Measurement of CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ channel

(Based on PLB 816 (2021) 136)

Samadhan Kamble

On behalf of the CMS Collaboration

December 12-16, 2022

CPV - Why care ?

The matter of Antimatter!

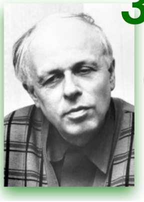
- Where did all the antimatter go?
- What caused that tiny imbalance?
- Why matter was preferred?

CPV - Why care ?

The matter of Antimatter!

- Where did all the antimatter go?
- What caused that tiny imbalance?
- Why matter was preferred?

A. D. Sakharov
1967

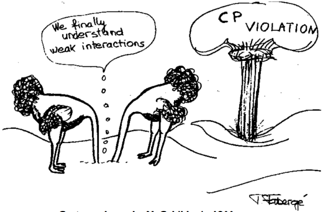


3 Conditions

C & CPV

Hunting the Asymmetry!

1. Baryon number violation
2. Breaking of C & CP symmetries
3. 1 & 2 to occur in non-thermal equil. phase



Cartoon shown by N. Cabibbo in 1966...

CP Violation in the SM

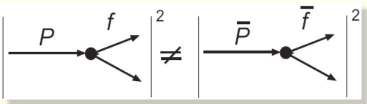
- Source of CPV: the complex phase in CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein, PRL 51, 1945 (1983)

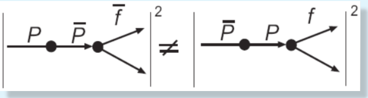
- Types of CP violation :

I. Direct CPV in decay



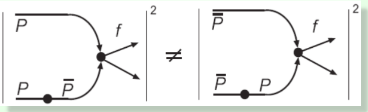
$P(B \to f) \neq P(\bar{B} \to \bar{f})$

II. Indirect CPV in mixing



$P(B \to \bar{B}) \neq P(\bar{B} \to B)$

III. CPV in interference



$P(B \to f_{CP}) \neq P(B \to \bar{B} \to f_{CP})$

This talk : CP Violation in $B_s \to J/\psi\phi$ due to interference of direct and indirect CPV!

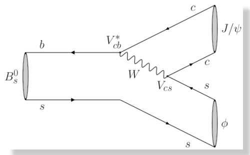
Outline

1. Introduction
   - ϕ_s in $B_s \to J/\psi\phi(1020)$
2. Analysis strategy
   - The Apparatus
   - Event selection & reconstruction
   - Flavor tagging
3. Results
   - Conclusion

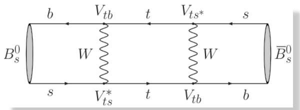
Outline

1. Introduction
   - ϕ_s in $B_s \to J/\psi\phi(1020)$
2. Analysis strategy
   - The Apparatus
   - Event selection & reconstruction
   - Flavor tagging
3. Results
   - Conclusion

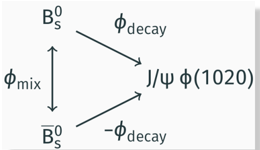
- ϕ_s : CP violating phase arising from the **interference** between **direct B_s^0 decays** to a CP final state and decays through **$B_s^0 - \bar{B}_s^0$ mixing** to the same final state.



Decay : $\phi_{decay} = arg(V_{cb}V_{cs}^*)$



Mixing : $\phi_{mix} = 2arg(V_{tb}V_{ts}^*)$



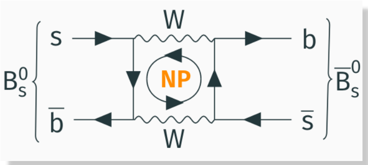
$\phi_s = \phi_{mix} - 2\phi_{decay}$

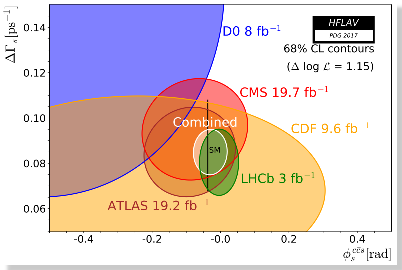
- $\phi_s^{c\bar{c}s}$ is related to CKM elements (β_s UT $= V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^*$)
- $\phi_s \simeq -2\beta_s = -2arg(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$
- **SM Prediction** $\phi_s = -36.96^{+0.72}_{-0.84}$ mrad [CKMFitter]

$\phi_s = \phi_s^{SM} + \phi_s^{NP} \Rightarrow$ **Excellent probe for BSM Physics!**

ϕ_s in $B_s \to J/\psi\phi(1020)$

- A 'golden channel' to measure ϕ_s!
  - Easier to reconstruct with high S/B
  - Excellent triggers sensitive to the final state
- **New Physics** can alter ϕ_s up to 10% via new particles contributing to the $B_s^0 - \bar{B}_s^0$ mixing box [JHEP04(2010)031]
- Same model can be used to measure **several other interesting observables**: $\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, $\Delta m_s^2 = (m_H - m_L)^2$
  - Decay width measurement gives interesting test of the theory ($\Delta\Gamma_s = 0.091 \pm 0.013 ps^{-1}$)
- **State of the art :** Results in agreement with SM but poor sensitivity (experimental uncertainty much higher than theoretical one)





Ref: HFLAV PDG

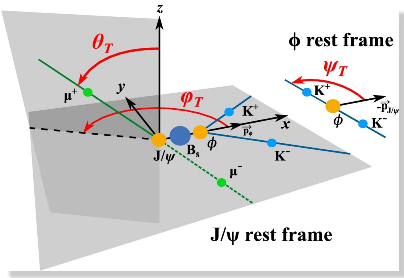
Outline

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: Analysis strategy

- B_s^0, $\bar{B}_s^0$ mesons decay to the same final state
- Final state: admixture of CP-even (L=0, 2) and odd (L=1) states
- Need angular analysis to disentangle the two components

Ingredients:

- **Angular variables**
  - $\boldsymbol{\theta_T}$: polar angle of μ^+ in the J/ψ rest frame
  - $\boldsymbol{\phi_T}$: azimuthal angle of μ^+ in the J/ψ rest frame
  - $\boldsymbol{\psi_T}$: helicity angle of K^+ in the ϕ rest frame
- **Proper decay time** of the B_s^0 meson
- **Flavor tagging** to infer flavor of the B_s^0 meson at production



An unbinned maximum-likelihood fit is performed on data extracting the parameters of interest.

Where to study it?

What do we need to fulfil this program?

- High statistics of B_s^0 mesons
- Good charge track reconstruction
- Triggers sensitive to final states

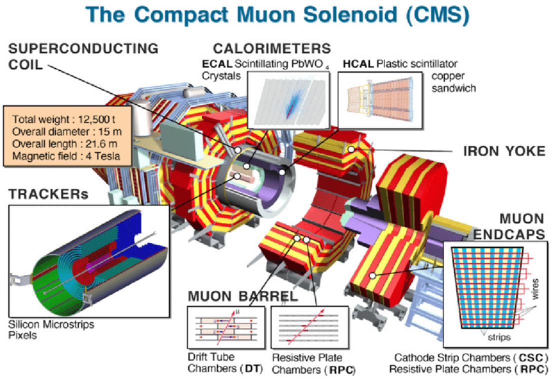
Where to study it?

What do we need to fulfil this program?

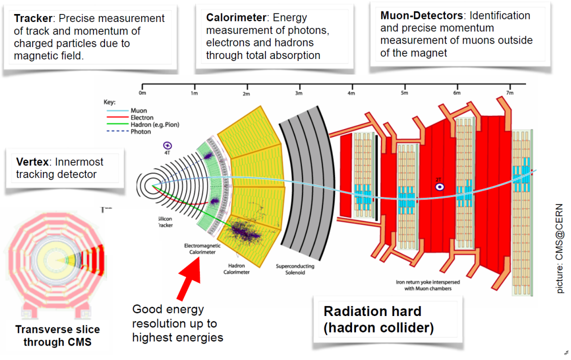
- High statistics of B_s^0 mesons
- Good charge track reconstruction
- Triggers sensitive to final states

Ans: The CMS experiment at LHC! [LHCC(2006)001]

- ✓ high cross section, energy and luminosity
- ✓ robust tracker and muon systems
- ✓ flexible trigger system



An overview of the CMS detector (CERN TDR)



Transverse slice of the CMS detector (Source: Wikimedia)

Event selection and reconstruction

Trigger strategy

- $J/\psi \to \mu^+\mu^-$ candidate plus an additional μ used to tag the B_s^0 flavour
- allows for an improved tagging efficiency at the cost of a reduced number of selected signal events

I. $J/\psi \to \mu^+\mu^-$

muon pair emerging from a common displaced vertex with:

- $p_T^{\mu} > 3.5\,\text{GeV}$, $|\eta^{\mu}| < 2.4$,
- $|m_{\mu^+\mu^-} - m_{J/\psi}^{PDG}| < 150\,\text{MeV}$

II. $\phi \to K^+K^-$

kaon pair from a displaced vertex with presections:

- $p_T^{K} > 1.2\,\text{GeV}$, $|\eta^{K}| < 2.5$
- $|m_{K^+K^-} - m_{\phi_{1020}}^{PDG}| < 10\,\text{MeV}$

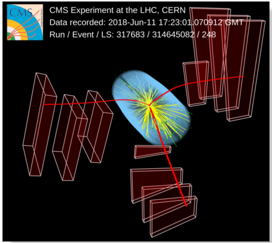
III. $B_s^0 \to J/\psi\phi$

$\mu^+\mu^-$ and K^+K^- tracks subjected to a combined vertex kinematic fit with:

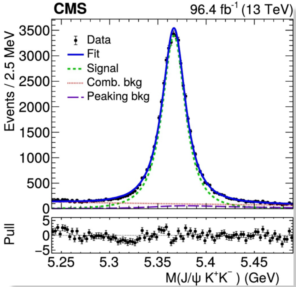
- displaced secondary decay vertex $p_T^{B_s^0} > 11\,\text{GeV}$, $c\tau^{B_s^0} > 70\mu m$
- consistent with B_s^0 mass - $5240 < m(K^+K^-\mu^+\mu^-) < 5490\,\text{MeV}$

Data

$\mathcal{L} = \mathbf{96.4 fb^{-1}}$: p-p collisions at $\sqrt{s} = 13\,TeV$ collected in 2016 & 17

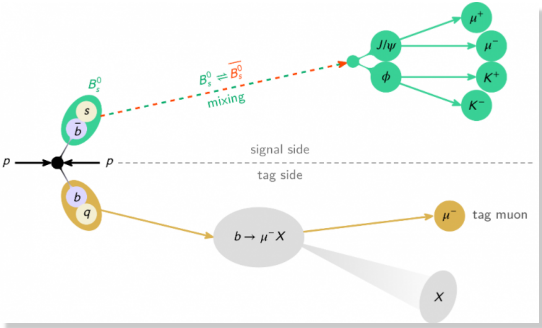


Source: *CMS images gallery*



Flavor tagging

- Identifying flavor of a given (neutral) particle (e.g., distinguish B_s^0 from $\bar{B}_s^0$)
  - greatly improves precision of ϕ_s



- **OS (opposite-side) muon tagger**:
  - Use $b - \bar{b}$ correlation $\Rightarrow$ initial B_s^0 flavour
  - Exploit the complementary b-quark decays: $b \to \mu X$
  - Diluted by oscillations, pileup, cascade
- **Developed** : simulated $B_s^0 \to J/\psi\phi$
- **Calibrated** : self-tagged $B^\pm \to J/\psi K^\pm$

Figures of merit

- Efficiency, $\epsilon_{tag} = N_{tag}/N_{tot}$
- Mistag fraction, $\omega_{tag} = N_{wrong_tag}/N_{tag}$
- Tagging power, $P_{tag} = \epsilon_{tag}(1 - 2\omega_{tag})^2$

Data set	ϵ_{tag}	ω_{tag}	P_{tag}
2017	$(45.7 \pm 0.1)\,\%$	$(27.1 \pm 0.1)\,\%$	$(\mathbf{9.6} \pm 0.1)\,\%$
2018	$(50.9 \pm 0.1)\,\%$	$(27.3 \pm 0.1)\,\%$	$(\mathbf{10.5} \pm 0.1)\,\%$
Run-1	$(8.31 \pm 0.03)\,\%$	$(30.2 \pm 0.3)\,\%$	$(1.31 \pm 0.03)\,\%$

Final tagging performance measured in data using $B^\pm \to J/\psi K^\pm$

Maximum Likelihood Fit

- The model parameters are estimated using an unbinned maximum likelihood fit
- The information used by the fit includes the following variables describing the $B_s^0 \to J/\psi\phi$ candidates:

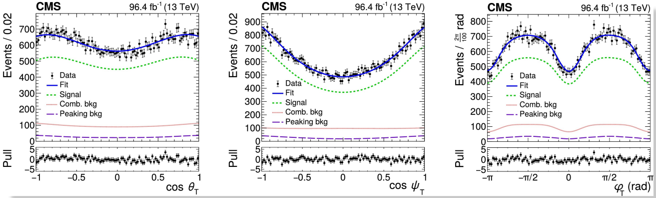
Input observables

- Mass, $\boldsymbol{M_{B_s^0}}$
- Proper decay time, $\boldsymbol{t_{B_s^0} = \frac{L_{xy} M_{B_s^0}}{p_T}}$
- 3 angles between final state particles in transversity basis $\boldsymbol{\Omega(\cos\theta_T, \cos\psi_T, \phi_T)}$
- **Flavor** tag information

Physics parameters

- CPV phase, ϕ_s
- Decay widths: $\boldsymbol{\Gamma_s}$, $\boldsymbol{\Delta\Gamma_s}$
- mass difference, $\boldsymbol{\Delta m_s}$
- CP-state decay amplitudes and their phases

- Likelihood function: components describing the signal and bkg contributions (combinatorial and peaking bkg, dominated by $B^0 \to J/\psi K^0_{892} \to \mu^+\mu^-K^+\pi^-$)



The angular distributions for the B_s^0 candidates

Outline

1. Introduction
   - ϕ_s in $B_s \to J/\psi\phi(1020)$
2. Analysis strategy
   - The Apparatus
   - Event selection & reconstruction
   - Flavor tagging
3. Results
   - Conclusion

Results

Parameter	Fit value	Stat.	Syst.
ϕ_s[mrad]	**-11**	**$\pm$50**	**$\pm$10**
$\Delta\Gamma_s[ps^{-1}]$	**0.114**	**$\pm$0.014**	**$\pm$0.007**
$\Gamma_s[ps^{-1}]$	0.6531	$\pm$0.0042	$\pm$0.0024
$\Delta m_s[\hbar ps^{-1}]$	17.51	$\pm$0.10	$\pm$0.03
$\lvert\lambda\rvert$	0.972	$\pm$0.026	$\pm$0.008

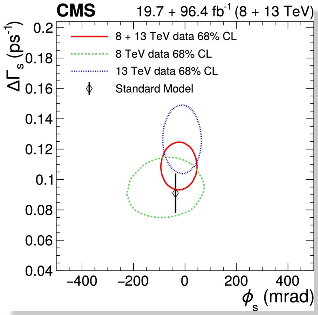
Table: Results of the fit to data

$$\phi_s^{SM} = -36.96^{+0.72}_{-0.84} \text{ mrad}$$
$$\Delta\Gamma_s^{SM} = 0.1032 \pm 0.013 \; ps^{-1}$$

Combination with 8 TeV results

The results are combined with those from the previous analysis at $\sqrt{s} = 8\,TeV$ [Phys. Lett. B 757 (2016) 97]

- The combination is in agreement with the SM
  ϕ_s = -21 $\pm$44 $\pm$10 *mrad*
  $\Delta\Gamma_s = 0.1032 \pm 0.0095 \pm 0.0048 \; ps^{-1}$
- Increased tag accuracy due new trigger strategy improved ϕ_s uncertainty



2-D likelihood contours in $\phi_s - \Delta\Gamma_s$ plane

Summary & Outlook

- The CPV phase ϕ_s and decay width difference $\Delta\Gamma_s$ are measured using 48,500 $B_s J/\psi\phi$ candidates at $\sqrt{s} = 13\,\text{TeV}$, corresponding to $\mathcal{L}_{int} = 96.4\ fb^{-1}$

New trigger strategy + **Novel OS-μ tagger** $\Rightarrow$ **Improved sensitivity** + **Reduced statistic**

- Results are consistent with the Standard Model predictions

Summary & Outlook

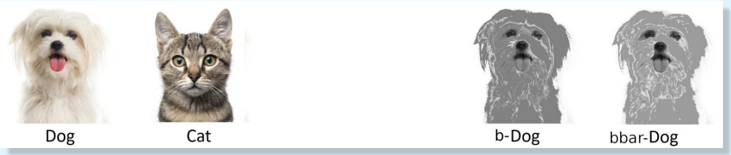
- The CPV phase ϕ_s and decay width difference $\Delta\Gamma_s$ are measured using 48,500 $B_s J/\psi\phi$ candidates at $\sqrt{s} = 13\,\text{TeV}$, corresponding to $\mathcal{L}_{int} = 96.4\ fb^{-1}$

New trigger strategy + Novel OS-μ tagger $\Rightarrow$ Improved sensitivity + Reduced statistic

- Results are consistent with the Standard Model predictions

What's Next ?

- CMS plans to analyze the **full Run-2 dataset**
- Jet flavour tagging algorithm



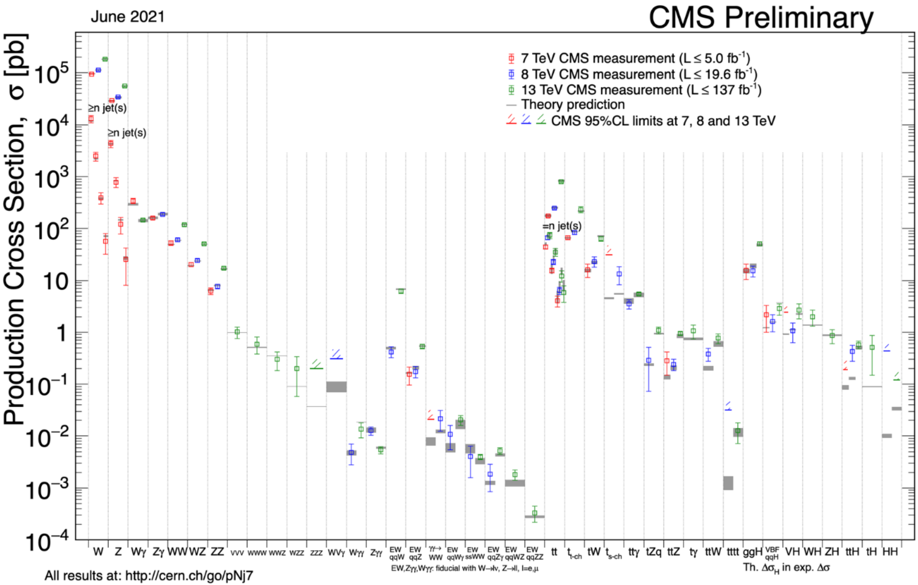
Red dogs vs Green dogs with B/W photos!

Thank You!

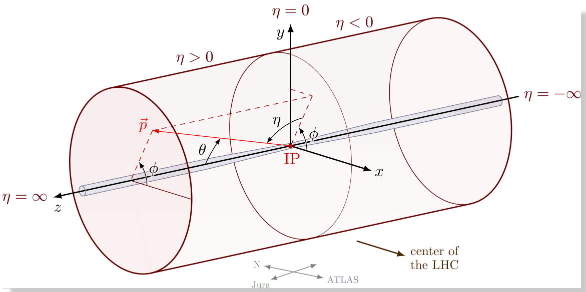
*Acknowledgement: Some information is adapted from Alberto and Ali's talk!

Extra Slides

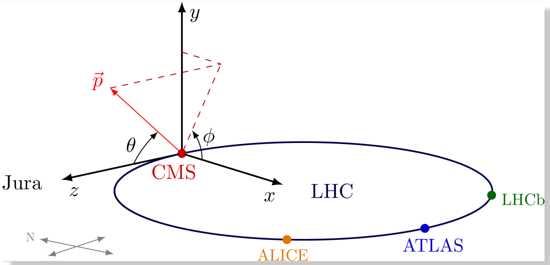
Greatness of the SM in a slide!



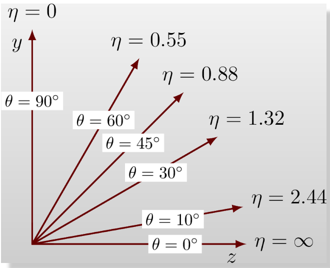
CMS co-ordinate system



A cylindrical detector

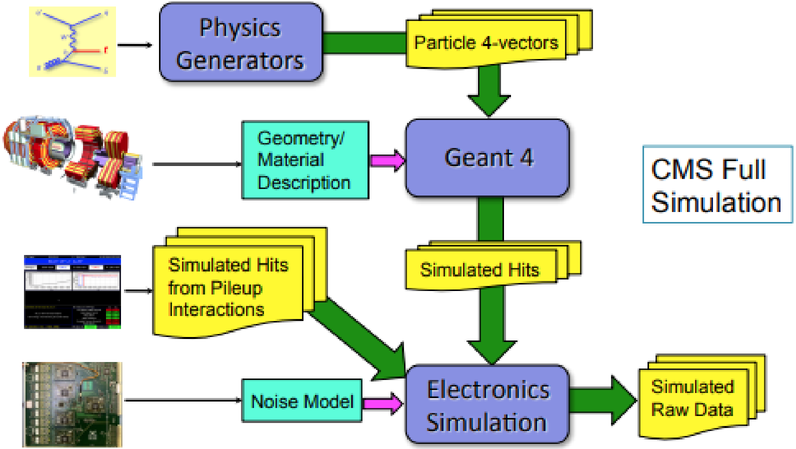


CMS at LHC



Pseudorapidity on a 2D coordinate axis

CMS simulation



Alternatively: CMS “Fast Simulation” is a slightly less realistic but much faster simulation of low-level objects (hits, clusters)

Price for higher luminosity!