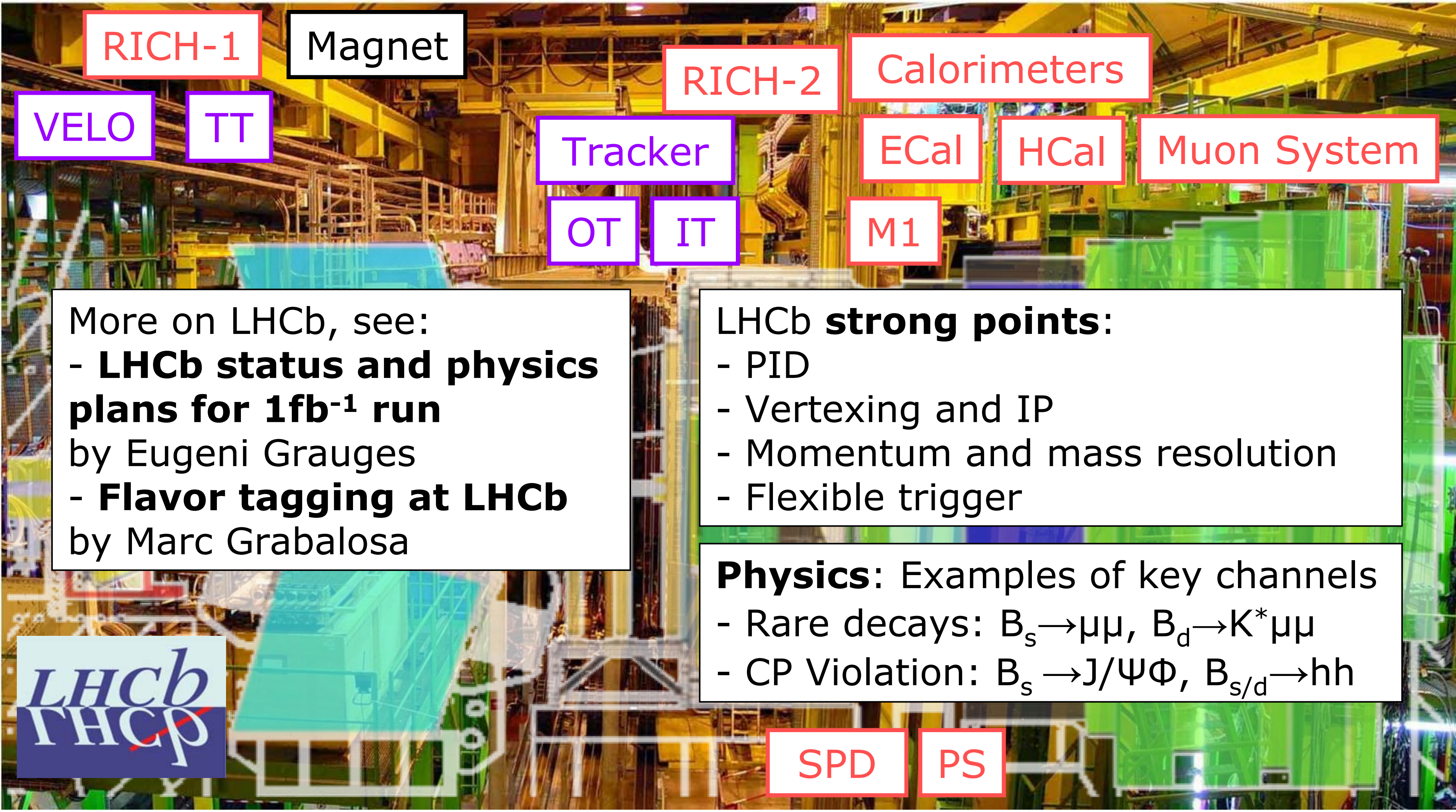


# LHCb overview




LHCb **strong points**:
- PID
- Vertexing and IP
- Momentum and mass resolution
- Flexible trigger

**Physics**: Examples of key channels
- Rare decays: $B_s \rightarrow \mu\mu$, $B_d \rightarrow K^{*}\mu\mu$
- CP Violation: $B_s \rightarrow J/\Psi\Phi$, $B_{s/d} \rightarrow hh$



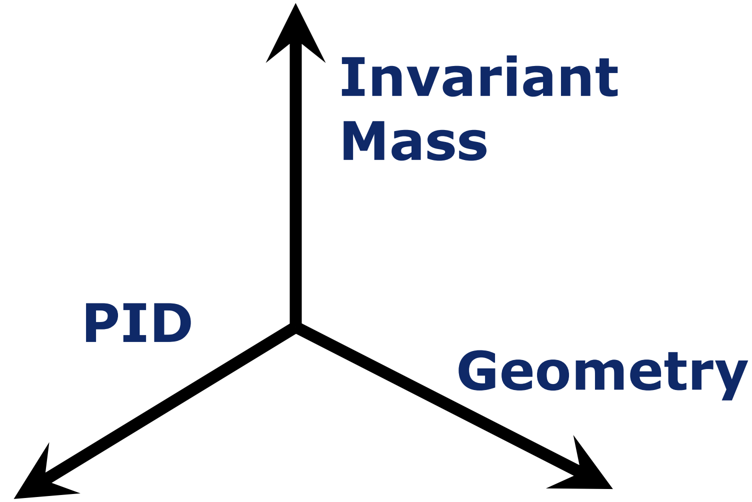

More on LHCb, see:
- **LHCb status and physics plans for 1fb$^{-1}$ run** by Eugeni Grauges
- **Flavor tagging at LHCb** by Marc Grabalosa

LHCb **strong points**:
- PID
- Vertexing and IP
- Momentum and mass resolution
- Flexible trigger

**Physics**: Examples of key channels
- Rare decays: $B_s \to \mu\mu$, $B_d \to K^*\mu\mu$
- CP Violation: $B_s \to J/\Psi\Phi$, $B_{s/d} \to hh$

# Analysis overview

- Selection: apply some cuts on all μμ candidates to remove most of the background.
- Classify each event using three properties (bins in a 3D parameter space):
  - **Particle Identification (PID):** Probability to be muons
  - **Geometrical properties** (Geometrical likelihood)
  - **Invariant Mass**




- 3D space is binned, so that each bin is treated as an independent experiment. Results combined using **Modified Frequentist Approach**

  see T. Junk NIM A434, 435,1999

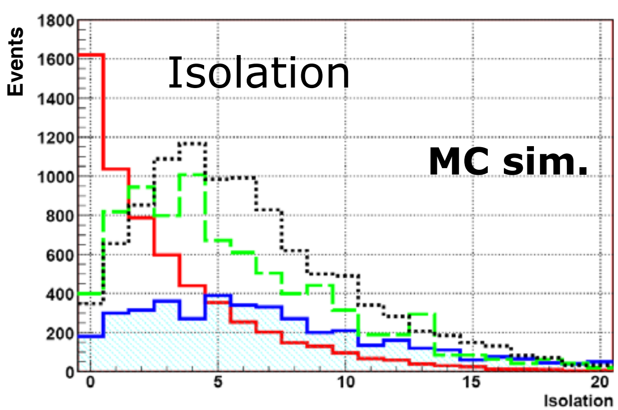
- Use of **control channels** to avoid dependence on simulation:
  - **Calibration of relevant variables**
  - **Normalization**

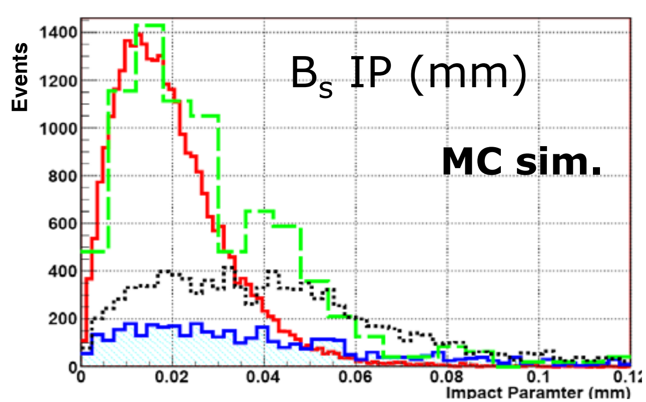
# Geometrical Likelihood

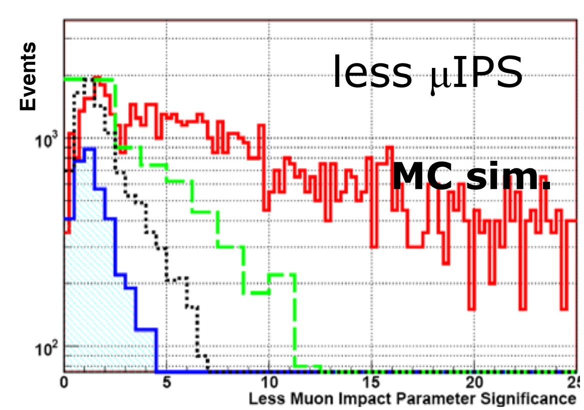
- How is the Geometrical Likelihood built?
  1. Input variables: min Impact Parameter Significance ($\mu^+,\mu^-$), DOCA, Impact Parameter of B, lifetime, iso - $\mu^+$, iso- $\mu^-$
     - What is isolation? Fake $B_s \to \mu\mu$ might originate in muons from another SV. For each muon, remove the other $\mu$ and look at the rest of the event: How many good - SVs (forward, DOCA, pointing) can it make?

***Red**: signal*
***Blue**: bb inc.*
***Black**: $b \to \mu$*
*$b \to \mu$*
***Green**:*
*$B_c^+ \to J/\Psi \mu \nu$*

Distributions of some relevant variables from MC signal and background



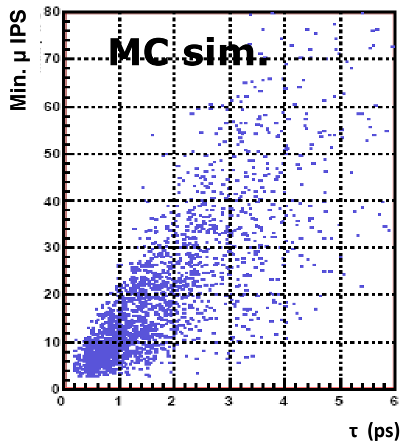



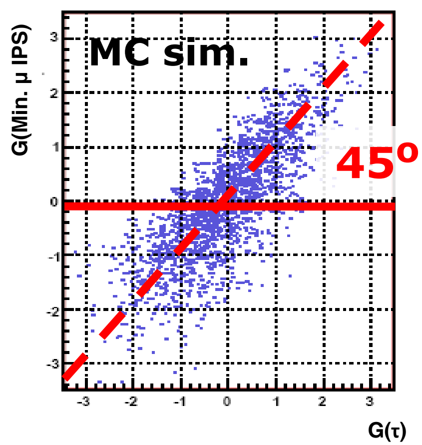
# Geometrical Likelihood

- How is the Geometrical Likelihood built?
  1. Input variables: min Impact Parameter Significance ($\mu^+$,$\mu^-$), DOCA, Impact Parameter of B, lifetime, iso - $\mu^+$, iso- $\mu^-$
  2. Transformed to Gaussian through cumulative and inverse error function
  3. In such space correlations are more linear-like → rotation matrix, and repeat 2

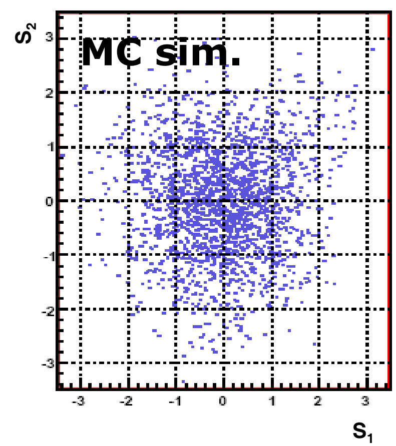
Original




Gaussian

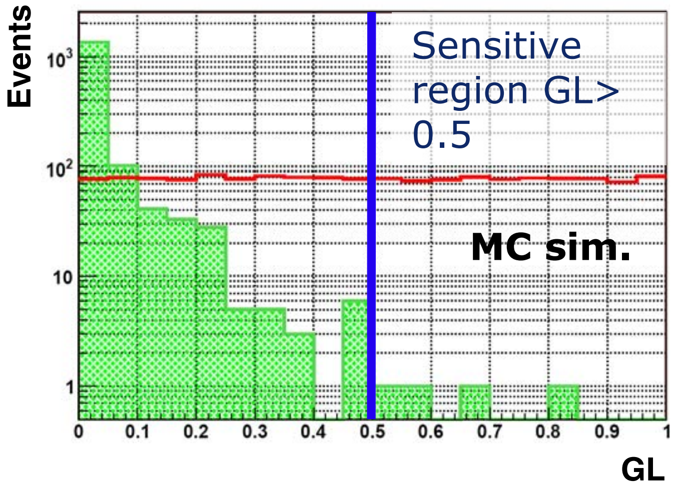



Uncorrelated gaussian



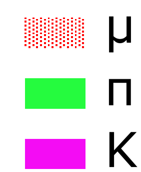
# Geometrical Likelihood

- How is the Geometrical Likelihood built?
  1. Input variables: min Impact Parameter Significance ($\mu^+,\mu^-$), DOCA, Impact Parameter of B, lifetime, iso - $\mu^+$, iso- $\mu^-$
  2. Transformed to Gaussian through cumulative and inverse error function
  3. In such space correlations are more linear-like → rotation matrix, and repeat 2
  4. Transformations under signal hyp. → $\chi^2_S$, under bkg. → $\chi^2_B$.
  5. Discriminating variable is $\chi^2_S - \chi^2_B$, flat again

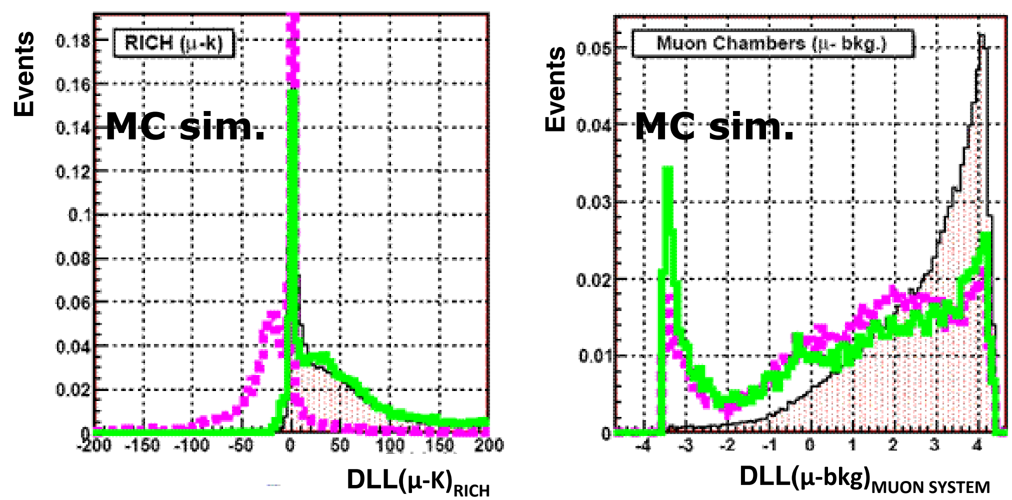


# PID Likelihood

- Particles with associated hits after extrapolation to the muon chambers are flagged as muons
- Some of them might not be actual muons (misidentification). Different subdetectors return probabilities for different kinds of particles, as seen before:
  - Muon chambers: distances of hits to track extrapolation, or fit of the track to hits
  - RICH: uses masses of the particles
  - CALOs: energy deposition




- Probabilities can be combined in a likelihood to fight against remaining misid

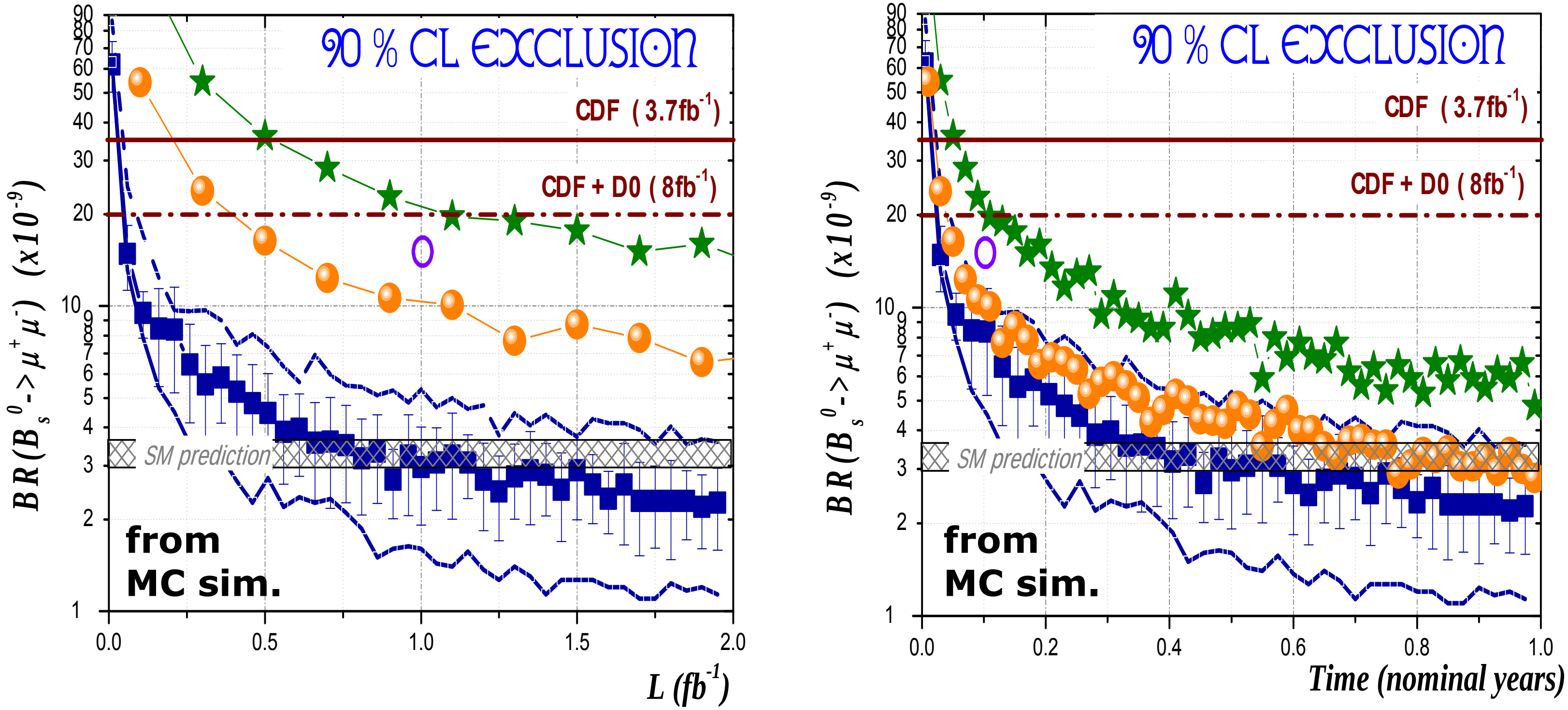


# Sensitivity (I)

- Signal 90% CL **exclusion sensitivity** as a function of Luminosity and time

★ Atlas
● CMS
■ LHCb

Assuming nominal luminosities since the beginning
ATLAS/CMS → L = $10^{33}$ $cm^{-2}s^{-1}$
LHCb → L = $2 \times 10^{32}$ $cm^{-2}s^{-1}$

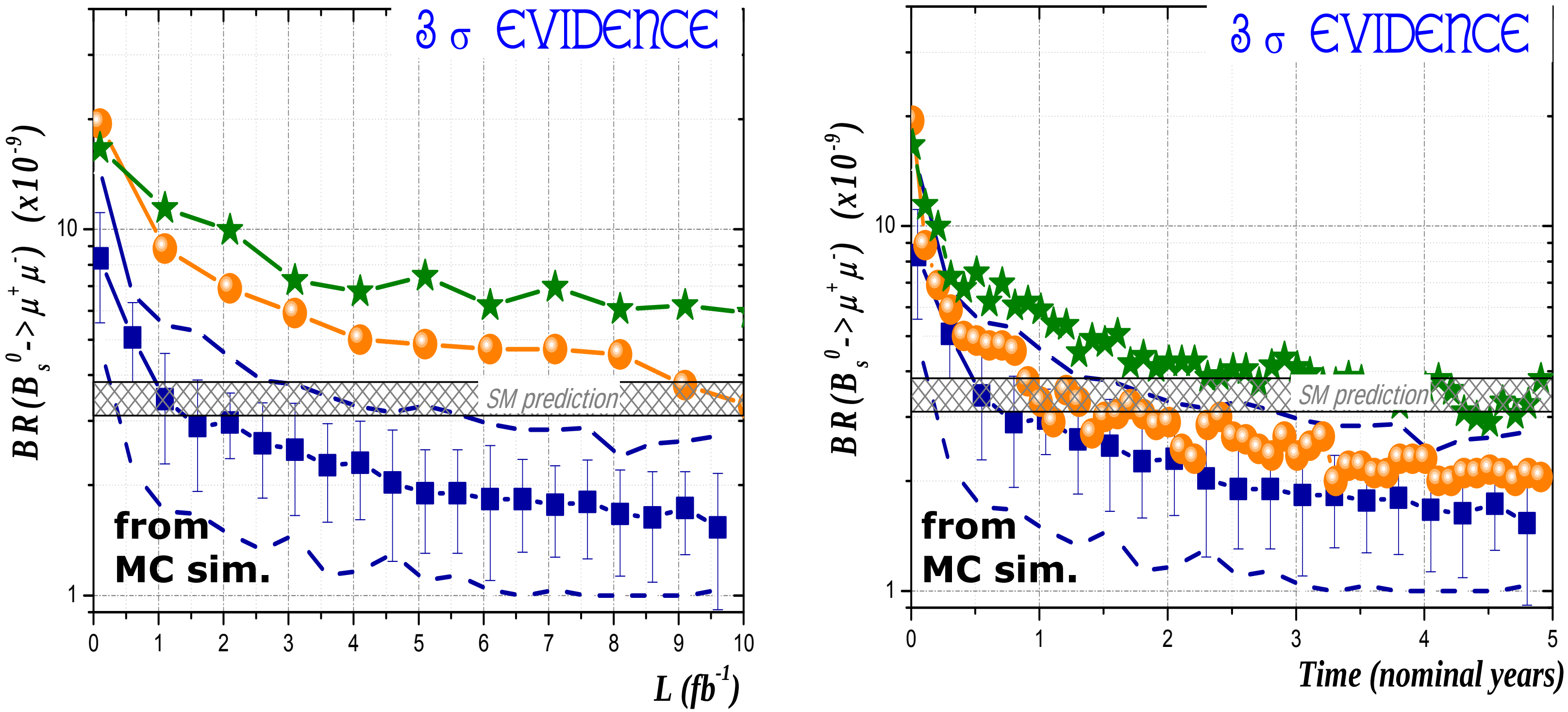


# Sensitivity (II)

- Signal **evidence sensitivity** as a function of Luminosity and time

★ Atlas
● CMS
■ LHCb

Assuming nominal luminosities since the beginning
ATLAS/CMS → L = $10^{33}$ $cm^{-2}s^{-1}$
LHCb → L = $2x10^{32}$ $cm^{-2}s^{-1}$



# Analysis in LHCb

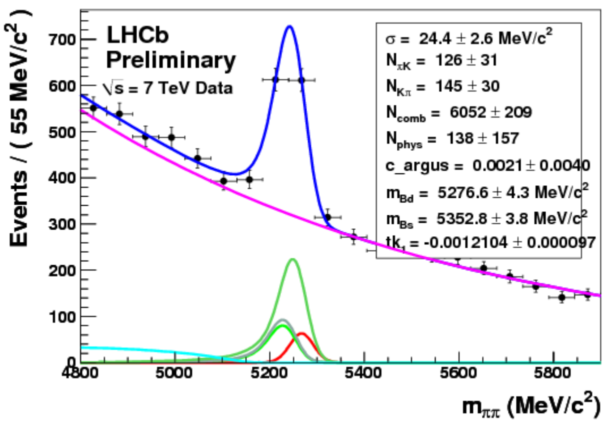
⟶ Calibration and normalization

# Calibration

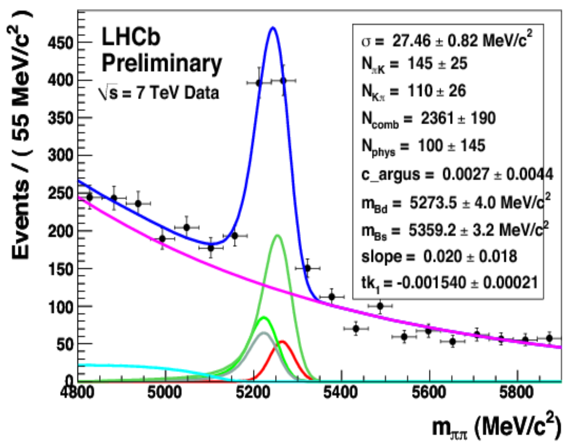
- Signal is distributed in several bins of a 3D space
- We need to know both the overall normalization and the fraction of signal in each bin
  - **Invariant mass:** Can be calibrated, e.g., with fit of $B \rightarrow hh$ line shape or from charmonium and bottonium resonances
  - **Geometrical Likelihood**: $B \rightarrow hh$ triggered independently of signal (event triggered by the other B)
  - **PID likelihood:** $J/\Psi$ taking p, pt distributions from $B \rightarrow hh$
- Will have a quick look at **invariant mass** and **geometrical likelihood**

# Invariant mass calibration (I)

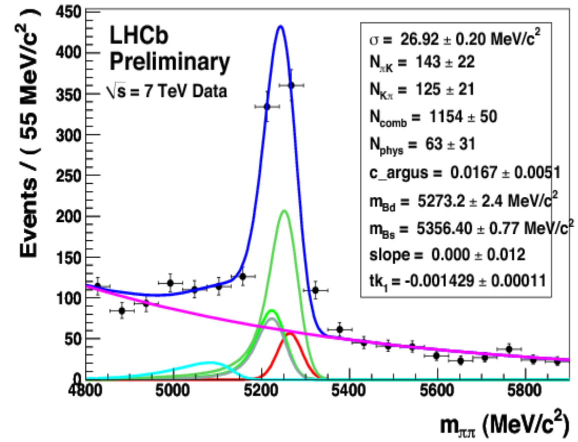
- Method 1: **Full fit of the B → hh line shape**
  - Use the Geometrical Likelihood to clean the sample!




GL=[0.25-0.5]




GL=[0.5-0.75]

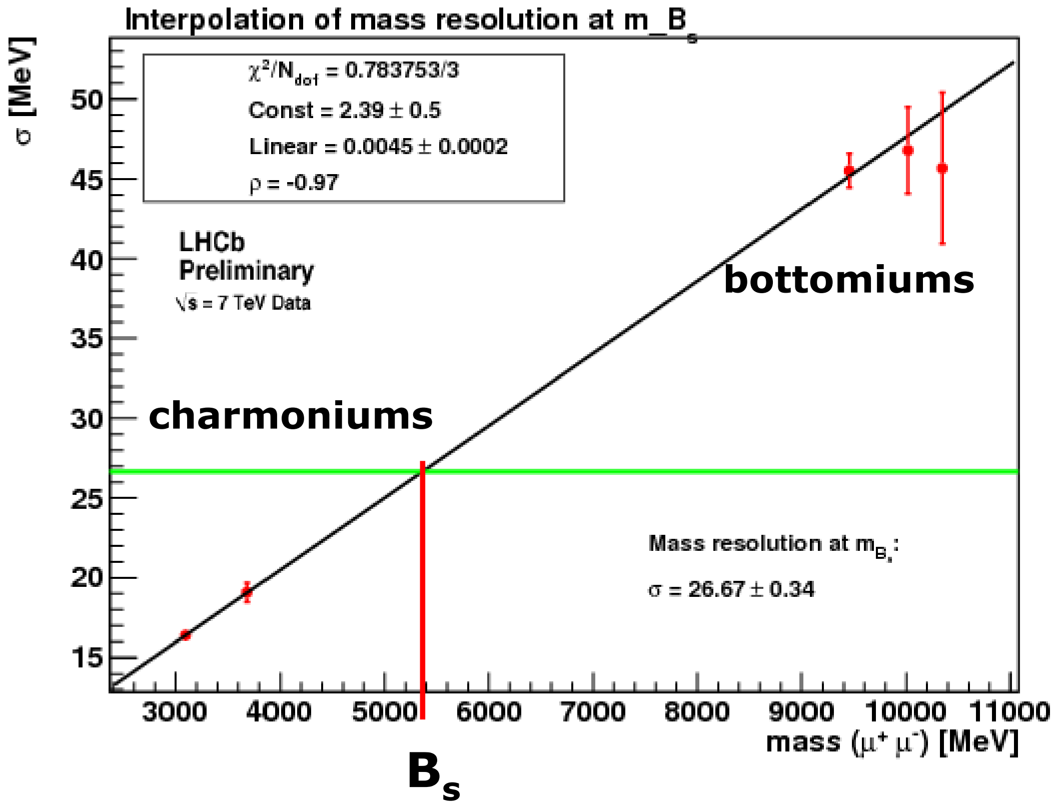



GL=[0.75-1.0]

| | GL:[0.25-0.5] | GL:[0.5-0.75] | GL:[0.75-1.0] |
|---|---|---|---|
| Ntot | 703 | 661 | 695 |
| σ (MeV/c²) | **24.4 ± 2.6** | **27.5±0.82** | **26.9±0.2** |
| $M(B_d)$ (MeV/c²) | 5276.6±4.3 | 5273±4.0 | 5273±0.71 |
| $M(B_s)$ (MeV/c²) | 5352.8±3.8 | 5359±3.2 | 5356±0.77 |

# Invariant mass calibration (II)

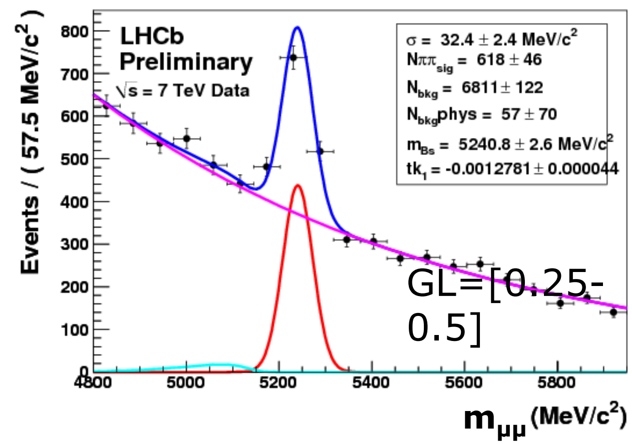
- Method 2: **Interpolation of σ between charmoniums and bottomiums**.
  - Correction for $B_s$ momentum spectrum.

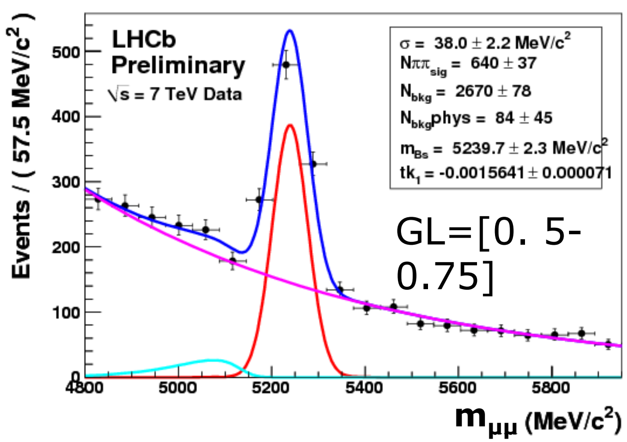


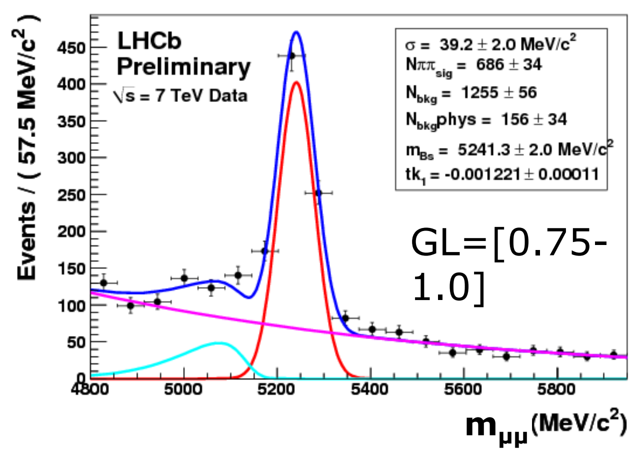

$\sigma_{mBs}$ = (26.7 ± 0.3) MeV/c$^2$

# Geometrical Likelihood calibration (I)

- Fit the distribution in GL bins to extract the **number of B → hh signal events**.
  - First bin difficult to fit. Get the number in this bin by:
    - Fitting all B → hh and subtracting events from other GL bins,
    - Cleaning with topological cuts before the fit and assessing signal loss via control channel.

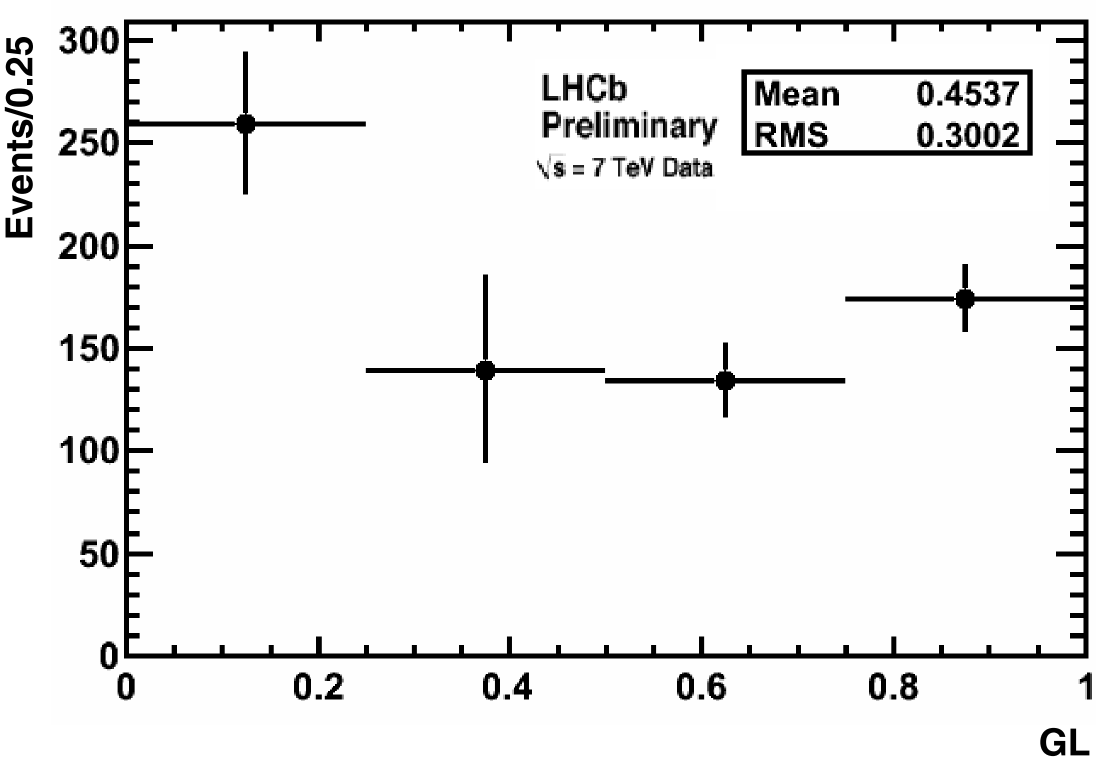


# Geometrical Likelihood calibration (II)

- GL distribution from B → hh:




Not as flat as expected. **Work ongoing to understand why!**

Normalised into a pdf, used in the computation of the limit

# Normalization

- Normalization needed to convert # events into a BR without relying on knowledge of $\sigma_{bb}$, integrated luminosity or absolute efficiencies

$$BR = BR_{cal} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{GEC} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{GEC} \varepsilon_{Bs}^{Trig}} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = norm \cdot N_{B\to\mu\mu}$$

*cal*: control channel
$B_s$: $B_s \to \mu\mu$

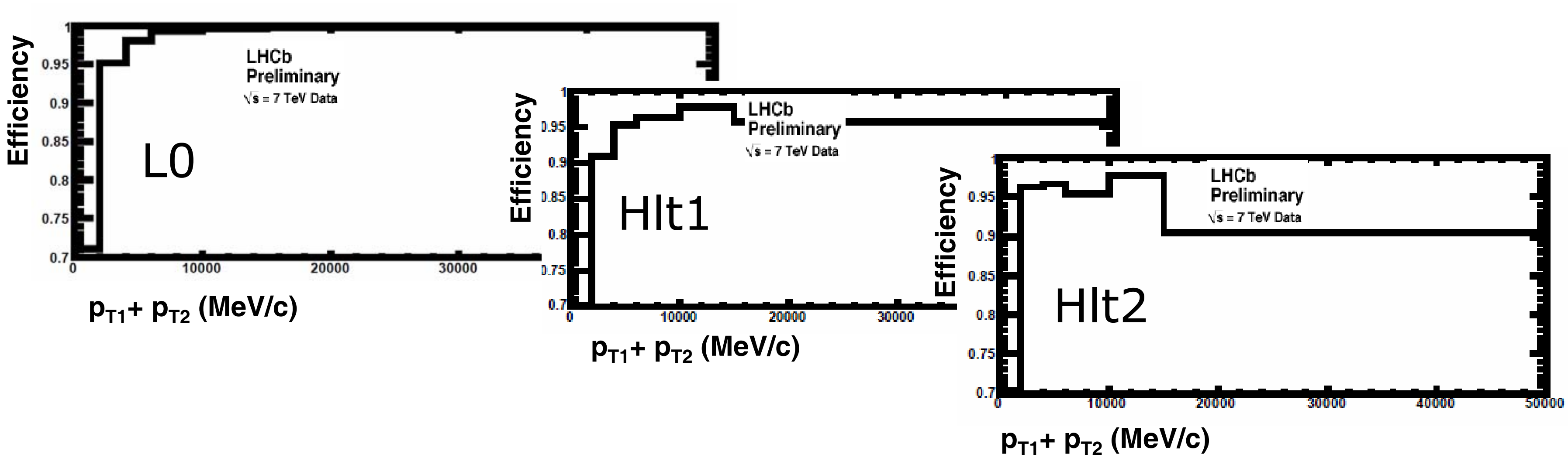
- Using any, $B^+$, $B^d$ as a control channel implies a **~13 % systematic from the knowledge of $f_d/f_s$** $(=f_+/f_s)$. Normalization to a $B_s$ mode would introduce in principle larger errors because of worse known of branching ratios.

> Several groups in LHCb are measuring **$f_d/f_s$**. Hope to reduce the error soon to **~7%**

- Some control channel candidates:
  - $B^+ \to J/\Psi(\mu\mu)K^+$, $B_s \to J/\Psi(\mu\mu)\Phi(KK)$
    - similar trigger and PID,
    - different reconstruction because of the extra track/tracks
    - $B_s$ : worse BR precision, but not $f_+/f_s$
  - $B \to hh$:
    - Same kinematics
    - different trigger & PID

# Normalization example: $B^+ \to J/\Psi(\mu\mu)K^+$

- The fraction of efficiencies (trigger, reconstruction, selection, PID…) needs to be computed/cancelled.
- Trigger on **data**:
  - J/Ψ trigger efficiency L0,HLT1 and HLT2



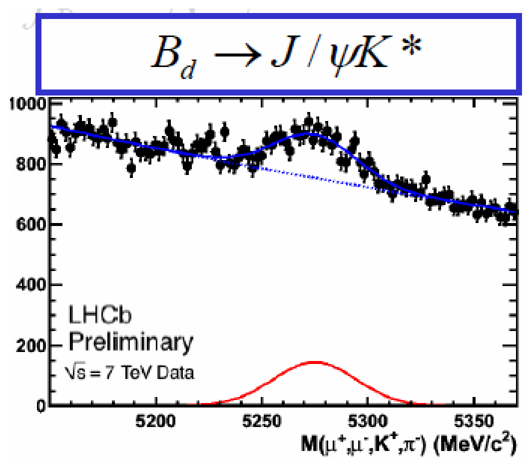

Integrated J/Ψ trigger efficiency → $\varepsilon_{J/\psi}^{L0xHLT1xHLT2} = 82\%$

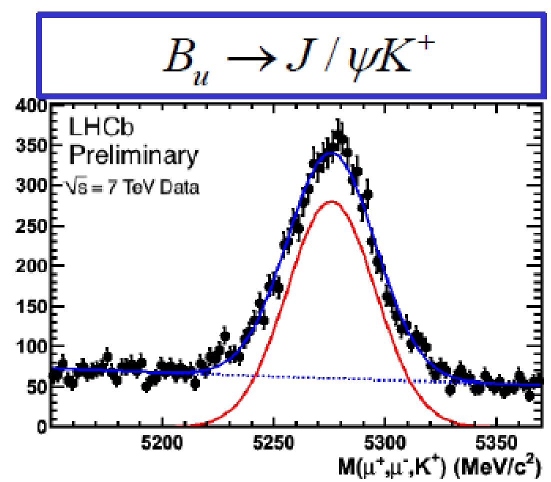
Apply J/Ψ map to harder $B_s$ spectrum → $\varepsilon_{Bs\to\mu\mu}^{L0xHLT1xHLT2} = 86\%$

# Normalization example: $B^+ \rightarrow J/\Psi(\mu\mu)K^+$

- The fraction of efficiencies (trigger, reconstruction, selection, PID…) needs to be computed/cancelled.
- Reconstruction/acceptance:
  - Ratio 4/3 body allows to evaluate with data the ratio 3/2 body
    - → Extra track effect: (acceptance + tracking)

$$\frac{\varepsilon^{rec}_{2body}}{\varepsilon^{rec}_{3body}} \approx \frac{\varepsilon^{rec}_{3body}}{\varepsilon^{rec}_{4body}} = 0.58 \pm 0.04 \quad (stat\ only)$$



# First results

# How do we extract a limit?

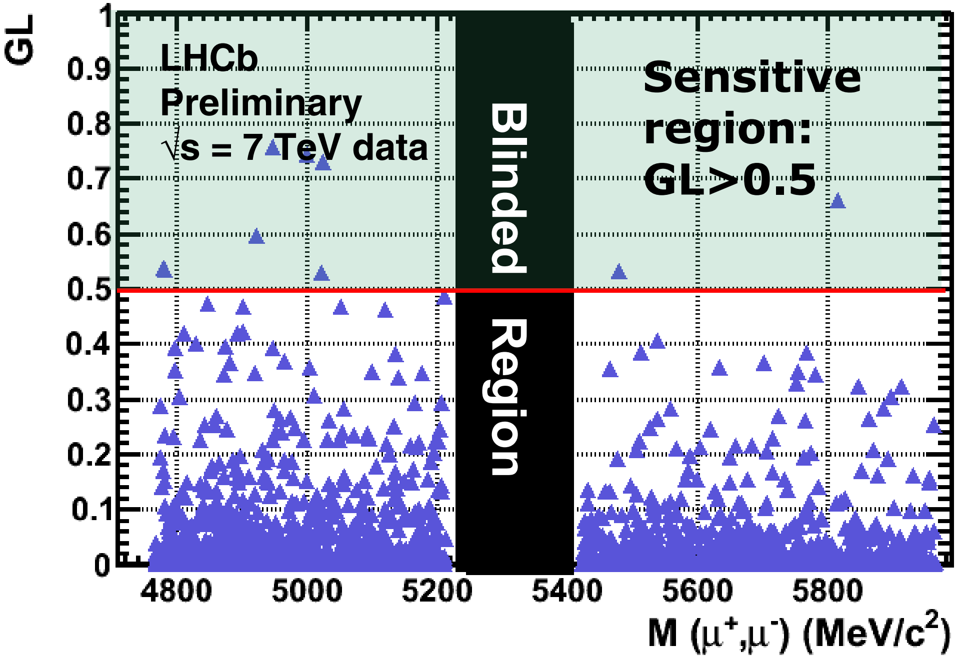
- For each bin we need to know:

  1) Number of ***expected signal*** *events* (for a given BR & Lumi)

  and the number of ***expected background*** *events* (for a given Lumi)

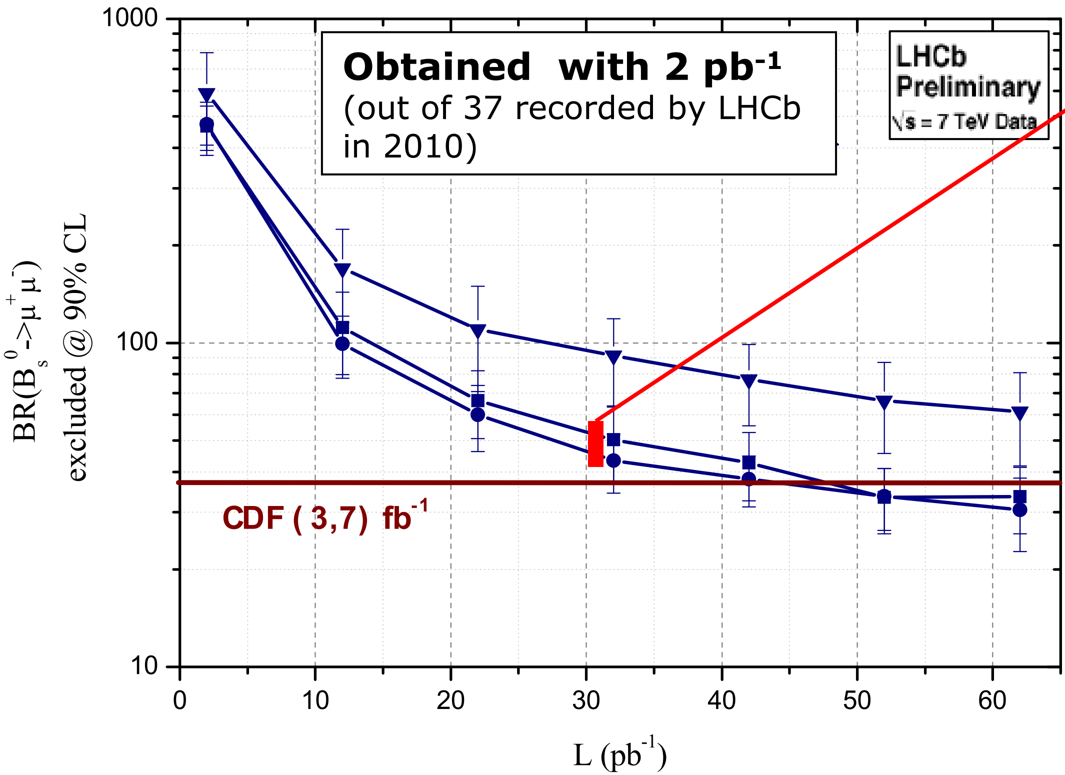
  2) The number of ***observed*** events from data (blinded until January!)

- For **expected limit** we generate toy experiments from signal and background expectations.



# Expected sensitivity

- No $B_s \rightarrow \mu\mu$ data from blinded region used. But all the pdfs (signal and background **mass** and **GL**) obtained from **data**, no MC.
  - **Expected 90% exclusion sensitivity**




Current status of the analysis (without opening of "the box")

Work ongoing to improve the GL → **improve sensitivity!**

Plot presented by **Diego Martínez (USC)** at last LHCb plenary meeting!

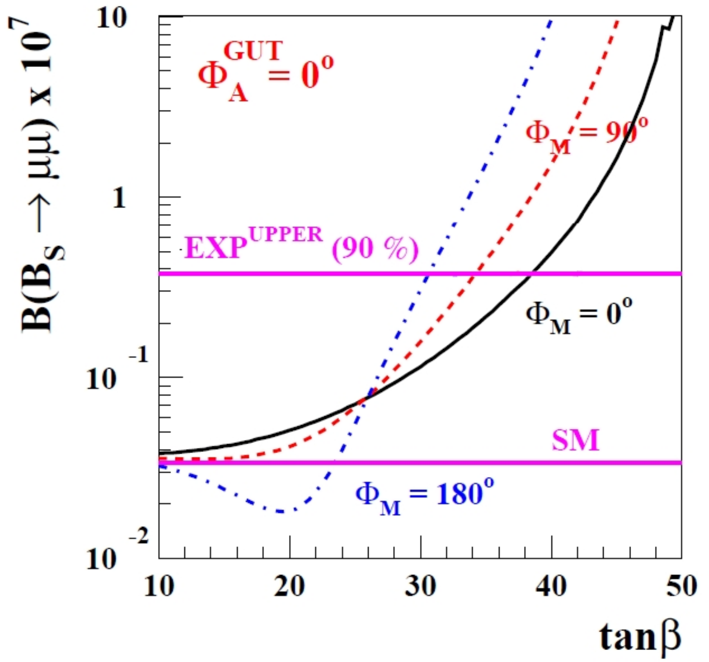
# Conclusions

# Conclusions

- BR($B_s \rightarrow \mu\mu$) can constraint **several NP models.**
  - Value allowed from current experimental upper limit to below SM prediction.
- Analysis in LHCb based in a 3D (**Geometrical Likelihood, Invariant Mass and Particle Identification**) space.
- **Calibration** of Invariant mass and Geometrical Likelihood needed to determine the fraction of signal in each bin. **Normalization** to control channels used to calculate BR.
- **LHCb working really fine**. Data approaching MC in momentum and mass resolution, IP, and PID.
- Experimental limit by LHCb close to current's world best at the end of this year. Hope to overtake it soon!

# Backup

# New Physics effects (III)

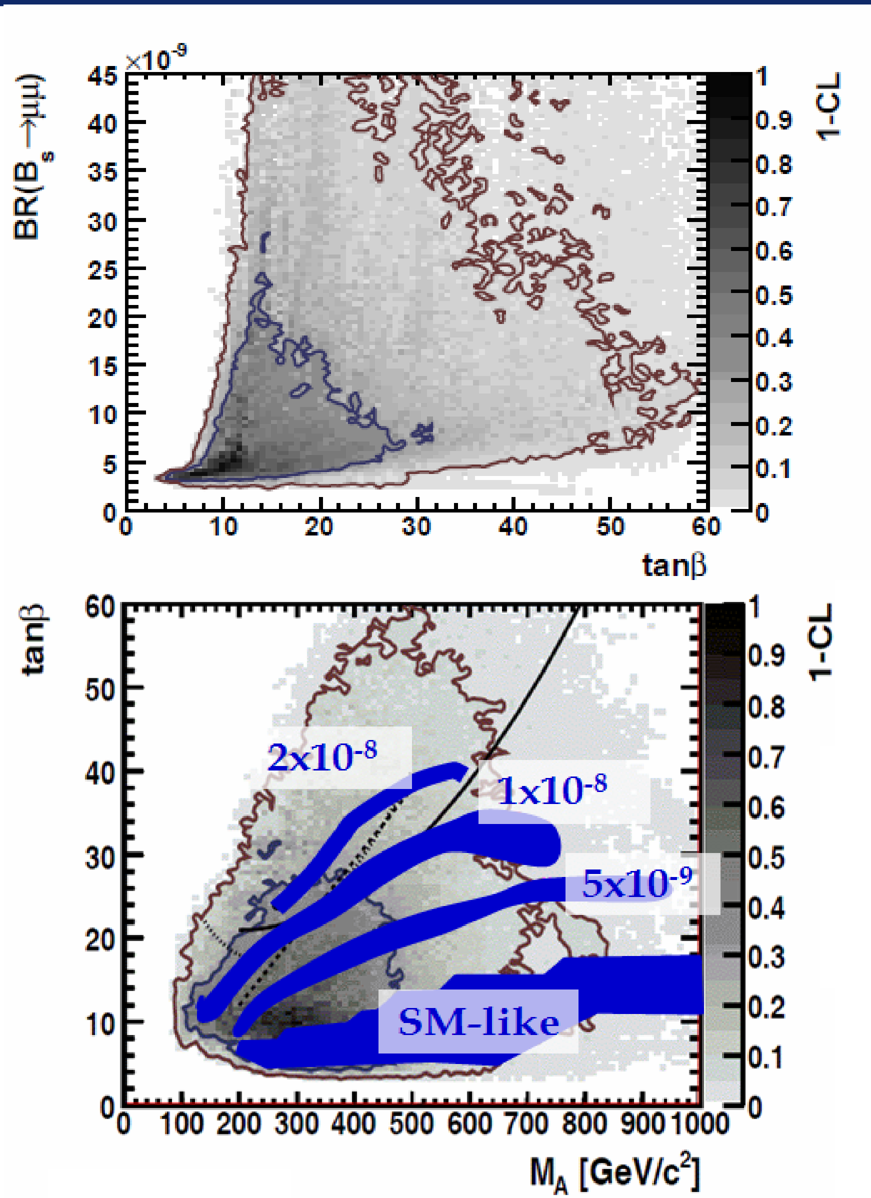


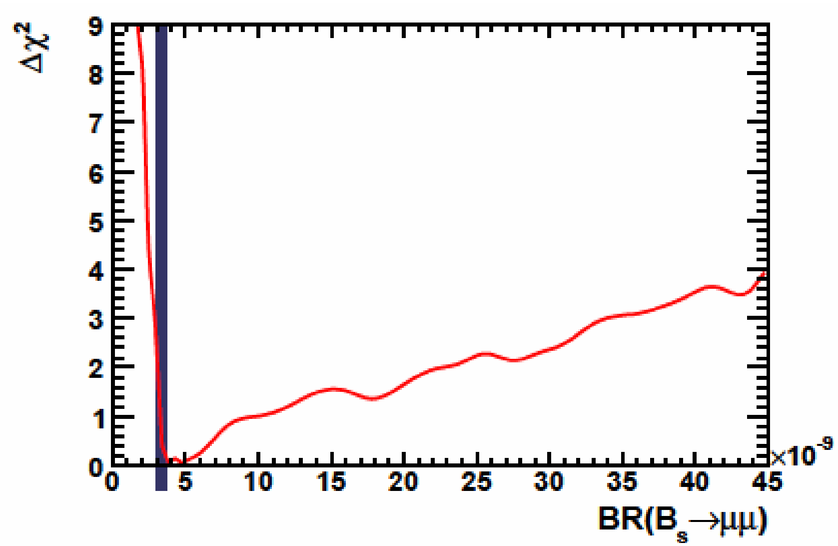

J.Ellis et. al. Phys.Rev.D76:115011, 2007
[ arXiv:0708.2079v4 [hep-ph] ] (2008)

**Maximal CP Violating Minimal Flavour Violation**: Enhancements up to current upper limit, but also < SM depending on the phases

**CMSSM**: departures from SM possible, but less likely taking into account current experimental constraints

# New Physics effects (II)




O. Buchmueller et al, Eur.Phys.J.C64:391-415,2009 [arXiv:0907.5568v1 [hep-ph] 31 Jul 2009]

**NUHM1**