Measurement of CP violating phase ϕ_s at CMS

BEAUTY 2019

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On behalf of CMS

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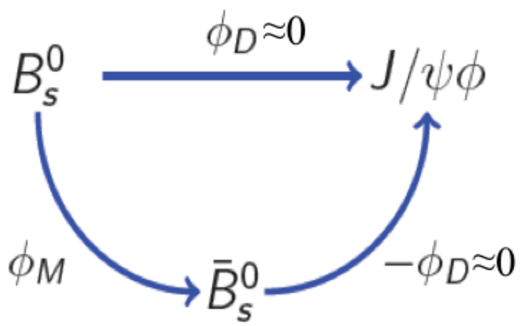
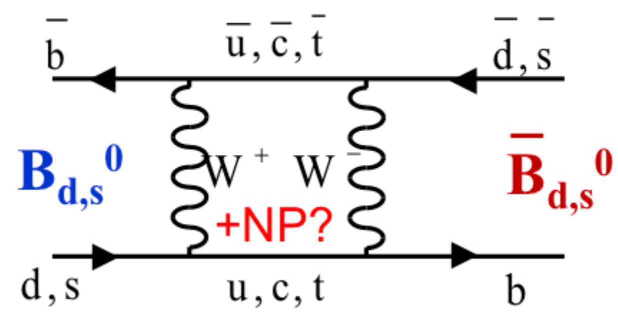
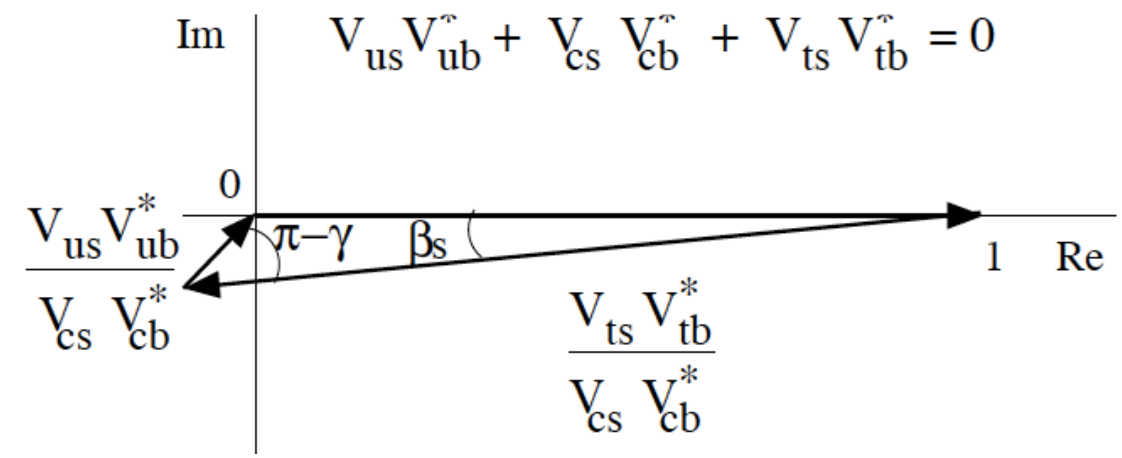
Introduction

- CP violating phase in B_s mesons decays arises from interference between direct $B_s \rightarrow J/\psi\ \phi$ decay amplitude with its mixed amplitude.







- Standard Model prediction
  - $\phi_s = -2\beta_s + P \sim 2\arg(V_{ts}V^*_{tb}/V_{cs}V^*_{cb}) = -(0.0370 \pm 0.0006)$

    [CKMfitter, Phys. Rev. D84, 033005 (2011), updated with Summer 2016 results]
    - where β_s is the B_s unitarity CKM triangle CP violating phase and P the penguin (~0) contribution

Ingredients for a measurement

- Time dependent angular analysis of differential decay rate

$$\frac{d^4\Gamma}{d\Theta d(t)} = f(\Theta, t, \alpha) \propto \sum_{i=1}^{10} \varepsilon(\Theta)\varepsilon(t) \cdot \tilde{O}_i(\alpha, t) \cdot g_i(\Theta)$$

$$\tilde{O}_i(\alpha, t) = \int O_i(\alpha, t')R(t - t')\mathrm{dt'}$$

  - where O_i are time dependent functions, g_i are angular functions, and α a set of parameters, and R a the per-event resolution function

$$\alpha = \{\Delta\Gamma_s, c\tau, \phi_s, \Delta m_s, |A_0|^2, |A_\perp|^2, |A_\parallel|^2, |A_S|^2, \delta_\parallel, \delta_\perp, \delta_S, \delta_0\}$$

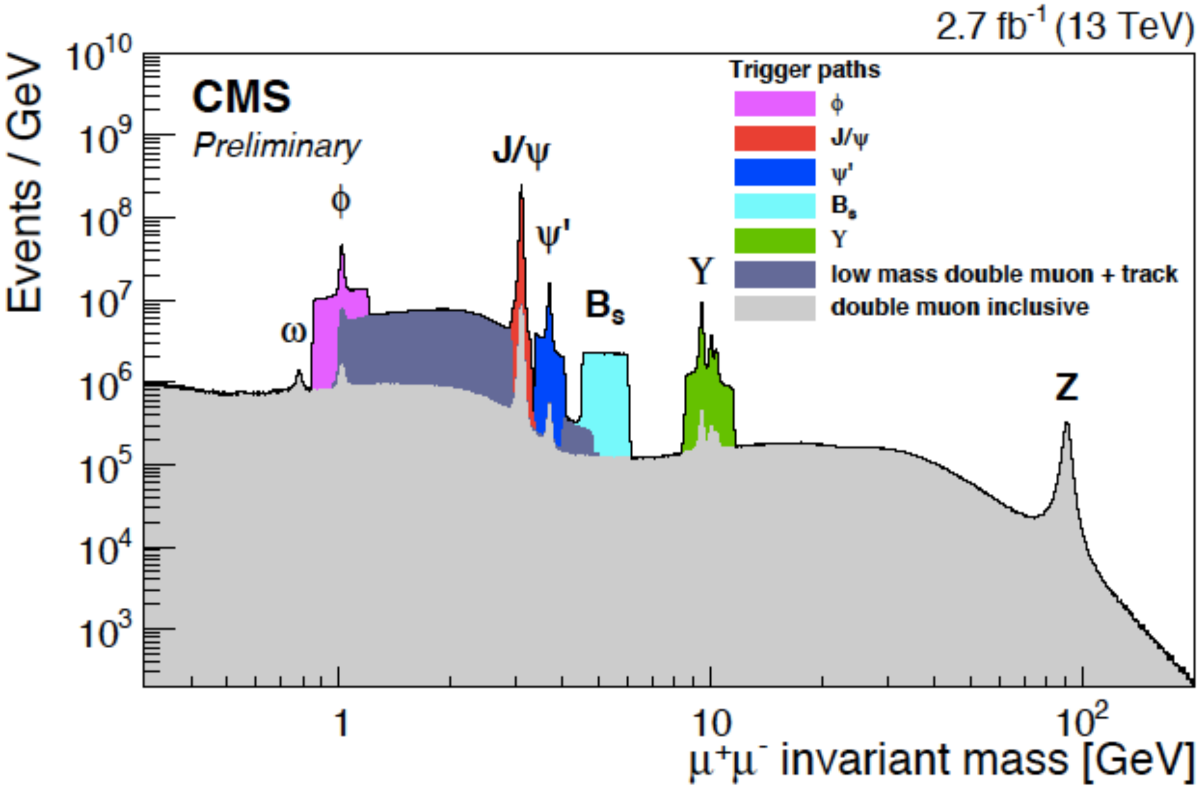
$$O_i(\alpha, t) = N_i e^{-ict/c\tau}\left[a_i \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_i \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + c_i\,\xi(1-2\omega)\cdot\cos(\Delta m_s t) + d_i\,\xi(1-2\omega)\cdot\sin(\Delta m_s t)\right]$$

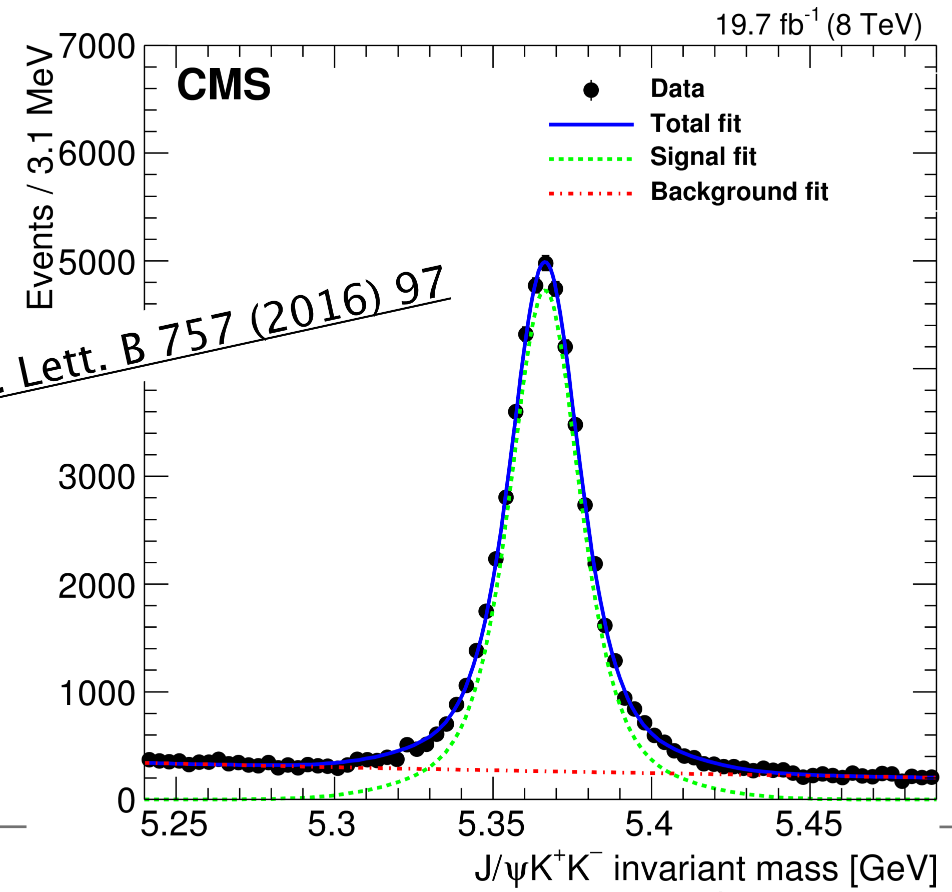
  - where ξ=0,±1 if tag is present or not, and ω is the fraction of mistagged events
    - Untagged events also contribute!

  - b_i and d_i coefficients are sensitive to $\cos(\phi_s)$ and $\sin(\phi_s)$

Reconstruction

- Trigger
  - Displaced J/ψ trigger
    - $p_T(\mu)>4$ GeV; $p_T(J/\psi)>6.9$ GeV; $|\eta(\mu)|<2.1$
    - $|M(\mu\mu)-M^{PDG}(J/\psi)|<0.2$ GeV
    - $\cos(L_{xy},p_T)_{J/\psi}>0.9$
    - $L_{xy}/\sigma_{xy}>3$; $D_{3D}(\mu\mu)<0.5$ cm
- Offline reconstruction
  - $|M(\mu\mu)-M^{PDG}(J/\psi)|<150$ MeV
  - $p_T(K)>700$ MeV
  - $|M(KK)-M^{PDG}(\phi)|<10$ MeV
  - B_s kinematic vertex fit (using J/ψ mass constraint)
    - 5.24 GeV $< M(B_s) < 5.49$ GeV
    - $CL(\chi 2$ fit$)>2\%$
  - PV maximises $\cos(L_{xy},p_T)_{J/\psi}$ pileup~16
  - B_s decay length between 0.02 and 3 cm



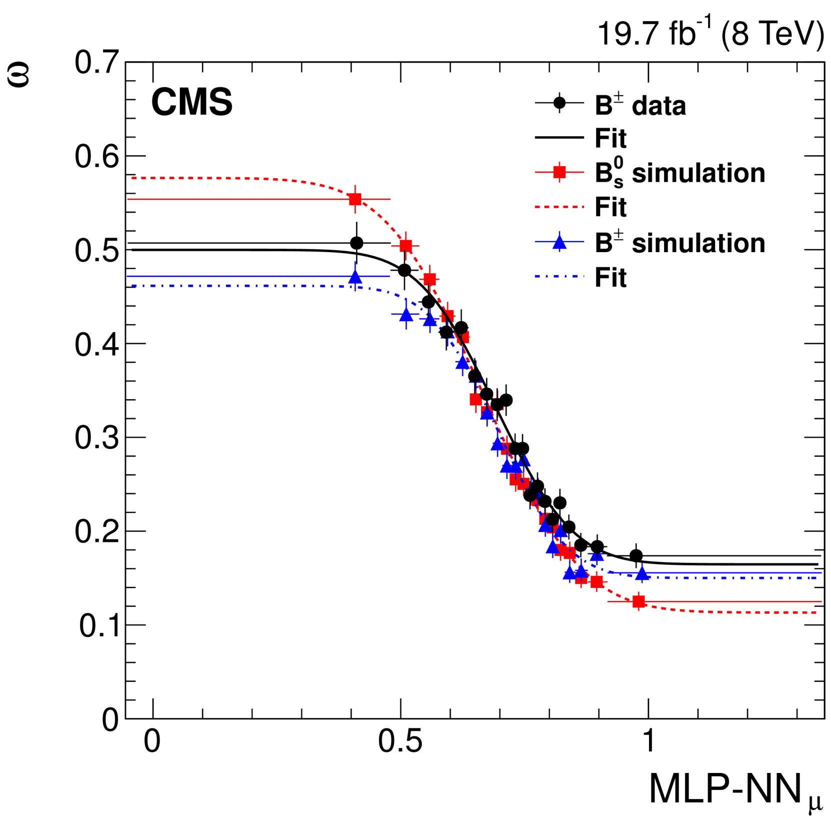


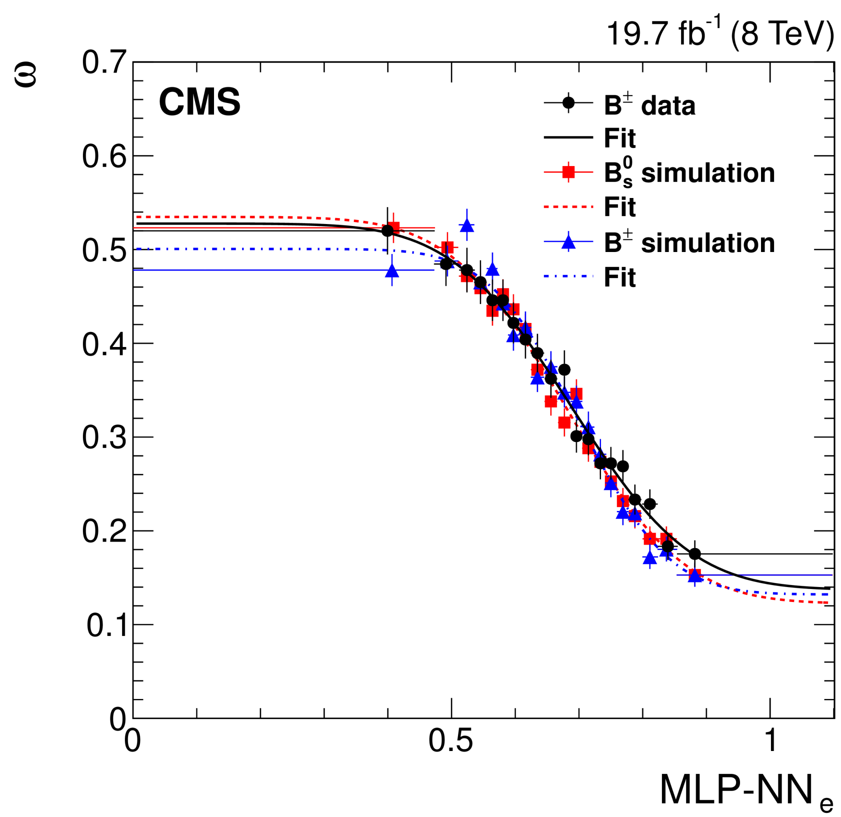
Phys. Lett. B 757 (2016) 97

☆ 49k events in 19.7 fb^{-1} @8 TeV pp (2011 and 2012)

Flavour tagging

- Opposite side muons and electrons
  - $p_T(\mu)>2.2$ GeV; $p_T(e)>2.0$ GeV
  - $d_{xyz}<0.1$ cm (to reject long-lived decays and pileup)
  - $\Delta R(B_s,\mu)>0.3$; $\Delta R(B_s,e)>0.2$
  - MLP-NN from TMVA toolkit based on simulated MC events (24K per each lepton) separates right- and wrong-tagged events
- Use self-tagged 700k $B^{\pm} \to J/\psi K^{\pm}$ events to obtain mistag probabilities in data



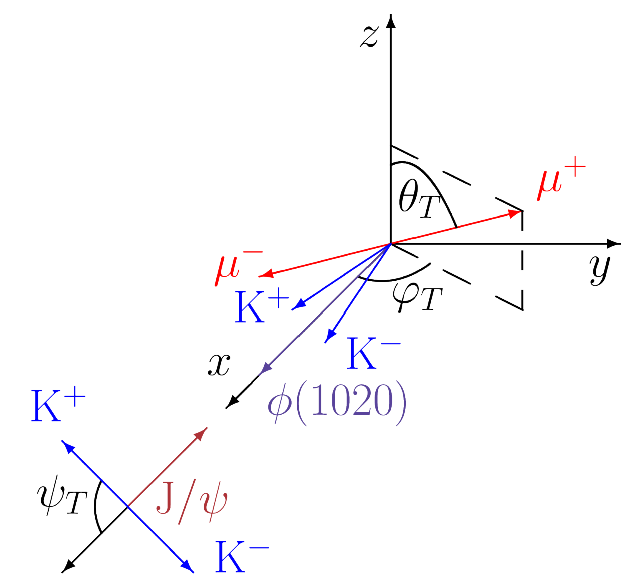


$\omega=(30.17\pm0.24\pm0.05)\%$
$\varepsilon=(8.31\pm0.03)\%$

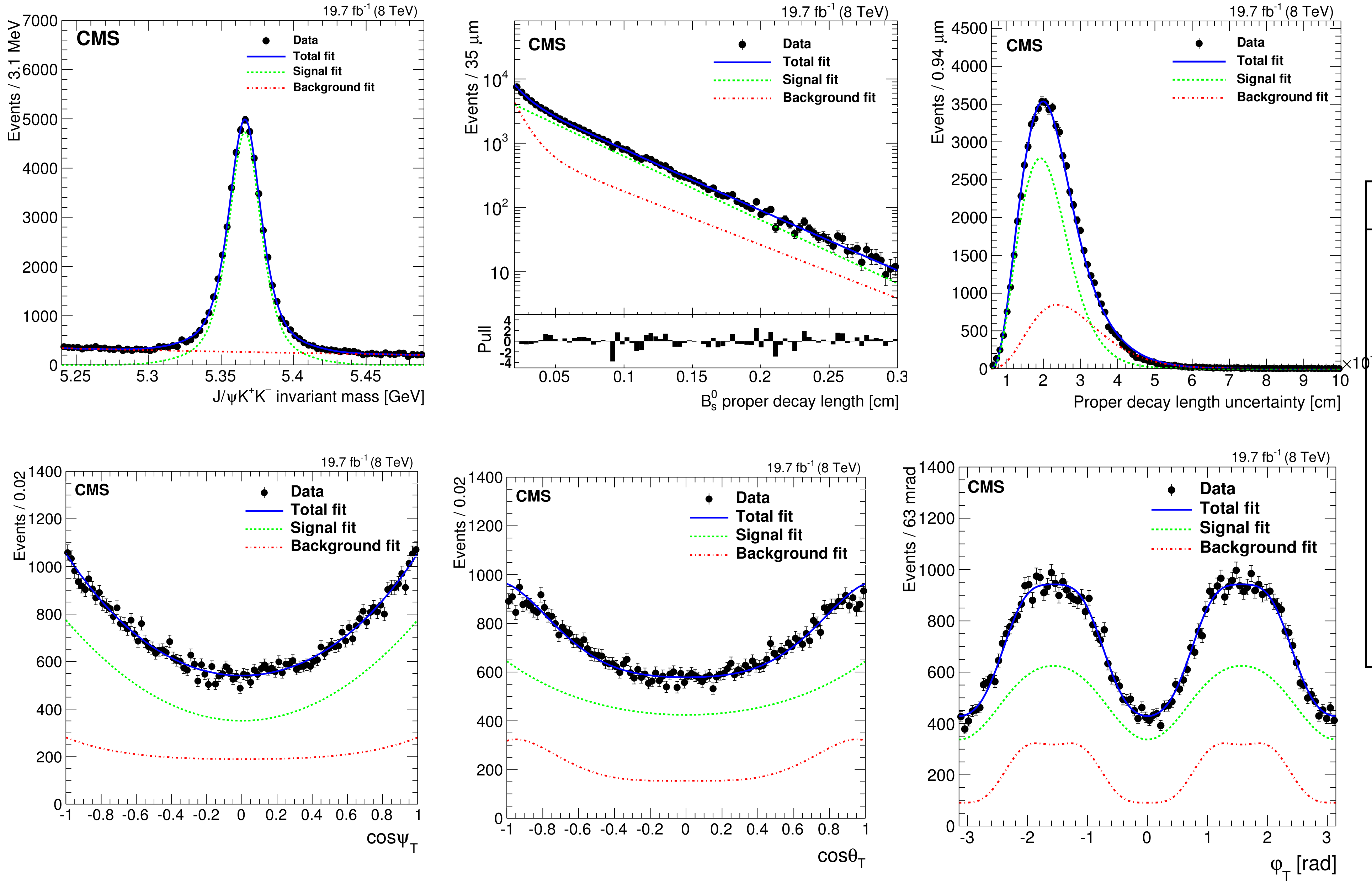
$\varepsilon D^2=(1.307\pm0.031\pm0.007)\%$

Fitting

- Angular efficiencies and resolutions from MC simulation
  - Resolutions not included in fit model
  - Efficiencies $\varepsilon(\boldsymbol{\Theta})=\varepsilon(\cos\psi_T,\cos\boldsymbol{\vartheta}_T, \varphi_T)$ used in the fit
  - Efficiency for proper decay-length (PDL) uniform between 0.02 and 3 cm
  - Average PDL uncertainty 23.4 μm (78 fs)
    - Systematic uncertainties due to angular resolutions and deviations from flat PDL efficiency taken as systematics
- Multidimensional fit to ϕ_s to mass & angular functions
  - $L_{signal}= [f(ct,\alpha,\boldsymbol{\Theta},\boldsymbol{\xi})\otimes G(ct, \sigma_{ct})]\varepsilon(\boldsymbol{\Theta})P_s(M_{Bs})P_s(\sigma_{ct})P_s(\boldsymbol{\xi})$
    - $f(ct,\alpha,\boldsymbol{\Theta},\boldsymbol{\xi})$ decay rate function
    - $G(ct, \sigma_{ct})$ per-event PDL resolution function
    - $\varepsilon(\boldsymbol{\Theta})$ angular efficiency function
    - $P_s(M_{Bs})$ Mass pdf for B_s signal
    - $P_s(\sigma_{ct})$ proper decay length error pdf for B_s signal
    - $P_s(\boldsymbol{\xi})$ tag decision pdf for B_s signal
  - $L_{total}= L_{signal} + L_{background}$



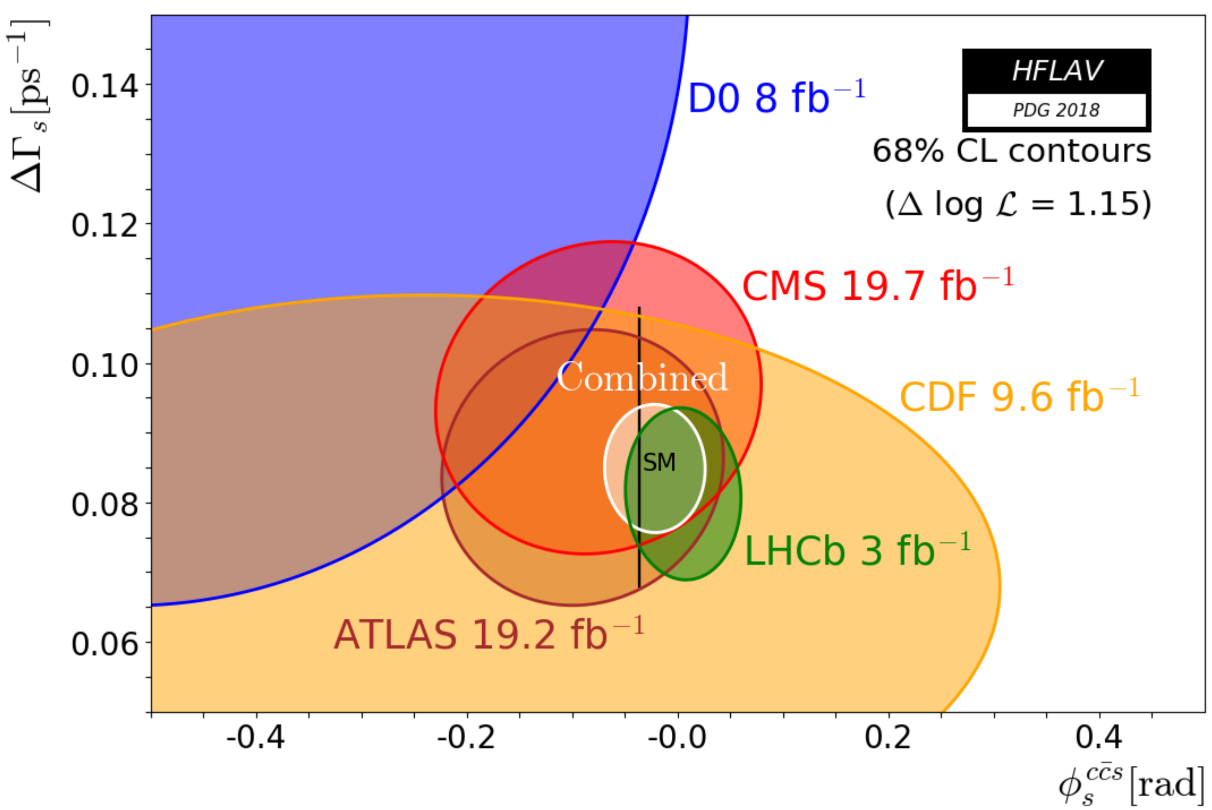
Fit results

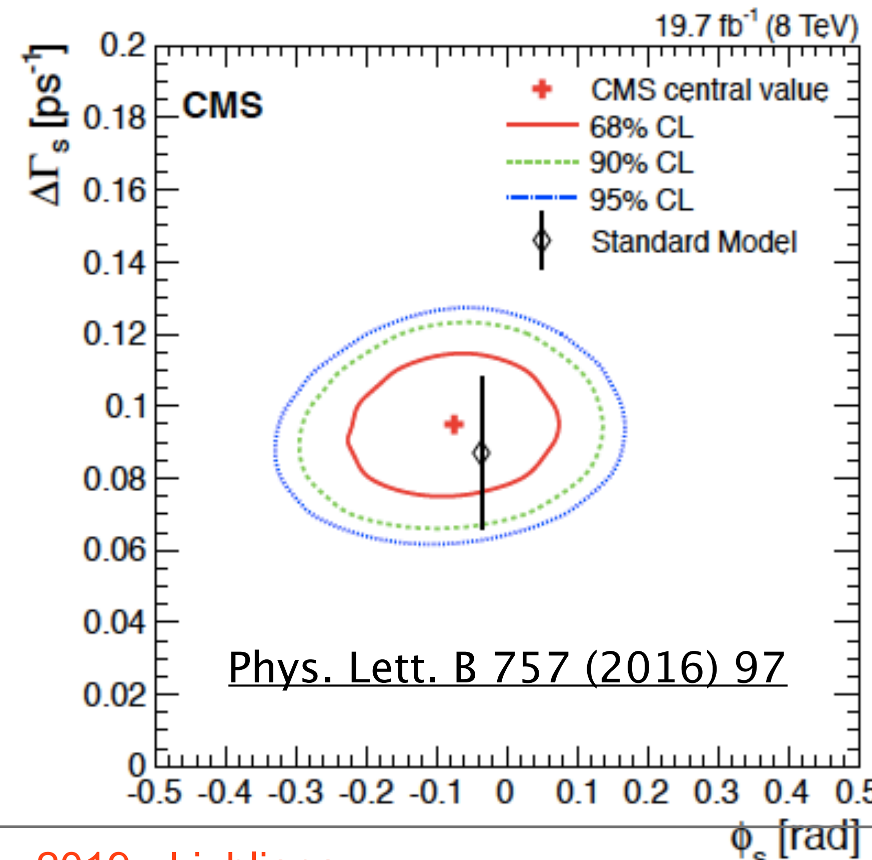


Parameter	Fit result
ϕ_s [rad]	-0.075 ± 0.097
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
$\|A_0\|^2$	0.510 ± 0.005
$\|A_S\|^2$	$0.012\,^{+0.009}_{-0.007}$
$\|A_\perp\|^2$	0.243 ± 0.008
$\delta_\parallel$ [rad]	$3.48\,^{+0.07}_{-0.09}$
$\delta_{S\perp}$ [rad]	$0.37\,^{+0.28}_{-0.12}$
$\delta_\perp$ [rad]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

Systematics and results

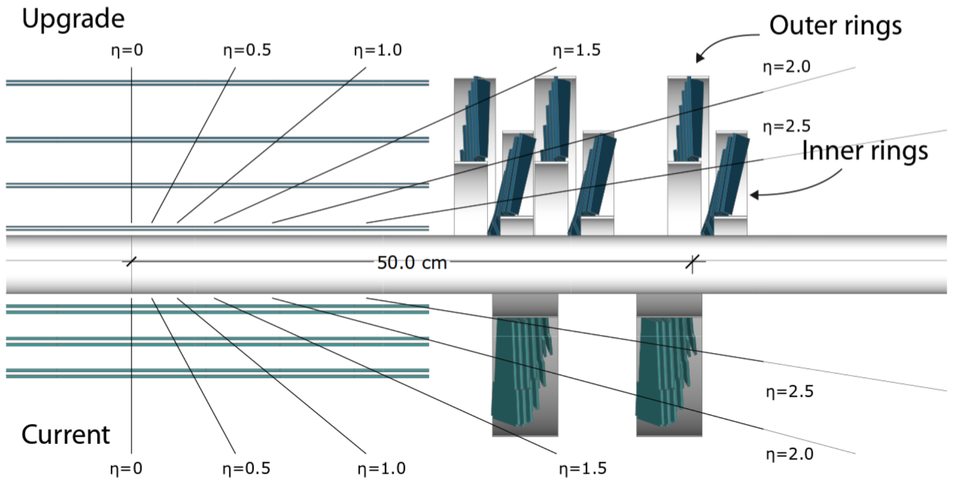
Source of uncertainty	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_S\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel$ [rad]	$\delta_{S\perp}$ [rad]	$\delta_\perp$ [rad]	$c\tau$ [μm]
PDL efficiency	0.002	**0.0057**	0.0015	-	0.0023	-	-	-	1.0
Angular efficiency	**0.016**	0.0021	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
PDL resolution	0.006	0.0021	0.0009	-	0.0008	0.004	-	0.02	2.9
Mistag distribution modelling	0.004	0.0003	0.0006	-	-	0.008	0.01	-	0.1
Flavour tagging	0.003	0.0003	-	-	-	0.006	0.02	-	-
Model bias	**0.015**	0.0012	0.0008	-	-	0.025	0.03	-	0.4
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	-
Tracker alignment	-	-	-	-	-	-	-	-	1.5
Total systematic uncertainty	0.031	0.0070	0.0114	0.022	0.0116	0.680	0.18	0.66	3.7
Statistical uncertainty	0.097	0.0134	0.0053	0.008	0.0075	0.081	0.17	0.36	2.9

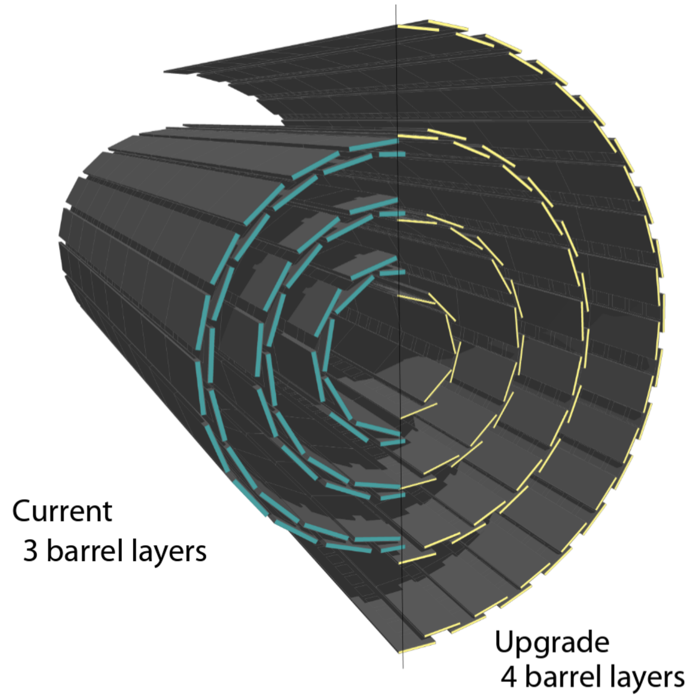




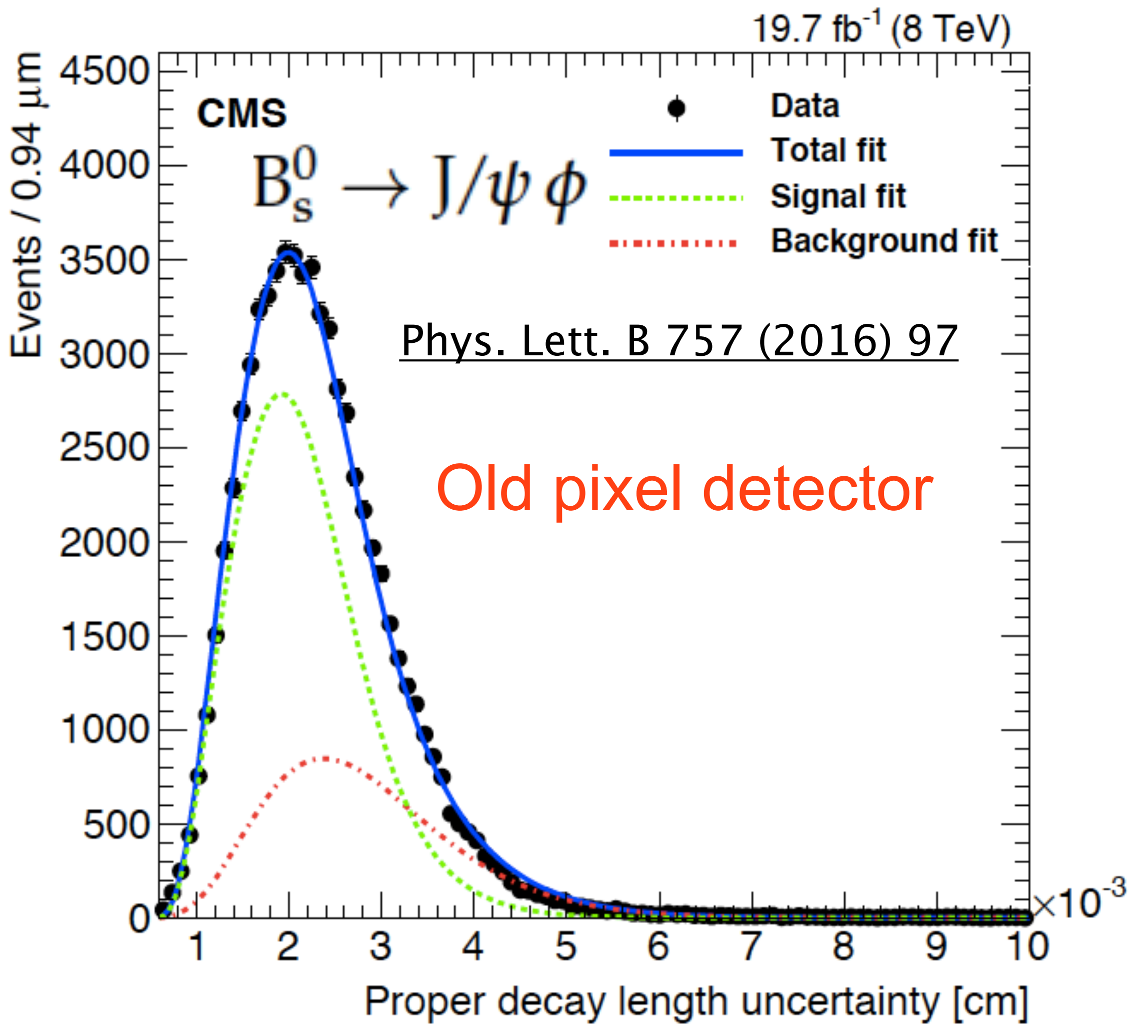
Prospects for Run2 - I

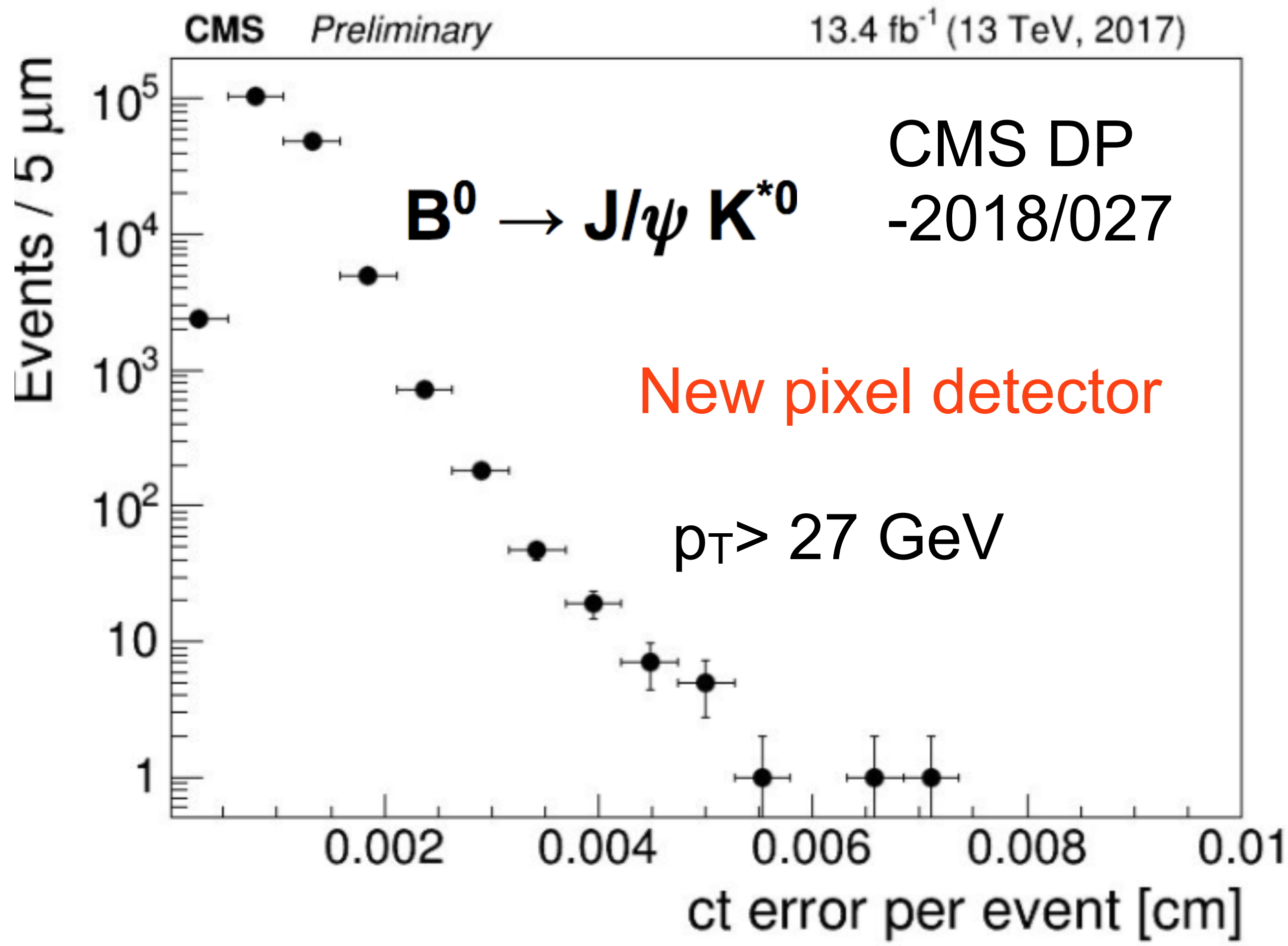
- Run 2 conditions
  - Pro's:
    - Higher c.o.m energy (13 TeV instead of 8 TeV), ~x2 cross-section
    - Upgraded pixel detector since 2017: Lower material budget and closer to beam pipe
  - Con's:
    - Higher pileup: trigger thresholds need to be raised or new triggers to be implemented, and more combinatorics





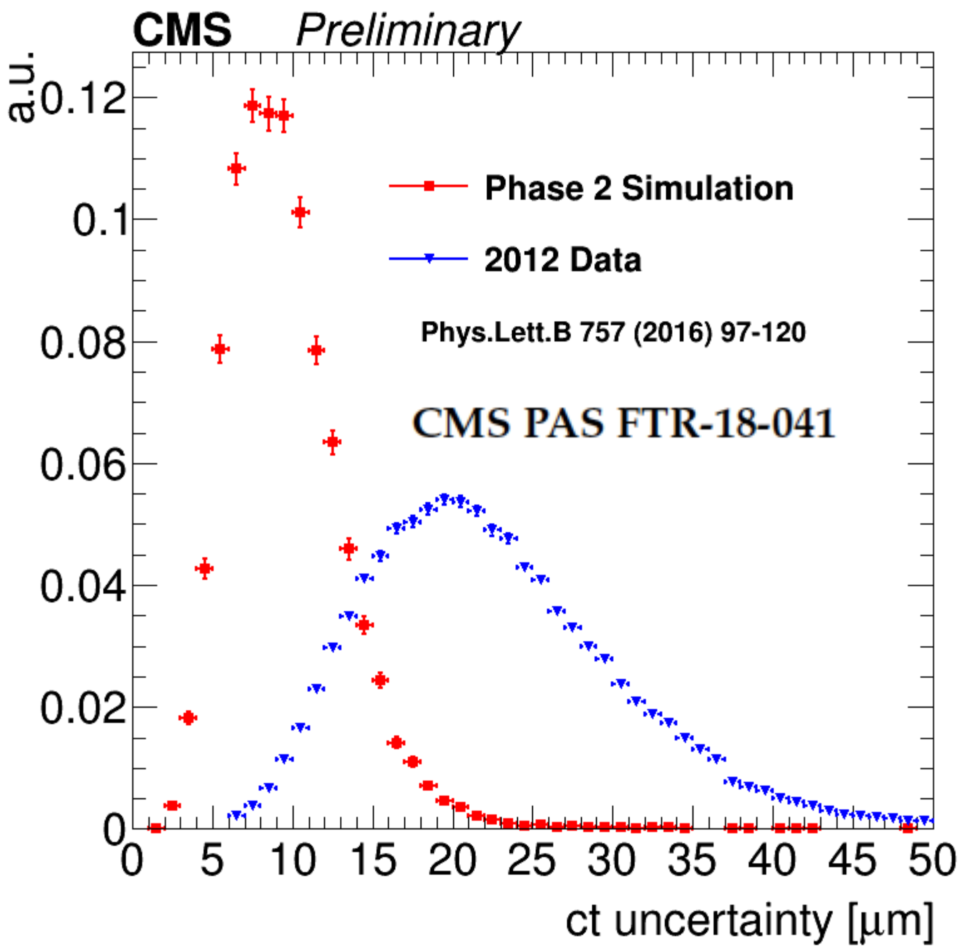
Decay length resolution improvement

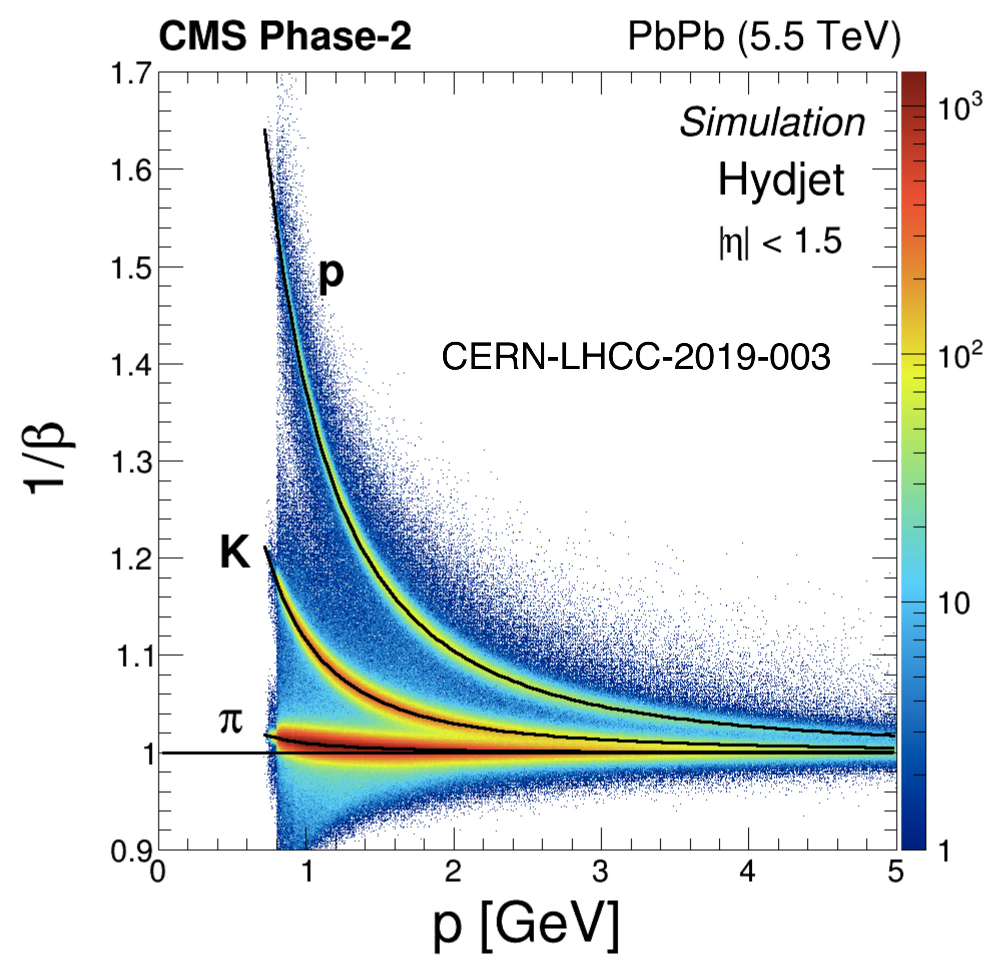




HL-LHC ϕ_s prospects - I

- New Tracker system
  - Less material budget, L1 track reconstruction for p_T>2 GeV
- Improved muon system
  - Extended forward coverage, better timing and trigger capabilities
- Timing detector
  - Offers capabilities to discriminate pileup and some K/π separation up to ~ 2-3 GeV



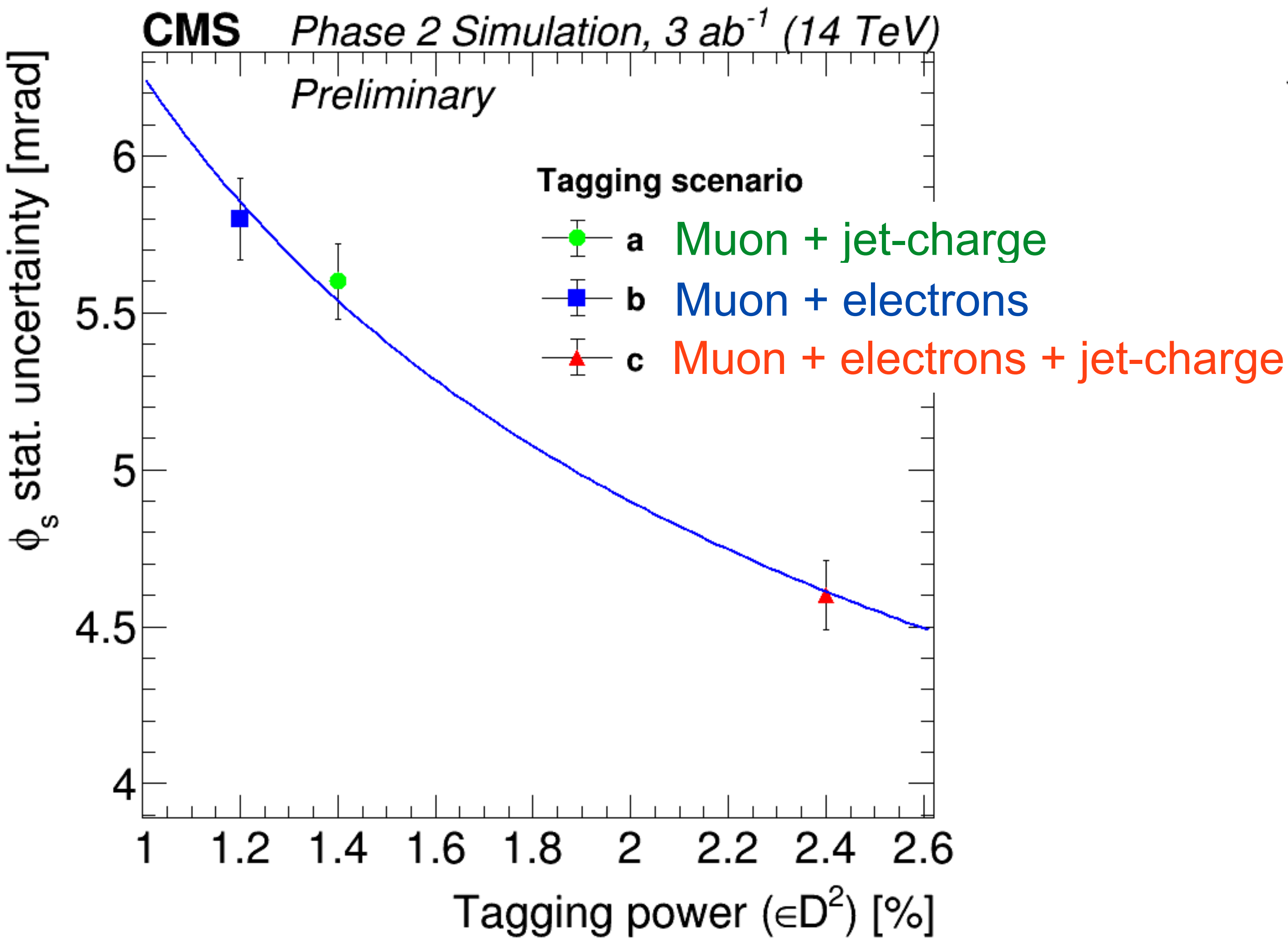


HL-LHC ϕ_s prospects - II

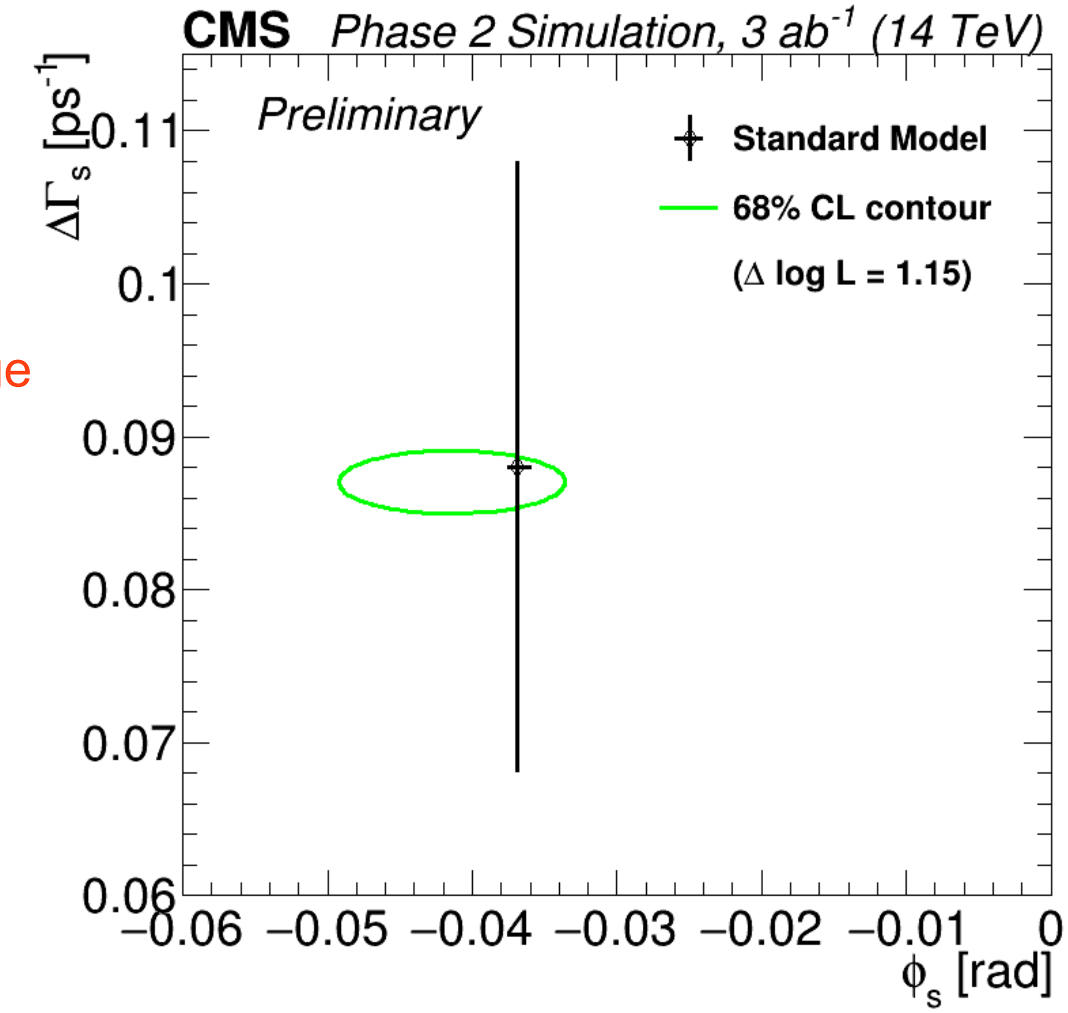
CMS PAS FTR-18-041

sensitivity scales as

$$S \propto \sqrt{\frac{\epsilon D^2 N_S}{2}} \sqrt{\frac{N_S}{N_S + N_{BG}}} e^{-\frac{\sigma_t^2 \Delta m_s^2}{2}}$$



scenario	ϵ [%]	ω [%]	ϵD^2 [%]	σ_{ϕ_s} [mrad]
a	32	39.4	1.4	5.6
b	8	30.2	1.2	5.8
c	33	36.4	2.4	4.6



From toy-MC experiments

Conclusions

- CMS measured the weak phase ϕ_s with 19.7 fb^{-1} of data at $\sqrt{s}$=8 TeV
  - The measurement is in agreement with the Standard Model prediction
- Currently working on Run-II data
  - Increased statistics
  - Improved proper time resolution thanks to better pixel detector
- HL-LHC reach will be statistically limited ~ 5 mrad