Study of $B_s^0 \to \mu^+\mu^-$ in CMS

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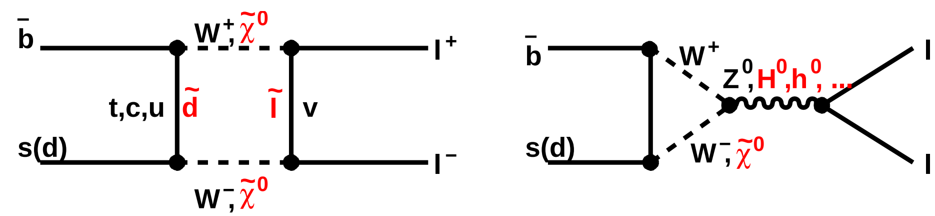
- Introduction
- The CMS Experiment
- Analysis

Introduction

- Decays highly suppressed in Standard Model (Buras, 2003)
  - ▷ effective FCNC
  - ▷ helicity suppression
  - ▷ $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$
    $\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$



- Sensitivity to new physics
  - ▷ 2HDM: $\mathcal{B} \propto (\tan\beta)^4, m_{H^+}$; MSSM: $\mathcal{B} \propto (\tan\beta)^6$

  $\longrightarrow$ ‘Measurement’ of $\tan\beta$ (Kane, *et al.* ph/0310042)

- $B_s^0 \to \mu^+\mu^-$ Cabibbo-favored over $B_d^0 \to \mu^+\mu^-$
  - ▷ not true for non-minimal flavor violation
  - ▷ mass resolution critical!

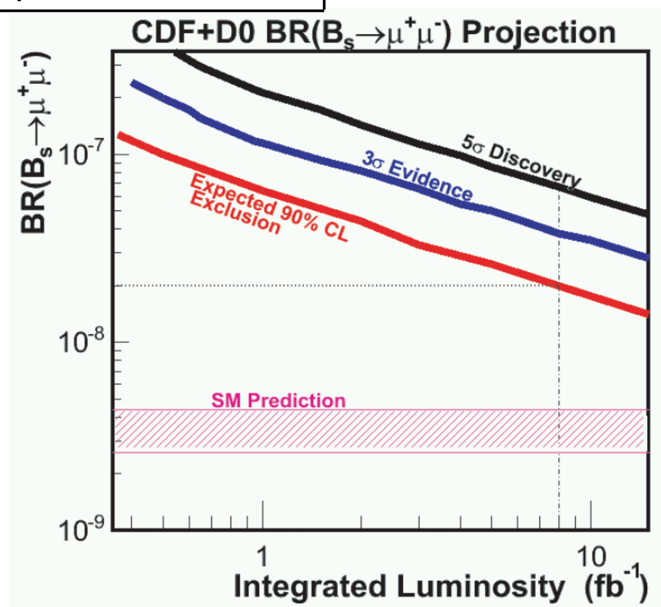
- This decay channel
  - ▷ not B physics, but a search for ‘new physics’
  - ▷ well suited for early CMS data (with pixel detector)

State of the art

- All decay channels beyond the reach of experiments:

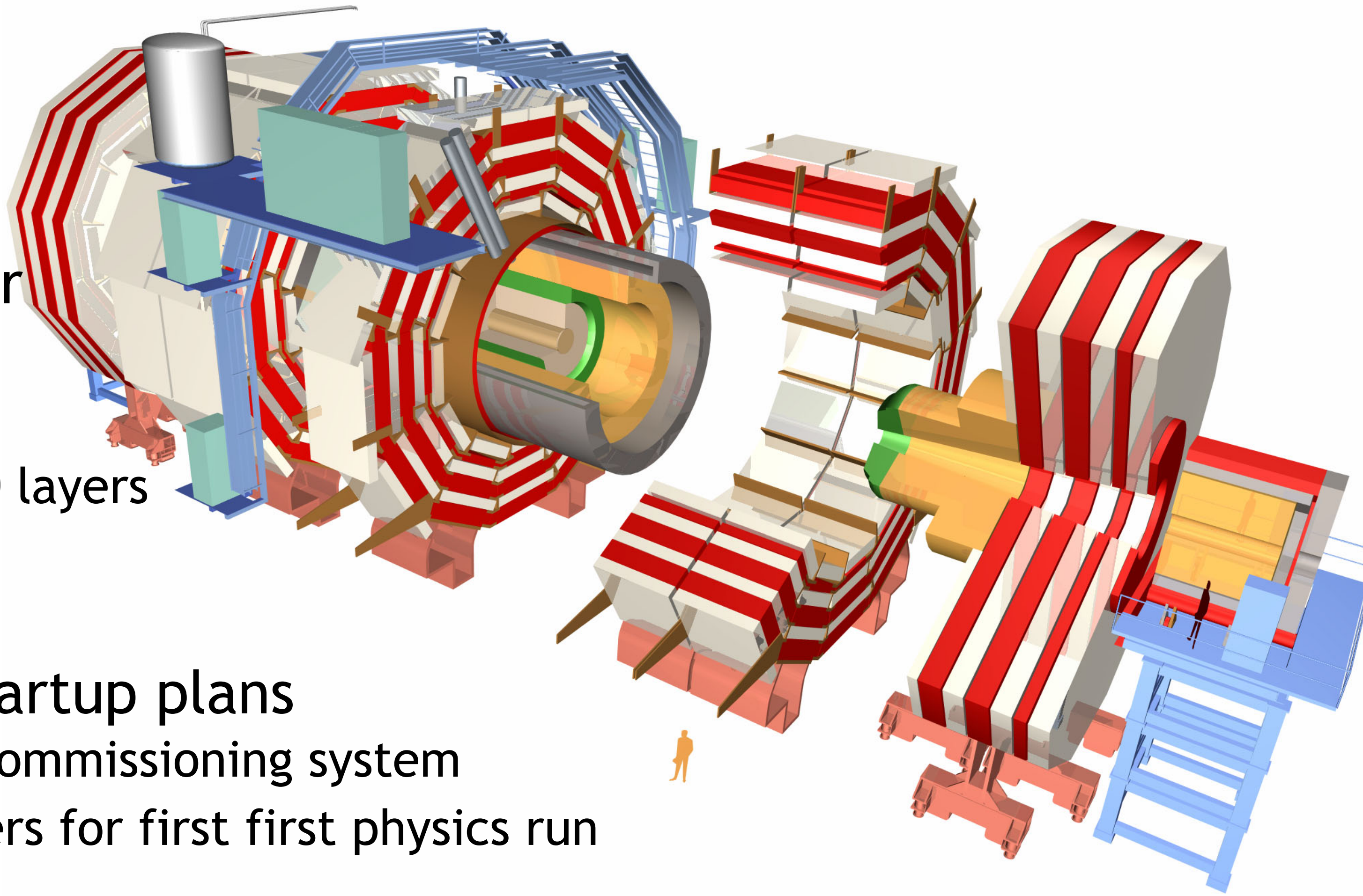
Mode	$B_s^0 \to \mu^+\mu^-$	$B_d^0 \to \mu^+\mu^-$	Reference
SM Expect.	3.5×10^{-9}	1.0×10^{-10}	Buras, 2003
CLEO	-	6.1×10^{-7}	PRD**62**, 091102
BELLE	-	1.6×10^{-7}	PRD**68**, 111101
CDF	5.8×10^{-7}	1.5×10^{-7}	PRL**93**, 032001
D0	4.1×10^{-7}	-	PRL**94**, 071802
BABAR	-	0.61×10^{-7}	PRL**94**, 221803
CDF	1.5×10^{-7}	0.39×10^{-7}	PRL**95**, 221805 + Err.
CDF	0.8×10^{-7}	0.23×10^{-7}	CDF public note 8176

- *B*-factories search also for
  - $B^0 \to e^+e^-$
  - $B^0 \to e^\pm\mu^\mp$
- SM branching ratio is very low:
  - $b\bar{b}$ cross section at LHC $\sim 10\times$ larger than at Tevatron
  - Events can be triggered at high luminosity



The CMS Experiment

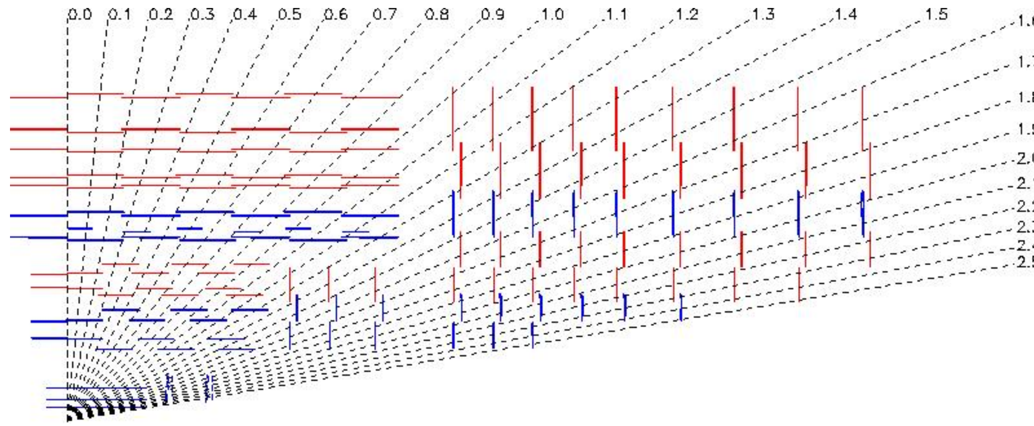
- The Compact Muon Solenoid
  - ▷ Length $22\,\mathrm{m}$, diameter $15\,\mathrm{m}$, $14\,\mathrm{kton}$
  - ▷ Magnetic field $4\,\mathrm{T}$
- Muon system
  - ▷ DT, CSC, RPC
  - ▷ $p_\perp > 3\,\mathrm{GeV}$
- All-silicon tracker
  - ▷ $|\eta| < 2.5$
  - ▷ pixel: 3 layers
  - ▷ strip tracker: 10 layers



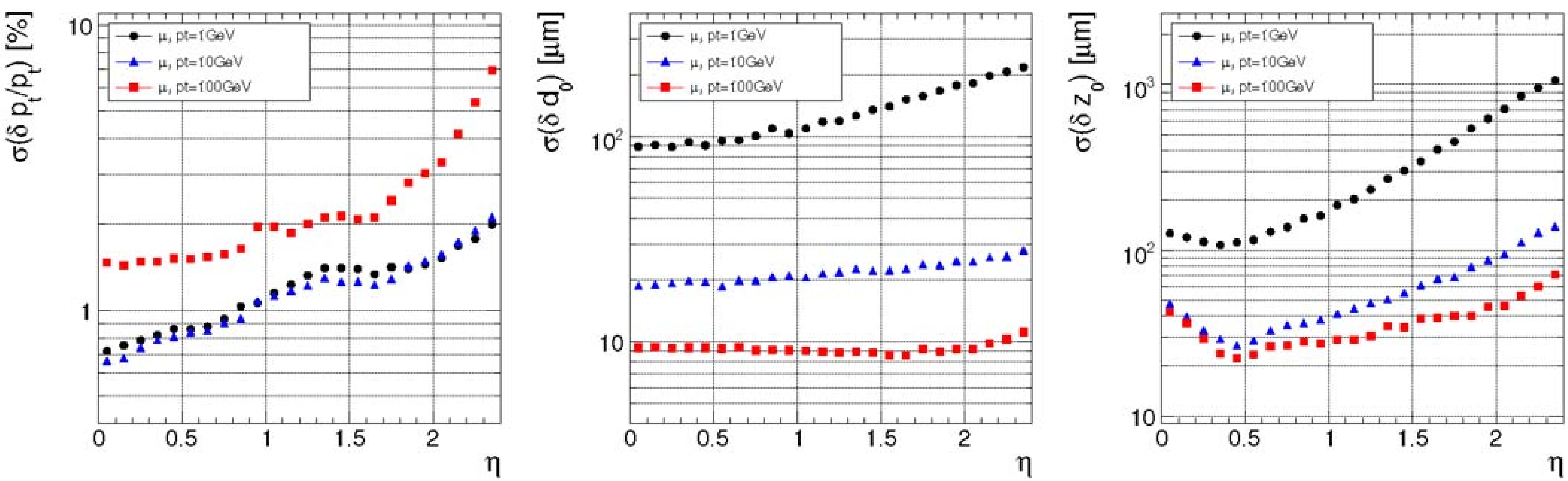
- Pixel detector startup plans
  - ▷ 2007: minimal commissioning system
  - ▷ 2008: three layers for first first physics run

The CMS Tracker

- All-silicon tracker configuration
  - ▷ Few measurement layers
  - ▷ Very precise measurements
- Pixel Detector
  - ▷ hit resolution: 10--15 μm
- Silicon Strip Detector
  - ▷ 10--14 points



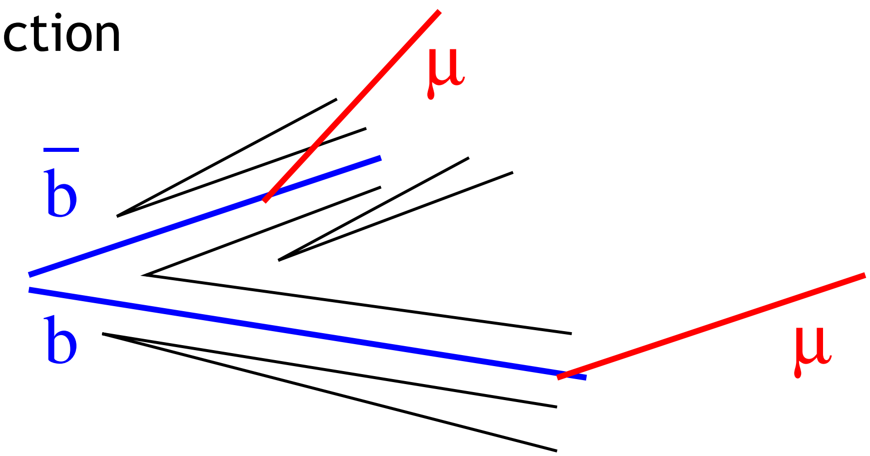
- Resolution:



Overview

- Search for a very rare decay
  - ▷ Clean experimental signature

    → Efficiency and background reduction
- b-hadrons produced in
  - ▷ gluon splitting
  - ▷ flavor excitation
  - ▷ gluon-gluon fusion



- Background composition
  - ▷ two independent semileptonic B decays (mostly from gluon splitting)
  - ▷ rare single B decays
- Background reduction in analysis
  - ▷ 2 final state muons consistent with one decay vertex
  - ▷ large (transverse) flight length
  - ▷ isolation of dimuon system

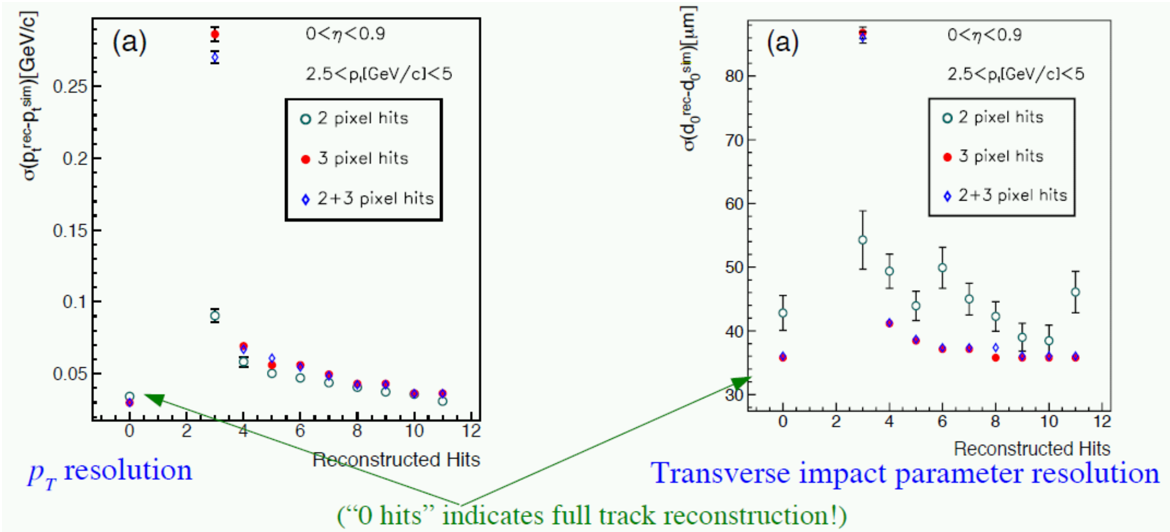
Event Samples

- Full MC simulation study for $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - ▷ Including 5 pile-up events
- Signal MC sample
  - ▷ 20k signal events
  - ▷ Minimum bias QCD events
- Background MC sample
  - ▷ 15k background events
  - ▷ Minimum bias QCD events
  - ▷ 2 muons on generator level, $p_\perp > 3\,\mathrm{GeV}$, $|\eta| < 2.4$, $0.3 < \Delta R(\mu\mu) < 1.2$
- Rare decays with PYTHIA (phasespace)
  - ▷ $B_d \to \pi^0 \mu^+ \mu^-$
  - ▷ $B^+ \to \mu^+ \mu^- \mu^+ \nu_\mu$

for first studies (with full simulation)

Trigger Strategy

- CMS has two-level trigger architecture
- Level 1
  - ▷ muons and calorimeters
    Latency: $3.2\,\mu$s
    40 MHz $\rightarrow 100$ kHz
- High-level trigger (HLT)
  - ▷ fast (local) reconstruction
    100 kHz $\rightarrow 100$ Hz

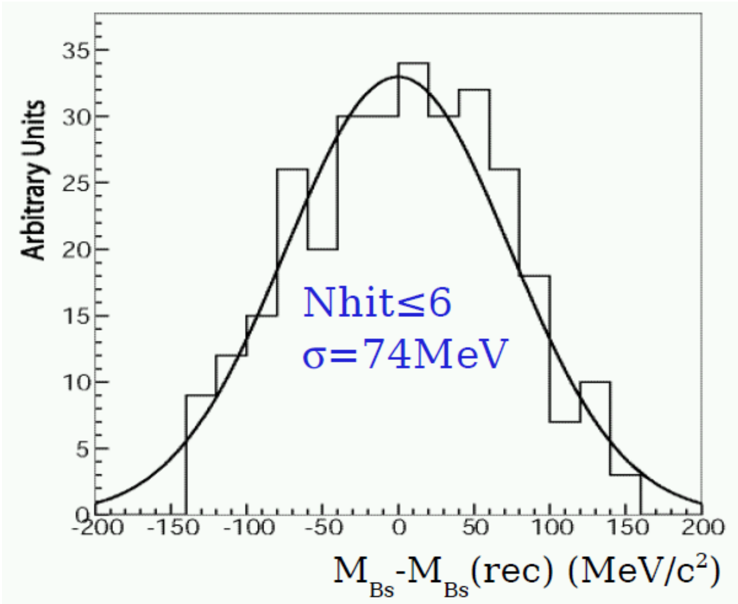


- B-physics triggers
  - ▷ Level 1: single- or di-muon trigger
    single-muon: $p_\perp > 14$ GeV
    di-muons: $p_\perp > 3$ GeV
  - ▷ HLT: exclusive and inclusive b, c triggers at ~ 5 Hz
    exclusive B decays: partial (local) reconstruction

High-level trigger selection study

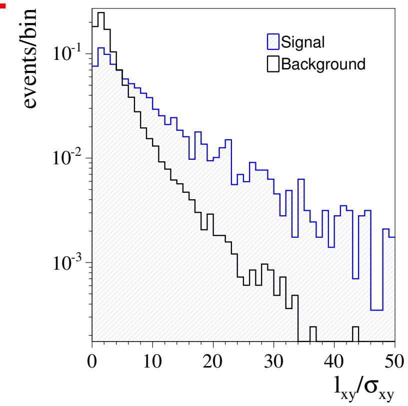
- Primary vertex reconstruction with pixel detector
  - ▷ use three most probable vertices
- Regional track reconstruction in cones around L1-muon candidates
  - ▷ partial reconstruction using ≤ 6 hits
  - ▷ $p_\perp > 4$ GeV
- Track pairs
  - ▷ mass windows for signal (and background)
  - ▷ (un)like sign charge
- Vertex fit
  - ▷ $\chi^2 < 20$
  - ▷ Decay flight length $l_{3d} > 150\,\mu$m

$\Rightarrow$ HLT accept rate < 1.7 Hz



Analysis: Variables

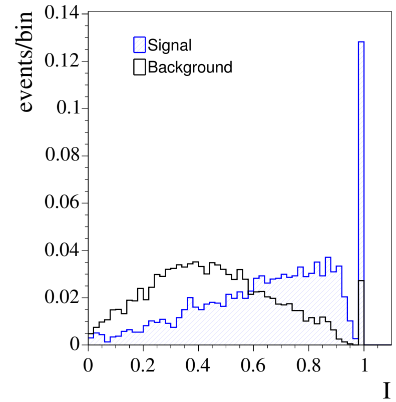
- Decay flight length significance l_{xy}/σ_{xy}
  - ▷ transverse plane: $l_{xy}/\sigma_{xy} > 18$



- Muon separation in $\eta\phi$:

$$\Delta R(\mu\mu) = \sqrt{(\eta_{\mu_1} - \eta_{\mu_2})^2 + (\phi_{\mu_1} - \phi_{\mu_2})^2}$$

  - ▷ $0.3 < \Delta R(\mu\mu) < 1.2$

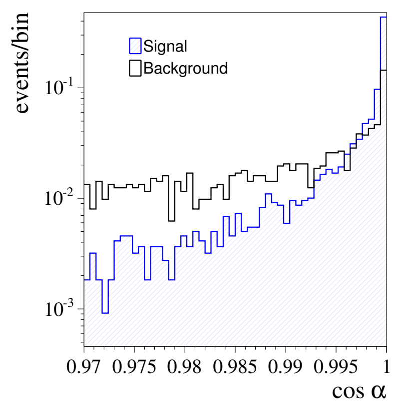


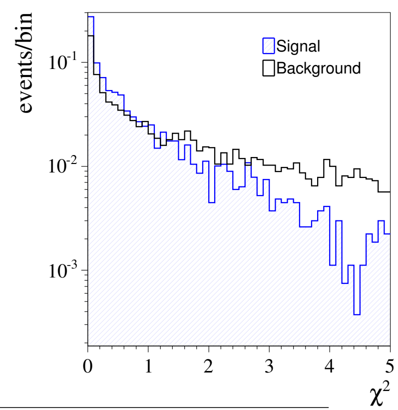
- Isolation of muon pair

$$I = \frac{p_\perp(B_s)}{p_\perp(B_s) + \sum_{trk} |p_\perp|}$$

  tracks in cone with $r = \sqrt{\eta^2 + \phi^2} < 1.0$
  and $p_\perp > 0.9$ GeV
  - ▷ $I > 0.85$

- Secondary vertex
  - ▷ Pointing angle: $\cos(\alpha) > 0.995$
  - ▷ vertex fit $\chi^2 < 1$





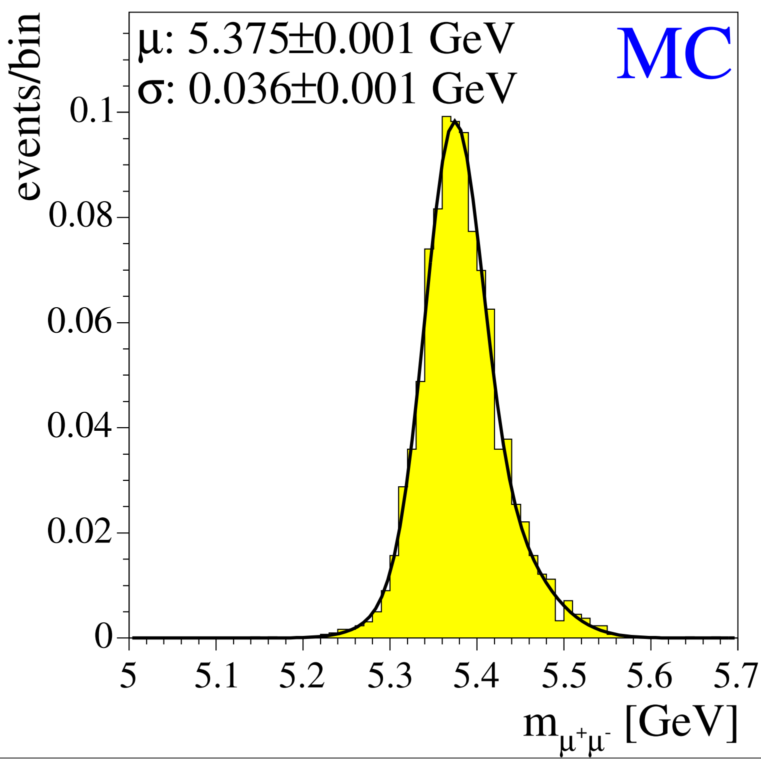
Mass Reconstruction

- Fit with two Gaussians

Gaussian	Narrow	Wide
Mean	5372.5 ± 1.3	5398.8 ± 3.3
Sigma	32.1 ± 1.4	60.2 ± 2.4
Normalization	0.08	0.03

(statistical errors only)

- Good mass resolution
  - ▷ essential against rare B decays
  - ▷ $\sim 2\sigma$ separation to B_d
- Impact of tracker misalignment on mass resolution
  - ▷ 2 alignment scenarios
    - short-term $\sim 20\%$
    - long-term $\sim 10\%$



Results

- Signal selection efficiency $\varepsilon = 0.019 \pm 0.002_{stat}$

  where the efficiency $\varepsilon = \varepsilon_{cuts}\, \varepsilon_I\, \varepsilon_{\chi^2}$ is factorized

  - ▷ In $10\,\text{fb}^{-1}$: $N_S = 6.1 \pm 0.6$ signal events

- Background rejection $\eta = 2.6 \times 10^{-7}$

  - ▷ In $10\,\text{fb}^{-1}$: $N_B = 13.8^{+22.0}_{-13.8}$ background events

    (one remaining background event in $5 < m_{\mu\mu} < 6\,\text{GeV}$)

- Extract upper limit with Bayesian procedure (CDF)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{\text{gen}}\, \varepsilon_{\text{total}}\, N_{B_s}} \leq 1.4 \times 10^{-8}\ (90\%\ \text{C.L.})$$

including statistical and systematic error

Systematics

- Systematics have minor impact compared to statistical error
  - ▷ with current background MC sample
- Determination of efficiency with factorizing cuts
  - ▷ 15%
- Tracker misalignment (decay flight significance, χ^2, $\cos\alpha$)
  - ▷ 10% for signal efficiency, 50% for background
- L1 trigger efficiency
  - ▷ 10%
- Particle identification
  - ▷ muon ID and hadron mis-ID
- Tracking
  - ▷ efficiency: isolation veto
- Normalization
  - ▷ 15%, a la CDF and D0

Summary:

$$\Delta(\varepsilon) \quad : \quad 24\%$$
$$\Delta(n_B) \quad : \quad 50\%$$
$$\Delta(N_{B_s}) \quad : \quad 15\%$$

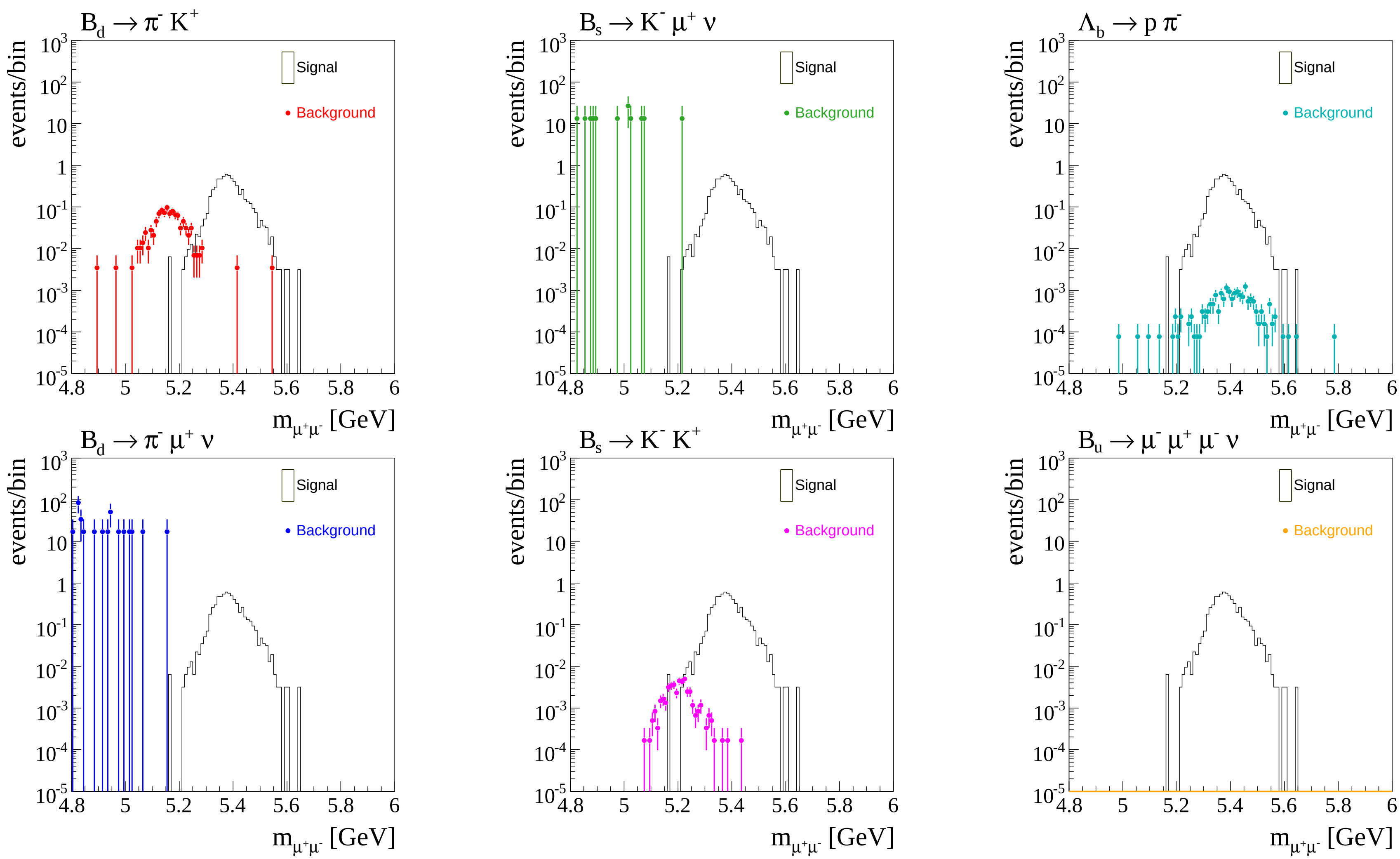
Background from rare b-hadron decays

- Study selected rare b-hadron decays
  - ▷ full simulation
  - ▷ average hadron muon fake rate $< 0.5\%$
- Background yields (misidentified dimuons)
  - ▷ for $\mathcal{L} = 10\,\text{fb}^{-1}$
  - ▷ no mass constraints
  - ▷ no analysis efficiency

Decay mode	N_{evt}	$N_{\mu\mu}$
$B_d \to K\pi$	2.5×10^6	61
$B_d \to \pi\pi$	7.3×10^5	18
$B_d \to \pi\mu\bar{\nu}$	4.5×10^6	22000
$B_s \to K\pi$	2.7×10^5	7
$B_s \to KK$	1.1×10^5	3
$B_s \to K\mu\bar{\nu}$	2.0×10^6	10000
$\Lambda_b \to p\pi$	4.2×10^4	1
$\Lambda_b \to pK$	8.4×10^4	2
$B^+ \to \mu^+\mu^-\mu^+\bar{\nu}$	1.4×10^5	13000

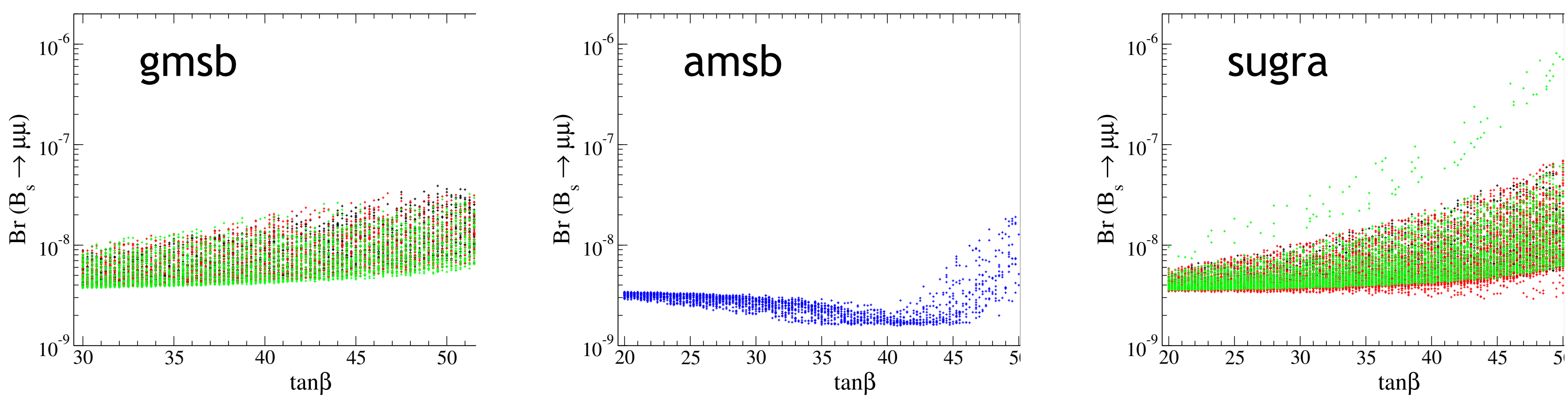
Rare b-hadron decays II

- Normalization to $10\,\text{fb}^{-1}$
  - Background: same analysis efficiency as for signal



Conclusions

- First CMS update on search for $B_s^0 \to \mu^+\mu^-$ since 1999
  - ▷ Full reconstruction with pileup for $2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Expected upper limit in 10 fb^{-1}: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq 1.4 \times 10^{-8}$
  - ▷ study limited by size of background MC sample
  - ▷ good mass resolution
- Outlook
  - ▷ include rare B decays
  - ▷ full analysis: likelihood selection and normalization sample



(from hep-ph/0310042)