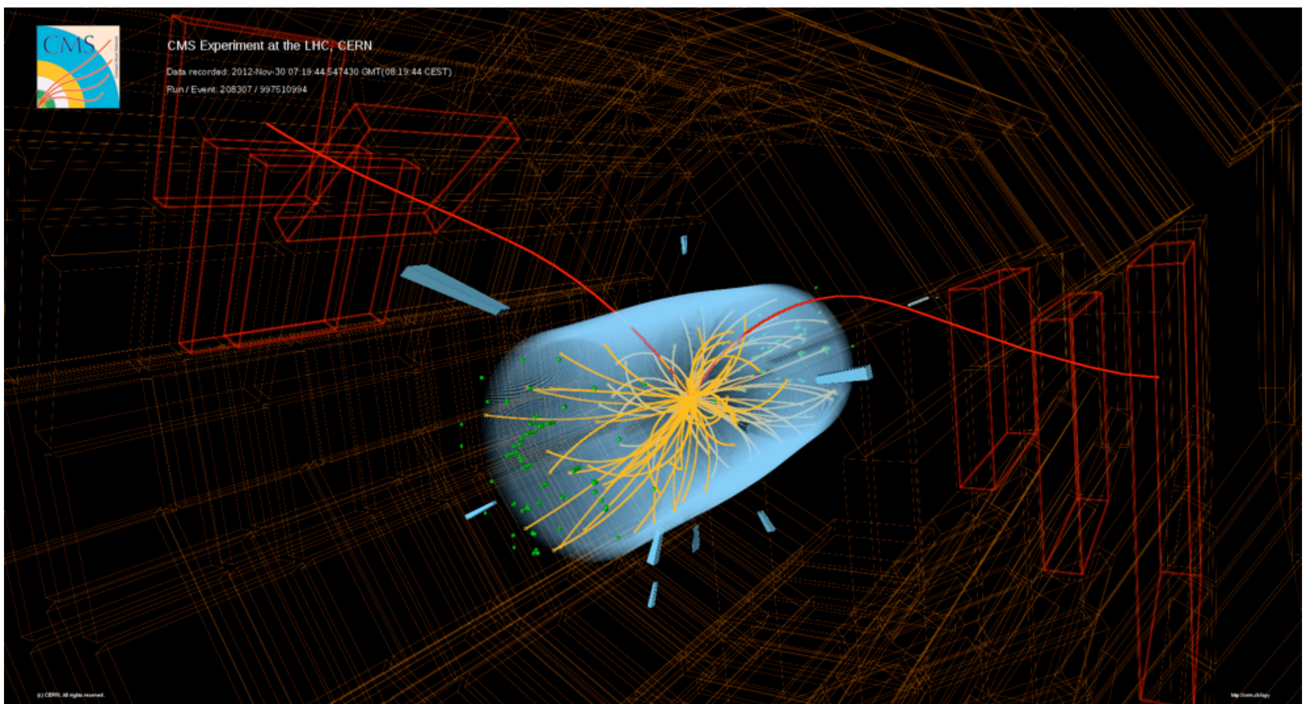
The Undefeated and Triumphant Standard Model of Particle Physics

Observation of Rare $B_s \rightarrow \mu\,\mu$ Decay



M. Baarmand
Oct. 10, 2013

A Standard Model

- A SM is a theoretical framework built from and consistent with all relevant available observations, which predicts new testable phenomena…
  - must be self-consistent and consistent with all relevant data
  - must have predictive power
  - must be "simple" and "elegant"

. Examples:

Ptolemy's epicycles for planets: predicted Paths of the Planets

Keppler's mechanics of planets: simplified/improved dramatically on the above!

Newton's mechanics: gave a deep understanding in terms of Gravity

Mendeleev's periodic table: deeper understanding of Chemistry

Einstein's STR: an "improvement" on Newtonian relativity!

Bohr model of atom

Synapse/neuron structure of brain

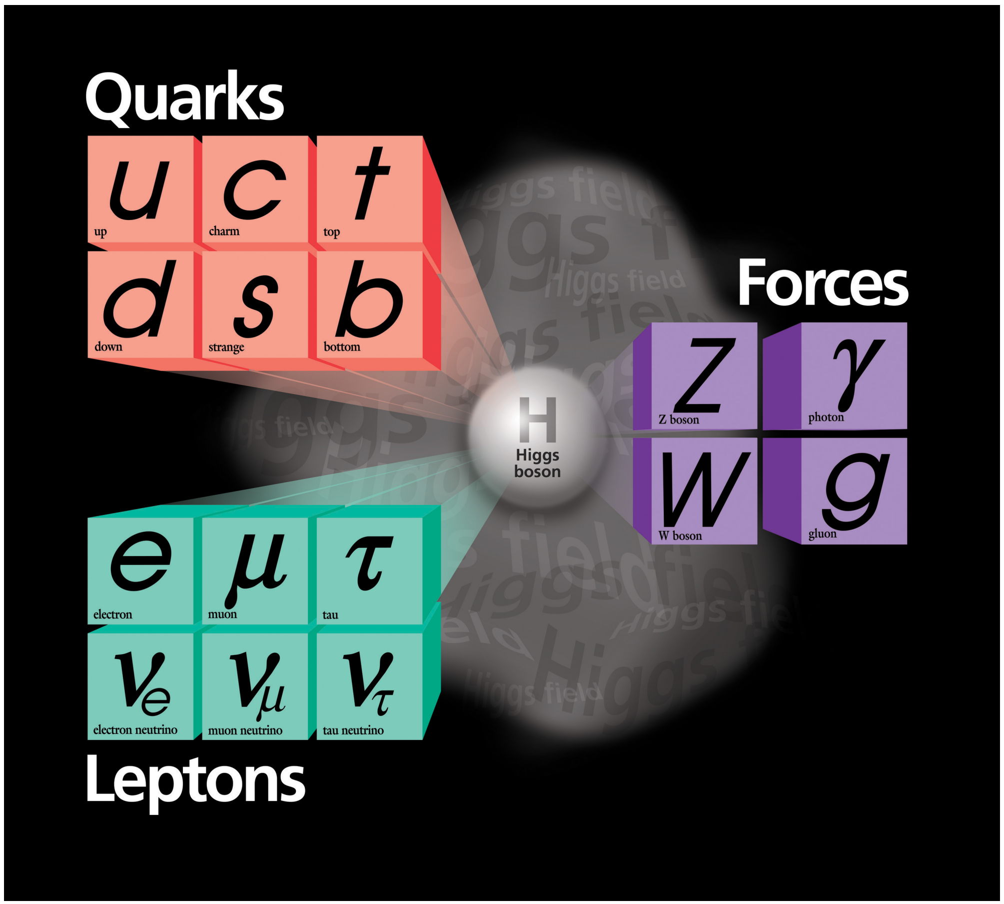
- As a larger realm is explored, a SM may need revision

The Standard Model of Particle Physics

A Crowning Achievement of 20th Century Science

Quantum Mechanics and Special Theory of relativity along with elementary particles discovered have led to the Standard Model of Particle Physics: Modern-day "Periodic Table" of fundamental particles and their interactions.

Matter particles



Force particles

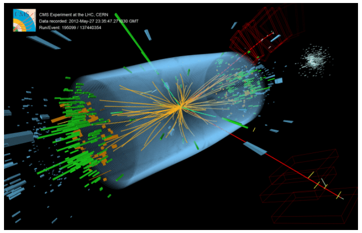
Over the past 50 years the SM has been tested to excellent precision.

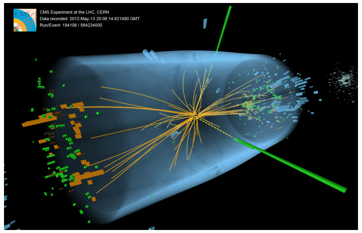
NB: Gravity not included!

Experimental Evidence for SM

- DIS experiments - existence of quarks
  SLAC 1972-73
- Observation of charm and bottom quarks
  SLAC, BNL, FNAL 1974-80
- Observation of neutral currents (Z boson exchange)
  CERN 1973
- Observation of jets and 3 jet final states (gluon radiation)
  DESY 1979-80
- Direct observation of W and Z bosons
  CERN 1983
- Direct observation of top quark
  FNAL 1995
- Direct observation of tau lepton
  FNAL 2000
- Observation of Higgs boson
  CERN 2012

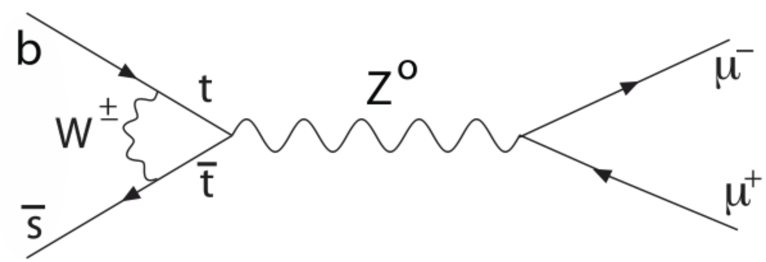
Several Nobel prizes!

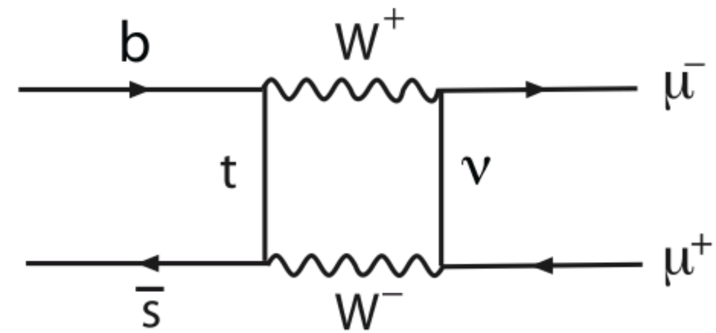




Most Recent Test of SM

- SM predicts a tiny branching fraction for $B_s \to \mu^+ \mu^-$
  - $BR^{t=0}(B_s \to \mu\mu) = (3.25 \pm 0.17) \times 10^{-9}$ [A. Buras et al. arXiv:1303.3820]
  - $BR^{\langle t \rangle}(B_s \to \mu\mu) = (3.56 \pm 0.18) \times 10^{-9}$ time-integrated measured [De Bruyn et al. (PRL 109, 041801)] [A. Buras et al. arXiv:1303.3820]
  - forbidden at tree level, only through higher-order loop diagrams
  - helicity suppressed

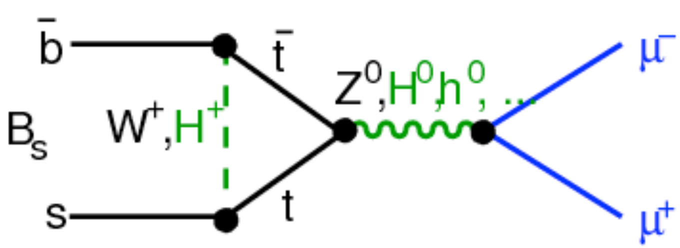


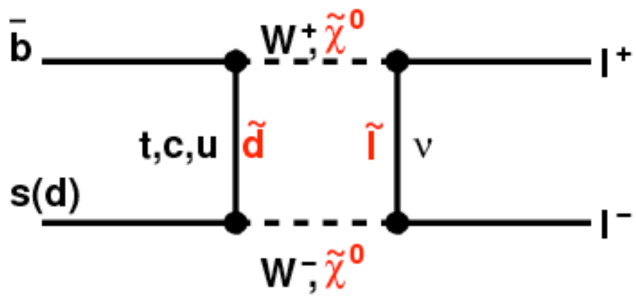


- Even smaller branching fraction for $B_d \to \mu^+ \mu^-$
  - $BR^{t=0}(Bd \to \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$
  - Cabibbo suppressed due to |Vtd|<|Vts|

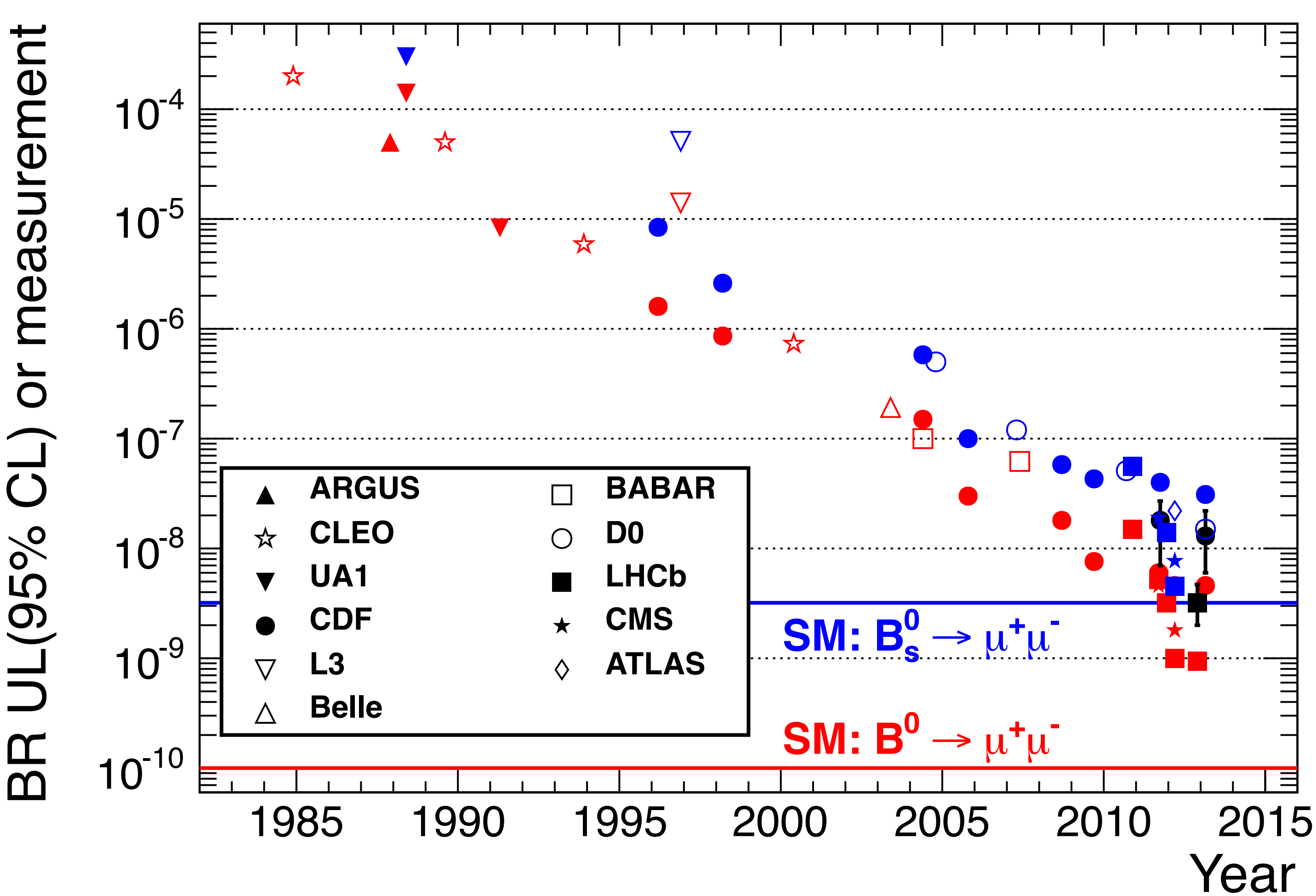
Motivation: Physics Beyond SM

- $B_s \to \mu^+ \mu^-$ and $B_d \to \mu^+ \mu^-$ sensitive probes for BSM physics
  - 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
  - 4th generation top
    - Wei-Shu Hou, Masaya Kohda, Fanrong Xu, Phys. Rev. D87, 094005 (2013)





25-year Quest for Rare B_s Decay



LHCb 3.5 σ evidence: $\mathrm{BR}(B_S \to \mu\mu) = \left(3.2^{+1.4}_{-1.2}\ (\mathrm{stat})^{+0.5}_{-0.3}\ (\mathrm{syst})\right) \times 10^{-9}$

Best until now

ATLAS+CMS+LHCb: $\mathrm{BR}(B_d \to \mu\mu) < 8.4 \times 10^{-10}$ @95% CL

Muon Trigger and Reconstruction

Muon Detectors

DT, CSC, RPC

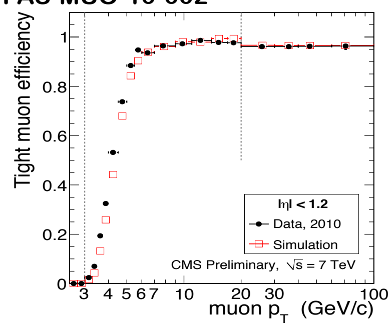
Large coverage $|\eta_\mu|<2.4$

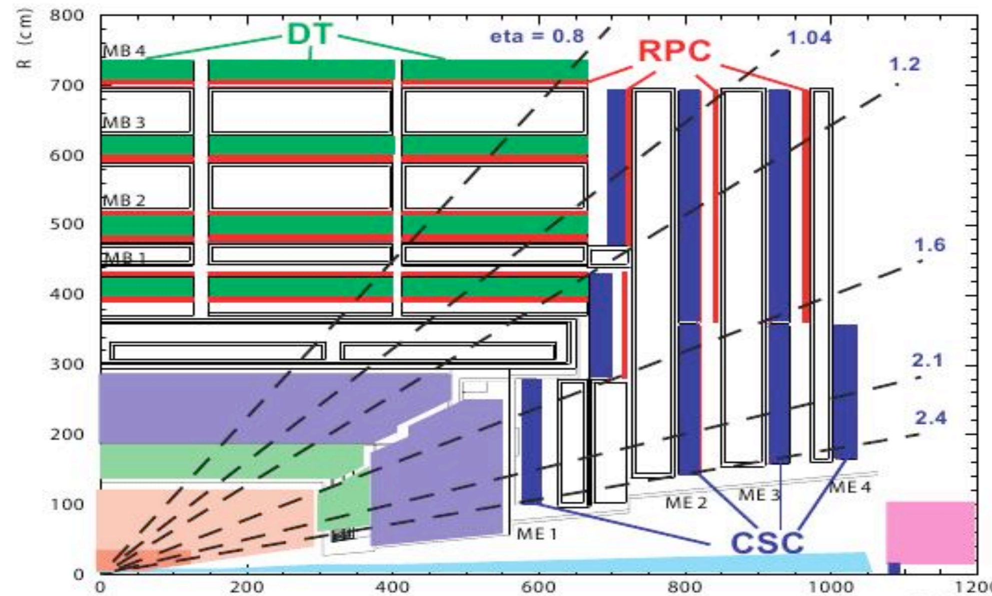
Excellent p_T resolution ≈ 1%

μ candidate: match between muon segments and silicon track

μ reconstruction efficiency ≈99%

CMS-PAS-MUO-10-002





L1

μ p_T> 3 GeV

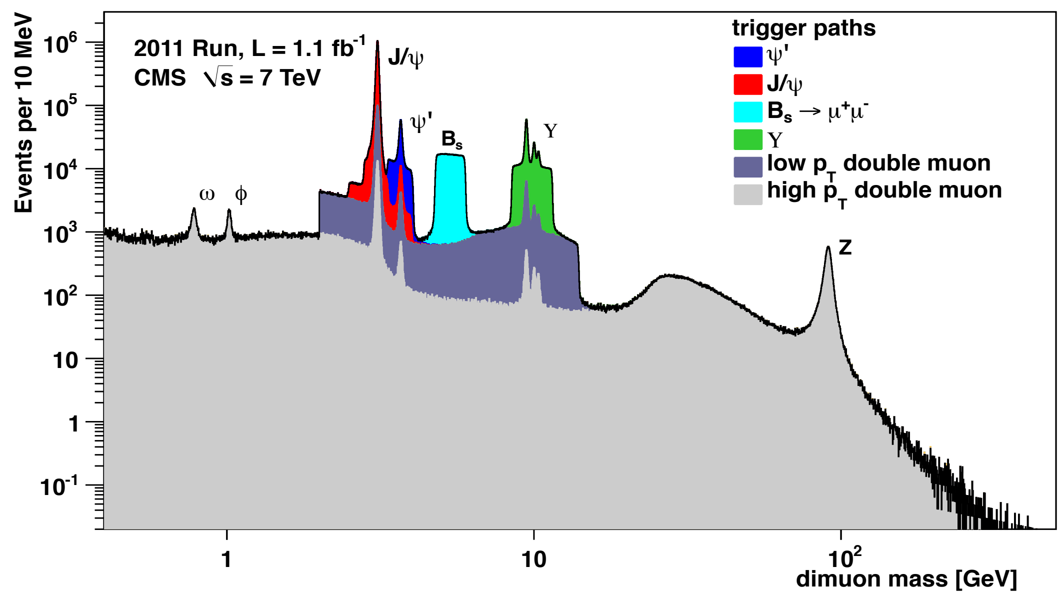
HLT $B_s \to \mu\mu$

μ,μ p_T> 3,4 GeV $|\eta_{\mu\mu}|<1.8$

μ,μ p_T> 4,4 GeV $1.8<|\eta_{\mu\mu}|<2.2$

p_T ($\mu\mu$) > 5 GeV

4.8 < m($\mu\mu$) < 6.0 GeV



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Analysis Overview

- Blind analysis of data samples
  - 5 fb^{-1} at √s=7 TeV in 2011
  - 20 fb^{-1} at √s=8 TeV in 2012

Region definitions	Invariant mass (GeV)
overall window	4.90 mμ1μ2 5.90
blind window	5.20 mμ1μ2 5.45
$B^0 \rightarrow \mu+\mu-$ window	5.20 mμ1μ2 5.30
$B_s \rightarrow \mu+\mu-$ window	5.30 mμ1μ2 5.45

- Unbinned maximum likelihood fit to *μμ* mass and discriminant

- Normalization sample: $B^{\pm} \rightarrow J/\psi\, K^{\pm} \rightarrow (\mu^+\mu^-)\, K^{\pm}$
  - avoid uncertainties in b production cross section
  - eliminate need for luminosity measurement
  - mitigate effects of uncertainties in efficiencies

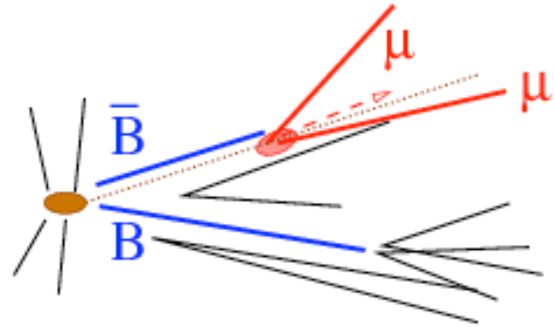
$$Br\left(B_s^0 \rightarrow \mu^+\mu^-\right) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} Br\left(B^+\right)$$

- Control sample: $B_s \rightarrow J/\psi\, \varphi \rightarrow (\mu+\mu-)(K^+K^-)$ validate B_s in data and simulations

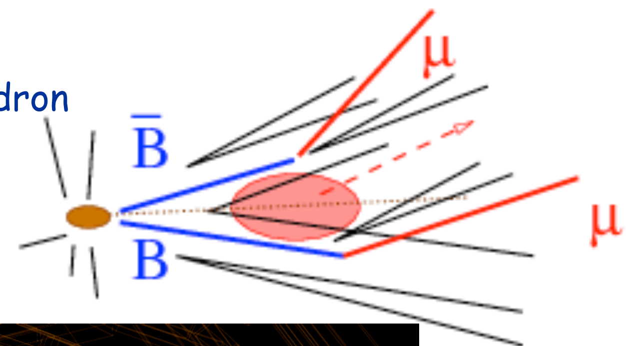
- Divide the data sample in two main categories for each year:
  - *μμ* in the barrel (|η|<1.4) ➨better sensitivity, B_s mass resolution ≈ 40 MeV
  - ≥1 *μ* in the endcap ➨more events but B_s mass resolution ≈ 60 MeV

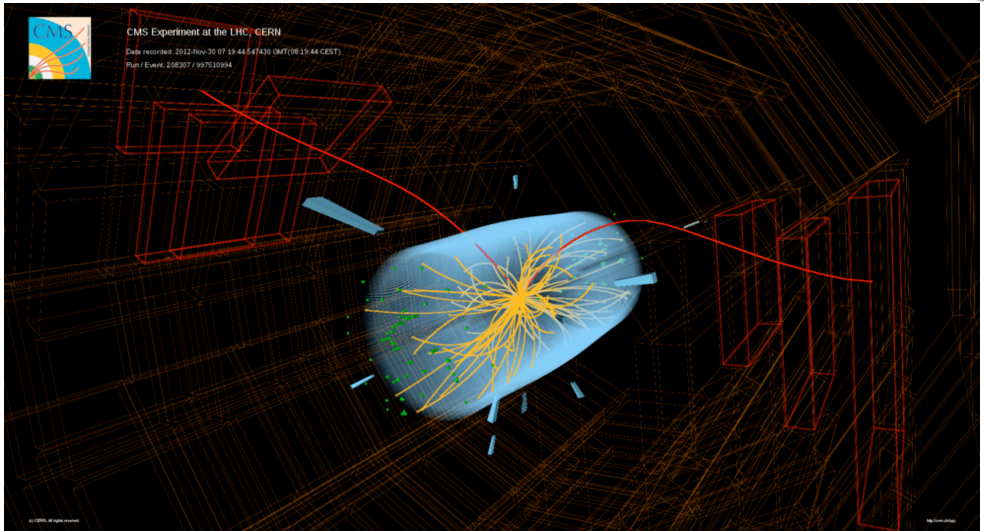
Event Characteristics

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

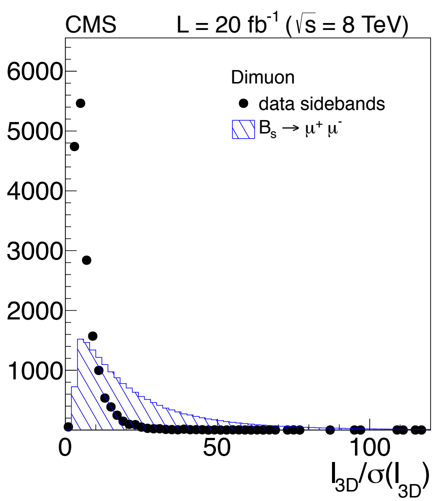


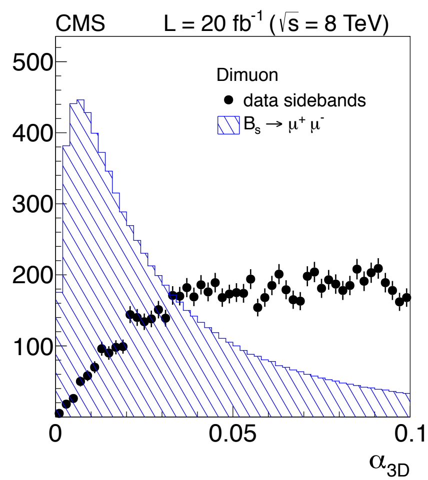
- Backgrounds:
  - two semileptonic B decays
  - one semileptonic B decay and one misidentified hadron
  - Single B decays:
    - peaking (ex. $B_s \rightarrow K^- K^+$)
    - rare semileptonic (ex. $\Lambda_b \rightarrow p\mu\nu$)

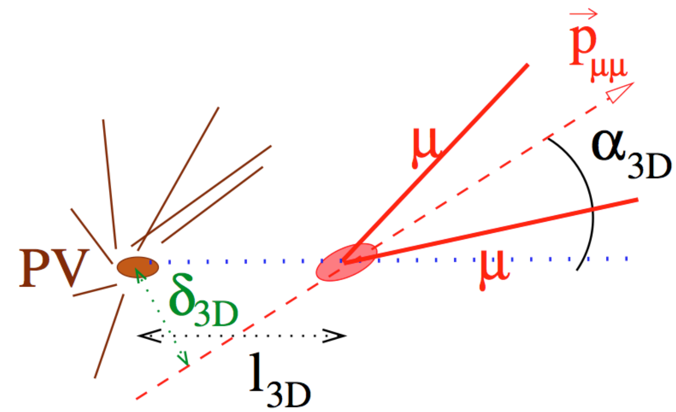


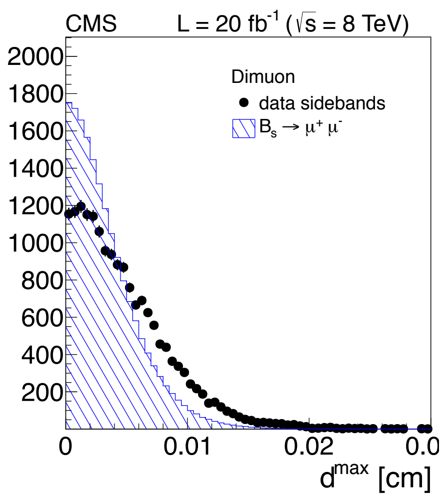


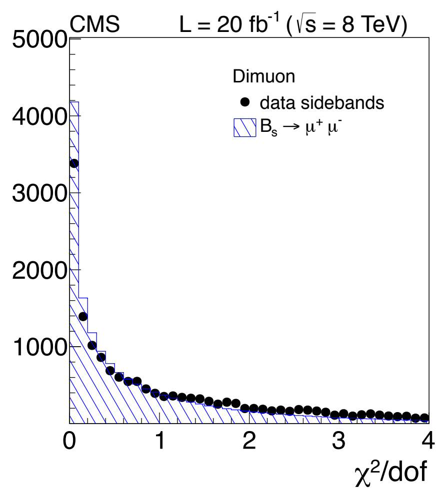
Vertex Variables

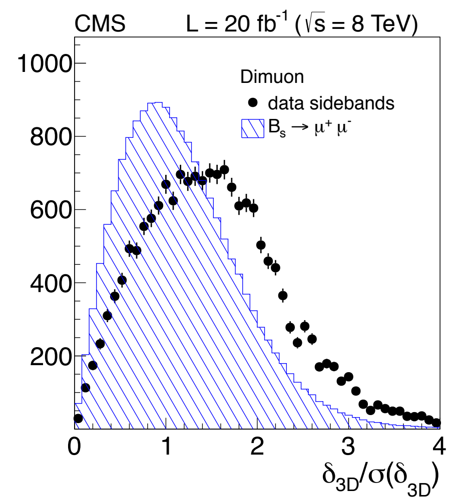


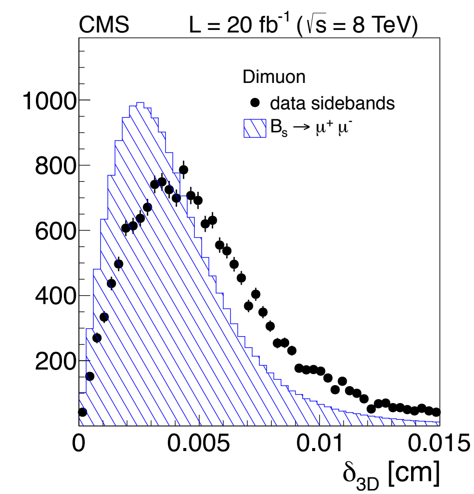








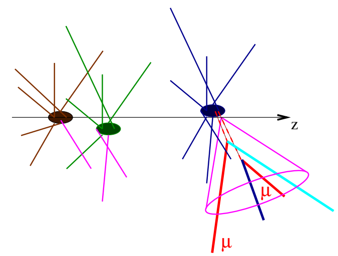


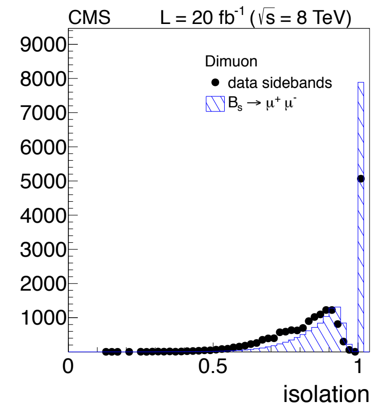


Event Selection - Isolation

- Primary vertex isolation: relative $\mu^+\mu^-$ isolation

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

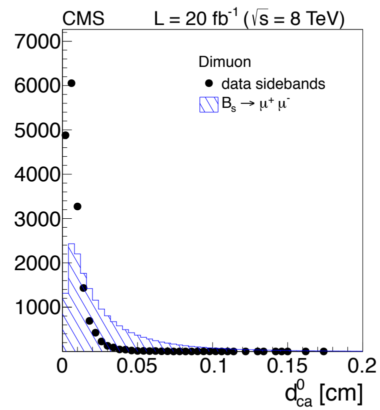


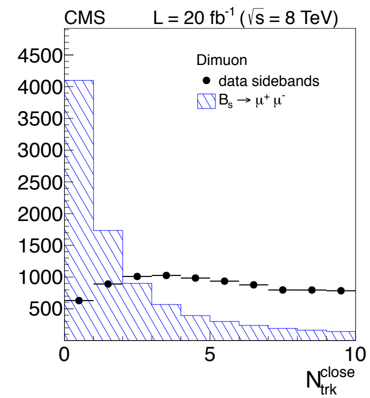


- B vertex isolation

Either tracks not associated to any P.V.
or tracks associated to same B candidate

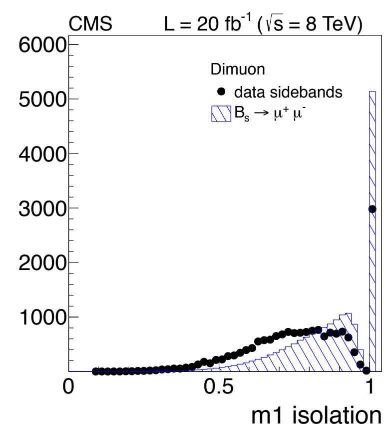
Distance of closest track to SV (d_{ca})
Number of close tracks in dca < 300 μm
and pT > 0.5 GeV





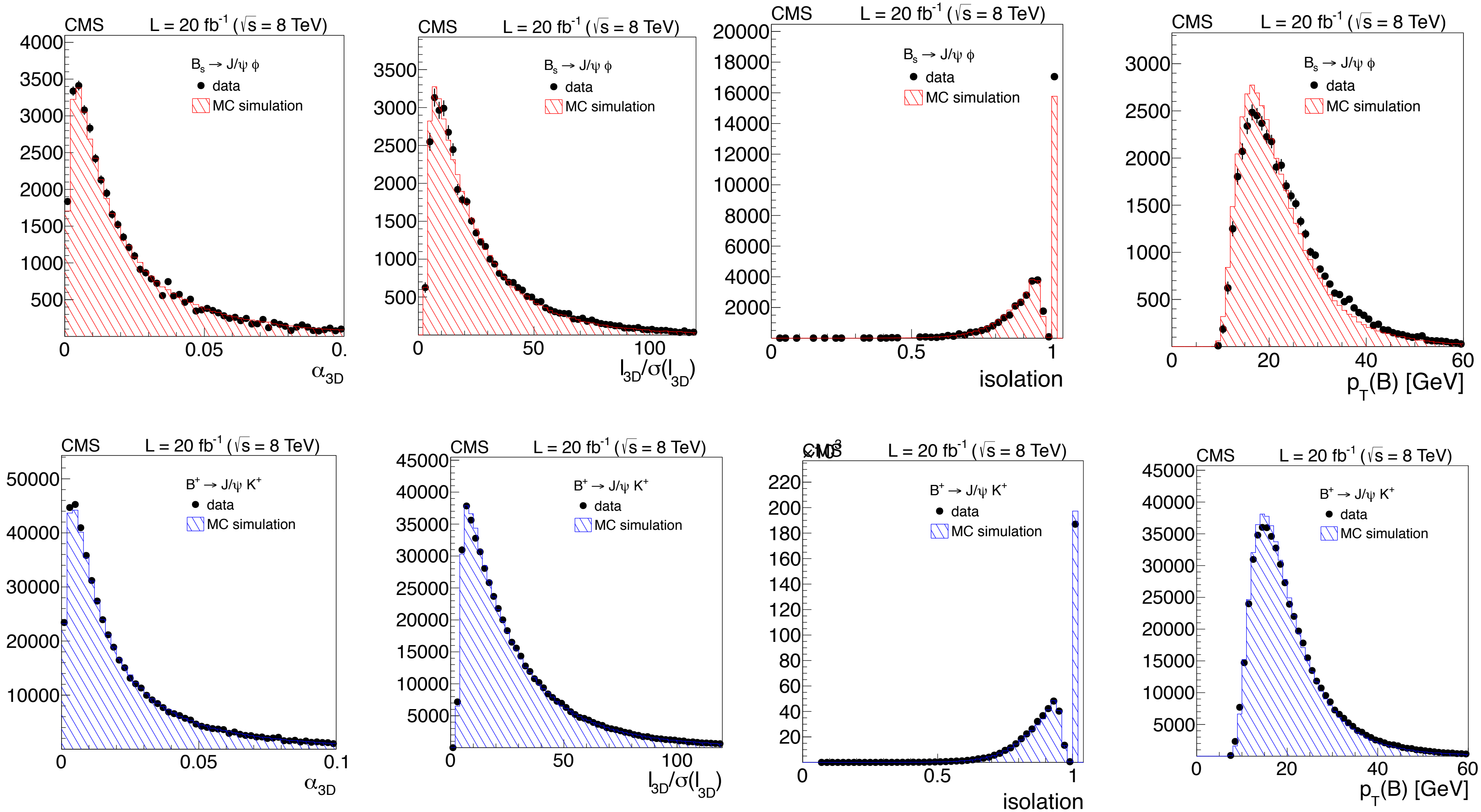
- Muon isolation

$$I_\mu = \frac{p_\mu}{p_\mu + \sum_{\Delta R<0.5;\, p_T>0.5GeV} p}$$



Data-MC Comparison

- Good agreement between sideband-subtracted distributions and MC



Boosted Decision Tree Selection

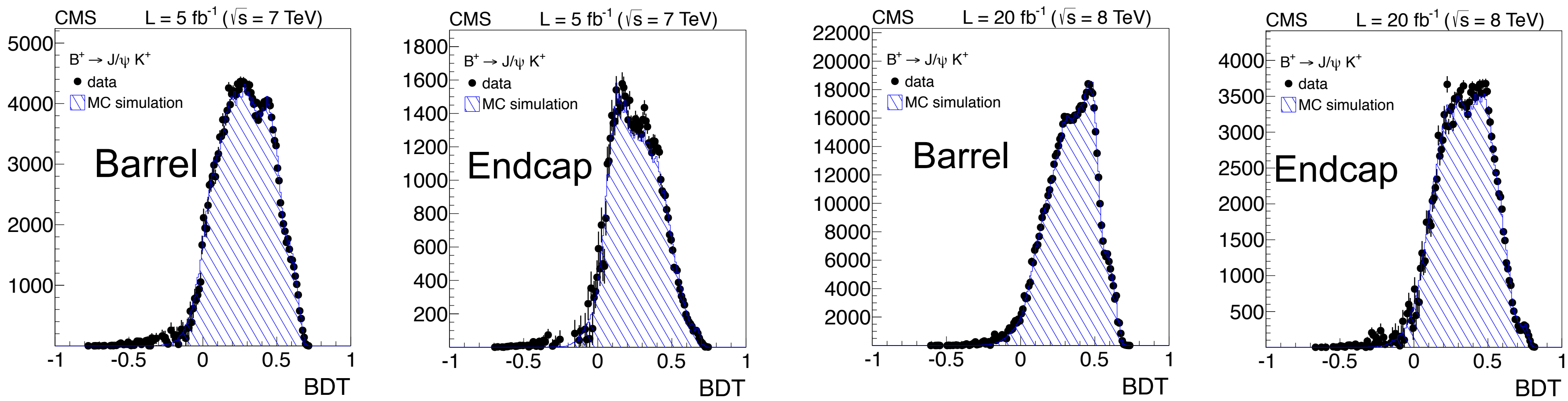
- BDT training – TMVA framework
  - MultiVariate Analysis: involves observation and analysis of more than one statistical outcome variable at a time, the technique is used to perform studies across multiple dimensions while taking into account the effects of all variables
  - signal: Bs MC simulation
  - background: dimuon data sidebands
  - to avoid bias, a given BDT used for training on "1st" event, tested on 2nd" and applied on "3rd", and then rotate

- Checks and studies
  - BDT output insensitive to mass using MC signal with shifted mass
  - BDT output shows no difference for high- and low-mass sidebands
  - BDT output insensitive to pileup

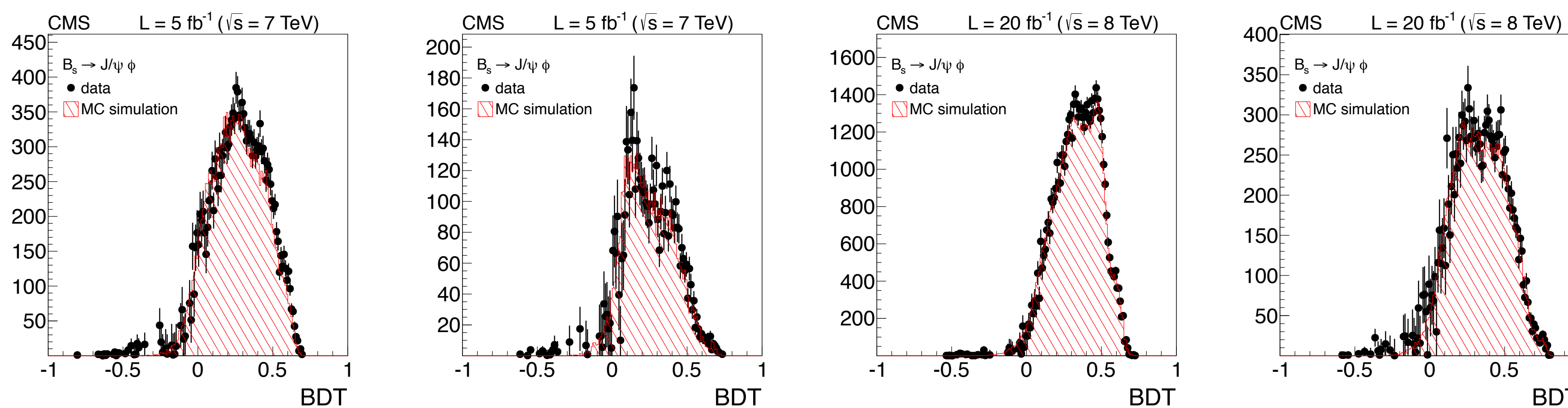
- Use the same BDT for normalization ($J/\psi\ K^{+}$) and control ($J/\psi\ \varphi$) samples

Simulation vs Data

$B^{\pm} \rightarrow J/\psi\, K^{\pm}$: difference → 3% systematic error



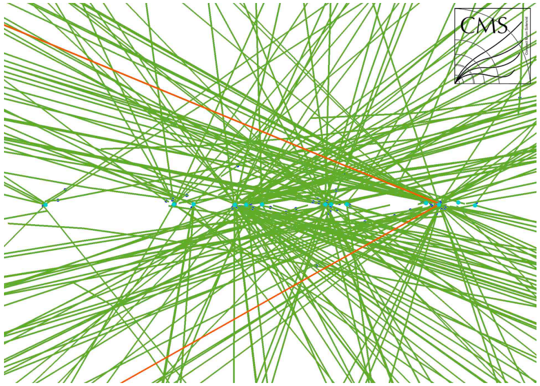
$B_s \rightarrow J/\psi\, \varphi$: 9.5% (2011) and 3.5% (2012)

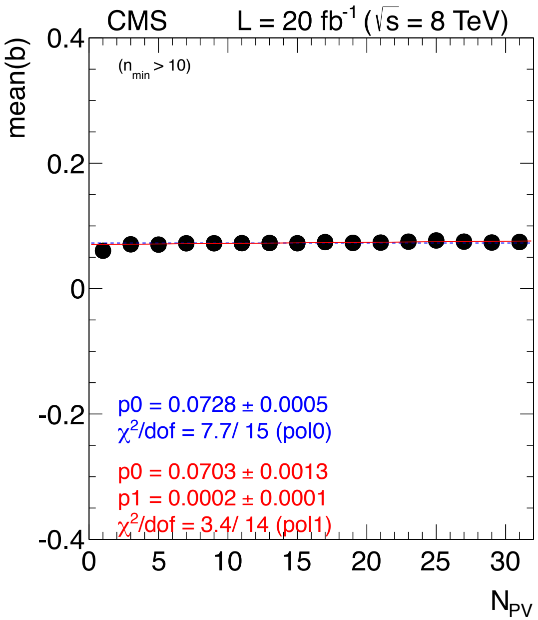


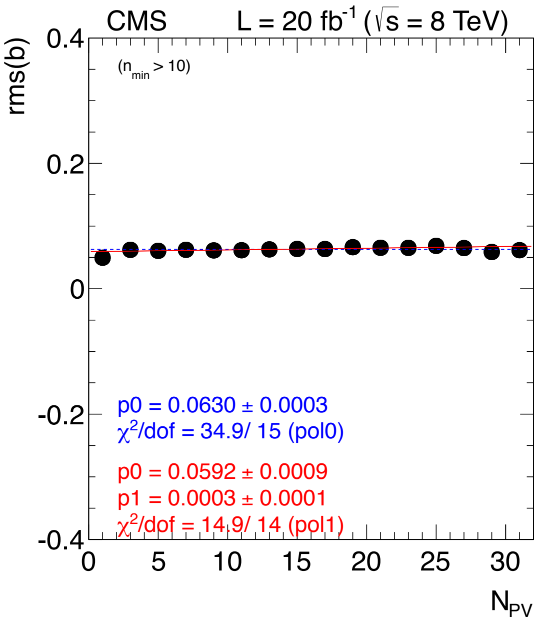
Multiple pp interactions - pileup

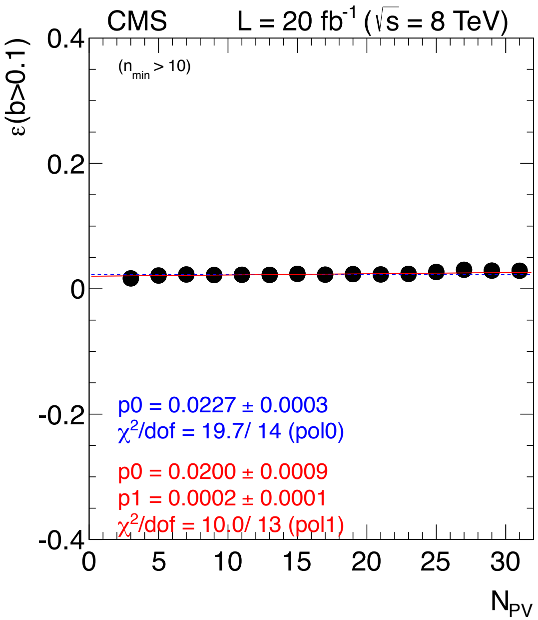
- Number of PU~ 9 (2011) and ~21 (2012)
- event selection tuned to be pileup independent

  e.g. isolation searches for tracks coming from the same primary vertex or not associated with any
- input variables insensitive to the number of primary vertices
- selection compatible with constant efficiency up to 30 PV (~40 PU)









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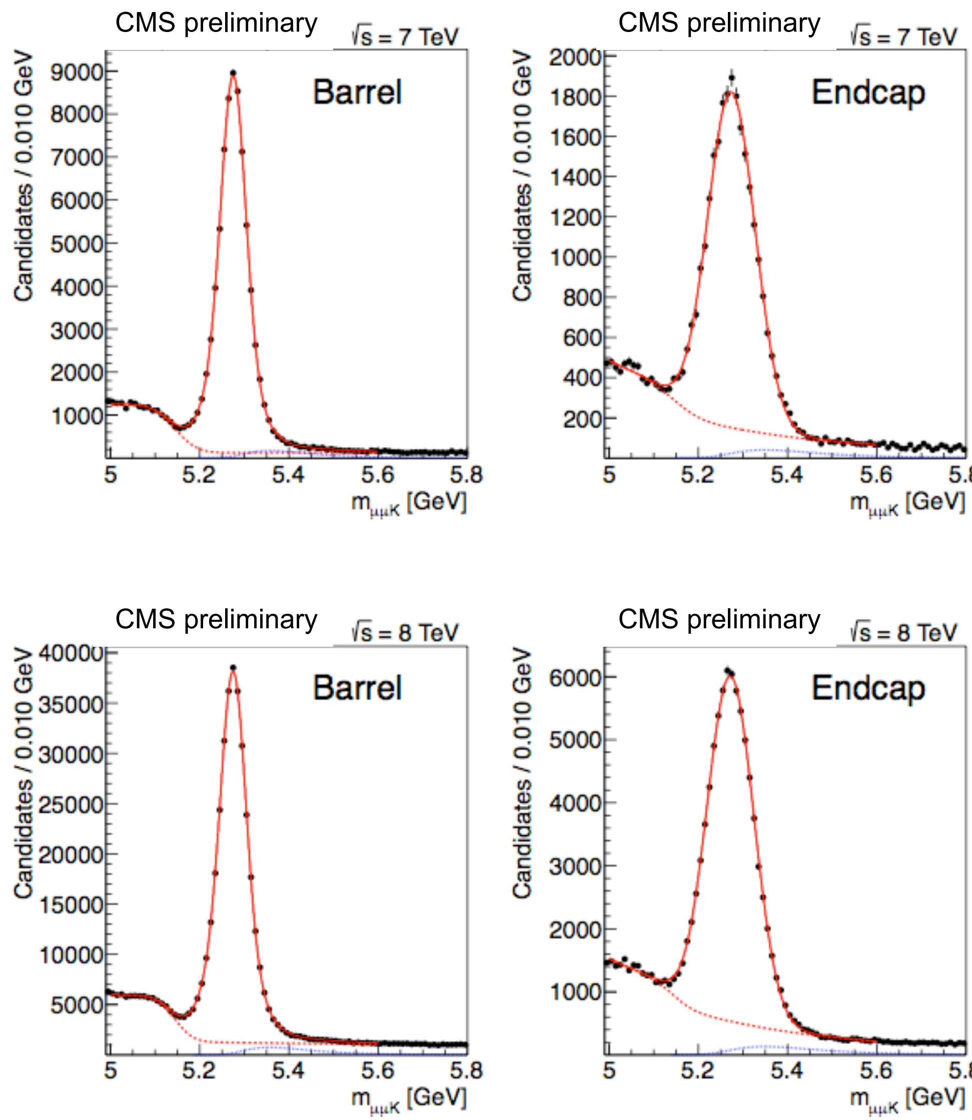
Normalization Channel: $B^{\pm} \rightarrow J/\psi K^{\pm}$

- 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

- Yield extraction
  - signal: double (single) Gaussian in barrel (endcap)
  - background: Error function for $B_d \rightarrow J/\psi K^{*} \rightarrow \mu+\mu\text{-}K\text{-}(\pi+)$ decays
  - background: Landau function for $B^{\pm} \rightarrow J/\psi \pi^{\pm}$ decays

- Estimated systematic error on the event yield: 5%

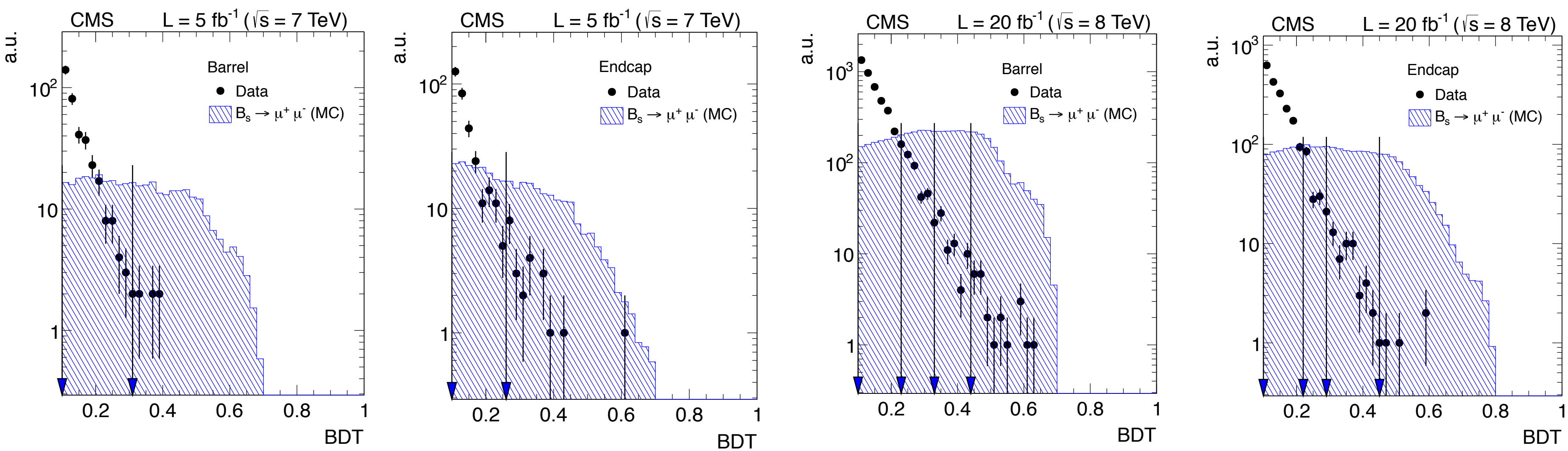


Determination of Branching Fraction

- UML fit to 12 mass distributions in BDT bins split in Barrel/Endcap:

min. bin edges	1	2	3	4
2011 barrel	0.10	0.31	-	-
2011 endcap	0.10	0.29	-	-
2012 barrel	0.10	0.23	0.33	0.44
2012 endcap	0.10	0.22	0.29	0.45

  - BDT binning chosen to equalize the expected number of signal events
  - systematic errors: branching fractions and f_s/f_u

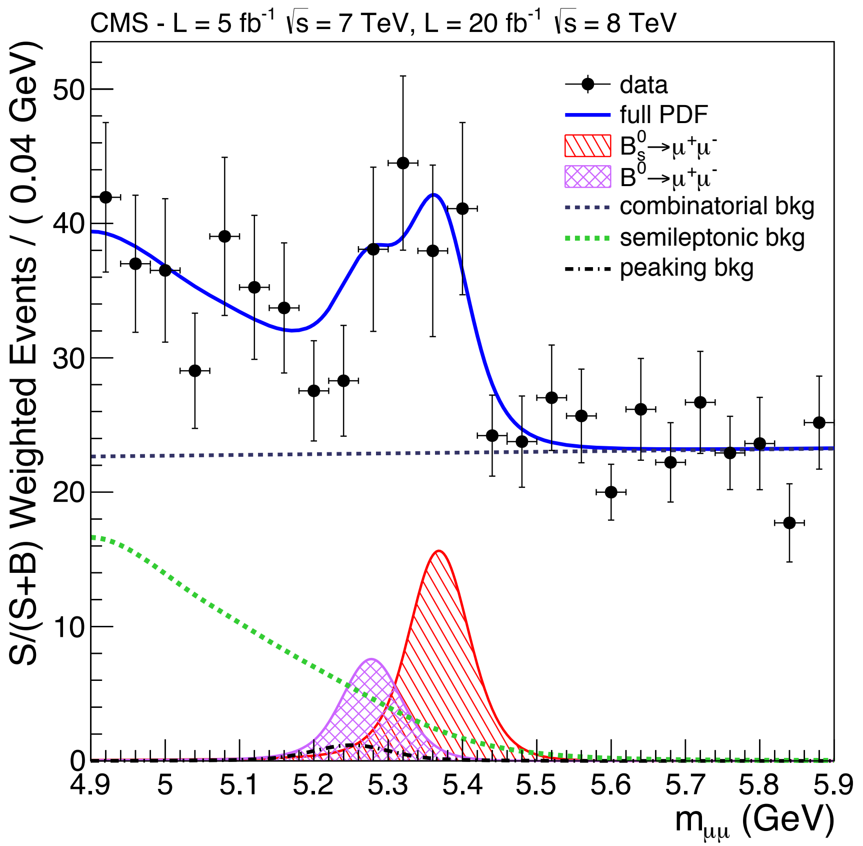


- To extract CL_S limits on BR($B_d \to \mu\mu$) use 1D-BDT
- Optimized cut on BDT output and event counting in mass windows

$b >$	barrel	endcap
2011	0.29	0.29
2012	0.38	0.39

Unbinned Maximum Likelihood Fit

- Fit B_s and B_d simultaneously
- Signals: Crystal Ball, normalization floating
- Peaking background:
  - sum of Gaussian and Crystal Ball (same mean)
  - constrained (Log-Normal) to expectation and normalized to the measured B^+ yield
  - yield cross checked on independent dataset
- Rare semileptonic background:
  - fixed shape, normalization floating constrained within 75% of nominal value
  - constrained Gaussian kernels from MC
- Combinatorial background:
  - first degree polynomial
  - validated with independent data set
- Per-event mass resolution included



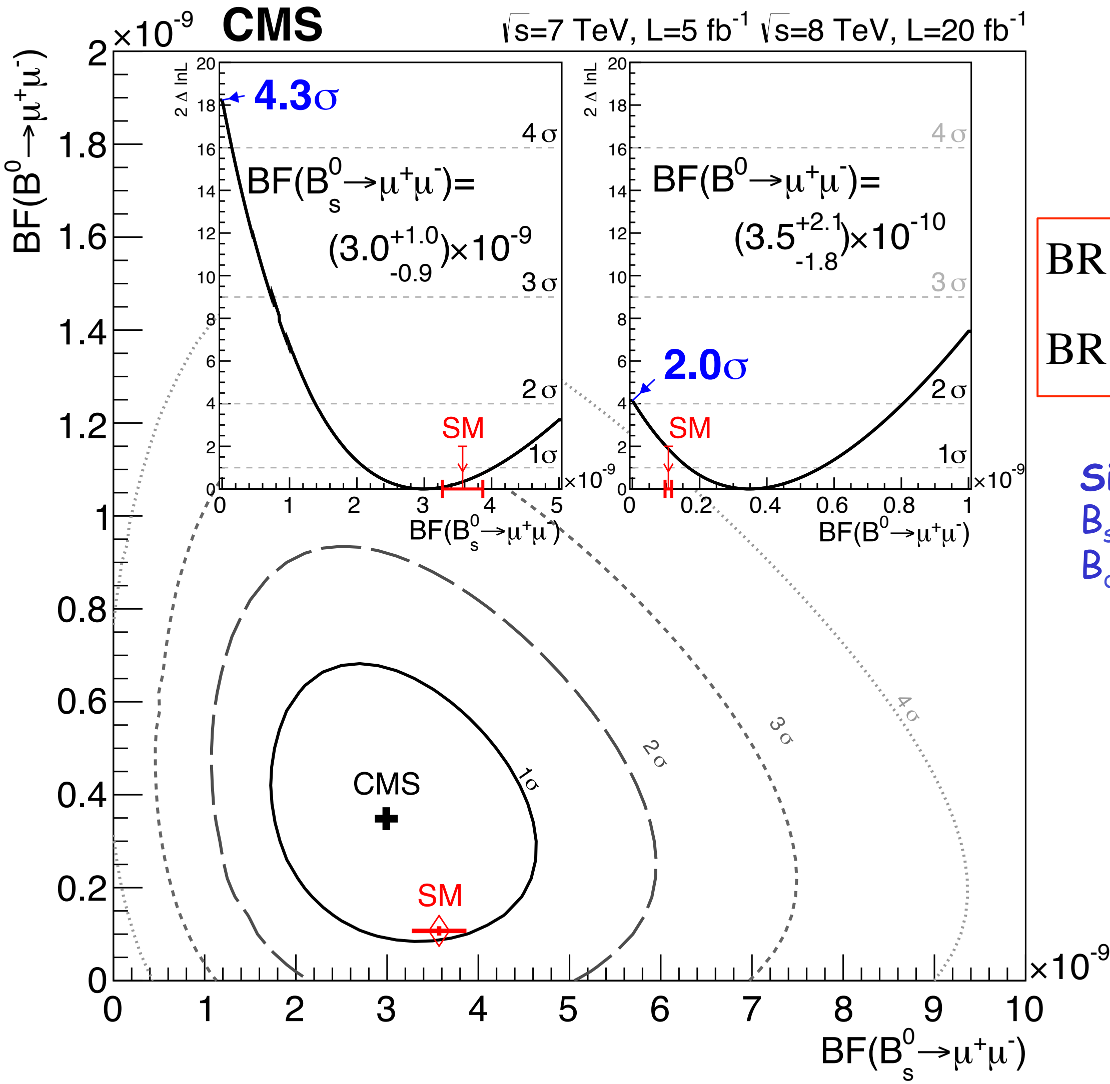
$$\mathrm{BR}(B_S \to \mu\mu) = \frac{N_S^i}{N_{B^+}^i} \times \frac{f_u}{f_s} \times \left(\frac{\varepsilon_s^i}{\varepsilon_u^i}\right) \times \mathrm{BR}(B_d \to J/\psi K^{\pm}) \times \mathrm{BR}(J/\psi \to \mu\mu)$$

$$\mathrm{BR}(B_d \to \mu\mu) = \frac{N_d^i}{N_{B^+}^i} \times \left(\frac{\varepsilon_s^i}{\varepsilon_u^i}\right) \times \mathrm{BR}(B_d \to J/\psi K^{\pm}) \times \mathrm{BR}(J/\psi \to \mu\mu)$$

Systematic Errors

- Implemented as Gaussian pdf constraints in the UML fit
  - hadron to muon misidentification probability
    - studied with $D^* \to D^0 \pi$, $D^0 \to K\pi$, $K_S \to \pi\pi$, $\Lambda \to p\pi$
    - 50% uncertainty, conservatively assumed to be uncorrelated
  - BR uncertainties
    - dominated by $\Lambda_b \to p\mu\nu$ (6.5×10^{-4}) with 100% uncertainty
  - $f_s/f_u = 0.256 \pm 0.020$ from LHCb
    - additional 5% to account for possible p_T and η dependence
    - in situ studies show no p_T dependence from ratios of $B^\pm \to J/\psi K^\pm$ vs $B_s \to J/\psi\, \varphi$
  - Normalization channel
    - yields 5%
    - $\mathrm{BR}(B_d \to J/\psi K^\pm) \times \mathrm{BR}(J/\psi \to \mu\mu) = (6.0 \pm 0.2) \times 10^{-5}$

Branching Fraction Results



$$\mathrm{BR}(B_S \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\mathrm{stat})^{+0.6}_{-0.4}\ (\mathrm{syst})\right) \times 10^{-9}$$

$$\mathrm{BR}(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\mathrm{stat+syst})\right) \times 10^{-10}$$

Significances

$B_s \to \mu\mu$ 4.3 σ (expected 4.8 σ)

$B_d \to \mu\mu$ 2.0 σ

Upper Limits on $B_d \to \mu\mu$

- No significant excess is observed for $B_d \to \mu\mu$
  - Upper limit computed using CL_s method, based on observed events in the signal and sideband regions with the 1D-BDT method

Expected and observed events in signal regions

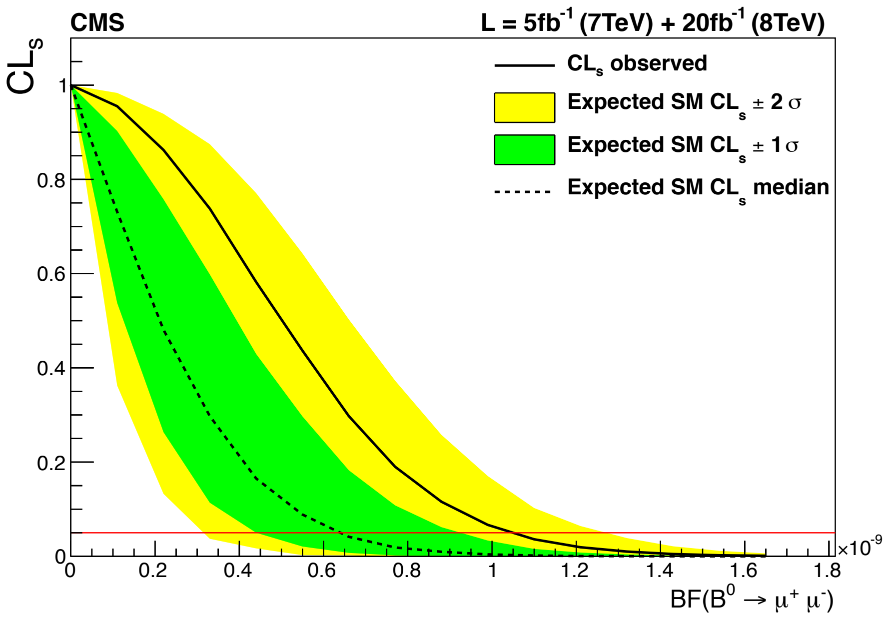
	2011 barrel		2012 barrel	
	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
$\varepsilon_{tot}[\%]$	0.33 ± 0.03	0.30 ± 0.04	0.24 ± 0.02	0.23 ± 0.03
N^{exp}_{signal}	0.27 ± 0.03	2.97 ± 0.44	1.00 ± 0.10	11.46 ± 1.72
N^{exp}_{total}	1.3 ± 0.8	3.6 ± 0.6	7.9 ± 3.0	17.9 ± 2.8
N_{obs}	3	4	11	16

	2011 endcap		2012 endcap	
	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
$\varepsilon_{tot}[\%]$	0.20 ± 0.02	0.20 ± 0.02	0.10 ± 0.01	0.09 ± 0.01
N^{exp}_{signal}	0.11 ± 0.01	1.28 ± 0.19	0.30 ± 0.03	3.56 ± 0.53
N^{exp}_{total}	1.5 ± 0.6	2.6 ± 0.5	2.2 ± 0.8	5.1 ± 0.7
N_{obs}	1	4	3	4

$$\mathrm{BR}(B_d \to \mu\mu) < 1.1\times10^{-9} \text{ @95\% CL}$$

(expected 6.3×10^{-10} in presence of SM+background)

$$\mathrm{BR}(B_d \to \mu\mu) < 9.2\times10^{-10} \text{ @90\% CL}$$



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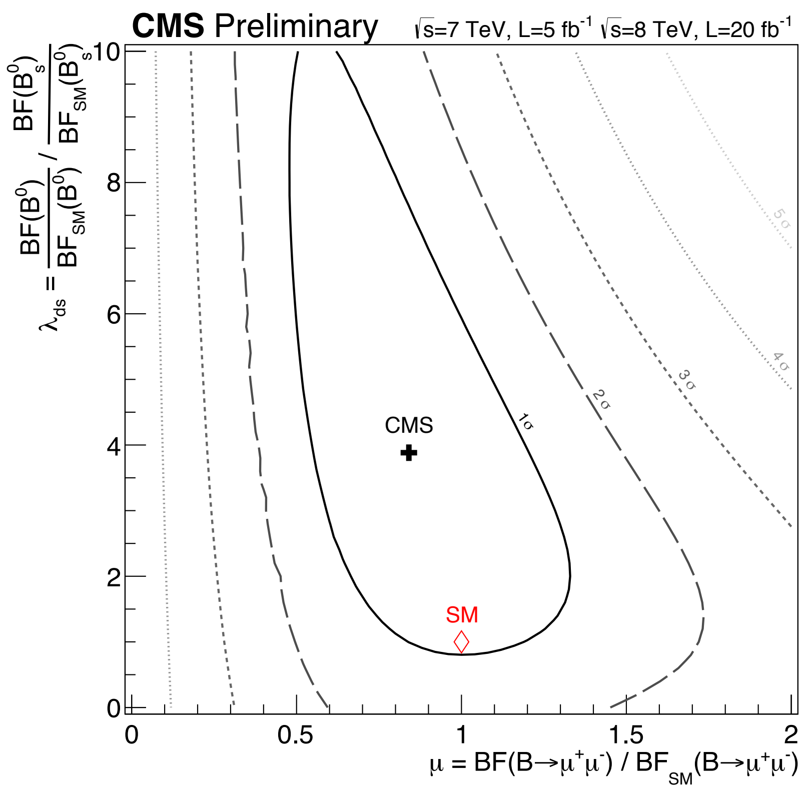
SM Compatibility Check

- $BR_{SM}(B_s \to \mu\mu) = (3.56 \pm 0.18) \times 10^{-9}$
- $BR_{SM}(B_d \to \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$



$$\mu = \frac{\mathrm{BR}(B_S \to \mu\mu)}{\mathrm{BR}_{SM}(B_S \to \mu\mu)}$$

$$\lambda_{ds} = \frac{\mathrm{BR}(B_d \to \mu\mu)}{\mathrm{BR}_{SM}(B_d \to \mu\mu)} \Big/ \frac{\mathrm{BR}(B_S \to \mu\mu)}{\mathrm{BR}_{SM}(B_S \to \mu\mu)}$$

Simultaneous fit

$$\mu = 0.84^{+0.31}_{-0.25}; \lambda_{ds} = 3.9^{+3.7}_{-2.2}$$

Fit for μ (fix Λ_{ds} to SM)

$$\mu = 1.01^{+0.31}_{-0.26}$$

Fit for Λ_{ds} (fix μ to SM)

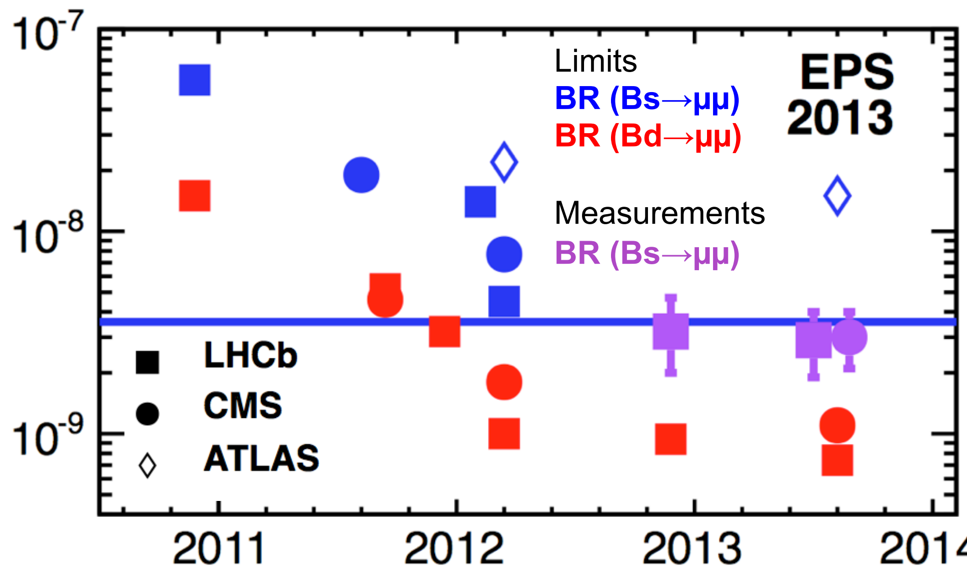
$$\lambda_{ds} = 3.1^{+2.0}_{-1.7}$$

Summary

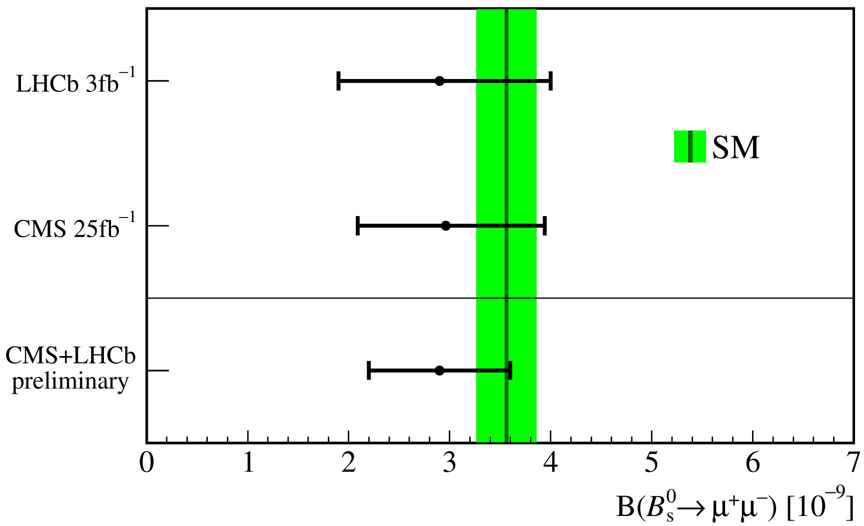
- CMS measurements using 25 fb^{-1} data

$$BR(B_S \to \mu\mu) = \left(3.0^{+1.0}_{-0.9}\right)\times 10^{-9}$$ statistics dominated, 4.3 σ significance

$$BR(B_d \to \mu\mu) < 1.1\times 10^{-9} \text{ @95\% CL}$$



- LHCb + CMS combined measurement: accounting for correlations



$BR^{\langle t \rangle}(B_s \to \mu^+\mu^-) = (2.9\pm0.7)\times 10^{-9}$

Consistent with SM expectations!

Is SM a Complete Theory?!

- SM successfully explains and predicts many observed phenomena
  - its predictions verified at 10^{-3} level up to TeV energies

- SM pasting together of strong and electroweak interactions

  SM = SU(3) x SU(2) x U(1)

  - 19 (26 with $m_\nu \neq 0$) arbitrary parameters that can only be determined from experimental measurements
  - Unanswered questions such as
    - origin of flavor
    - number of generations
    - fermion masses ($m_t/m_u \sim 3\times10^4$; $m_\tau/m_e \sim 4\times10^3$)
    - matter – antimatter asymmetry
    - dark matter / dark energy
  - Lack of grand unification of fundamental forces

- SM merely an effective (low energy) theory valid up to some scale, where new physics appears!

Beyond the Standard Model

Supersymmetry:

Extension of Poincare group to include boson-fermion symmetry

New mirror spectrum of particles

Large number of new parameters (105 in minimal SUSY SM)

Theoretically nice:

- additional particles cancel divergences in m_H - can naturally be of order EW scale
- SUSY closely approximates SM at low energies
- allows unification of forces at higher energies
- provides a path to incorporation of gravity and string theory
- lightest neutralino is a cosmic dark matter candidate

Extra dimensions:

Large-scale compactification of extra dimensions

String theory motivated but with observed effects at EW scale O(TeV)

Theoretically nice:

- solves hierarchy problem by reducing GUT scale
- gravity may propagate in 4+n dimensions, would see effects only at very small distances, perhaps reachable in pp LHC Collisions e.g. Kaluza-Klein gravitons and Z-like particles

Conclusions

- The SM passes yet another test – still victorious!
- But its demise will come – it is logically incomplete
- The defeater will have to address
  - number of quark/lepton generations, origin of flavor
  - matter – antimatter asymmetry
  - unification of forces, including gravity
  - dark matter / dark energy, etc.

Flammarion engraving
unknown artist, circa 1800

The Quest for Knowledge and Understanding Continues!

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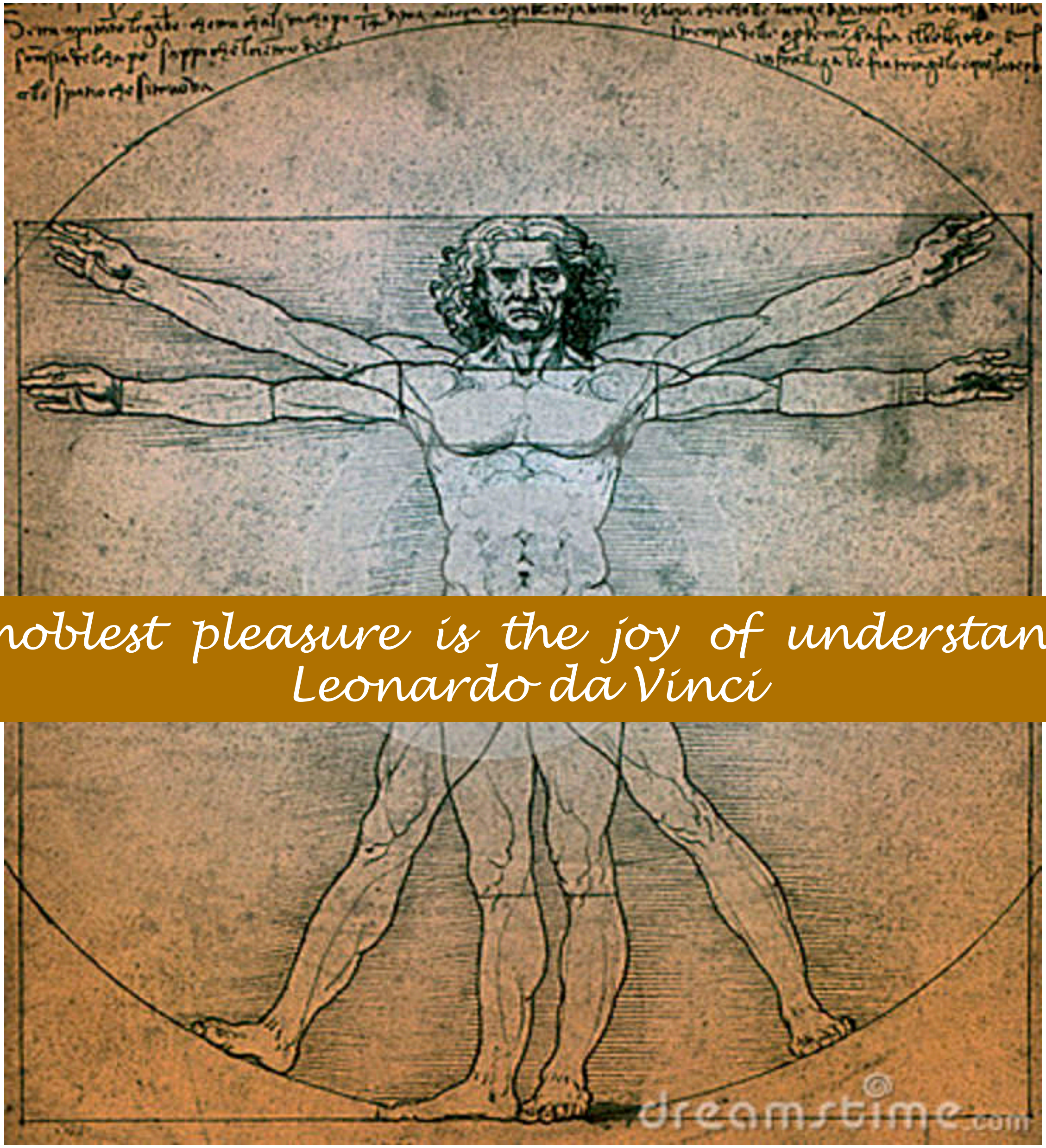


"The noblest pleasure is the joy of understanding."
Leonardo da Vinci

Vitruvian Man
Leonardo da Vinci
circa 1490

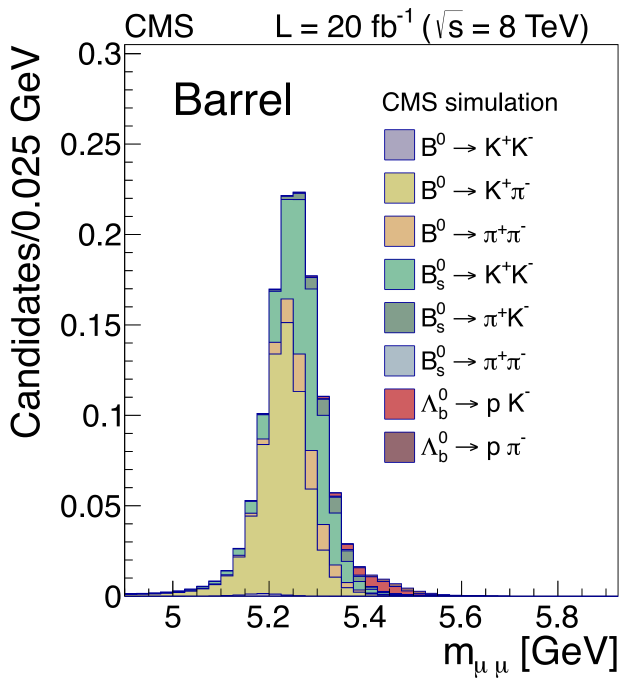
Backup Slides

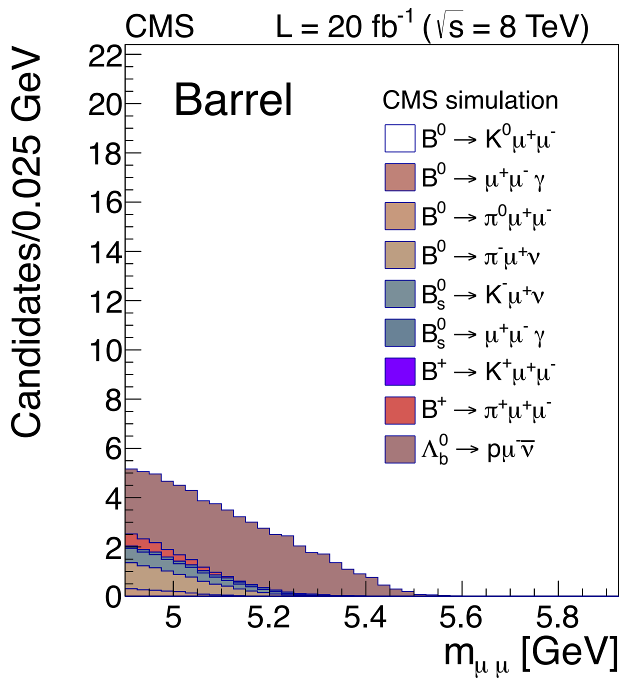
Rare Backgrounds

- Expected number of events in each channel normalized to $B^{\pm}$ in data:

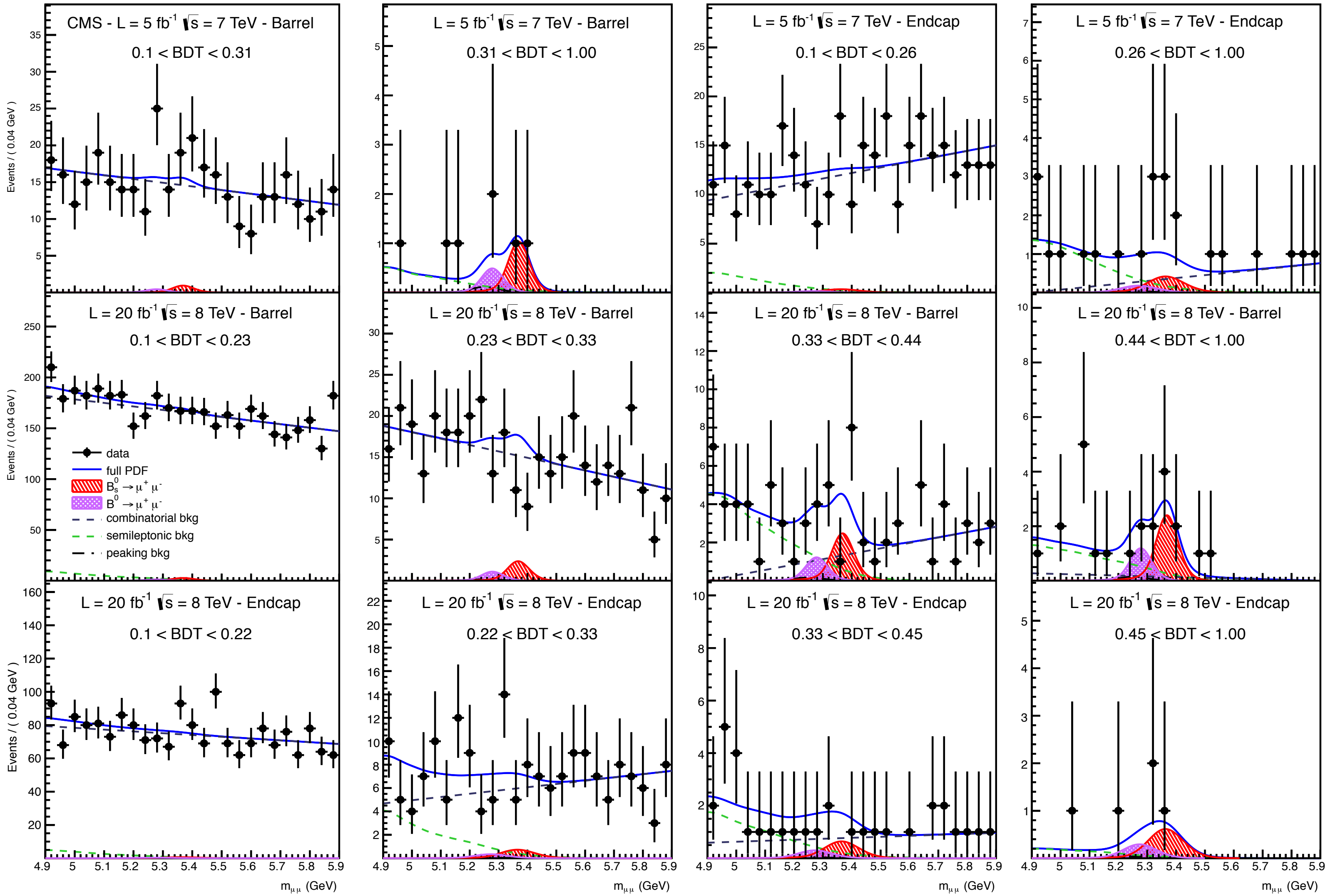
$$N(X) = \frac{Br(Y \to X)}{Br(B^{\pm} \to J/\psi K^{\pm})} \frac{f_Y}{f_u} \frac{\varepsilon_{tot}(X)}{\varepsilon_{tot}(B^{\pm})} N_{obs}(B^{\pm})$$

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





Categorized-BDT Fits Results



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1D BDT Results - Cross Check

- Significance
  $B_s \to \mu\mu$ 4.8 σ (expected 4.7 σ)

- Less sensitive wrt categorized-BDT
- used as a cross check