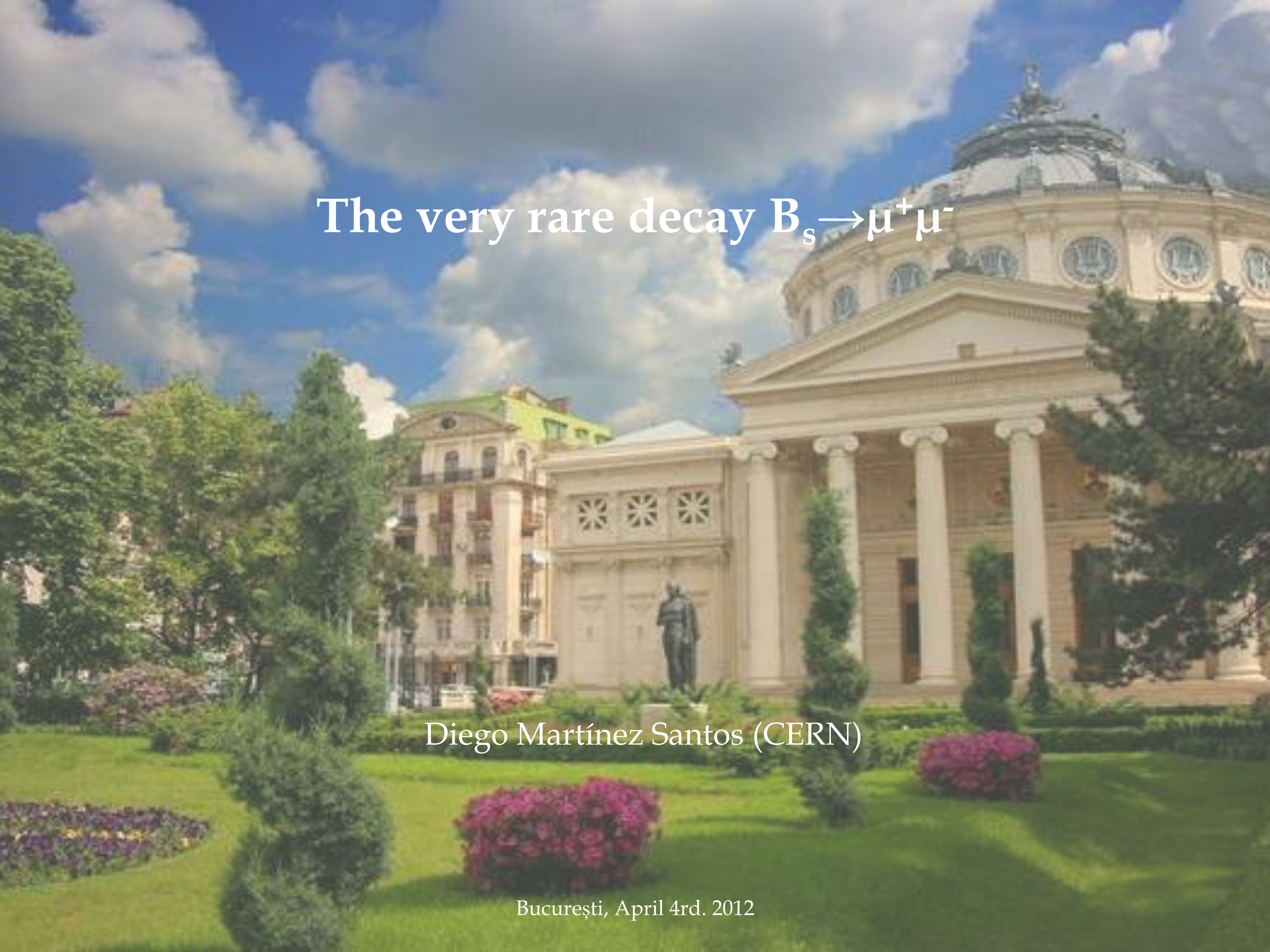


The very rare decay $B_s \rightarrow \mu^+\mu^-$

Diego Martínez Santos (CERN)

București, April 4rd. 2012

Overview

- Introduction
  - Standard Model, what it does not explain, extensions
  - Brief description of MSSM (where usually $B_s \rightarrow \mu\mu$ matters a lot)

  - Indirect approach, $B_s \rightarrow \mu\mu$ as a probe of NP
  - LHCb detector, trigger

- LHCb analysis and results

Standard Model

1. Gauge part: $$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{<\phi^0> = \frac{v}{\sqrt{2}} \neq 0} SU(3)_C \times U(1)_{EM}$$

   Higgs scalar Field $\Phi(1,2)_{1/2}$

2. Fermion content (5 **representations** of G_{SM}):

$$Q_{L,i}(3,2)_{+1/6} \qquad U_{R,i}(3,1)_{+2/3} \qquad D_{R,i}(3,1)_{-1/3}$$

$$L_{L,i}(1,2)_{-1/2} \qquad E_{R,i}(1,1)_{-1}$$

With i : generation index. i = 1, 2, 3

Indeed SM is very successful, with extremely accurate predictions in most cases. But:

- It says neutrinos are massless. They have very small masses, but is not the same
  - Although, this can be accommodate without changing too much SM
- SM has not an explanation for the Dark Matter (see next slide)

Dark Matter

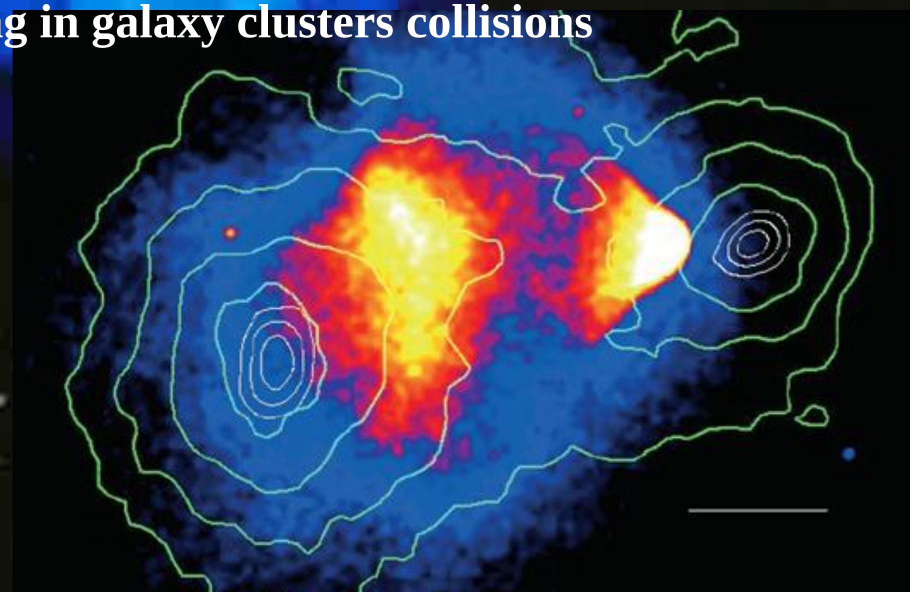
Astronomical measurements: gravitational effects that cannot be explained by visible/known matter distribution. Either:

- **Gravity theory is wrong?**
- **Large amount Invisible matter (Dark Matter) with very weak interaction with ordinary matter (more likely). It should be ~20 % of the energy of the universe**

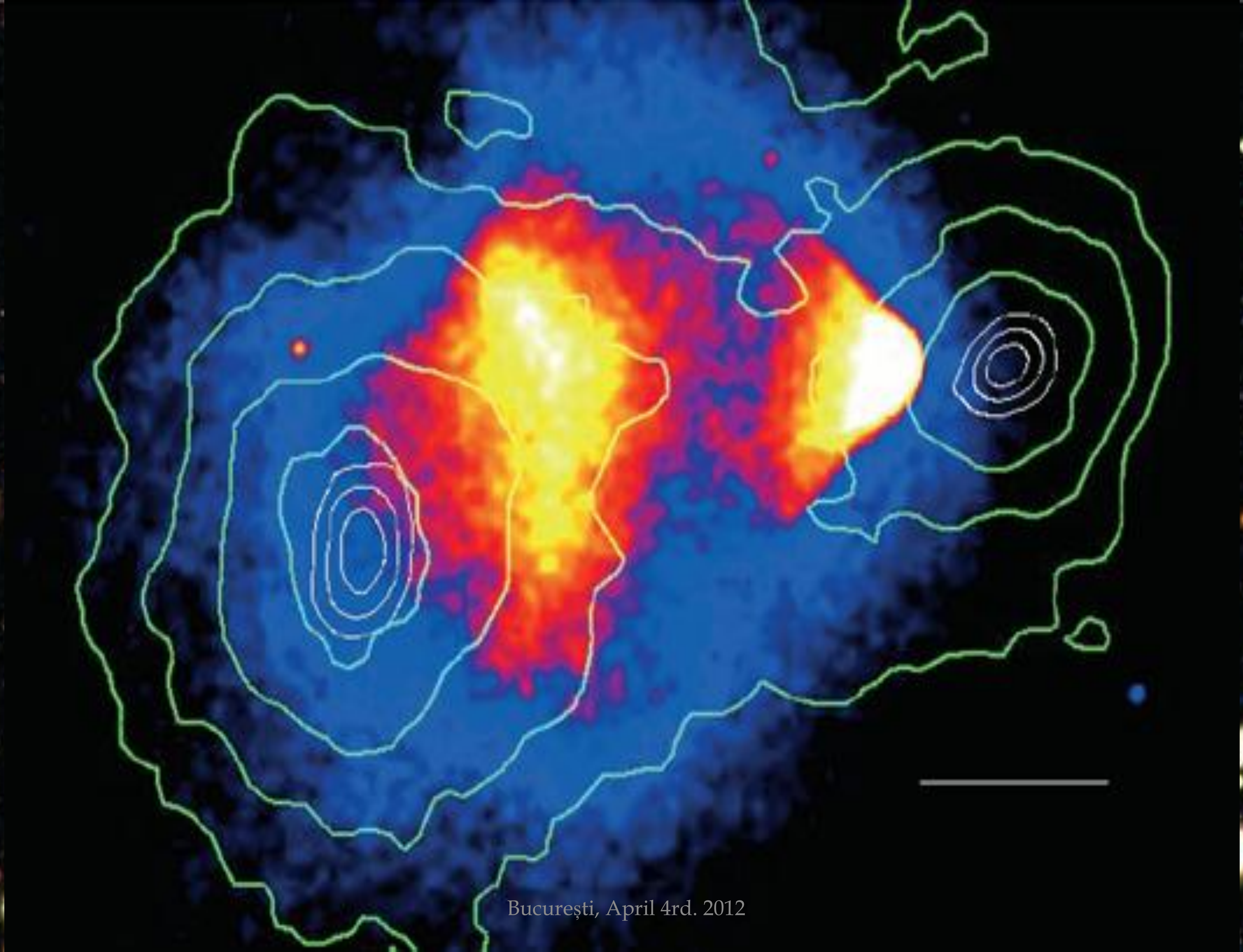
Most direct prove: gravitational lensing in galaxy clusters collisions

Gravitational lensing effect <u>8 sigma</u> deviated from expected by the distribution of visible matter

But fits very well if most of the matter of the original clusters is invisible and did not interact in the collision



SM does not offer an explanation for such matter



Other motivations

- Muon anomalous dipole moment deviated by >3 sigma from SM prediction
- Fine tuning is needed to avoid quadratic divergences in the Higgs mass
- Gravity is not included
- Large number of parameters
- Number of fermion families is an input
- Unification of gauge interactions into a higher symmetry group is also sometimes preferred

→ SM is likely a effective low energy theory→ Need for New Physics (NP)

SM extension**s**: Supersymmetry, Little Higgs can explain DM, and solve at least some of those points….

MSSM

Higgs scalar Fields Hu, Hd

1. Gauge part = SM:

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_C \times U(1)_{EM}$$

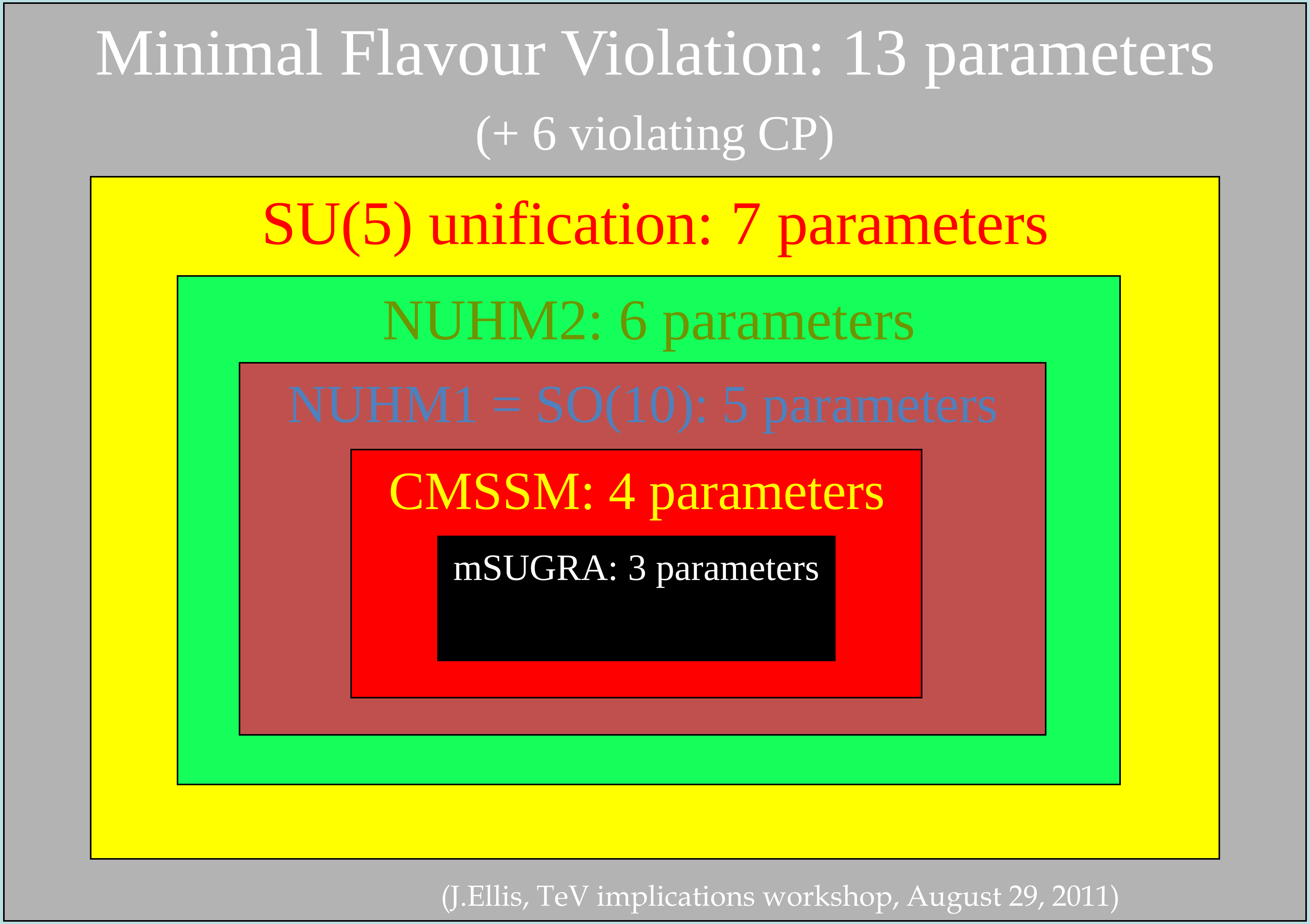
2. Supersymmetry: SM particles ⬄ "superpartners" (particle + superpartner ➔ superfield):
   SM fermion ⬄ SUSY boson (sfermions: selectron, squark …)
   SM boson / higgses ⬄ SUSY fermion (-inos: gluino, photino …)

   → Broken (superpartners not been seen yet → heavier): All renormalizable SUSY breaking terms are considered (in principle) ➔ A total of 124 free parameters

3. **R – parity** (= $(-1)^{3(B-L)+2S}$) conservation (consequence of B-L invariance)
   SM particles: R = +1; superpartners : R = -1.
   ➔Superpartners produced/annihilated in pairs ➔ Exists **one stable SUSY particle**: LSP (Lightest SUSY Particle), candidate for Dark Matter

MSSM is usually simplified by imposing some conditions, usually related to the way in which SUSY is broken. mSUGRA, CMSSM, NUHM (I and II), AMSB, GMSB

MSSM: > 100 parameters



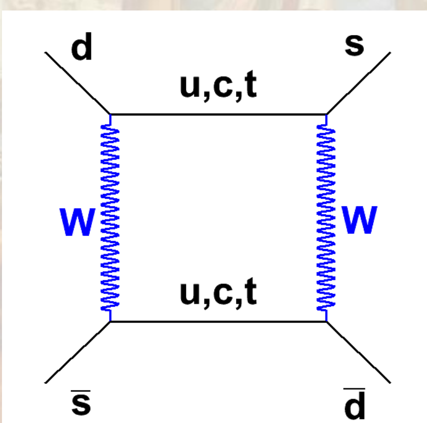
$B_s \longrightarrow \mu\mu$

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

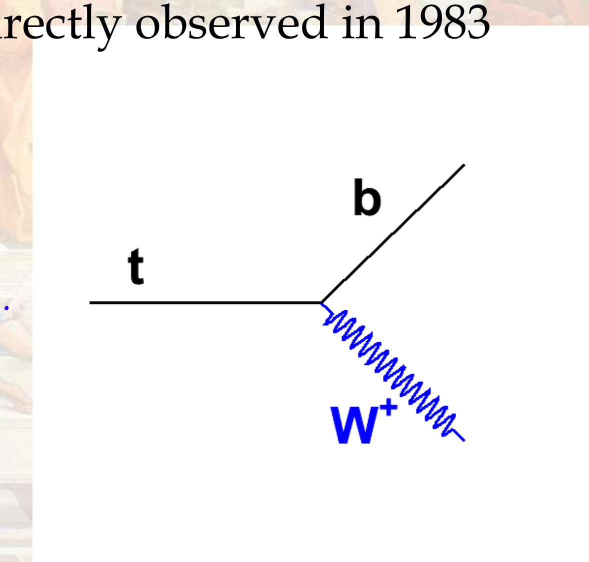
- Indirect approach can access higher energy scales and see NP effects earlier:

    - 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…



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    - 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**

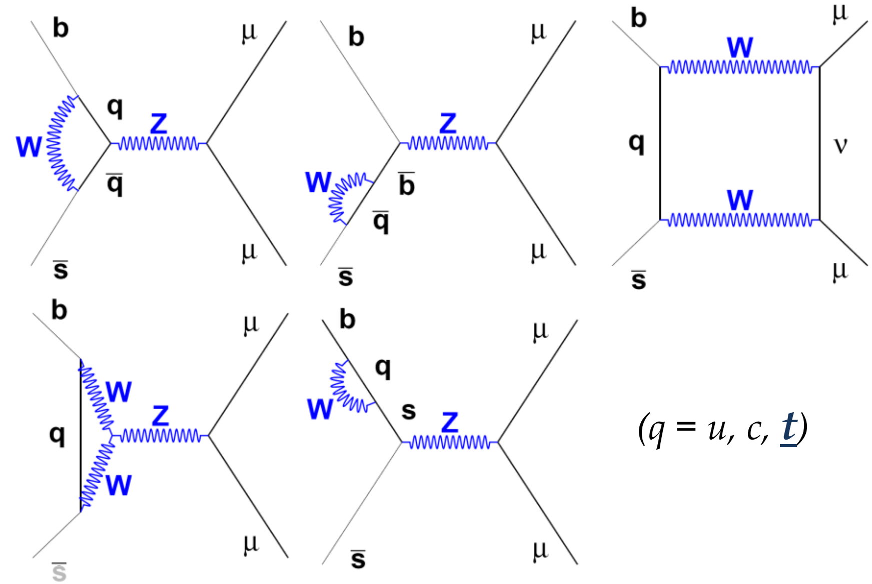
Eratosthenes

~2.3 K years till the direct observation…

SM and New Physics

This decay is very suppressed in SM :

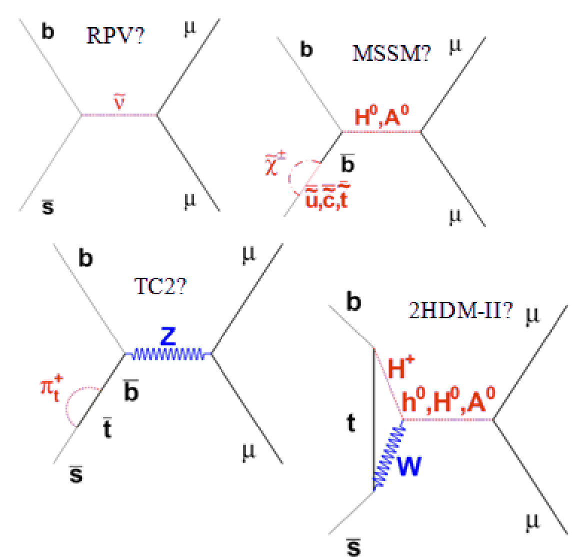
$$BR(B_s \rightarrow \mu\mu) = (3.2 \pm 0.2)x10^{-9}$$
$$BR(B_d \rightarrow \mu\mu) = (1.0 \pm 0.1)x10^{-10}$$



But in NP models it can take any value from << SM (e.g, some NMSSM) up to current experimental upper limit (e.g. SUSY at high tanβ).

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

+?



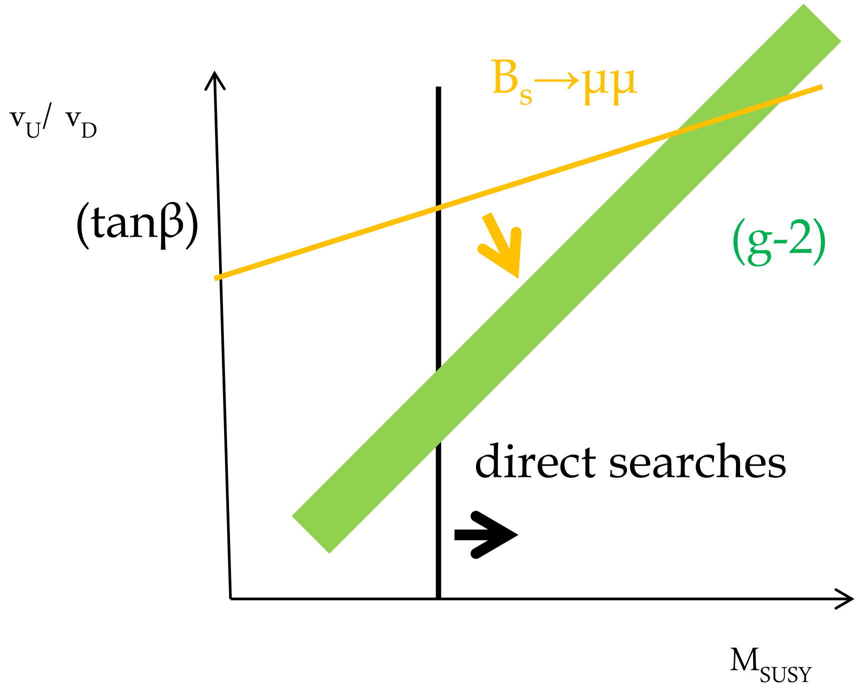
New Physics effects

Scenario	would point to ...
$BR(B_s \to \mu\mu) >> SM$	Big enhancement from NP in scalar sector, SUSY high tanβ
$BR(B_s \to \mu\mu) \neq SM$	SUSY (C_S, C_P) , ED's, LHT, TC2 (C_{10})...
$BR(B_s \to \mu\mu) \sim SM$	Anything (→ rule out regions of parameter space that predict sizable departures from SM. Obviously)
$BR(B_s \to \mu\mu) << SM$	NP in scalar sector, but full MSSM ruled out. NMSSM (Higgs singlet) good candidate
$BR(B_s \to \mu\mu) / BR(B_d \to \mu\mu) \neq SM$	CMFV ruled out. New FCNC sources fully independent of CKM matrix (RPV SUSY, ED's etc...)

New Physics effects

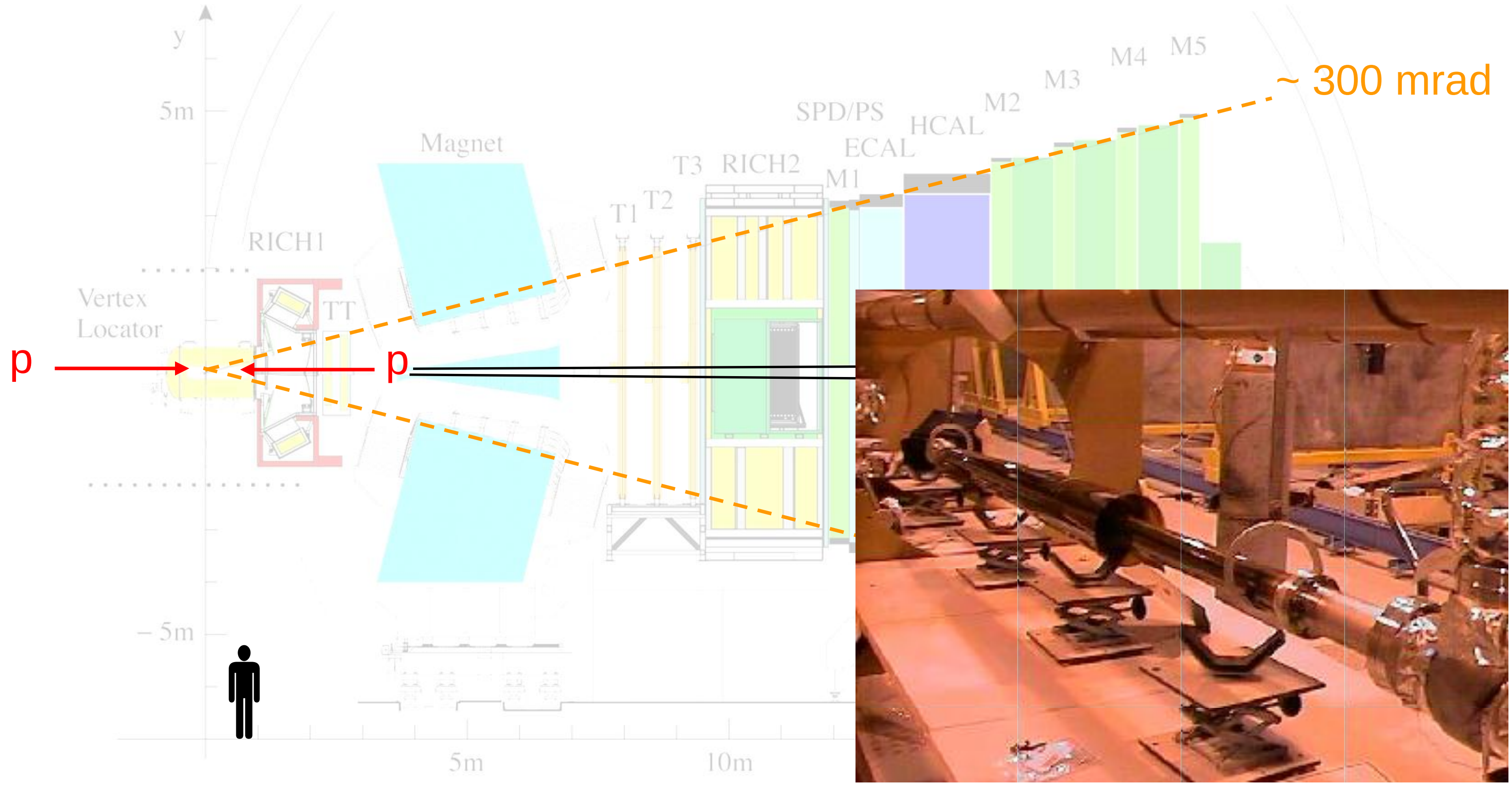
Well, we have seen that it can access NP. But…
Is there some NP that it can access better than any other current measurement?

Yes. Most popular example is SUSY at high tan□



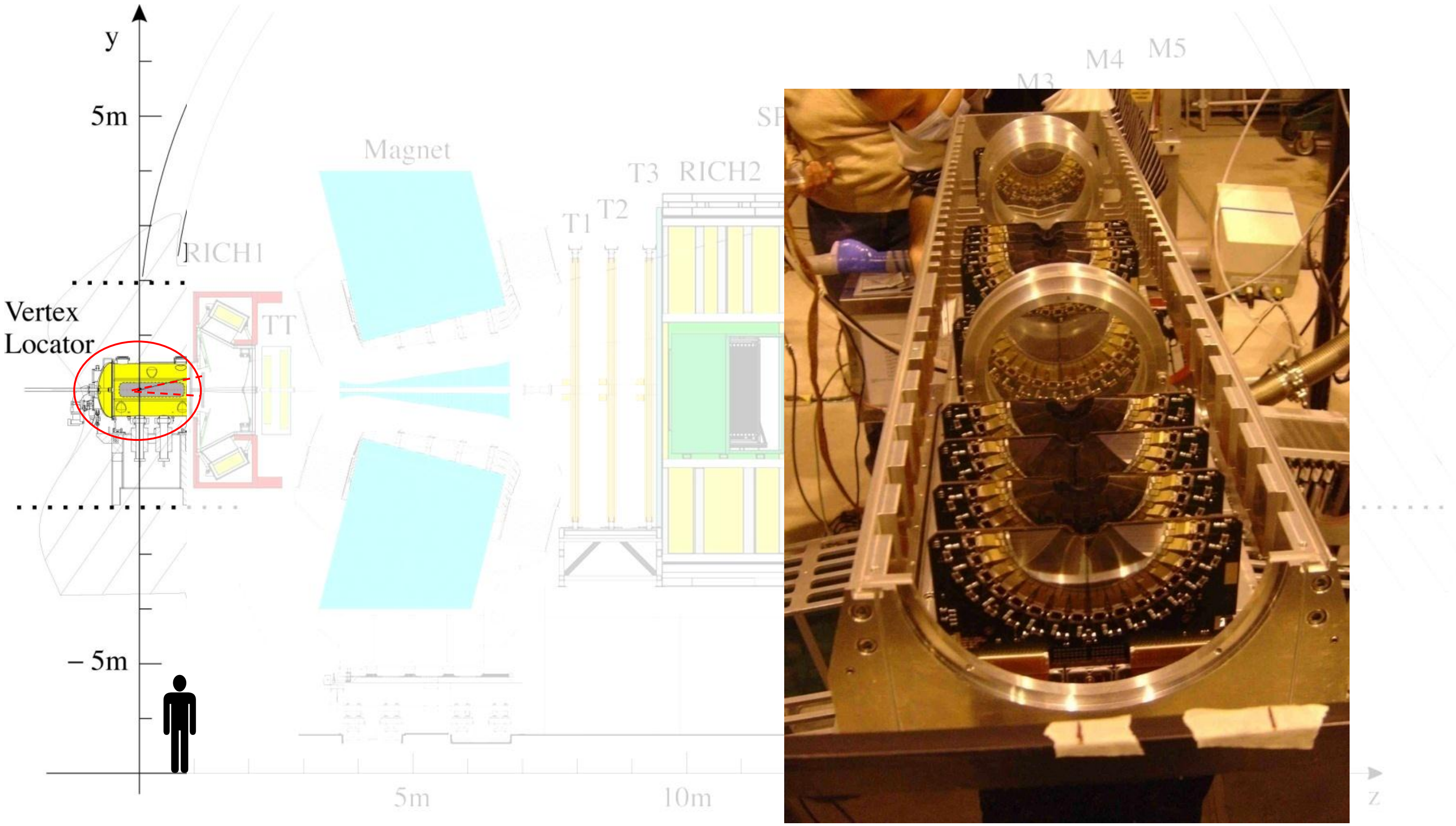
LHCb detector

LHCb detector



Forward spectrometer (running in pp collider mode)
Inner acceptance 10 mrad from conical beryllium **beam pipe**

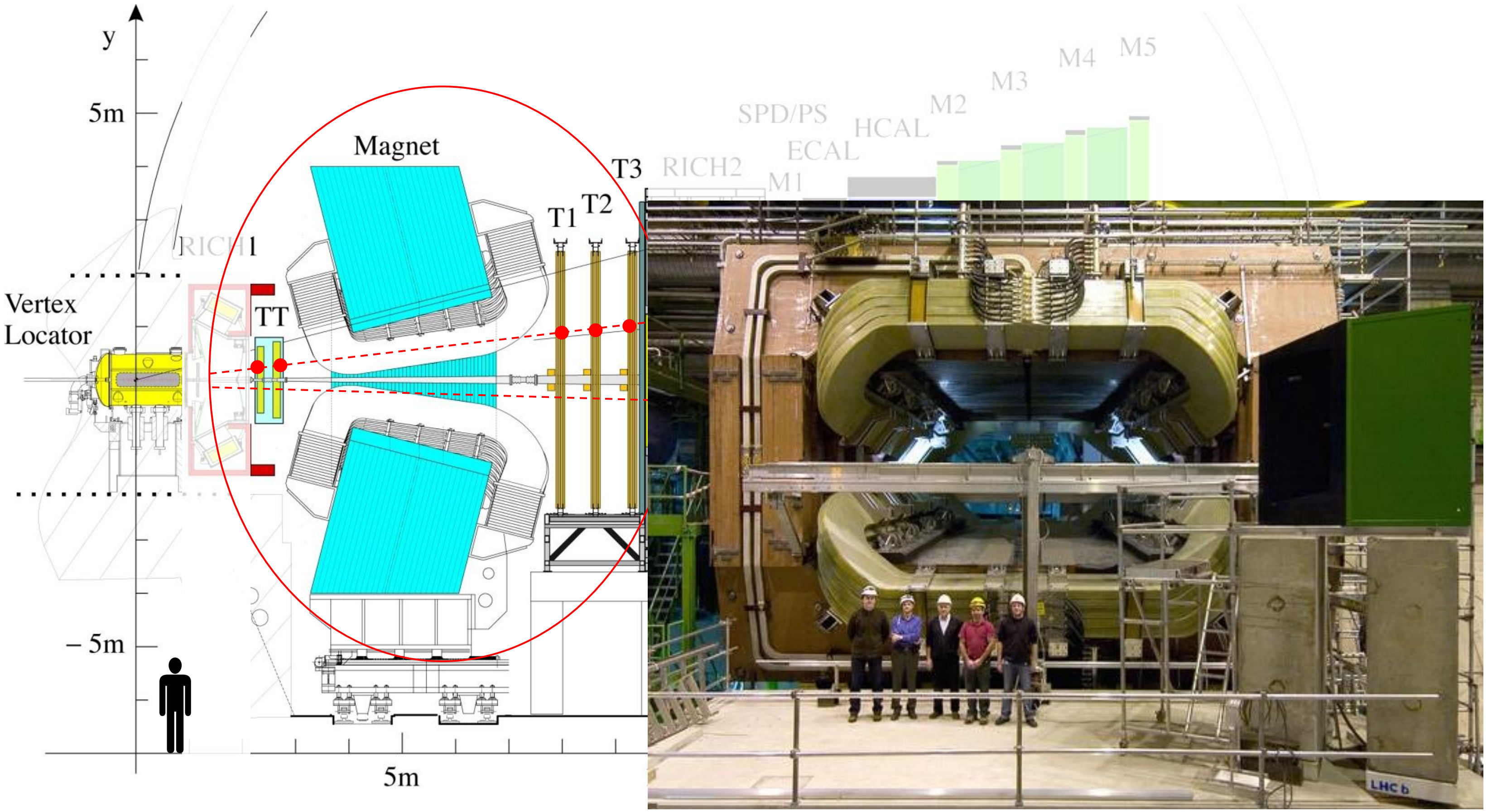
LHCb detector



Vertex locator around the interaction region

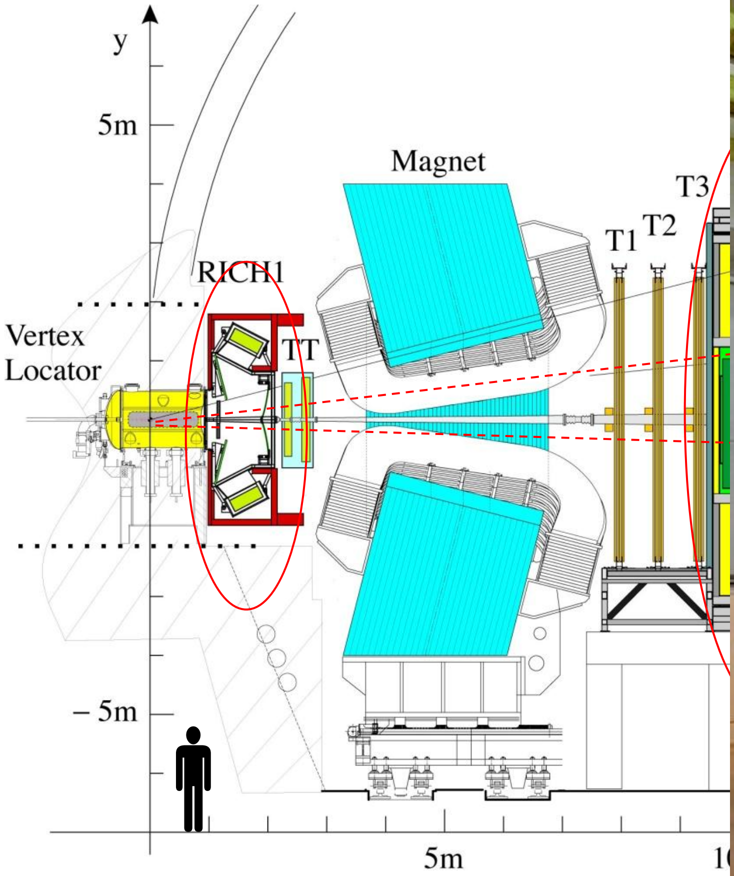
Silicon strip detector with ~ 30 µm impact-parameter resolution

LHCb detector



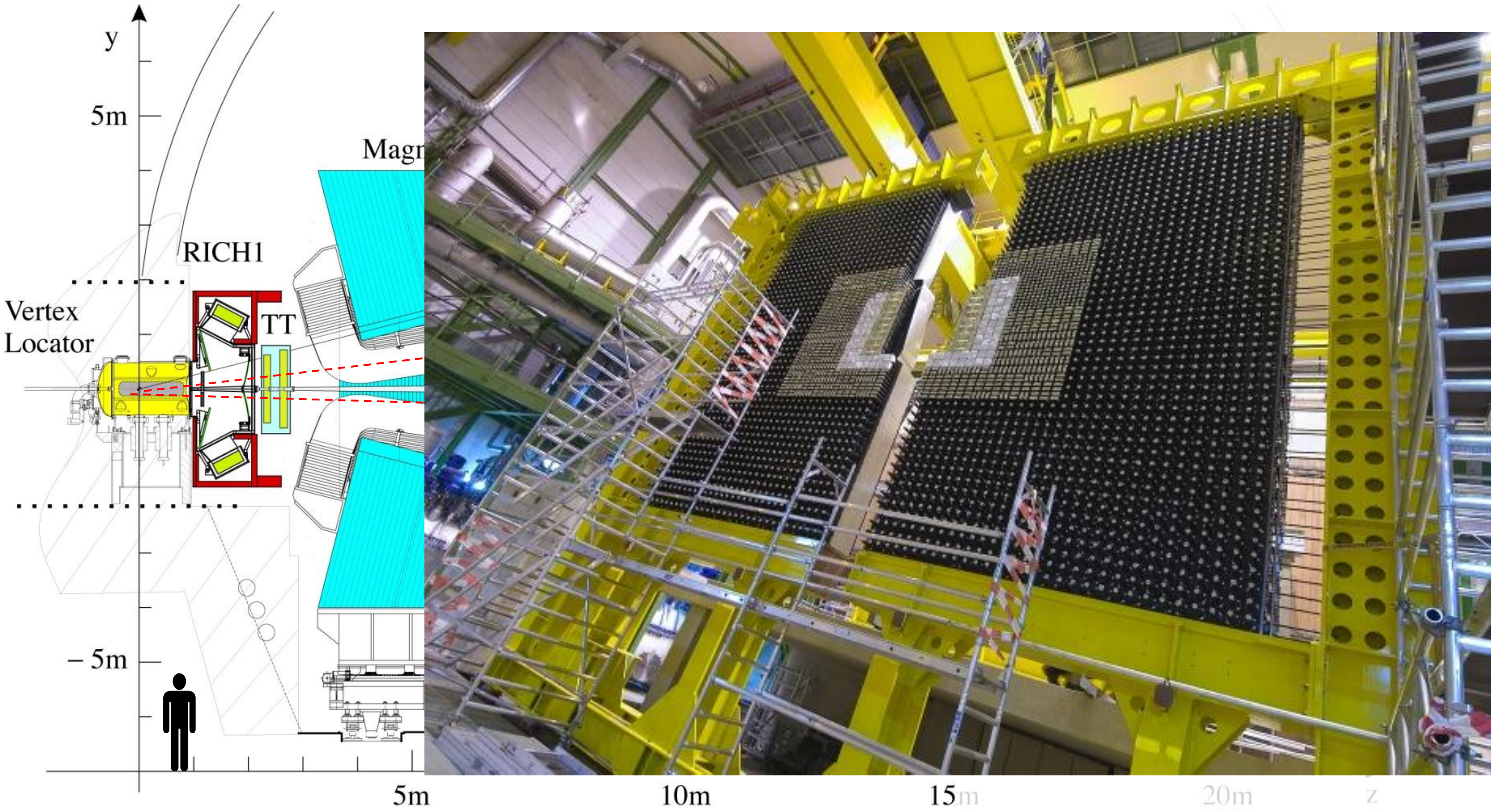
Tracking system and dipole magnet to measure angles and momenta $\Delta p/p$ ~ 0.5 %, mass resolution, together with VELO ~ 25 MeV (for $B_s \rightarrow \mu\mu$)

LHCb detector



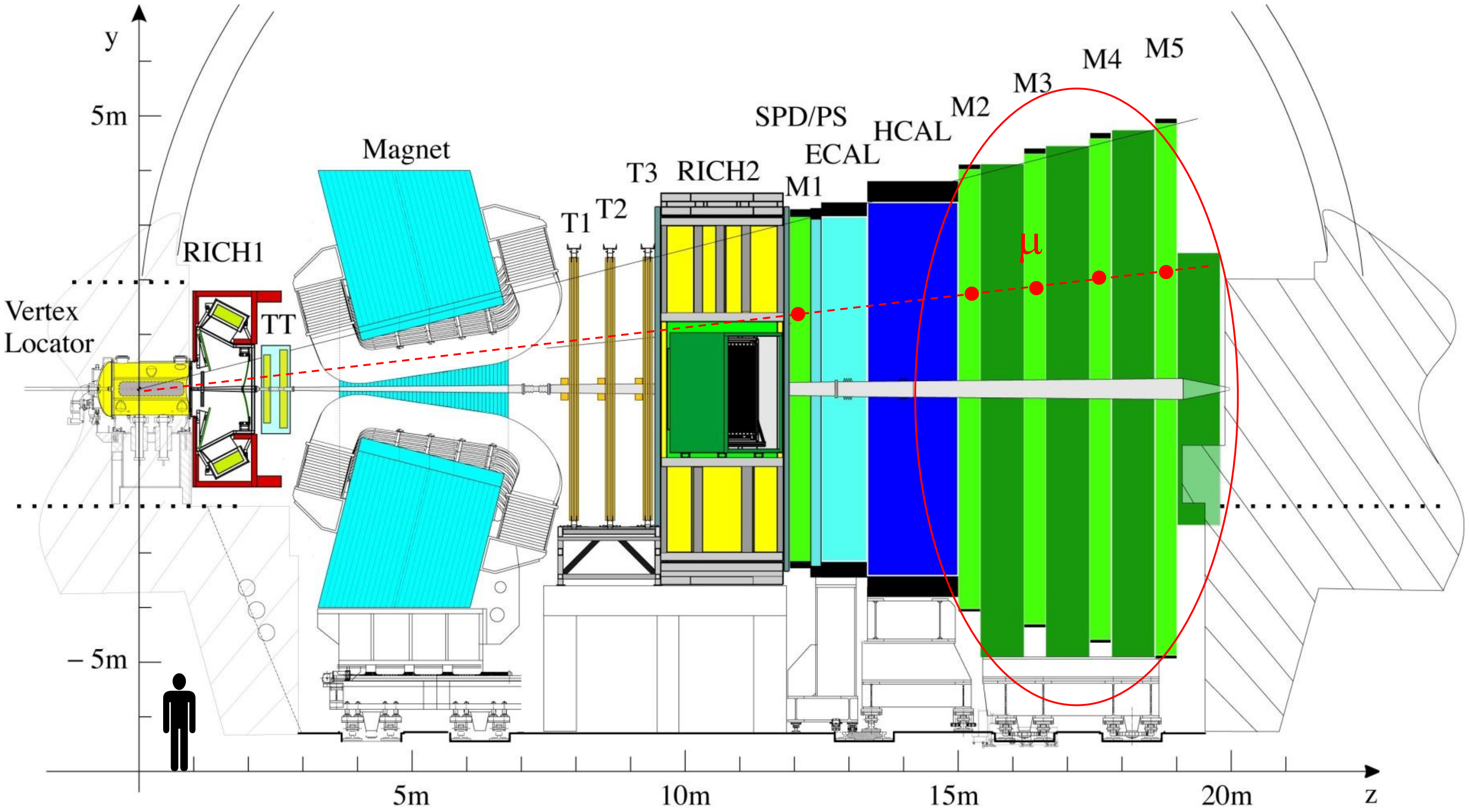
Two **RICH** detectors for charged hadron identification

LHCb detector



Calorimeter system to identify electrons, hadrons and neutrals.
Important for the first level of the trigger

LHCb detector



Muon system to identify muons, also used in first level of trigger

Analysis

Analysis strategy

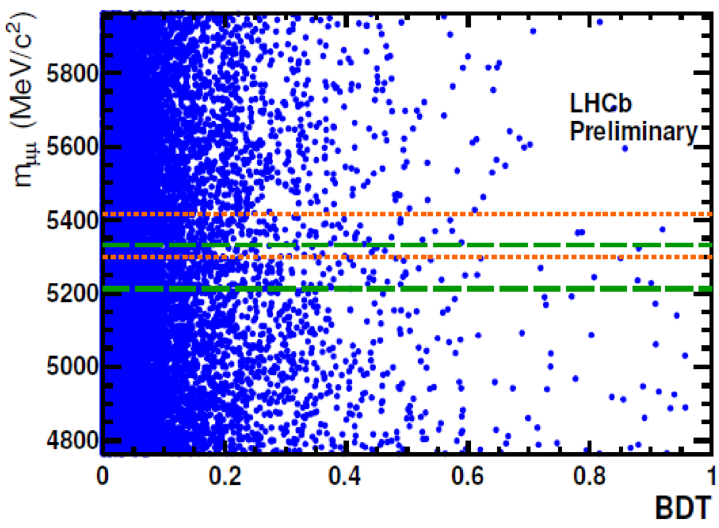
- Selection cuts in order to reduce the amount of data to analyze and get clean enough control channels

- Classification of $B_{s,d} \rightarrow \mu\mu$ events in bins of a 2D space

    - Invariant mass of the $\mu\mu$ pair

    - BDT combining geometrical and kinematical information about the event

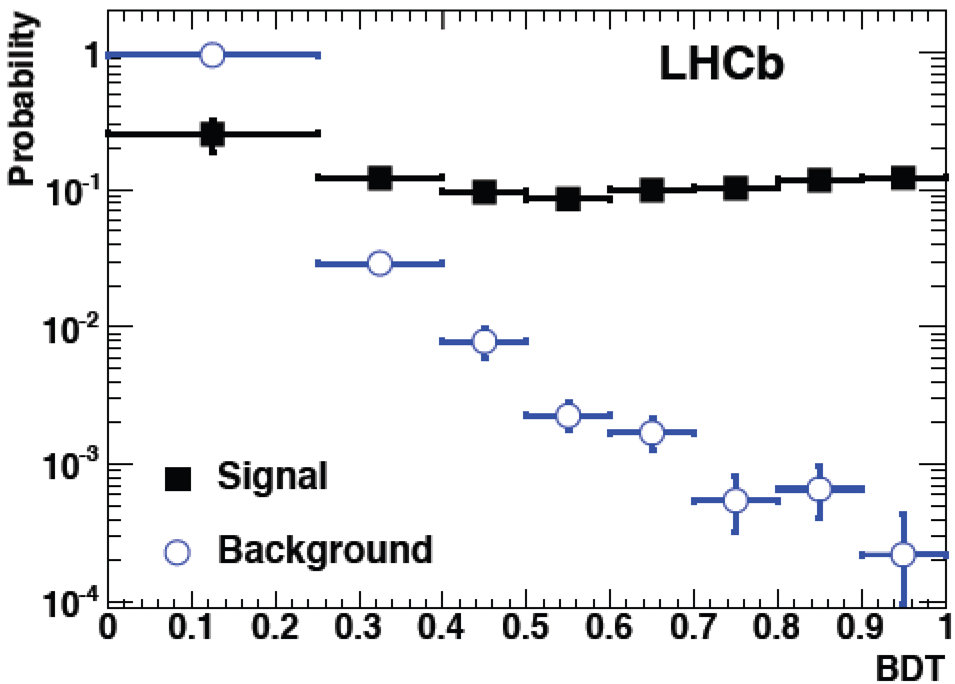
        - Flat distributed for signal, background peaks at 0



- Control channels to get signal and background expectations w/o relying on simulation

- Compare expectations with observed distribution. Results combined using CL_s method.

BDT



- S-B separation relies strongly on this variable

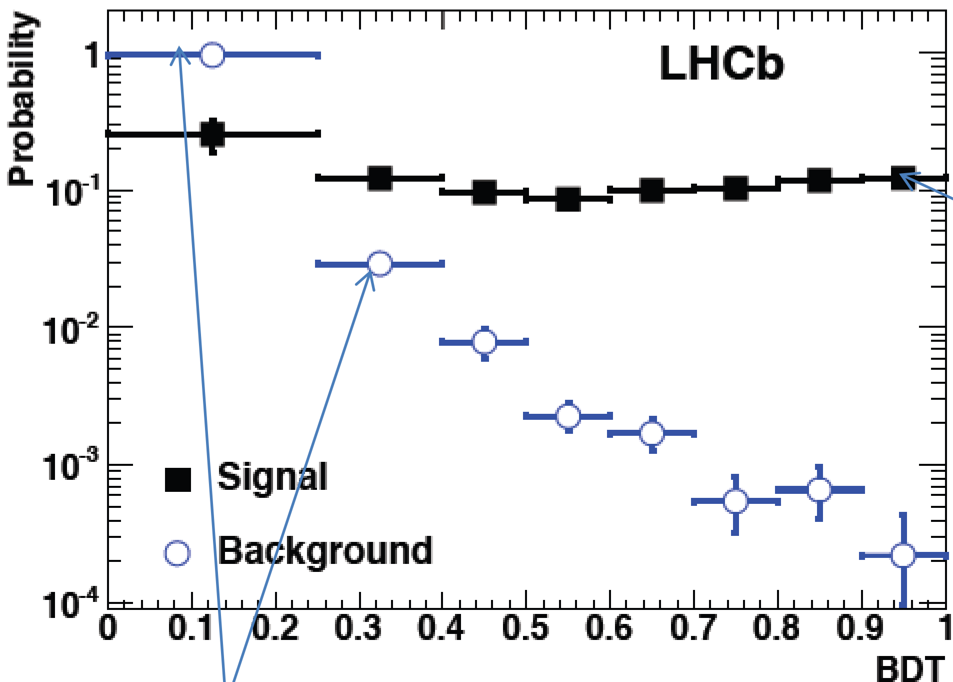
- Combines several variables related to the kinematics and geometry of the event: transverse momentum, polarization angle, vertex displacement, isolation …

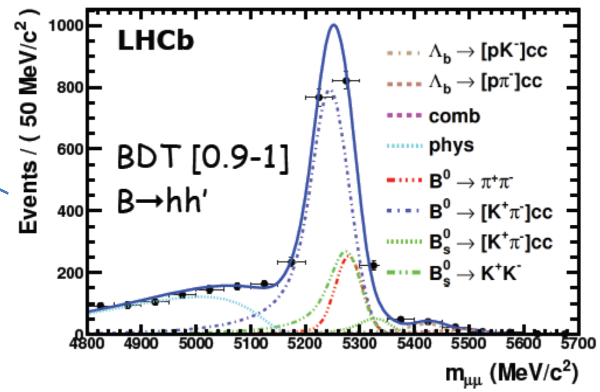
- The BDT has not enough information to know about the mass → cannot create fake peaks out of the bkg.

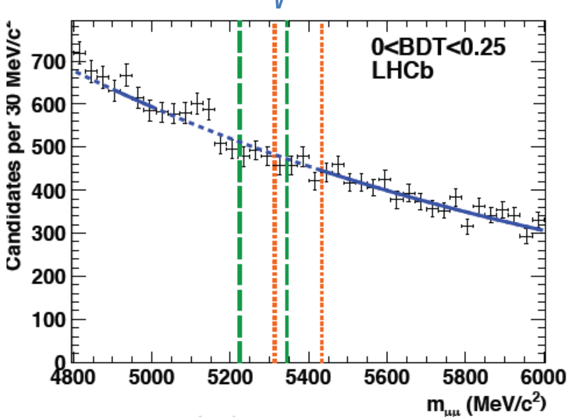
- Trained using **simulated** samples of $B_s \to \mu\mu$ signal and bb $\to \mu\mu X$ background.

- Distributions taken from data to not rely on the accuracy of the simulation

BDT







- Distribution of real signal obtained by looking at B $\to h^+h^-$ in real data

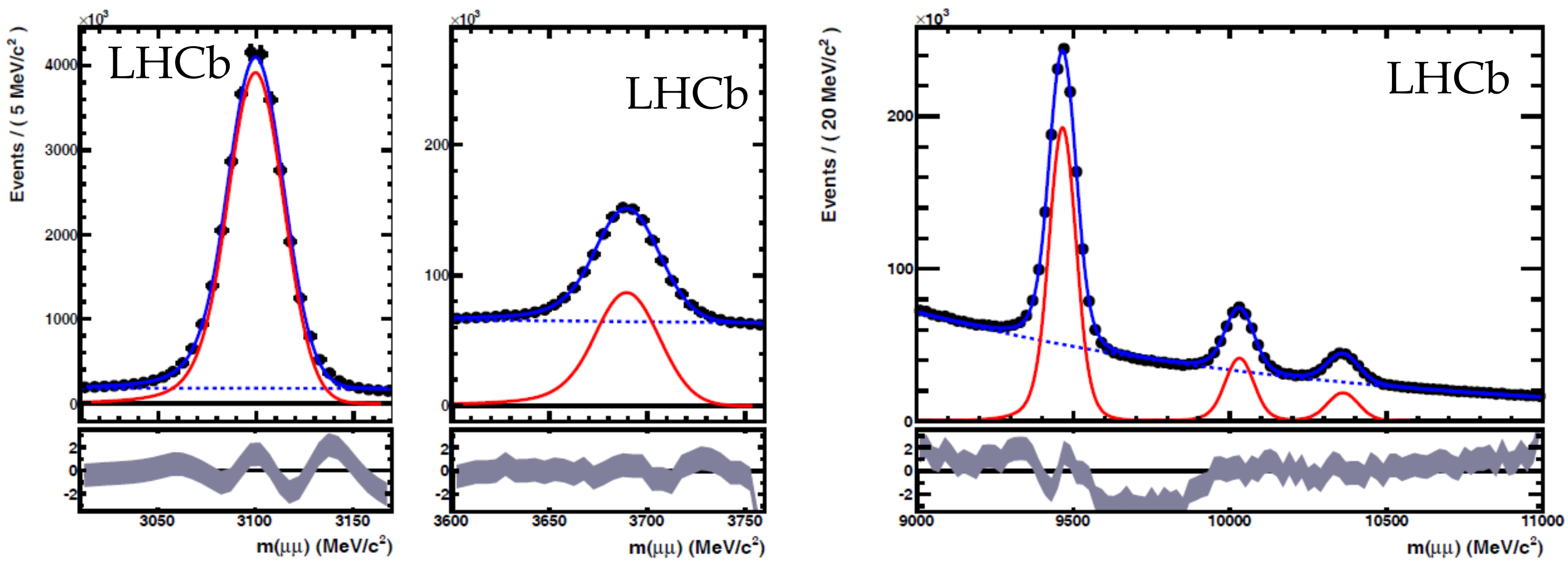
- Background distribution is obtained from data by interpolating from mass sidebands in BDT bins

Invariant Mass

- Signal distribution depends on the actual mass resolution of LHCb in the B mass region (resolution depends on mass, almost linearly)

- Measured in data by **interpolating from dimuon resonances** (J/ψ (m<mB) , Y (m>mB)…) **and** looking at $\mathbf{B \to h^+h^-}$ ($B_{d,s} \to K^+\pi^-$, $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$)

- μμ background yield in mass bins is interpolated from mass sidebands



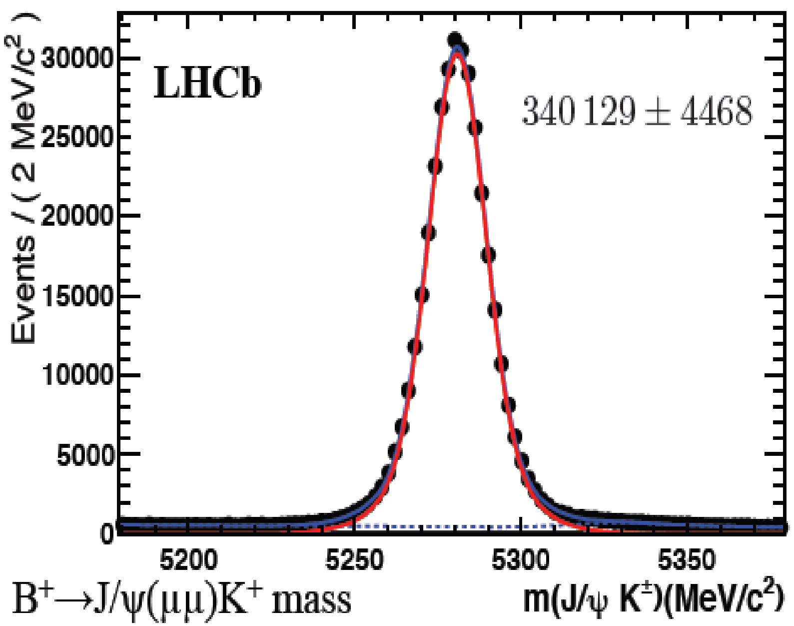
Normalization

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

efficiencies

Ratio of probabilities of b quark to hadronize into the different mesons, $f_d/f_s = 3.75 \pm 0.29$ (LHCb measurement)

- Three channels are used, each one with different (dis)advantages:
  - $B^+ \to J/\psi(\to \mu\mu)K^+$:
    - Similar trigger (muon triggers) to the signal, similar particle identif.
    - Different number of tracks in the final state



B⁺→J/ψ(μμ)K⁺ mass

Normalization

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

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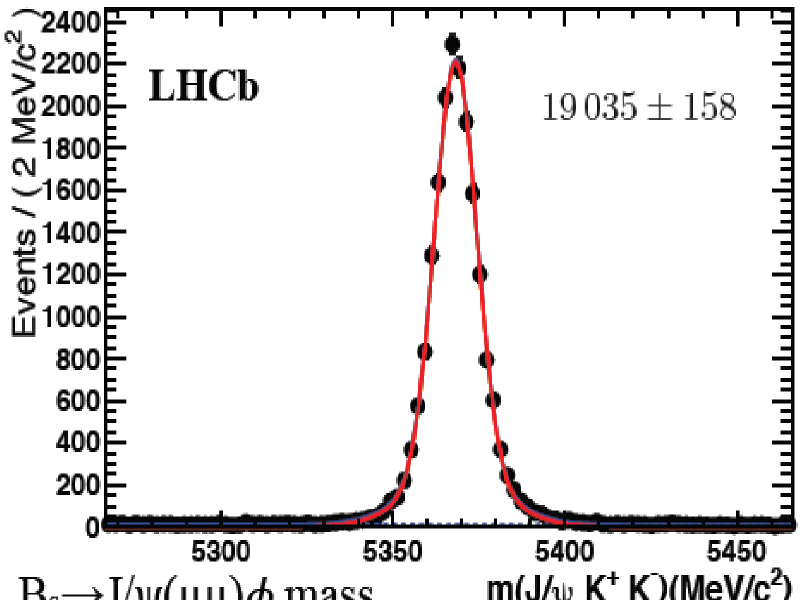
  - $B_s \to J/\psi(\to \mu\mu)\varphi\ (\to K^+K^-)$:

    - Similar trigger (muon triggers) to the signal, similar particle identif.

    - It's a B_s, but BR known only with 26% precision

    - Different number of tracks in the final state



$B_s \to J/\psi(\mu\mu)\phi$ mass

Normalization

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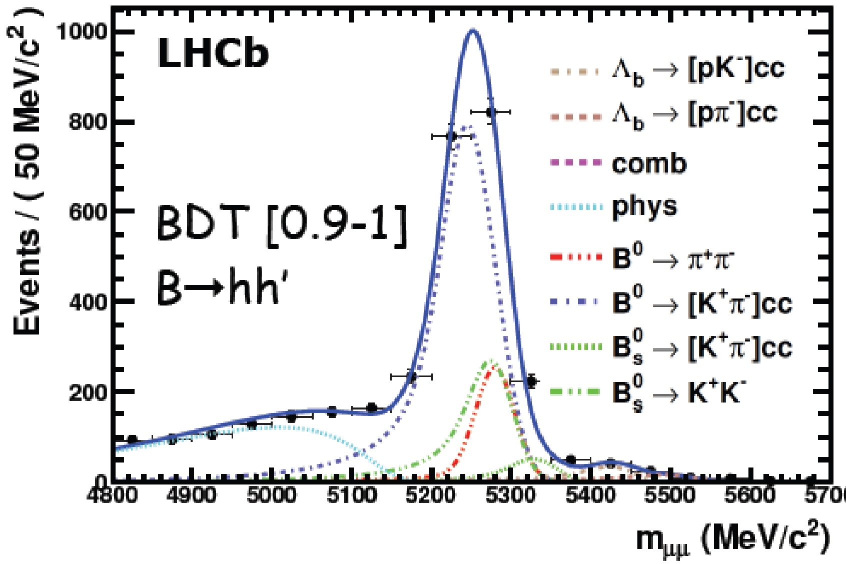
efficiencies

Ratio of probabilities of b quark to hadronize into the different mesons,
$f_d/f_s = 3.75 \pm 0.29$ (LHCb measurement)

- Three channels are used, each one with different (dis)advantages:
  - $B_d \to K^+\pi^-$
    - Different trigger (used triggered on the underlying event/other b used)
    - Same kinematics, number of tracks in final state



Normalization

Bd normalization | Bs normalization

	$\alpha^{cal}_{B_d\to\mu^+\mu^-}$ $(\times 10^{-11})$	$\alpha^{cal}_{B_s\to\mu^+\mu^-}$ $(\times 10^{-10})$
$B^+ \to J/\psi K^+$	8.464 ± 0.433	3.170 ± 0.297
$B_s^0 \to J/\psi\phi$	11.13 ± 3.124	4.169 ± 1.123
$B^0 \to K^+\pi^-$	7.709 ± 0.957	2.887 ± 0.424

Bs average $\alpha_{B_s^0\to\mu^+\mu^-} = (3.19 \pm 0.28) \times 10^{-10}$,

Bd average $\alpha_{B^0\to\mu^+\mu^-} = (8.38 \pm 0.39) \times 10^{-11}$,

→ As BR(SM) ~3.2×10^{-9} , this means one expect 10 SM signal

Normalization

	Bd normalization	Bs normalization
	$\alpha^{cal}_{B_d\to\mu^+\mu^-}$ $(\times 10^{-11})$	$\alpha^{cal}_{B_s\to\mu^+\mu^-}$ $(\times 10^{-10})$
$B^+ \to J/\psi K^+$	8.464 ± 0.433	3.170 ± 0.297
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Bd average $\alpha_{B^0\to\mu^+\mu^-} = (8.38 \pm 0.39) \times 10^{-11}$,

All the ingredients for the limit are in!

CLs method

•Set limit using CLs

•One calculates 2 frequentist CL's : CL_{s+b} and CL_b, done via pseudo experiments (=toy experiments)

•For each pseudoexperiment calculate test statistic

$$Q = \frac{e^{-(s+b)}(s+b)^d/d!}{e^{-(b)}(b)^d/d!}$$

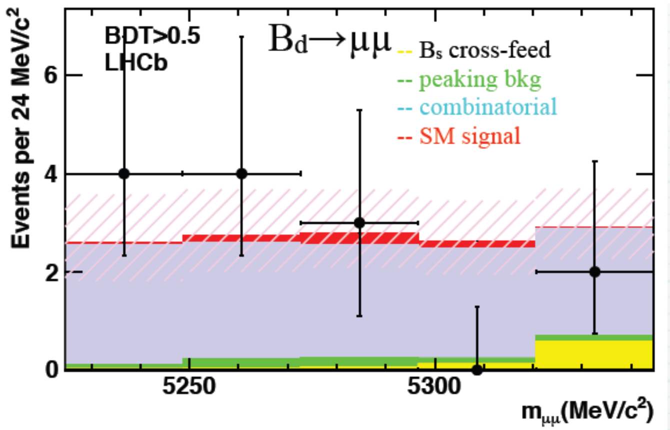
•CL_{s+b} = P_{s+b}(Q □ Qobs), while CL_b = P_b(Q □ Qobs)

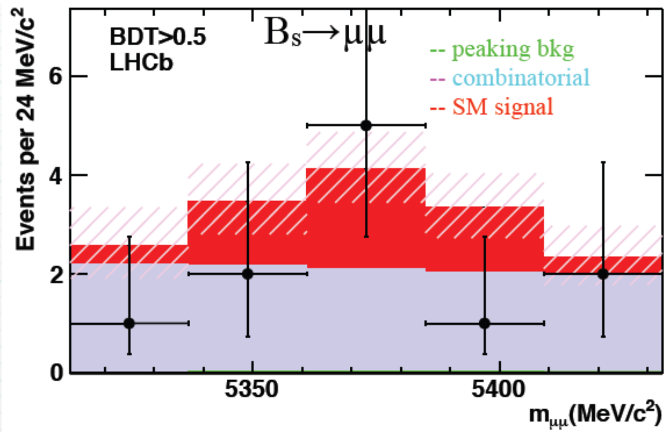
•CL_s = CL_{sb}/CL_b, is a ratio of confidence levels (not a CL itself). This construction avoids exclusions of the null hypothesis due to downward background fluctuations

•A BR is considered excluded at 90(95)% CL if CLs < 0.1(0.05)
1- CL_b is used as the p-value to claim for evidence of signal

- 3□ 1 - CL_b = 1.35×10^{-3} (or twice that)
- 5□ 1 - CL_b = 2.87×10^{-5} (or twice that)

Results



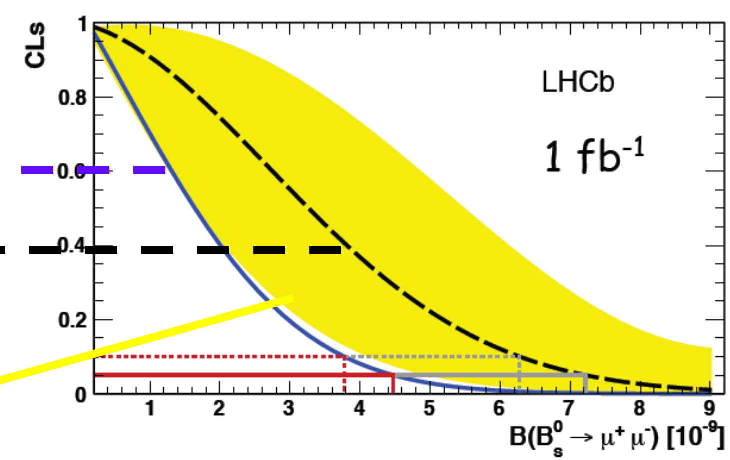


Observed pattern of events integrating over the most sensitive BDT bins

Observed CLs curve

Expected CLs curve for a SM signal

The "yellow banana" (aka Brazilian flag when it has also a green band) contains 68% of the CLs curves of SM pseudo-experiments



New Physics effects

Scenario	would point to …
$BR(B_s \to \mu\mu) >> SM$	Big enhancement from NP in scalar sector, SUSY high tanβ
$BR(B_s \to \mu\mu) \neq SM$	SUSY (C_S, C_P) , ED's, LHT, TC2 (C_{10})…
$BR(B_s \to \mu\mu) \sim SM$	Anything (→ rule out regions of parameter space that predict sizable departures from SM. Obviously)
$BR(B_s \to \mu\mu) << SM$	NP in scalar sector, but full MSSM ruled out. NMSSM (Higgs singlet) good candidate
$BR(B_s \to \mu\mu) / BR(B_d \to \mu\mu) \neq SM$	CMFV ruled out. New FCNC sources fully independent of CKM matrix (RPV SUSY, ED's etc…)

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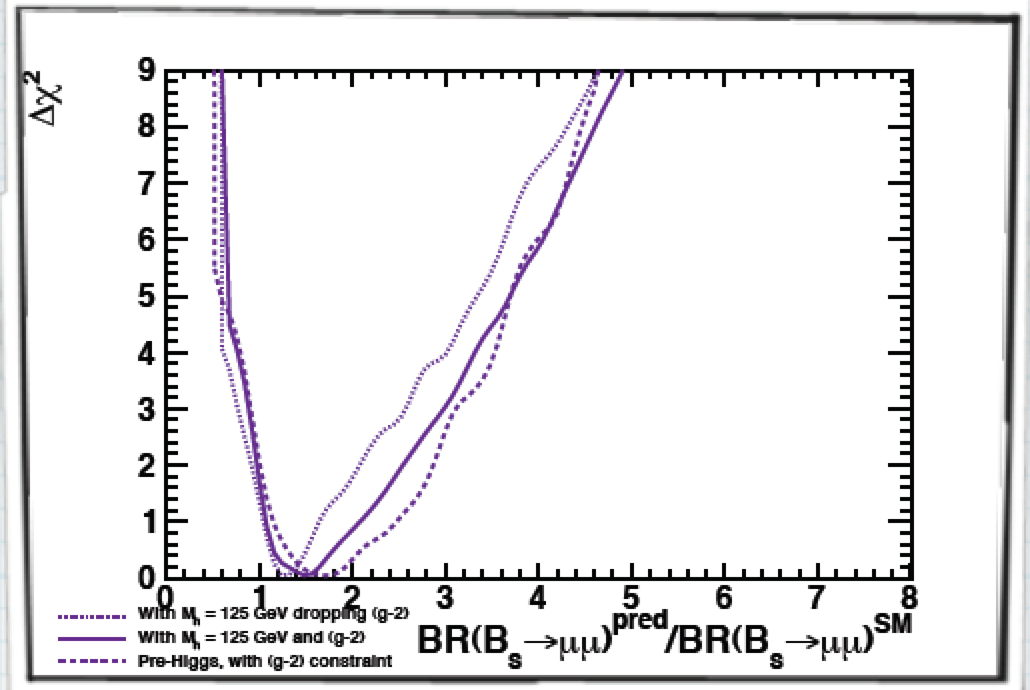
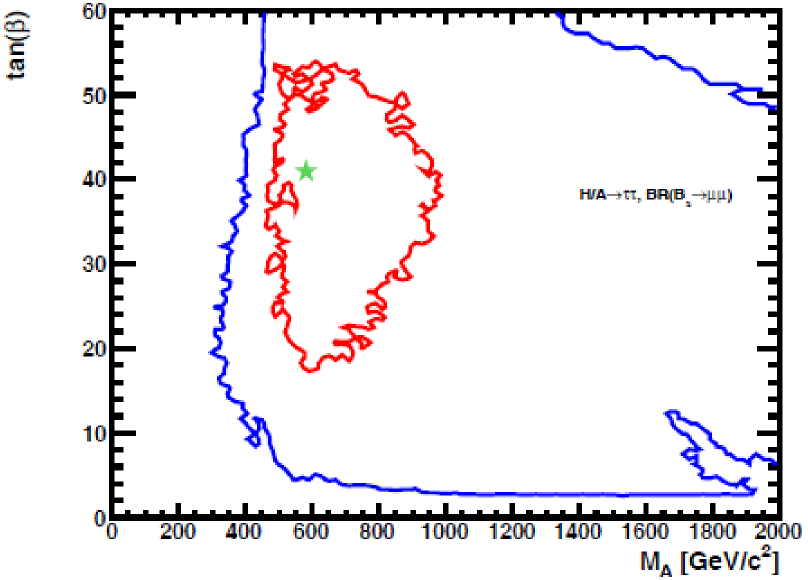
SUSY effects

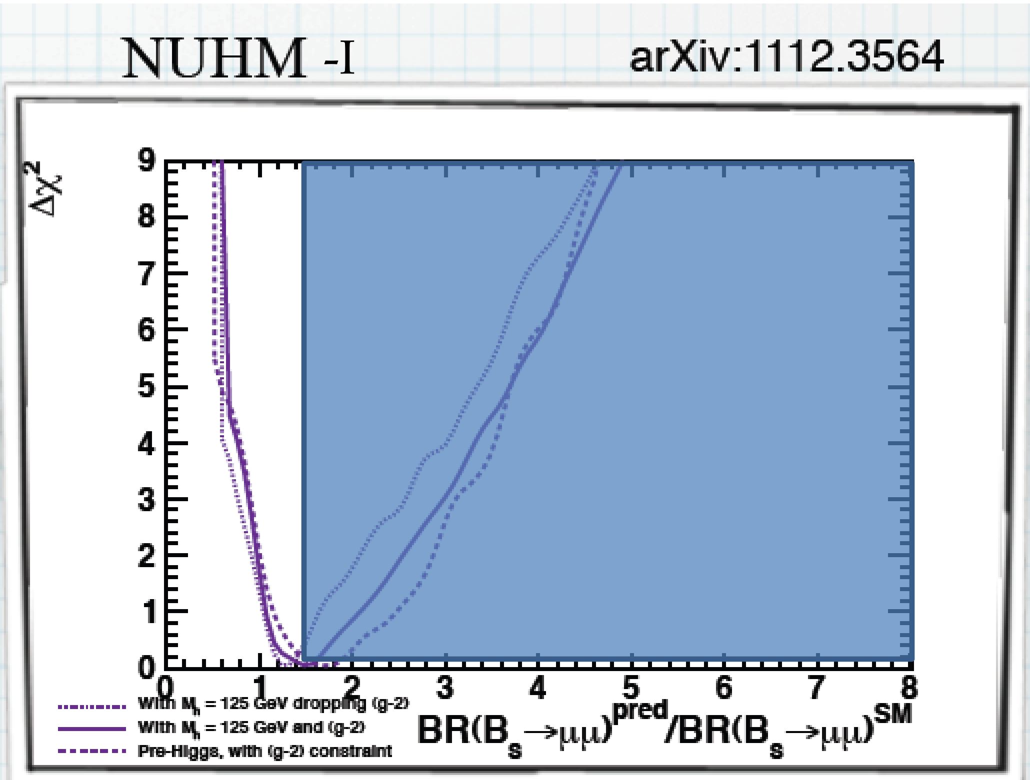
NUHM -I

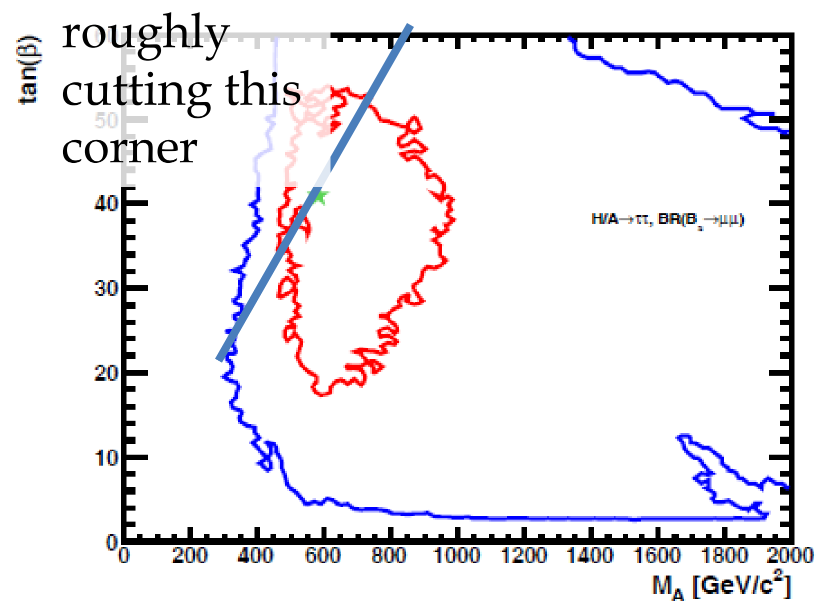
arXiv:1112.3564





SUSY effects





Conclusions

- LHCb sets a limit $BR(B_s \to \mu\mu) < 4.5 \times 10^{-9}$

- This result will constrain NP, particularly SUSY parameter space at high tan□.

Backup