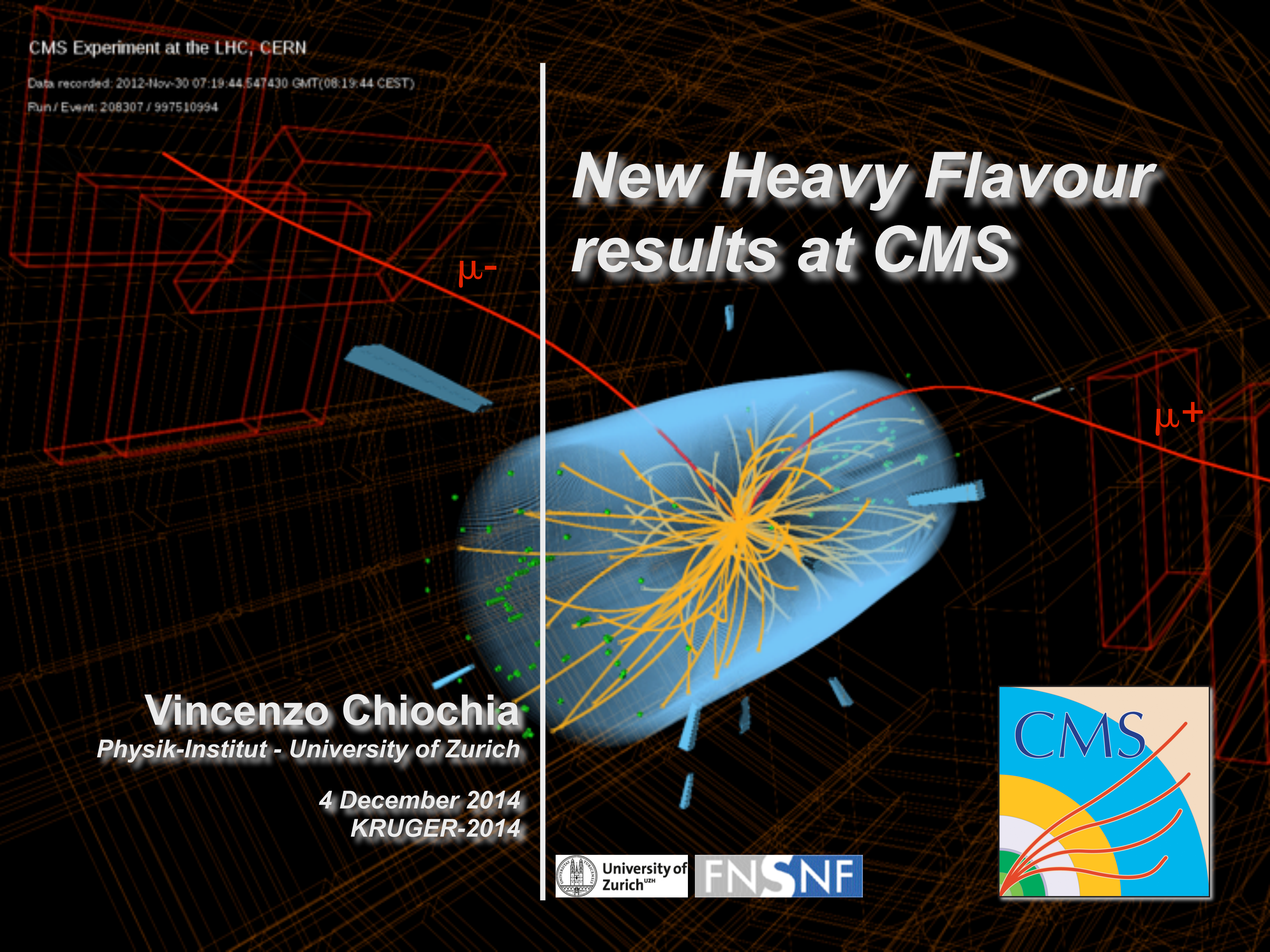


New Heavy Flavour results at CMS

Vincenzo Chiochia
Physik-Institut - University of Zurich

4 December 2014
KRUGER-2014

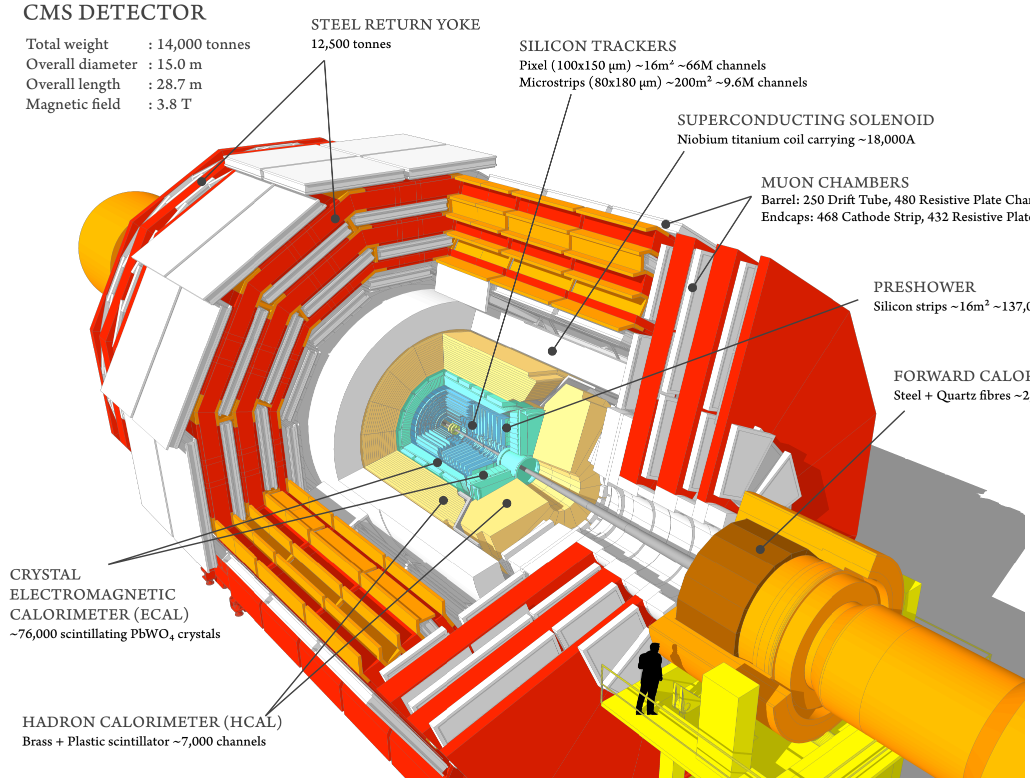
Why heavy flavour physics?

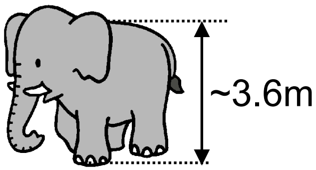
- **Physics of beauty and charm quarks in p-p collisions**
- **Research area with rich of phenomenology:**
  - **Heavy flavor production measurements**
    - Tests of QCD (hard scattering, fragmentation, NRQCD, etc.)
  - **Spectroscopy and particle properties**
    - Heavy baryon spectroscopy
    - Spectrum of standard and exotic quarkonium states
    - Particle lifetimes, masses, decays, etc.
  - **Rare beauty decays**
    - Complementary to direct searches: access multi-TeV energy scales through loop contributions

CMS published 28 journal articles in the heavy flavour area
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

In this talk

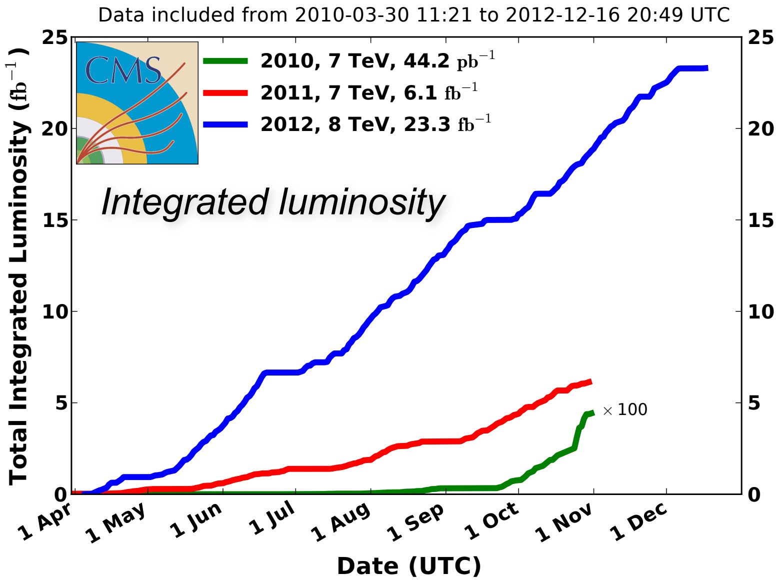
- **Recent selected CMS highlights in heavy flavours:**
  - **Combined CMS+LHCb search for $B_{s,d} \rightarrow \mu\mu$ decays**
  - **CP violation in $B_s \rightarrow J/\psi\phi$ decays**
  - **Production of J/ψ, $\psi(2S)$ and χ_b**
  - **B_c decays, observation of a new B^+ rare decay**





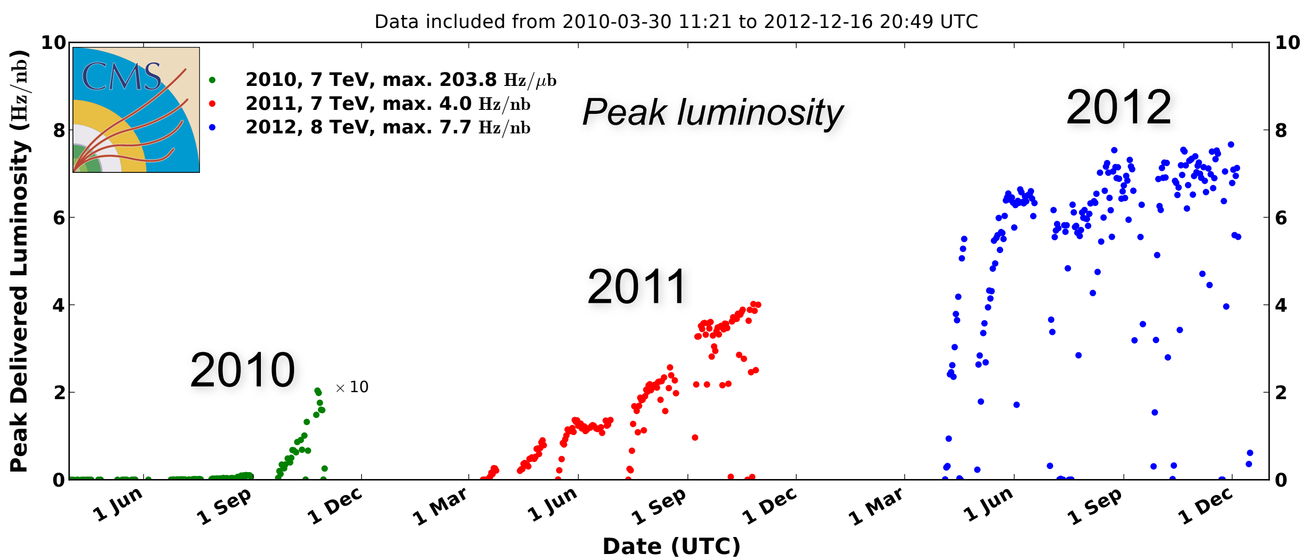
Variable	Resolution
Dimuon mass	32 MeV/c (barrel) - 75 MeV/c (endcap)
Impact parameter	10 μm (100 GeV/c) - 20 μm (10 GeV/c)

Datasets and LHC luminosity

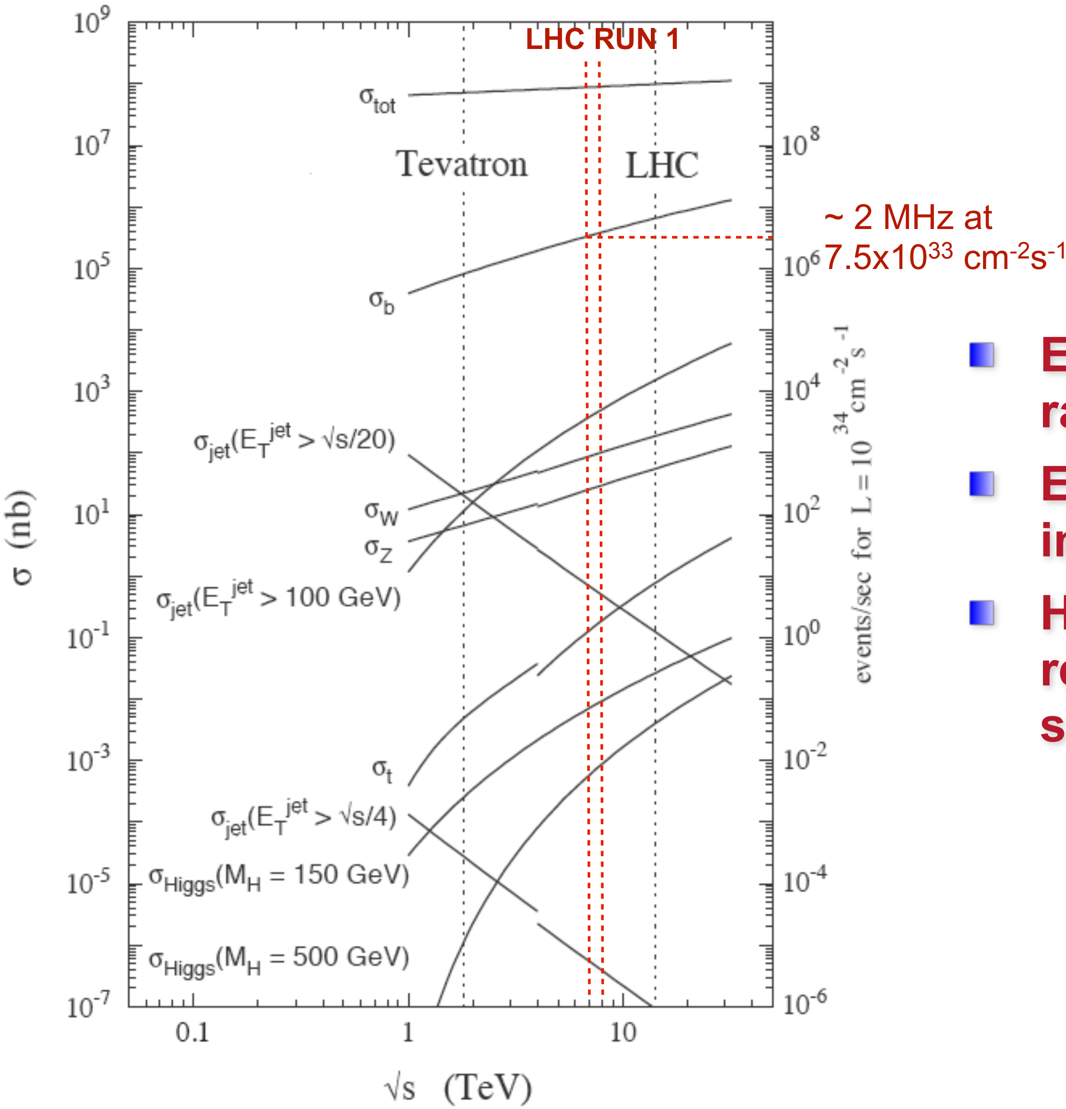


2010: **~40/pb** at L_{inst}~10^{32} $cm^{-2}s^{-1}$
2011: **~6/fb** at L_{inst}<$4x10^{33}$ $cm^{-2}s^{-1}$
2012: **~23/fb** at L_{inst}<$7.5x10^{33}$ $cm^{-2}s^{-1}$

Steady increase of L_{inst} in **2011**
Rather stable in **2012**

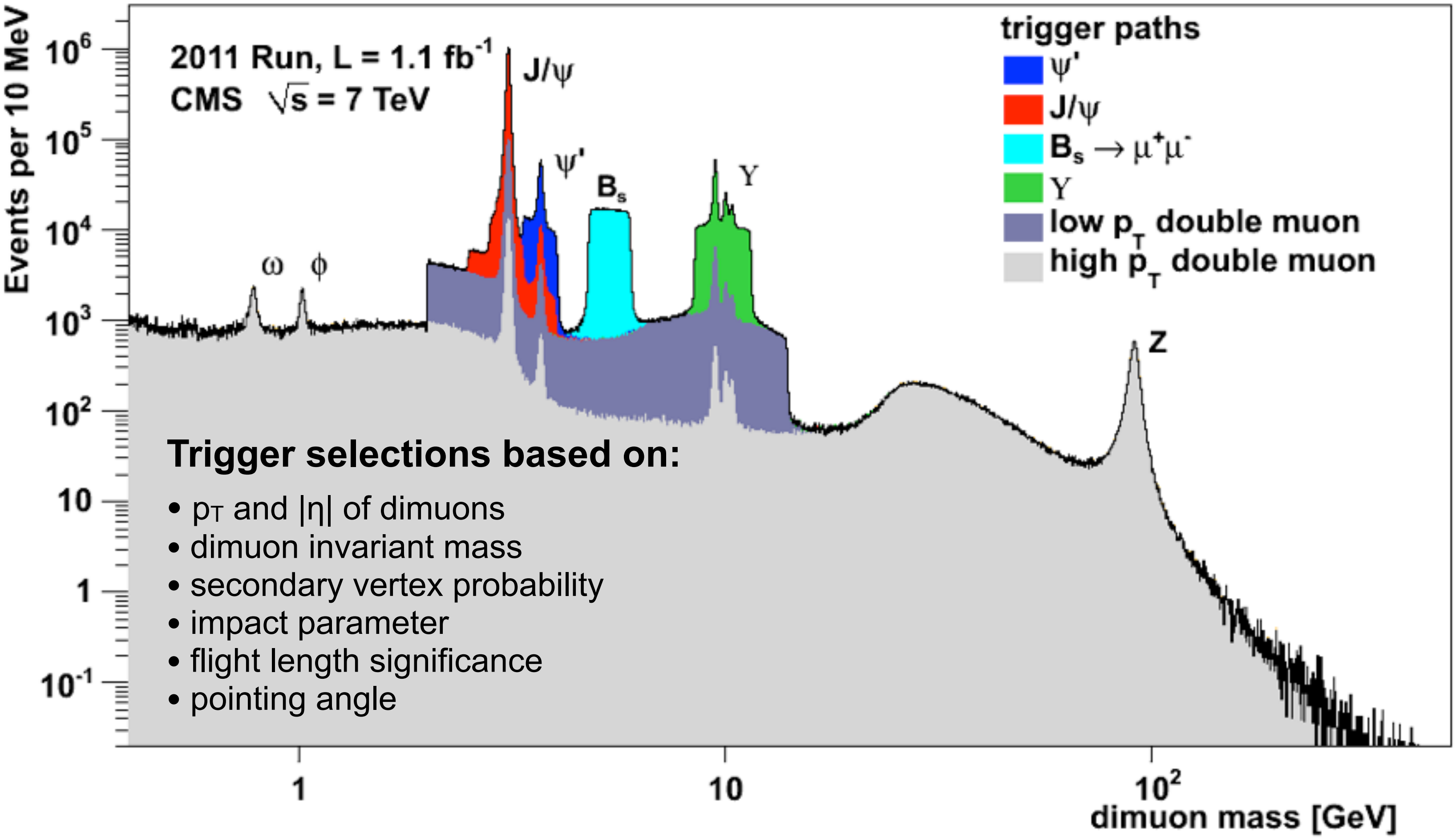


b quark production at the LHC



- **Enormous b quark production rate at the LHC Run 1**
- **Expected to more than double in Run 2**
- **High rates imply very selective requirements at trigger level to store interesting b decays**

Triggers for heavy flavor physics

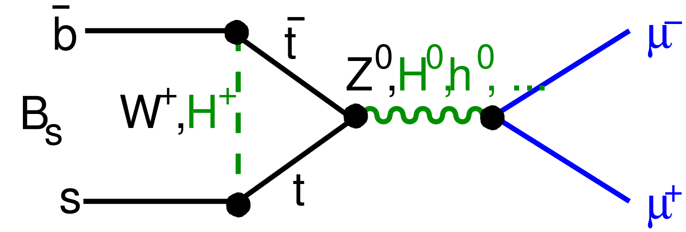


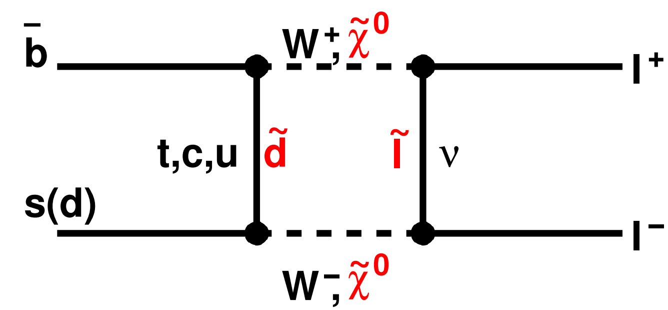
- Trigger requirements tightened following the increase in instantaneous luminosity.
- About 10% of CMS bandwidth assigned to heavy flavor physics
- Single muon trigger efficiencies measured from data (tag&probe), di-muon correlations from MC


Quest for rare B decays:
the LHC Run 1 heritage

Why searching for $B_{s,d} \to \mu^+\mu^-$?

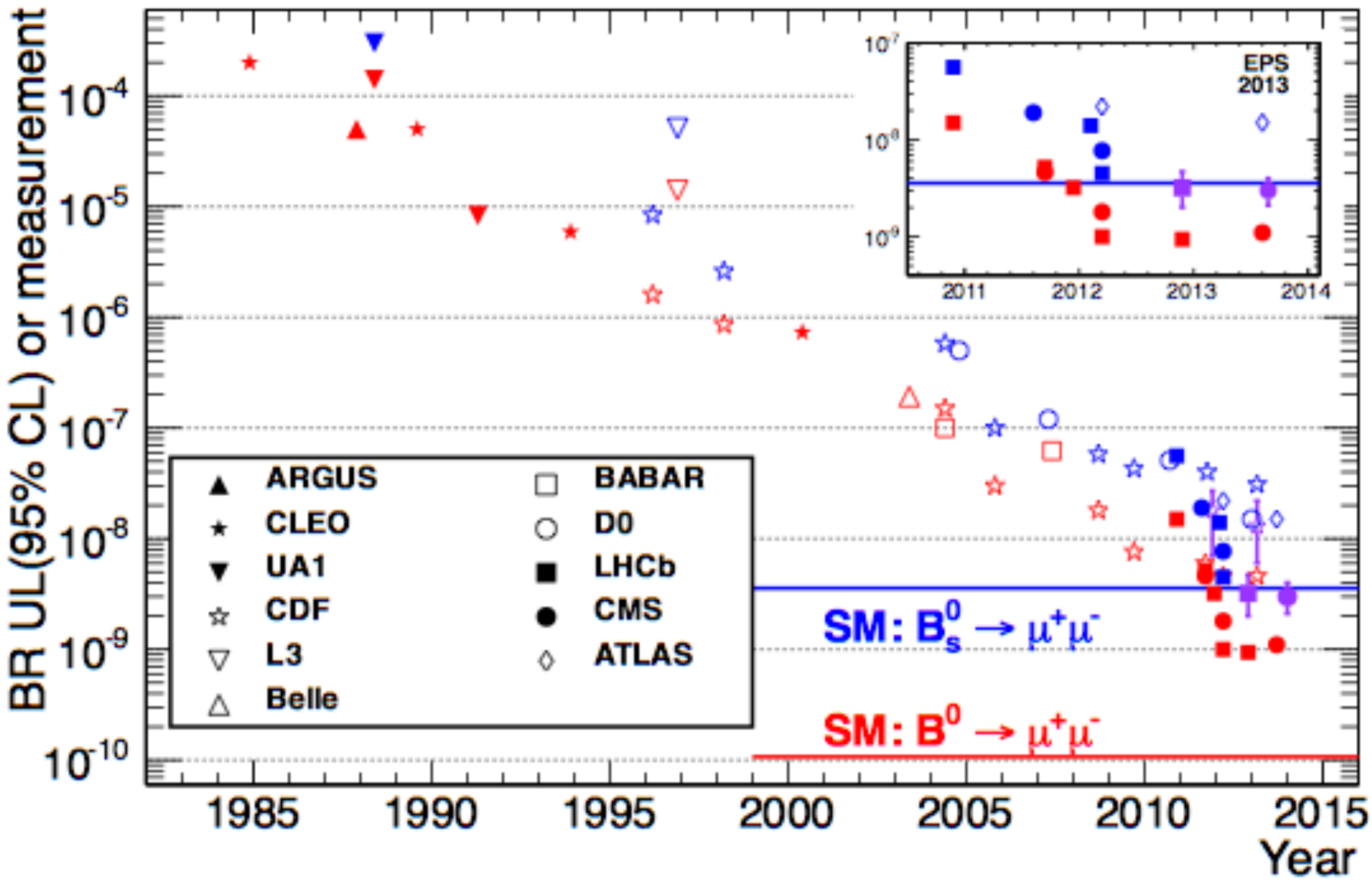
- **Decays highly suppressed in SM**
  - Forbidden at tree level
  - $b \to s(d)$ FCNC transitions only through *Penguin* or *Box* diagrams
  - Cabibbo ($|V_{td}|<|V_{ts}|$) and helicity suppressed
- **Standard Model predictions**
  - $\mathcal{B}(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$ [1]
    - ~10% corrections from B_s mixing when comparing to experiments included [2]
    - CKM best fit: $(3.6^{+0.2}_{-0.3}) \times 10^{-9}$ [3]
  - $\mathcal{B}(B^0 \to \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$ [1]
- **Sensitivity to new physics, e.g. extended Higgs sector and SUSY particles:**
  - 2HDM branching ~$(\tan\beta)^4$ and $m(H^+)$
  - MSSM branching ~$(\tan\beta)^6$
  - Leptoquarks
  - 4th generation top



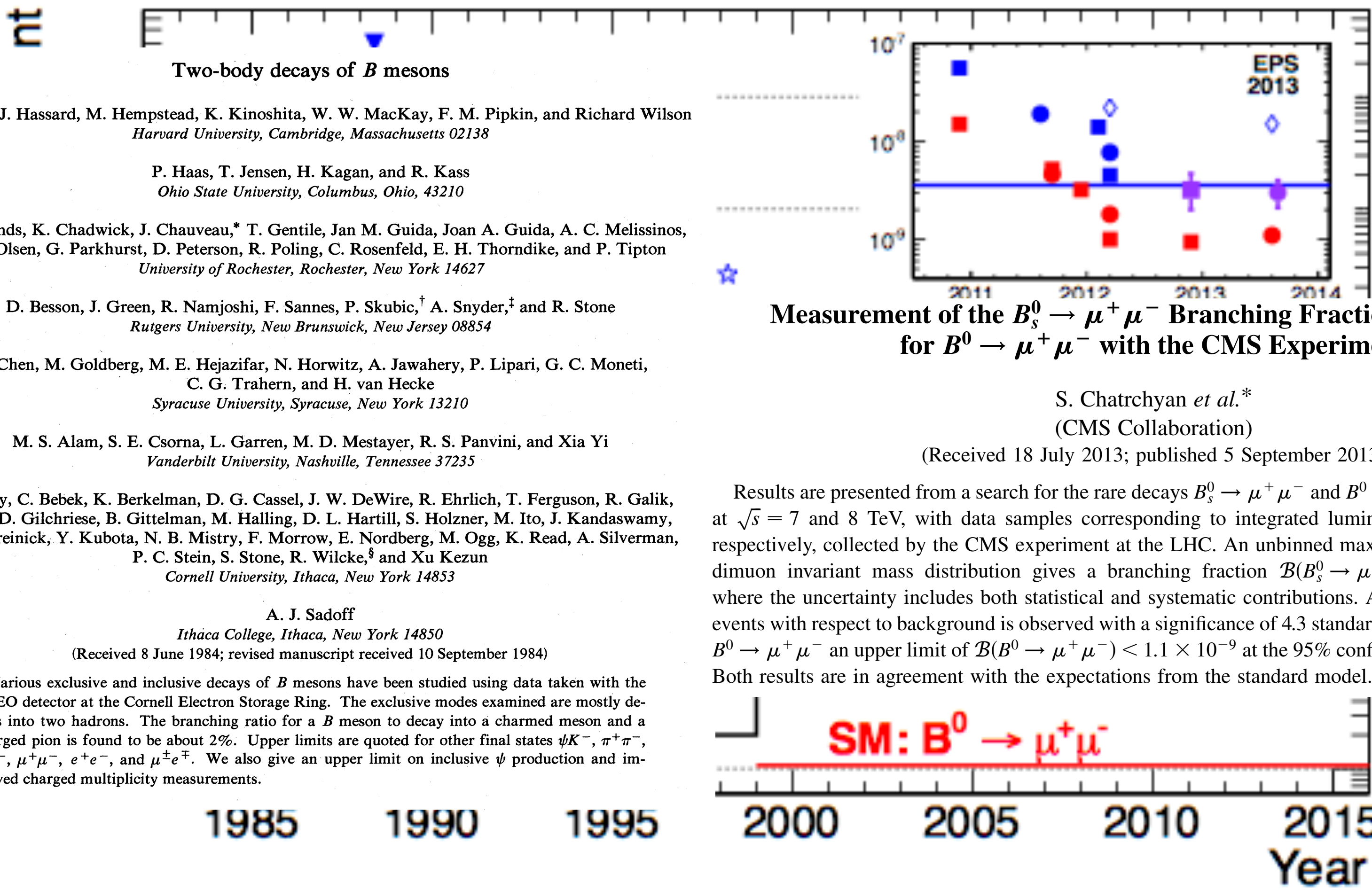


[1] PRL112, 101801 (2014)
[2] JHEP 1307 (2013) 77, PRL 109, 041801 (2012), arXiv:1208.0934
[3] Phys. Rev. D85: 033005, 2011

A 30-years quest!



A 30-years quest!



Two-body decays of B mesons

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(Received 8 June 1984; revised manuscript received 10 September 1984)

Various exclusive and inclusive decays of B mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a B meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

Measurement of the $B_s^0 \to \mu^+\mu^-$ Branching Fraction and Search for $B^0 \to \mu^+\mu^-$ with the CMS Experiment

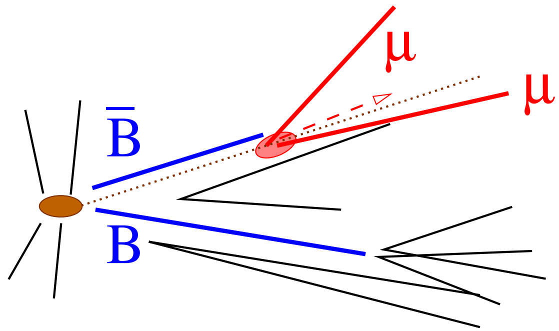
S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 18 July 2013; published 5 September 2013)

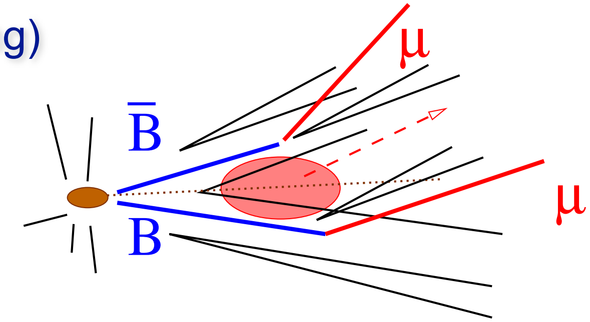
Results are presented from a search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV, with data samples corresponding to integrated luminosities of 5 and 20 fb^{-1}, respectively, collected by the CMS experiment at the LHC. An unbinned maximum-likelihood fit to the dimuon invariant mass distribution gives a branching fraction $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$, where the uncertainty includes both statistical and systematic contributions. An excess of $B_s^0 \to \mu^+\mu^-$ events with respect to background is observed with a significance of 4.3 standard deviations. For the decay $B^0 \to \mu^+\mu^-$ an upper limit of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at the 95% confidence level is determined. Both results are in agreement with the expectations from the standard model.

Key ingredients:
Good dimuon vertex, correct B mass assignment, isolation, momentum pointing to interaction point

- **Signal characteristics:**
  - Two muons from a well reconstructed decay vertex
  - Mass compatible with B_s (or B^0)
  - Dimuon momentum aligned with B flight direction

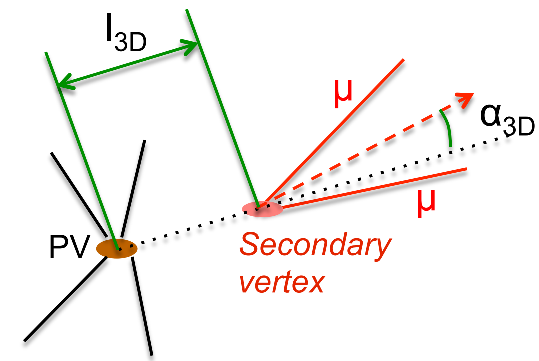


- **Background sources:**
  - Two semi-leptonic B decays (e.g. from gluon splitting)
  - One semi-leptonic B decay + misidentified hadron
  - Hadronic B decays
    - Peaking: $B_s \rightarrow K^- K^+$
      - More problematic within the B^0 mass window
    - Rare semileptonic: $B_s \rightarrow K^- \mu^+ \nu$, $\Lambda_b \rightarrow p \mu \nu$

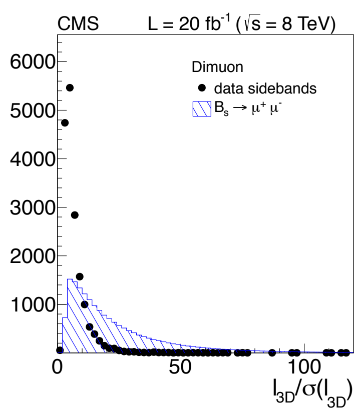


Discriminating variables

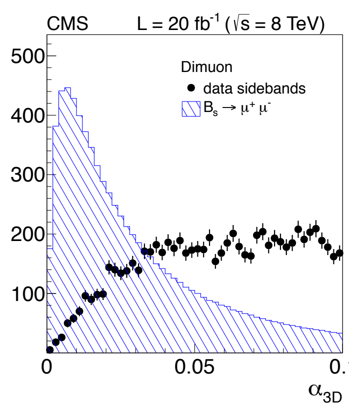
- **Boosted decision tree (BDT) selection**
  - 12 input variables: kinematic, Tracker only, Muon only,Tracker+Muon variables
  - Trained on signal MC sample and dimuon mass sidebands from data
- **Same BDT for normalisation ($B^+ \to J/\psi K$) and control ($B_s \to J/\psi\phi$) channels**
- **Robustness studies**
  - Insensitive to invariant mass using MC signal events with shifted mass
  - Output independent on high- or low-mass sideband
  - Insensitive to multiple collisions (pileup)



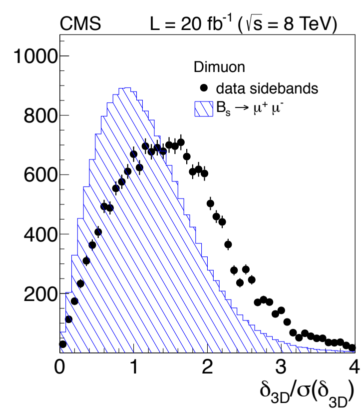
Examples of background separation variables



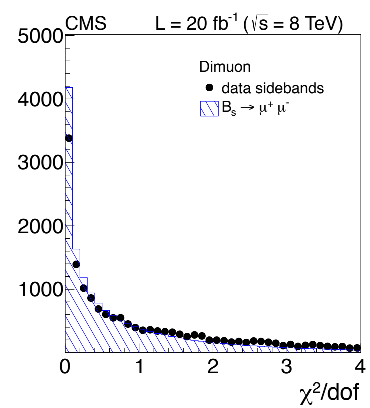
Flight length significance



Pointing angle



Impact parameter significance



B-vertex reduced chi²

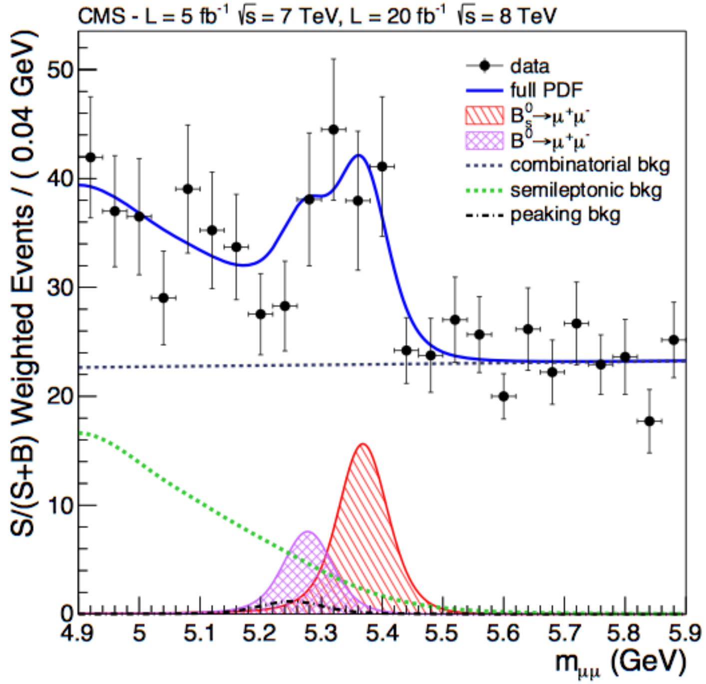
Branching ratio measurement

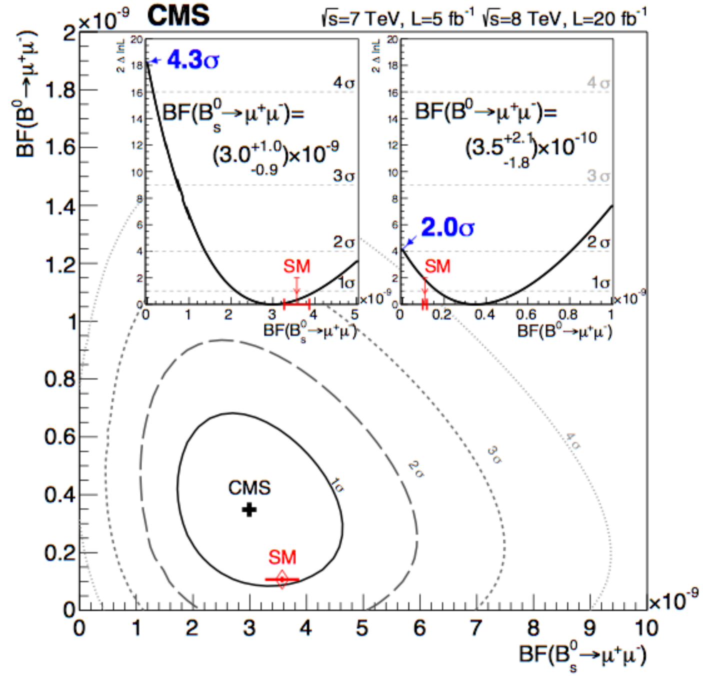
- BDT output divided into 4 (2) bins for 2012 (2011) data and barrel/endcap categories
- Simultaneous UML fit of B_s and B^0 candidates:
  - B^s and B^0 decays signal
  - Peaking backgrounds (e.g. $B^0 \to K\pi$, $B_s \to KK$)
  - Rare s-l backgrounds (e.g. $\Lambda_b \to p\mu\nu$)
  - Combinatorial background
- Event-per-event mass resolution included

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

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

Significance:
$B_s \to \mu\mu$: 4.3 σ (exp. median 4.8 σ)
$B^0 \to \mu\mu$: 2.0 σ





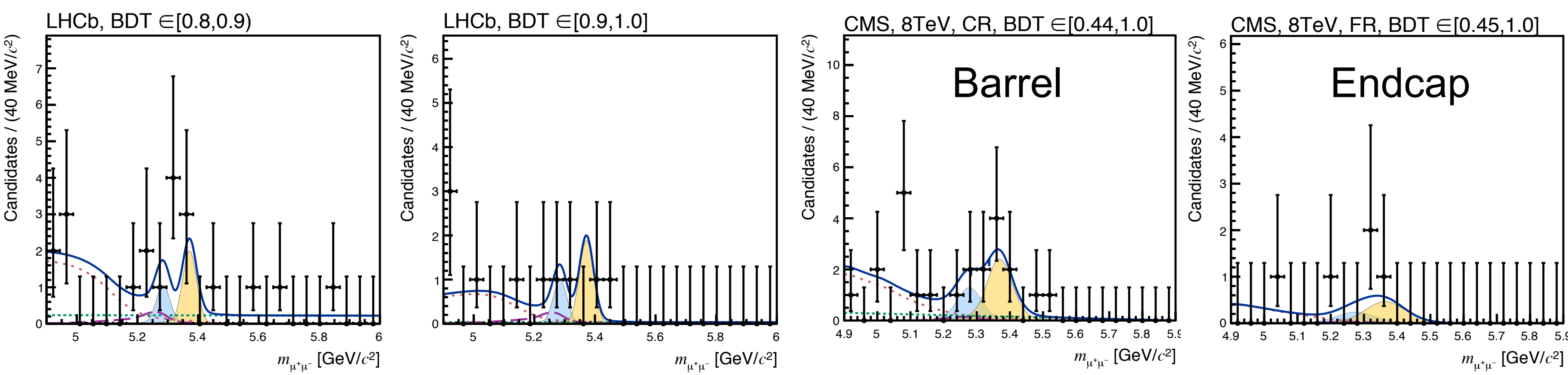
PRL 111 (2013) 101804

Combined CMS+LHCb analysis

- **Combined analysis of CMS and LHCb data submitted very recently** [arXiv:1411.4413]
  - Combines 25/fb (CMS) and 3/fb (LHCb) collected in 2011-12
  - A total of **20 event categories** defined by:
    - **BDT ranges** (LHCb,CMS), √**s** and **detector region** (CMS)
  - $Br(B_{s,d} \to \mu\mu)$, the hadronisation fraction ratio f_d/f_s, and $Br(B^+ \to J/\psi K^+)$ treated as common parameters.

New!

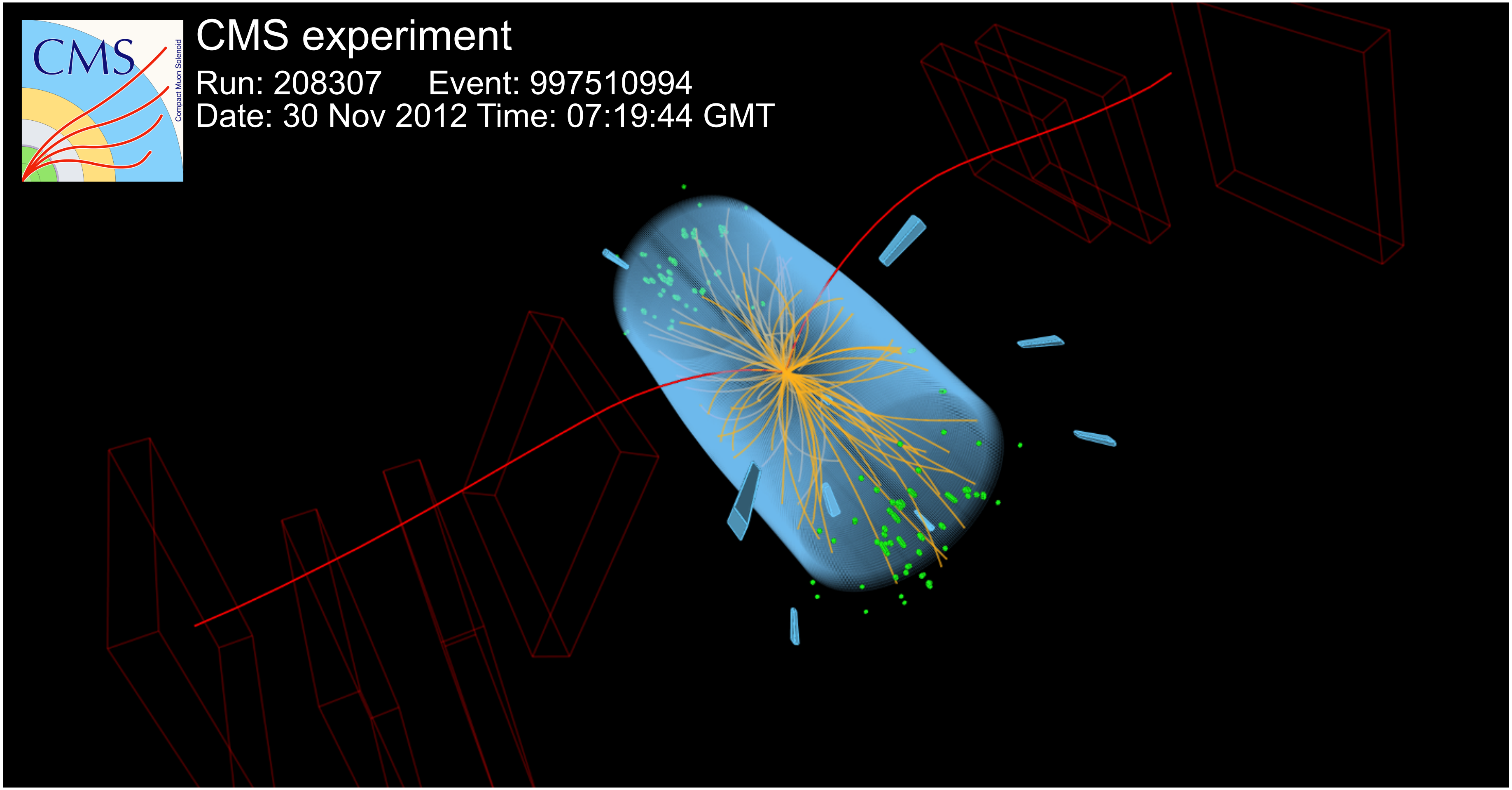
- **Updates to CMS analysis since PRL paper:**
  - $\Lambda_b \to p\mu\nu$ branching ratio updated to recent prediction: $(4.94 \pm 2.19)\times10^{-4}$
  - Semileptonic phase space used for $\Lambda_b \to p\mu\nu$ decay mode
  - Introduce decay time bias correction to signal acceptance in each category



LHCb: most sensitive categories

*See dedicated talk by **M.Schlupp** in parallel session*

CMS candidate event

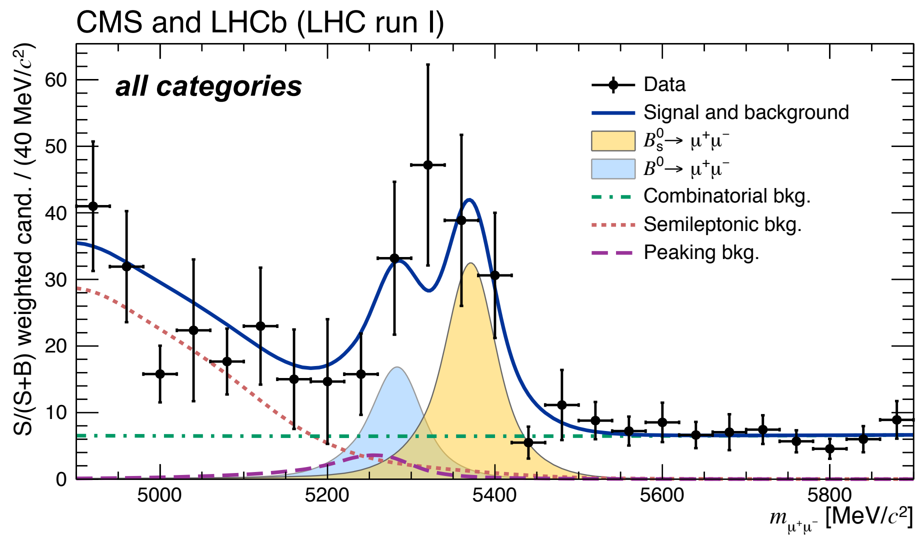


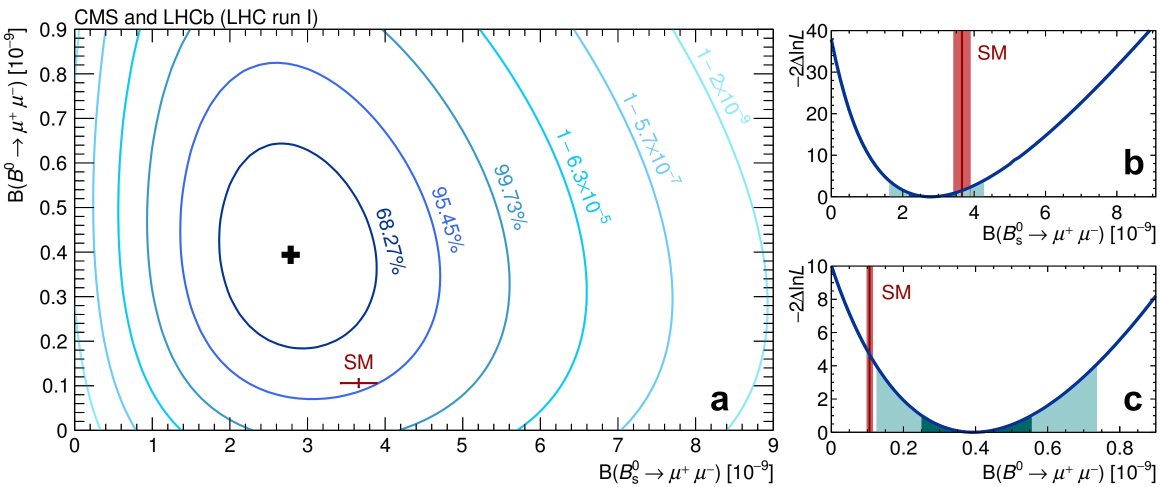
Combined CMS+LHCb analysis

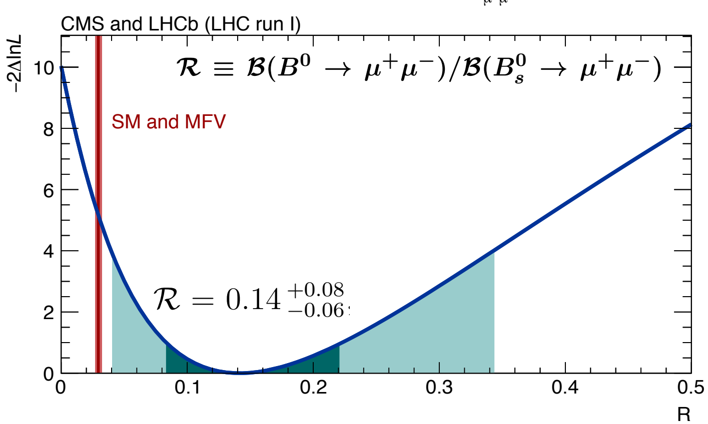
- **Results:**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

- **Observed (Expected) significance**
  - B_s: 6.2σ (7.4σ)
  - B^0: 3.2σ [WT], 3.0 [FC]σ (0.8σ)







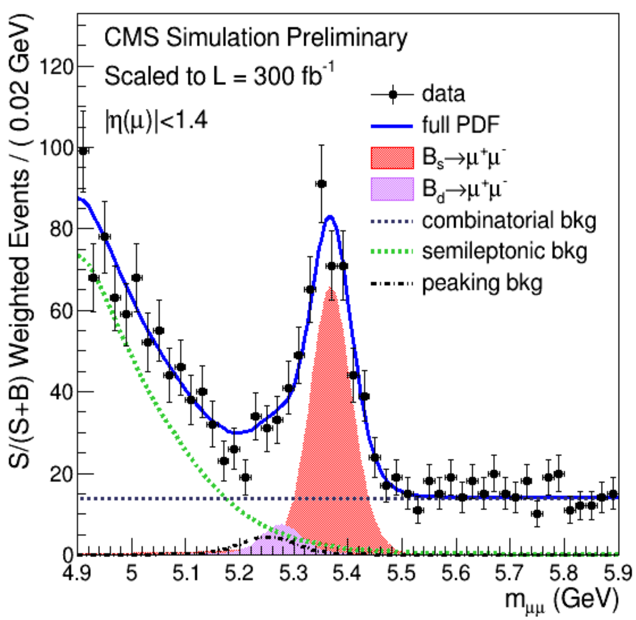
"The combined analysis of data from CMS and LHCb, […] establishes conclusively the existence of the $B_s^0 \to \mu^+\mu^-$ decay and provides an improved measurement of its branching fraction."

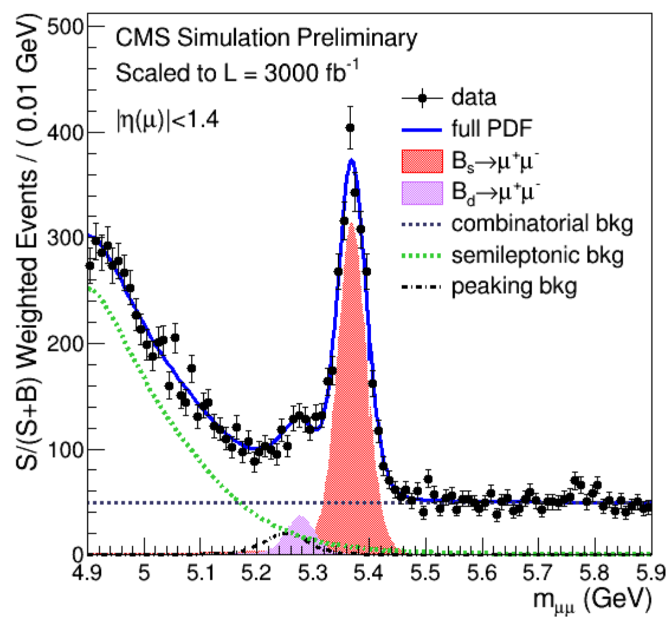
Future sensitivity

- Extrapolations using Phase I/II detector setups and L1 triggers
- Invariant mass resolution from full GEANT4 simulation
- Restrict analysis to barrel region

New!

	Mass resolution	$\delta Br[B_s(\mu\mu)]$	$\delta Br[B^0(\mu\mu)]$	δR	$B^0(\mu\mu)$ Sign.
Phase 1 (300/fb)	42 MeV	13%	48%	50%	2.2σ
Phase 2 (3000/fb)	28 MeV	11%	18%	21%	6.8σ



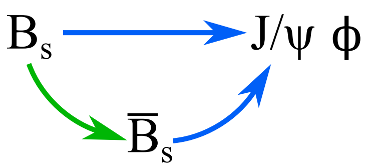


ECFA 2014 - FTR-14-015


CP Violation in
$B_s \to J/\psi\phi$ decays

CP violation in B_s decays

- B_s mesons **mix with relatively large decay width difference** ($\Delta\Gamma_s$) between the two mass eigenstates
- Final state of the $B_s \rightarrow J/\psi(\mu\mu)\varphi(KK)$ decay is accessible by both B_s and B_s
- The weak phase ϕ_s arises from the **quantum interference** between direct and mixing-mediated decays



$$\phi_s \simeq -2\beta_s,\ \beta_s = \arg(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*})$$

$$2\beta_s = [0.0363^{+0.0016}_{-0.0015}]\ \text{rad in the SM}$$ [1]

- **Precise SM predictions** for ϕ_s (4% uncertainty) and **experimentally clean final state** ($\mu\mu$KK) with low background
- Several new physics scenarios predict **enhanced values of ϕ_s**
- Final state with two vector mesons: **mixture of CP-even and CP-odd states**

[1] [PRD 84, 033005 (2011)]

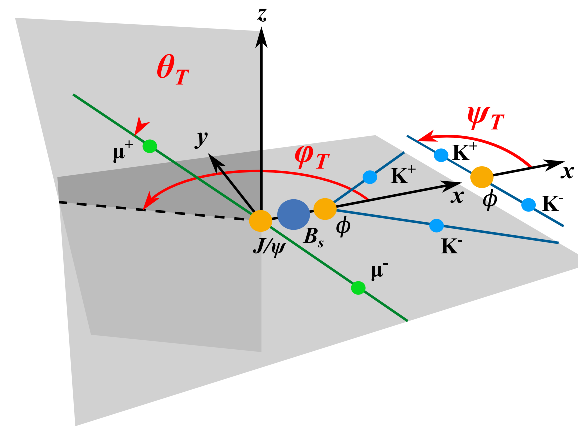
Decay analysis

- **Time dependent** and **flavour tagged angular analysis** to disentangle CP states
- **Opposite-side lepton tagger** to determine Bs flavour at production time: $P_{tag}=\epsilon(1-2\omega)=(0.97\pm0.04)\%$

physics parameters to be determined — decay angles

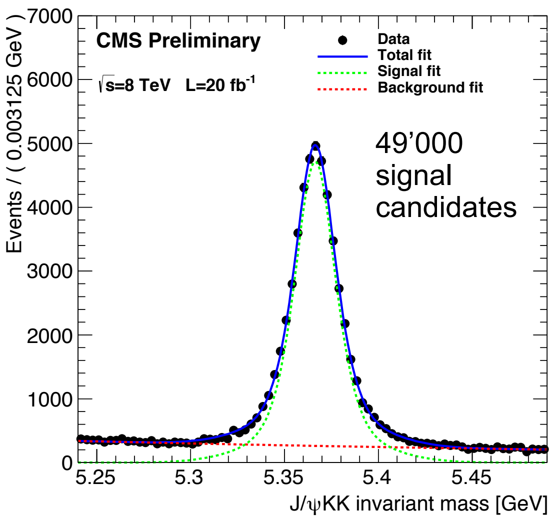
$$\frac{d^4\Gamma(B_s)}{d\Theta dt} = X(\Theta,\alpha,t) = \sum_{i=1}^{10} O_i(\alpha,t)\cdot g_i(\Theta)$$

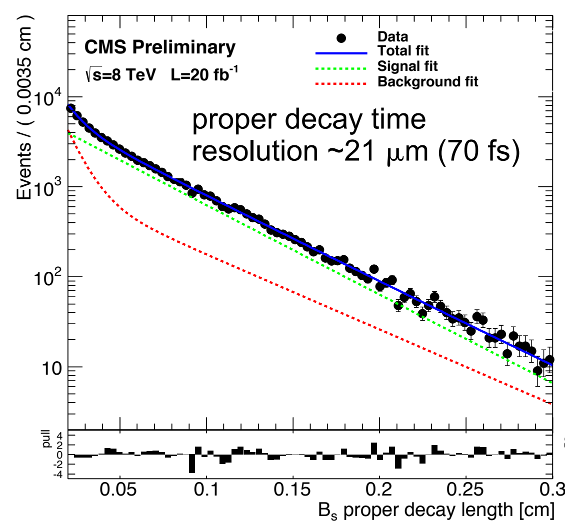
B_s proper decay time

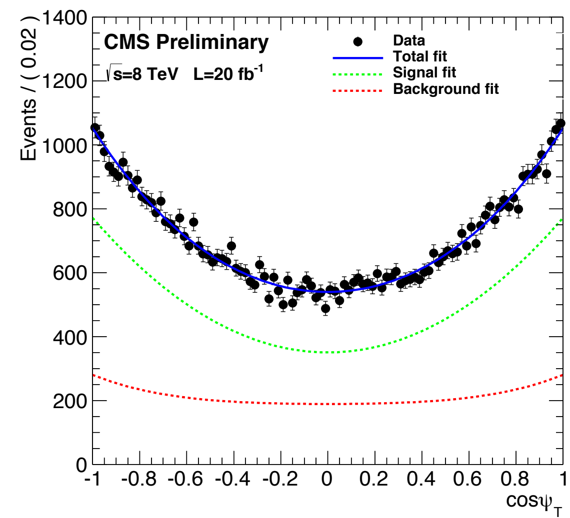


$$O_i(\alpha,t) \propto e^{-\Gamma_s t}\left[a_i\cosh(\tfrac{1}{2}\Delta\Gamma_s t) + b_i\sinh(\tfrac{1}{2}\Delta\Gamma_s t) + c_i\cos(\Delta m_s t) + d_i\sin(\Delta m_s t)\right]$$

depend on $\cos\phi_s$ and $\sin\phi_s$







CMS PAS BPH-13-012

Fit results and uncertainties

Parameter	Fit result
$\|A_0\|^2$	0.511 ± 0.006
$\|A_S\|^2$	0.015 ± 0.016
$\|A_\perp\|^2$	0.242 ± 0.008
$\delta_\parallel$	3.48 ± 0.09 rad
$\delta_{S\perp}$	0.34 ± 0.24 rad
$\delta_\perp$	2.73 ± 0.36 rad
$c\tau$	$447.3 \pm 3.0\ \mu$m
$\Delta\Gamma_s$	0.096 ± 0.014 ps^{-1}
ϕ_s	-0.03 ± 0.11 rad

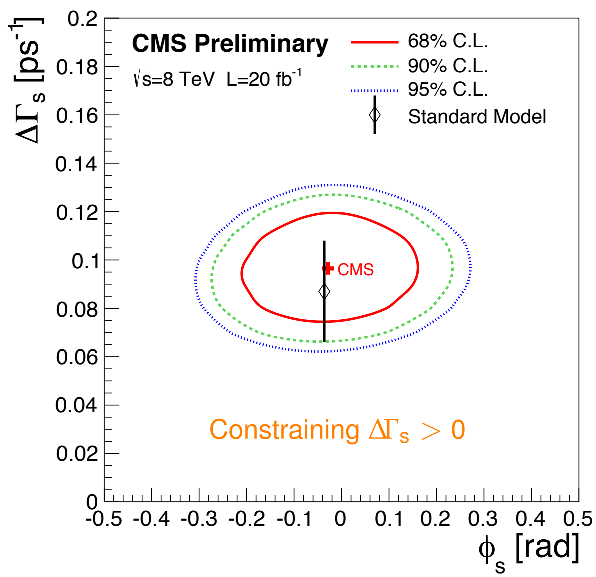
Source	$\|A_0\|^2$	$\|A_S\|^2$	$\|A_\perp\|^2$	$\Delta\Gamma_s$ [ps^{-1}]	$\delta_\parallel$ [rad]	$\delta_{S\perp}$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$c\tau$ [μm]
Statistical uncertainty	0.0058	0.016	0.0077	**0.0138**	0.092	0.24	0.36	**0.109**	3.0
Proper time efficiency	0.0015	-	0.0023	**0.0057**	-	-	-	**0.002**	1.0
Angular efficiency (*)	0.0060	0.008	0.0104	**0.0021**	0.674	0.14	0.66	**0.016**	0.8
Model bias (**)	0.0008	-	-	**0.0012**	0.025	0.03	-	**0.015**	0.4
Proper time resolution	0.0009	-	0.0008	**0.0021**	0.004	-	0.02	**0.006**	2.9
Background mistag modelling	0.0021	-	0.0013	**0.0018**	0.074	1.10	0.02	**0.002**	0.7
Flavour tagging	-	-	-	**-**	-	-	0.02	**0.005**	-
PDF modelling	0.0016	0.002	0.0021	**0.0021**	0.010	0.03	0.04	**0.006**	0.2
Free $\|\lambda\|$ fit (***)	0.0001	0.005	0.0001	**0.0003**	0.002	0.01	0.03	**0.015**	-
Kaon p_T re-weighting (****)	0.0094	0.020	0.0041	**0.0015**	0.085	0.11	0.02	**0.014**	1.1
Total systematics	0.0116	0.022	0.0117	**0.0073**	0.684	1.12	0.66	**0.032**	3.5

(*) evaluated from the statistical uncertainty of the model

(**) determined from toy MC bias tests

(***) let $|\lambda|$ as a free parameter in the fit

(****) propagated from discrepancy between data and simulations

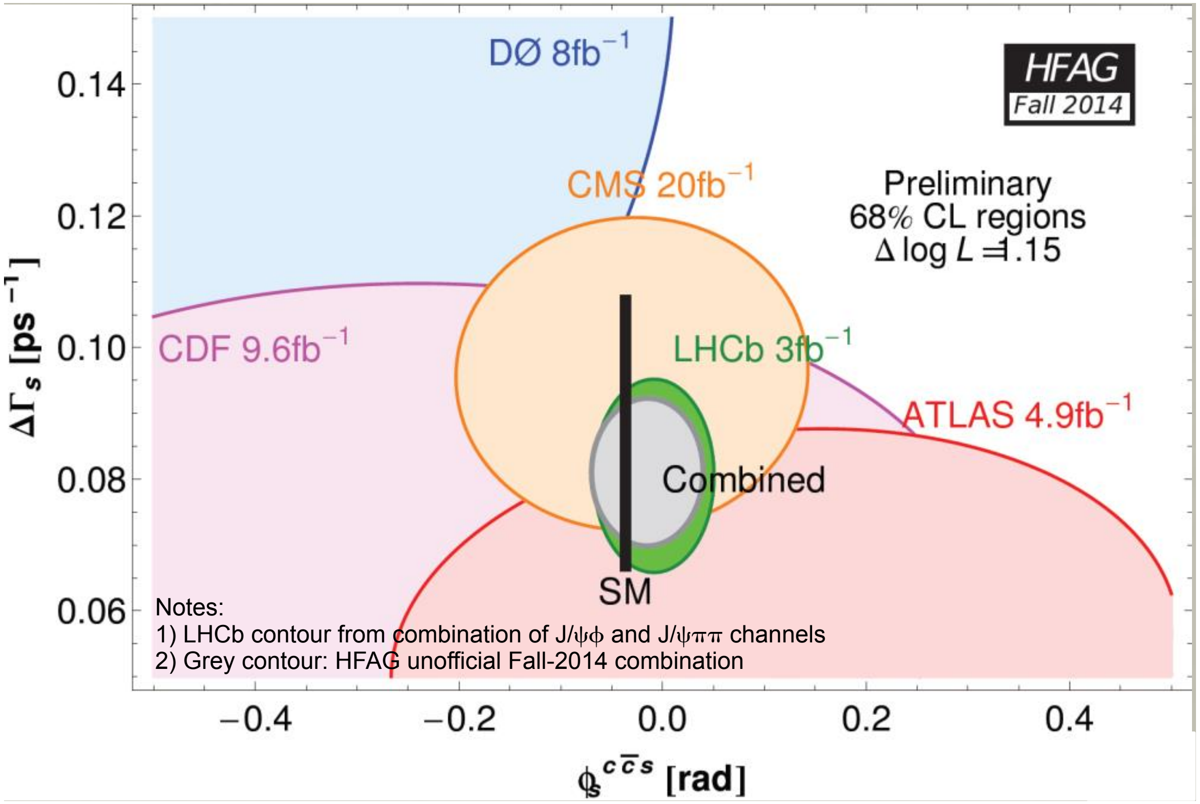


$$\phi_s = -0.03 \pm 0.11(\text{stat.}) \pm 0.03(\text{syst.})\ \text{rad}$$

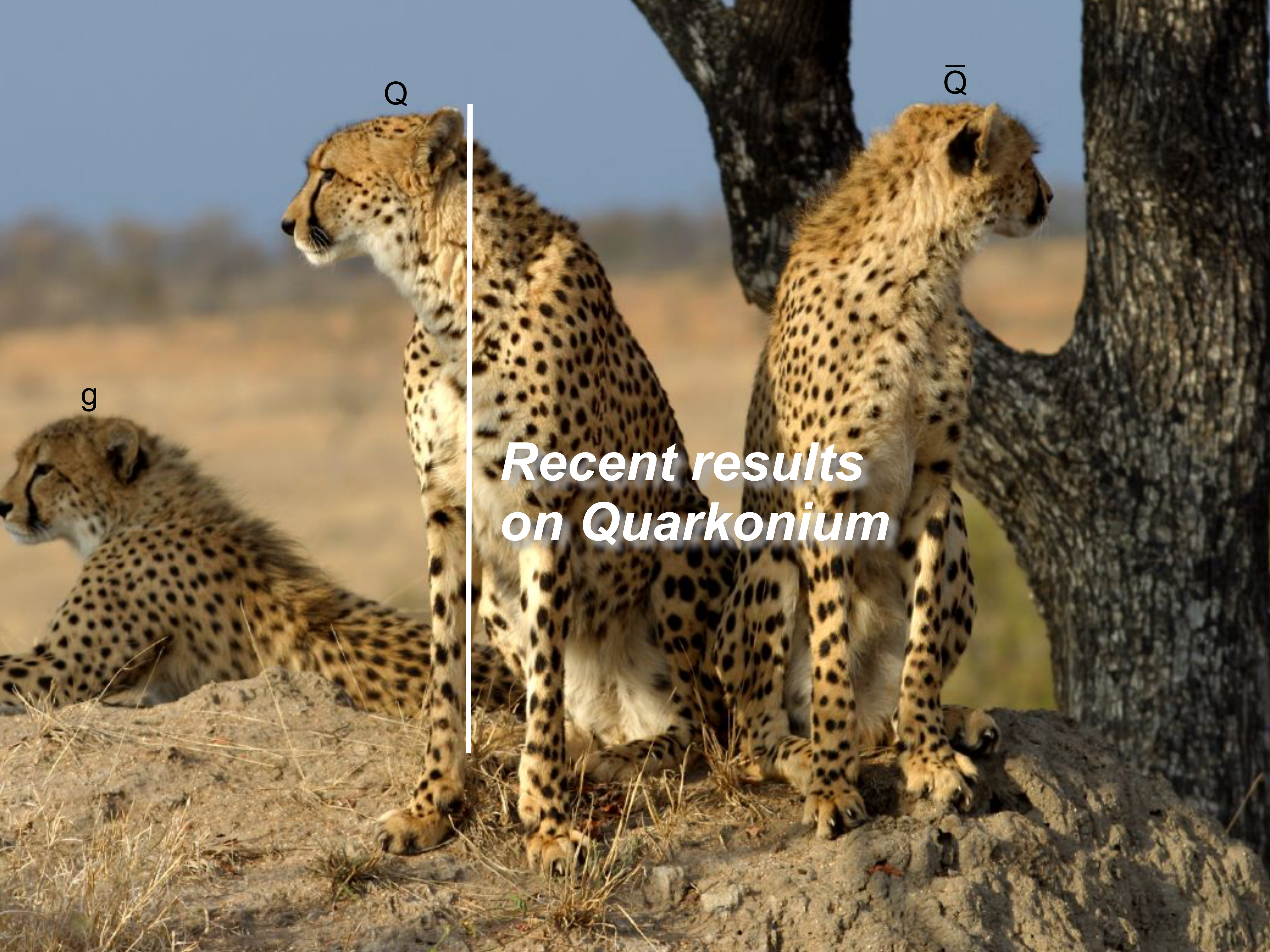
$$\Delta\Gamma_s = 0.096 \pm 0.014(\text{stat.}) \pm 0.007(\text{syst.})\ \text{ps}^{-1}$$

- **$\Delta\Gamma_s$ confirmed to be non zero**
- **Very competitive ϕ_s determination**
- **Good agreement with SM**
- **Statistical uncertainties dominant**

World summary



Experiment	$\Delta\Gamma_s$ (ps^{-1})	ϕ_s (rad)
ATLAS (4.9/fb)	0.053±0.021±0.010	0.12±0.25±0.05
CMS (20/fb)	0.096±0.014±0.007	−0.03±0.11±0.03
LHCb (3/fb)	0.0805±0.0091±0.0032	−0.058±0.049±0.006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Recent results
on Quarkonium

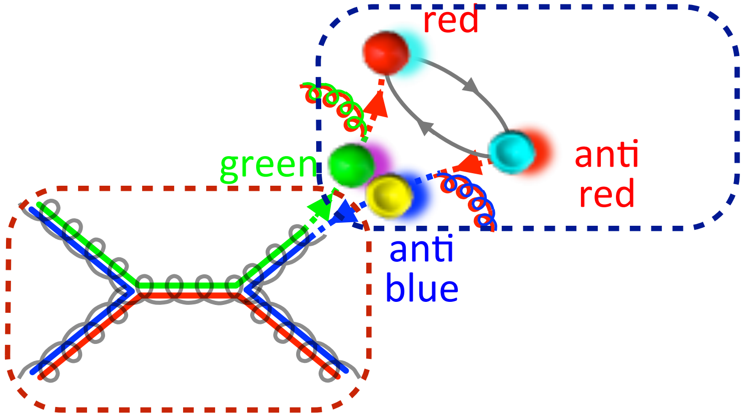
Quarkonium production

- Study of quarkonium (cc and bb) production tests key aspects of QCD phenomenology:
  - Perturbative QCD, hadron formation, non-relativistic QCD (NRQCD), factorisation, etc.
- CMS has released a set of production and polarisation measurements for s-wave and p-wave quarkonium states

Perturbative QCD — Long-distance matrix elements

$$\sigma(\mathcal{Q}) = \sum_n \mathcal{S}[q\bar{q}(n)] \langle \mathcal{O}^Q(n) \rangle$$

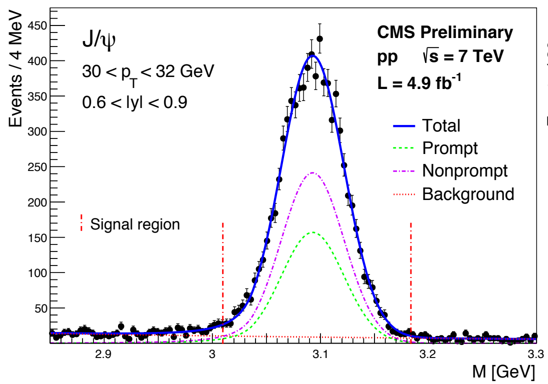
$$n = {}^{2S+1}L_J^{[C]} \qquad [C]=1,8$$

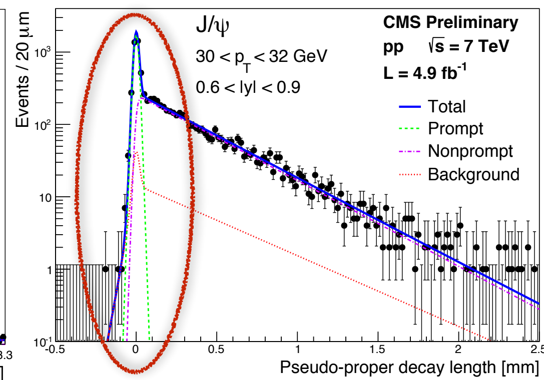


- Conjecture: long-distance matrix elements are independent on momentum and production process
- Constrained by cross section and polarisation measurements

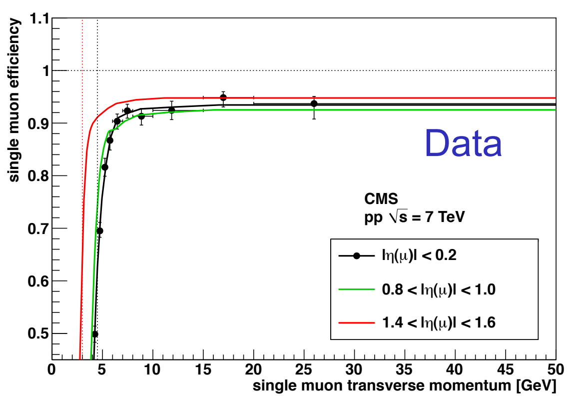
*See dedicated talk by **I.Kratschmer** in parallel session*

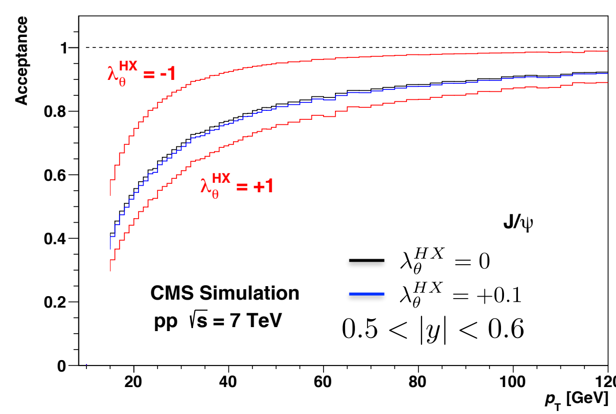
- New results based on 2011 data extend p_T reach to 120 GeV (100 GeV) for J/ψ (ψ')
- Yields extracted from combined fit to the mass and proper decay length distributions





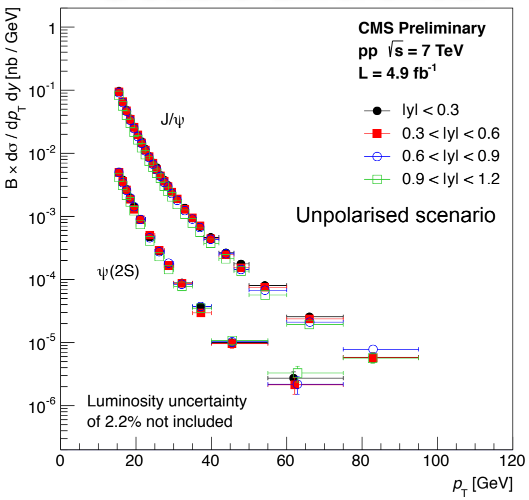
- Single muon efficiency measured from data and dimuon correlations from MC
- Acceptance computed for different polarisation scenarios



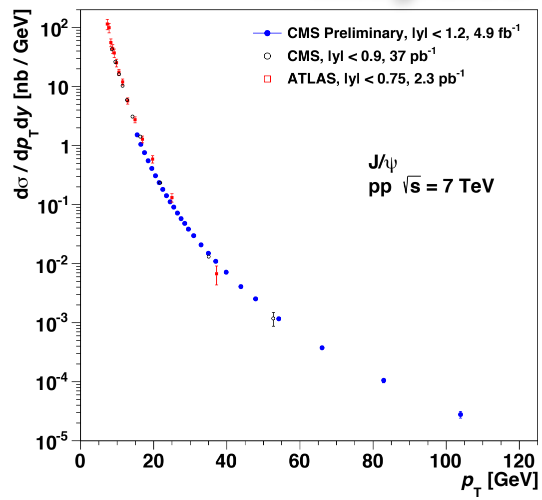


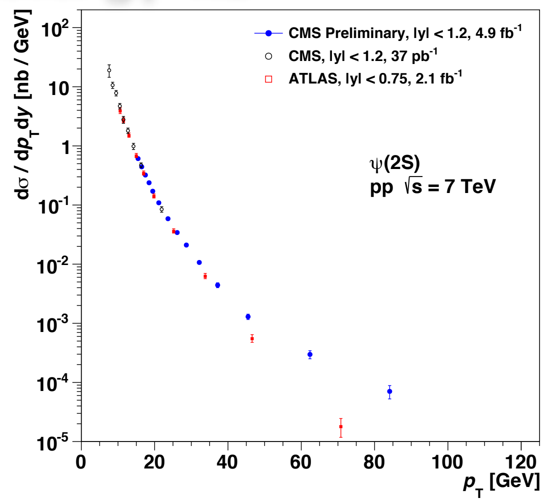
J/ψ and ψ(2S) production

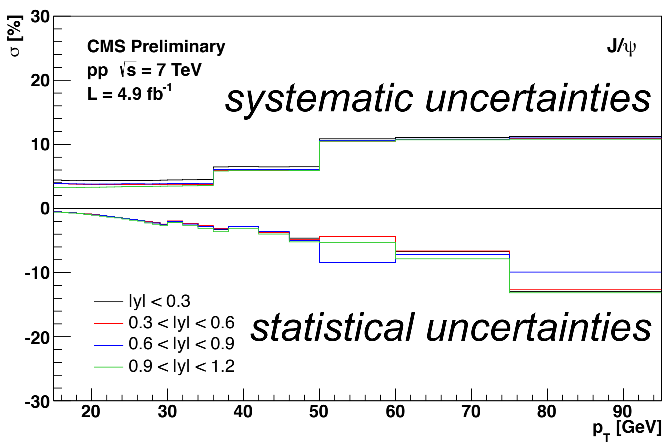
Double differential

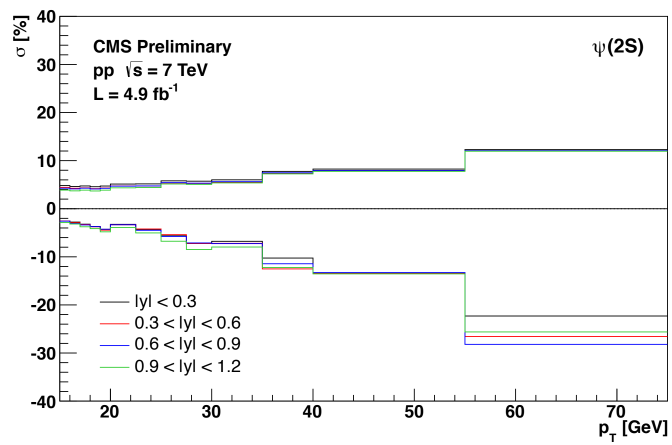


Integrated over |y|<1.2





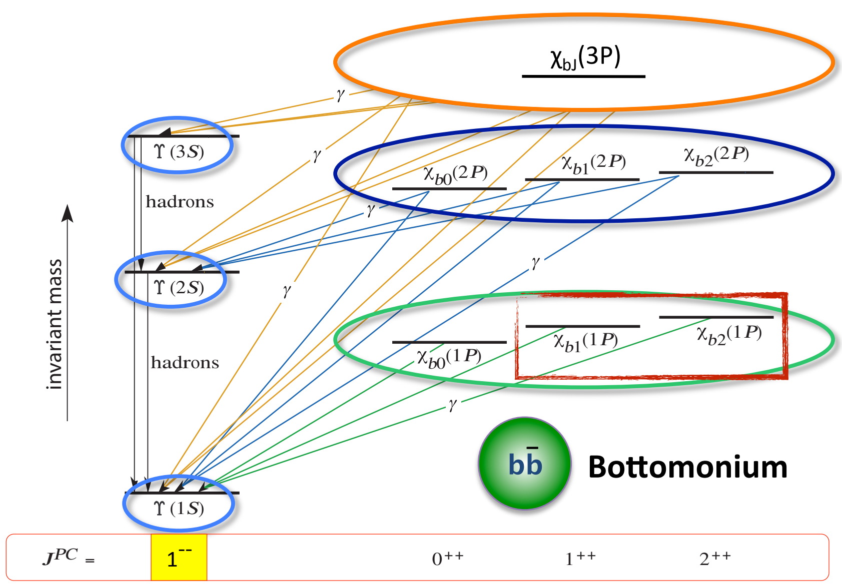


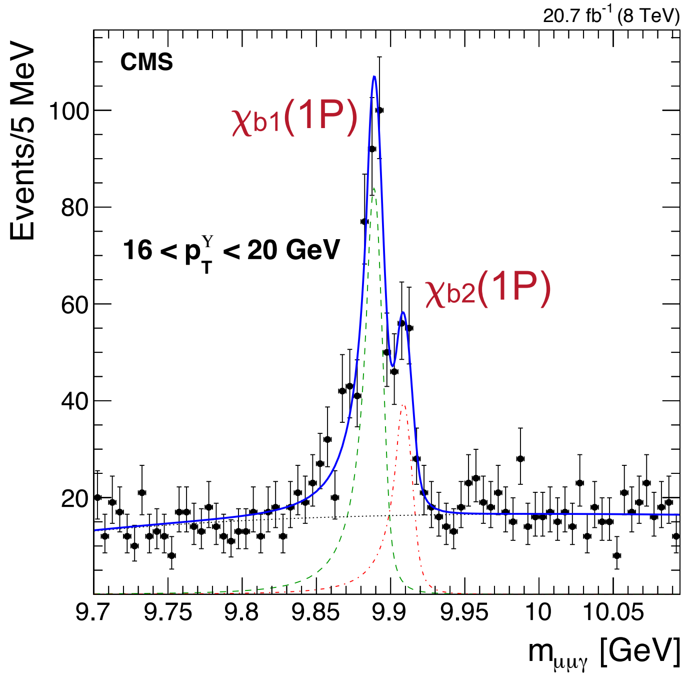


Key results for testing predictions at large transverse momenta

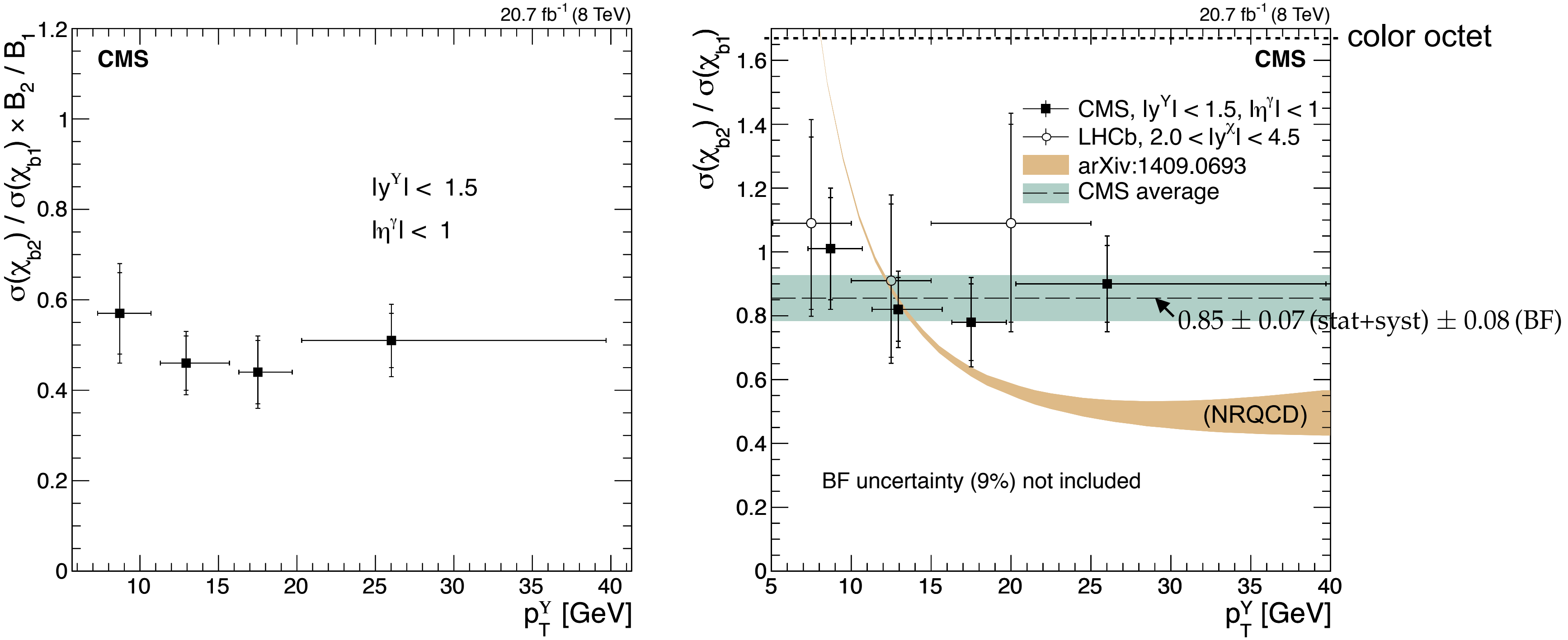
P-wave bottomonium

- Υ(1S, 2S, 3S) resonances and ratios well studied, much less known about P–waves
  - P-wave states provide complementary information about NRQCD, as they depend on long distance matrix elements of the color octets
  - Quarkonium polarization measurements so far are limited to S-wave states
  - Decays from P-wave states non-negligible effects on measurements.
- CMS has the most precise differential measurement in of $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b2}(1P))$ at the LHC
  - Experimentally quite challenging, small mass difference (19.4 MeV)
  - Use photon conversions to reconstruct Υ(1S)+γ final state in four p_T bins





P-wave bottomonium



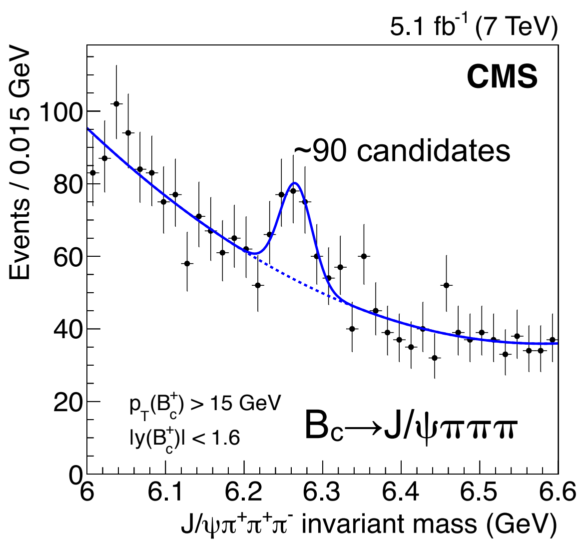
- Data do not exhibit strong p_T^{Υ} dependence and closer to color-singlet predictions
  - χ_b three times heavier than χ_c and relative velocity of QQ pair is 3 times smaller
  - Impact of color octet is expected to be smaller than in χ_c case
  - No cross section data available yet to extract χ_b NRQCD parameters. Simple scaling from χ_c fits is used

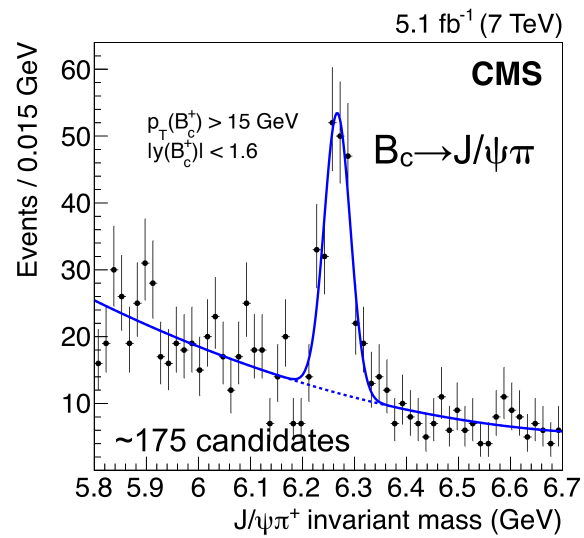

B_c studies and
a new B^+ rare decay

B_c decays

arXiv:1410.5729

- B_c is the lightest meson with two heavy quarks of different flavour
  - Excellent laboratory to study heavy quark dynamics, unprecedented rates at LHC
- CMS confirms the $B_c \to J/\psi\pi\pi\pi$ decays and measures the ratio to $J/\psi\pi$ and $B^+ \to J/\psi K$





Predictions

1.9-2.3 (*)

$$R_{B_c} = \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst})\,^{+0.04}_{-0.01}\,(\tau_{B_c})$$

covers lifetime uncertainty

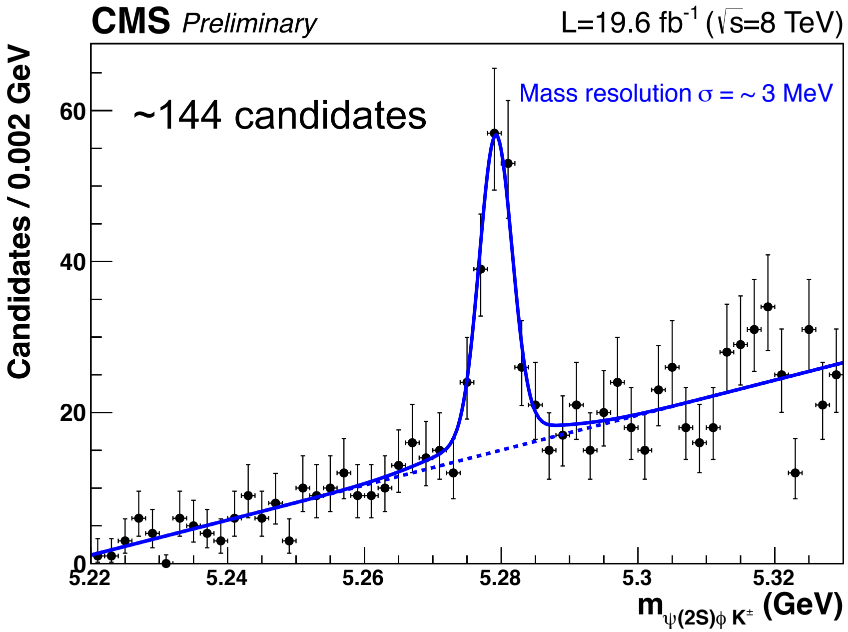
$p_T > 15\,\text{GeV}$, $|y| < 1.6$

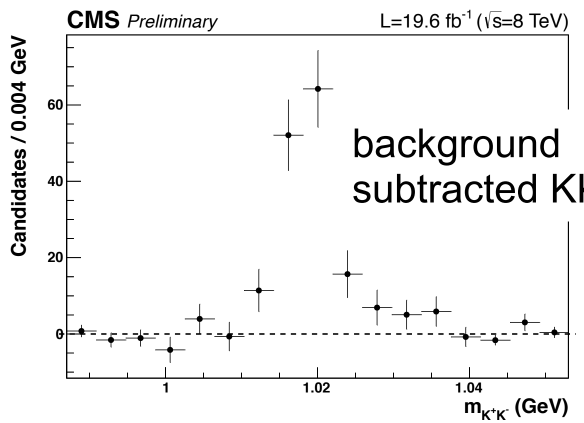
$$R_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = [0.48 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})]\%$$ **CMS**

$p_T > 4\,\text{GeV}, 2.5 < \eta < 4.5$ $\quad [0.68 \pm 0.10\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})]\%$ **LHCb (NB: softer p_T)**

(*) PRD 81, 014015 - range covers different form factors

New decay: $B^+ \to \psi(2S)\phi K^+$





New!

- Study of resonant structures in $B^+ \to J/\psi\phi K^+$ decays lead to the first observation of the rare decay $B^+ \to \psi(2S)\phi K^+$
- Ongoing: measurement of branching ratio

CMS BPH-13-009 Paper in preparation

Summary

- The excellent performance of the CMS detector and LHC have allowed key contributions to the field heavy flavor physics
  - The CMS and LHCb collaborations have finally nailed down the $B_s \rightarrow \mu\mu$ rare decay and will keep hunting for the even rarer $B^0 \rightarrow \mu\mu$ during run 2. No surprises so far.
  - CMS has the second most precise determination of the CP violating fase ϕ_s and lifetime difference in B_s decays. Amazing agreement between experiments and with SM.
  - Prompt charmonium measurements have been extended beyond p_T=100 GeV. P-wave quarkonium studied differentially.
  - New measurements of B_c production will help understanding heavy quark dynamics
  - New B+ rare decay discovered!


Thanks to the
organizers
for this
wonderful
experience!

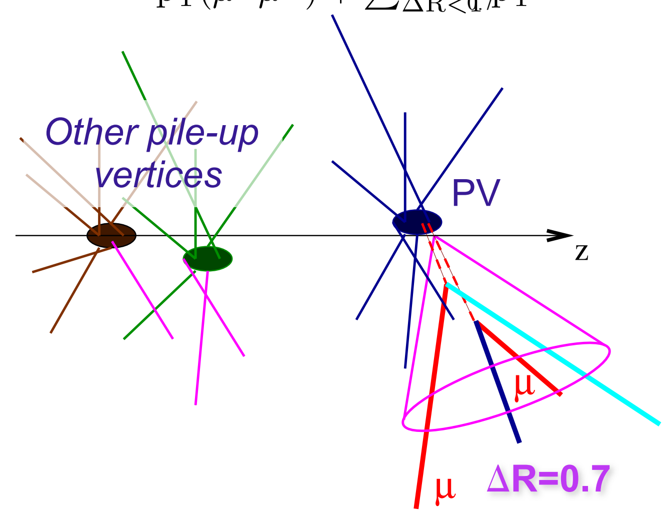
BACKUP SLIDES

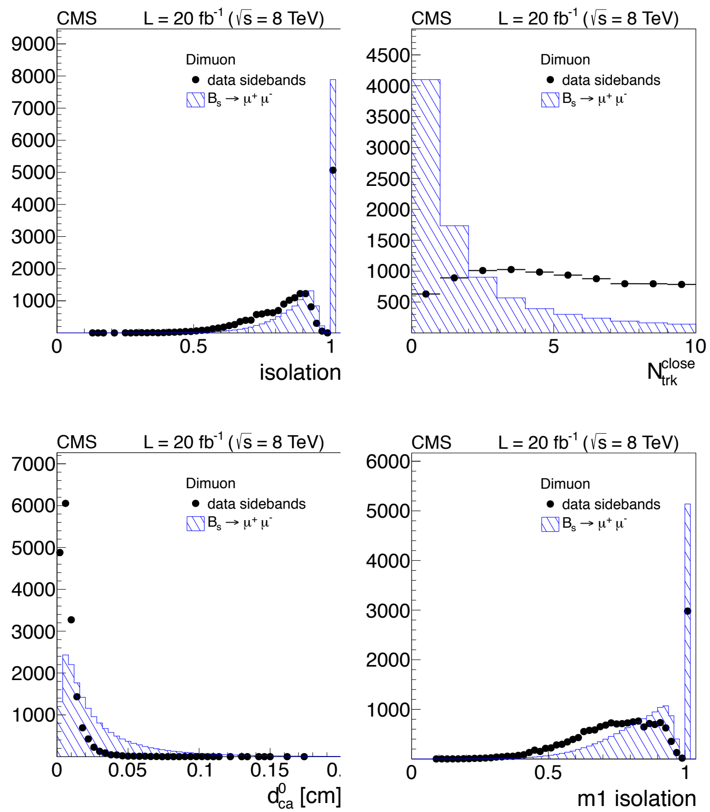
Isolation variables

Relative isolation of muon pairs

- Cone with ΔR=0.7 around di-muon momentum
- Include all tracks with p_T>0.9 GeV from same PV or d_{CA}<500 μm from B vertex
- Dip at ~0.97 from minimum track p_T requirement

$$\text{Isolation} = \frac{p_T(\mu^+\mu^-)}{p_T(\mu^+\mu^-) + \sum_{\Delta R<0.7} p_T}$$





B-vertex isolation

- either tracks not associated to any primary vertex or tracks associated to the same B candidate
- Distance of the closest track to SV (d_{ca})
- Number of close tracks in d_{ca}<300 μm and p_T>0.5 GeV

Muon isolation

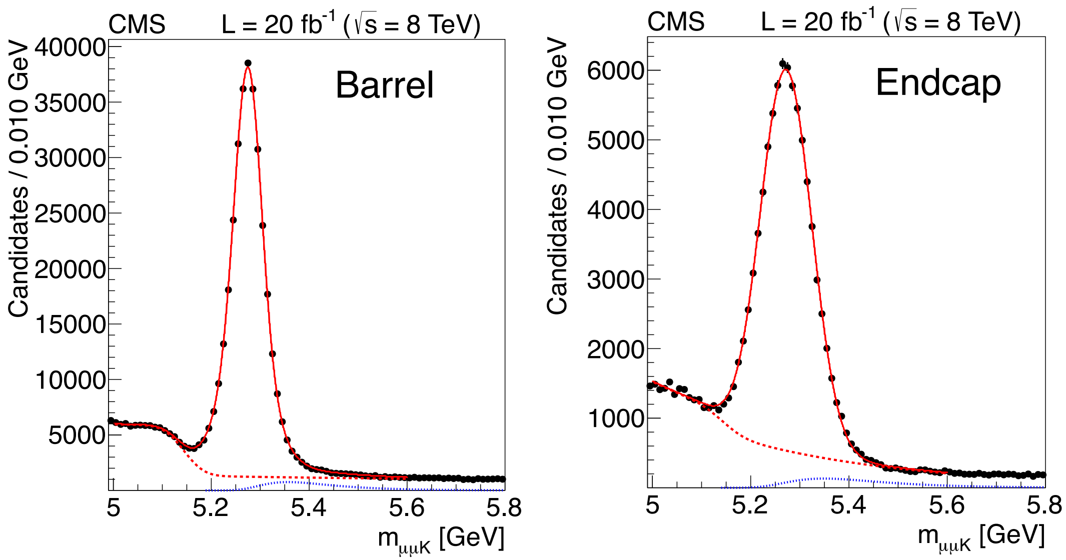
- tracks in muon cone with ΔR=0.5

Signal normalization

- **Branching ratios calculated w.r.t. normalization channel $B^+ \to J/\psi(\mu^+\mu^-)K^+$**
  - Many systematic uncertainties cancel in ratio
  - No need for absolute luminosity and b-quark cross section
  - Large B^+ yield and well known branching ratio to $J/\psi K^+$ (3% uncertainty)
  - Ratio of b-quark fragmentation fractions to B_s/B^+: f_s/f_u**=(256±20)×10^{-3}** [JHEP 04 (2013) 001]

From LHCb

$$\mathrm{Br}(\mathrm{B_s} \to \mu^+\mu^-) = \frac{\mathrm{N}(\mathrm{B_s} \to \mu^+\mu^-)}{\mathrm{N}(\mathrm{B}^+ \to \mathrm{J}/\psi \mathrm{K}^+)} \frac{\mathrm{f_u}}{\mathrm{f_s}} \frac{\epsilon^{\mathrm{B}^+}_{\mathrm{tot}}}{\epsilon^{\mathrm{B_s}}_{\mathrm{tot}}} \mathrm{Br}(\mathrm{B}^+ \to \mathrm{J}/\psi \mathrm{K}^+)$$



2011-12
B^+ Candidates:
380×10^3 barrel
90×10^3 endcap

Bs(mm) BDT validation

- Use differences between data and MC for systematics
  - $B^{\pm} \to J/\psi K^{\pm}$ 3% ; $B_s \to J/\psi \phi$ 9.5% (2011) and 3.5% (2012)