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CMS measurements with the $B^0_s \rightarrow J/\psi\phi(1020)$ and $B^0_s \rightarrow J/\psi f_0(980)$ decays

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Vienna, Austria

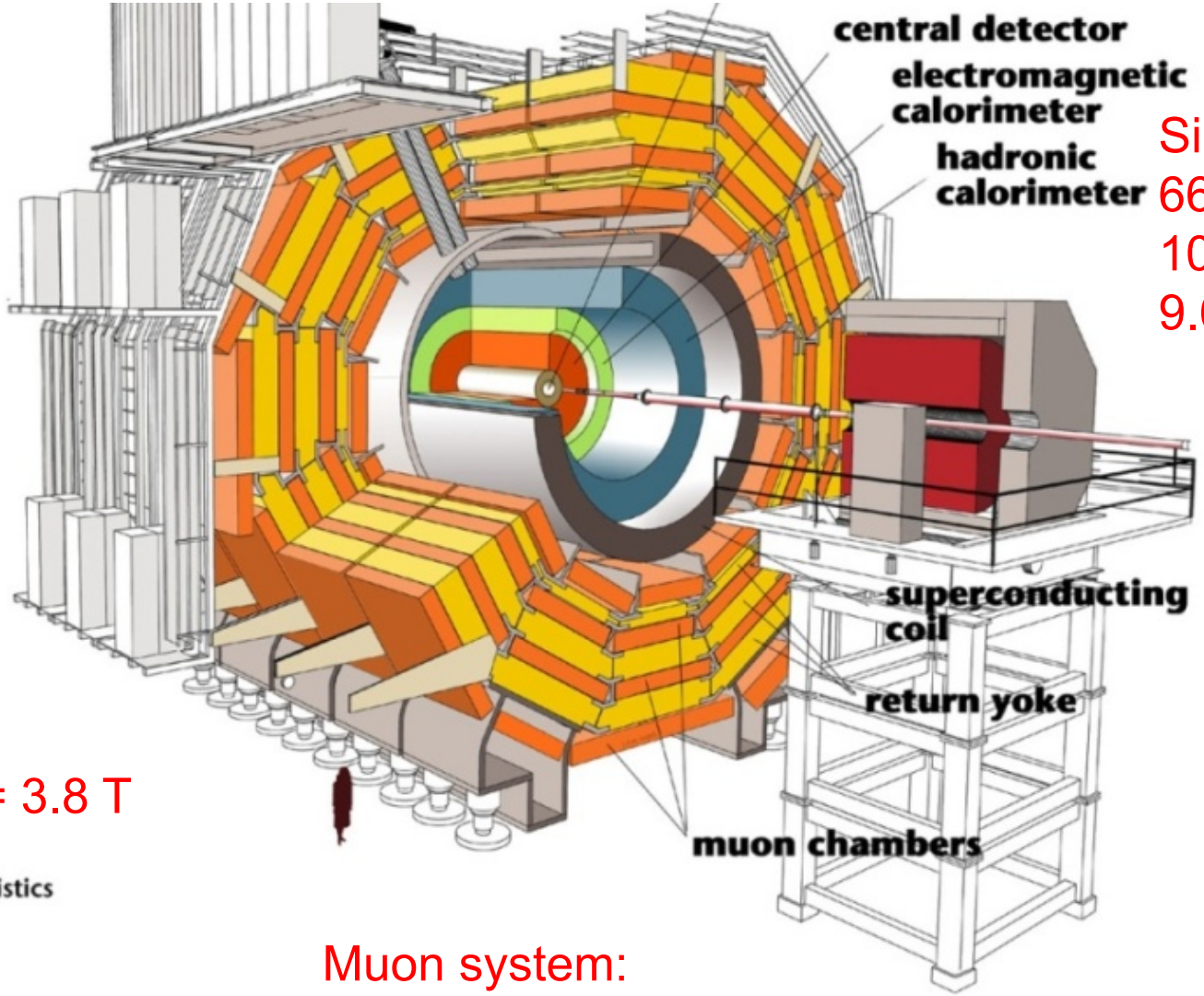
Paula Eerola for the CMS collaboration

Outline

- The CMS detector
- Measurement of

  $R(f_0/\phi) = B(B^0_s \rightarrow J/\psi f_0(980))/B(B^0_s \rightarrow J/\psi\phi(1020))$
- Measurement of ϕ_s and $\Delta\Gamma_s$ with $B^0_s \rightarrow J/\psi\phi(1020)$
  - Selections, angular analysis
  - Flavour tagging
  - Results and uncertainties
- Summary

CMS: a general purpose detector at the LHC



Silicon tracker
66M pixels
100x150 μm^2
9.6M Si strips

ECAL
76k $PbWO_2$
scintillating
crystals

B = 3.8 T

Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

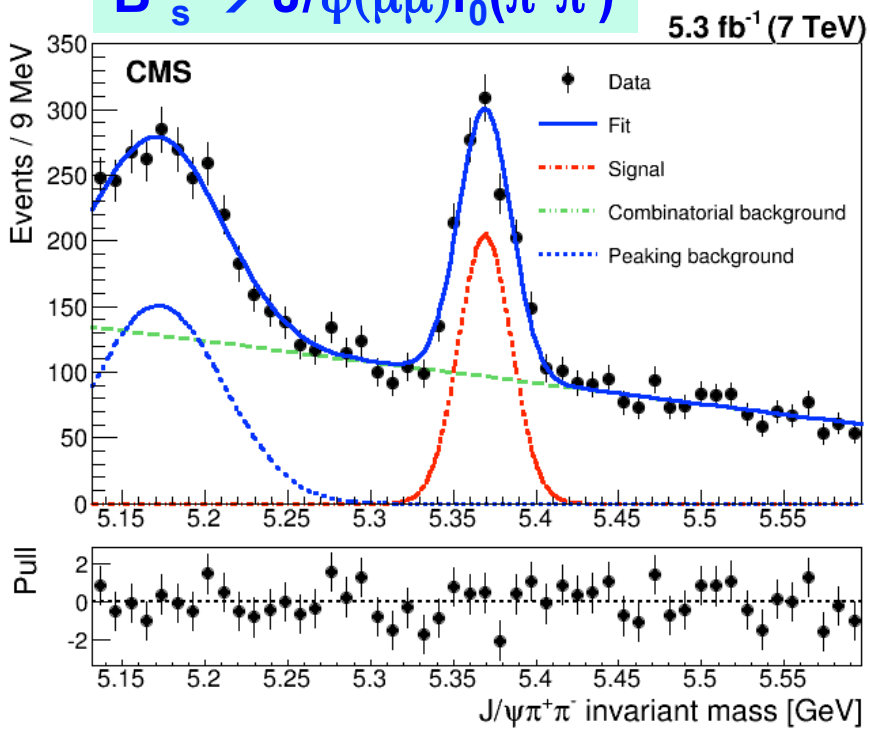
Muon system:
DTs, RPCs,
CSCs

Measurement of the ratio $B(B^0_s \to J/\psi\, f_0(980))/B(B^0_s \to J/\psi\phi(1020))$

- CMS-BPH-14-002 arXiv:1501.06089; CERN-PH-EP-2015-003
- Production of $B^0_s \to J/\psi\, f_0(980)$
  - better understanding of the modelling of $J/\psi - KK/\pi\pi$ final states, $f_0(980)$ di/tetraquark nature
  - CP-odd eigenstate $J/\psi\, f_0(980)$: can be used for measurement of weak phase ϕ_s, no angular analysis needed
- 7 TeV data sample, L = 5.3 fb^{-1}, displaced J/ψ trigger
- Relative ratio: some systematic uncertainties cancel

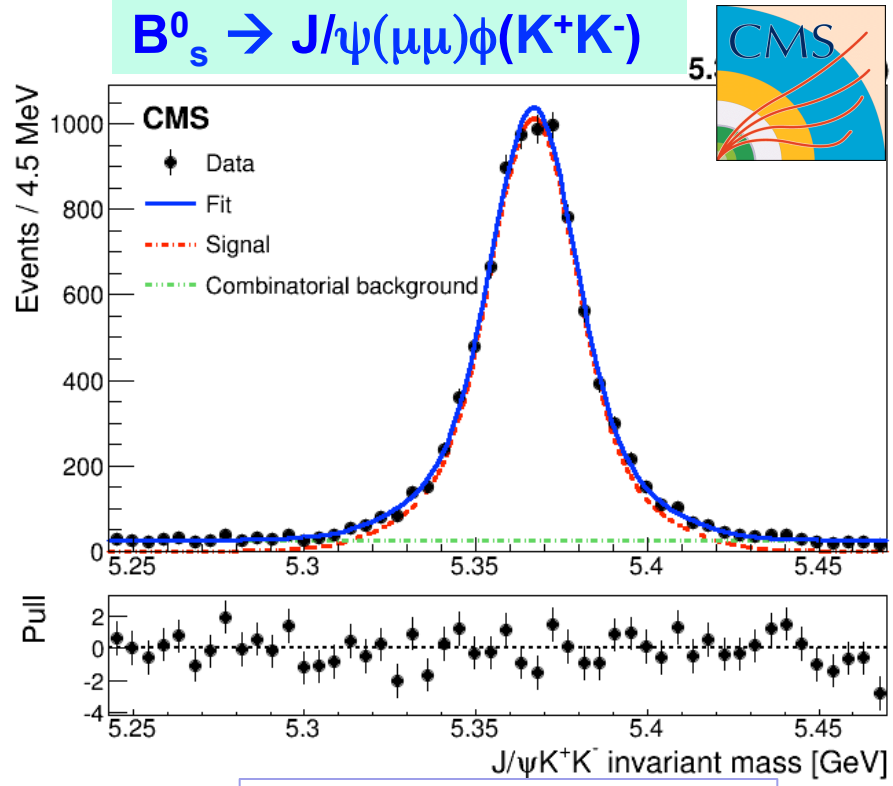
$$R_{f_0/\phi} = \frac{\mathcal{B}(B^0_s \to J/\psi\, f_0)\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B^0_s \to J/\psi\, \phi)\mathcal{B}(\phi \to K^+K^-)} = \frac{N^{f_0}_{obs}}{N^{\phi}_{obs}} \times \epsilon^{\phi/f_0}_{reco}$$

$B^0_s \rightarrow J/\psi(\mu\mu)f_0(\pi^+\pi^-)$



Yield = 873 ± 49
σ_M = 15.9 ± 0.9 MeV

$B^0_s \rightarrow J/\psi(\mu\mu)\phi(K^+K^-)$



Yield = 8377 ± 107
σ_M = 17.1 ± 0.1 MeV

$R(f_0/\phi)$ = 0.140 ± 0.013 (stat.) ± 0.018 (syst.)

LHCb: $R(f_0/\phi)$ = 0.162 ± 0.022 (stat.) ± 0.016 (syst.) PLB 698 (2011) 115
Th. predictions, Stone and Zhang: $R(f_0/\phi) \approx 0.2$, PRD 79 (2009) 074024

$B^0_s \rightarrow J/\psi\phi(1020)$: probe the weak phase ϕ_s

- Weak phase ϕ_s originates from interference between direct decays $B^0_s \rightarrow J/\psi\phi(1020)$ and decays via mixing $B^0_s \rightarrow \bar{B}^0_s \rightarrow J/\psi\phi(1020)$
- $\phi_s \approx -2\beta_s$, where $\beta_s = \arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb})$
- Accurate Standard Model prediction: $2\beta_s = (0.0363\ ^{+0.0016}_{-0.0015})$ rad
- Sensitivity to New Physics beyond the SM

NEW
to be submitted to PLB

CMS ANALYSIS

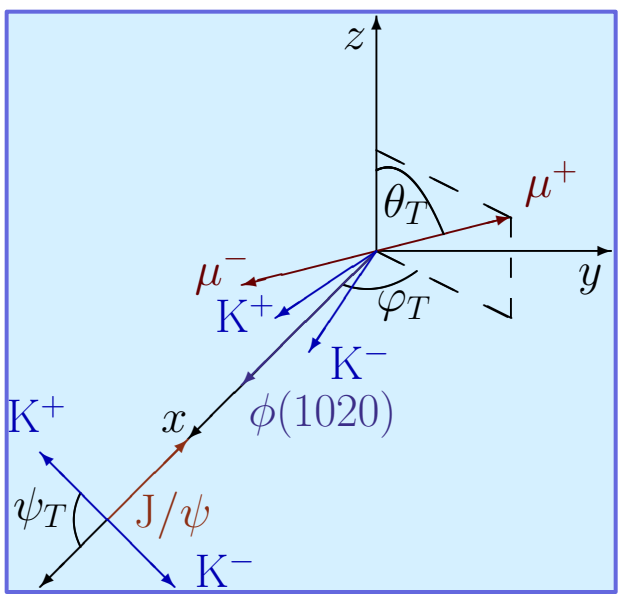
- 2012 8 TeV data, 19.7 fb^{-1}
- $B^0_s \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)\ \phi(1020)\ (\rightarrow K^+K^-)$ + opposite side tag lepton (μ, e)
- Fully reconstructed final state, small background
- Replaces preliminary results CMS-BPH-13-012 (2014)
  - here: new tagger

$B^0_s \rightarrow J/\psi\phi(1020)$: angular analysis

- **Time-dependent angular analysis to disentangle CP-odd and CP-even components of the final state**

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

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

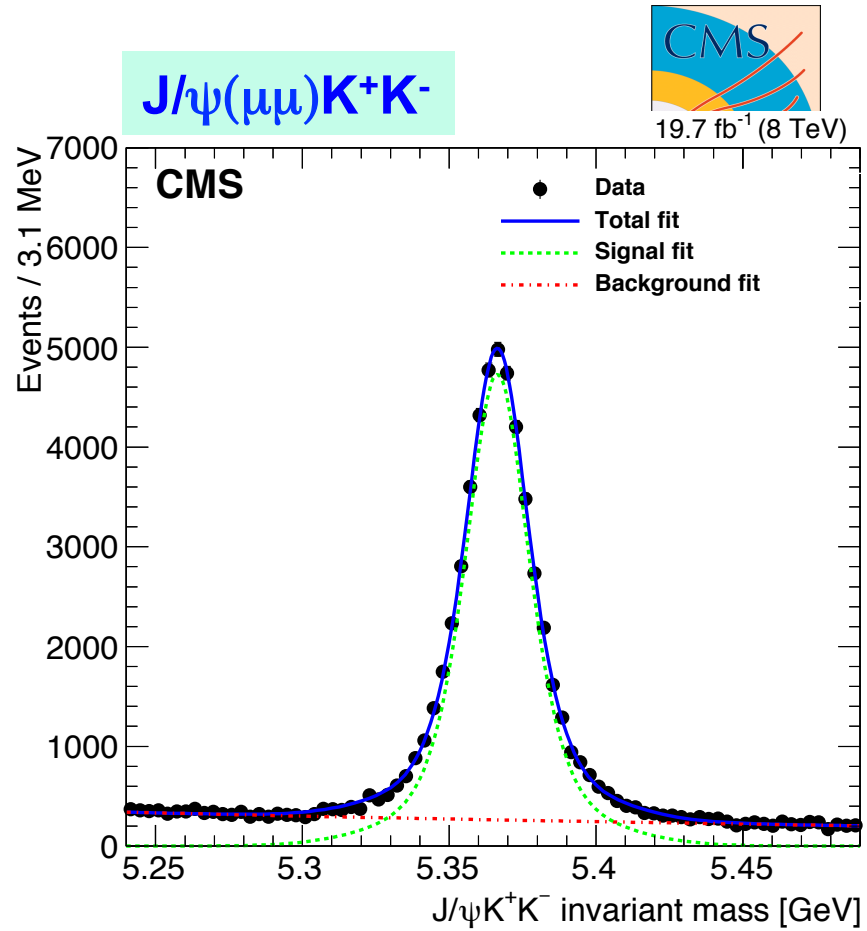


Depend on ϕ_s

α: ($\Delta\Gamma_s$, ϕ_s, $c\tau$, $|A_0|^2$, $|A_S|^2$, $|A_T|^2$, $\delta_{||}$, δ_{ST}, δ_T)
$\Theta = (\theta_T, \psi_T, \varphi_T)$ transversity basis
$g_i(\Theta)$ angular functions

$B^0_s \rightarrow J/\psi\phi(1020)$: reconstruction and selections

- **Trigger: displaced J/ψ from B**
  - $p_T(\mu\mu)>6.9$ GeV, $p_T(\mu)>4$ GeV, $|\eta|<2.1$,
  - $L_{xy}/\sigma_{xy} > 3$, $DCA_{3D}(\mu\mu) > 0.5$ cm,
  - $2.9 < M(\mu\mu) < 3.3$ GeV,
  - χ^2 vertex fit prob > 10%, $\cos\Delta\alpha > 0.9$
- **$|m(J/\psi) - m(J/\psi)_{PDG}| < 150$ MeV**
- **$p_T(K) > 0.7$ GeV, ≥ 4 tracker hits**
- **$|m(KK) - m(\phi)| < 10$ MeV**
- **B^0_s kinematic and vertex fit:**
  - J/ψ mass constraint,
  - χ^2 vertex fit prob > 2%,
  - mass 5.24–5.49 GeV, *ct* 0.02–0.3 cm
- **PV: closest to B^0_s (min angle $\Delta\alpha$ between L_{xyz} and p)**

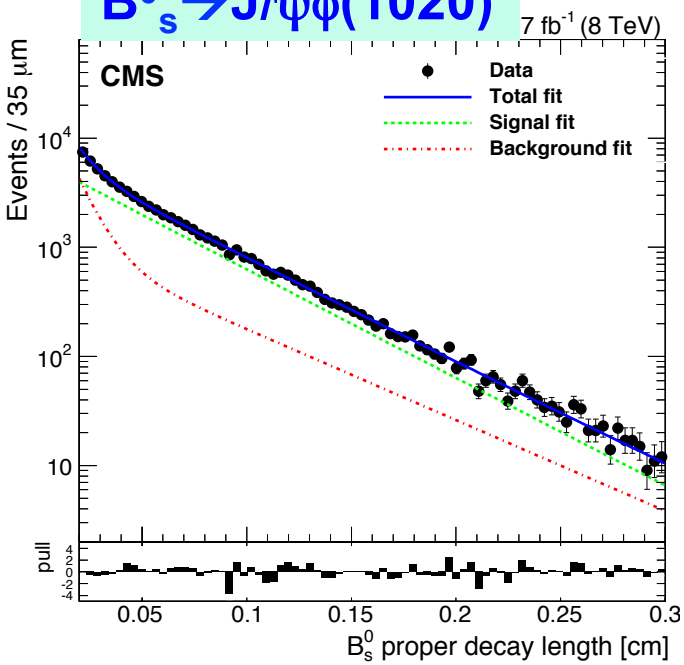


S/B ≈ 6.8 in 5.33–5.40 GeV
49 200 signal events
Main background: displaced J/ψ's from B's with combinatorial tracks

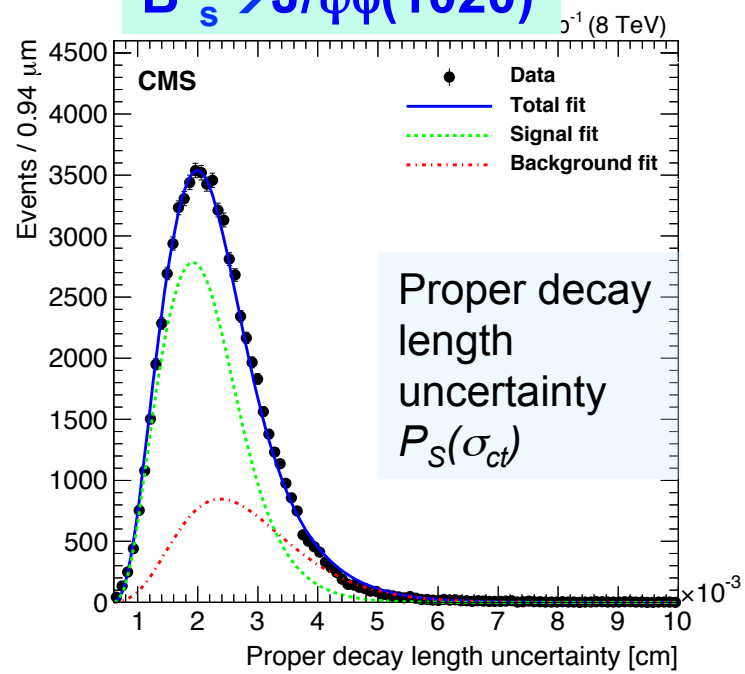
Efficiencies and resolutions

- Angular efficiency $\varepsilon(\Theta) = \varepsilon(\cos\theta_T, \cos\psi_T, \varphi_T)$
  - from full simulation, parametrized as a 3D-function
- Proper decay time efficiency: simulation, cross-checked with data
  - flat in the fit range *ct* = [0.02 – 0.3] cm → not included in the fit
  - variation from flat considered as systematic uncertainty
- Proper decay time resolution: ≈ 70 fs (≈ 21 μm), included per-event
  - taken from the proper decay time uncertainty and scaled with $\kappa(ct)$, cross-checked with prompt J/ψ data

$B^0_s \rightarrow J/\psi\phi(1020)$

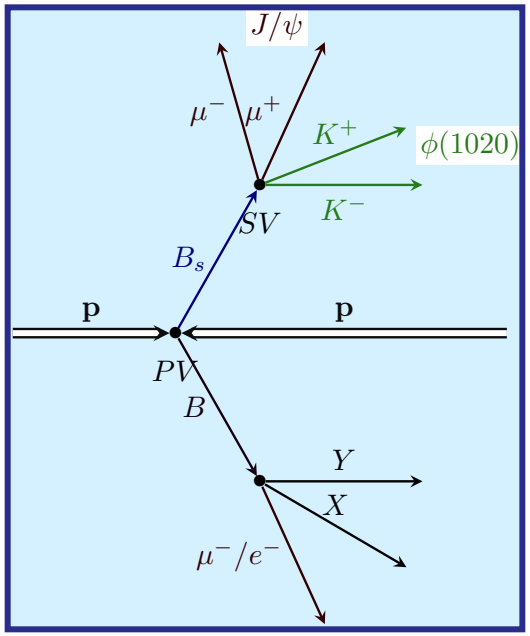


$B^0_s \rightarrow J/\psi\phi(1020)$



Opposite side flavour tagging

- **Opposite side leptons (μ, e) used to tag the flavour of the B^0_s at the production time**
- **Tagging performance optimized by maximizing** $P = \varepsilon_{tag}(1-2\omega)^2$
  - ω = *wrong tag fraction,* ε_{tag}= *tagging efficiency*
  - muons: $p_T > 2.2$ GeV, $|IP_{3D}| < 1$ mm w.r.t. B^0_s primary vertex, $\Delta R(\mu, B_s) > 0.3$
  - electrons: $p_T > 2.0$ GeV, $|IP_{3D}| < 1$ mm w.r.t. B^0_s primary vertex, $\Delta R(e, B_s) > 0.2$, MVA discriminator cut



- **Multilayer perceptron neural network, MLP-NN,** using the TMVA package, to **further separate right and wrong tag leptons***

*J. Pazzini, PhD thesis Univ. of Padua 2015

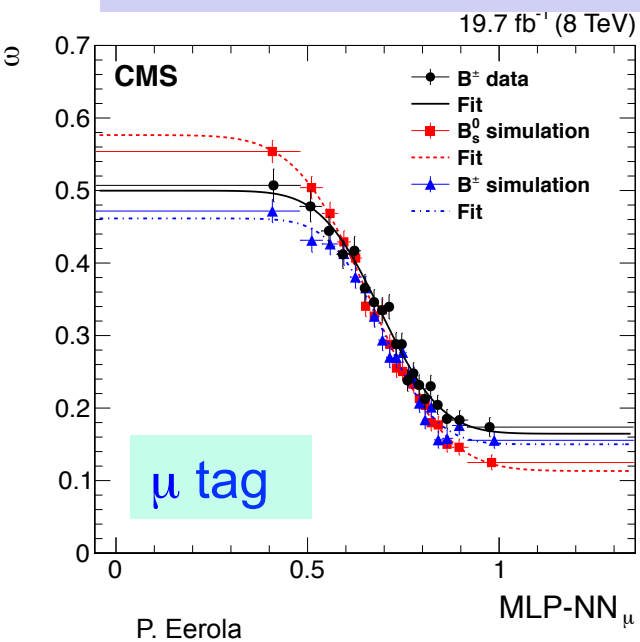
Tagging performance

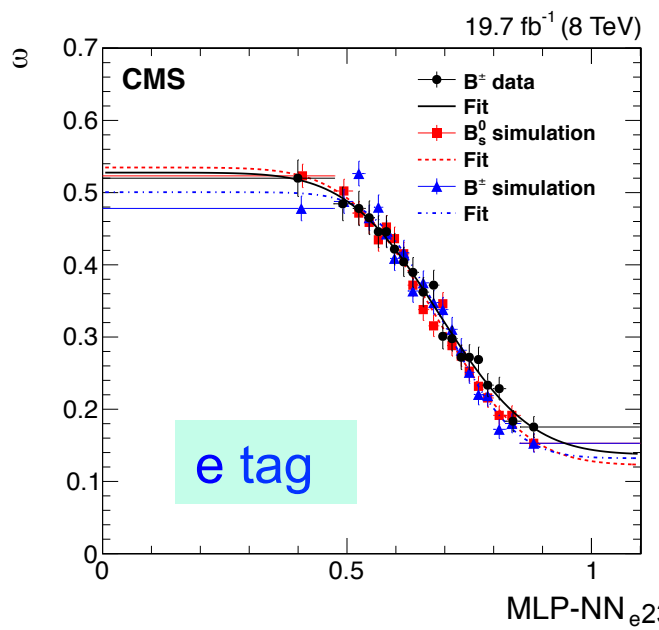
- **Optimal choice of lepton NN input variables:**
  - p_T, η, isolation, charge in a cone, d_{xyz}, p_T^{rel} (μ), MVA discriminator (e)
  - NN trained and tested with simulated $B^0_s \rightarrow J/\psi\phi$ events
- **Per-event mistag probabilities from $B^\pm \rightarrow J/\psi K^\pm$ data**
  - analytical parametrisation of MLP-NN output
  - tested with $B^\pm \rightarrow J/\psi K^\pm$ data, $B^\pm \rightarrow J/\psi K^\pm$ simulation, $B^0_s \rightarrow J/\psi\phi$ simulation

Average tagging performance, combined e, μ

P_{tag} = 1.307 ± 0.031 ± 0.007 %

ω = 30.17 ± 0.24 ± 0.05 %, ε_{tag} = 8.31 ± 0.03 %



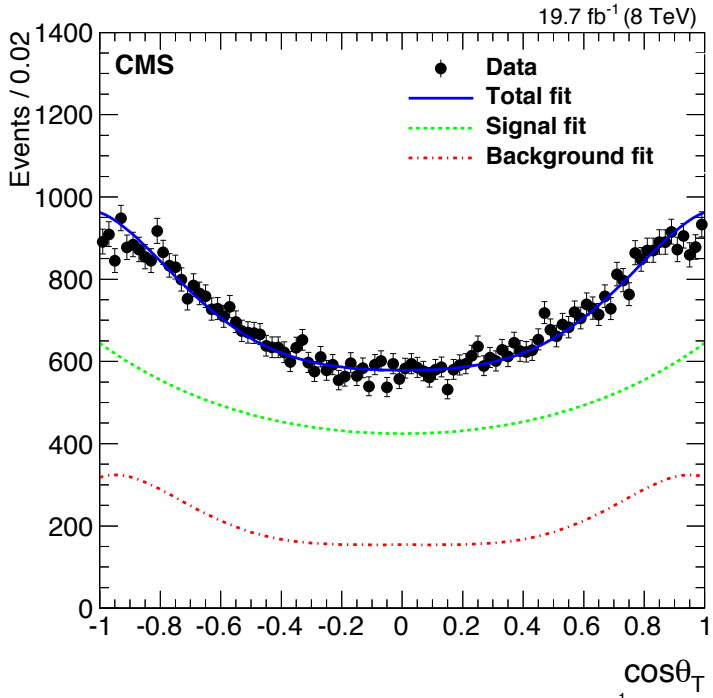


Data fit

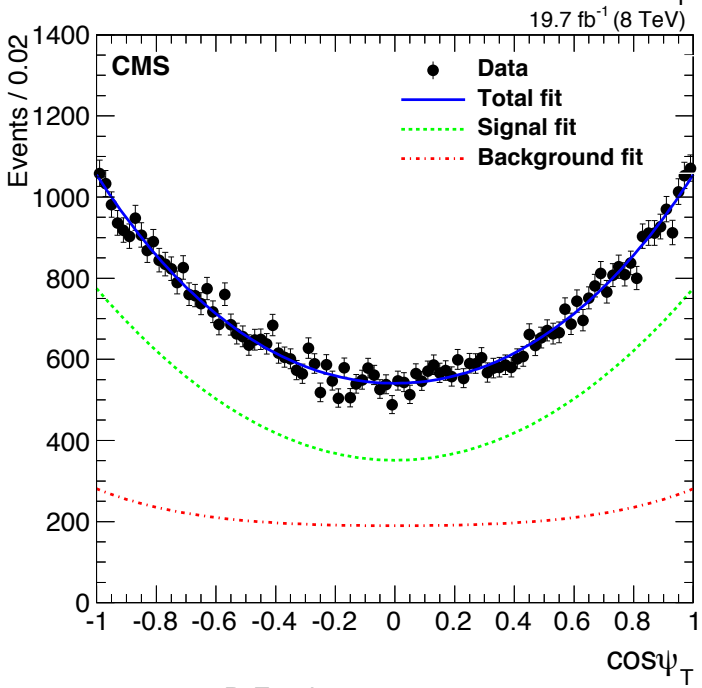
- Extended maximum likelihood fit, with a Gaussian constraint on Δm_s
- Fit range B_s mass [5.24 – 5.49] GeV, *ct* [0.02 – 0.3] cm

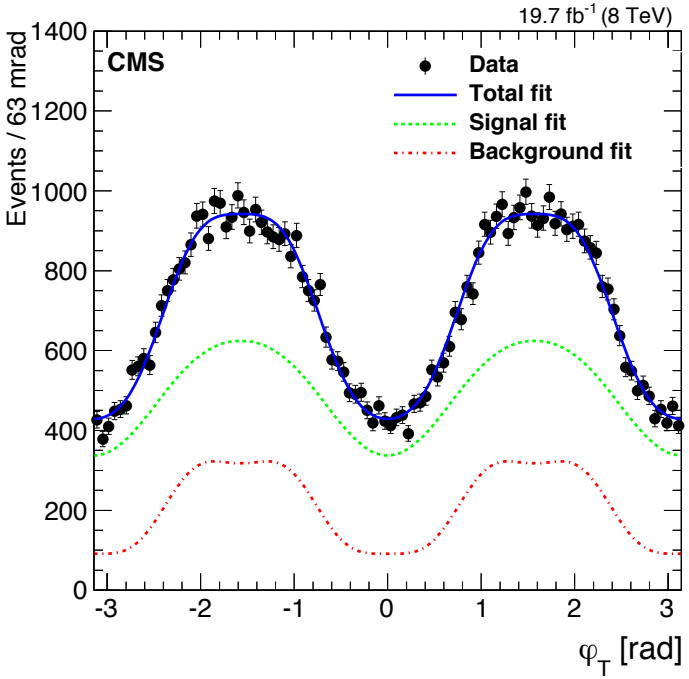
$$
\begin{aligned}
\mathcal{L} &= L_{\mathrm{s}} + L_{\mathrm{bkg}}\,, \\
L_{\mathrm{s}} &= N_{\mathrm{s}} \cdot \left[\tilde{f}\left(\Theta, \alpha, ct\right) \otimes G\left(ct, \sigma_{ct}\right) \cdot \epsilon\left(\Theta\right)\right] \cdot P_{\mathrm{s}}\left(m_{\mathrm{B}_{\mathrm{s}}^{0}}\right) \cdot P_{\mathrm{s}}\left(\sigma_{ct}\right) \cdot P_{\mathrm{s}}\left(\xi\right)\,, \\
L_{\mathrm{bkg}} &= N_{\mathrm{bkg}} \cdot P_{\mathrm{bkg}}\left(\cos\theta_{\mathrm{T}}, \varphi_{\mathrm{T}}\right) \cdot P_{\mathrm{bkg}}\left(\cos\psi_{\mathrm{T}}\right) \cdot P_{\mathrm{bkg}}\left(ct\right) \cdot P_{\mathrm{bkg}}\left(m_{\mathrm{B}_{\mathrm{s}}^{0}}\right) \cdot P_{\mathrm{bkg}}\left(\sigma_{ct}\right) \cdot P_{\mathrm{bkg}}\left(\xi\right)
\end{aligned}
$$

- $\tilde{f}(\Theta, \alpha, ct)$ signal PDF
- $G(ct, \sigma_{ct})$ Gaussian proper decay time resolution, per-event
- $\varepsilon(\Theta) = \varepsilon(\cos\theta_T, \cos\psi_T, \varphi_T)$ angular efficiencies
- $P_S(m_{Bs})$ signal mass PDF, triple-Gaussian with a common mean
- $P_S(\sigma_{ct})$ proper time uncertainty (Γ functions)
- $P_S(\xi)$ tag decision, per-event
- P_{bkg} background PDFs



Parameter	Fit result
ϕ_s [rad]	-0.075 ± 0.097
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
$\lvert A_0\rvert^2$	0.510 ± 0.005
$\lvert A_S\rvert^2$	$0.012\,^{+0.009}_{-0.007}$
$\lvert A_\perp\rvert^2$	0.243 ± 0.008
$\delta_\parallel$ [rad]	$3.48\,^{+0.07}_{-0.09}$
$\delta_{S\perp}$ [rad]	$0.37\,^{+0.28}_{-0.12}$
$\delta_\perp$ [rad]	2.98 ± 0.36
$c\tau$ [μm]	447.2 ± 2.9





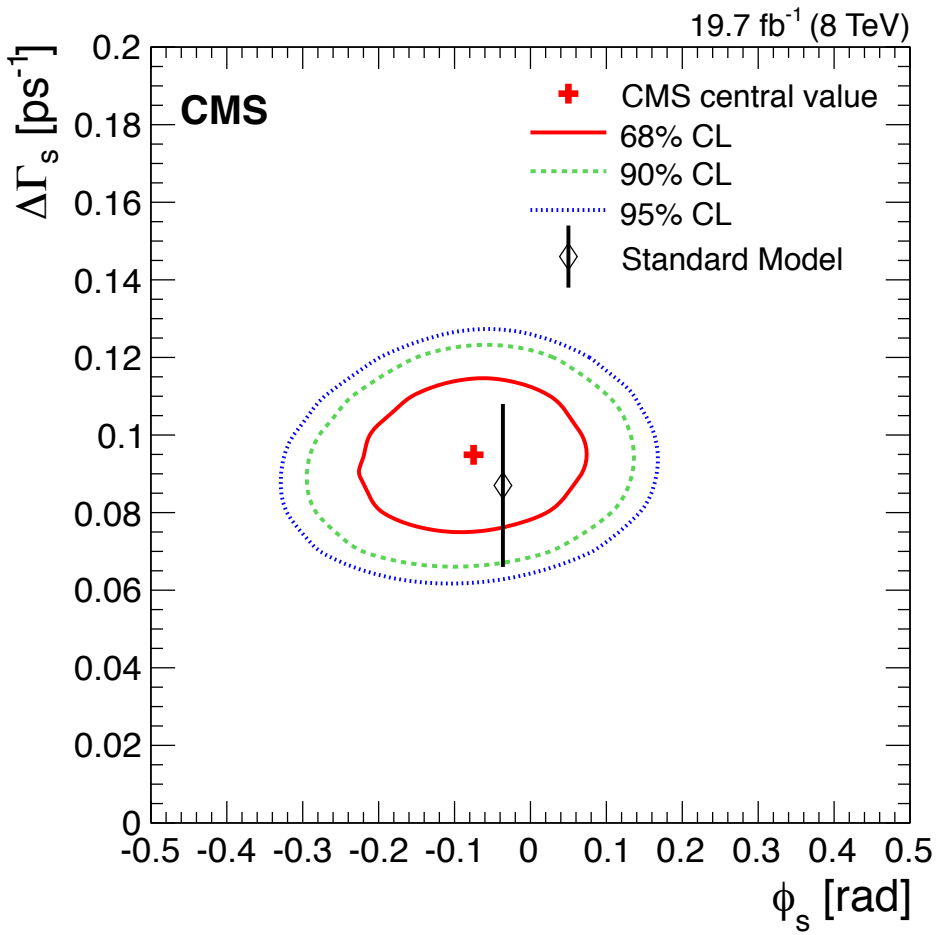
Systematic uncertainties

Source of uncertainty	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_S\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel$ [rad]	$\delta_{S\perp}$ [rad]	$\delta_\perp$ [rad]	$c\tau$ [μm]
ct efficiency	0.002	0.0057	0.0015	-	0.0023	-	-	-	1.0
Angular efficiency	0.016	0.0021	0.0060	0.008	0.0104	0.674	0.14	0.66	0.8
Kaon p_T weighting	0.014	0.0015	0.0094	0.020	0.0041	0.085	0.11	0.02	1.1
ct resolution	0.006	0.0021	0.0009	-	0.0008	0.004	-	0.02	2.9
Flavour tagging	0.003	0.0003	-	-	-	0.006	0.02	-	-
Model bias	0.015	0.0012	0.0008	-	-	0.025	0.03	-	0.4
Mistag distribution modelling	0.004	0.0003	0.0006	-	-	0.008	0.01	-	0.1
pdf modelling assumptions	0.006	0.0021	0.0016	0.002	0.0021	0.010	0.03	0.04	0.2
$\lvert\lambda\rvert$ as a free parameter	0.015	0.0003	0.0001	0.005	0.0001	0.002	0.01	0.03	-
Total systematic uncertainty	0.031	0.0070	0.0114	0.022	0.0116	0.680	0.18	0.66	3.4
Statistical uncertainty	0.097	0.0134	0.0053	0.008	0.0075	0.081	0.17	0.36	2.9

Results

- ϕ_s = -0.075 ± 0.097 (stat.) ± 0.031 (syst.) rad
- $\Delta\Gamma_s$ = 0.095 ± 0.013 (stat.) ± 0.007 (syst.) ps^{-1}

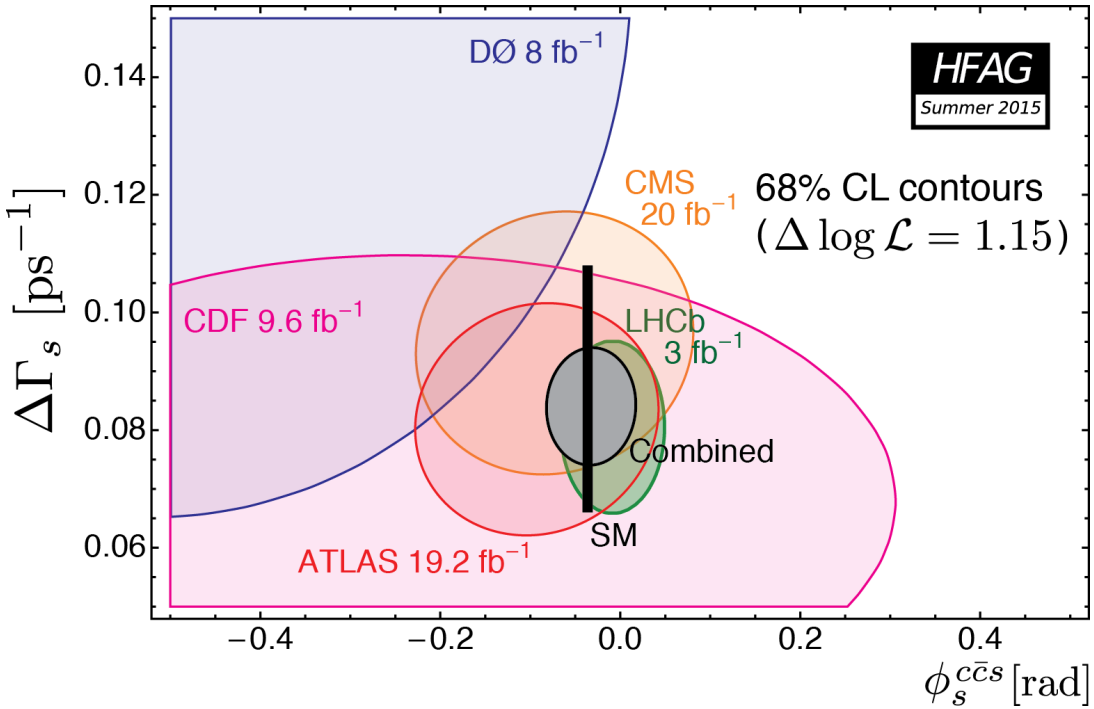
constraining $\Delta\Gamma_s > 0$



The 68%, 90% and 95% CL contours with the SM fit prediction. Uncertainties are statistical only.

Preliminary HFAG average, July 2015

Includes latest results from ATLAS and CMS



Summary

- Using 2012 data corresponding to 19.7 fb^{-1}, CMS measured ϕ_s and $\Delta\Gamma_s$ using lepton-tagged $B^0_s \rightarrow J/\psi\phi(1020)$ decays
- Results well in agreement with the Standard Model
- Measurement error dominated by statistical uncertainties → good prospects for LHC Run 2
- Accurate measurement of the ratio $R(f_0/\phi) = B(B^0_s \rightarrow J/\psi f_0(980))/B(B^0_s \rightarrow J/\psi\phi(1020))$