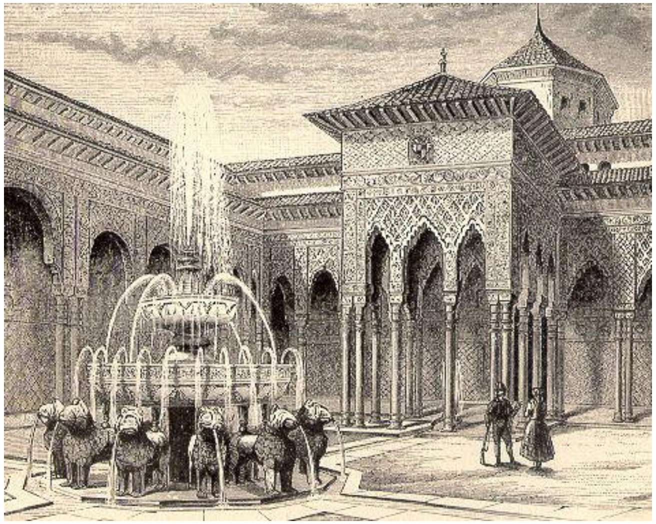
New Physics in $B_s \rightarrow \mu^+\mu^-$

Diego Martínez Santos (USC)



PROGRAMA NACIONAL DE BECAS FPU

Overview

- Motivation for the study of $B_s \rightarrow \mu\mu$ as an indirect probe of NP
- Analysis in LHCb
  - Overview of the analysis and involved groups
  - How to find such a rare decay and disentangle from background
  - Normalization and Calibration to get a correct BR
- Conclusions

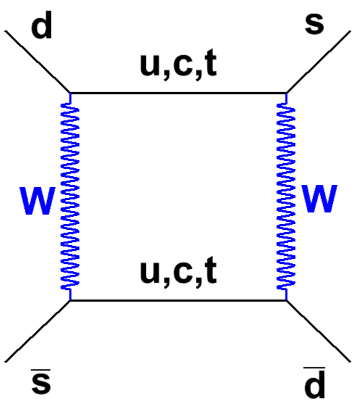
Indirect Approach

- $B_s \rightarrow \mu\mu$ can access NP through new virtual particles entering in the loop → indirect search of NP

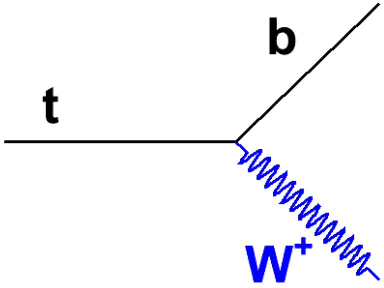
- Indirect approach can access higher energy scales and see NP effects earlier:

  - Some examples:
    - 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…



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:

- •A very early example of how indirect measurements give information about higher scales ☺:
  - •**Ancient Greece**: Earth must be some round object, Eratosthenes measurement of Earth's radius in **c. III BC** (using differences in shadows at different cities)
  - •Roundness of Earth not directly observed until middle of **c. XX**

Eratosthenes

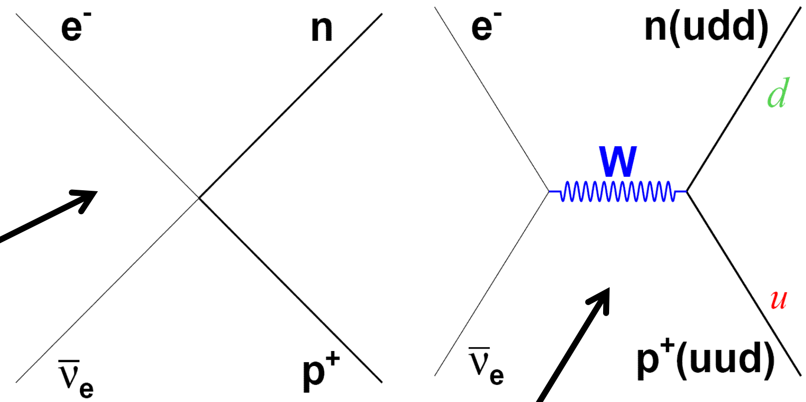
~2.3 K years till the direct observation…

Wilson coefficients

Hadronic weak decays are often studied in terms of effective hamiltonians of local operators Q_i:

$$H_{eff} \propto \sum_i C_i \hat{Q}_i$$

effective local theory



Degrees of freedom of exchanged particles are integrated out giving rise to the **Wilson coefficients C_i**.

underlying "fundamental" theory (SM)

An **example** of similar approach: **Fermi's theory of neutron decay**

BR($B_s \to \mu\mu$) expressed in eff. th. as:

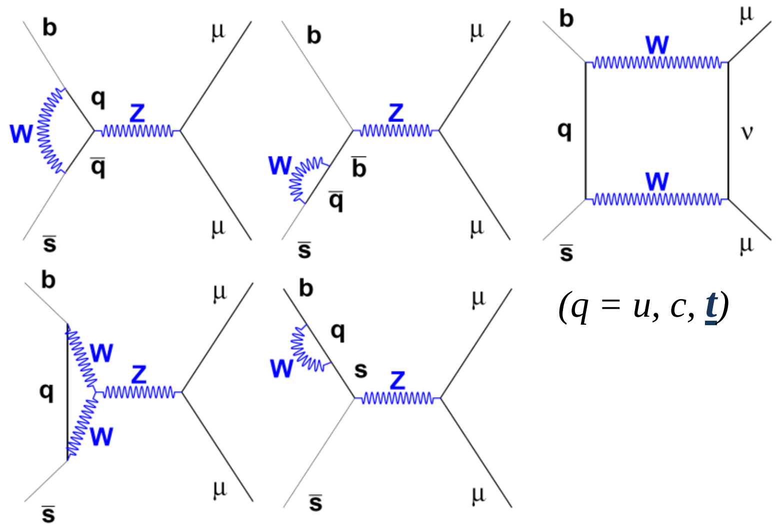
$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} |V_{tb}^* V_{tq}|^2 \tau_{Bq} M_{Bq}^3 f_{Bq}^2 \sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}} \times \left\{ M_{Bq}^2 \left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right) C_S^2 + \left[M_{Bq} C_P + \frac{2m_\mu}{M_{Bq}} C_{10} \right]^2 \right\}$$

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

Decay Physics (SM)

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

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



(q = u, c, t)

$C_{S,P} \longrightarrow$ scalar and pseudo scalar are negligible in SM

C_{10} gives the only relevant contribution

This decay is very suppressed in SM:

$BR(B_s \to \mu\mu) = (3.35 \pm 0.32)\times10^{-9}$ $BR(B_d \to \mu\mu) = (1.03 \pm 0.09)\times10^{-10}$

M.Blanke et al., JHEP 10 003,2006

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

$BR(B_s \to \mu\mu) < 3.6\times10^{-8}$ $BR(B_d \to \mu\mu) < 6.0\times10^{-9}$

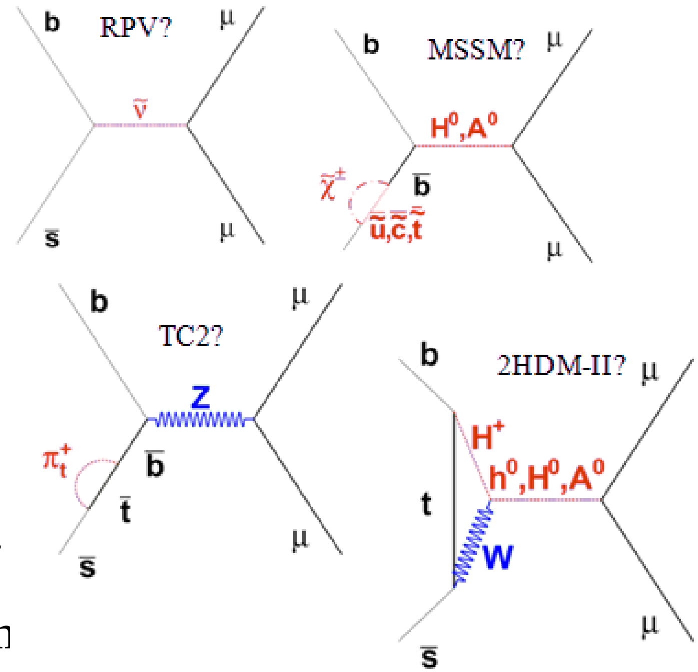
CDF collab., CDF Public Note 9892

New Physics effects

NP can contribute to this decay rate (specially SUSY at high tanβ ($tan\beta = v_u/v_d$)):

- More than one Higgs → contributions to $\mathbf{C_{S,P}}$
    - 2HDM-II : BR proportional to $\tan^4\beta$
    - SUSY (MSSM): above + extra $\tan^6\beta$ +…

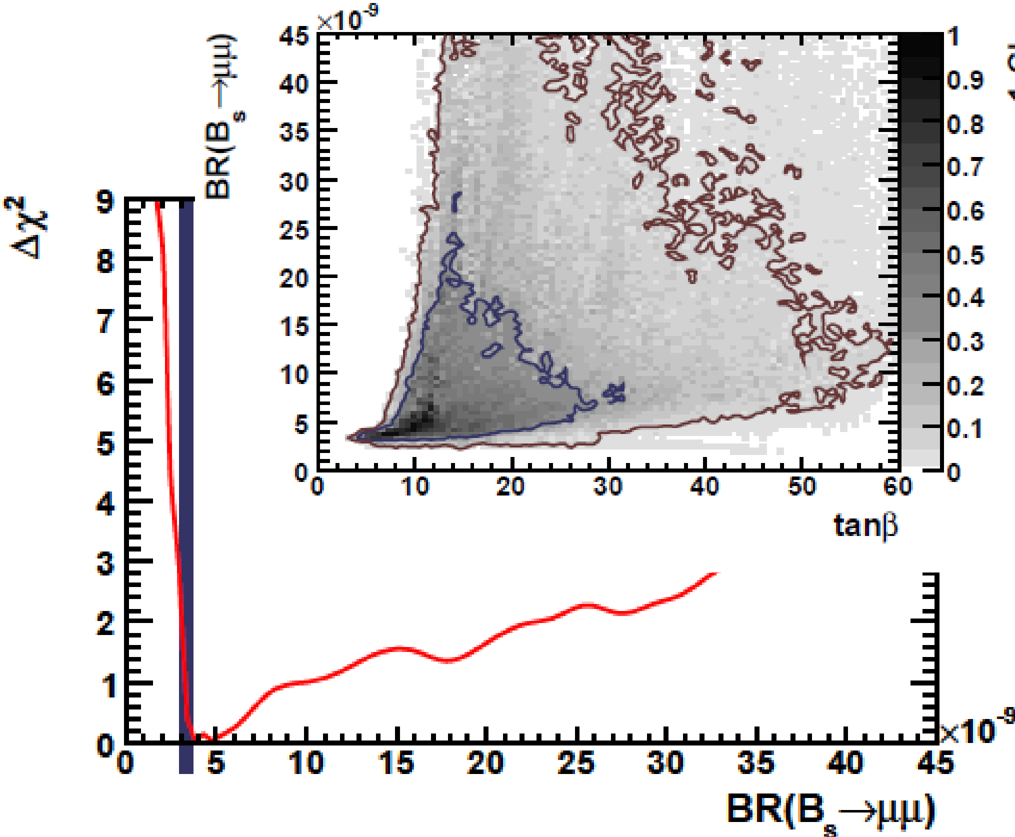
- RPV SUSY: tree level diagrams
- Technicolor (TC2), Little Higgs (LHT) … modify $\mathbf{C_{10}}$.



NP can modify the BR from < SM up to current experin

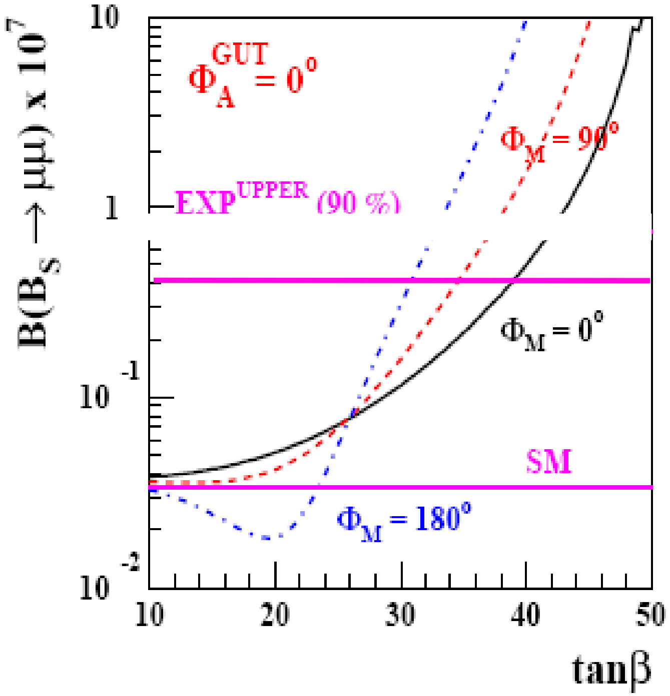
→ ***Whatever the actual value is, it will have an impact on NP searches***

New Physics effects (II)



NUHM1

J.Ellis , yesterday's talk



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

MCPVMFV: Enhancements up to current u.l, but also < SM depending on the phases

Analysis

Analysis Overview

Triggered and offline reconstructed (incl. muon identification) **signal** events per fb^{-1} (i.e., effective $B_s \rightarrow \mu\mu$ cross section)

	ATLAS	CMS	LHCb
# evts/fb^{-1}	13.3	11.6	**36.2**
For trigger strategy	$L = 10^{33}$	$L > 10^{32}$	$\mathbf{L = 2x10^{32}}$

$\sigma_{b\bar{b}}$ assumed to be 500 μbarn, $BR(B_s \rightarrow \mu\mu) = 3.35 \times 10^{-9}$ (SM)

Main issues:

- Background discrimination: offline cuts/ multivariate analysis

- Normalization to another B channel with well known BR
  - It avoids needing the knowledge of xsections & integrated luminosity
  - Cancelation of systematic uncertainties

ATLAS analysis: CERN-OPEN-2008-020 [arXiv:0901.0512] (B-physics chapter)
CMS analysis: CMS PAS BPH-07-001 (2009)
LHCb analysis: LHCb-PUB-2007-033 (2007) , LHCb-PUB-2008-018 (2008)

Analysis Overview

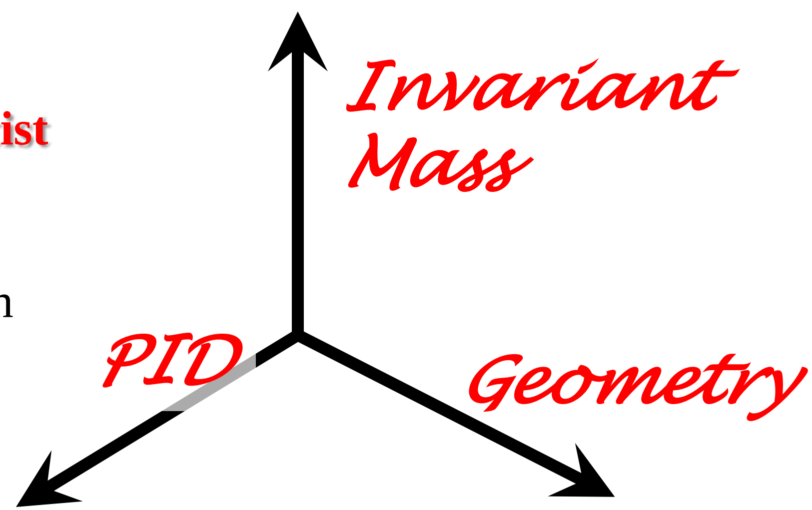
- **Selection**: apply some cuts on all μμ candidates to remove most of the background

- **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 are combined using **Modified Frequentist Approach**

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



The group

•LHCb analysis group is coordinated by **Frederic Teubert** (CERN)

•The analysis started to be designed in 2006: F. Teubert (CERN), J.A. Hernando (CERN/**USC**), D. Martinez Santos (**USC**)

•LHCb sensitivities, basic lines of the analysis:

D. Martinez Santos, J. A. Hernando, F. Teubert : LHCb-PUB-2007-033
D. Martinez Santos, LHCb-PUB-2008-019, Yad. Fiz. 72, 9 (2009)

• **USC has strong contribution in all aspects** of the analysis (J. A. Hernando, X. Cid Vidal, D. Martinez Santos)

• **UB** also working on the analysis, involved in the use of B→ hh control channel (see later) and in trigger aspects (H. Ruiz, E. Lopez, A. M. Perez Calero, A. Camboni, R. Vazquez)

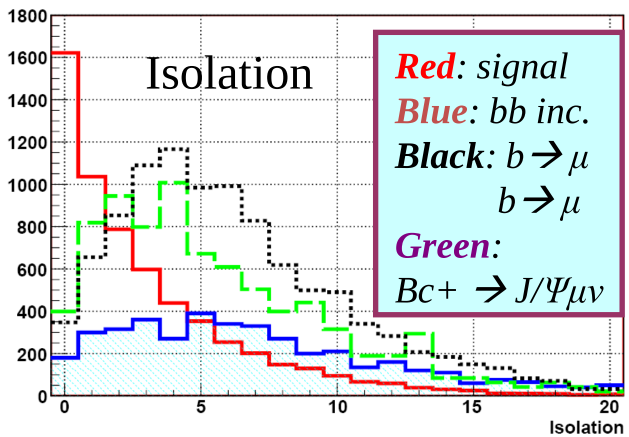
•Several groups now joining the effort: Laussane, Marseille, Zurich, NIKHEF, INFN, Rio de Janeiro

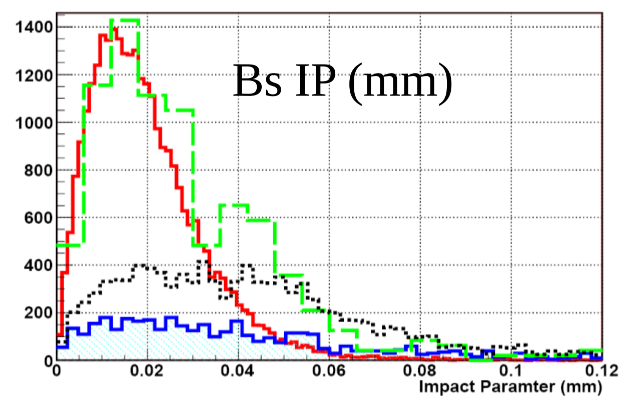
Geometrical Likelihood

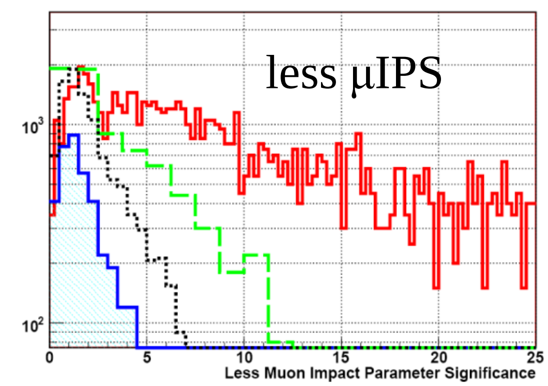
How the Geometry likelihood is built:

1. Input variables: min Impact Parameter Significance (μ^+,μ^-), DOCA, Impact Parameter of B, lifetime, iso - μ^+, iso- μ^-

•**Isolation:** Idea: muons making fake $Bs\to\mu\mu$ might came from another SV's
→ For each muon; remove the other μ and look at the rest of the event: How many good - SV's (forward, DOCA, pointing) can it make?
The precise criteria used is inherited from Hlt Generic







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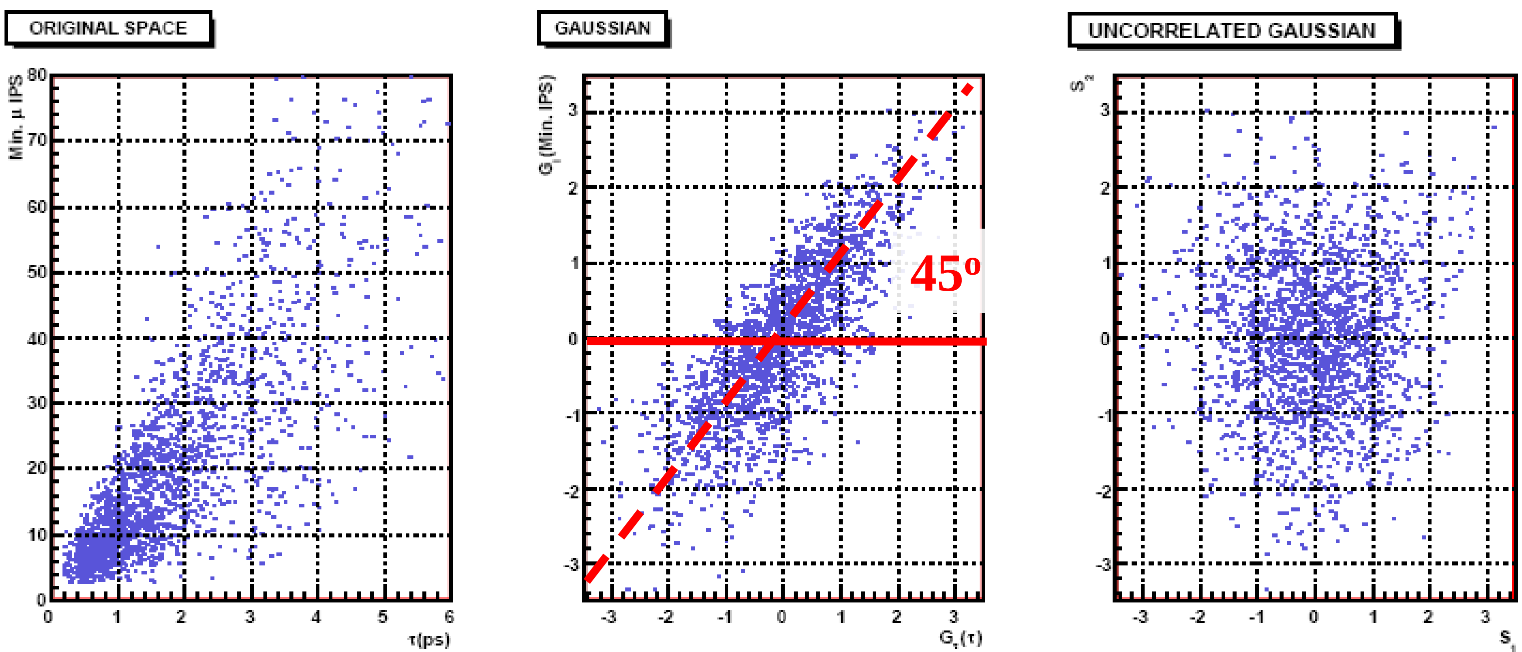
2. They are transformed to Gaussian through cumulative and inverse error function
3. In such space correlations are more linear-like → rotation matrix, and repeat 2



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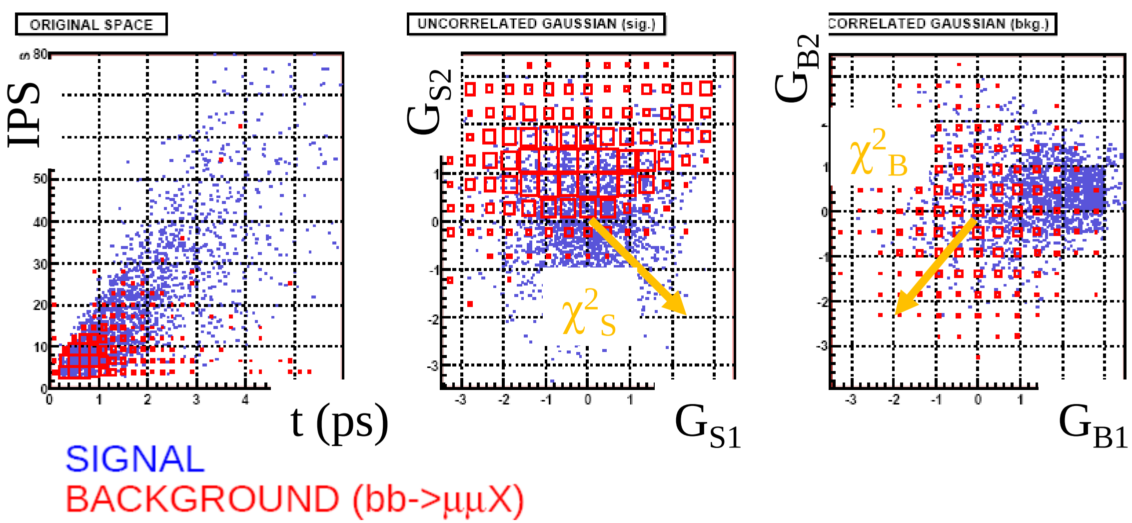
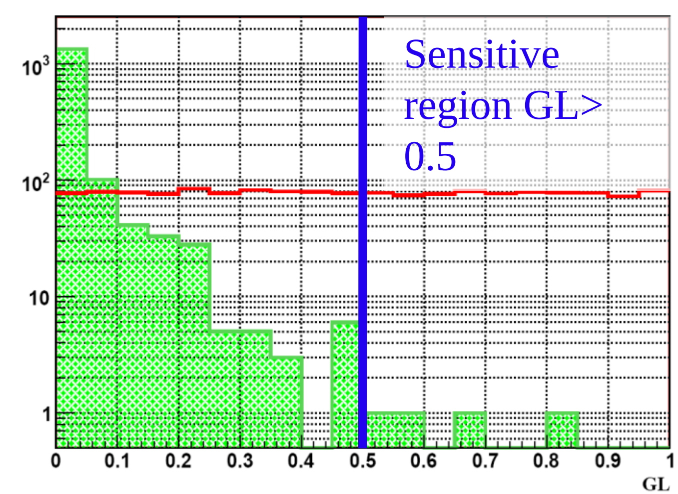
4. Transformations under signal hyp. → χ^2_S, under bkg. → χ^2_B.
5. Discriminating variable is $\chi^2_S - \chi^2_B$, made flat for better visualization.

lifetime





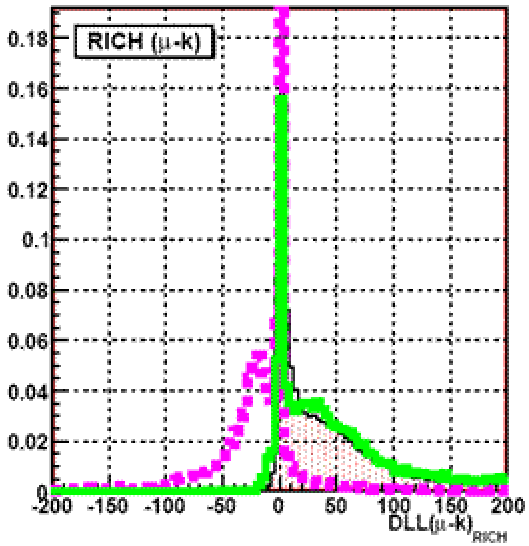
PID likelihood

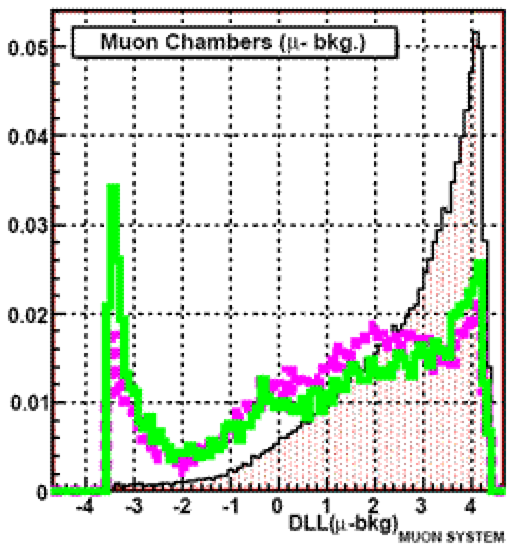
•Particles with associated hits in the muon chambers are flagged as muons

•Some of them might not be actual muons (=misid). Different subdetectors return probabilities for different kinds of particles:

- •Muon chambers: distances of hits to track extrapolation, or others…
- •RICH: uses mass of the particles
- •CALO's : energy deposition

•This probabilities can be combined in a likelihood to fight against remaining misid





Sensitivities

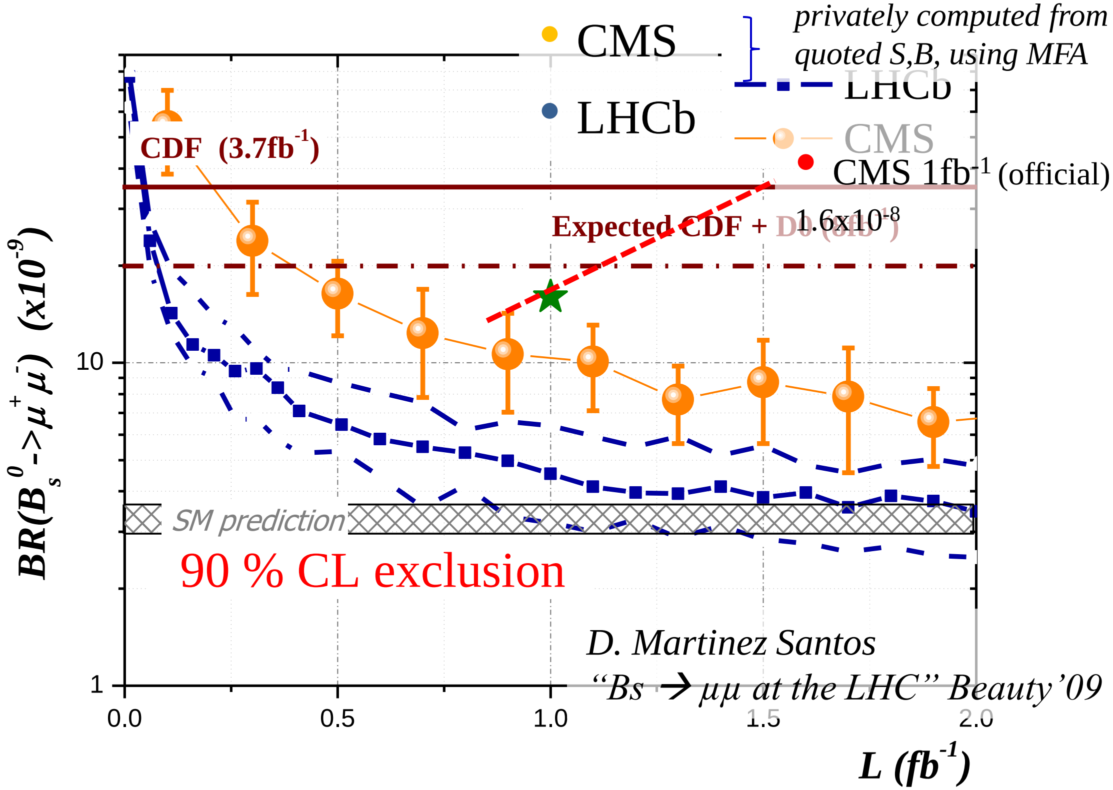
(expected S (for BR = 3.35e-9) & B per fb^{-1} in each experiment LHCb bins parameter space → N experiments)

- 90% CL exclusion sensitivity as a function of L
- (Only bkg is observed)

CMS

S (BR = 3.35e-9) = 2.05
B = 6.53

LHCb	GL	
Mass (MeV)	**0.5–0.65**	**0.65-1**
5406.6 - 5429.6	$S = 0.13$ $B = 8^{+10}_{-5}$	$S = 0.3$ $B = 8^{+10}_{-5}$
5384.1 - 5406.6	$S = 0.55$ $B = 8^{+10}_{-5}$	$S = 1.4$ $B = 8^{+10}_{-5}$
5353.4 - 5384.1	$S = 1.6$ $B = 11^{+15}_{-7}$	$S = 3.8$ $B = 11^{+15}_{-7}$
5331.5 – 5353.4	$S = 0.6$ $B = 8^{+10}_{-5}$	$S = 1.5$ $B = 8^{+10}_{-5}$
5309.6 – 5331.5	$S = 0.2$ $B = 8^{+10}_{-5}$	$S = 0.45$ $B = 8^{+10}_{-5}$



D. Martinez Santos
"Bs → μμ at the LHC" Beauty'09

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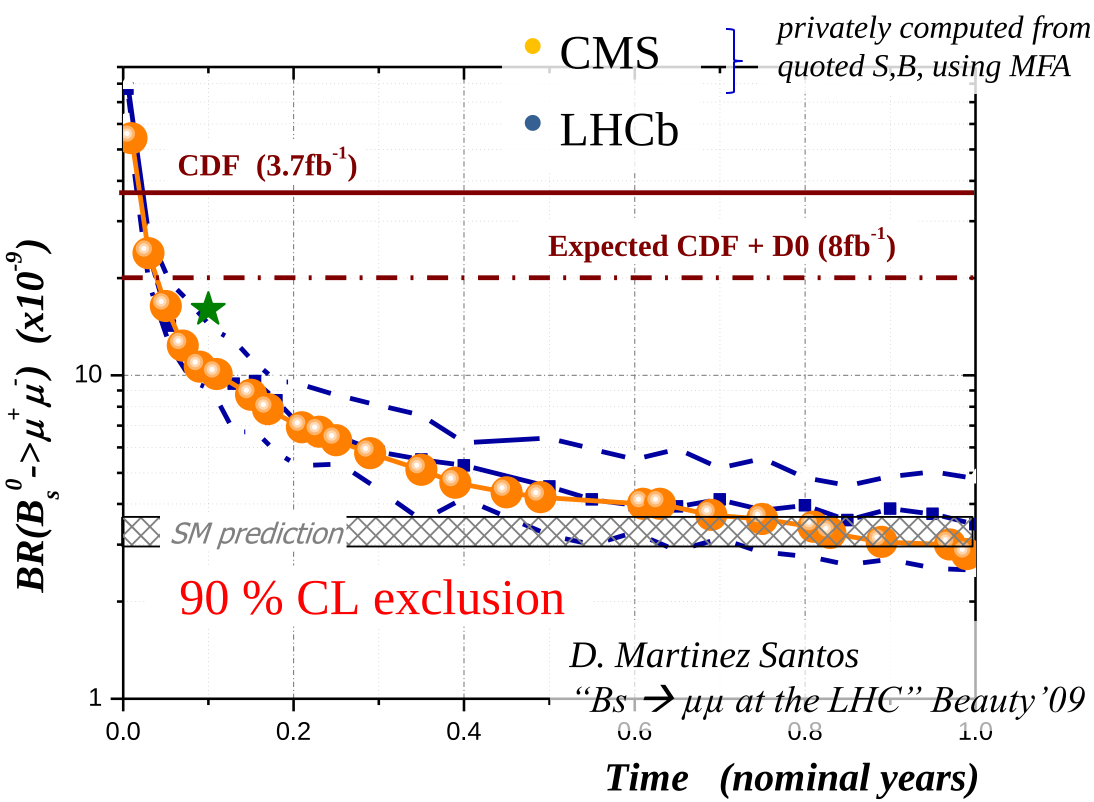
• 90% CL exclusion sensitivity as a function of time

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



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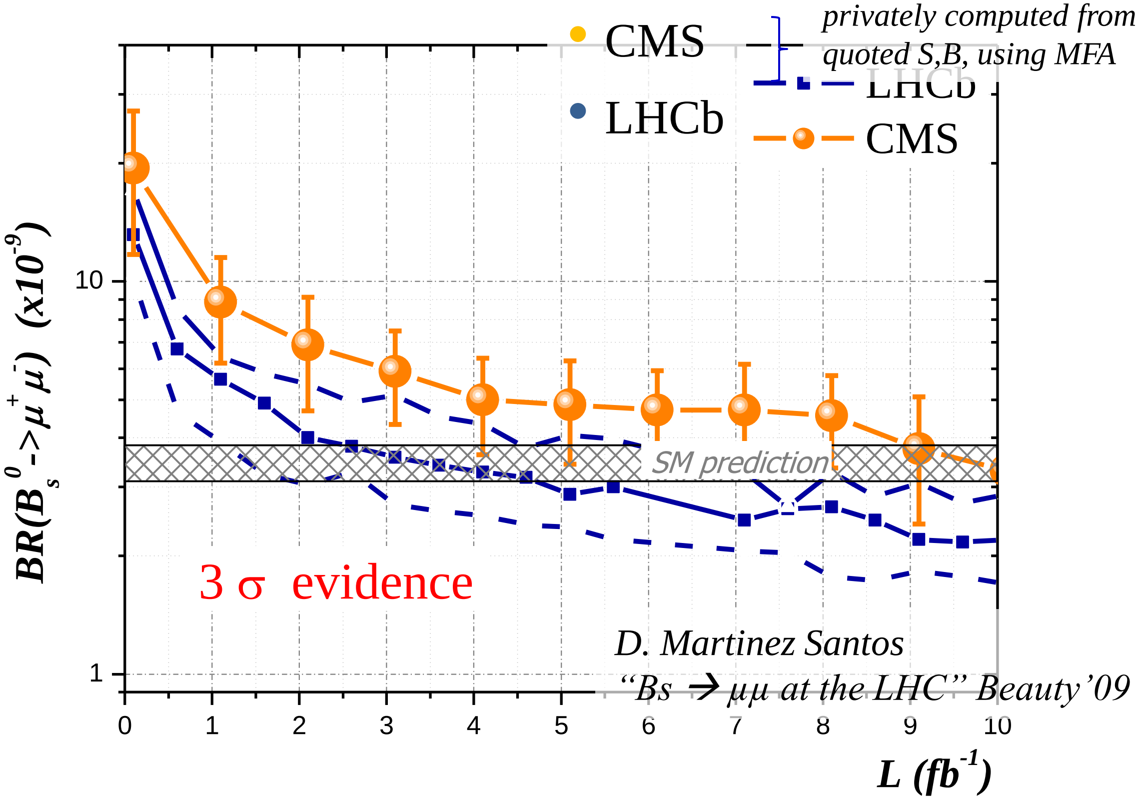
- Signal evidence sensitivity as a function of L
- (Signal + Background observed)



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- Signal evidence sensitivity as a function of time

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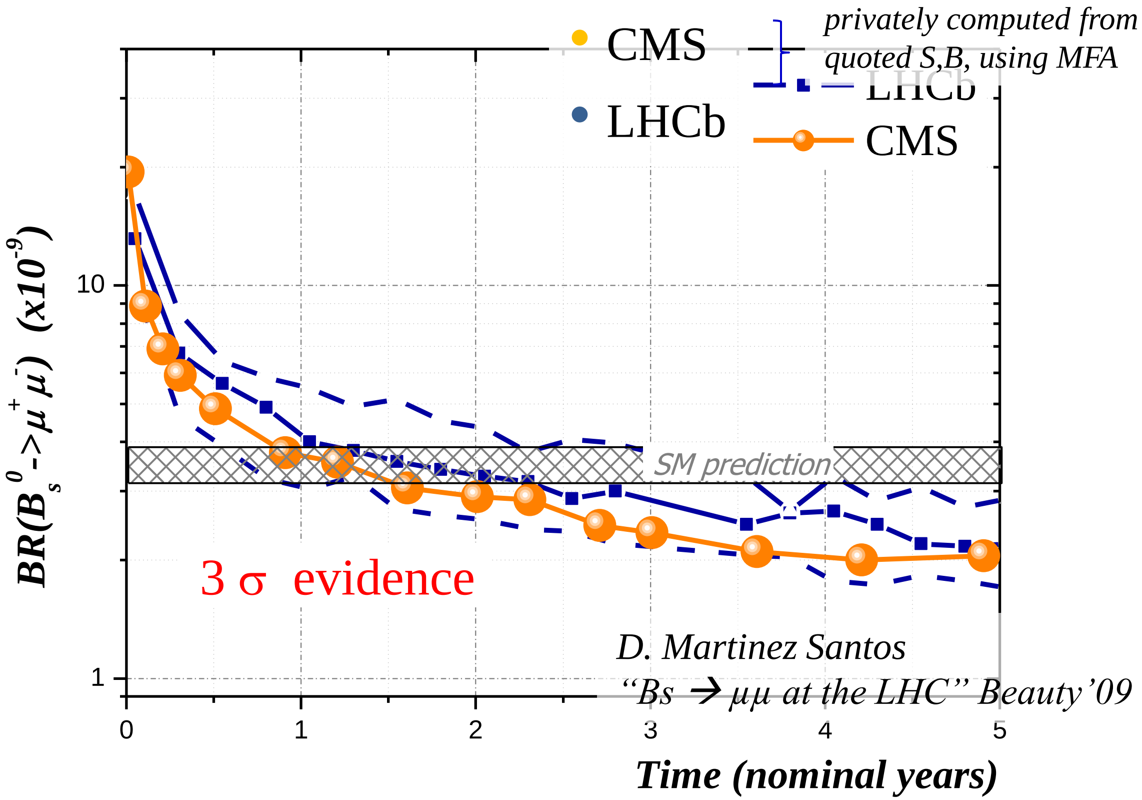
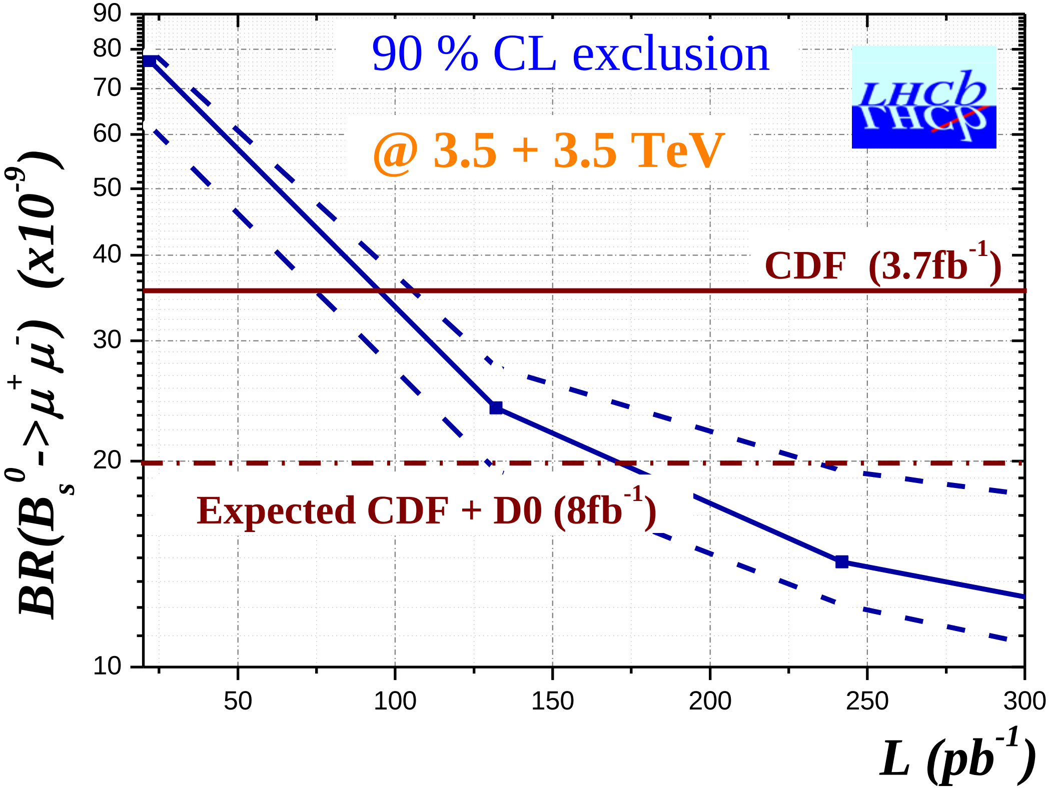
LHCb → L = $2x10^{32}$ $cm^{-2}s^{-1}$



LHC Startup

- LHC first data:
  - •Less energy (3.5 + 3.5 TeV)
  - •Less instant luminosity
- Exclusion sensitivity for
  - •45% of σ_{bb} w.r.t. 14 TeV (Pythia ratio $\sigma_{bb\_7TeV}/\sigma_{bb\_14TeV}$), so 225 μb
  - •First 10 months after LHC startup (assumed 300 pb^{-1})
- This data could allow LHCb to overtake Tevatron limits and impose new constraints on SUSY models



Normalization & Calibration

Normalization

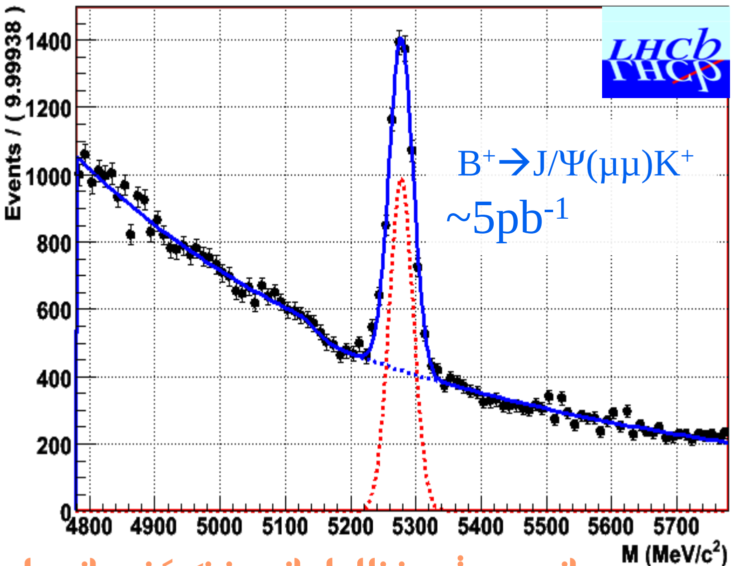
- Normalization is needed to convert # events into a BR w/o relying on knowledge of σ_{bb}, integrated luminosity or absolute efficiencies

$$BR = BR_n \frac{\varepsilon_n}{\varepsilon} \cdot \frac{P(b \to B_n)}{P(b \to B_s)} \cdot \frac{N}{N_n}$$

- $P(b \to B^+, B_d)/P(b \to B_s)$ implies a **~14 % systematic**. Normalization to a B_s mode would introduce larger errors because of poorly known B_s BR's

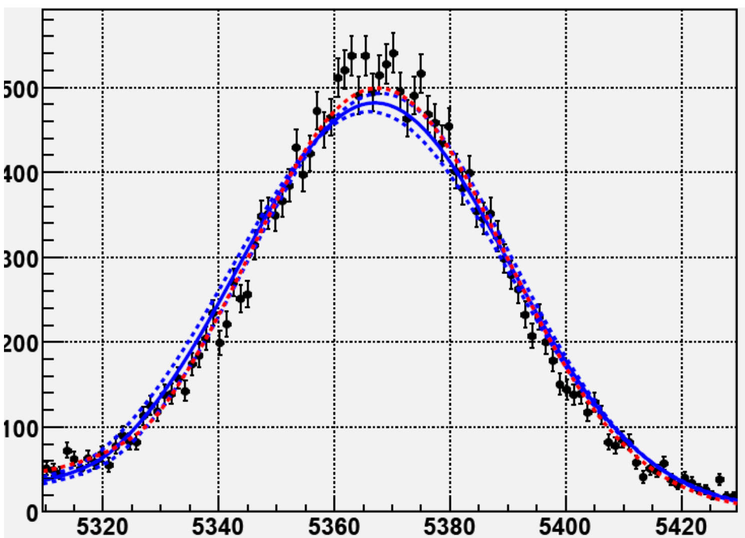
- The fraction of efficiencies (acceptance, trigger, selection, PID…) needs to be computed/cancelled.

- **Good candidates**:
  - $B^+ \to J/\Psi(\mu\mu)K^+$:
    - similar trigger and PID, different reconstruction because of the extra track
  - $B \to hh$:
    - Same kinematics but different trigger & PID



Calibration

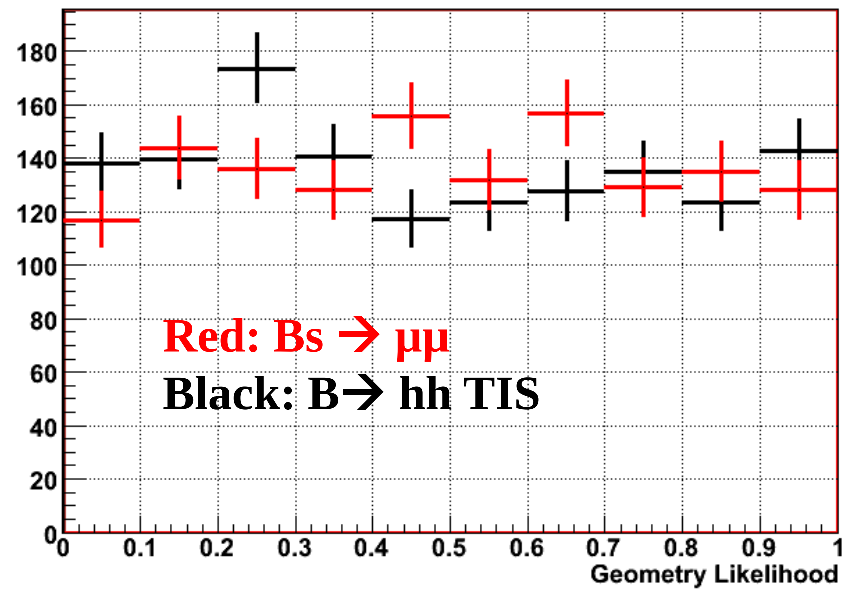
- Signal is distributed in several bins of a 3D space
- We need to know not only overall normalization, also the fraction of signal in each bin
  - **Invariant mass** → Can be calibrated with B_s → KK
  - **GL** → (inclusive) B→hh triggered independent of signal (TIS)
  - **PID likelihood** → J/Ψ taking p, pt distributions from B→ hh TIS



Data: Bs → μμ

Red: Fit to data itself

Blue: Function from calibration

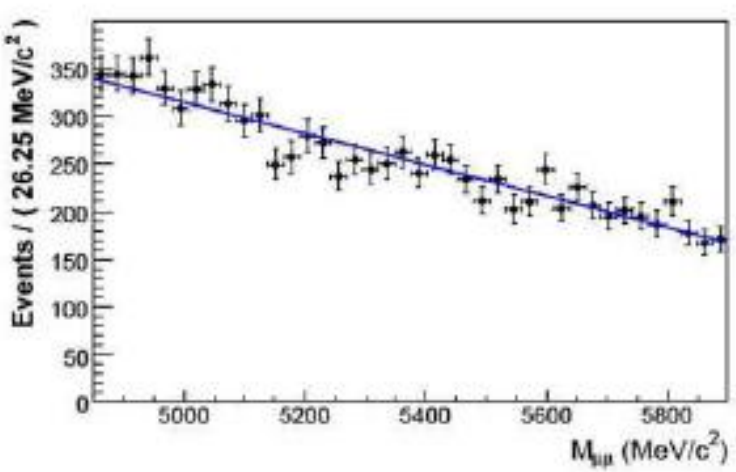


Background level

- The amount of bkg in the signal region also has to be known

- Bkg is dominated by combinatorial ($bb \rightarrow \mu\mu X$) and hence can be understood from sidebands

- Linear or exponential fit gives the bkg level in the signal region



- Specific/peaking bkg is negligible in current simulations

Conclusions

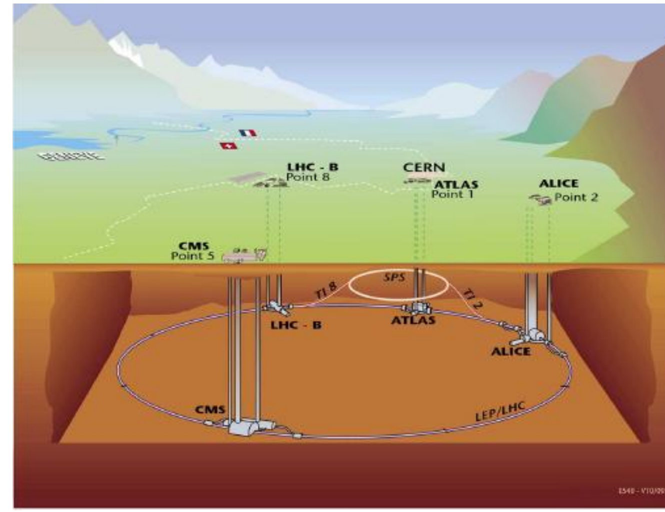
- A measurement/exclusion of BR($B_s \rightarrow \mu\mu$) will have an important impact on NP searches

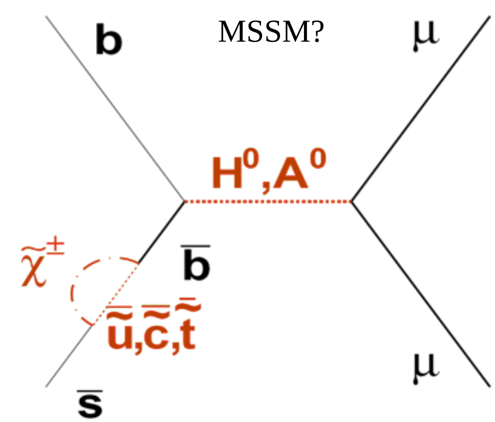
- LHC offers exceptional conditions for this study, scanning from current upper limit to < SM prediction

- LHCb takes advantage of its B-physics dedicated trigger, as well as good invariant mass resolution, having the best sensitivity for a given luminosity

- The use of control channels such as $B^+ \rightarrow J/\Psi(\mu\mu)K^+$ and $B \rightarrow hh$ allows to perform a MC free analysis

- Very relevant Spanish contribution



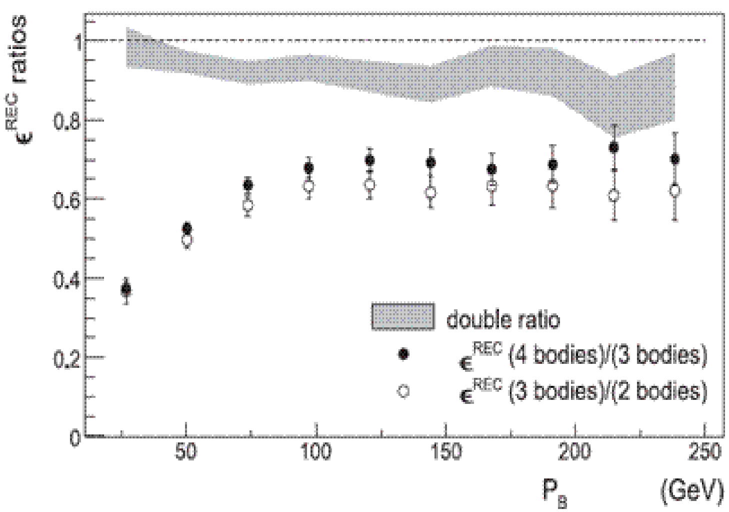


Normalization to $B^+ \rightarrow J/\psi K^+$

~ 1, selected with almost same criteria

$$BR = BR_n \frac{\varepsilon_n^{REC}}{\varepsilon^{REC}} \cdot \frac{\varepsilon_n^{SEL/REC}}{\varepsilon^{SEL/REC}} \cdot \frac{\varepsilon_n^{TRIG/SEL}}{\varepsilon^{TRIG/SEL}} \cdot \frac{P(b \rightarrow B_n)}{P(b \rightarrow B_s)} \cdot \frac{N}{N_n}$$

- Very different! (ratio ~ 0.6)
- But can be understood looking at other ratios such as $B_d \rightarrow J/\Psi K^* / B^+ \rightarrow J/\Psi(\mu\mu)K^+$

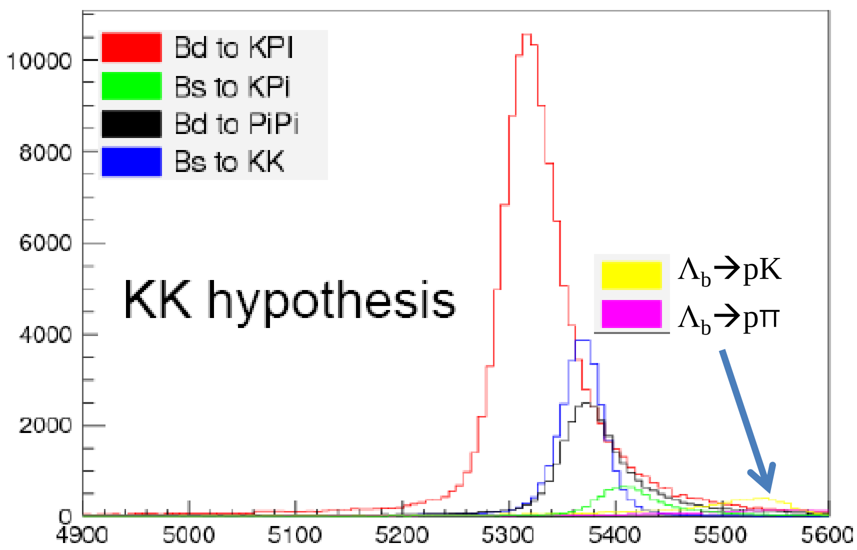


Similar. But also
The efficiency for B+ can be known from data looking at TIS (trigger Indep. of Signal) events

The efficiency for signal can be known emulation muon ID and trigger in B→ hh TIS events.

Normalization to $B_d \rightarrow K\pi$

- **LHCb** also uses normalization to $B \rightarrow h^+h^-$ ($B_{d,s} \rightarrow K\pi$, $B_d \rightarrow \pi\pi$, $B_s \rightarrow KK$…)
- Same geometry & kinematics than signal, different trigger (hadronic) and PID
- How to get rid of the differences:
  - Use $B \rightarrow hh$ events **Triggered Independently of Signal**
    - Several thousands of such events per fb^{-1} will be available
  - Use $b \rightarrow J/\Psi X$ to **emulate muon ID and trigger** on that sample as a function of p/pt

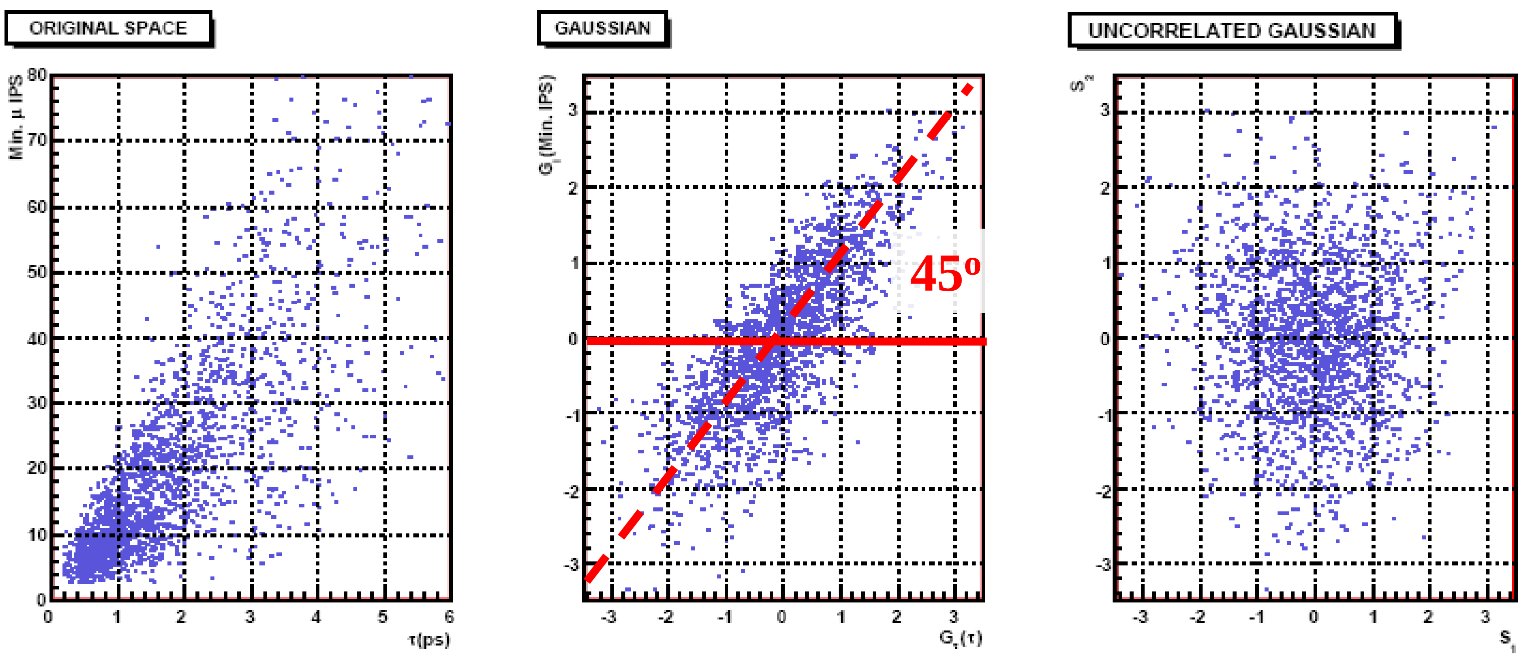


- The most suitable mode: $B_d \rightarrow K\pi$ (well known BR, largest statistics…)
- It can be separated from the inclusive sample using the RICH

BACKUP

How the Geometry likelihood is built:

1. Input variables: min IPS (μ^+,μ^-), DOCA, IP of B, lifetime, iso - μ^+, iso- μ^-
2. They are transformed to gaussian through cumulative and inverse error function
3. In such space correlations are more linear-like → rotation matrix, and repeat 2



sensitivity to Bd

Supposing bb → mumu is also the dominant bkg at the
Bd window, for each luminosity you can access to 3-4 times smaller BR for Bd than for Bs.

Rough SENSITIVITY CALCULATION

- Signal yield → $\sigma^{eff}*L$
- bkg under the peak scales linearly with invariant mass resolution σ_M

$$S/\sqrt{B} \propto \frac{\sigma_{sig}^{eff}}{\sqrt{\sigma_{bkg}^{eff}\sigma_M}}\sqrt{L}$$

normalization (B→kπ)

• B_d→Kπ has to be separated from the inclusive sample → Use of the RICH system→ Extra efficiency factor to account for

• B→hh can self-calibrate this eff. using ratio B_d → Kπ / B_d → ππ (very well known ratio of xsections) and the number of inclusive B→hh, as well as the good B_s-B_d mass separation in LHCb

• Alternatively, D*→D^0(Kπ) π reweighting by p,pt, can be also used (see Laurence Carson talk)

f(Bd → Kπ) = 0.677 ± 0.039
(MC = 0.681)

f(Bd → π π) = 0.169 ± 0.015
(MC = 0.172)

f(Bs → Kπ) = 0.0401 ± 0.0012
(MC = 0.0435)

f(Bs → KK) = 0.114 ± 0.011
(MC = 0.102)

Output of a MC experiment using B_d → Kπ / B_d → π π to calibrate RICH effs.

Full expression (μ_q the ratio of masses m_q/m_b)

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

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

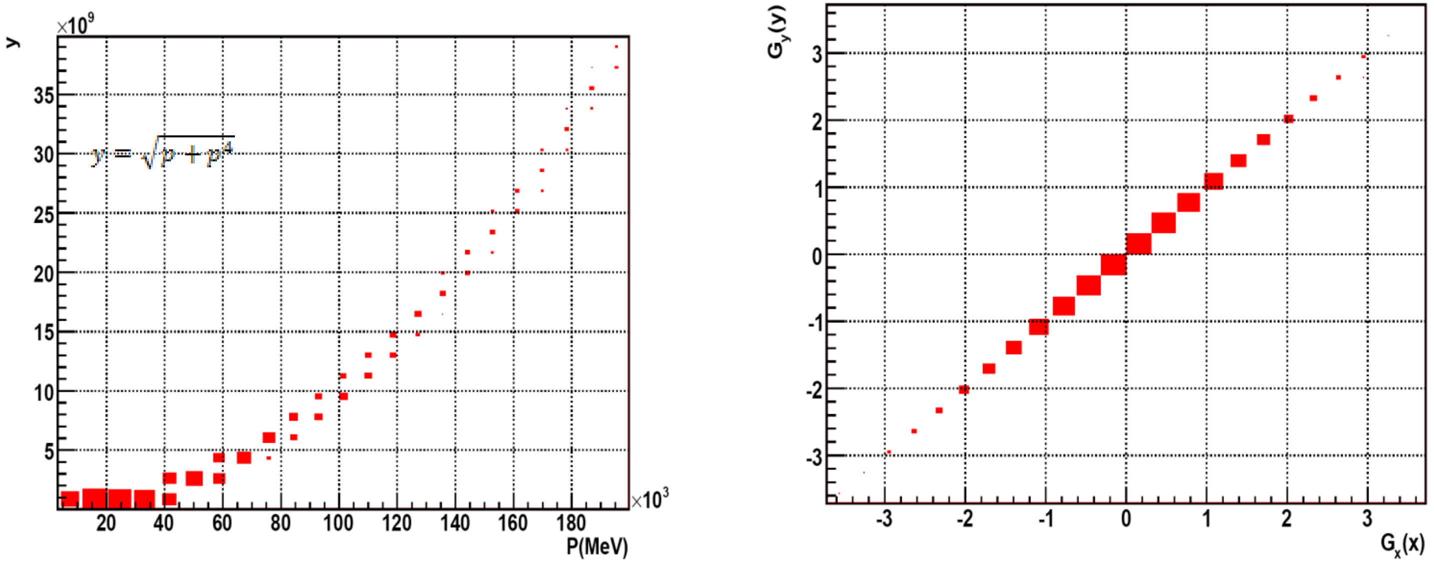


Figure -: Correlation in initial and Gaussian space.

Separation of Bd→Kπ

Extract the **fraction** of different components of B → hh, without relying on MC PID efficiencies:

1. Measure those fractions in a "high purity" limit (PID cuts > X):

(Example for X = 20):

KK → $N'_{kk} = 502$
Kπ → $N'_{k\pi} = 3292$
ππ → $N'_{\pi\pi} = 827$

→

$f'_{kk} = 0.109$
$f'_{k\pi} = 0.712$
$f'_{\pi\pi} = 0.179$

Not necessary the same as in the nonPID B→ hh sample !!!

(Then the true fraction should be):

$$f_{K\pi} = \frac{f'_{K\pi}/\varepsilon_K\varepsilon_\pi}{f'_{KK}/\varepsilon_K^2 + f'_{K\pi}/\varepsilon_K\varepsilon_\pi + f'_{\pi\pi}/\varepsilon_\pi^2} = \frac{f'_{K\pi}}{f'_{K\pi} + f'_{KK}\left(\varepsilon_\pi/\varepsilon_K\right) + f'_{\pi\pi}\left(\varepsilon_K/\varepsilon_\pi\right)}$$

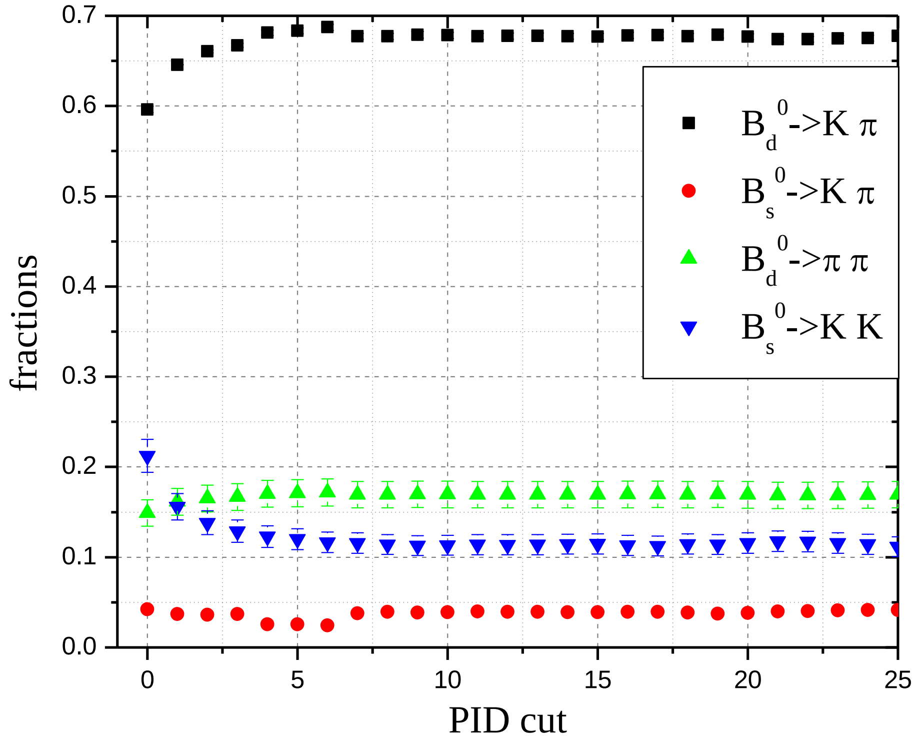
(Separate Bs → Kπ and Bd → Kπ is not an issue because of the mass resolution)

Separation of Bd□Kπ (II)

2. The ratio ($\varepsilon_\pi/\varepsilon_K$) □ thus the right fractions can be easily extracted from Bd modes, where the BR's are known.

$$\frac{N(B_d^0 \to K\pi)}{N(B_d^0 \to \pi\pi)} = \frac{BR(B_d^0 \to K\pi)}{BR(B_d^0 \to \pi\pi)} = 3.96 \pm 0.36 \Rightarrow \boxed{\frac{\varepsilon_\pi}{\varepsilon_K} = (3.96 \pm 0.36) \cdot \frac{N'_{\pi\pi}}{N'^{(d)}_{K\pi}}}$$

3. To ensure the high purity limit, repeat 1 & 2 until a plateau on the results is reached



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f(Bs □ KK) = 0.114 ± 0.011
(MC = 0.102)

Sensitivities

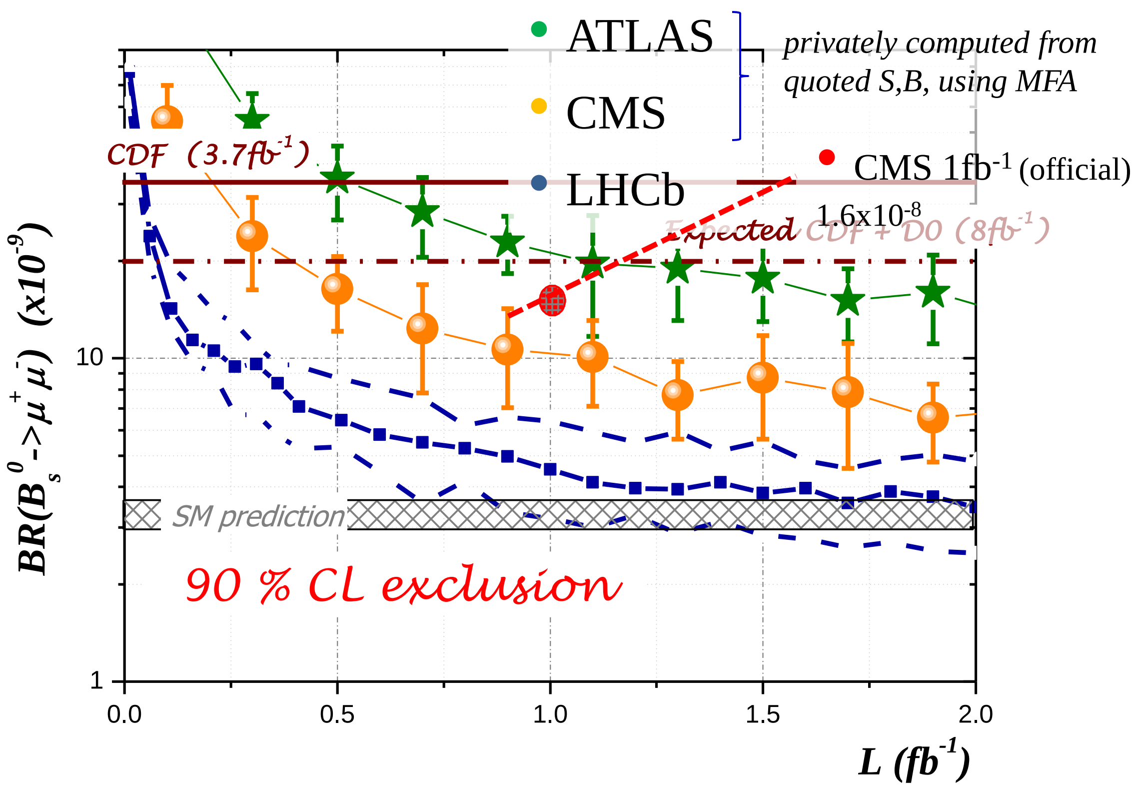
(expected S (for BR = 3.35e-9) & B per fb^{-1} in each experiment LHCb bins parameter space → N experiments)

ATLAS: S = 0.56, B = 1.4

CMS: S = 2.05, B = 6.53

LHCb	GL	
Mass (MeV)	**0.5–0.65**	**0.65-1**
5406.6 - 5429.6	$S = 0.13$, $B = 8^{+10}_{-5}$	$S = 0.3$, $B = 8^{+10}_{-5}$
5384.1 - 5406.6	$S = 0.55$, $B = 8^{+10}_{-5}$	$S = 1.4$, $B = 8^{+10}_{-5}$
5353.4 - 5384.1	$S = 1.6$, $B = 11^{+15}_{-7}$	$S = 3.8$, $B = 11^{+15}_{-7}$
5331.5 – 5353.4	$S = 0.6$, $B = 8^{+10}_{-5}$	$S = 1.5$, $B = 8^{+10}_{-5}$
5309.6 – 5331.5	$S = 0.2$, $B = 8^{+10}_{-5}$	$S = 0.45$, $B = 8^{+10}_{-5}$

- 90% CL exclusion sensitivity as a function of L
  - (Only bkg is observed)



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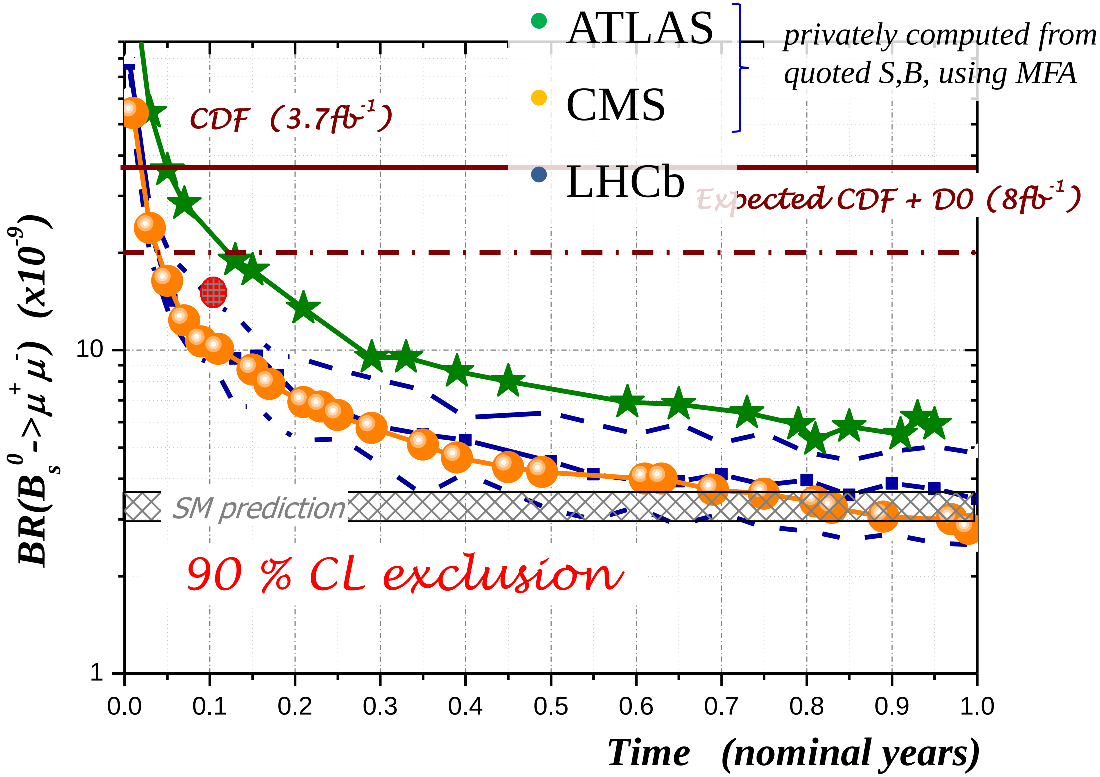
5331.5 – 5353.4	$S = 0.6$ $B = 8^{+10}_{-5}$	$S = 1.5$ $B = 8^{+10}_{-5}$
5309.6 – 5331.5	$S = 0.2$ $B = 8^{+10}_{-5}$	$S = 0.45$ $B = 8^{+10}_{-5}$

- 90% CL exclusion sensitivity as a function of time

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



Sensitivities

(expected S (for BR = 3.35e-9) & B per fb^{-1} in each experiment LHCb bins parameter space → N experiments)

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CMS
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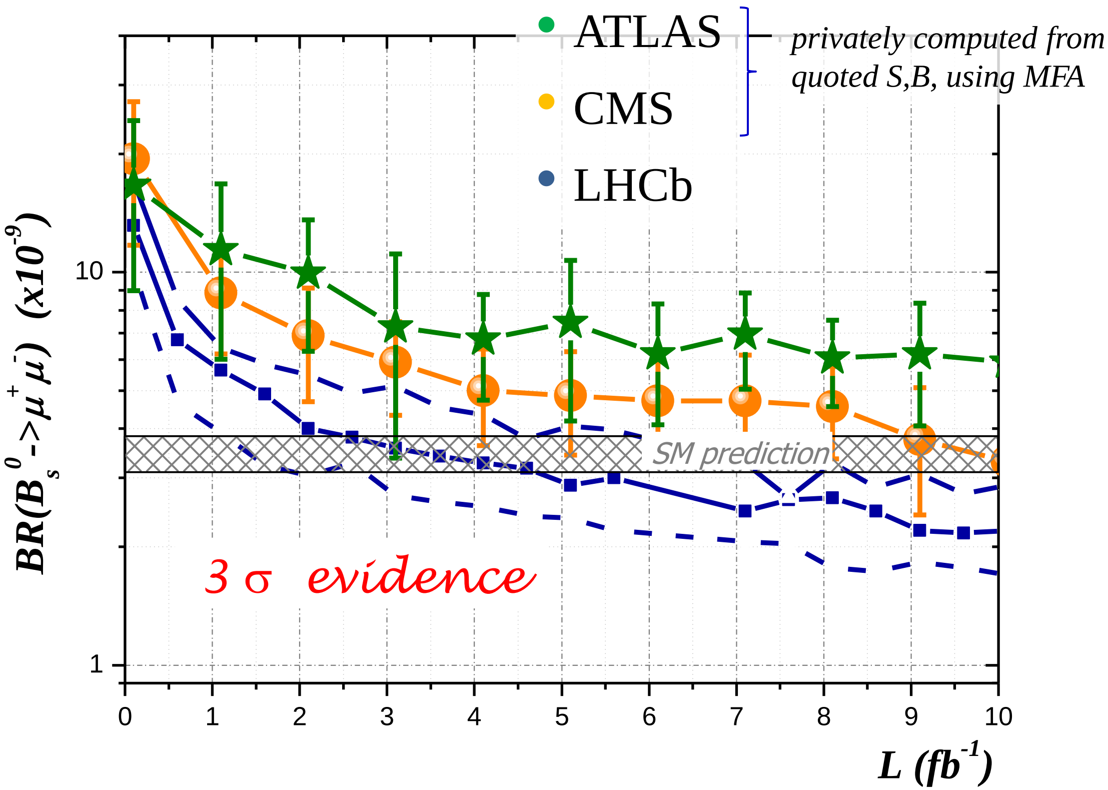
- Signal evidence sensitivity as a function of L
  - (Signal + Background observed)



Sensitivities

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- Signal evidence sensitivity as a function of time

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