Rare Decays and other Electroweak *b*-physics Measurements at ATLAS and CMS

P. Ronchese - CMS/ATLAS collaborations

University and INFN Padova

50^{th} Rencontres de Moriond - EW 2015

La Thuile, Aosta valley, Italy
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Outline

- Introduction
- Rare decays:
  - $\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$ measurement
  - $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis
- CP violation:
  - B^0_s lifetime difference and CPV phase in $B^0_s \to J/\psi\phi$
  - $B^0_s \to J/\psi f_0$ propaedeutic studies
- Conclusions

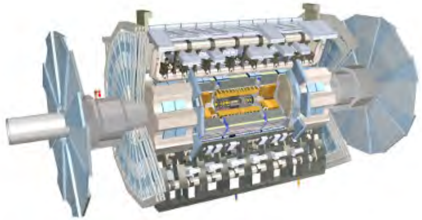
Motivations

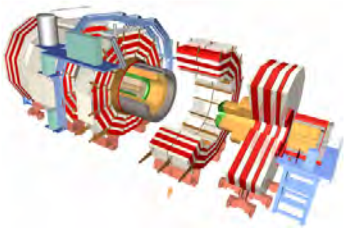
Motivations to study HF physics at CMS & ATLAS

Look for indirect evidence or constraints
to new physics beyond SM

- Tree level W exchange hardly modified by NP processes
- Exploit the sensitivity of some processes to loop diagrams at high mass scales
- Rare FCNC decays branching ratios modified by new degrees of freedom in the loops
- Angular analysis to probe specific terms in effective lagrangian
- Measure CP violation to investigate NP contributions to mixing processes

ATLAS and CMS experiments





Data samples

- $\sqrt{s} = 7$ TeV , $\mathcal{L} \sim$ 5 fb^{-1} (2011 run)
- $\sqrt{s} = 8$ TeV , $\mathcal{L} \sim$ 20 fb^{-1} (2012 run)

All shown results involve dimuons
Dedicated triggers developed for analyses
Selections: dimuon mass, p_T, displaced vertex, pointing angle

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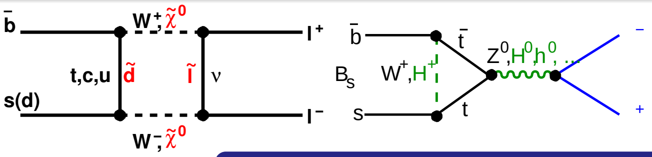
$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: SM predictions

$B^0_{d,s} \to \mu^+\mu^-$ highly suppressed in the SM

- FCNC: only at higher order processes (box, penguin)
- Cabibbo suppressed: $\left|V_{ts(td)}\right|^2$
- Helicity suppressed: $(m_\mu/m_B)^2$
- Internal annihilation: $(f_B/m_B)^2$



new
NLO-EW and NNLO-QCD
corrections

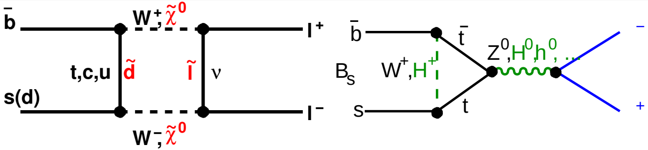
C.Bobeth *et al.*, PRL 112 (2014) 101801

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0_d \to \mu^+\mu^-)_{\mathrm{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: beyond SM

Significant deviations predicted by theories beyond SM

- New degrees of freedom are present
- Discrimination among BSM theories from $\mathcal{R} \equiv \mathcal{B}(B^0_d \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$ ratio
- $\mathcal{R}$ prediction by BSM theories with minimal flavour violation equal as in SM



BSM processes

NUHM J.R.Ellis *et al.*, JHEP 05 (2006) 063

MCPMFV J.R.Ellis *et al.*, PRD 76 (2007) 115011

Leptoquarks S.Davidson *et al.*, JHEP 11 (2010) 073

MSSM with large tan β S. R. Choudhury *et al.*, IJMPA 21 (2006) 2017, J.K.Parry *et al.*, PLB 760 (2006) 38

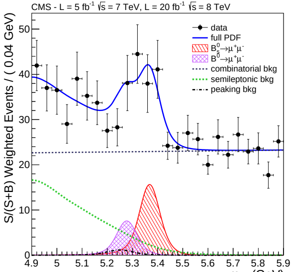
$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: search/measurement

BR determined by comparison with another channel

$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \frac{N_{\text{sig}}}{N_{\text{nrm}}} \frac{\epsilon_{\text{nrm}}}{\epsilon_{\text{sig}}} \frac{f_u}{f_{d,s}} \mathcal{B}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm)$$

Background:

- Combinatorial (from sidebands)
- Non-peaking: semileptonic b-decays
- Peaking: $(B^0_{d,s}, \Lambda^0_b) \to hh'$ (from simulation)



PRL 111 (2013) 101804

ATLAS($\sqrt{s} = 7$ TeV) ATLAS-CONF-2013-076

$\mathcal{B}(B^0_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$@ 95% C.L.

CMS($\sqrt{s} = 7, 8$ TeV)(*) arXiv:1411.4413

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+1.0}_{-0.9}) \times 10^{-9}$

$\mathcal{B}(B^0_d \to \mu^+\mu^-) = (4.4^{+2.2}_{-1.9}) \times 10^{-10}$

(*) Changed vs. previously published on PRL

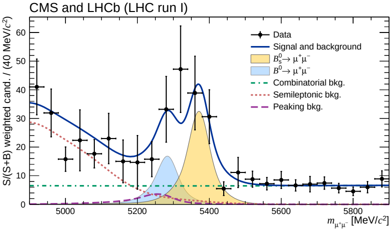
More infos at frame 28

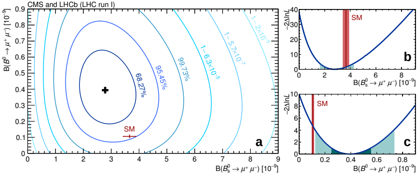
$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: updates & CMS+LHCb combination

Updated quantity	old	new
f_u/f_s	3.91 ± 0.31	3.86 ± 0.22
$\mathcal{B}(\Lambda^0_b \to p\mu^-\nu)$	$(6.50 \pm 6.50) \times 10^{-4}$	$(4.94 \pm 2.19) \times 10^{-4}$ event by event weights

Time dependent corrections:

- Decay time dependent selection: time dependent efficiency
- Superposition of different mass eigenstates: time dependent width





CMS+LHCb arXiv:1411.4413

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B^0_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

More infos at frames 28,29

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: evolution

- Higher energy (up to $\sqrt{s} = 14$ TeV):
  - higher cross-section
- Higher luminosity (up to $L = 5 \times 10^{34}$ cm^{-2}s^{-1}):
  - larger events sample
  - higher pile-up (up to 140)

CMS evolution

- Improved muon system (for Run2, limited effect)
- Improved tracker (after LS2 & for HL-LHC)
- Improved trigger

- Vertexing efficiency loss
- Tracking efficiency loss
- f_u/f_s improved
- Background estimation improved

CMS expectations

2nd ECFA workshop

$\mathcal{L}(\text{fb}^{-1})$	$\delta\mathcal{B}/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(B^0_d \to \mu^+\mu^-)$	$\delta\mathcal{R}$
300	13%	48%	50%
3000	11%	18%	21%

More infos at frame 30

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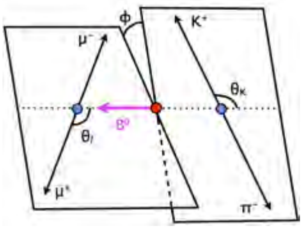
$B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^+\pi^-$ angular analysis



Possible
BSM physics effects
through contributions
in Wilson coefficients
C_7 , C_9 and C_{10}

Differential branching ratio

- Kinematic variables:
  - θ_L , θ_K , ϕ angles
  - $q^2 = m^2(\mu^+\mu^-)$
- Parameters:
  - $A_{\rm FB}$: muon forward/backward asymmetry
  - $F_{\rm L}$: K^{*0} longitudinal polarization
  - $F_{\rm S}$, $A_{\rm S}$: $K^+\pi^-$ S-wave contribution and interference
- Form-factor independent observables

- Events divided in q^2 bins
- $B^0 \to K^{*0}(J/\psi , \psi')$ regions removed
- ϕ angle integrated out

2011
data

More infos at frame 32

$B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^+\pi^-$: fit strategy

ATLAS

ATLAS-CONF-2013-038

Sequential fit:

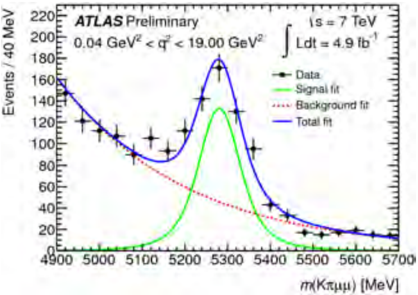
- Yields from mass fit
- A_{FB} , F_{L} from angles fit
- F_{S} from BaBar

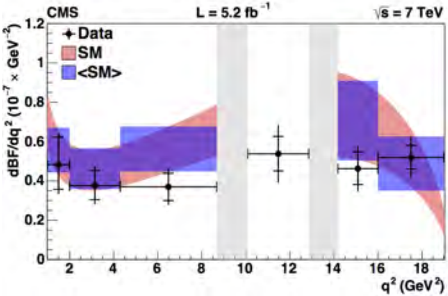
CMS

PLB 727 (2013) 77

Simultaneous fit:

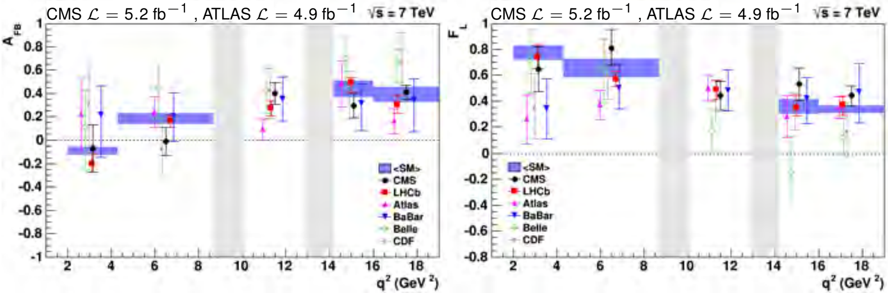
- A_{FB} , F_{L}, F_{S} , A_{S}
- $d\mathcal{B}/dq^2$ by comparison with $B^0 \to K^{*0}J/\psi$





More infos at frames 32,33

$B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^+\pi^-$: results



- $B^0 \to K^{*0}\mu^+\mu^-$ decay parameters compatible with other experiments
- Parameters dependence on q^2 compatible with SM predictions at low and high q^2

- Waiting for $\sqrt{s} = 8$ TeV results
- Looking for form-factor independent observables

More infos at frame 33

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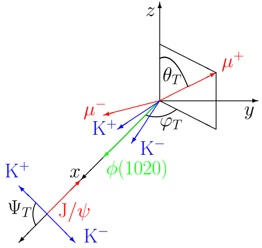
$B_s^0 \to J/\psi\phi$: lifetime difference and CPV phase

Flavoured initial state: admixture of B_L and B_H

- Unflavoured final state:
  - direct and mixing-mediated decays
  - interference: phase $\phi_s \simeq -2\beta_s$
- Non-definite CP final state:
  - admixture of CP odd and even
  - components disentangled by time-dependent angular analysis: $\Theta = \theta, \varphi, \psi$



$|\Phi_s| < 0.05$ in MFV models

G.Isidori, arXiv:1302.0661

Reduced sensitivity of $\Delta\Gamma_s$ to physics beyond SM

J.Charles *et al.*, PRD 84 (2011) 033005

$$2\beta_{s(\mathrm{SM})} = 0.0363^{+0.0016}_{-0.0015} \text{ rad}$$

A.Lenz and U.Nierste, arXiv:1102.4274

$$\Delta\Gamma_{s(\mathrm{SM})} = 0.087 \pm 0.021 \text{ ps}^{-1}$$

$B_s^0 \to J/\psi\phi$: decay width parameters

Differential decay width

$$\frac{d^4\Gamma(B_s^0(t))}{d\Theta dt} = f(\Theta, \alpha, ct) \propto \sum_{i=1}^{10} O_i(\alpha, ct) \cdot g_i(\Theta)$$

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

N_i, a_i, b_i, c_i, d_i terms depending on α parameters:

- Φ_s in b_i , d_i

- $A_\perp$, A_0 , $A_\parallel$, A_S : P-wave and S-wave amplitudes
- $\delta_\perp$, δ_0 , $\delta_\parallel$, δ_S : wave phases
- $|\lambda|$: direct CP violation
- $+(c_i , d_i)$ for B_s^0 , $-(c_i , d_i)$ for $\bar{B}_s^0$

Parameters fit

- $\delta_0 = 0$, $|\lambda| = 1$ fixed
- $\delta_{S\perp} = \delta_S - \delta_\perp$
- Δm_s from PDG

$B_s^0 - \bar{B}_s^0$ discrimination

Other b flavour tagging

$B_s^0 \to J/\psi\phi$: flavour tagging

- $B_s^0/\bar{B}_s^0$ flavour at production inferred from charge of decay products of the second b
- Charge-flavour correlation diluted (cascade, oscillations, ...)

ATLAS($\sqrt{s} = 7$ TeV) PRD 90 (2014) 052007

- combined muon charge
- combined jet charge

$\epsilon_{\text{tag}} = (32.1 \pm 0.01(\text{stat}))\%$

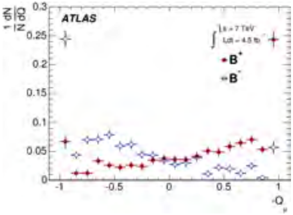
$P_{\text{tag}} = (1.45 \pm 0.05(\text{stat}))\%$

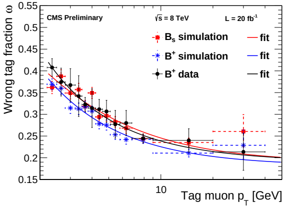
CMS($\sqrt{s} = 8$ TeV) CMS-PAS-BPH-13-012

- muon charge
- electron charge

$\epsilon_{\text{tag}} = (7.67 \pm 0.04(\text{stat}))\%$

$P_{\text{tag}} = (0.97 \pm 0.03(\text{stat}))\%$



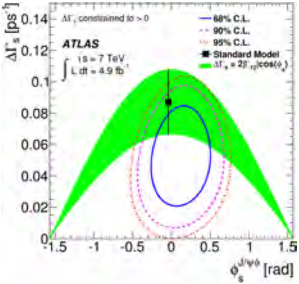


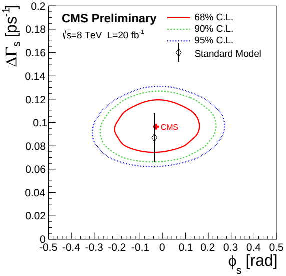
Performances measured with $B^+ \to J/\psi K^+$ events

$B_s^0 \to J/\psi\phi$: results

Unbinned maximum likelihood fit
including per-event resolution and tagging probability terms

	ATLAS ($\sqrt{s} = 7$ TeV)	CMS ($\sqrt{s} = 8$ TeV)
$\Delta\Gamma_S[\text{ps}^{-1}]$	$0.053 \pm 0.021 \pm 0.010$	$0.096 \pm 0.014 \pm 0.007$
$\phi_S[\text{rad}]$	$0.12 \pm 0.25 \pm 0.05$	$-0.03 \pm 0.11 \pm 0.03$





Results compatible with world averages and SM expectations

More infos at frame 34

$B_s^0 \to J/\psi\phi$: evolution

ϕ_s error much bigger than theoretical uncertainty:

- more data needed...
- more difficult environment with increasing luminosity

ATLAS evolution

Tracker improvements:

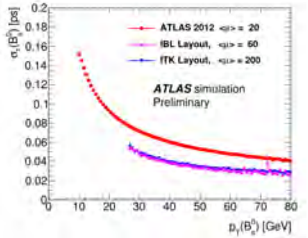
- fourth pixel layer (for Run2)
- reduced pixel size (for HL-LHC)

Limited trigger bandwidth: harder $p_{T,\mu}$ cuts with increasing luminosity

- 6 GeV at Phase-1
- 11 GeV at Phase-2

Higher tracker performances

- better vertex reconstruction
- proper decay time resolution improved by $\sim$ 30%



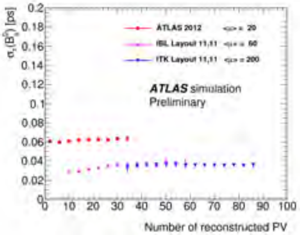
More infos at frame 35

$B_s^0 \to J/\psi\phi$: evolution

Estimated PU

- 60 at Phase-1
- 200 at Phase-2

No significant effect on time resolution



Signal yield estimated from 2012 data by applying muon p_T cuts and rescaling for efficiencies and luminosities

ATLAS expectations ATL-PHYS-PUB-2013-010

$\mathcal{L}(\text{fb}^{-1})$	$p_{T\mu}$ cut [GeV]	$\sigma(\phi_s)$(stat)[rad]
100	6	0.054
100	11	0.10
250	11	0.064
3000	11	0.022

Expectations validated with 2011 measurement

More infos at frame 35

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$B_s^0 \to J/\psi f_0$: study motivations

Alternative channel to measure ϕ_s

- f_0 is a scalar ($J^{PC} = 0^{++}$)
- The final state is a CP-odd eigenstate
- No need to disentangle two components
- Angular analysis no more needed

$$\Gamma(B_s^0/\bar{B}_s^0 \to J/\psi f_0) = \mathcal{N} e^{-\Gamma_s t} \left\{ e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s t) \right\}$$

Hadronic structure of $f_0(980)$

- quark-antiquark
- tetraquark
- $K\bar{K}$ molecule

Critical hadronic corrections

B_s^0 flavour at production

Tagged analysis

- Same technique used as for $B_s^0 \to J/\psi\phi$
- Tagging info added to $\sin\phi_s$

$B_s^0 \to J/\psi f_0$: BR measurement

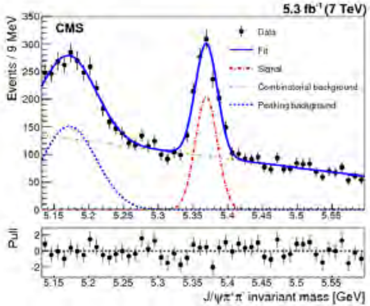
Propaedeutic studies

- $\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-)/\mathcal{B}(B_s^0 \to J/\psi \phi)\mathcal{B}(\phi \to K^+K^-)$ has been measured
- lifetime and CPV measurement to come

BR and lifetime: useful to probe hadronic structure

Event selection:

- J/ψ : dimuon originating from a displaced vertex
- f_0 : Two opposite-charge π $|m_{\pi\pi} - 974 \text{ MeV}| < 50 \text{ MeV}$
- Φ : Two opposite-charge K $|m_{KK} - 1020 \text{ MeV}| < 10 \text{ MeV}$



$B_s^0 \to J/\psi f_0$: results

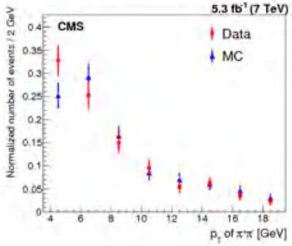
BR ratio measurement: systematic uncertainties cancellation

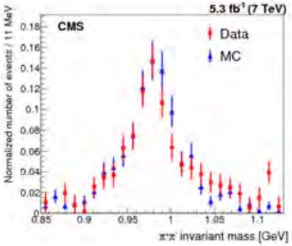
$$R_{f_0/\phi} = \frac{\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B_s^0 \to J/\psi \phi)\mathcal{B}(\phi \to K^+K^-)} = \frac{N_{\text{obs}}^{f_0}}{N_{\text{obs}}^{\phi}} \times \epsilon_{\text{reco}}^{\phi/f_0}$$

- Yield from unbinned max likelihood fit
- Efficiency from MC

CMS($\sqrt{s} = 7$ TeV) arXiv:1501.06089

$R_{f_0/\phi} = 0.140 \pm 0.013 \pm 0.018$





More infos at frame 27

Conclusions

- ATLAS and CMS have produced significant EW results in HF physics
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ have been measured
- An angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ have been performed
- The CP violation phase ϕ_s in $B_s^0 \to J/\psi\phi$ decay has been measured
- The study of the $B_s^0 \to J/\psi f_0$ decay begun

All results are, up to now, compatible with SM predictions
...but there's still room to squeeze it further

Extra informations

BACKUP

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: additional material

Signal and background discriminated by mean of a multivariate analysis (BDT):

- ATLAS:
  - cut on BDT output
- CMS:
  - events divided in 12 categories
  - dimuon invariant mass fitted simultaneously in all categories

Background from $\Lambda^0_b \to p\mu^-\nu$ (CMS):

- mis-reconstruction probability strongly dependent on $q^2 = m^2_{\mu\nu}$
- simulated distribution different from the predicted one (other predictions now available) A.Khodjamirian *et al.*, JHEP 09 (2011) 106
- weight defined as the ratio of the two distributions

Back to main frames 8,9

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: additional material

$$\Gamma(B^0_s \to \mu^+\mu^-) = (R_H + R_L)e^{-\Gamma_s t}\left[\cosh\frac{y_s t}{\tau_{B^0_s}} + \mathcal{A}_{\Delta\Gamma}\sinh\frac{y_s t}{\tau_{B^0_s}}\right]$$

$$y_s = (\Gamma_L - \Gamma_H)/(\Gamma_L + \Gamma_H) = 0.0615 \pm 0.0085 \;\; \text{(from HFAG)}$$

Y.Amhis *et al.*, arXiv:1207.1158

$$\mathcal{A}_{\Delta\Gamma} = (R_H - R_L)/(R_H + R_L) = 1.0 \;\; \text{(from SM)}$$

K. De Bruyn *et al.*, PRL 109 (2012) 041801

- Time dependent quantities used in the selection (e.g. impact parameters)
- Time integrated efficiency dependent on the decay rate

Back to main frame 9

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: additional material

Only muons in the barrel

Phase-1

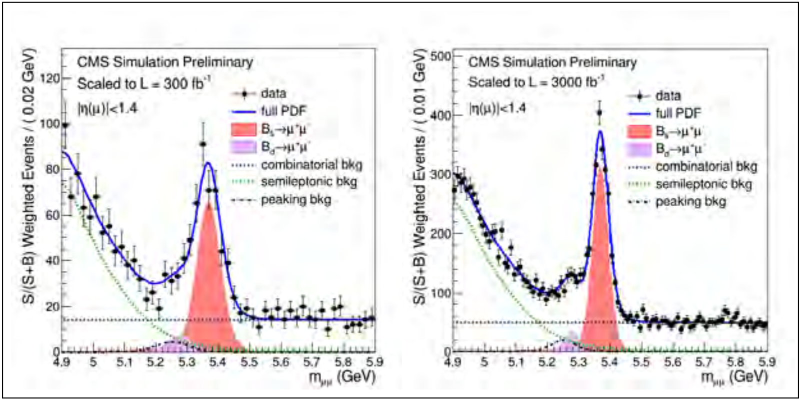
- Mass resolution $\approx$ 42 MeV
- Uncertainties:
  - B^+ : 5%
  - on peaking bg: 20%
  - on semileptonic bg: 25%
  - on f_s/f_u : 5%
- Trigger & PU: same as $\sqrt{s} = 8$ TeV

Phase-2

- Mass resolution: $\approx$ 28 MeV
- Uncertainties:
  - on B^+ : 3%
  - on peaking bg: 10%
  - on semileptonic bg: 20%
  - on f_s/f_u : 5%
- Trigger & PU: reduced efficiency
  - 35% signal and normalization
  - 30% backgrounds

Back to main frame 10

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: additional material



Back to main frame 10

$B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^+\pi^-$ additional material

CMS parametrization

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K d\cos\theta_L dq^2} = \frac{9}{16}\left\{\left[\frac{2}{3}F_S + \frac{4}{3}A_S\cos\theta_K\right](1-\cos^2\theta_L)\right.$$
$$+(1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_L)\right.$$
$$+\frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_L)$$
$$\left.\left.+\frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_L\right]\right\}$$

F_S , A_S constrained from $B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi'$

$$\frac{d\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{\epsilon_N}{\epsilon_S}\frac{\mathcal{B}(B^0\to K^{*0}J/\psi)}{Y_N}\frac{dY_S}{dq^2}$$

ATLAS parametrization

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_L dq^2} = \frac{3}{4}F_L(1-\cos^2\theta_L)$$
$$+\frac{3}{8}(1-F_L)(1+\cos^2\theta_L) + A_{FB}\cos\theta_L$$
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_K dq^2} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

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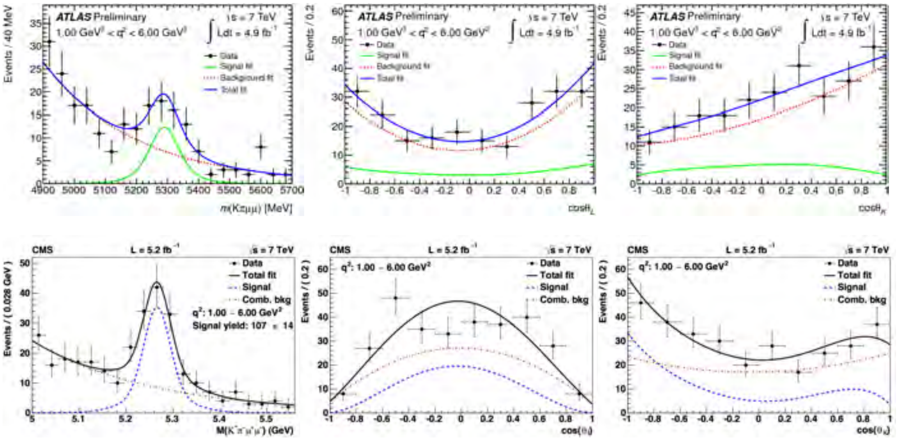
$B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^+\pi^-$: additional material



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$B_s^0 \to J/\psi\phi$: additional material

	ATLAS ($\sqrt{s} = 7$ TeV)	CMS ($\sqrt{s} = 8$ TeV)
$\|A_0\|^2$	$0.529 \pm 0.006 \pm 0.012$	$0.511 \pm 0.006 \pm 0.012$
$\|A_S\|^2$	$0.024 \pm 0.014 \pm 0.028$	$0.015 \pm 0.016 \pm 0.022$
$\|A_\perp\|^2$		$0.242 \pm 0.008 \pm 0.012$
$\|A_\parallel\|^2$	$0.220 \pm 0.008 \pm 0.009$	
$\delta_\parallel$[rad]	$[3.04, 3.23]$	$3.48 \pm 0.09 \pm 0.68$
$\delta_\perp$[rad]	$3.89 \pm 0.47 \pm 0.11$	$2.73 \pm 0.36 \pm 0.66$
$\delta_S - \delta_\perp$[rad]		$0.34 \pm 0.24 \pm 1.12$
$\delta_\perp - \delta_s$[rad]	$[3.02, 3.25]$	
τ	$[1/(0.677 \pm 0.007 \pm 0.004)]$ ps	$[447.3 \pm 3.0 \pm 3.5]$ μm$/c$

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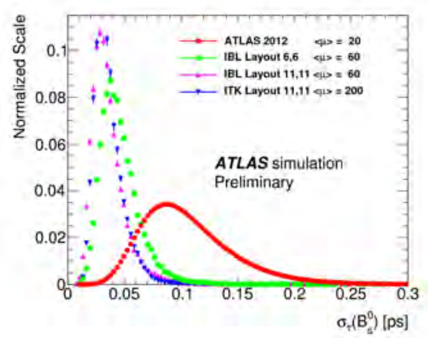
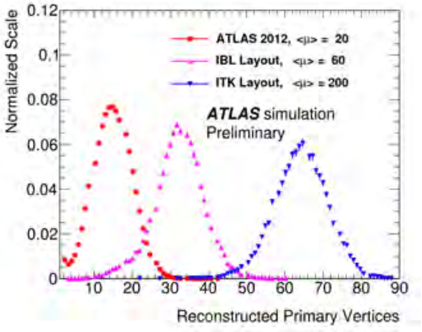
$B_s^0 \to J/\psi\phi$: additional material

$\sigma(pp \to J/\psi)$ at $\sqrt{s} = 14$ TeV assumed to be twice as at $\sqrt{s} = 7$ TeV





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