Electroweak Heavy Flavor Measurements with ATLAS and CMS

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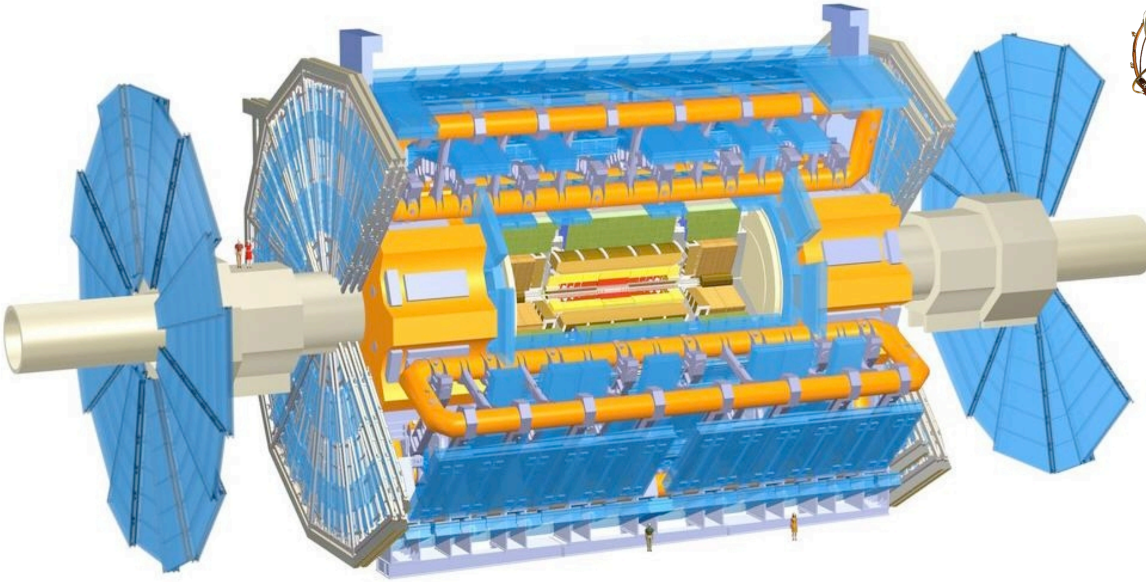
Outline

- Introduction: rationale
- ATLAS and CMS
- $B_{s,d} \longrightarrow \mu\mu$: latest CMS result, combination with LHCb, discussion
- $B_0 \longrightarrow K^*\mu\mu$: ATLAS and CMS analyses
- $B_s \longrightarrow J/\psi\ \phi$, latest analysis from ATLAS
- Summary and outlook

Introduction: rationale

The Heavy Flavor sector, or : “why are we doing all this ?”

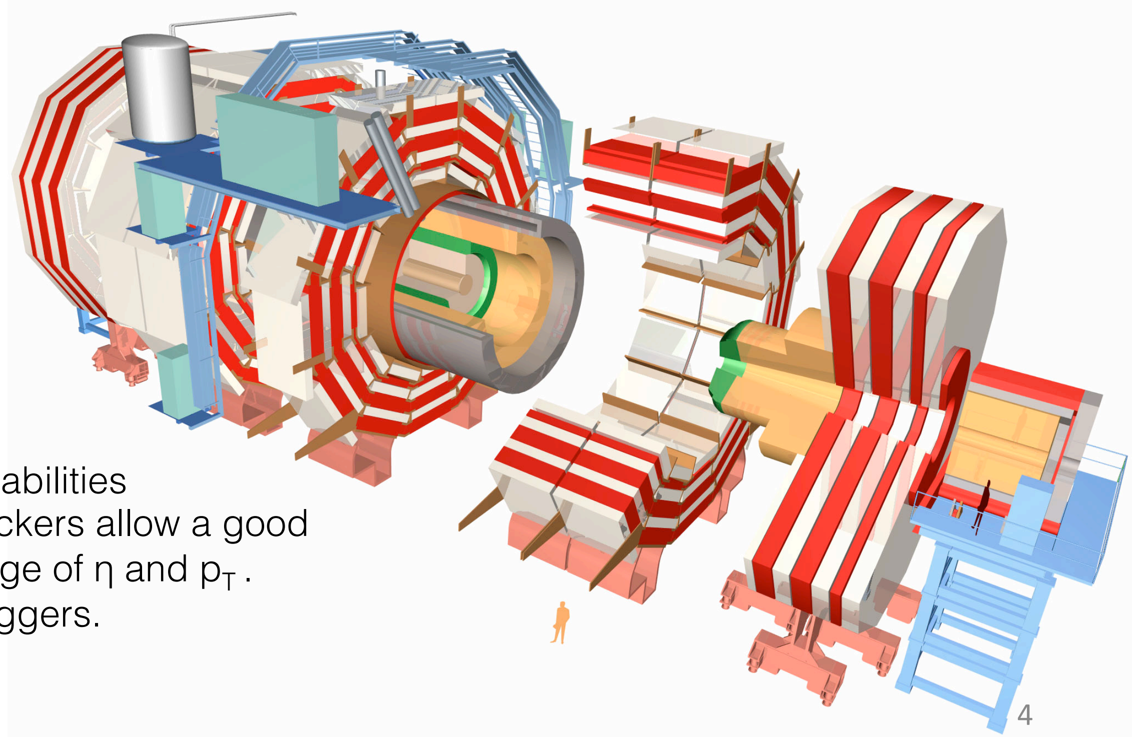
- Chance to probe high mass scales by exploiting the sensitivity of certain processes to diagrams containing virtual quantum loops
- Indirect search for New Phenomena
- Eventually explain puzzles as the origin of flavor, the hierarchy problem and the matter-antimatter asymmetry
- “Observing new sources of flavor mixing (..) is a natural expectation of the SM with new d.o.f. not far from the TeV scale” [arXiv:1302.0661]
- Absence, so far, of NP at LHC: if the NP scale is currently above the reach of direct searches, this might be the only option.



Axial B: 2T
Track p_T resolution: ~ 2.5%
lifetime resolution: ~100 fs

Flexible trigger systems

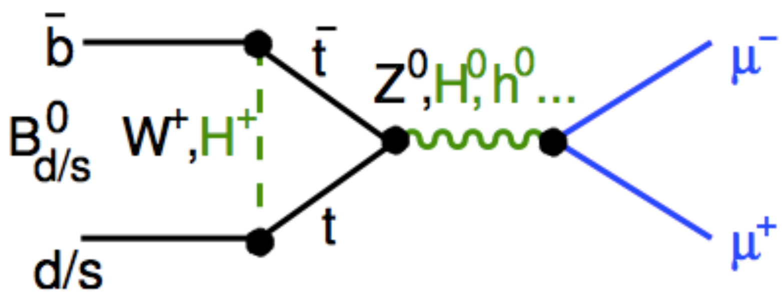
Axial B: 3.8T
Track p_T resolution: ~1%
lifetime resolution: ~70 fs

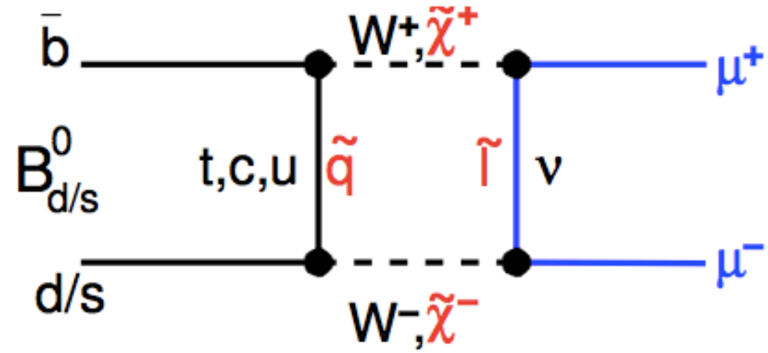


- Excellent muon, e, γ id and detection capabilities
- The muon systems, B field and silicon trackers allow a good measurement of dimuons over a wide range of η and p_T . HF analyses generally based on muon triggers.
- Limited or no hadron identification

$B_{s,d} \longrightarrow \mu\mu$

- Highly suppressed in the SM (GIM and helicity), yet theoretically clean.
- No contribution from tree level diagrams, only loop diagrams.
- Deviations from SM hint of NP "in the loops".





$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = (3.2 \pm 0.2) \cdot 10^{-9}$$
$$\mathcal{B}(B_d^0 \rightarrow \mu\mu) = (1.1 \pm 0.1) \cdot 10^{-10}$$

Buras et al., EPJC (2012) **72**: 2172

Theory ingredients:

1. Evaluation of non-radiative branching fractions
2. Treatment of soft-photon radiation (insensitive to NP)
3. Time dependence and initial state flavor (B_s)

Theory uncertainties:

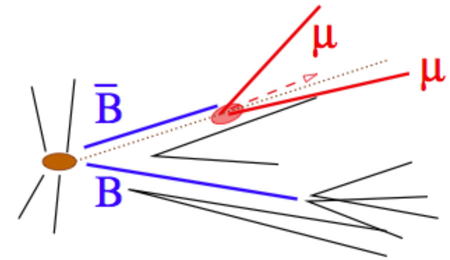
f_{Bs} from lattice calculations

higher order EWK corrections, $V_{tb}{}^*V_{ts}$, τ_{Bs}, M_t

CMS: $B_{s,d} \longrightarrow \mu\mu$

PRL 111 101804 (2013)

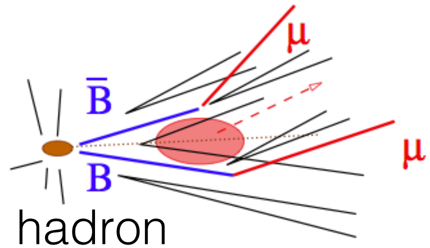
Experimental signatures and challenges



Signal

two isolated muons from a secondary vertex

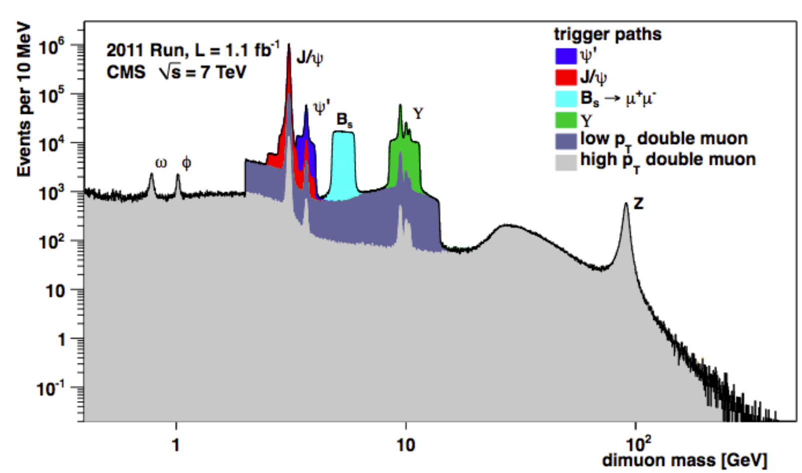
Background



- combinatorial
  - two semileptonic B decays
  - one semileptonic B decay and one misid hadron
- rare decays
  - non-peaking: $B_s^0 \to K^-\mu^+\nu$, $\Lambda_b \to p\mu\cdot\nu$
  - peaking: $B_s^0 \to K^+K^-$

Challenges

- Control muon misidentification
- Pileup
- Selection efficiency vs purity



Trigger on dimuons 2011(2012)
Central:
p_T^{μ}>4.0 (3.0) GeV, $p_T^{\mu\mu}$ >3.9(4.9) GeV, 4.8<$m^{\mu\mu}$<6.0 GeV
Forward: p_T^{μ}>4.0 GeV, $p_T^{\mu\mu}$ >7.0 GeV, vProb> 0.5%

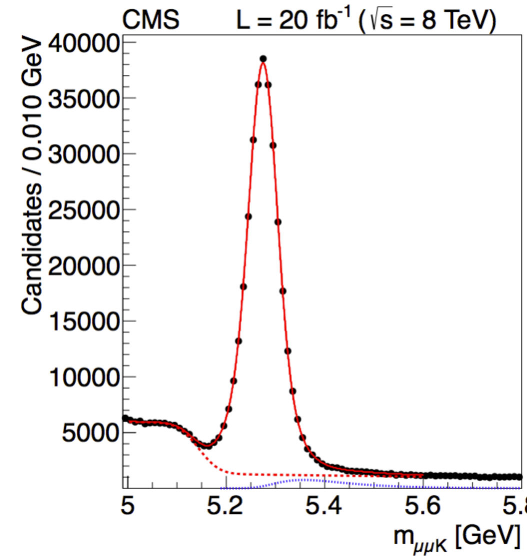
Dataset and luminosity
5 fb^{-1} (2011) + 20 fb^{-1} (2012)

CMS: $B_{s,d} \longrightarrow \mu\mu$

Strategy:

measure $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ relative to a normalization channel: $B^+ \rightarrow J/\psi K^+$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_S}{N_{\text{obs}}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\text{tot}}^{B^+}}{\varepsilon_{\text{tot}}} \mathcal{B}(B^+),$$

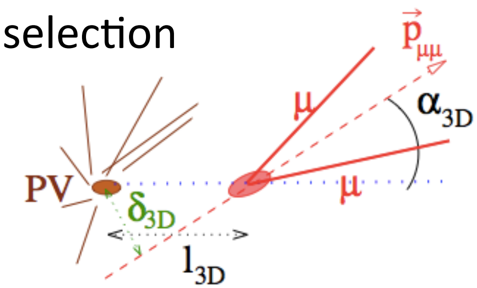


Features:

- BDT-based muon identification, high fake rejection power
- MVA selection and unbinned maximum likelihood analysis
- data blinding

Training on signal MC + background from data sidebands

12 Variables exploited for selection
- kinematic variables
- vertexing variables
- isolation variables



Data/MC agreement tested on

$B^+ \rightarrow J/\psi K^+$ and

$B_s \rightarrow J/\psi \Phi$

CMS: $B_{s,d} \longrightarrow \mu\mu$ Final Selection

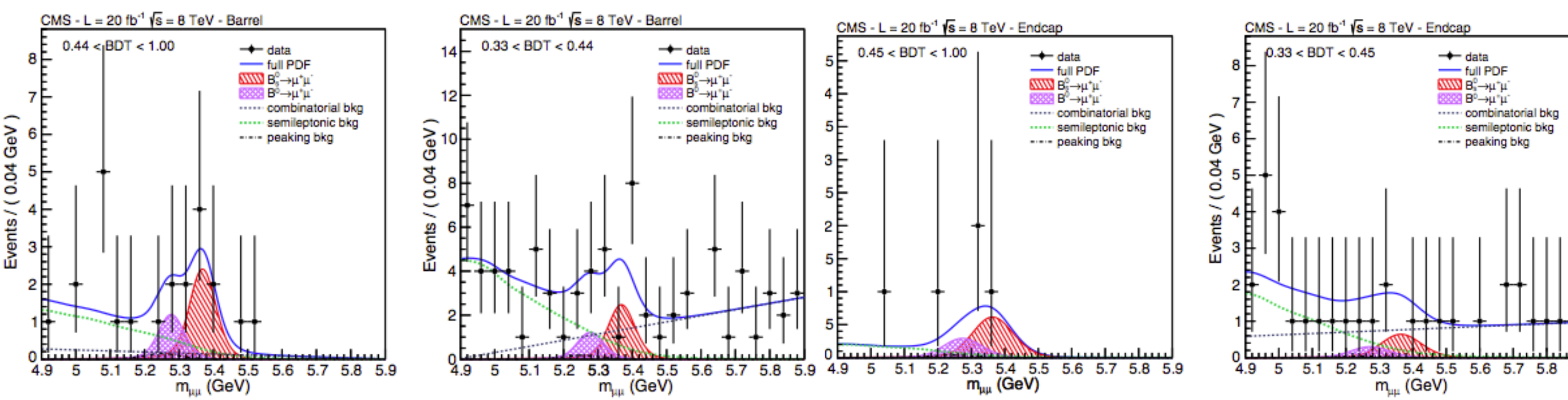
- **Categorized BDT** : discriminant used to define 4(2) regions with different $S/\sqrt{(S+B)}$ in the central and forward pseudorapidity ranges for 2012(2011) data. Regions are defined by equalizing expected signal yield in each bin.
- 1D BDT (x-check) : cut on BDT discriminant, optimizing $S/\sqrt{(S+B)}$, separately for barrel/endcap

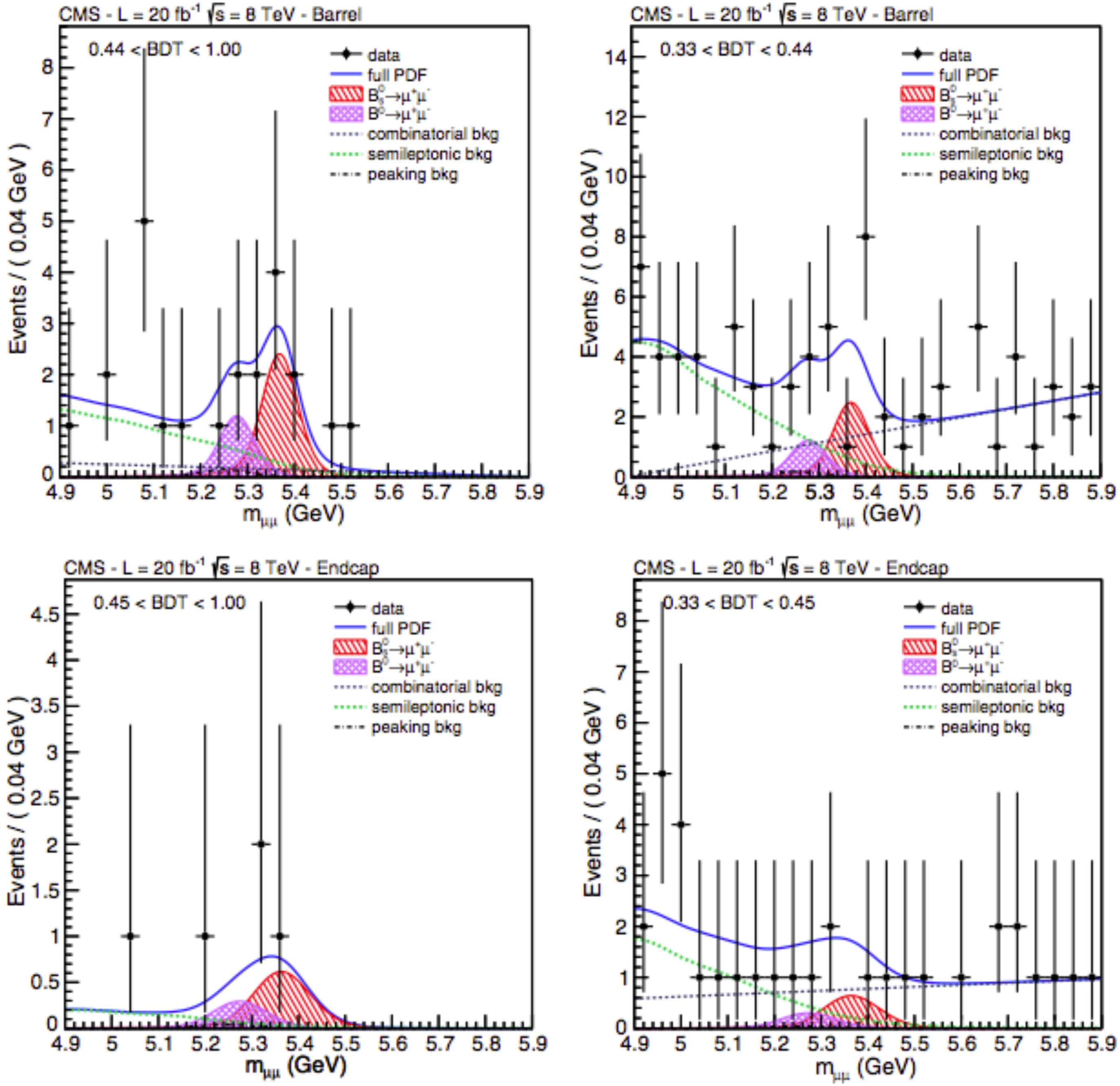
Unbinned maximum likelihood simultaneously applied to mass distributions.

Signal and Background PDF

- peaking components: Crystal Ball PDF

  peaking backgrounds constrained to expectations, normalized to B^+ yield, cross checked on independent data set
- combinatorial background: 1^{st} degree polynomial
- $b \rightarrow u\mu\bar{\nu}$ background: Gaussian kernels to MC-predicted mixture normalization floated within uncertainties ($\Lambda \rightarrow p\mu\nu$)
- per-event mass resolution included in signal PDF



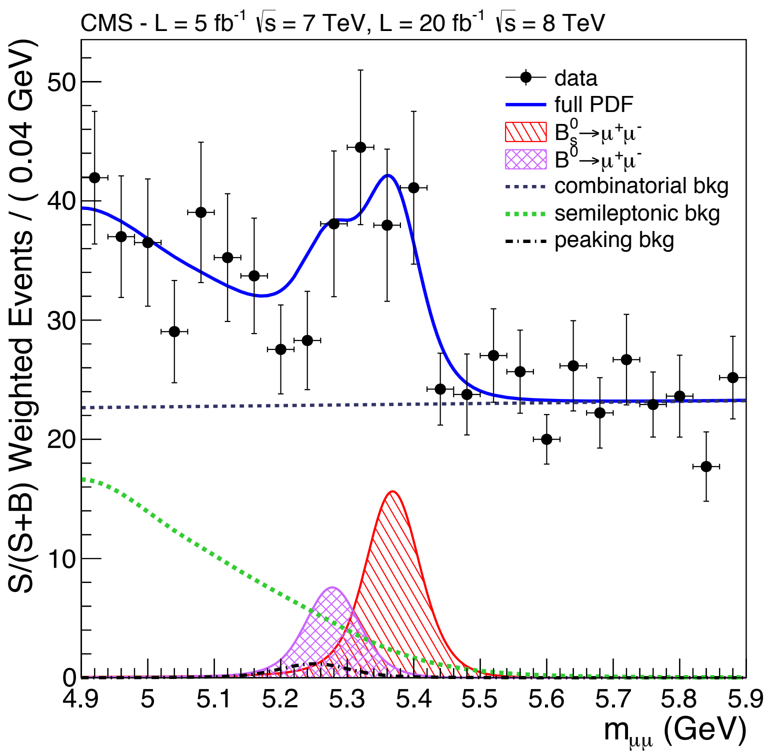


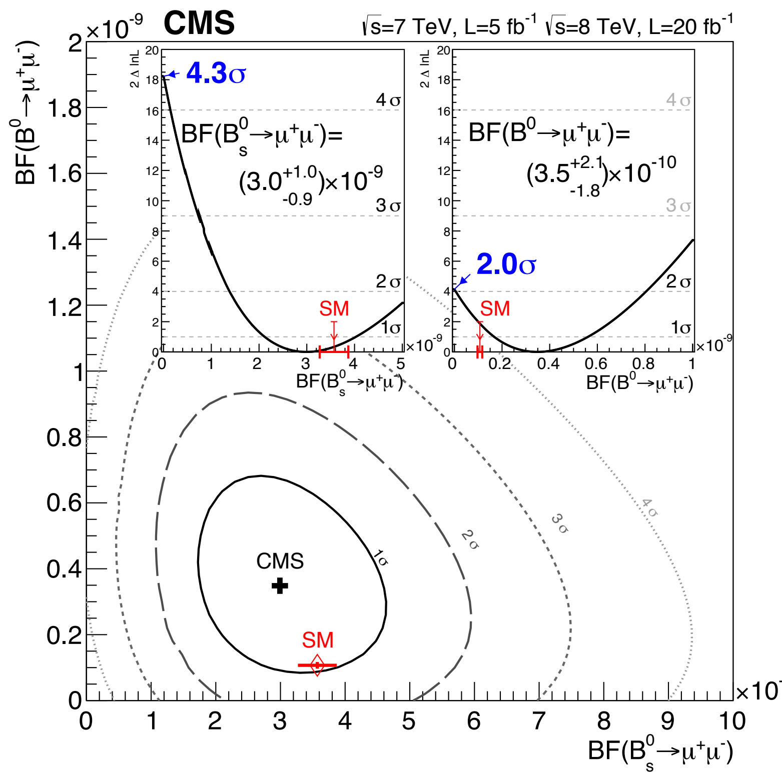
Zoom:
four of the 12 categorized $m_{\mu\mu}$ spectra from which $B(Bs^0 \rightarrow \mu+\mu-)$ is derived

CMS: $B_{s,d} \longrightarrow \mu\mu$

Systematics :

- ratio of B^+ and B_s fragmentation fractions f_s/f_u from LHCb , +5% for possible $p_{T,}\eta$ dependence
- hadron misidentification probability in $K_0 \to \pi^+\pi^-$, $\Lambda \to p\pi$, and $D^{*+} \to D_0(K^-\pi^+)\pi^+$ (50% uncert)
- BF uncertainties in rare decays, particularly $\Lambda_b \to p\mu\nu$ (100% uncertainty assigned)
- Normalization of peaking background



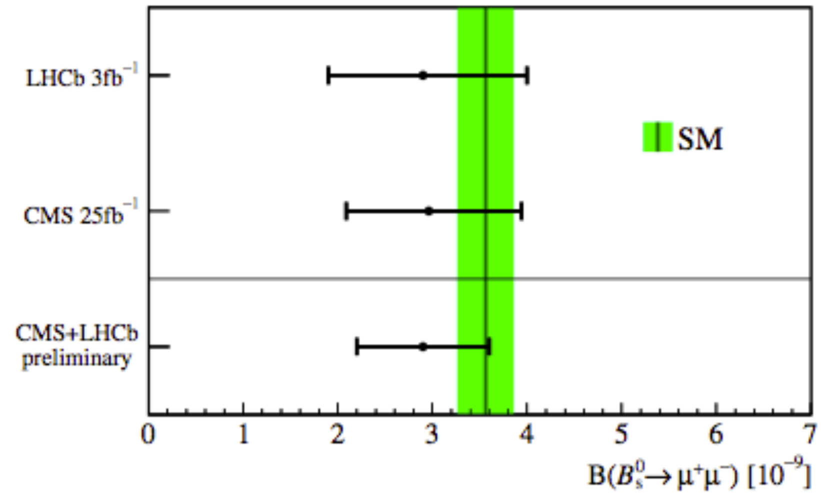


CMS + LHCb combination of $B_{s,d} \longrightarrow \mu\mu$

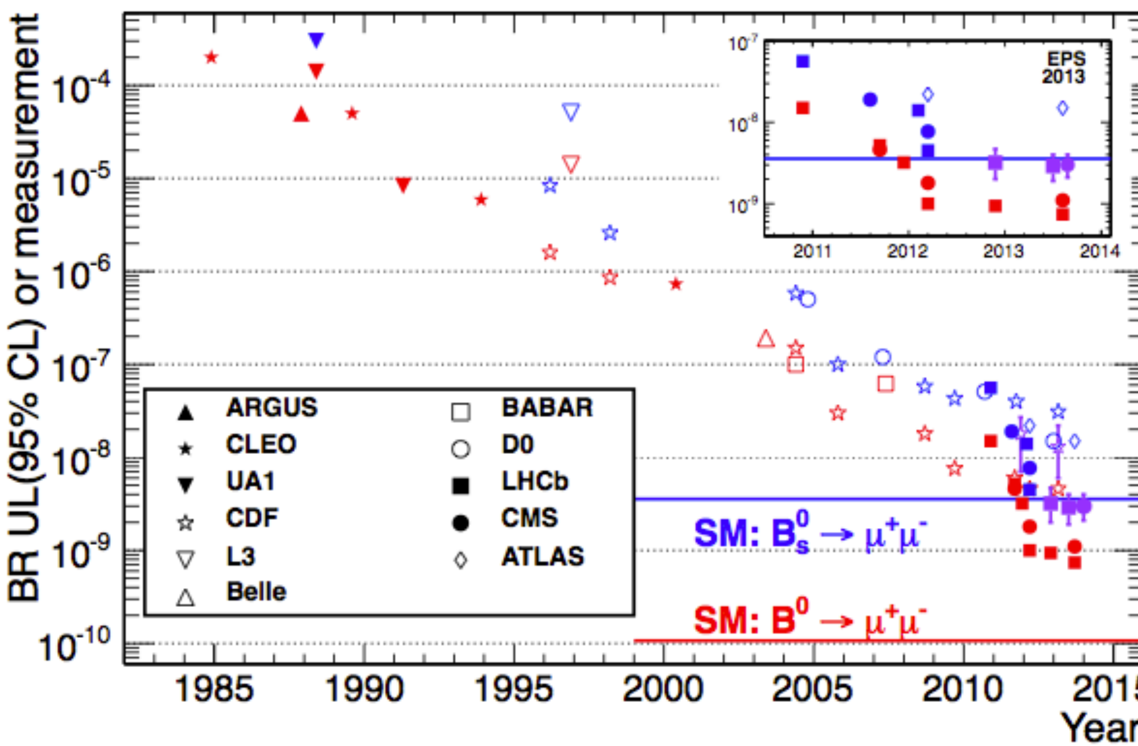
CMS-PAS-BPH-13-007
LHCb-CONF-2013-012

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}, \quad > 5\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10}, \quad < 3\sigma$$

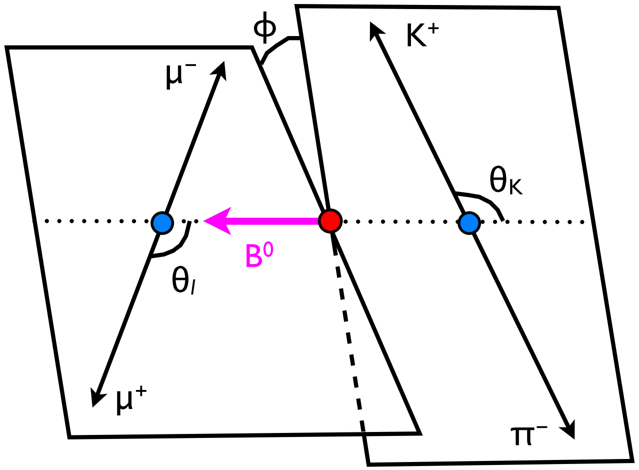


Common systematics:
$f_s/f_u = 0.256 \pm 0.020$ (LHCb)



$B_0 \longrightarrow K^*\mu\mu$: ATLAS and CMS

CMS: PLB 727 (2013) 77–100
ATLAS-CONF-2013-038



Another example of a decay sensitive to NP.
The forward-backward asymmetry of the muons (**A_{FB}**) and the fraction of longitudinally polarized K* (**F_L**) can be calculated with high precision in the SM.

Kinematics of decay determined by three angles (Φ, θ_l, θ_K) and $q^2 = m(\mu\mu)$. [Φ integrated in these analyses]

$B/\bar{B}$ tagging from $K\pi$ sign

Background:

- peaking background from $B^0 \rightarrow K^{*0}\, J/\psi$ and $B^0 \rightarrow K^{*0}\, \psi'$
- combinatorial background

ATLAS

Sequential fit to partial decay rates:

- Fit $m(K\pi\mu\mu)$ to determine shape and yields
- 3D fit to θ_K, θ_l, m to measure F_L, A_{FB}

CMS

Simultaneous fit (including S wave) to three variables in bins of q^2

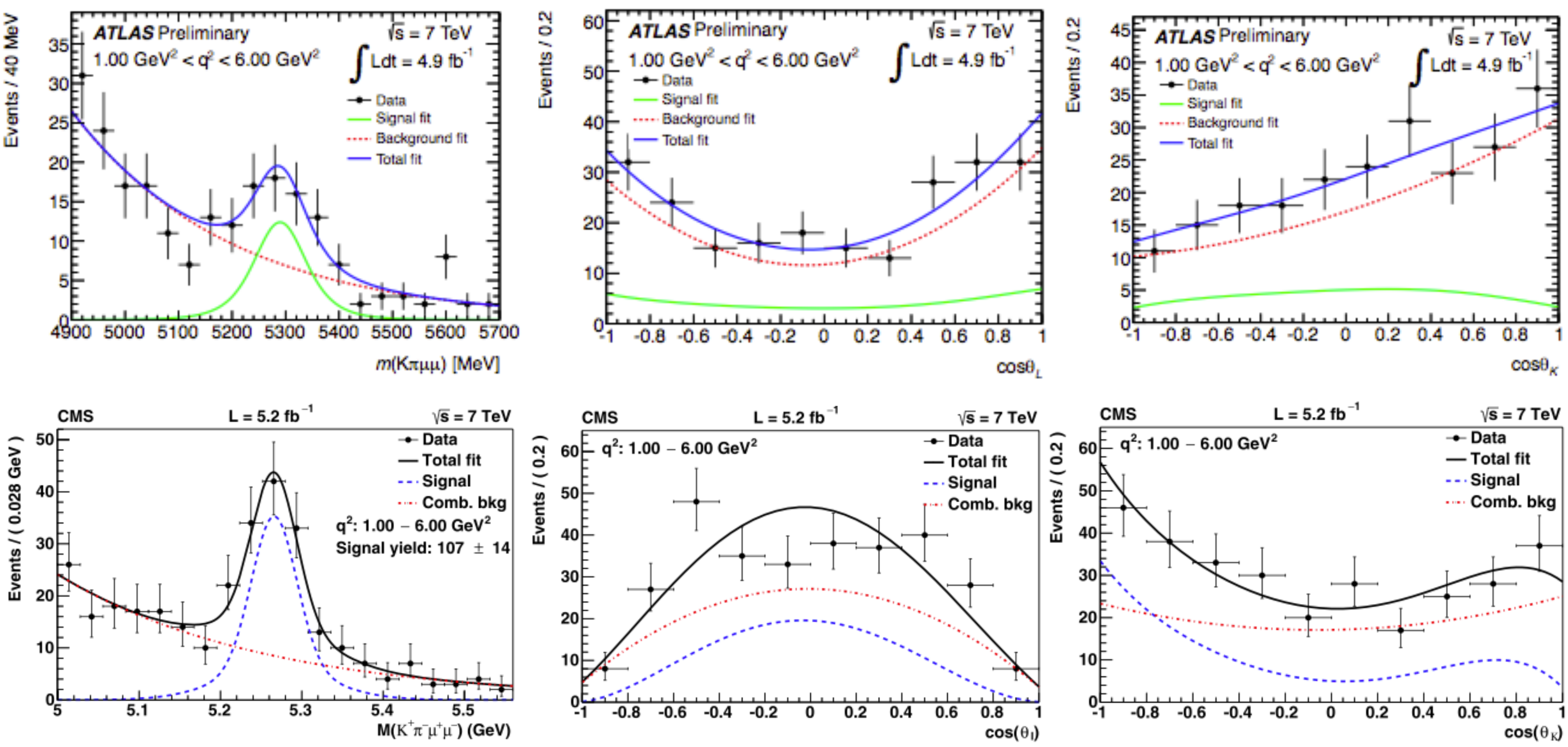
- $m(K\pi\mu\mu)$ θ_K, θ_l
- simultaneous extraction of A_{FB}, F_L, A_S, F_S
- Obtain differential BRs

$B_0 \longrightarrow K^*\mu\mu$

Systematics:

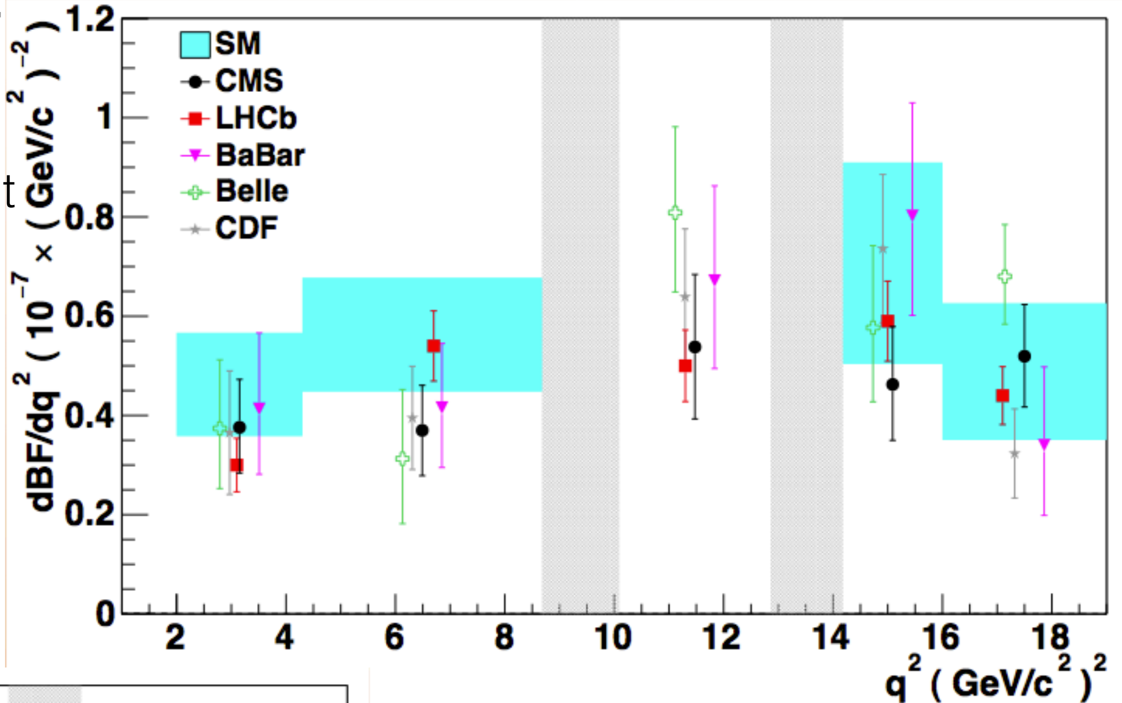
- Fit strategy
- Efficiencies
- Effect of $K\pi$ S-wave contribution
- Background shapes
- Normalization to $B^0 \to K^{*0} J/\psi$

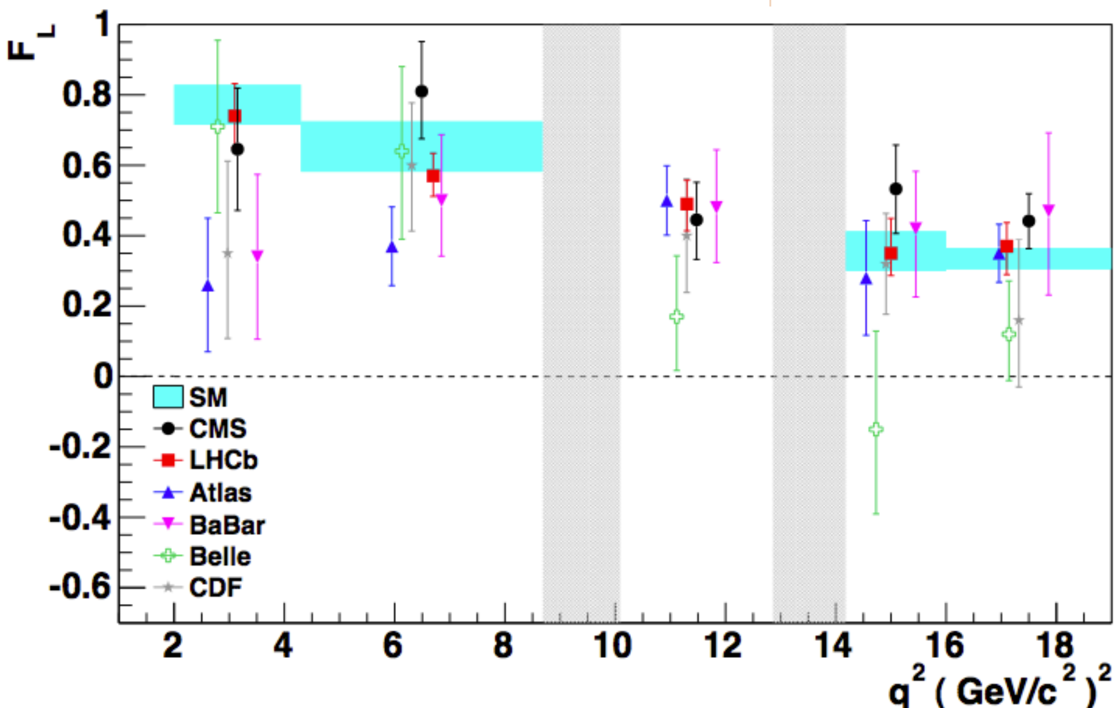
Datasets: 2011 data, ~ 5 fb^{-1}



$B_0 \longrightarrow K^*\mu\mu$

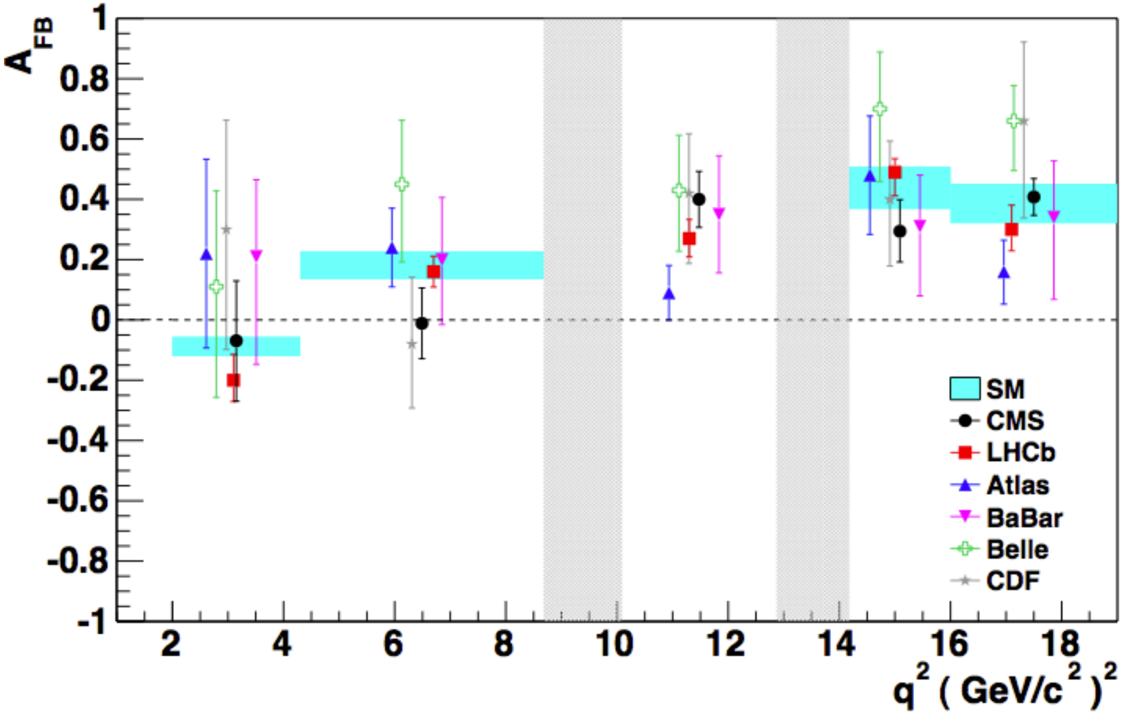
The Branching fraction measurement relies on the normalization channel $B^0 \rightarrow J/\psi\, K^{*0}$.
Results are consistent with SM predictions

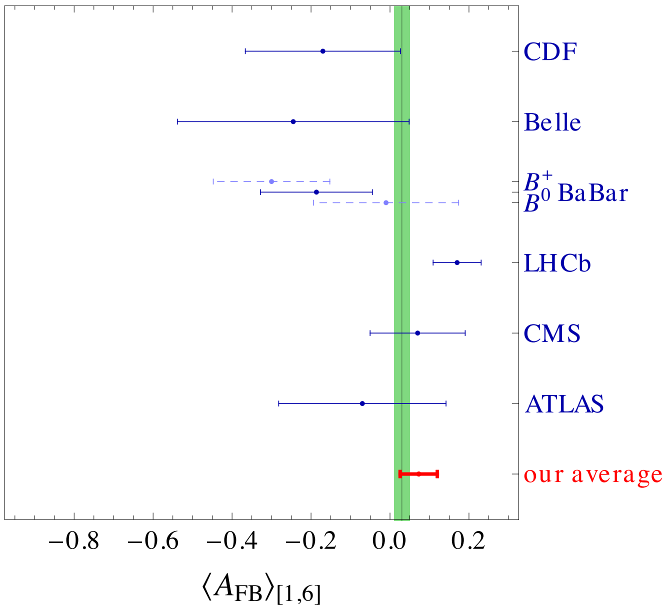




The 3 LHC results are more precise than the B-factory results.
No striking evidence of tensions with SM. Theoretical and experimental uncertainties are comparable.

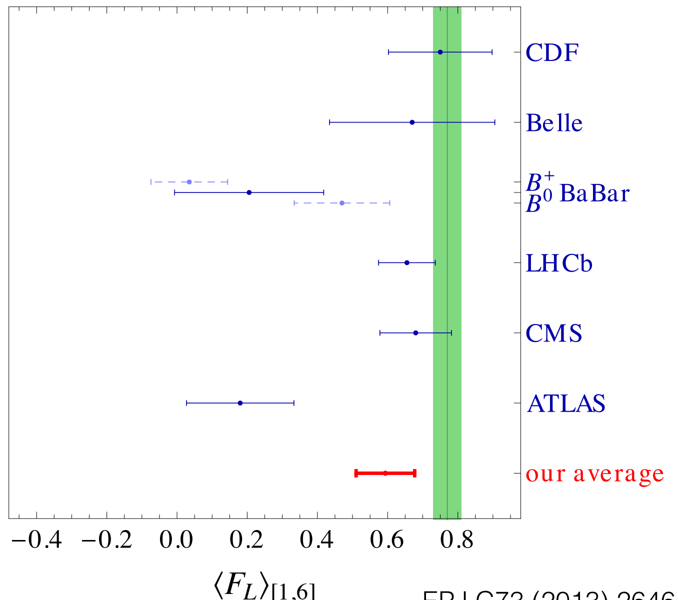
$B_0 \longrightarrow K^*\mu\mu$





LHCb measures the location of the zero-crossing point at 4.9±0.9 GeV[4], consistent with SM.

Experiments are now looking at form-factor independent observables



EPJ C73 (2013) 2646

CP violation in B_s mixing as a probe for NP

NP beyond the SM may affect the CP violating phase Φ_s in $B_s \longrightarrow J/\psi\ \phi$.
Φ_s is defined as the weak phase difference between the B_s-$\bar{B}_s$ mixing and the $b \rightarrow c\ \bar{c}\ s$ decay amplitude.

PRL 97 (2006) 151803

$$\phi_s^{SM} \simeq -2 \arg \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} = -0.0368 \pm 0.0018$$

many NP models predict a large value of Φ_s

The difference between the widths of the two mass eigenstates (B_L,B_H), $\Delta\Gamma_s$, is not expected to be affected in a striking way, but allows to test theoretical predictions . arXiv:1102.4274 [hep-ph]

A challenging analysis, requires:

- Flavor tagging for B_s-$\bar{B}_s$ separation (missing in the less precise previous result)
- Accounting for CP=+1/CP=-1 final states

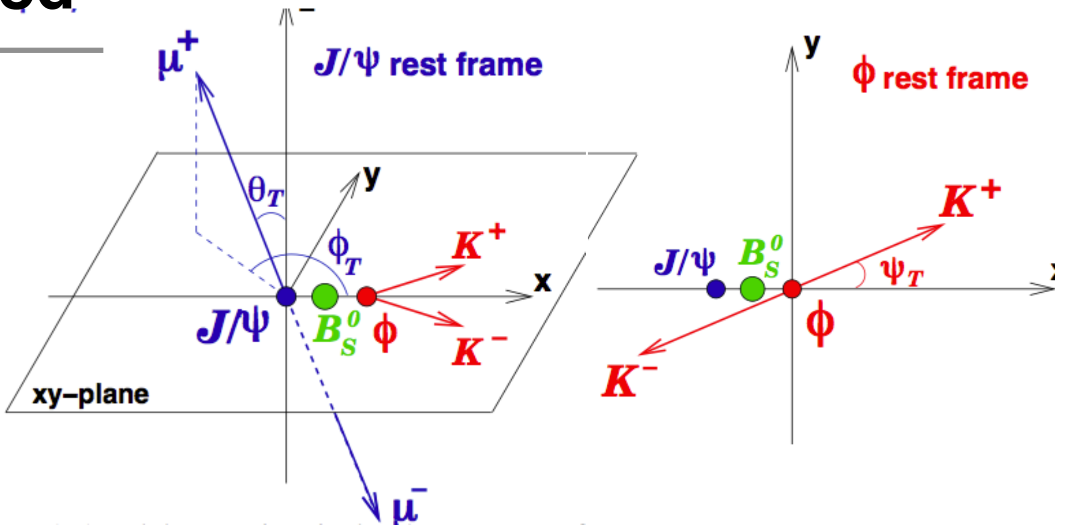
  Final states are CP-even or odd depending on the value of the orbital angular momentum L, that can be inferred by time-dependent angular analysis

ϕ_s from $B_s \longrightarrow J/\psi\ \phi$: method

$$\frac{d^4\Gamma}{dt\ d\Omega} = \sum_{k=1}^{10} \boxed{\mathcal{O}^{(k)}(t)}\boxed{g^{(k)}(\theta_T, \psi_T, \varphi_T)}$$

Time-dependent amplitudes

Angular distributions



The ten time-dependent amplitudes are expressed in terms of

- $A_0(0)$, δ_0 (latter can be chosen =0)
- $A_{||}(0)$, $\delta_{||}$
- $A_\perp(0)$, $\delta_\perp$ (CP-odd)

time dependence expressed in terms of Γ_s , $\Delta\Gamma$, Φ_s, Δm_s (measured elsewhere)

example: $\mathcal{O}^{(1)} = \frac{1}{2}|A_0(0)|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$

B_s or $\bar{B}_s$

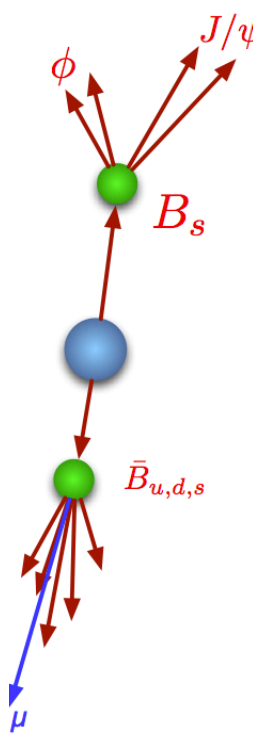
ϕ_s from $B_s \longrightarrow J/\psi\ \phi$, ATLAS

ATLAS-CONF-2013-039

Dataset: ATLAS 2011 data, 4.9 fb^{-1}, 131k B_s candidates

Flavor tagging increases sensitivity on Φ_s , as additional terms appear in the decay amplitude.
Opposite-side tagging strategy : $b - \bar{b}$ pair correlations used to infer signal flavor from the opposite B meson

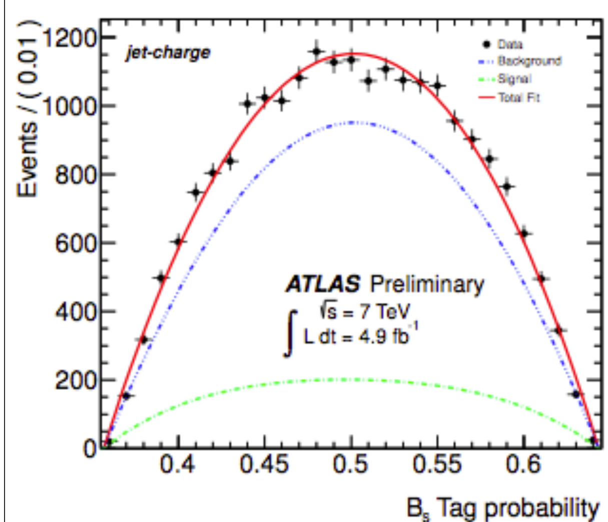
Selection:
Trigger: 1μ, 2μ
J/ψ: p_T^{μ}>4.0 GeV, η dependent $m^{\mu\mu}$ cut
ϕ: opposite charge tracks p_T>1 GeV, m^{KK} cut
B_s: μμKK fit, m(J/ψKK) cut



Muon cone charge tagging:
exploits b→μ transitions. Clean, but diluted by b→c→μ and oscillations

Jet-charge tag when the opposite-side muon is not found, use b-tagged jet. Jet-charge is the momentum-weighted charge of jet tracks

Both methods can be controlled using
$$B^+ \longrightarrow J/\psi\ K^+$$
Tagging power:
0.15 – 0.86 % (mu), 0.45% (jet), 1.45% (combined)



ϕ_s : Parameter extraction

Multi-dimensional likelihood including signal, background due to $B^0 \to J/\psi\ K^{*0}$ and $B^0 \to J/\psi\ K\pi$, combinatorial background, run dependent trigger efficiencies .

25 free parameters.

$$\ln \mathscr{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathscr{F}_s(m_i, t_i, \Omega_i) + f_s \cdot f_{B^0} \cdot \mathscr{F}_{B^0}(m_i, t_i, \Omega_i) + (1 - f_s \cdot (1 + f_{B^0}))\mathscr{F}_{\mathrm{bkg}}(m_i, t_i, \Omega_i)) \}$$

$$\mathscr{F}_s(m_i, t_i, \Omega_i, P(B|Q)) = P_s(m_i|\sigma_{m_i}) \cdot P_s(\sigma_{m_i}) \cdot P_s(\Omega_i, t_i, P(B|Q)|\sigma_{t_i}) \cdot P_s(\sigma_{t_i}) \cdot P_s(P(B|Q)) \cdot A(\Omega_i, p_{\mathrm{T}i}) \cdot P_s(p_{\mathrm{T}i})$$

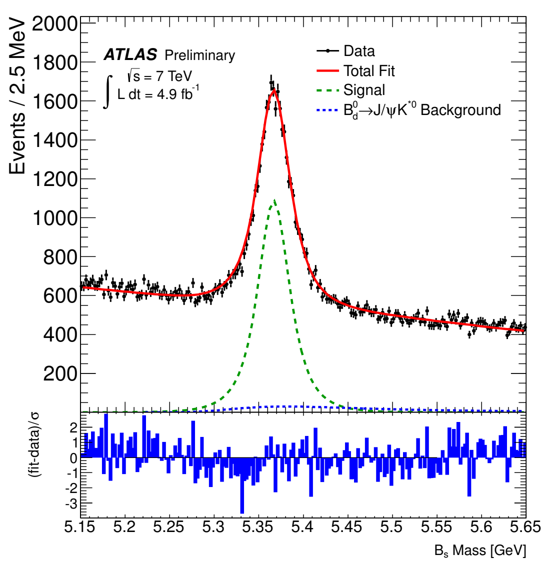
Per event errors

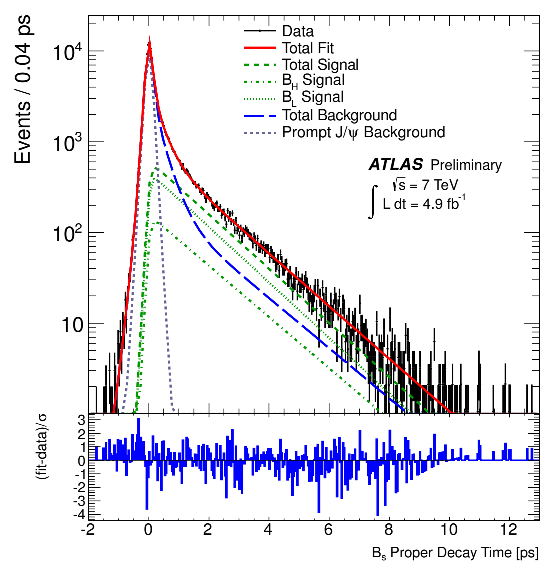
Time-dependent angular distribution

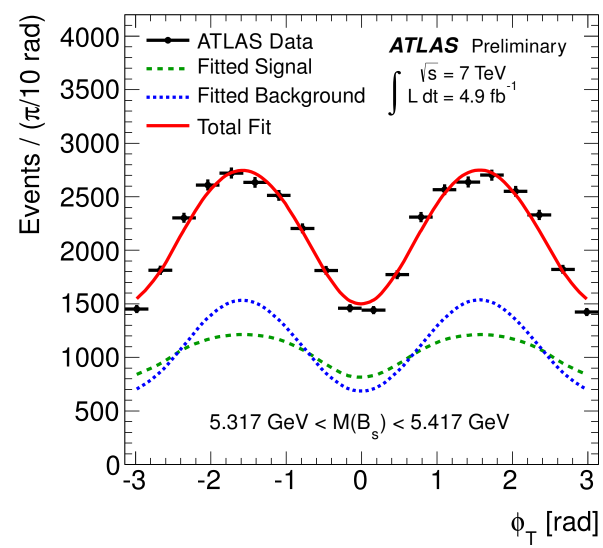
Invariant mass PDF

Acceptance

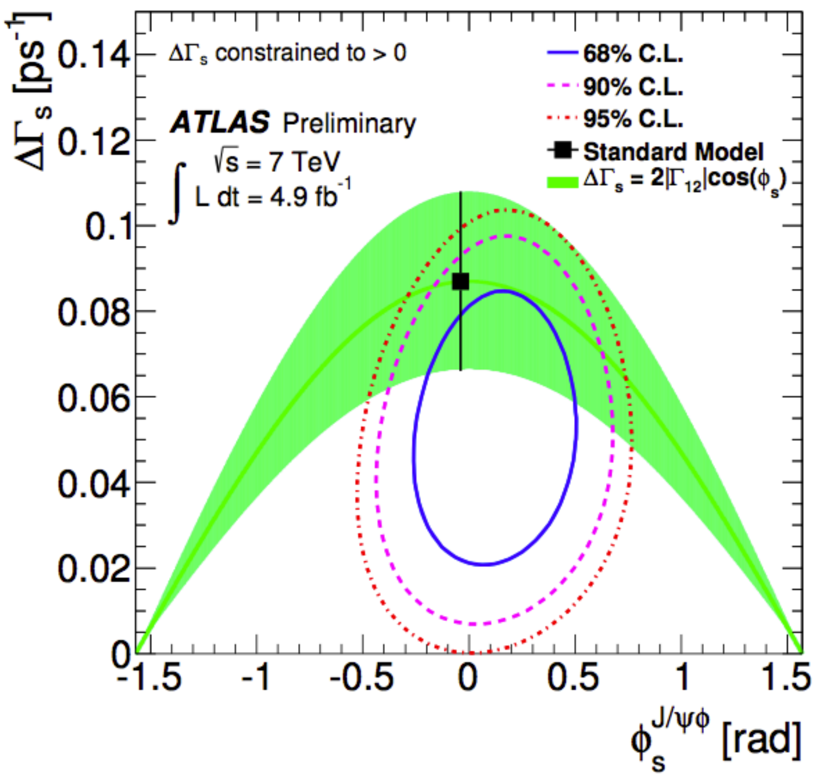
Flavor Tagging







ϕ_s : results



Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.12	0.25	0.11
$\Delta\Gamma_s$(ps^{-1})	0.053	0.021	0.009
Γ_s(ps^{-1})	0.677	0.007	0.003
$\|A_{\|\|}(0)\|^2$	0.220	0.008	0.009
$\|A_0(0)\|^2$	0.529	0.006	0.011
$\|A_S\|^2$	0.024	0.014	0.028
$\delta_\perp$	3.89	0.46	0.13
$\delta_{\|\|}$	[3.04-3.23]		0.09
$\delta_\perp - \delta_S$	[3.02-3.25]		0.04

	ϕ_s	Stat	Sys
ATL	0.12	0.25	0.11
LHCB	0.07	0.09	0.01
CMS	-		
CDF		-0.60 – 0.12	
D0	0.56	+.36/-.32	
TH.	-0.0368	0.0018	

	ΔΓs	Stat	Sys
ATLAS	0.053	0.021	0.009
LHCB	0.100	0.016	0.003
CMS	0.048	0.024	0.003
CDF	0.068	0.026	0.009
D0	0.179	+-0.060	
TH.	0.087	+-0.021	

Dominant **systematics** from tagging (stat in the calibration channel) and angular background modeling, estimated with pseudo-experiments.

Previous ATLAS untagged result :

Φ_s = 0.21 ± 0.41 (stat.) ± 0.10 (syst.) rad

Still some way to match theory uncertainty.

Summary and outlook

- Search for New Phenomena in the loops in HF decays is complementary to direct searches, and an option that cannot be overlooked.

NP is playing the Godot everyone is waiting for. No show so far.

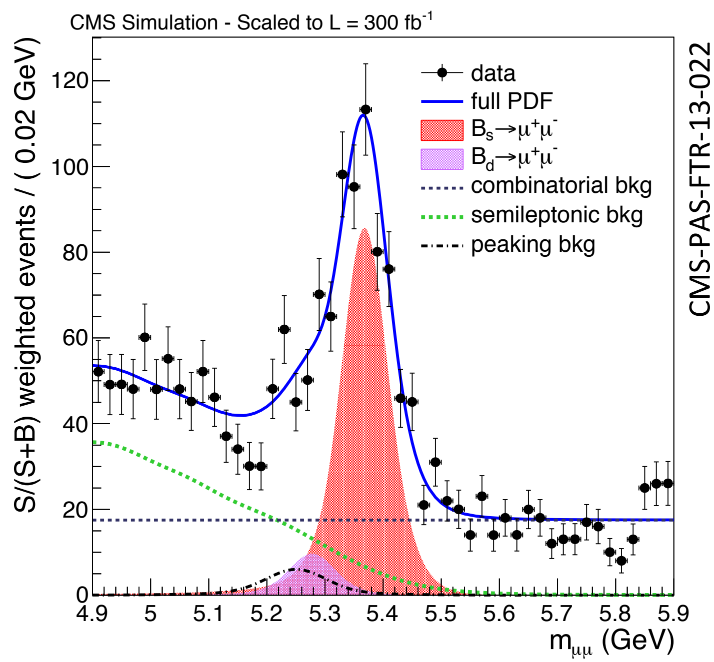
$B_s^0 \rightarrow \mu^+\mu^-$: compatible with SM predictions
A_{FB} and F_L in $B_0 \longrightarrow K^*\mu\mu$: compatible with SM predictions, but …
ϕ_s from $B_s \longrightarrow J/\psi\ \phi$: compatible with SM predictions

- LHC in Run I has been a success in covering region of NP parameters inaccessible to B factories. Improved results expected from the analysis of 2012 data.

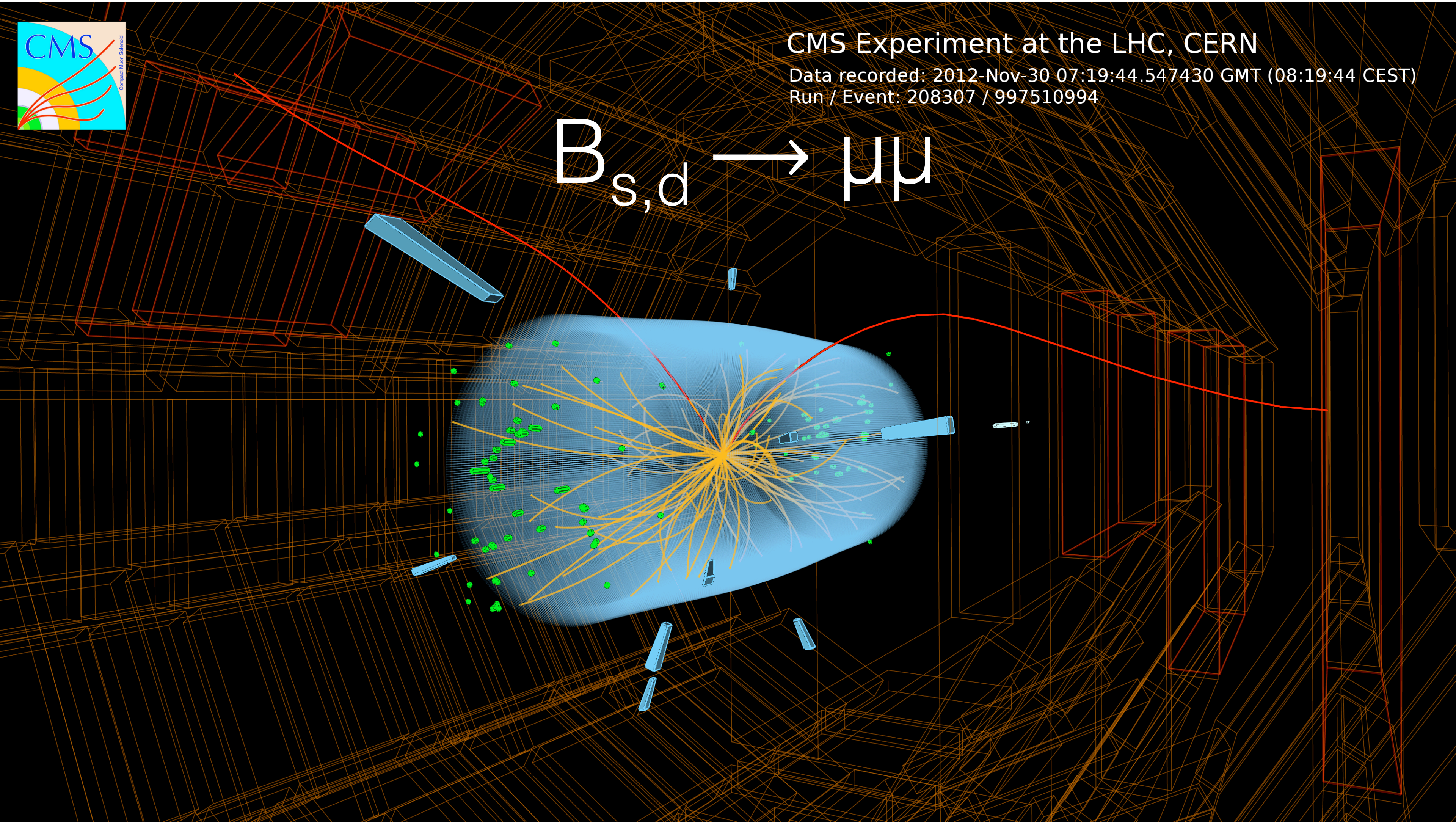
- With 300 fb^{-1} foreseen in Run II the precision of the measurement will allow to set set serious constraints on NP models.

$\delta\mathcal{B}/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ ~ 10%

$\delta\mathcal{B}/\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ ~ 50% (3σ)



Extras

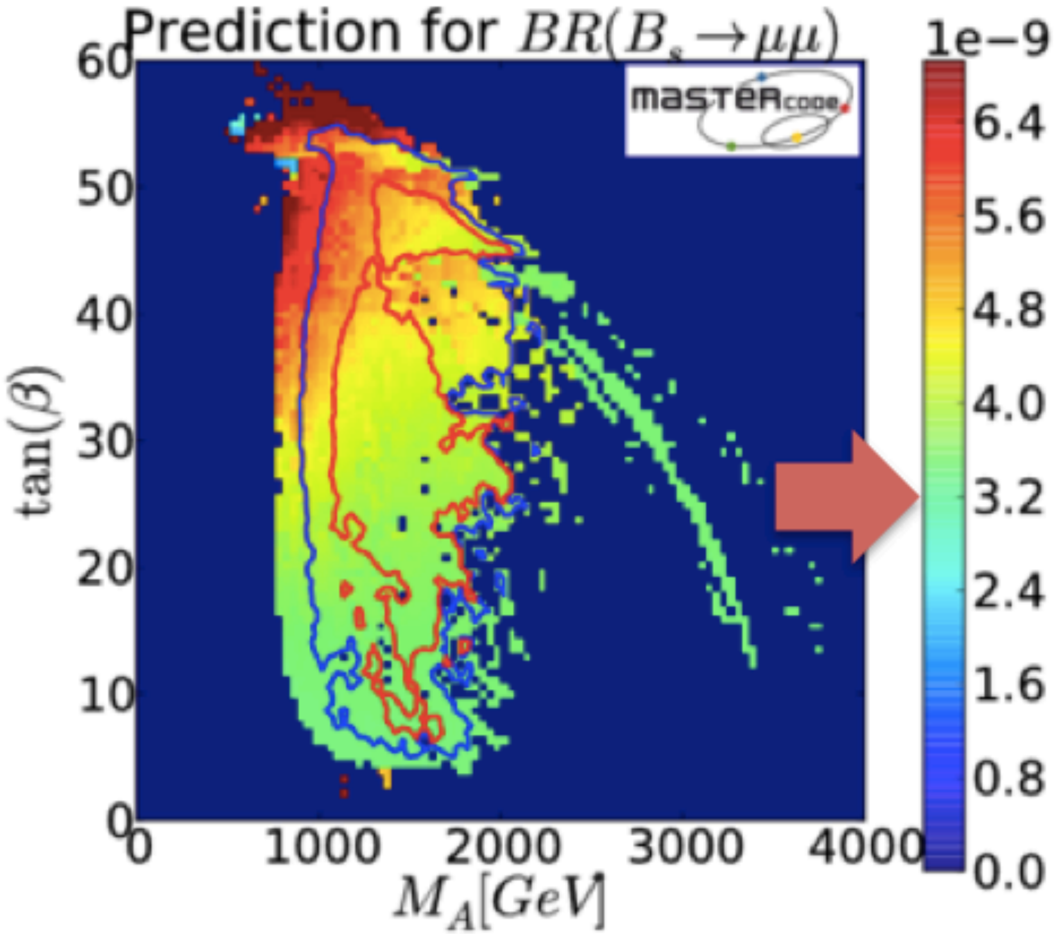

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-Nov-30 07:19:44.547430 GMT (08:19:44 CEST)
Run / Event: 208307 / 997510994
$B_{s,d} \longrightarrow \mu\mu$

B mumu 1D BDT

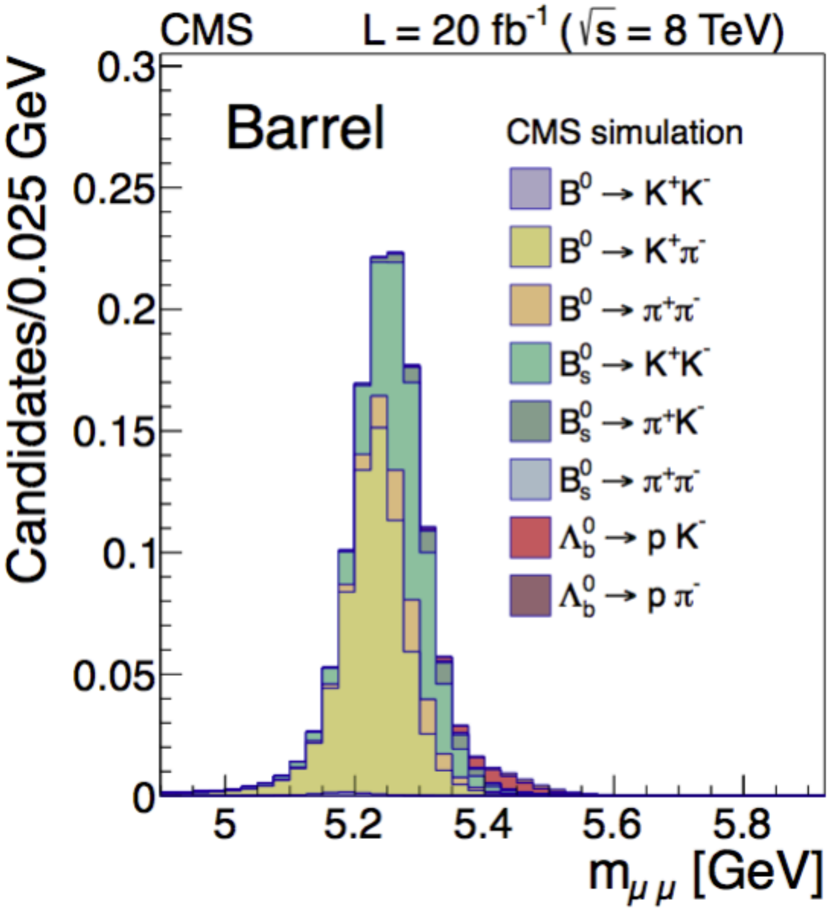
	2011 barrel		2012 barrel	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
$\varepsilon_{\rm tot}[\%]$	0.33 ± 0.03	0.30 ± 0.04	0.24 ± 0.02	0.23 ± 0.03
$N_{\rm signal}^{\rm exp}$	0.27 ± 0.03	2.97 ± 0.44	1.00 ± 0.10	11.46 ± 1.72
$N_{\rm total}^{\rm exp}$	1.3 ± 0.8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

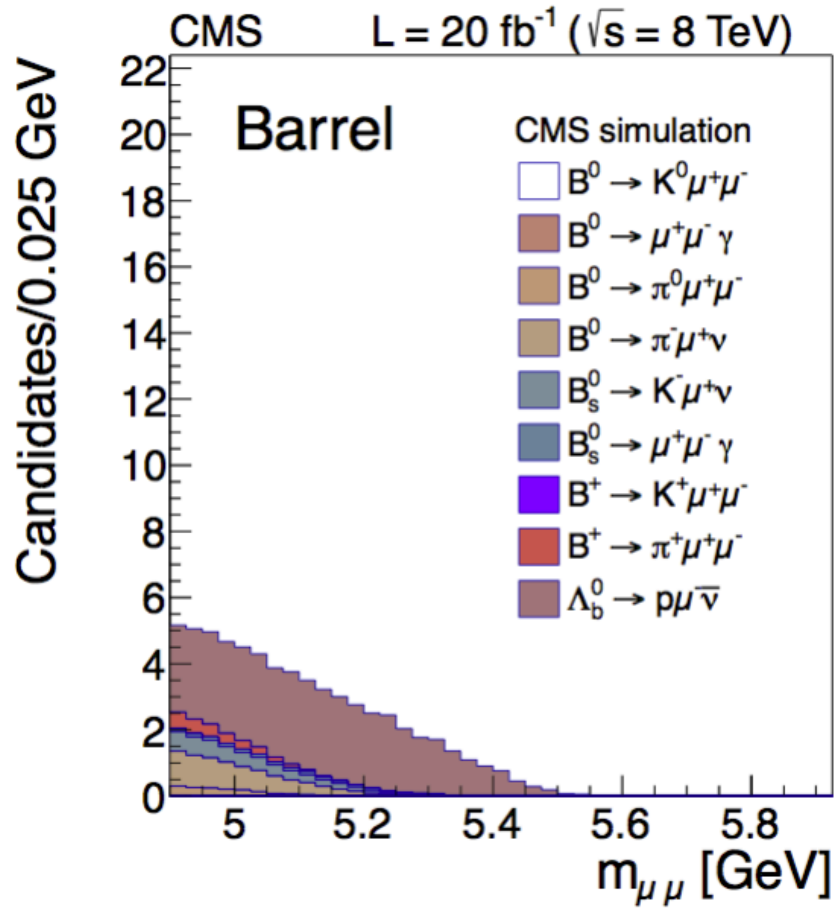
	2011 endcap		2012 endcap	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
$\varepsilon_{\rm tot}[\%]$	0.20 ± 0.02	0.20 ± 0.02	0.10 ± 0.01	0.09 ± 0.01
$N_{\rm signal}^{\rm exp}$	0.11 ± 0.01	1.28 ± 0.19	0.30 ± 0.03	3.56 ± 0.53
$N_{\rm total}^{\rm exp}$	1.5 ± 0.6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

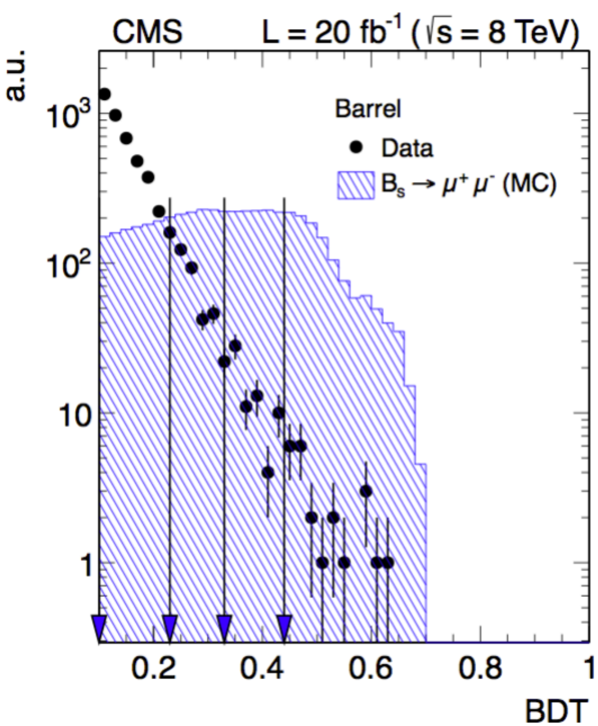
FCNCs set constraints on NP

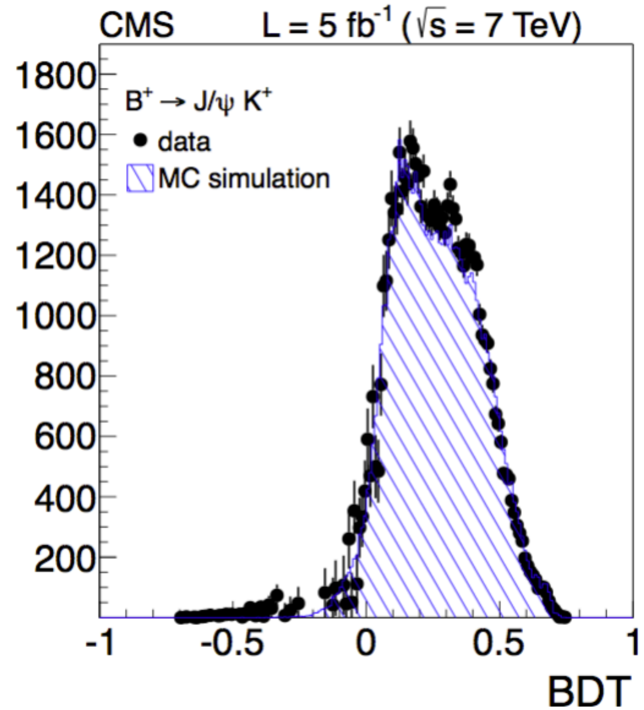


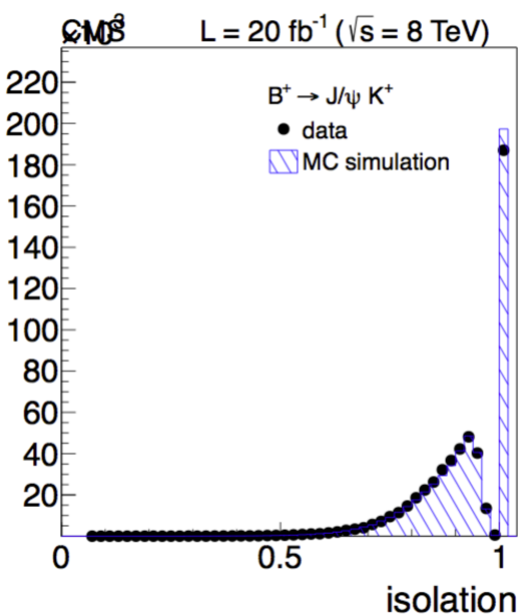
CMSSM

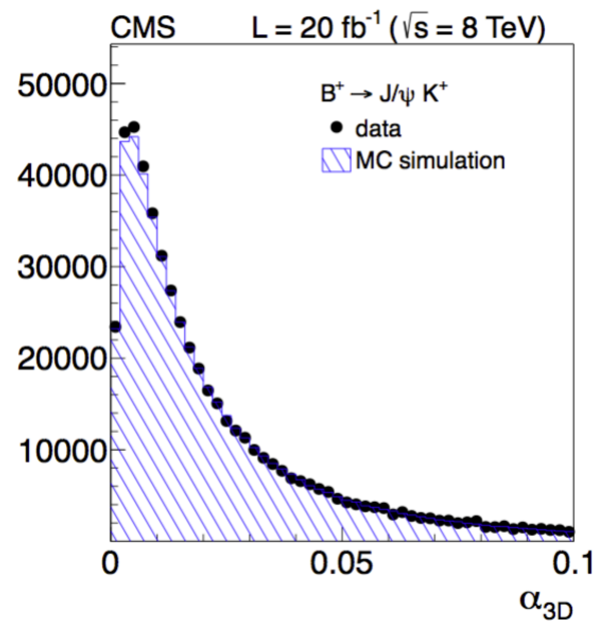

CMS
L = 20 fb^{-1} ($\sqrt{s}$ = 8 TeV)
Barrel
CMS simulation
$B^0 \to K^+K^-$
$B^0 \to K^+\pi^-$
$B^0 \to \pi^+\pi^-$
$B^0_s \to K^+K^-$
$B^0_s \to \pi^+K^-$
$B^0_s \to \pi^+\pi^-$
$\Lambda^0_b \to p K^-$
$\Lambda^0_b \to p \pi^-$
Candidates/0.025 GeV
$m_{\mu\mu}$ [GeV]


CMS
L = 20 fb^{-1} ($\sqrt{s}$ = 8 TeV)
Barrel
CMS simulation
$B^0 \to K^0\mu^+\mu^-$
$B^0 \to \mu^+\mu^-\gamma$
$B^0 \to \pi^0\mu^+\mu^-$
$B^0 \to \pi^-\mu^+\nu$
$B^0_s \to K^-\mu^+\nu$
$B^0_s \to \mu^+\mu^-\gamma$
$B^+ \to K^+\mu^+\mu^-$
$B^+ \to \pi^+\mu^+\mu^-$
$\Lambda^0_b \to p\mu^-\bar{\nu}$
Candidates/0.025 GeV
$m_{\mu\mu}$ [GeV]


CMS
L = 20 fb-1 (√s = 8 TeV)
a.u.
Barrel
Data
Bs → μ+ μ- (MC)
BDT


CMS
L = 5 fb-1 (√s = 7 TeV)
B+ → J/ψ K+
data
MC simulation
BDT


CMS
×10³
L = 20 fb-1 (√s = 8 TeV)
B+ → J/ψ K+
data
MC simulation
isolation


CMS
L = 20 fb-1 (√s = 8 TeV)
B+ → J/ψ K+
data
MC simulation
α3D

$B_0 \longrightarrow K^*\mu\mu$

$$
\begin{aligned}
\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{dcos}\,\theta_K\,\mathrm{dcos}\,\theta_\ell\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[& \mathbf{S_1^s}\sin^2\theta_K + \mathbf{S_1^c}\cos^2\theta_K + \\
& \mathbf{S_2^s}\sin^2\theta_K\cos 2\theta_\ell + \mathbf{S_2^c}\cos^2\theta_K\cos 2\theta_\ell + \\
& \mathbf{S_3}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \mathbf{S_4}\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \\
& \mathbf{S_5}\sin 2\theta_K\sin\theta_\ell\cos\phi + \mathbf{S_6}\sin^2\theta_K\cos\theta_\ell + \\
& \mathbf{S_7}\sin 2\theta_K\sin\theta_\ell\sin\phi + \mathbf{S_8}\sin 2\theta_K\sin 2\theta_\ell\sin\phi + \\
& \mathbf{S_9}\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]
\end{aligned}
$$

$$
\begin{aligned}
\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{dcos}\,\theta_K\,\mathrm{dcos}\,\theta_\ell\,\mathrm{d}\phi} = \frac{9}{16\pi}\Big[& \mathbf{F_L}\cos^2\theta_K + \frac{3}{4}(1-\mathbf{F_L})\left(1-\cos^2\theta_K\right) - \\
& \mathbf{F_L}\cos^2\theta_K\left(2\cos^2\theta_\ell - 1\right) + \frac{1}{4}(1-\mathbf{F_L})\left(1-\cos^2\theta_K\right)\left(2\cos^2\theta_\ell - 1\right) + \\
& \mathbf{S_3}\left(1-\cos^2\theta_K\right)\left(1-\cos^2\theta_\ell\right)\cos 2\phi + \\
& \frac{4}{3}\mathbf{A_{FB}}\left(1-\cos^2\theta_K\right)\cos\theta_\ell + \\
& \mathbf{A_9}\left(1-\cos^2\theta_K\right)\left(1-\cos^2\theta_\ell\right)\sin 2\phi\Big]
\end{aligned}
$$

$B_s \longrightarrow J/\psi\ \phi$

$$\mathscr{A}(t) = \frac{\Gamma(\mathrm{B_s}(t) \to f) - \Gamma(\overline{\mathrm{B}}_\mathrm{s}(t) \to f)}{\Gamma(\mathrm{B_s}(t) \to f) + \Gamma(\overline{\mathrm{B}}_\mathrm{s}(t) \to f)} \sim \sin(\phi_\mathrm{s}) \cdot \sin(\Delta m_\mathrm{s} t).$$

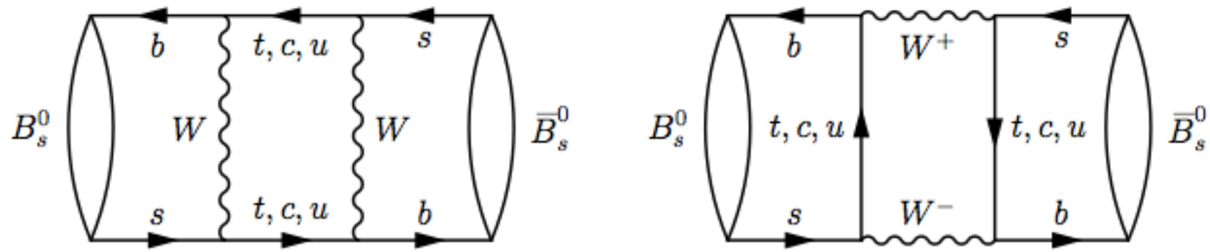


Figure 1: Feynman diagrams for B_s^0–$\overline{B}_s^0$ mixing, within the SM.

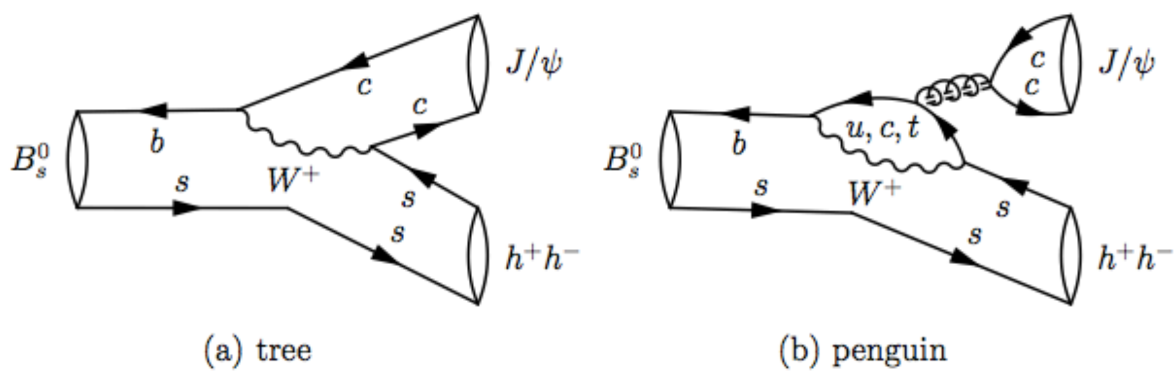
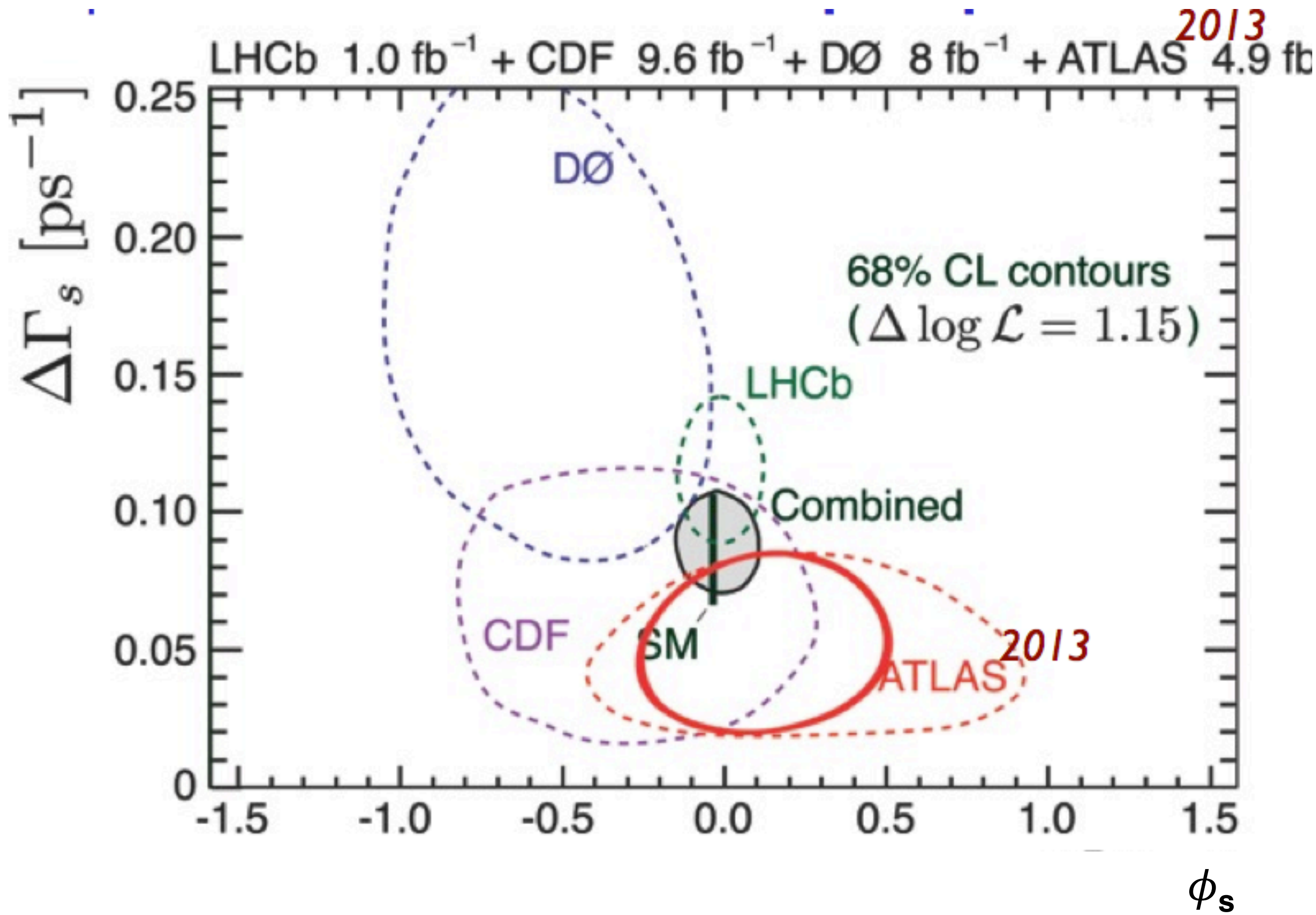


Figure 2: Feynman diagrams contributing to the decay $B_s^0 \to J/\psi h^+ h^-$ within the SM, where $h = \pi, K$.

ϕ_s : results



Still far from the theoretical error on ϕ_s (although latest LHCb result not in this plot)