Precision tests of SM with heavy flavour decays at CMS

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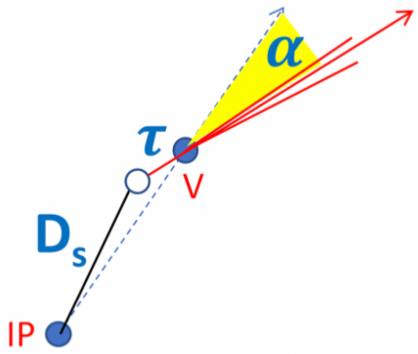
Outline

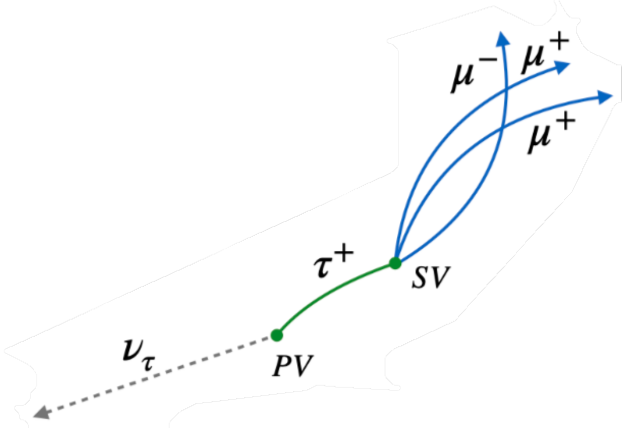
$\tau \to 3\mu$ search

- Motivations
- τ leptons production @LHC
- Analysis strategy – *Heavy Flavour* channel
- Results - *Heavy Flavour* channel
- Analysis strategy – *W* channel
- Results – *W* channel and combination
- Conclusions

CP violating phase ϕ_s in $\mathrm{B_s^0} \to \mathrm{J/\psi}\ \phi(1020) \to \mu^+\mu^-K^+K^-$

- Motivations
- Angular analysis
- Events selection
- Flavour tagging
- Fit model
- Fit results
- Combination with 8 TeV results
- Conclusions



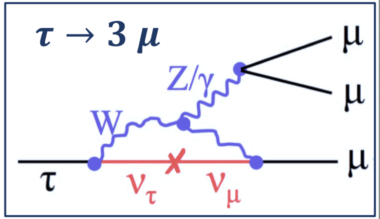


$\tau \to 3\mu$ search

Motivations

In the Standard Model there is **NO symmetry** than enforces the conservation of the **lepton flavor**.

- The observation of neutrino oscillations is an evidence of the lepton flavor violation (LFV) in *neutral* lepton sector.
- *Charged* LFV decays are possible in SM with neutrino oscillations. $\boldsymbol{\mathcal{B}(\tau \to 3\mu) \sim 10^{-54}}$



BSM theories predict : $\boldsymbol{\mathcal{B}(\tau \to 3\mu) \sim 10^{-8}}$- $\boldsymbol{10^{-9}}$

observable at present-day experiments

State of the art

*The $\boldsymbol{\tau \to 3\mu}$ decay has **never** been observed so far.*

- The best experimental upper limit was set by

  Belle : $\mathcal{B}(\tau \to 3\mu) < \mathbf{2.1 \cdot 10^{-8}}$ at 90% confidence level

- At LHC :

  LHCb : $\mathcal{B}(\tau \to 3\mu) < \mathbf{4.6 \cdot 10^{-8}}$ **ATLAS :** $\mathcal{B}(\tau \to 3\mu) < \mathbf{3.8 \cdot 10^{-7}}$

τ leptons production at LHC

Two main channels for τ production

Process	number of τ leptons (L=33 fb^{-1})
$pp \to c\,\bar{c} + \ldots$	
$D \to \tau\nu$	4.0×10^{12} (95% D_s, 5% $D^{\pm}$)
$pp \to b\,\bar{b} + \ldots$	
$B \to \tau\nu + \ldots$	1.5×10^{12} (44% $B^{\pm}$, 45% B^0, 11% B_s^0, 0% $B_c^{\pm}$)
$B \to D(\tau\nu) + \ldots$	6.3×10^{11} (98% D_s, 2% $D^{\pm}$)
$pp \to W + \ldots \to \tau\nu + \ldots$	6.7×10^8
$pp \to Z + \ldots \to \tau\tau + \ldots$	$1.3 \times 10^8 (60 < m(\tau\tau) < 120\ GeV)$

Heavy Flavour channel

τ from **D** and **B** meson decays

W channel

Inclusive production cross section expected for tau production $\sim 2\times10^{11}\ fb$

Analysis strategy – *Heavy Flavour* channel

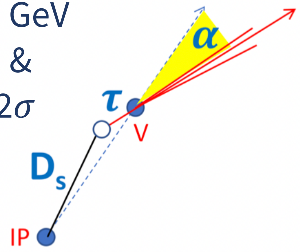
Selection of events with **D** and **B** mesons decaying into **τ** leptons

Characterized by **low p_T muons**

Background events ~ $\mathbf{10^7}$ signal events

Trigger

2 muons with $p_T > 3$ GeV + track with $p_T > 1.2$ GeV
Invariant mass of the triplet in [1.62 - 2] GeV &
distance of 3μ vertex from the beam-spot > 2σ



Background composition:

- Semi-leptonic decays of B mesons, with 1-2 pions and/or kaons reconstructed as muons
- Decays in flight

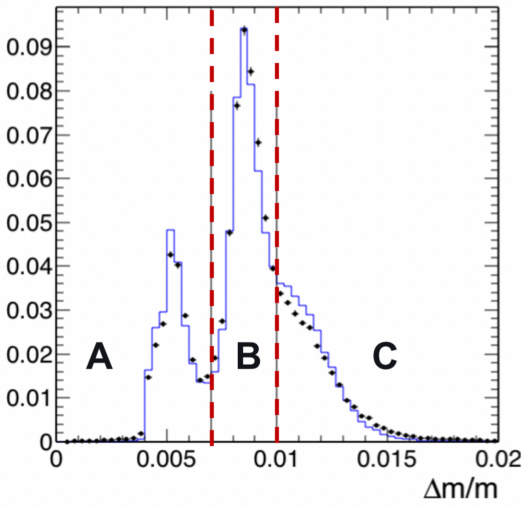
Analysis strategy – *Heavy Flavour* channel

Selection of events with **D** and **B** mesons decaying into **τ** leptons

Event classification into **3 exclusive categories**

GOAL: increase the analysis sensitivity

Classification based on the **resolution of the three muon mass**



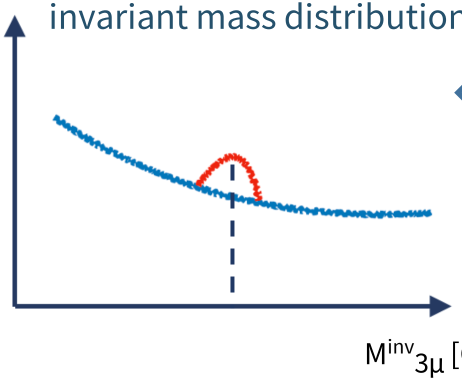
Analysis strategy – *Heavy Flavour* channel

Selection of events with **D** and **B** mesons decaying into **τ** leptons

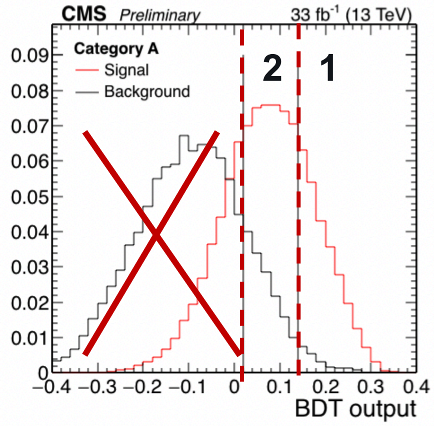
Event classification into **3 exclusive categories**

Multivariate analysis with **Boosted Decision Tree**

- Signal extraction from simultaneous fit of the 6 invariant mass distributions



- Each category is split into 3 subcatyegories based on the BDT output and the worst one is discarded
- In the end: **6 categories**



Results
Heavy Flavour channel

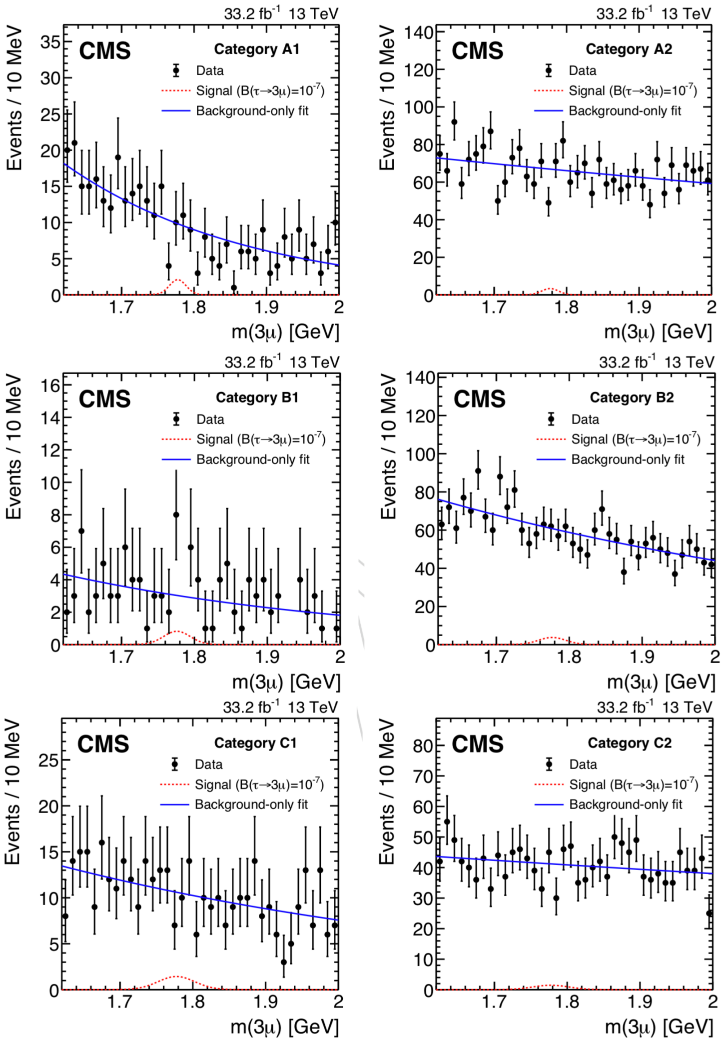
Maximum likelihood fit of the 3 muons invariant mass in the 6 categories

- signal MC fit with Gaussian + Crystal Ball functions
- background fit with exponential

Systematics are used as *nuisance* parameters in the fit

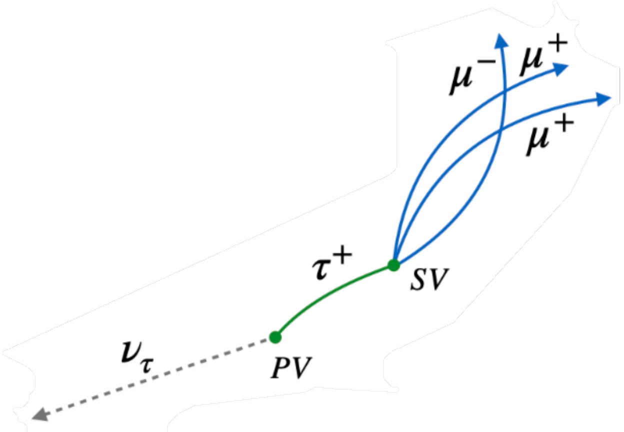
Upper limit observed (expected)
at 90% confidence level

$$\mathcal{B}(\tau \rightarrow 3\mu) < 9.2\ (10.0) \cdot 10^{-8}$$



Analysis strategy – *W* channel

Selection of events with ***W*** bosons decaying into **τ** → Multivariate analysis with **Boosted Decision Tree** → Event classification in **2 categories**: **barrel** & **endcap**



- **VETO** to suppress events from decays of hadronic resonances in 2 muons:

  η, ω(783), ρ(770), ϕ(1020), J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S), Z

- *jet* used are clustered with anti-k_T algorithm (with tracks assigned to the candidate vertices as input) and the relative *missing transverse momentum* (opposite of the vectorial sum of the jets p_T)

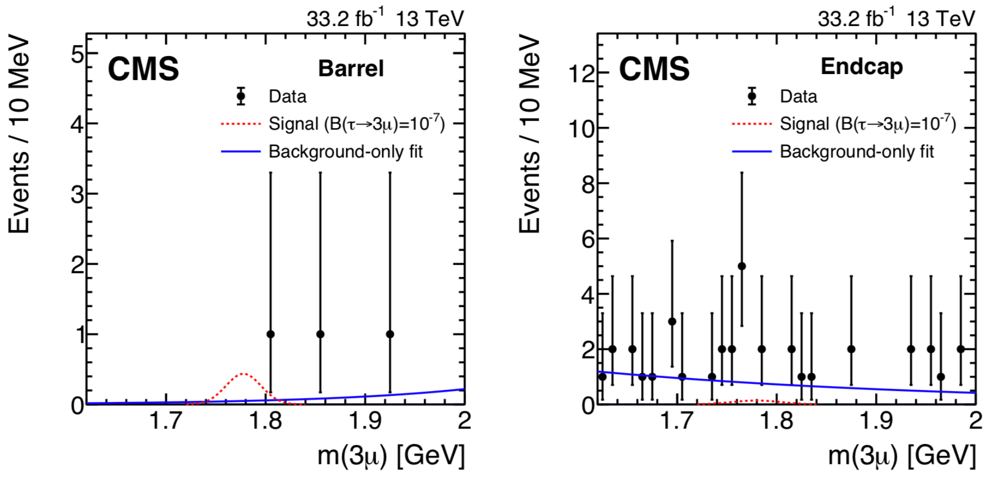
Results – *W* channel and combination

Maximum likelihood fit of the 3 muons invariant mass in the 2 categories

- signal MC fit with Gaussian
- background fit with exponential

Upper limit observed (expected) at 90% confidence level

$$\mathcal{B}(\tau \rightarrow 3\mu) < 2.0\ (1.3) \cdot 10^{-7}$$



Combination of the 2 channels

Upper limit observed (expected) at 90% confidence level

$$\mathcal{B}(\tau \rightarrow 3\mu) < 8.0\ (6.9) \cdot 10^{-8}$$

- Events (data & MC) in common between the two channels are removed from the Heavy Flavour one in the combination
- Systematics considered not correlated among the two channels

Conclusions

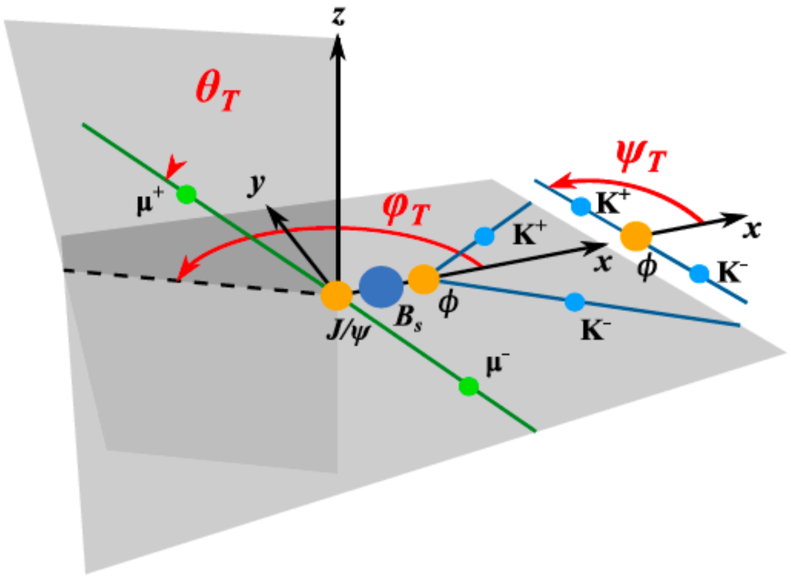
➡ Search for charged lepton flavor violation in the $\tau \to 3\mu$ decays carried out by CMS with 2016 data [JHEP 01 (2021) 163]:

- ✓ ***Heavy Flavour*** channel: $\mathcal{B}(\tau \to 3\mu) < 9.2 \cdot 10^{-8}$ at 90% C.L.
- ✓ ***W*** channel : $\mathcal{B}(\tau \to 3\mu) < 2.0 \cdot 10^{-7}$ at 90% C.L.

✓ Combination of the two channels

$$\mathcal{B}(\tau \to 3\mu) < 8.0 \cdot 10^{-8}$$ at 90% C.L.

❑ Analysis with 2017 and 2018 data in both channels is being finalized.



CP violating phase ϕ_s in

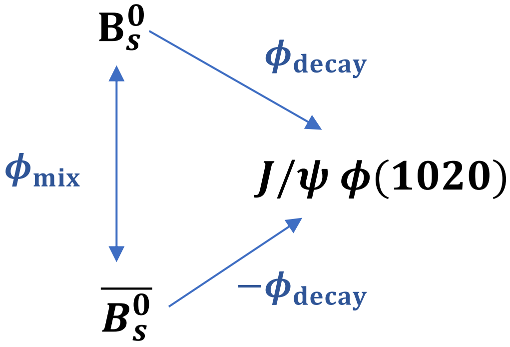
$$B_s^0 \rightarrow J/\psi\ \phi(1020) \rightarrow \mu^+\mu^-K^+K^-$$

Motivations

$\boldsymbol{\phi_s}$: CPV phase arises from interference between direct B_s^0 decays to a CP eigenstate and decays through B_s^0 - $\overline{B_s^0}$ mixing

- In SM: $\phi_s \cong -2\,\beta_s = -2\arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = \mathbf{-36.96^{+0.72}_{-0.84}\ mrad}$

current best determination from a SM global fit to experimental data



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

→ BSM theories predict a modification in $\boldsymbol{\phi_s}$ value up to a ~**10%** (new particles contribute to B_s^0 - $\overline{B_s^0}$ mixing)

State of the art

*Current measurements agree with SM, but the **experimental uncertainty is much larger than theoretical one***

- At LHC :

LHCb : $\phi_s = -0.042 \pm 0.025$ rad

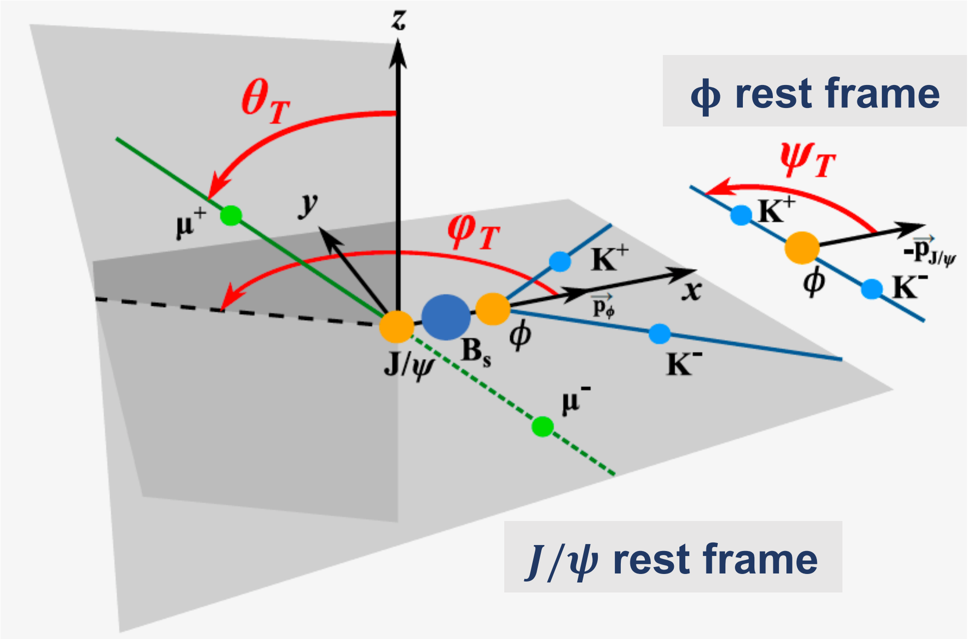
ATLAS : $\phi_s = -0.087 \pm 0.036 \pm 0.021$ rad

Angular analysis

- Final states are **mixtures of CP eigenstates**
- **Time dependent angular analysis** needed to disentagle ***CP-odd*** and ***CP-even*** components

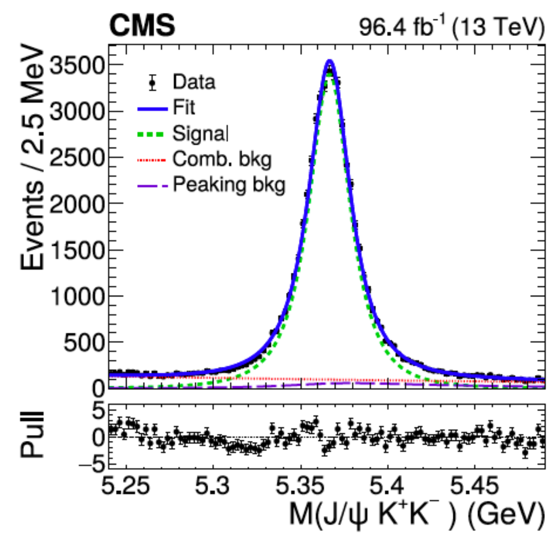
Angular variables

- ψ_T: helicity angle of K^+ in ϕ rest frame (w.r.t. negative J/ψ momentum direction)
- θ_T: polar angle of μ^+ in J/ψ rest frame
- φ_T: azimuthal angle of μ^+ in J/ψ rest frame



Event selections

$\mathcal{L} = 96.4\ fb^{-1}$



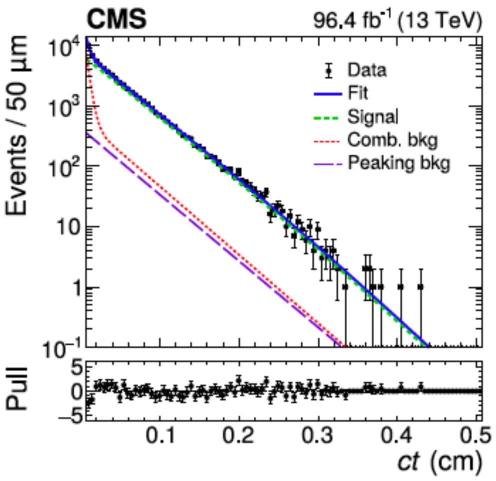
Trigger

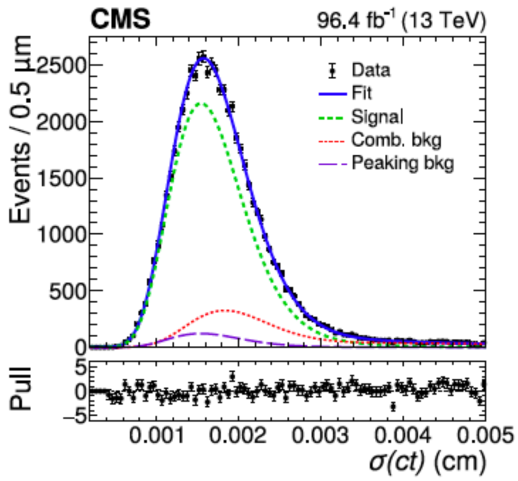
2 OS muons non-displaced and forming a J/ψ candidate +
1 additional muon

used to tag the B_s^0 flavour

- **Tagging efficiency**: $\varepsilon_{\text{tag}} = \frac{N_{\text{tagged}}}{N_{\text{events}}} \sim \mathbf{50\%}$

Offline	
$p_T(\mu)$	≥ 3.5 GeV
$\lvert\eta(\mu)\rvert$	≤ 2.4
$p_T(K)$	≥ 1.2 GeV
$\lvert\eta(K)\rvert$	≤ 2.5
$\lvert m(\mu^+\mu^-) - m^{PDG}_{J/\psi}\rvert$	< 150 MeV
$\lvert m(K^+K^-) - m^{PDG}_{\phi(1020)}\rvert$	< 10 MeV
$p_T(B^0_s)$	≥ 11 GeV
$ct(B^0_s)$	≥ 0.007 cm
$B^0_s \to J/\psi\,\phi$ Vtx prob	$\geq 0.1\%$
$m(\mu^+\mu^-K^+K^-)$	[5.24, 5.49] GeV

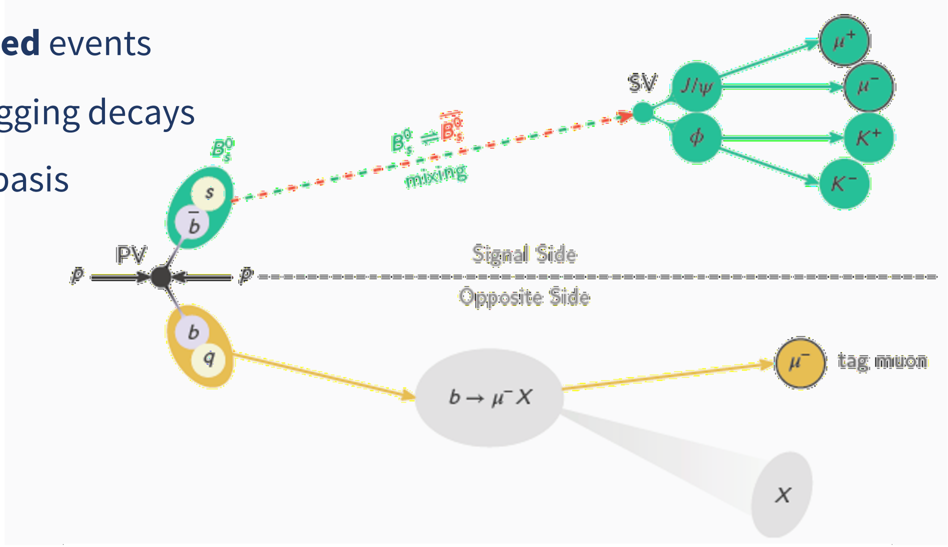




Flavour tagging

- Angular analysis requires an accurate estimation of **initial flavour** of the $\mathbf{B}_s^0$ meson

- **Opposite side taggers**:
  - exploits $\mathbf{b} \rightarrow \boldsymbol{\mu X}$ decays of the other **b** produced in the event
  - Developed using $\mathbf{B}_s^0 \rightarrow \boldsymbol{J/\psi\ \phi}(\mathbf{1020})$ **simulated** events
  - Calibrated in **data** using $\mathbf{B}^{\pm} \rightarrow \boldsymbol{J/\psi\ K^{\pm}}$ self-tagging decays
  - **Mistag probability** evaluated on a per-event basis with a dedicated **Deep Neural Network:**
    - average measured **~27%**



Fit model

Event PDF: $P = \frac{N_{\text{sig}}}{N_{\text{tot}}} P_{sig} + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}$

$$P_{sig} = \varepsilon(ct)\,\varepsilon(\Theta)\left[\tilde{\mathcal{F}}(\Theta, ct, \alpha) \otimes G(ct, \sigma_{ct})\right] P_{\text{sig}}\left(m_{B_s^0}\right) P_{sig}(\sigma_{ct})\, P_{sig}(\zeta)$$

efficiency functions

- $\tilde{\mathcal{F}}(\Theta, ct, \alpha)$: differential decay rate
- $G(ct, \sigma_{ct})$: Gaussian resolution model

- $P_{\text{sig}}\left(m_{B_s^0}\right)$: signal mass pdf
- $P_{sig}(\sigma_{ct})$: signal σ_{ct} pdf
- $P_{sig}(\zeta)$: tag distribution

$$P_{\text{bkg}} = P_{\text{bkg}}(\cos\vartheta_{\text{T}}, \phi_T)\, P_{\text{bkg}}(\cos\psi_T)\, P_{bkg}(ct)\, P_{bkg}\left(m_{B_s^0}\right) P_{\text{bkg}}(\sigma_{ct})\, P_{\text{bkg}}(\zeta)$$

bkg angular and lifetime pdfs

Background from $\Lambda_b \to J/\psi\, K^{\pm} p^{\mp}$ is negligible

neg log likelihood: $-\ln \mathcal{L} = -\sum_{i=0}^{N_{\text{evt}}} \ln P_i + N_{\text{tot}} - N_{\text{evt}} \ln N_{\text{tot}}$

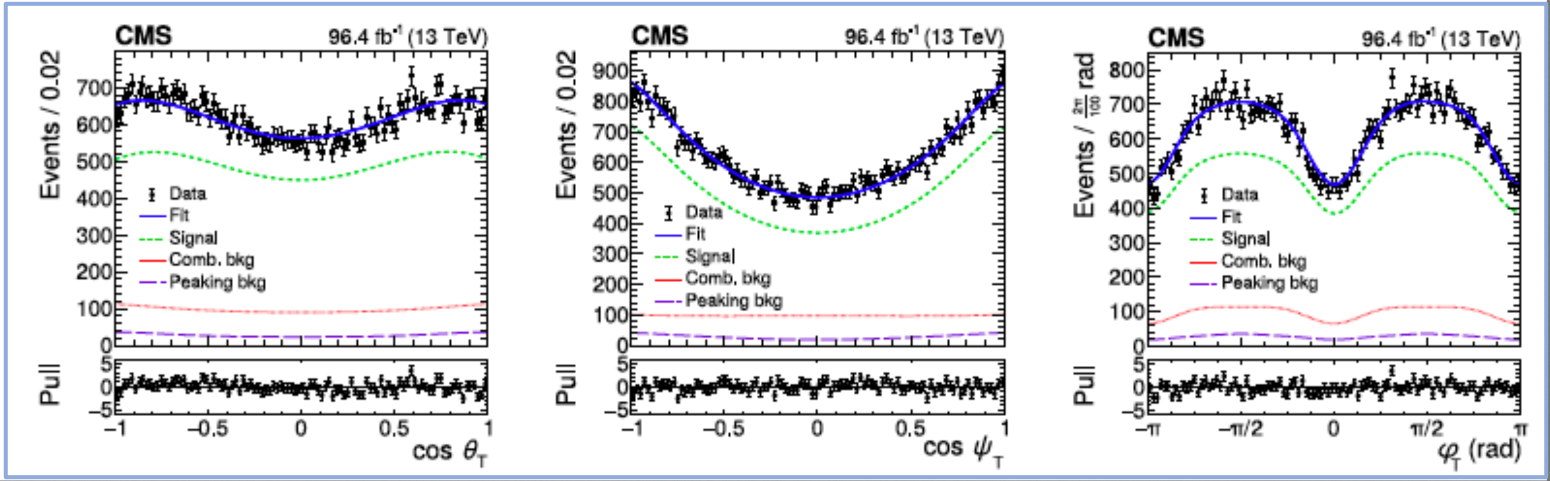
Fit results

- Model parameters estimated by performing an ***unbinned maximum likelihood fit***

In agreement with SM

- First CMS measurement of Δm_s and $|\lambda|$

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0045
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048



Combination with 8 TeV results

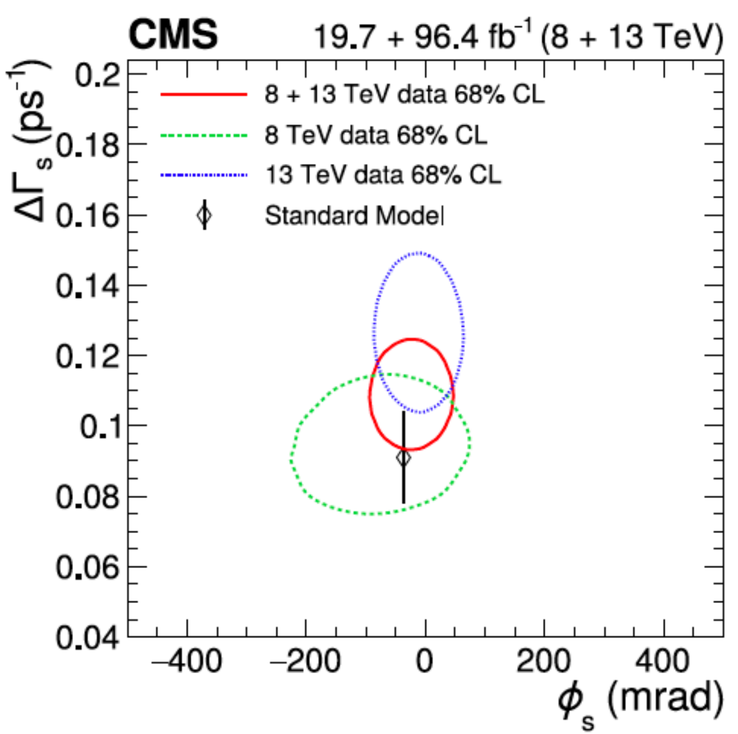
- Results combined with those of the analysis carried out with 8 TeV data [Phys. Lett. B 757 (2016) 97]

$$\boldsymbol{\Phi_s = -0.021 \pm 0.044\ \mathrm{rad}}$$

$$\boldsymbol{\Delta\Gamma_s = 0.1032 \pm 0.0095\ \mathrm{ps}^{-1}}$$

In agreement with SM

- **No** source of **systematic uncertainty** is considered **correlated** between the two analysis
- In all contours **only *statistical uncertainties*** (which are the dominant ones) are taken into account



Conclusions

➡ CP violating weak phase Φ_s, and decay width difference $\Delta\Gamma_s$ between the light and heavy B_s mass eigenstates have been measured in a sample of reconstructed $B_s^0 \to J/\psi\, \phi(1020) \to \mu^+\mu^-K^+K^-$ decays: [Phys. Lett. B 816 (2021) 136188]

$$\Phi_s = -0.011 \pm 0.050\,(\text{stat}) \pm 0.010(\text{syst})\ \text{rad}$$
$$\Delta\Gamma_s = 0.114 \pm 0.014(\text{stat}) \pm 0.007(\text{syst})\ \ \text{ps}^{-1}$$

→ *In agreement with SM predictions*

✓ Combination with results measured with center-of-mass energy of 8 TeV:

$$\Phi_s = -0.021 \pm 0.044(\text{stat}) \pm 0.010(\text{syst})\ \text{rad}$$
$$\Delta\Gamma_s = 0.1032 \pm 0.0095(\text{stat}) \pm 0.0048(\text{syst})\ \text{ps}^{-1}$$

→ *In agreement with SM predictions*

Thank you for your attention!

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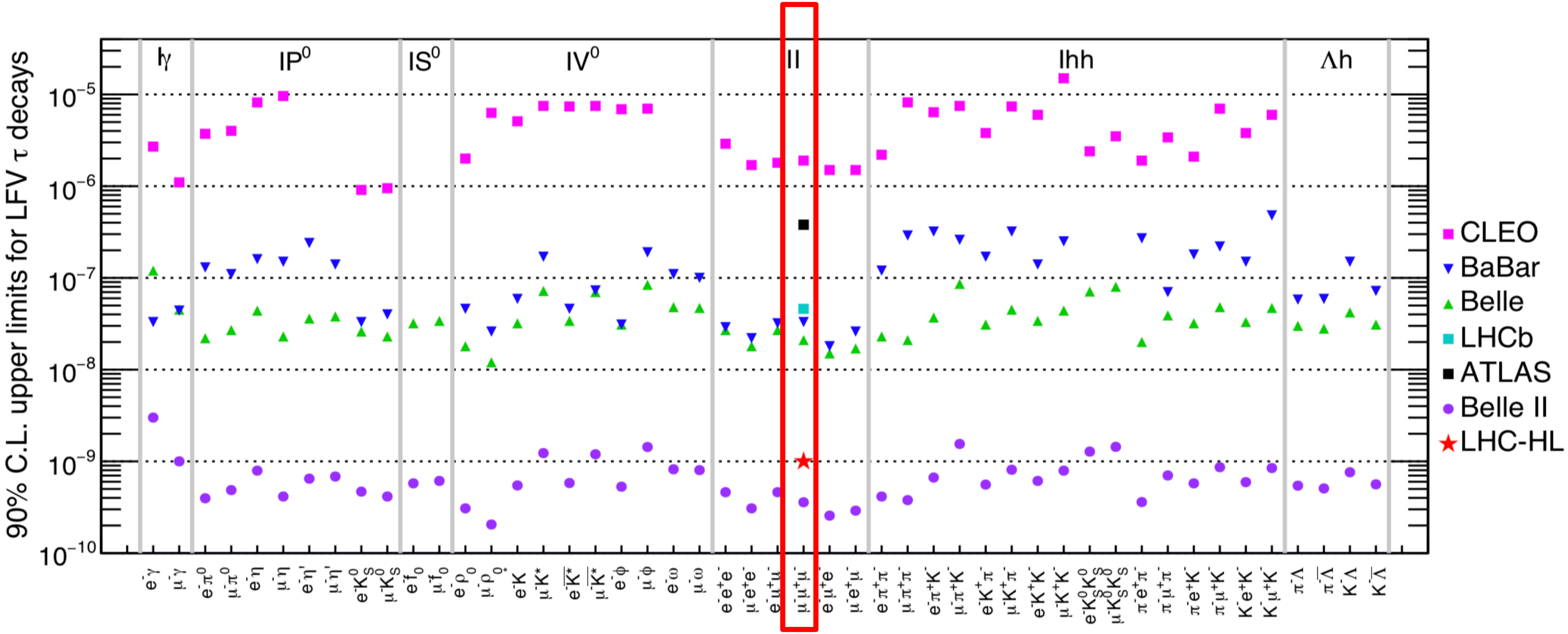
Backup slides

Future perspectives for LFV search in τ decays



Bounds on Tau Lepton Flavour Data from the existing experiments are compiled by HFLAV; projections of the Belle-II bounds were performed by the Belle-II collaboration assuming 50 ab^{-1} of integrated luminosity.

arXiv:1812.07638

Search for τ → 3μ at HL-LHC

	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4580	3640
Trimuon mass resolution	18 MeV	31 MeV
$\mathcal{B}(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$\mathcal{B}(\tau \to 3\mu)$ 90% C.L. limit	3.7×10^{-9}	
$\mathcal{B}(\tau \to 3\mu)$ for 3-σ evidence	6.7×10^{-9}	
$\mathcal{B}(\tau \to 3\mu)$ for 5-σ observation	1.1×10^{-8}	

(Top) The expected numbers of signal and background events in the mass window 1.55 -2.0 GeV for CMS. An integrated luminosity of **3000 fb^{-1}** and a signal $B(\tau \to 3\mu) = 2 \times 10^{-8}$ is assumed.

(Bottom) The search sensitivities for the combined categories.

Category 1 for events with all three muons reconstructed only with the Phase-1 detectors, and Category 2 for events with at least one muon reconstructed by the new triple Gas Electron Multiplier (GEM) detectors.

Statistical analysis / τ → 3μ

The CMS **Higgs Combined Limit** tool is used to perform statistical analysis. Upper limits on branching fraction $B(\tau \rightarrow 3\mu)$ are set using the modified frequentist CLs criterion. The chosen test statistic q, used to determine how signal or background-like the data are, is based on the profile likelihood ratio. Systematic uncertainties are incorporated in the analysis via nuisance parameters and are treated according to the frequentist paradigm.

The profile likelihood ratio is defined in equation: $q_\mu = -2\ \ln \dfrac{\mathcal{L}\ (\text{obs}|\ \mu \cdot s + b,\ \hat{\theta}_\mu)}{\mathcal{L}\ (\text{obs}|\ \hat{\mu} \cdot s + b,\ \hat{\theta})}$

- ***s*** stands for the signal that would be expected for B(τ → 3μ) = 1
- **μ** is a signal strength modifier, i.e. the parameter of interest in the search;
- ***b*** stands for backgrounds
- **θ** are nuisance parameters describing systematic uncertainties ($\hat{\theta}_\mu$ maximizes the likelihood in the numerator for a given μ, while μ̂ and $\hat{\theta}$ define the point at which the likelihood reaches its global max).

Statistical analysis / τ → 3μ

The log-normal probability density function is assumed for the nuisance parameters affecting the signal yields.
An unbinned version of likelihood is used, which can be written as in equation

$$\mathcal{L}(\mathrm{data}|\ \mu s + b) \ \sim \ e^{-(\mu S + B)} \prod_i \mathcal{P}(\mathrm{x_i}|\ \mu s + b)$$

where:

- S is the total number of signal events,
- B is the total number of background events,
- the index i runs over all events,
- P(xi|μ s + b) is an event density function of x such that the expected event rate in vicinity of a given value of x is predicted as P(x|μ s + b)dx.

Statistical analysis / τ → 3μ

The ratio of probabilities to observe a value of the test statistic at least as large as the one observed in data, q_{μ}^{obs}, under the signal + background (s + b) and background only (b) hypothesis:

$$\mathrm{CL_s} = \frac{P\left(q_\mu \geq q_\mu^{obs} \mid \mu \cdot s + b\right)}{P\left(q_\mu \geq q_\mu^{obs} \mid b\right)} \leq 0.1$$

is used as the criterion for excluding the signal at the 90% confidence level.

Evaluation of systematics / τ → 3μ

Source of uncertainty	Yield
Uncertainty on D_s normalization [6.4%]	6.4%
Uncertainty on measuring f (B/D ratio) [10%]	3%
Uncertainty on n. of events triggered by trimuon trigger [3.3%]	1.3%
Relative uncertainty in $\mathcal{B}(D_s \to \phi\pi \to \mu\mu\pi)$ [8%]	8%
Relative uncertainty in $\mathcal{B}(D_s \to \mu\nu)$ [4%]	3%
Uncertainty on scaling D_s to include D^+ [4%]	3%
Uncertainty on scaling B^0 and B^+ to include B_s [12%]	4%
Relative uncertainty in $\mathcal{B}(B \to D_s + ...)$ [16%]	4%
Relative uncertainty in $\mathcal{B}(B \to \tau + ...)$ [11%]	3%
Muon ID and trigger uncertainty [6%]	6%

Evaluation of systematics / CPV phase $B_s^0 \to J/\psi\, \phi(1020) \to \mu^+\mu^-K^+K^-$

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar$ps^{-1}]	$\|\lambda\|$	Γ_s [ps^{-1}]	$\|A_0\|^2$	$\|A_\perp\|^2$	$\|A_S\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	50	0.014	0.10	0.026	0.0042	0.0047	0.0063	0.0077	0.12	0.16	0.083
Model bias	7.9	0.0019	—	0.0035	0.0005	0.0002	0.0012	0.001	0.020	0.016	0.006
Model assumptions	—	—	—	0.0046	0.0003	—	0.0013	0.001	0.017	0.019	0.011
Angular efficiency	3.8	0.0006	0.007	0.0057	0.0002	0.0008	0.0010	0.002	0.006	0.015	0.015
Proper decay length efficiency	0.3	0.0062	0.001	0.0002	0.0022	0.0014	0.0023	0.001	0.001	0.002	0.002
Proper decay length resolution	3.5	0.0009	0.021	0.0015	0.0006	0.0007	0.0009	0.007	0.006	0.025	0.022
Data/simulation difference	0.6	0.0008	0.004	0.0003	0.0003	0.0044	0.0029	0.007	0.007	0.007	0.028
Flavor tagging	0.5	$<10^{-4}$	0.006	0.0002	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-3}$	0.001	0.007	0.001
Sig./bkg. ω_{evt} difference	3.0	—	—	—	0.0005	—	0.0008	—	—	—	0.006
Peaking background	0.3	0.0008	0.011	$<10^{-4}$	0.0002	0.0005	0.0002	0.003	0.005	0.007	0.011
S-P wave interference	—	0.0010	0.019	—	0.0005	0.0005	—	0.013	—	0.019	0.019
$P(\sigma_{ct})$ uncertainty	$<10^{-1}$	0.0019	0.028	0.0004	0.0008	0.0006	0.0008	0.001	0.001	0.002	0.005
Total systematic uncertainty	10.0	0.0070	0.032	0.0083	0.0026	0.0049	0.0045	0.016	0.028	0.045	0.048