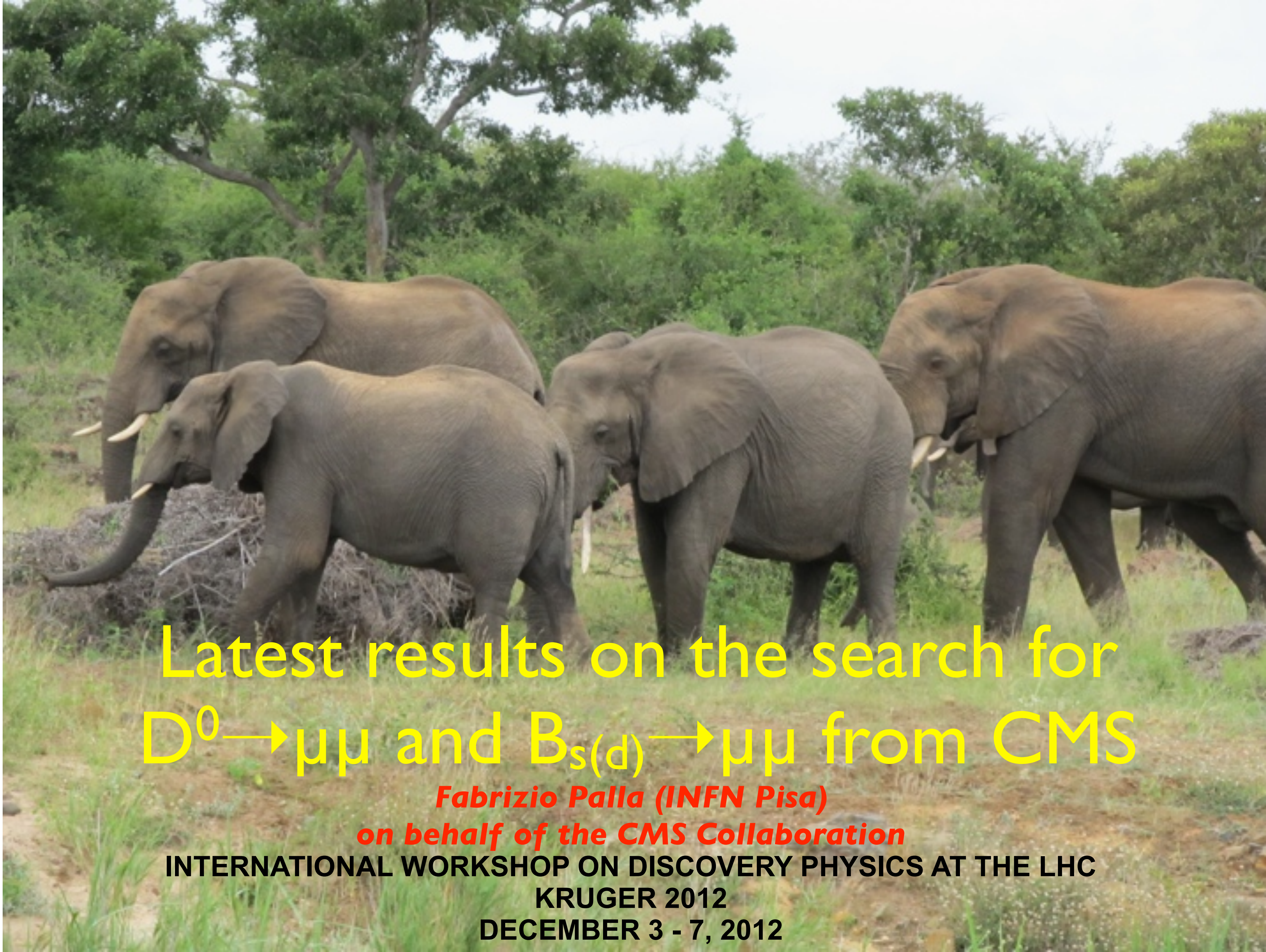


Latest results on the search for $D^0 \rightarrow \mu\mu$ and $B_{s(d)} \rightarrow \mu\mu$ from CMS

Fabrizio Palla (INFN Pisa)
on behalf of the CMS Collaboration

INTERNATIONAL WORKSHOP ON DISCOVERY PHYSICS AT THE LHC
KRUGER 2012
DECEMBER 3 - 7, 2012

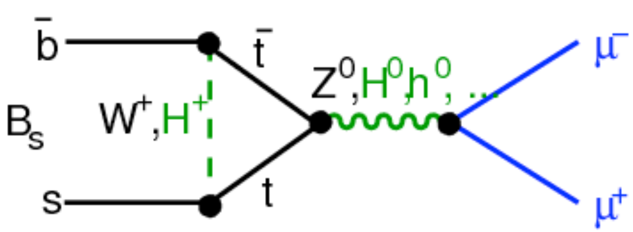
Motivations

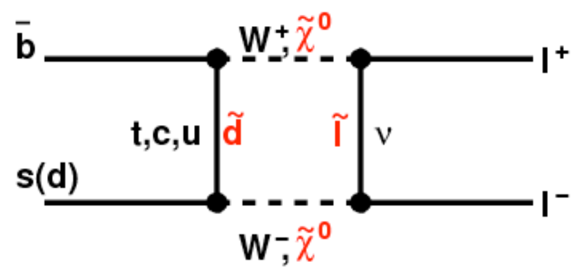
In SM $B_{s/d}^0 \rightarrow \mu\mu$ and $D^0 \rightarrow \mu\mu$ have highly suppressed rates:

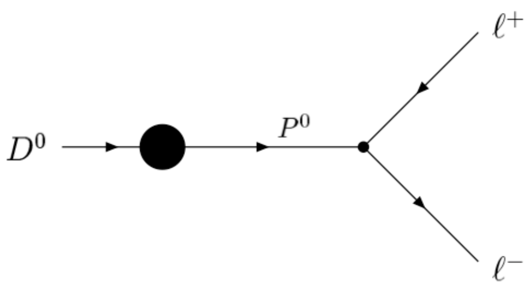
1. **forbidden at tree level** and can only proceed through higher-order loop diagrams
2. **helicity suppressed** by factors of $(m_\mu/m_{B/D})^2$
3. **require an internal quark annihilation** within the B (D) meson
4. **Long-distance effects sizable in D^0**

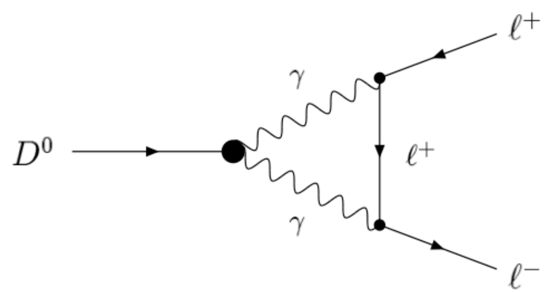
Decay channel	BR SM predictions*
$B_s \rightarrow \mu^+\mu^-$	$(3.2 \pm 0.2) \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$(1.0 \pm 0.1) \times 10^{-10}$
$D^0 \rightarrow \mu^+\mu^-$	$\sim 10^{-18} - 10^{-13}$

**Buras arXiv:1009.1303. Burdnam et al, Phys. Rev. D66:014009, 2002*





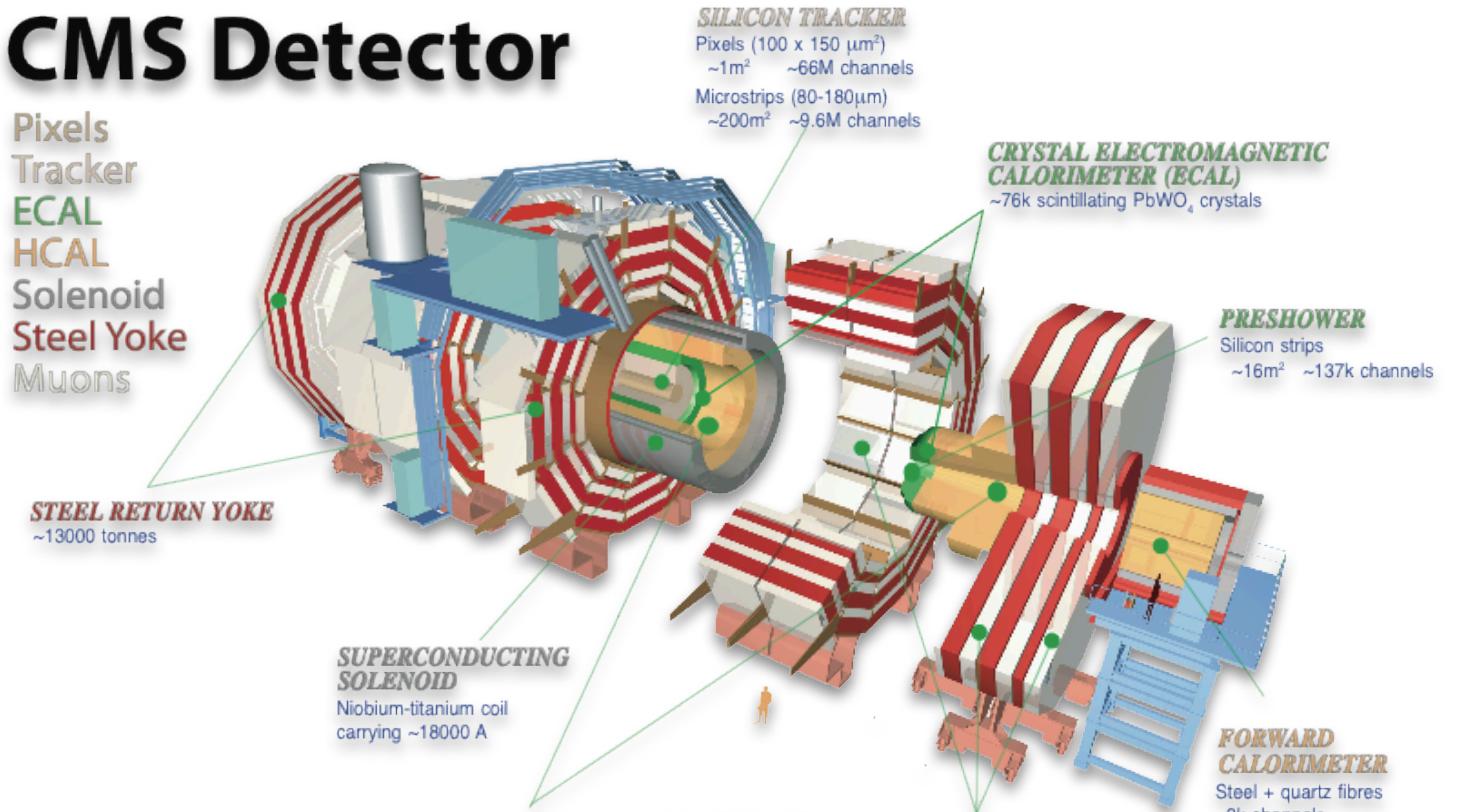




Physics Beyond SM

- **BR($B_{(s,d)}/D^0 \to \mu\mu$) are potentially sensitive probes for Physics Beyond SM:**
  - **Sensitivity to extended Higgs boson sectors**
    - **2HDM: BR($B_{s/d} \to \mu\mu$) $\propto$ $\tan^4 \beta$ and m(H^+)**
      - J. R. Ellis et al, JHEP 05 (2006) 063
    - **MSSM: BR($B_{s/d} \to \mu\mu$) $\propto$ $\tan^6 \beta$**
      - J.Parry, Nucl. Phys. B 760 (2007) 38
    - **Leptoquarks**
      - S. Davidson and S. Descotes-Genon, JHEP 11 (2010) 073
- **Any difference in branching ratio from the SM will be evidence of new Physics**
  - **LHC experiments are close to reaching the SM predictions. LHCb reported an evidence at 3.5 σ consistent with the SM prediction (see E. Grauges talk this morning)**
    - **An observation could come with the 2012 LHC run.**

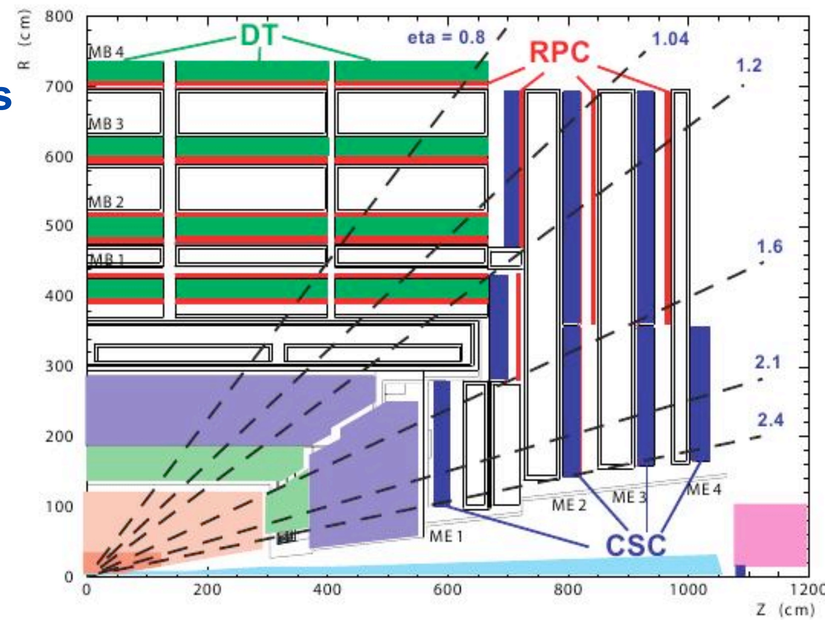
The CMS Detector



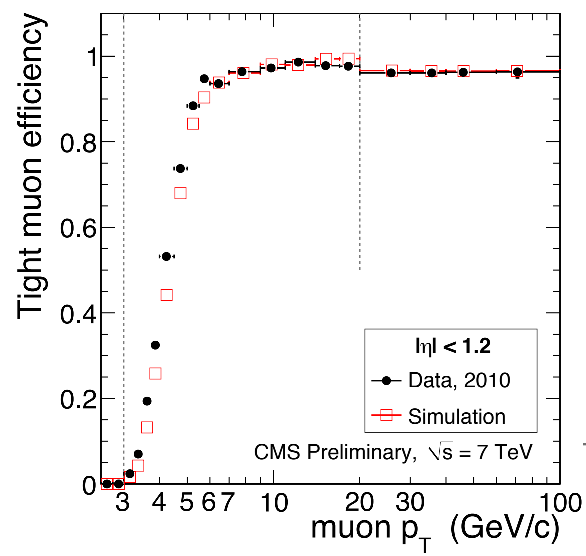
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Muon reconstruction

- **Tracks: Excellent p_T resolution ≈ 1%**
  - Tracking efficiency > 99% for central muons
  - Excellent vertex reconstruction and impact parameter resolution (≈ 15 μm)
- **Muon candidates:**
  - Match between muon segments and a silicon track
  - Large pseudorapidity coverage: $|\eta| < 2.4$
- **Muon identification and trigger efficiencies evaluated with**
  - MC methods
  - Data-driven methods: Tag & Probe
- **Muon misidentification rates measured in data using**
  - $D^* \to D^0 \pi$, $D^0 \to K\pi$
  - $\Lambda \to p\pi$
  - Misid $\pi/K \to \mu$ (0.10 ± 0.02)%
  - Misid $p \to \mu$ (0.05 ± 0.01)%



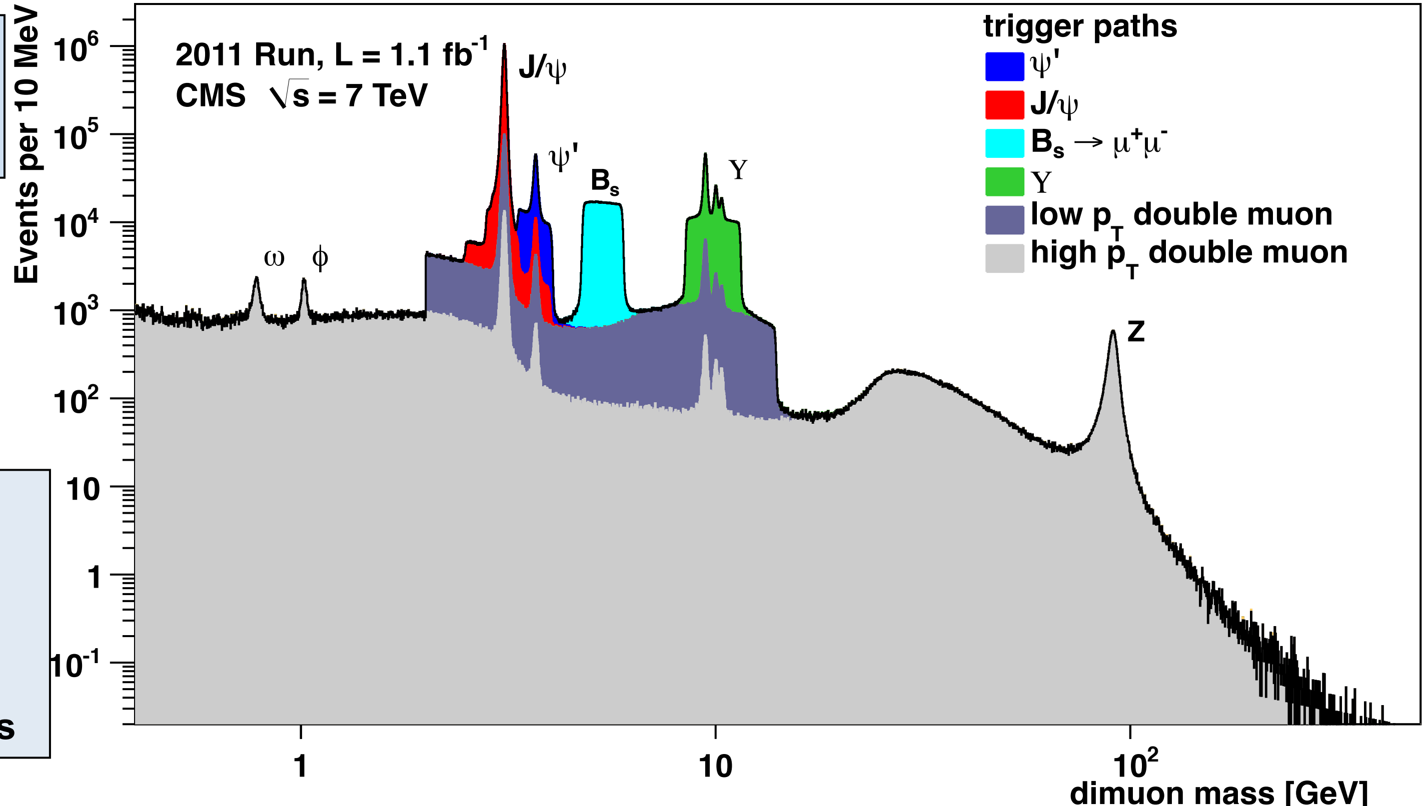
CMS-PAS-MUO-10-002



Trigger

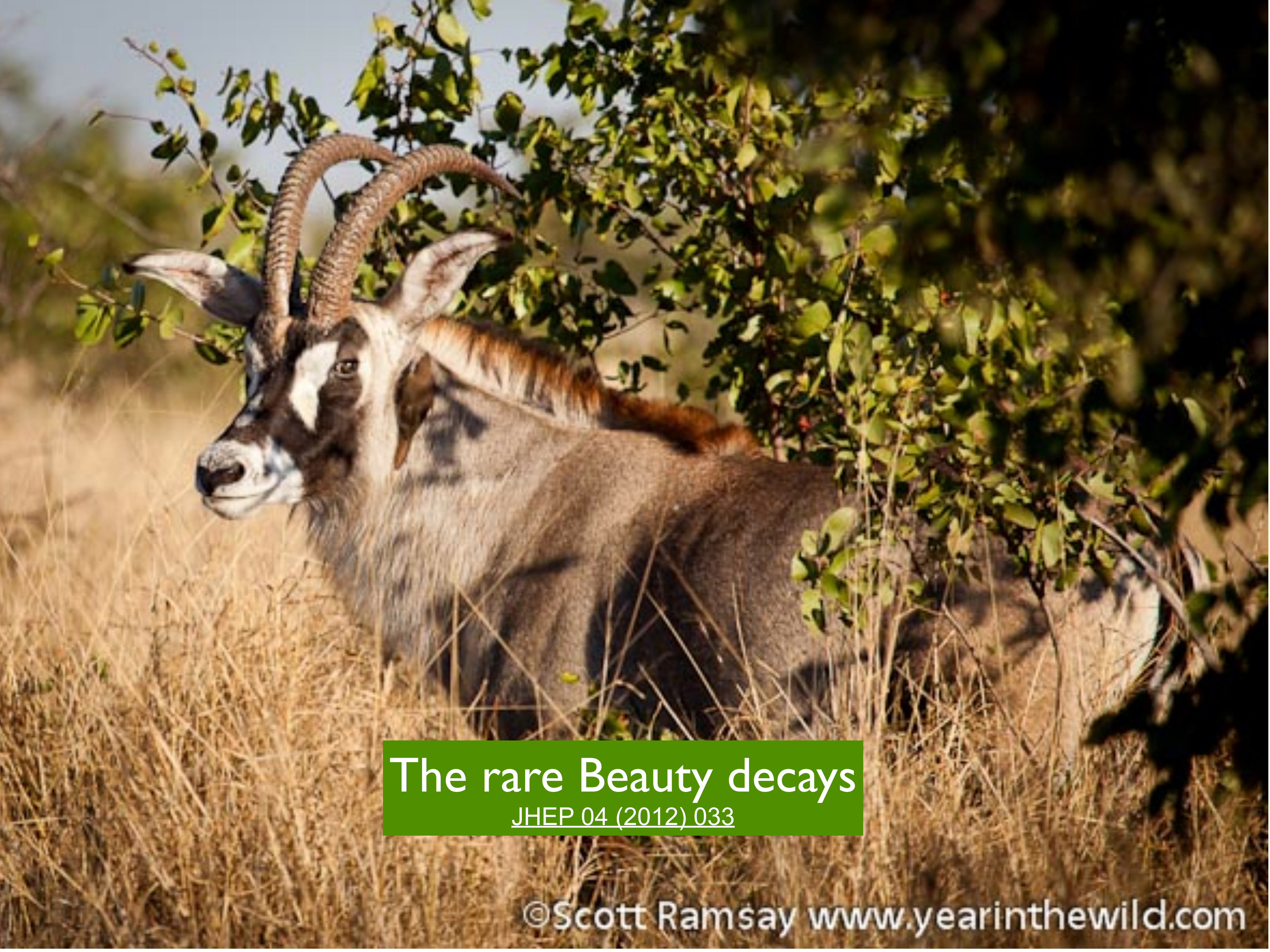
L1: hardware
muon system and calorimeters only

High Level Trigger (HLT): software
matching of different sub-detectors.
Fast local tracker reconstruction for muons



p_T threshold for the low-p_T muon trigger had to be steadily increased with the increased instantaneous luminosity

- **Single μ: p_T threshold went from p_T>3 GeV (2010 run), to more than 19 GeV (2012 run)**
- **Dimuon:p_T threshold stayed at p_T>3 GeV thanks to further kinematic cuts on the di-muon vertex and invariant mass**



The rare Beauty decays

JHEP 04 (2012) 033

Analysis overview

- Cut analysis with blinding of signal region on 5 fb^{-1} data at $\sqrt{s}$=7 TeV in 2011
- Backgrounds estimated from the sidebands and from MC
- Normalization sample $B^{\pm} \rightarrow J/\psi K^{\pm} \rightarrow (\mu^+\mu^-) K^{\pm}$ to:
  - avoid uncertainties in the b production cross section
  - eliminate the need for luminosity measurement
  - mitigate the effects of uncertainties in efficiencies

$$Br\left(B_s^0 \rightarrow \mu^+\mu^-\right) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} Br\left(B^+\right)$$

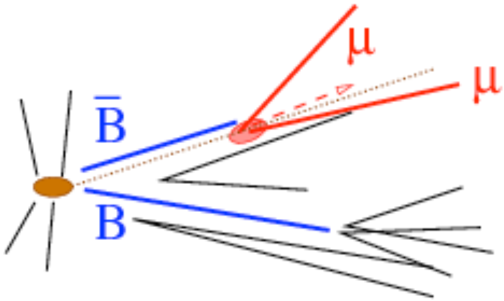
f_s / f_u = 0.267 ± 0.021 [LHCb arxiv:1111.2357]
$Br(B^+)$ from the PDG

Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu1\mu2} < 5.90$
blinding window	$5.20 < m_{\mu1\mu2} < 5.45$
$B^0 \rightarrow \mu^+\mu^-$ window	$5.20 < m_{\mu1\mu2} < 5.30$
$B_s \rightarrow \mu^+\mu^-$ window	$5.30 < m_{\mu1\mu2} < 5.45$

- Control sample $B_s \rightarrow J/\psi\varphi \rightarrow (\mu^+\mu^-)(K^+K^-)$ to compare and validate B_s mesons in data and MC simulations
- Divide the sample in two groups:
  - both muons in the barrel ($|\eta|<1.4$) ➨better sensitivity, B_s mass resolution ≈ 40 MeV
  - ≥1 μ in the endcap ➨more events but B_s mass resolution ≈ 60 MeV

Event characteristics

- **Signal $B_{s/d} \rightarrow \mu^+\mu^-$:**
  - two reconstructed muons
  - invariant mass around $m(B_{s/d})$
  - long lived B, with a well reconstructed secondary vertex and a momentum aligned with flight direction

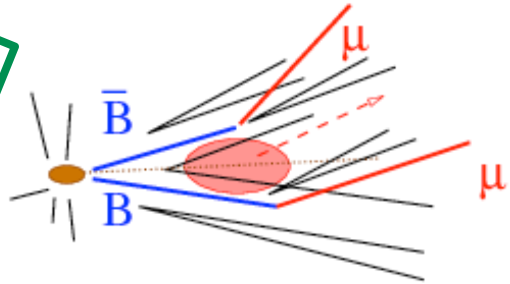


- **Backgrounds**
  - two semileptonic B decays
  - one semileptonic B decay and one misidentified hadron

combinatorial
flat shape from data
sidebands

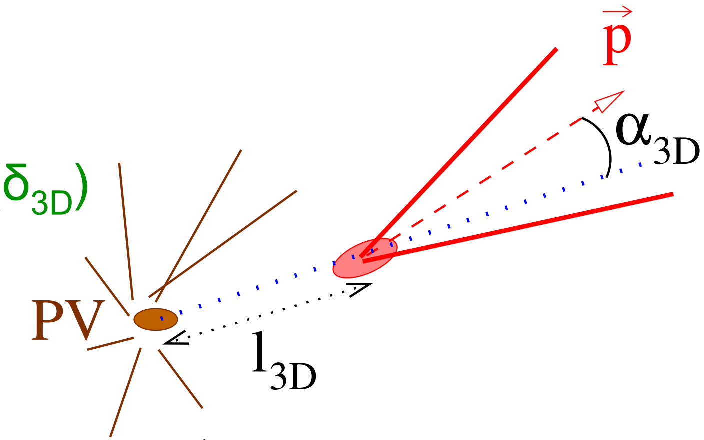
  - Single-B decays
    - peaking (ex. $B_s \rightarrow K^- K^+$)
    - non peaking (ex. $B_s \rightarrow K^- \mu^+ \nu$)

rare
shape from MC

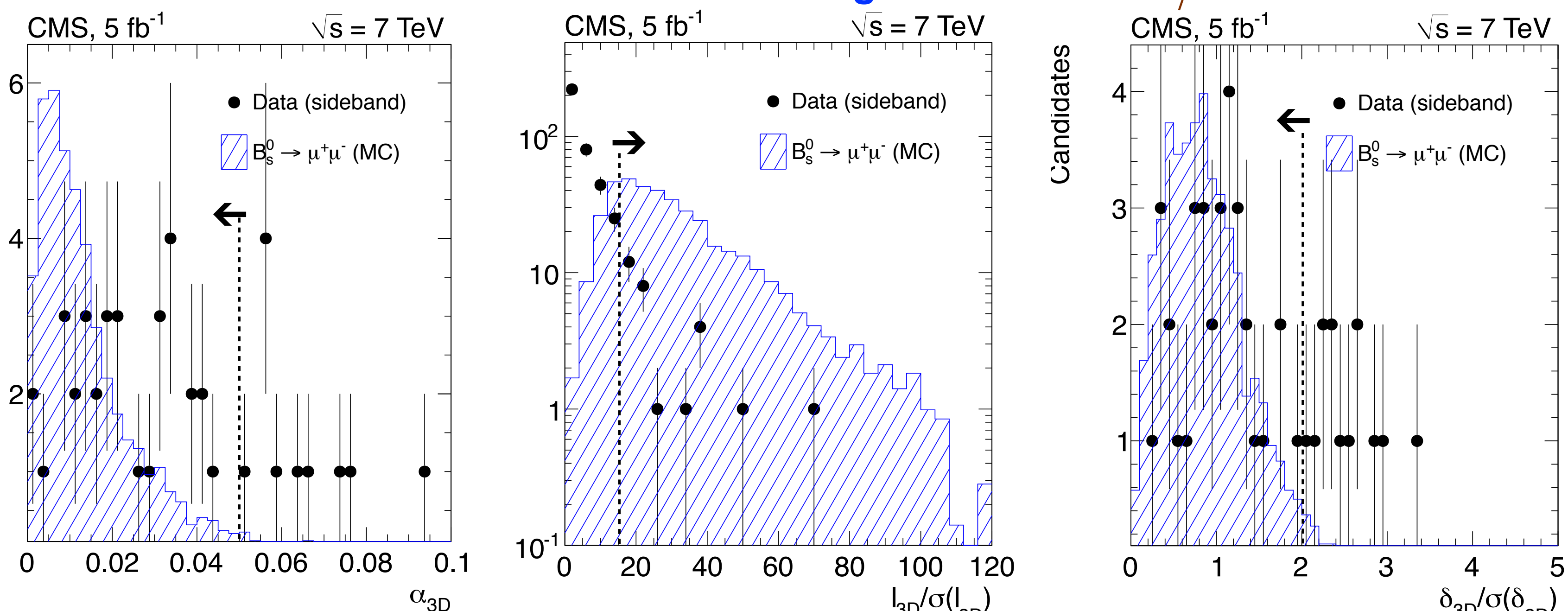


Signal selection: most discriminating variables

- Pointing angle α_{3D}
- Flight length significance $l_{3D}/\sigma(l_{3D})$
- Impact parameter significance of the B: $\delta_{3D}/\sigma(\delta_{3D})$
- Selections optimized (random grid search) for best upper limit



Data side-bands vs signal MC:

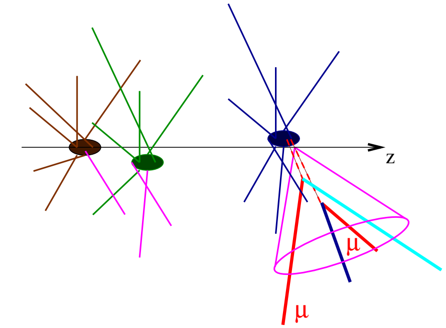


Isolation

- **Isolation cone around the Primary vertex:**

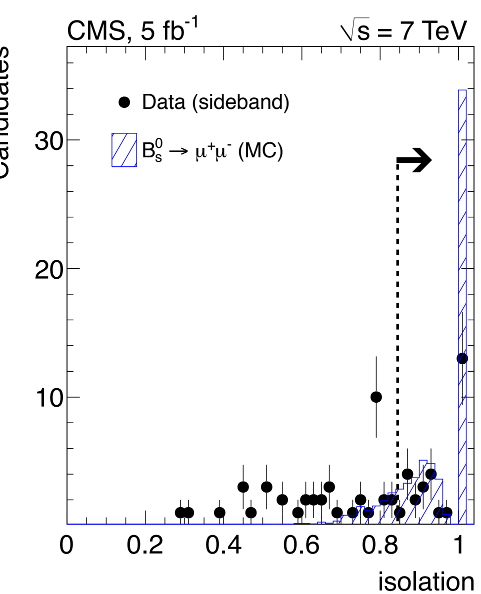
$$I = \frac{p_T(B)}{p_T(B) + \sum_{\Delta R<0.7, p_T>0.9GeV} p_T}$$

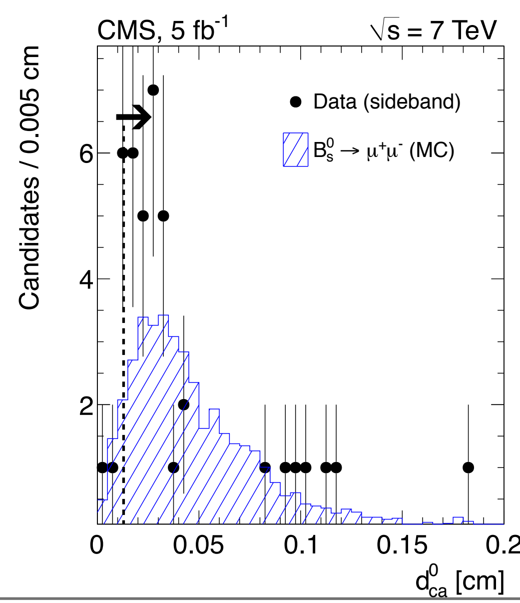
  - Include all tracks within cone of ΔR=0.7 with p_T>0.9 GeV from the same PV or (if not associated to any PV) d_{ca}<500 μm from B vertex.
  - The larger the *I* value, the more isolated

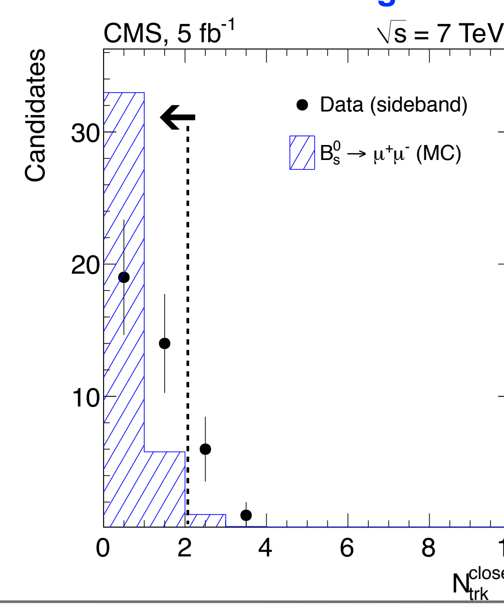


- **Isolation on the Secondary vertex:**
  - Distance of the closest track to SV (d^0_{ca})>150μm
  - Number of close tracks in d_{ca} < 300 μm and p_T > 0.5 GeV

Data side-bands vs signal MC



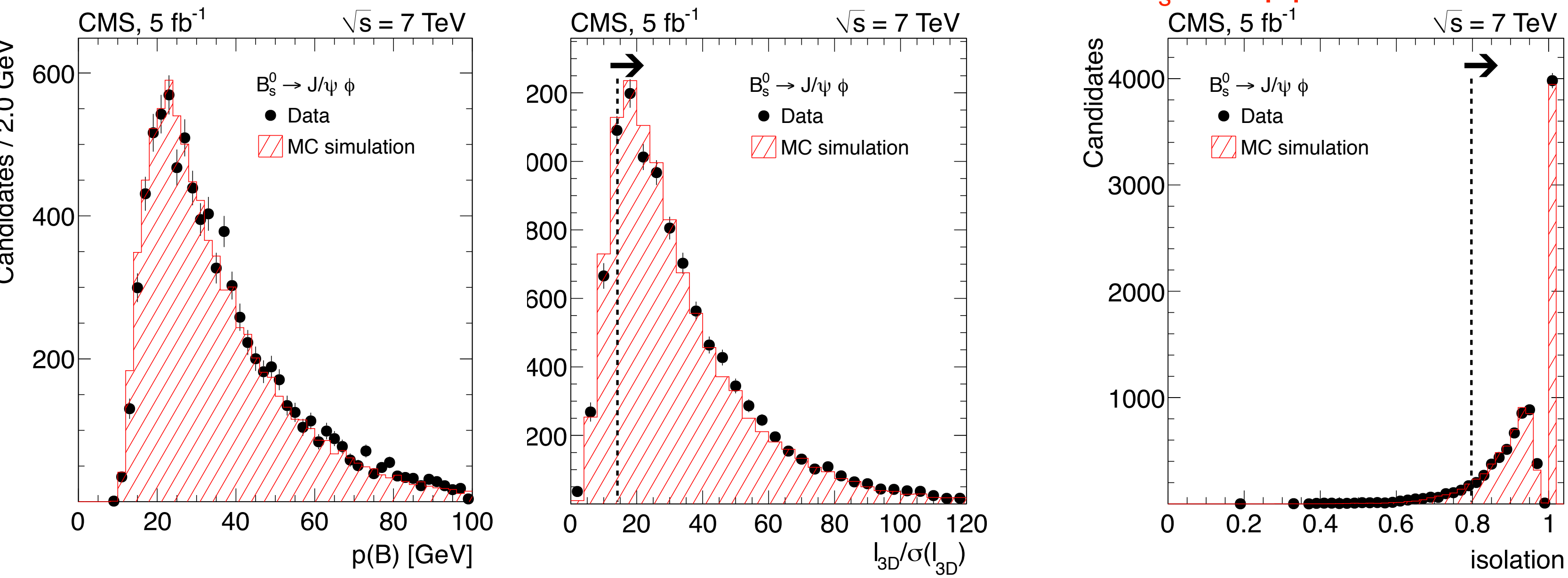




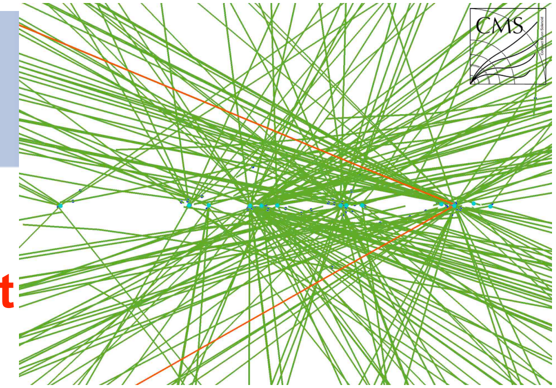
Data - Simulation comparison

- Needed to validate signal (through the control sample) and normalization samples
- Differences data – MC taken as systematics uncertainties:
  - On $B^{\pm} \rightarrow J/\psi K^{\pm}$, max diff = 2.5% (isolation) tot = 4%
  - On $B_s \rightarrow J/\psi\varphi$, max diff = 1.6% (secondary vertex χ^2/ndof) tot = 3%
- Excellent MC – data comparison

Side-bands subtracted data vs control $B_s \rightarrow J/\psi\varphi$ MC:

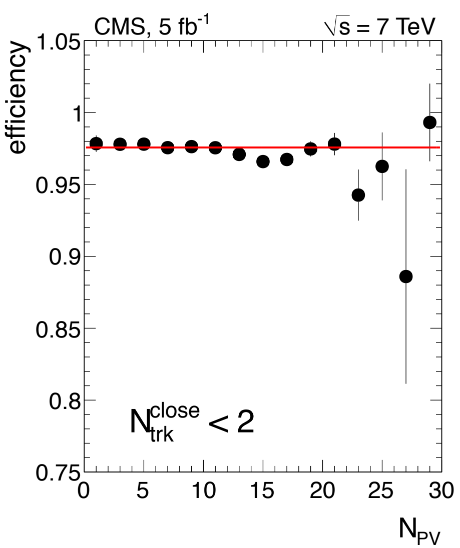


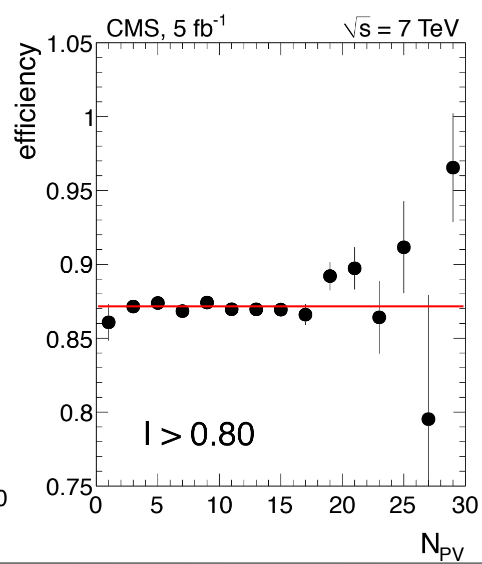
Pile-up



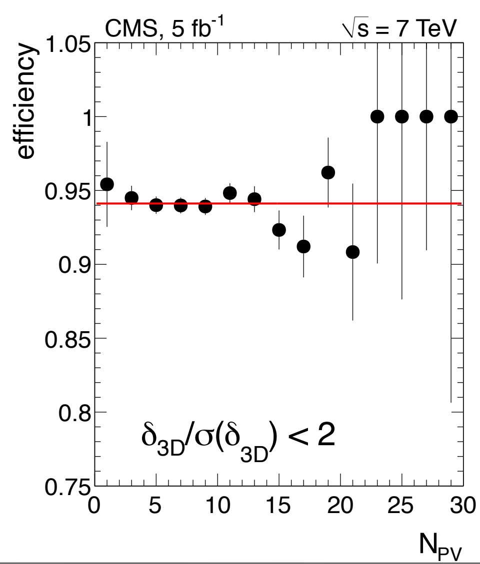
- **In 2011: $\langle N_{PV} \rangle = 8$, RMS(z) = 5.6 cm**
- **Selections have been tuned to be pile-up independent**
  - **e.g. isolation searches only for tracks coming from the same primary vertex or not associated with any**
- **Efficiencies of all selection criteria have been evaluated versus the number of reconstructed primary vertices**
- **All selections are compatible with a constant efficiency up to at least 30 PV**

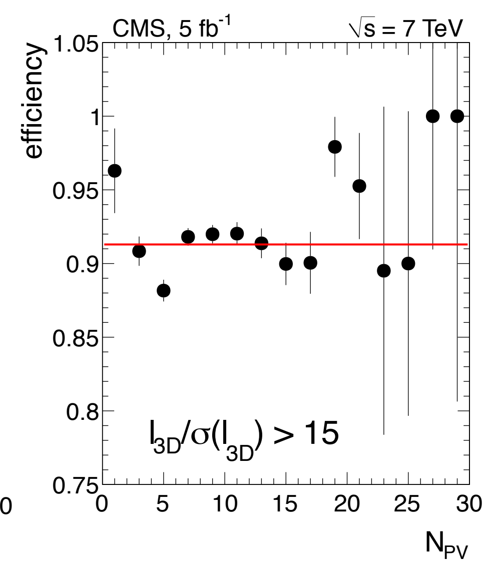
Normalization sample $B^{\pm} \to J/\psi K^{\pm}$





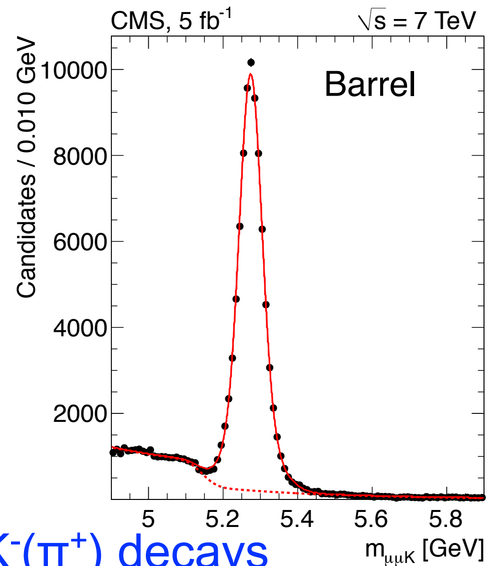
Control sample $B_s \to J/\psi\varphi$

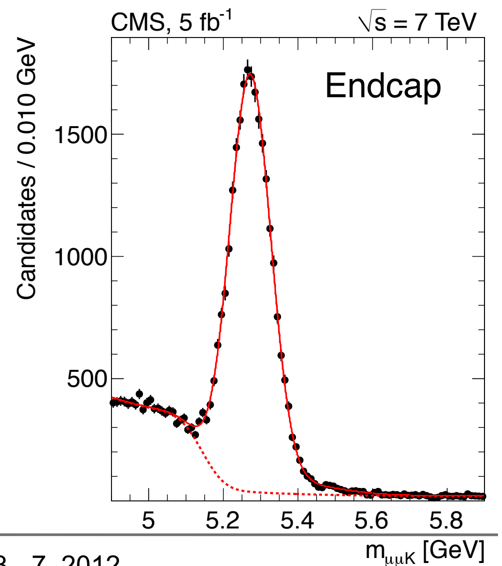




Normalization Channel: $B^{\pm} \rightarrow J/\psi\, K^{\pm}$

- Needed for the extraction of the branching fraction
- Same selections as for signal, plus
  - $3.0 < m(\mu\mu) < 3.2$ GeV
  - $p_T(\mu\mu) > 7$ GeV
  - $p_T(K) > 0.5$ GeV
  - all tracks used in vertexing
- Fit mass pdf:
  - signal: double Gaussian
  - bkg: exponential + error function for $B^0 \rightarrow J/\psi\, K^* \rightarrow \mu^+\mu^- K^-(\pi^+)$ decays
  - estimated syst. error on the event yield: 5%
    - varying bkg, signal pdf
    - mass-constraining dimuons to J/ψ





	Barrel	Endcap
Acceptance	0.162 ± 0.006	0.111 ± 0.006
ε_{tot} (10^{-4})	11.0 ± 0.09	3.2 ± 0.4
N_{obs}	82 712 ± 4146	23 809 ± 1203

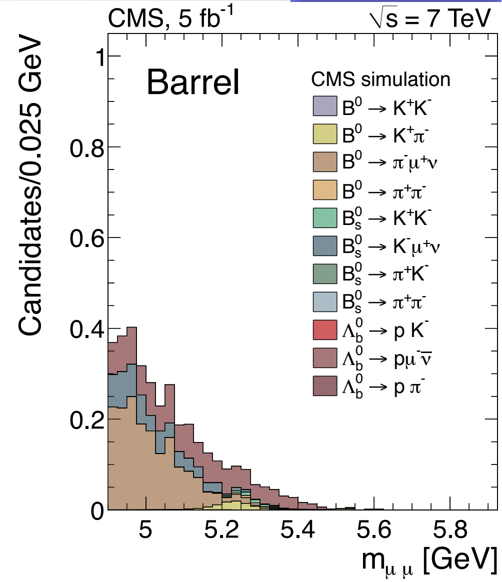
Rare Backgrounds

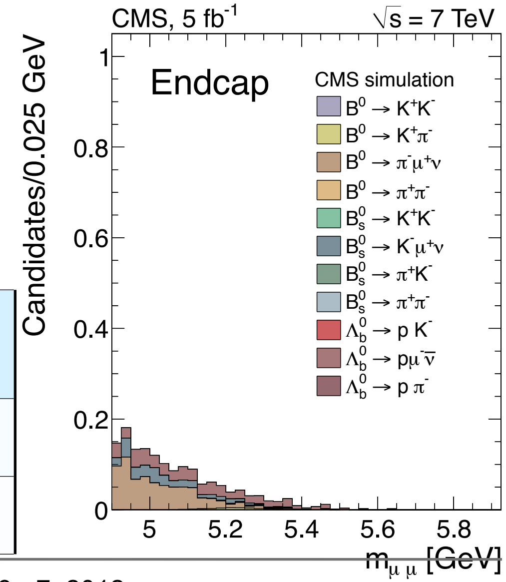
- CKM-suppressed semileptonic decays
  - e.g. $B_s \rightarrow K^- \mu^+ \nu$, with one fake muon (continuous shape)
- Peaking hadronic decays
  - e.g. $B_s \rightarrow K^- K^+$, with two fake muons
- Each channel normalized to $B^\pm$ in data:

$$N(X) = \frac{Br(Y \rightarrow X)}{Br(B^\pm \rightarrow J/\psi K^\pm)} \frac{f_Y}{f_u} \frac{\varepsilon_{tot}(X)}{\varepsilon_{tot}(B^\pm)} N_{obs}(B^\pm)$$

- weighted with muon-misid evaluated from data
- sys errors: branching fractions and f_s/f_u
- Expected events:

Channel	B_d window	B_s window
Barrel	**0.33 ± 0.07**	**0.18 ± 0.06**
Endcap	**0.15 ± 0.03**	**0.08 ± 0.02**





Systematics

Acceptance

- mixture of production processes (gluon fusion, flavor excitation and gluon splitting)
  - bb pairs $\Delta R<0.8$ and $\Delta R>2.4$ in data and MC - half of the difference
  - Also studied variables sensitive to mixture, but not clear indication that the MC mixture is questionable
    - muon vs B candidate: $\Delta R(B, \mu)$, $p_T(\mu)$

Barrel	Endcap
3.5%	5%

Selection efficiency

- from data/MC comparisons

Category	Barrel	Endcap
ε_{tot} (signal)	3%	3%
ε_{tot} (normalization)	4%	4%
kaon tracking	4%	4%

Muon trigger and efficiency

- full variation, for thresholds $4 < p_T < 8$ GeV
- efficiency difference between data and MC

Category	Barrel	Endcap
μ trigger	3%	6%
μ ID	4%	8%

Rare backgrounds

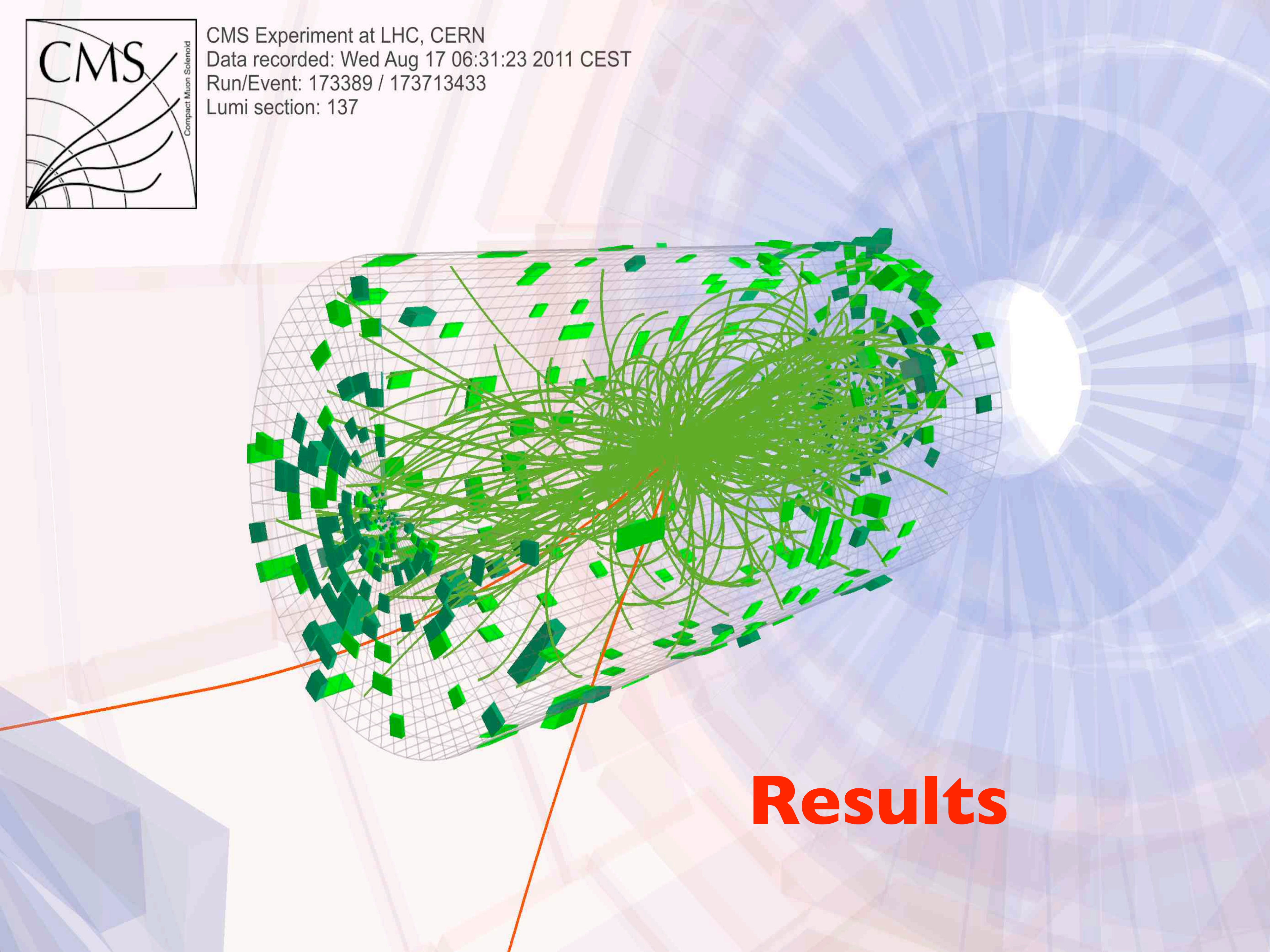
- uncertainties from production cross-section (for B_s and Λ_b), BR and muon mis-id.
  - 20% error for both Barrel and Endcap

Control checks

- **Checking of $BR(B_s \to J/\psi\phi)/BR(B^\pm \to J/\psi K^\pm)$**
  - consistent results with PDG both in barrel and in endcap
  - validate B^+ fitting procedure
  - validate the factorization of the acceptances and efficiencies
- **Inverted isolation sample ($I < 0.7$, not blinded)**
  - comparison of prediction vs. observation
    - validation of rare backgrounds
    - background interpolation
- **Stability vs. time (HLT changes)**
  - yields (dimuons, normalization and control sample)
  - yield ratios

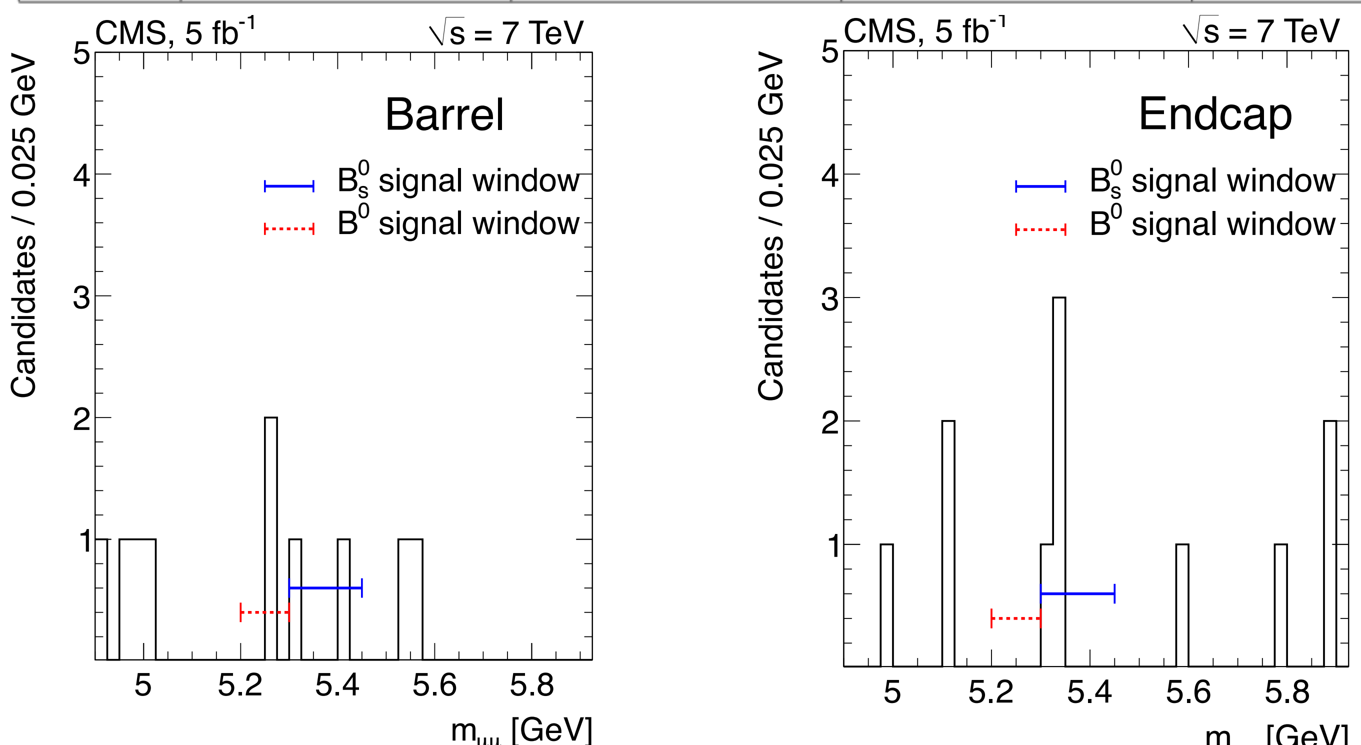
- **All checks performed give us confidence that the result is robust**

Results


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Wed Aug 17 06:31:23 2011 CEST
Run/Event: 173389 / 173713433
Lumi section: 137

Unblinded results

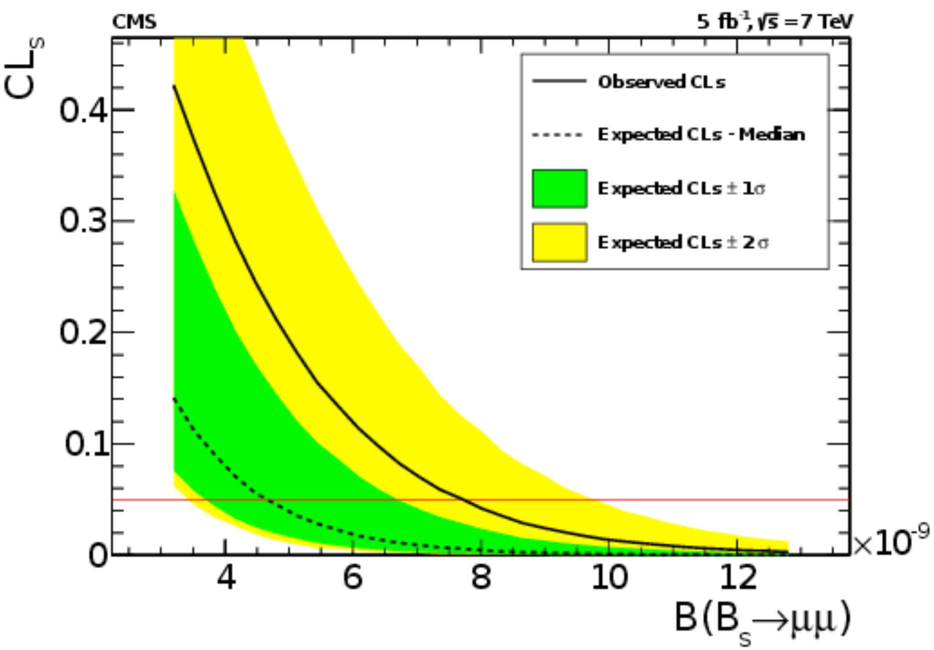
Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B_s^0 \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B_s^0 \to \mu^+\mu^-$ Endcap
$\varepsilon_{\mathrm{tot}}$	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
$N_{\mathrm{signal}}^{\mathrm{exp}}$	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
$N_{\mathrm{peak}}^{\mathrm{exp}}$	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
$N_{\mathrm{comb}}^{\mathrm{exp}}$	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
$N_{\mathrm{total}}^{\mathrm{exp}}$	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
N_{obs}	2	2	0	4



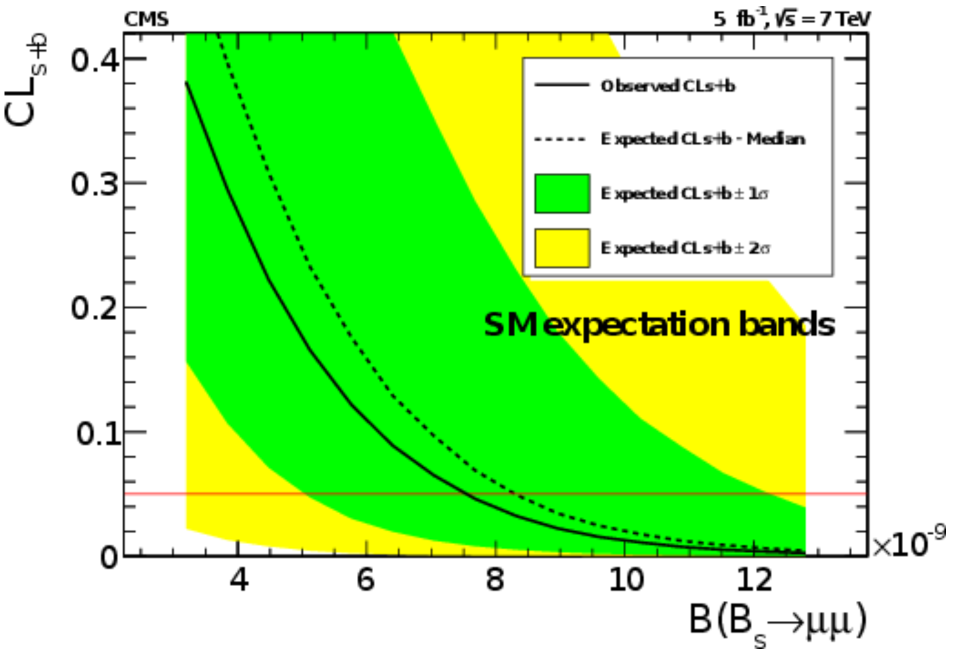
Upper limits

Decay	Expected (95% CL)	Observed (95% CL)	Background-only p-value
$B_s \to \mu\mu$	8.4×10^{-9}	**7.7×10^{-9}**	0.11 (1.2 σ)
$B_d \to \mu\mu$	1.6×10^{-9}	**1.8×10^{-9}**	0.24 (0.7 σ)

Bkg only hypothesis



Bkg + SM hypothesis



Searching for the rarest birds

$D^0 \rightarrow \mu^+\mu^-$

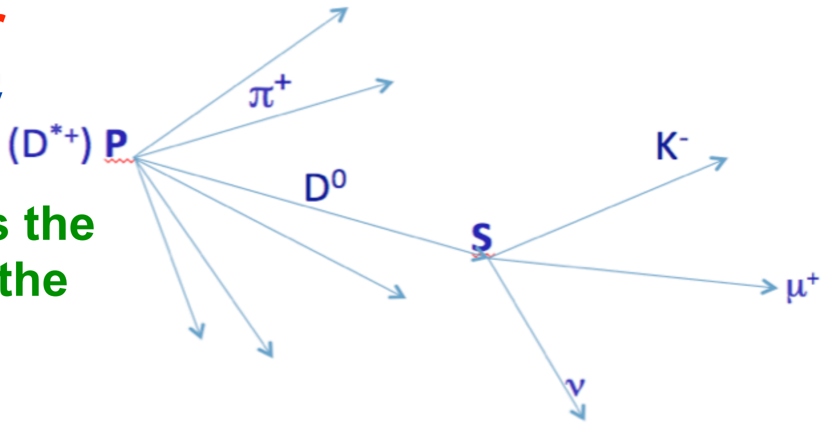
CMS-PAS-BPH-11-017

$D^0 \to \mu\mu$ search strategy

- **The strategy of the analysis is to measure the ratio of the branching ratios**
  - $D^{*+} \to D^0(\mu^+\mu^-)\pi^+ / D^{*+} \to D^0(K^-\mu^+\nu)\pi^+$

  so as to cancel most of the systematic uncertainties
  - The semileptonic decay mode minimizes the differences between the two decay modes and reduces the uncertainties in the trigger efficiencies. Other topologically similar hadronic topological decays - such as $D^0 \to \pi\pi$ - are not feasible in CMS
  - The detection of double μ is doable in CMS, but the real problem is the normalization channel - that has a single muon trigger

- **Decay modes are topological similar**
  - Determination of primary and secondary vertices
    - $D^{*+} \to D^0(K^-\mu^+\nu)\pi^+$ reconstruction uses the sufficiently precise measurement of the D^0 direction.

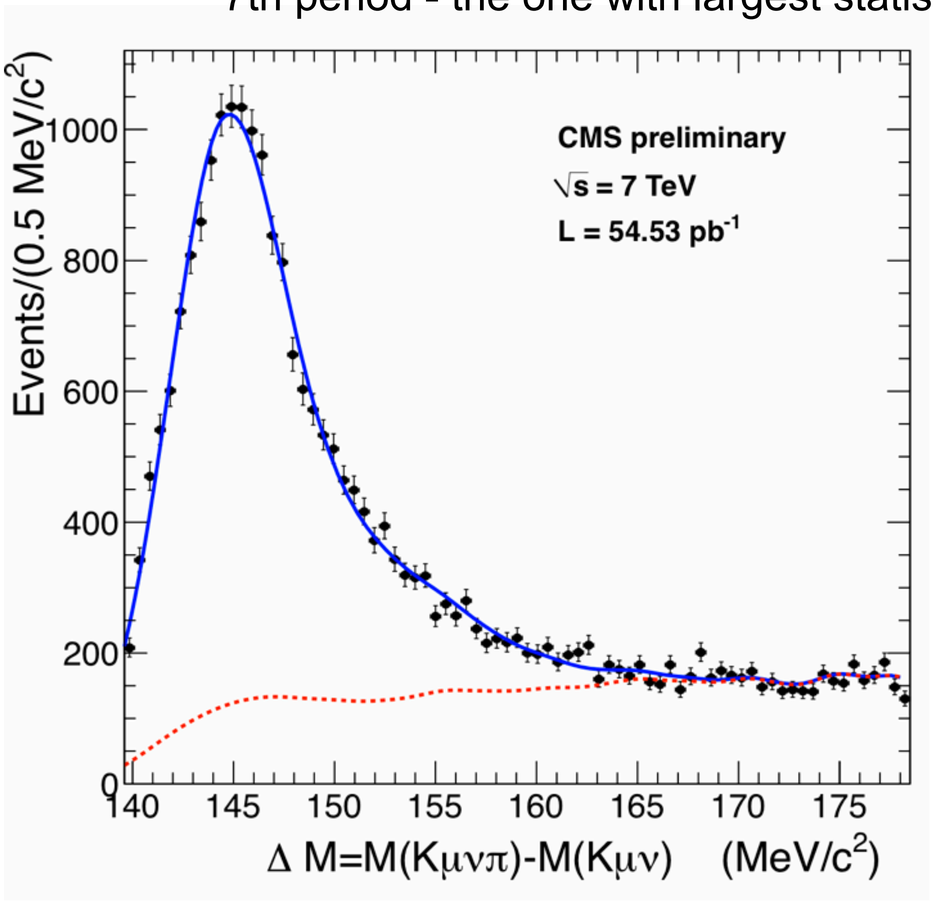


Topological analysis

- Very tight cuts on muons identification and kaon reconstruction
- Trigger events using the same single muon trigger
  - Seven different periods of data taking in 2010 and 2011, single-muon p_T trigger thresholds, from 3 GeV to 15 GeV. 90 pb^{-1} in total
    - Bulk of the data with $p_T(\mu)$ > 15 GeV (54 pb^{-1})
- Reconstruct a D^{*+} by pairing candidate D^0 candidates with π_{soft} from primary vertex
- Secondary Vertex CL > 1%
- Require
  - $D^0(\mu\mu)$ pointing to the primary vertex
  - L/σ >3

$D^{*+} \rightarrow D^0(K^-\mu^+\nu)\pi^+$ analysis

7th period - the one with largest statistics



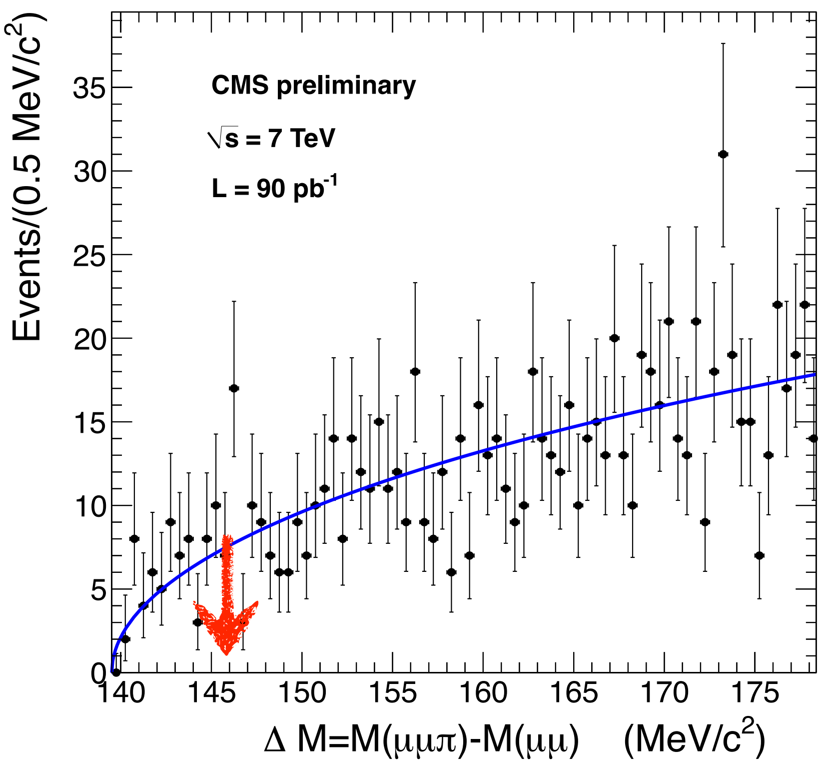
Unbinned ML fit to the mass difference

Two Gaussian functions + combinatorial shape (from the wrong sign sample)

$$\text{Yield}(D^{*+} \rightarrow D^0(K^-\mu^+\nu)\,\pi^+) = 16458 \pm 204 \ \text{candidates}$$

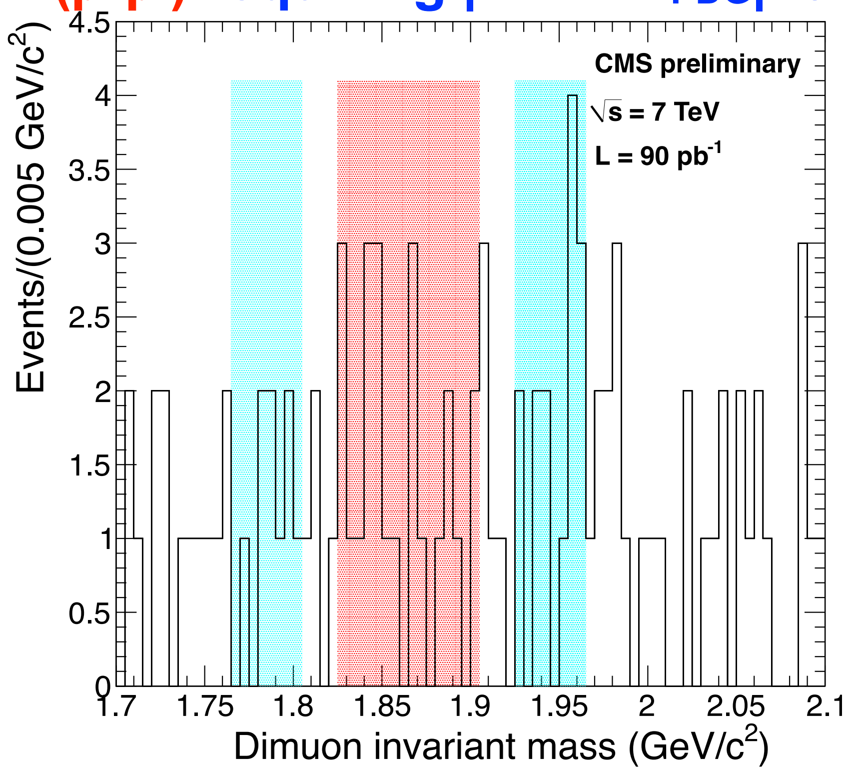
$D^{*+} \rightarrow D^0(\mu^+ \mu^-)\pi^+$ analysis

$D^{*+} \rightarrow D^0(\mu^+\mu^-)\pi^+$



Background function (ΔM)=P3×[$(\Delta M - M_\pi)^{1/2}$ + P4×$(\Delta M - M_\pi)^{3/2}$]

$M(\mu^+\mu^-)$ requiring $|\Delta M - \Delta M_{PDG}| < 3$ MeV



N_{obs} = 23 events (signal region)

N_{bkg} = 23 events (sidebands)

No evidence of $D^0 \rightarrow \mu^+\mu^-$ in D* decays

Upper limits

$$B(D^0 \to \mu^+\mu^-) \leq B(D^0 \to K^-\mu^+\nu) \times \frac{N(\mu\mu)}{N(K\mu\nu)} \times \frac{a(K\mu\nu)}{a(\mu\mu)} \times \frac{\epsilon_{trig}(K\mu\nu)}{\epsilon_{trig}(\mu\mu)} \times \frac{\epsilon_{rec}(K\mu\nu)}{\epsilon_{rec}(\mu\mu)}$$

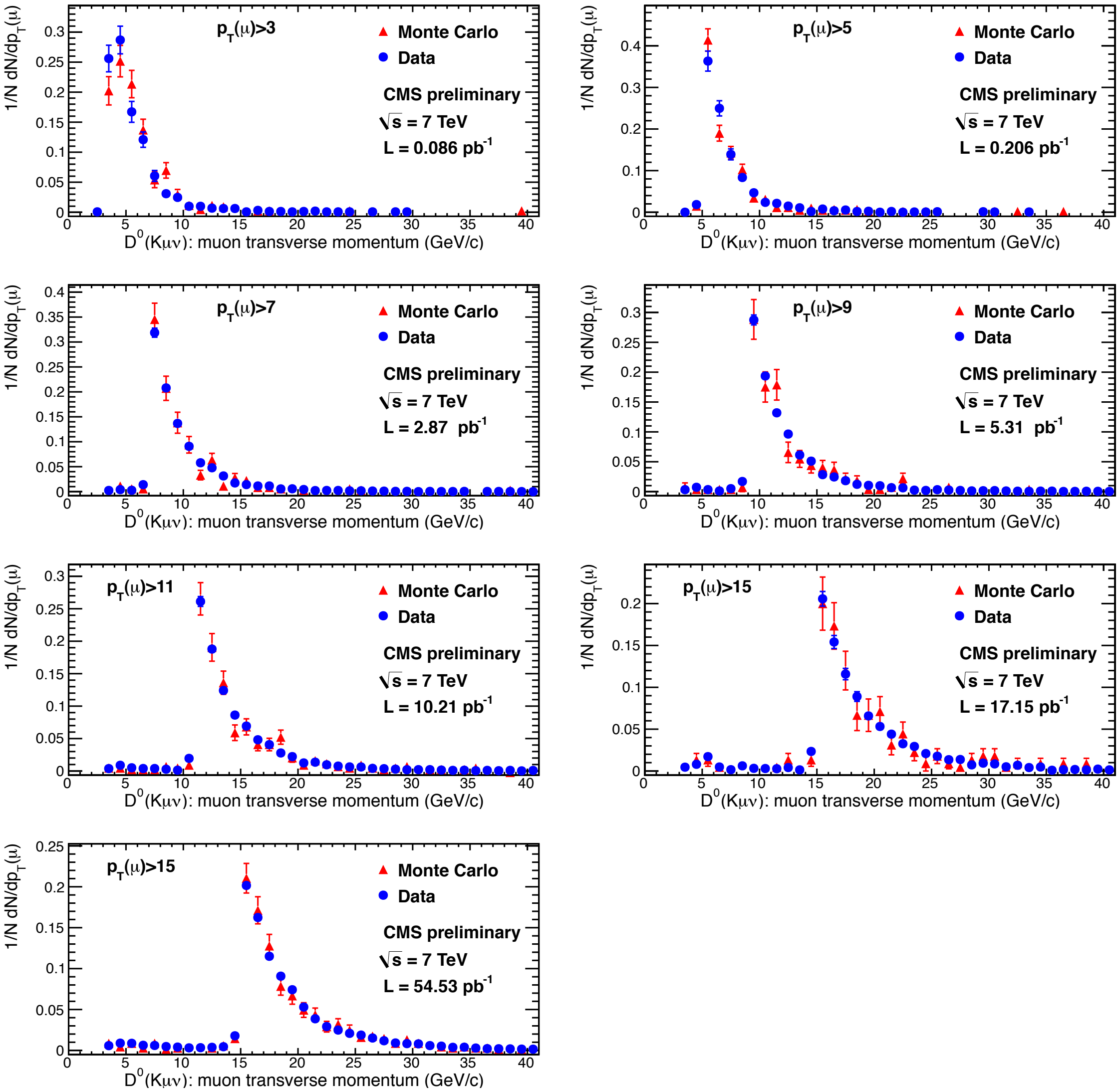
- $B(D^0(K^-\mu^+\nu))$ from PDG
- Ratio of acceptances and efficiencies from Monte Carlo simulation
  - The efficiency is validated using data by checking that the efficiency corrected yields in different periods of data taking do not depend on the different HLT triggers, at the level of 13.1%
  - Uncertainty from the fitting function range from 1% to 9% in different run periods
  - Contamination from $D^0 \to K^*(K^-\pi^0)\mu^+\nu$ 1.8%

$$B(D^0 \to \mu^+\mu^-) \leq 5.4 \times 10^{-7} (90\% \, CL)$$

Although this measurement is not the best limit, it is the first with a semileptonic channel used as normalization

Experiment	Upper limit at 90% CL
BABAR [13]	$< 1.3 \times 10^{-6}$
CDF [14]	$< 2.1 \times 10^{-7}$
BELLE [15]	$< 1.4 \times 10^{-7}$
this measurement	$< 5.4 \times 10^{-7}$

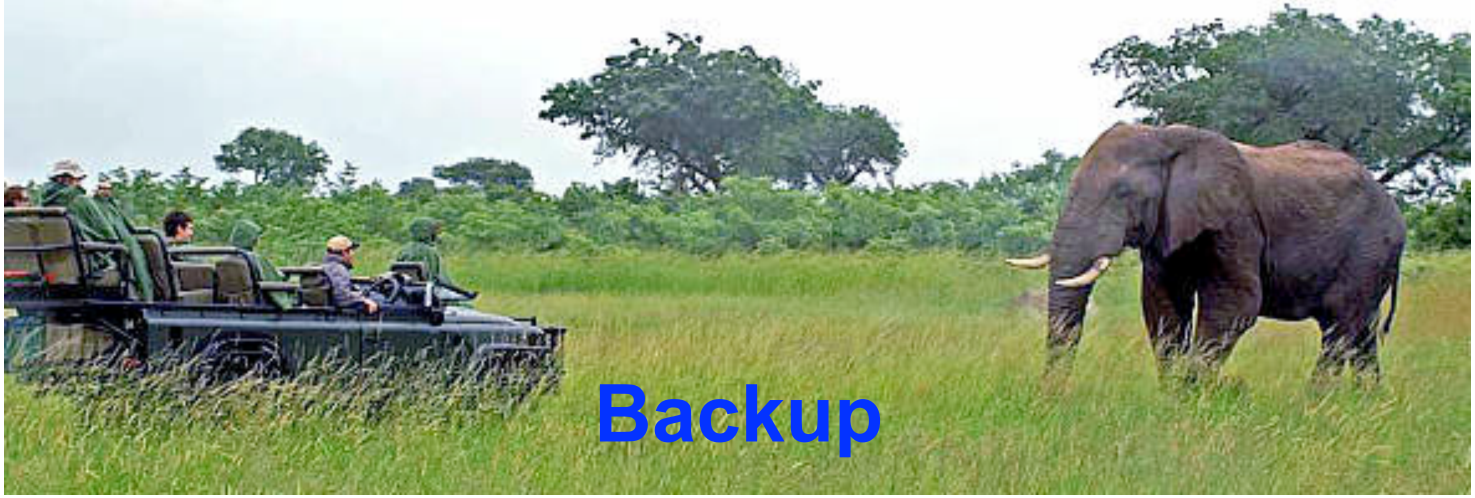
Comparison data/mc



Good agreement between Data and MC simulation for all 7 periods with different single-μ p_T trigger thresholds

Conclusions

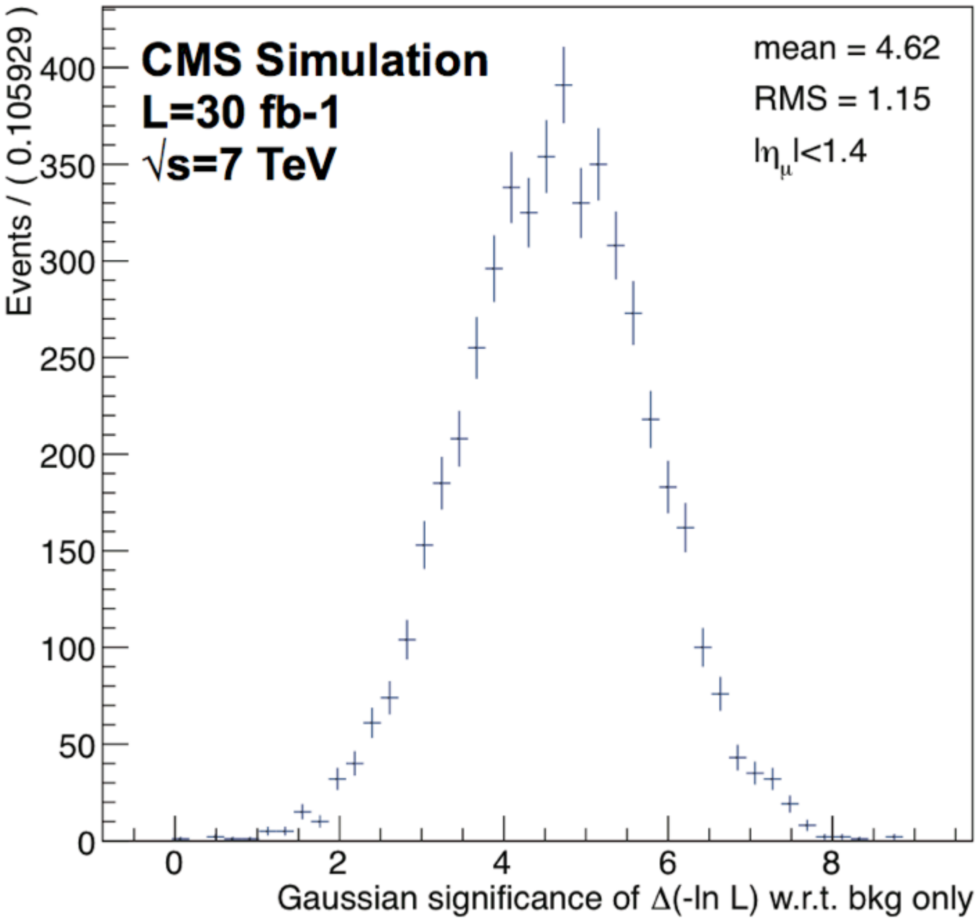
- **We have looked for rare decays of $B_{s/d}$ and D^0 mesons decaying into $\mu^+\mu^-$ in CMS in pp collisions at $\sqrt{s}$= 7 TeV**
  - The data sample corresponds to an integrated luminosity of 5 fb^{-1} in 2011 for Beauty mesons, and to 90 pb^{-1} for Charm.
  - The $B_{d/s} \rightarrow \mu^+\mu^-$ result supersedes our previous measurements and gives a 95% CL upper limit of 7.7×10^{-9} for B_s and 1.8×10^{-9} for B_d
    - Stricter selection requirements are applied resulting in a better sensitivity and a higher signal-to-background ratio
  - The $D^0 \rightarrow \mu^+\mu^-$ is normalized to $D^0 \rightarrow K^-\mu^+\nu$ decay mode, giving 5.4×10^{-7} upper limit at 90% CL
    - The main limitation in the analysis relies on the efficiency of the normalization sample
- **With the luminosity to be collected by the end of the 2012 LHC run (a factor 5 more than the current one), we will be able to tackle the $B_{s/d}$ Standard Model predicted BR and either establish or exclude it.**


Backup

Projected CMS sensitivity on $B_s \to \mu\mu$

- Extrapolation based on the 5 fb^{-1} search
- Barrel region only ($|\eta|<1.4$)
- Assuming SM branching ratio corrected for Bs mixing effects:

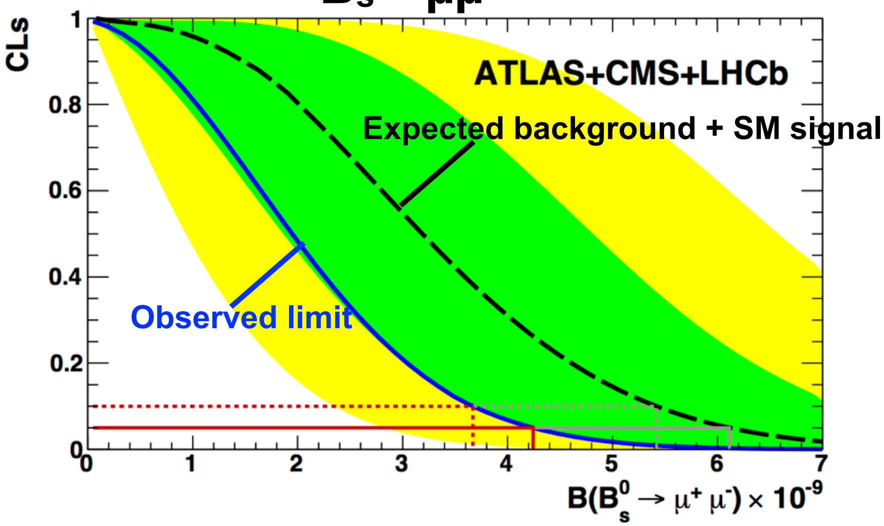
  $Br(B_s \to mm)=3.5\times10^{-9}$



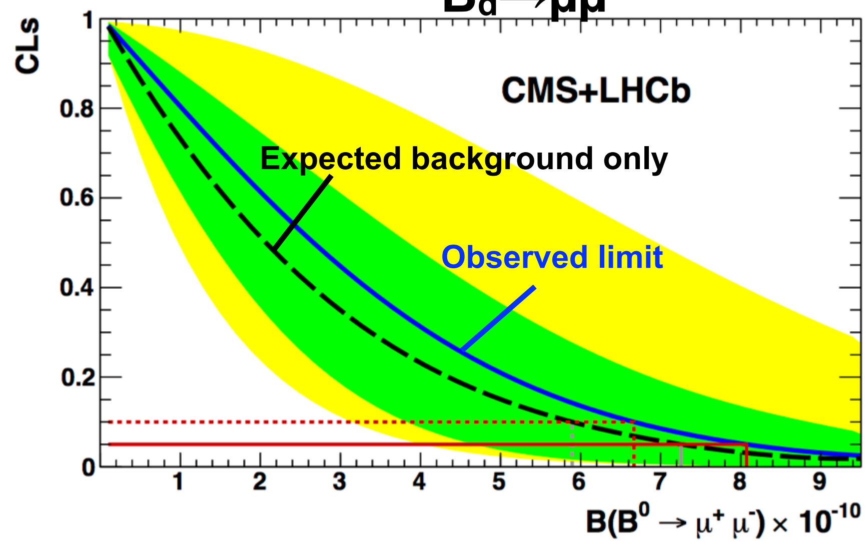
LHC combination

- **ATLAS, CMS and LHCb searches combined into a single limit**
  - Use CL_S method
  - Normalized to $B^{\pm} \rightarrow J/\psi K^{\pm}$ for ATLAS and CMS
  - $f_s/f_u = 0.267 \pm 0.021$ from LHCb

$B_s \rightarrow \mu\mu$

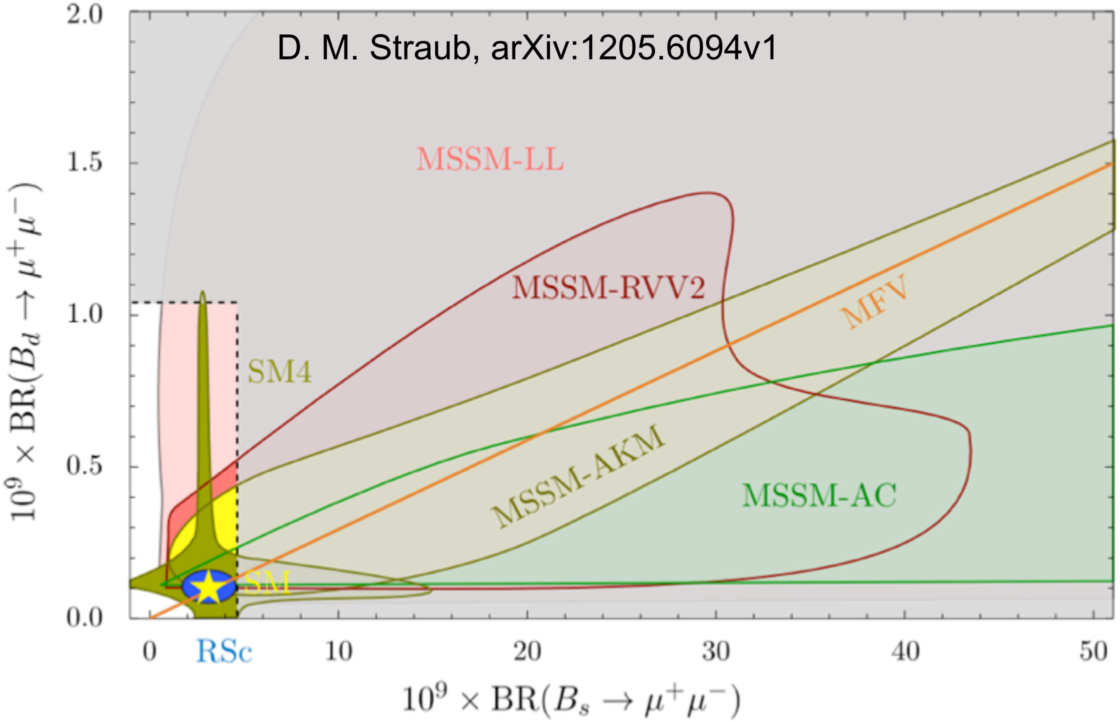


$B_d \rightarrow \mu\mu$



Exclusion bounds on New Physics

95% CL CL_s exclusion bounds



Selection cuts on $B_s \rightarrow \mu\mu$

Random grid optimization

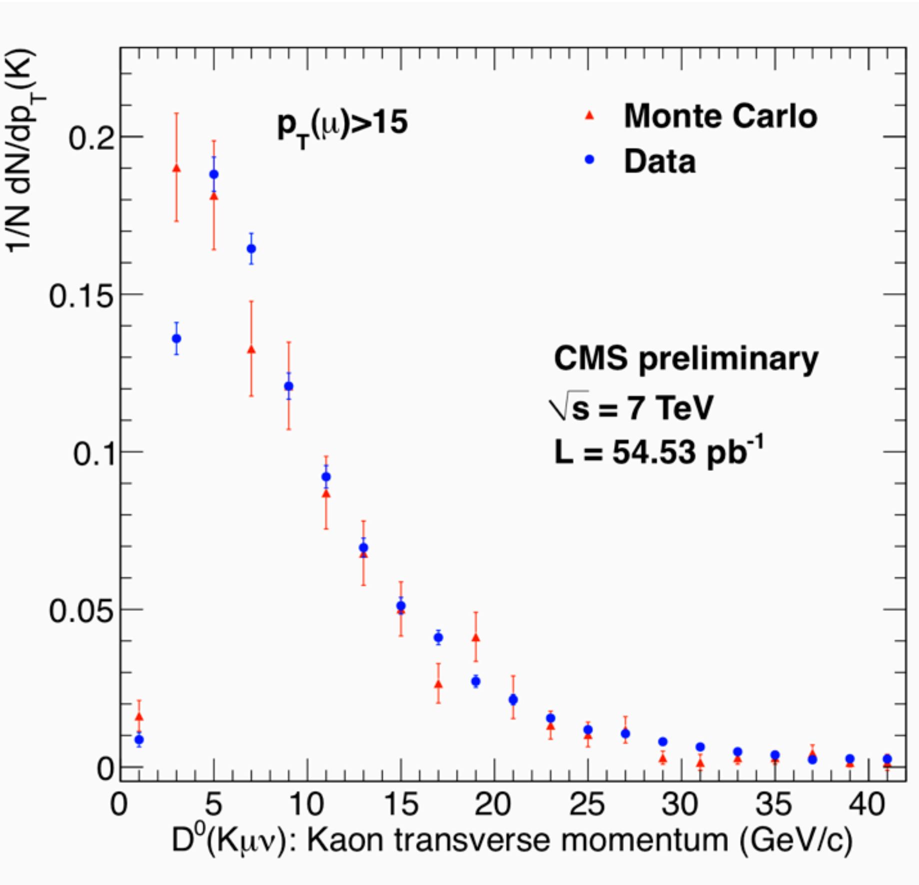
14 variables included in 1.4×10^6 runs

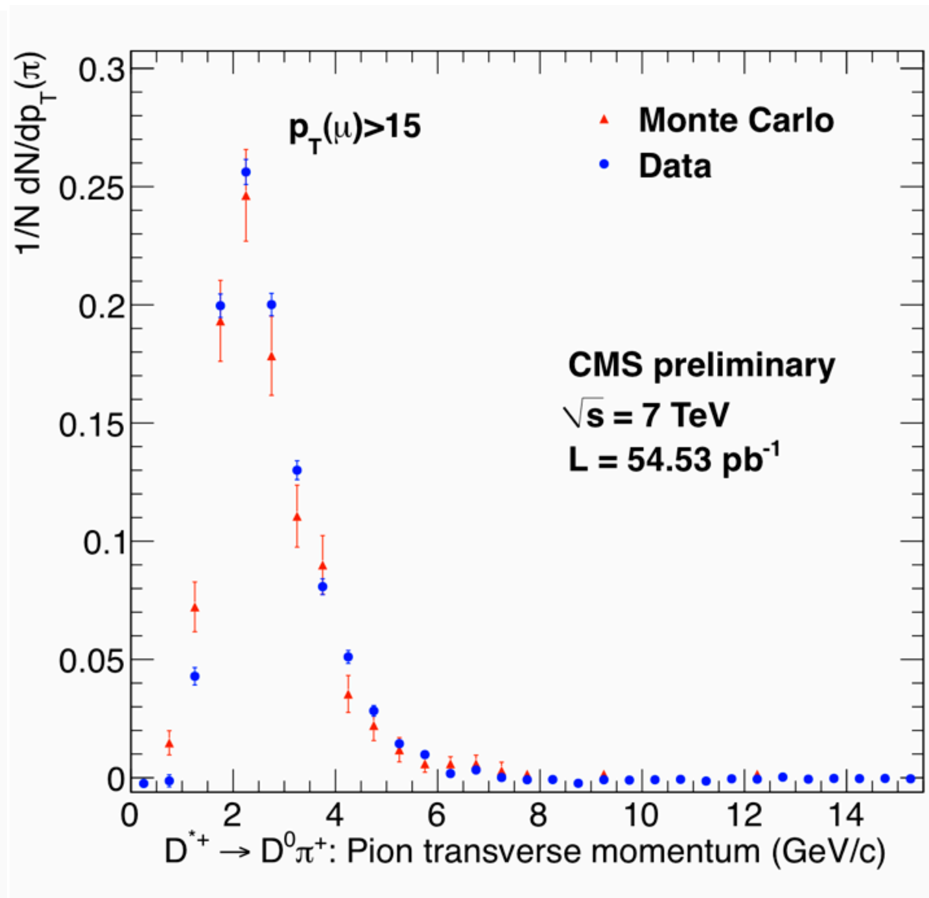
Variable	Barrel	Endcap	units
$p_{T\,\mu,1} >$	4.5	4.5	GeV
$p_{T\,\mu,2} >$	4.0	4.2	GeV
$p_{T\,B} >$	6.5	8.5	GeV
$\delta_{3D} <$	0.008	0.008	cm
$\delta_{3D}/\sigma(\delta_{3D}) <$	2.000	2.000	
$\alpha <$	0.050	0.030	rad
$\chi^2/\mathrm{dof} <$	2.2	1.8	
$\ell_{3d}/\sigma(\ell_{3d}) >$	13.0	15.0	
$I >$	0.80	0.80	
$d^0_{\mathrm{ca}} >$	0.015	0.015	cm
$N^{\mathrm{close}}_{\mathrm{trk}} <$	2	2	tracks

Systematics on B_s

Systematics	Barrel	Endcap
f_s/f_u uncertainty	8%	8%
acceptance	3.5%	5%
mass scale & resol.	3%	3%
Bs efficiency	3%	3%
$B^+ \rightarrow J/\psi K^+$ efficiency	4%	4%
K tracking efficiency	4%	4%
Trigger efficiency	3%	6%
Muon Id	4%	8%
$B^+ \rightarrow J/\psi K^+$ mass fit pdf	5%	5%
Background shape	4%	4%
Rare decays background	20%	20%

Comparison Data/MC $D^0 \to \mu\mu$





$D^0 \to \mu\mu$ systematics

Trigger	$\epsilon_{trig}(K\mu\nu)/\epsilon_{trig}(\mu\mu)$	$\epsilon_{rec}(K\mu\nu)/\epsilon_{rec}(\mu\mu)$	$Y(D^0 \to K^-\mu^+\nu)$	N_{obs}, N_{bkg}	Systematic uncertainty
HLT_Mu3	0.149 ± 0.002	2.215 ± 0.197	2412 ± 145	0, 0	19.1%
HLT_Mu5	0.112 ± 0.002	1.651 ± 0.128	2447 ± 357	1, 0	18.0%
HLT_Mu7	0.102 ± 0.003	1.268 ± 0.152	11799 ± 215	6, 4	19.0%
HLT_Mu9	0.099 ± 0.003	1.018 ± 0.097	9982 ± 176	6, 6	17.4%
HLT_Mu11	0.097 ± 0.003	0.947 ± 0.069	10079 ± 185	3, 5	16.4%
HLT_Mu15 (2010)	0.085 ± 0.003	0.844 ± 0.088	5302 ± 118	1, 3	17.9%
HLT_Mu15 (2011)	0.087 ± 0.002	0.814 ± 0.048	16458 ± 204	6, 5	15.6%