# Measurement of CP Violation in $B_s \to J/\psi\, \phi$ decays with the CMS detector

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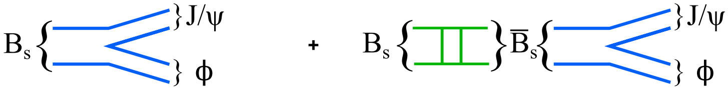
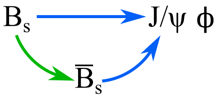
# CP-VIOLATION IN $B_s \to J/\psi\,\phi$ DECAYS

- $B_s$ mesons mix via box diagrams with relatively large decay width difference ($\Delta\Gamma_s$) between the two mass eigenstates
- Final state of the $B_s \to J/\psi\,\phi$ decay is un-flavoured and therefore accessible by both $B_s$ and $\overline{B}_s$




- The weak phase $\phi_s$ arises from the quantum interference between direct and mixing-mediated decays




$$\phi_s \simeq -2\beta_s\,,\ \ \beta_s = \arg(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*})$$

$$2\beta_s = 0.0363^{+0.0016}_{-0.0015}\ \text{rad in the SM}$$

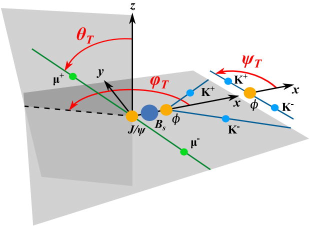
- Theoretically clean decay channel with precise SM predictions [PRD 84, 033005 (2011)]
- Sensitive to New Physics in mixing → many NP scenarios predict enhanced values of $\phi_s$

$$\phi_s = \phi_s^{SM} + \Delta\phi \qquad\qquad \Delta\phi = arg(M_{12}/M_{12}^{SM}) \tag{1}$$

- Experimentally clean fully renconstructed ($\mu^+\mu^- K^+K^-$) final state, with low background
- Two vector mesons final state: mixture of CP-even and CP-odd states
- Tagged angular analysis to disentangle the two CP components

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

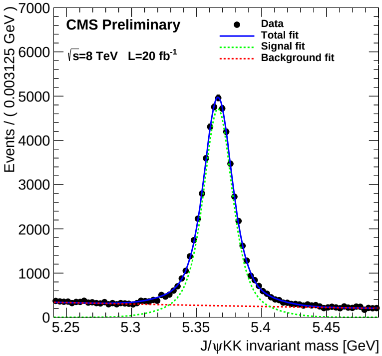
- $\Theta \to$ decay angles defined in the transversity basis
  - $(\theta_T, \varphi_T, \psi_T)$
- $t \to B_s$ proper decay time
- $\alpha \to$ physics parameters to be determined
  - $\phi_s$, $\Delta\Gamma_s$, $c\tau$, $|A_0|^2$, $|A_S|^2$, $|A_\perp|^2$, $\delta_\parallel$, $\delta_{S\perp}$, $\delta_\perp$
- $O_i \to$ time dependent functions
  - $b_i$, $d_i$ terms dependent to $\cos\phi_s$ and $\sin\phi_s$




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

- Opposite side tagger used to infer the $B_s$ flavour at production time
  - Modify $c_i$, $d_i$ terms to take into account the tagger response

- Displaced vertex di-muon trigger ($J/\psi \to \mu^+\mu^-$)
- $p_T(\mu) > 4$ GeV, $p_T(\mu\mu) > 7$ GeV
- $\left|M_{\mu\mu} - M_{J/\psi}^{PDG}\right| < 150$ MeV
- $p_T(K) > 0.7$ GeV, at least 5 tracker hits
- $\left|M_{KK} - M_{\phi}^{PDG}\right| < 10$ MeV
- Kinematic fit to the 4 track vertex ($\mu^+\mu^-K^+K^-$) candidate
  - ▷ $\mu\mu$ mass contstrained to $J/\psi$
  - ▷ $\chi^2$-probability $> 2\%$
- Fit ranges:
  - ▷ $B_s$ candidate proper decay length $[0.02, 0.3]$ cm
  - ▷ $B_s$ candidate invariant mass $[5.24, 5.49]$ GeV




$20\ \text{fb}^{-1}$ at 8 TeV (full 2012 dataset)

$N^{sig}(B_s) \sim 49000$

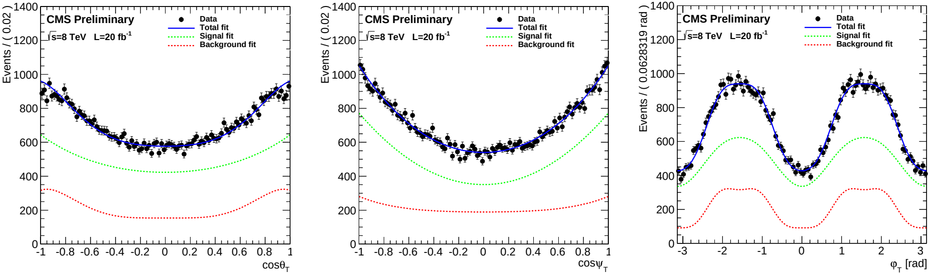
$N^{bkg} \sim 21000$

$S/B \approx 6.8$ in $[5.33 - 5.40]$ GeV

# EFFICIENCIES AND RESOLUTIONS

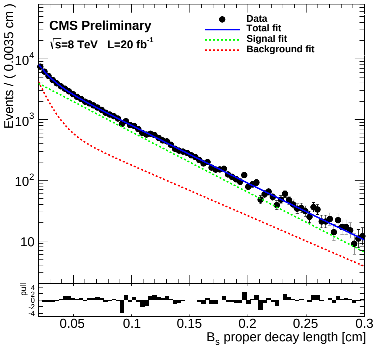
Key elements for the $\phi_s/\Delta\Gamma_s$ measurement: resolution and efficiency modeling for proper time and $\Theta$.

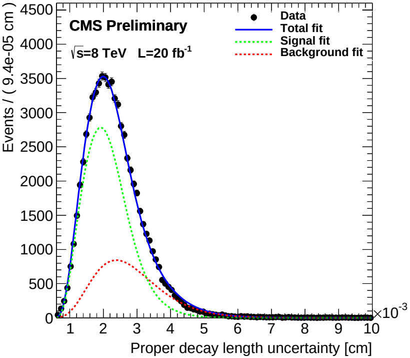
- Angular efficiency:
  - ▷ Evaluated using MC simulations, parametrized with a 3D function of decay angles $\varepsilon\left(\Theta\right) = \varepsilon\left(\cos\theta_T, \cos\psi_T, \varphi_T\right)$ in order to take into account the angular cross terms
- Angular resolution:
  - ▷ From MC. Not included in the fit model but considered as systematic uncertainty



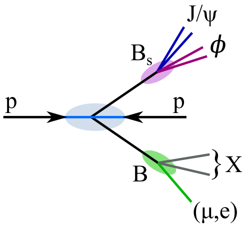

- Proper time efficiency:
  - ▷ From MC and cross-checked in data. Flat in the fitting range $[0.02, 0.3]$ cm, variations included as systematic uncertainties

- Estimated on a per-event basis from the $B_s$ decay vertex proper time uncertainty, scaled by a $\kappa\,(c\tau)$ factor to take into account the differences wrt the resolution
  - ▷ Cross checked with a prompt $J/\psi$ sample
  - ▷ $B_s$ proper decay length resolution $\sim 21\,\mu$m $(70\,\text{fs})$



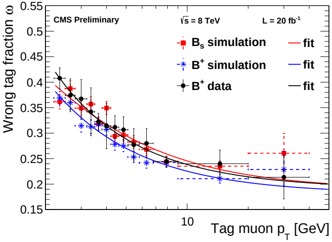
- $B_s$ flavour can be inferred from the *other* B meson in the event ($b\bar{b}$ pair production)
- The charge of the Opposite Side leptons (*e*, $\mu$) tags the $B_s$ flavour under the assumption of direct semileptonic $b \to \ell X$ decay
- Dilution of the tagger (mistag) is induced by
  - ▷ Sequential $b \to c X \to \ell X'$ decays
  - ▷ Opposite side B meson mixing
  - ▷ Leptons arising from other sources (K-$\pi$ DIF, $c \to \ell X$, ...)
- Tagging perfomances optimized by maximizing the tagging power $\mathcal{P}_{tag} = \varepsilon_{tag}(1 - 2\omega)$

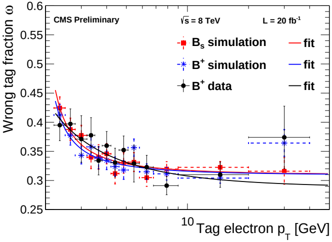



Tagging efficiency: $\varepsilon_{tag} = N^{tag} / N^{B_s}$

Mistag fraction: $\omega = N^{wrong-tag} / N^{tag}$

- Tagger performances measured with $B^+ \to J/\psi K^+$ data, and validated with $B^+ \to J/\psi K^+$ and $B_s \to J/\psi \phi$ simulated events
- Mistag fractions are parametrized as functions of $p_T$ for both muons and electrons



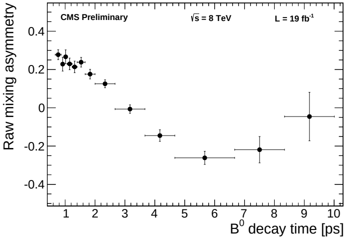




| [%] | Muons | Electrons | **Combined** |
|---|---|---|---|
| $\varepsilon_{tag}$ | $4.55 \pm 0.03 \pm 0.08$ | $3.26 \pm 0.02 \pm 0.01$ | $7.67 \pm 0.04$ |
| $\omega$ | $30.7 \pm 0.4 \pm 0.7$ | $34.8 \pm 0.3 \pm 1.0$ | $32.2 \pm 0.2$ |
| $\mathcal{P}_{tag}$ | $0.68 \pm 0.03 \pm 0.05$ | $0.30 \pm 0.02 \pm 0.04$ | $0.97 \pm 0.04$ |

- Tagging performances tested with $B^0 \to J/\psi\, K^*$ data
  - Same $J/\psi$ triggers as for $B_s$
  - Similar selection cuts as for $B_s$
  - Raw mixing asymmetry :

$$A_{mix}^{signal} = \frac{N_{unmixed} - N_{mixed}}{N_{unmixed} + N_{mixed}}$$

- $B^0$ oscillation $\Rightarrow$ seen



- Extended maximum likelihood fit applied
  - ▷ Tagged signal model
  - ▷ Gaussian constraint on $\Delta m_s$ to the PDG value $17.69 \pm 0.08\,\hbar/\mathrm{ps}$

$$\begin{aligned}
\mathcal{L} &= L_{sig} + L_{bkg} \\
L_{sig} &= N_{sig} \cdot \left[X(\Theta, t; \alpha) \otimes G(t, \sigma_t) \cdot \varepsilon(\Theta)\right] \cdot P_{sig}(m_{\mathrm{B_s}}) \cdot P_{sig}(\sigma t) \cdot P_{sig}(\xi) \\
L_{bkg} &= N_{bkg} \cdot P_{bkg}(\cos\theta_{\mathrm{T}}, \varphi_{\mathrm{T}}) \cdot P_{bkg}(\cos\psi_{\mathrm{T}}) \cdot P_{bkg}(t) \cdot P_{bkg}(m_{\mathrm{B_s}}) \cdot P_{bkg}(\sigma t) \cdot P_{bkg}(\xi)
\end{aligned}$$

- $\mathrm{B_s}$ mass range $[5.24, 5.49]$ GeV; proper time range $[0.02, 0.3]$ cm

| Parameter | Fit result |
|---|---|
| $\lvert A_0\rvert^2$ | $0.511 \pm 0.006$ |
| $\lvert A_{\mathrm{S}}\rvert^2$ | $0.015 \pm 0.016$ |
| $\lvert A_\perp\rvert^2$ | $0.242 \pm 0.008$ |
| $\delta_\parallel$ | $3.48 \pm 0.09$ rad |
| $\delta_{\mathrm{S}\perp}$ | $0.34 \pm 0.24$ rad |
| $\delta_\perp$ | $2.73 \pm 0.36$ rad |
| $c\tau$ | $447.3 \pm 3.0\,\mu\mathrm{m}$ |
| $\Delta\Gamma_{\mathrm{s}}$ | $0.096 \pm 0.014\,\mathrm{ps}^{-1}$ |
| $\phi_{\mathrm{s}}$ | $-0.03 \pm 0.11$ rad |

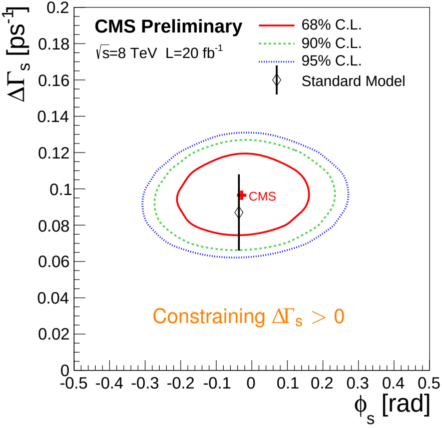
| Source | $\|A_0\|^2$ | $\|A_S\|^2$ | $\|A_\perp\|^2$ | $\Delta\Gamma_s$ [ps$^{-1}$] | $\delta_\parallel$ [rad] | $\delta_{S\perp}$ [rad] | $\delta_\perp$ [rad] | $\phi_s$ [rad] | $c\tau$ [$\mu$m] |
|---|---|---|---|---|---|---|---|---|---|
| Statistical uncertainty | 0.0058 | 0.016 | 0.0077 | **0.0138** | 0.092 | 0.24 | 0.36 | **0.109** | 3.0 |
| Proper time efficiency | 0.0015 | - | 0.0023 | **0.0057** | - | - | - | **0.002** | 1.0 |
| Angular efficiency (*) | 0.0060 | 0.008 | 0.0104 | **0.0021** | 0.674 | 0.14 | 0.66 | **0.016** | 0.8 |
| Model bias (**) | 0.0008 | - | - | **0.0012** | 0.025 | 0.03 | - | **0.015** | 0.4 |
| Proper time resolution | 0.0009 | - | 0.0008 | **0.0021** | 0.004 | - | 0.02 | **0.006** | 2.9 |
| Background mistag modelling | 0.0021 | - | 0.0013 | **0.0018** | 0.074 | 1.10 | 0.02 | **0.002** | 0.7 |
| Flavour tagging | - | - | - | **-** | - | - | 0.02 | **0.005** | - |
| PDF modelling | 0.0016 | 0.002 | 0.0021 | **0.0021** | 0.010 | 0.03 | 0.04 | **0.006** | 0.2 |
| Free $\|\lambda\|$ fit (***) | 0.0001 | 0.005 | 0.0001 | **0.0003** | 0.002 | 0.01 | 0.03 | **0.015** | - |
| Kaon $p_T$ re-weighting (****) | 0.0094 | 0.020 | 0.0041 | **0.0015** | 0.085 | 0.11 | 0.02 | **0.014** | 1.1 |
| Total systematics | 0.0116 | 0.022 | 0.0117 | **0.0073** | 0.684 | 1.12 | 0.66 | **0.032** | 3.5 |

(*) evaluated from the statistical uncertainty of the model

(**) determined from toy MC bias tests

(***) let $|\lambda|$ as a free parameter in the fit

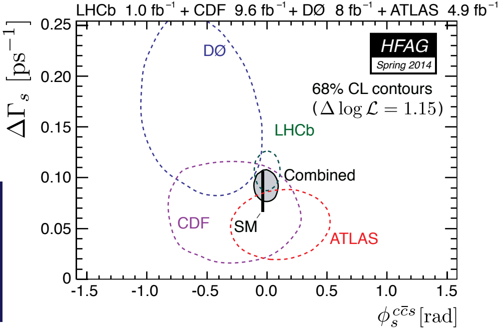
(****) propagated from discrepancy between data and simulations




**CMS 2012 data (20 $fb^{-1}$) results:**

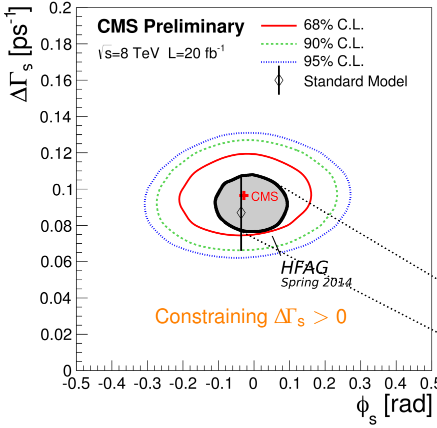
$$\phi_s = -0.03 \pm 0.11 \pm 0.03 \text{ rad}$$

$$\Delta\Gamma_s = 0.096 \pm 0.014 \pm 0.007 \text{ ps}^{-1}$$



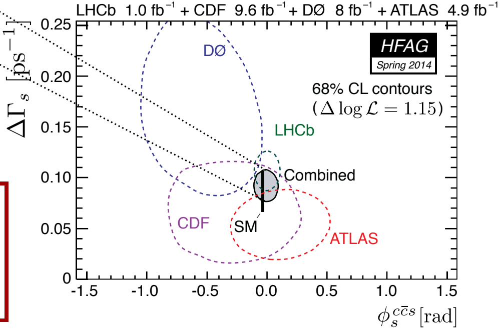

$\Delta\Gamma_s$ confirmed to be non-zero

Measurement precision still dominated by statistical uncertainty




Plot for illustrative purpose only

Result not yet included in the HFAG average




Results consistent with SM

Consistent and competitive with world average

- First CMS measurement of $\phi_s$ and $\Delta\Gamma_s$ from a time-dependent angular analysis of the $B_s \to J/\psi\,\phi$ decay using the full 2012 dataset (20 $fb^{-1}$, corresponding to 49k $B_s$ signal events)
- Tagged signal model introduced in the final fit: $\mathcal{P}_{tag} = (0.97 \pm 0.04)$ %

$$\phi_s = -0.03 \pm 0.11(\text{stat.}) \pm 0.03(\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.096 \pm 0.014(\text{stat.}) \pm 0.007(\text{syst.})\ \text{ps}^{-1}$$

- $\Delta\Gamma_s$ is confirmed to be non-zero
- Accurate and compentitive results in agreement with the Standard Model and the HFAG world average
- Results still dominated by the statistical uncertainties
  - ▷ Work in progress on an improved (MVA-based) flavour tagger
  - ▷ Looking forward to the start of the LHC Run2
- Reference: CMS PAS BPH-13-012

# BACKUP

$$\frac{d^4\Gamma(\mathrm{B_s})}{d\Theta dct} = X(\Theta, \alpha, ct) \propto \sum_{i=1}^{10} O_i(\alpha, ct) \cdot g_i(\Theta)$$

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

| $i$ | $g_i(\theta_T, \psi_T, \varphi_T)$ | $N_i$ | $a_i$ | $b_i$ | $c_i$ | $d_i$ |
|---|---|---|---|---|---|---|
| 1 | $2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$ | $\lvert A_0(0)\rvert^2$ | 1 | $D$ | $C$ | $-S$ |
| 2 | $\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$ | $\lvert A_\parallel(0)\rvert^2$ | 1 | $D$ | $C$ | $-S$ |
| 3 | $\sin^2\psi_T\sin^2\theta_T$ | $\lvert A_\perp(0)\rvert^2$ | 1 | $-D$ | $C$ | $S$ |
| 4 | $-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$ | $\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$ | $C\sin(\delta_\perp-\delta_\parallel)$ | $S\cos(\delta_\perp-\delta_\parallel)$ | $\sin(\delta_\perp-\delta_\parallel)$ | $D\cos(\delta_\perp-\delta_\parallel)$ |
| 5 | $\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$ | $\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$ | $\cos(\delta_\parallel-\delta_0)$ | $D\cos(\delta_\parallel-\delta_0)$ | $C\cos(\delta_\parallel-\delta_0)$ | $-S\cos(\delta_\parallel-\delta_0)$ |
| 6 | $\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\sin\varphi_T$ | $\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$ | $C\sin(\delta_\perp-\delta_0)$ | $S\cos(\delta_\perp-\delta_0)$ | $\sin(\delta_\perp-\delta_0)$ | $D\cos(\delta_\perp-\delta_0)$ |
| 7 | $\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$ | $\lvert A_S(0)\rvert^2$ | 1 | $-D$ | $C$ | $S$ |
| 8 | $\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$ | $\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$ | $C\cos(\delta_\parallel-\delta_S)$ | $S\sin(\delta_\parallel-\delta_S)$ | $\cos(\delta_\parallel-\delta_S)$ | $D\sin(\delta_\parallel-\delta_S)$ |
| 9 | $\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$ | $\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$ | $\sin(\delta_\perp-\delta_S)$ | $-D\sin(\delta_\perp-\delta_S)$ | $C\sin(\delta_\perp-\delta_S)$ | $S\sin(\delta_\perp-\delta_S)$ |
| 10 | $\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$ | $\lvert A_S(0)\rvert\lvert A_0(0)\rvert$ | $C\cos(\delta_0-\delta_S)$ | $S\sin(\delta_0-\delta_S)$ | $\cos(\delta_0-\delta_S)$ | $D\sin(\delta_0-\delta_S)$ |

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}$$

- $|\lambda|$ includes possible contributions from CP violation in direct decay
  - Assuming $|\lambda| = 1 \rightarrow$ the variation of $|\lambda|$ is considered as a systematic uncertainty
- $\Delta\Gamma_s > 0$ using LHCb results [PRL 108, 241801 (2012)] which resolved the $\Delta\Gamma_s$ sign ambiguity

- The $c_i$ and $d_i$ terms of the $O_i$ time dependent functions are modified according to the flavour tagging response

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

- $\xi$ is the tag decision, based on the charge of the lepton:
  - $0 \rightarrow$ untagged
  - $+1 \rightarrow \mathrm{B_s}$ tagged
  - $-1 \rightarrow \overline{\mathrm{B}}_\mathrm{s}$ tagged
- $\omega$ is the mistag fraction evaluated as a function of the lepton tranverse momentum: $\omega = \omega\left(p_\mathrm{T}^\ell\right)$

$$\mathcal{L} = L_{sig} + L_{bkg}$$
$$L_{sig} = N_{sig} \cdot [X(\Theta, \mathrm{ct}; \alpha) \otimes G(\mathrm{ct}, \sigma_{\mathrm{ct}}) \cdot \varepsilon(\Theta)] \cdot P_{sig}(m_{\mathrm{B_s}}) \cdot P_{sig}(\sigma_{\mathrm{ct}}) \cdot P_{sig}(\xi)$$
$$L_{bkg} = N_{bkg} \cdot P_{bkg}(\cos\theta_{\mathrm{T}}, \varphi_{\mathrm{T}}) \cdot P_{bkg}(\cos\psi_{\mathrm{T}}) \cdot P_{bkg}(\mathrm{ct}) \cdot P_{bkg}(m_{\mathrm{B_s}}) \cdot P_{bkg}(\sigma_{\mathrm{ct}}) \cdot P_{bkg}(\xi)$$

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- $G(\mathrm{ct}, \sigma_{\mathrm{ct}})$: gaussian resolution function, which makes use of the per-event proper decay length uncertainty $\sigma(\mathrm{ct})$ scaled by a factor $\kappa(\mathrm{ct})$
- $\varepsilon(\Theta) = \varepsilon(\cos\theta_{\mathrm{T}}, \cos\psi_{\mathrm{T}}, \varphi_{\mathrm{T}})$: 3-dimensional angular efficiency
- $P_{sig}(m_{\mathrm{B_s}})$: $\mathrm{B_s}$ mass signal PDF $\rightarrow$ triple gaussian with common mean
- $P_{sig}(\sigma_{\mathrm{ct}})$: proper decay length uncertainty signal PDF $\rightarrow$ sum of two Gamma functions
- $P_{sig}(\xi)$: signal tag decision obtained from data

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- $P_{bkg}(\cos\theta_{\mathrm{T}}, \varphi_{\mathrm{T}})$ and $P_{bkg}(\cos\psi_{\mathrm{T}})$: angular background PDFs $\rightarrow$ Legendre polynomials for $\cos\theta_{\mathrm{T}}$ and $\cos\psi_{\mathrm{T}}$ and sinusoidal functions for $\varphi_{\mathrm{T}}$. A 2-dimensional PDF is used for $\cos\theta_{\mathrm{T}}$ and $\varphi_{\mathrm{T}}$ to take into account the correlations
- $P_{bkg}(\mathrm{ct})$: proper decay length background PDF $\rightarrow$ sum of two exponential functions
- $P_{bkg}(m_{\mathrm{B_s}})$: $\mathrm{B_s}$ mass background PDF $\rightarrow$ single exponential
- $P_{bkg}(\sigma_{\mathrm{ct}})$: proper decay length uncertainty background PDF $\rightarrow$ single Gamma function
- $P_{bkg}(\xi)$: background tag decision obtained from data

- **Proper time efficiency:** fitting the data with a proper decay length efficiency which takes into account a small contribution of the decay length significance cut at small ct and a first order polynomial variations at high ct
- **Angular effieciency:** propagated the statistical uncertainty of the angular efficiency parameters to the physics observables
- **Fit model:** reported the bias of the pulls that were measured using toy MC pseudo-experiments
- **Proper decay time resolution ($\kappa$ factor):** varied the $\kappa\,(\mathrm{ct})$ factors within their stat. errors; the difference with respect to the nominal fit is investigated, and one standard deviation of the obtained distribution is taken as the systematic uncertainty
  - Difference of $\kappa\,(\mathrm{ct})$ in simulation and a prompt J/$\psi$ data sample is also studied
- **BG mistag modelling:** no background PDF for $\omega$. Systematic estimated by generating simulated pseudo-experiments with different mistag distributions for signal and background and fitting them with the nominal fit
- **Flavour tagging:** systematic and statistical tagging uncertainties propagated to the physics observables uncertainty
- **PDF modelling assumptions:** all the systematics due to the assumption on the PDF model are evaluated with toy MC pseudo-experiments
- **Kaon $p_T$ re-weighting:** small discrepancy in the kaon $p_T$ spectrum between data and simulations $\rightarrow$ syst. evaluated by re-weighting the simulated kaon $p_T$ spectrum to agree with the data
- $|\lambda| = 1$ **assumption:** tested by leaving $|\lambda|$ free in the fit $\Rightarrow$ $|\lambda|$ from fit agrees with 1 within one $\sigma$. The differences found in the fit results with respect to the nominal fit are used as systematic uncertainties

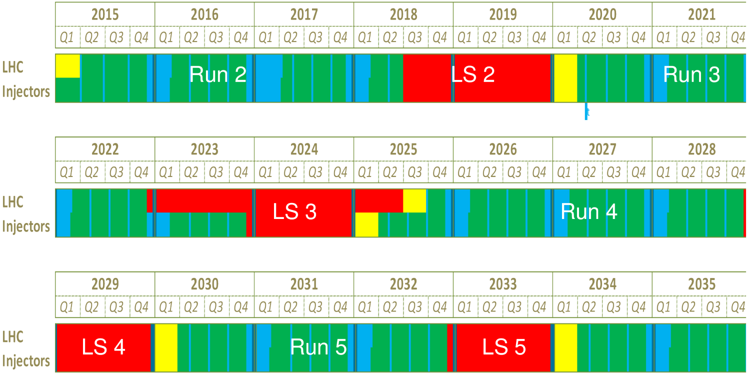
## LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

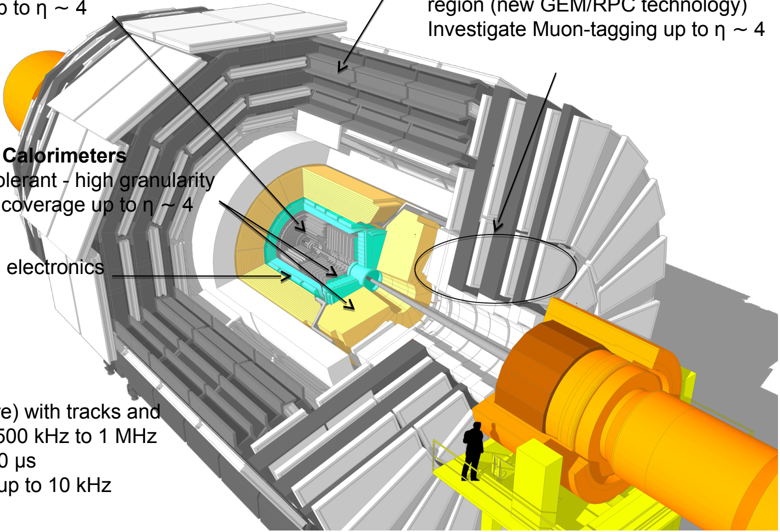
injectors: in 2024 => 13 months + 3 BC



# CMS UPGRADE PLANS

**New Tracker**
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ∼ 4

**Muons**
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ∼ 4



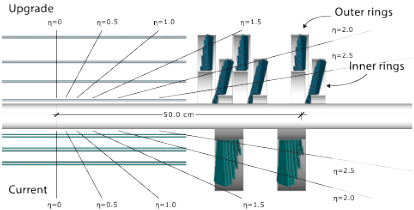
**New Endcap Calorimeters**
- Radiation tolerant - high granularity
- Investigate coverage up to η ∼ 4

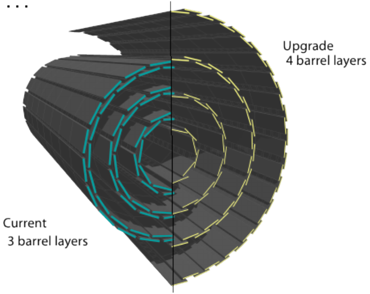
**Barrel ECAL**
- Replace FE electronics

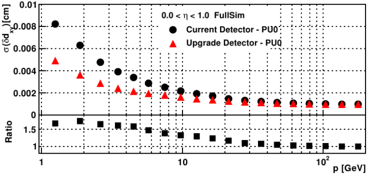
**Trigger/DAQ**
- L1 (hardware) with tracks and rate up ∼ 500 kHz to 1 MHz
- Latency ≥ 10 μs
- HLT output up to 10 kHz

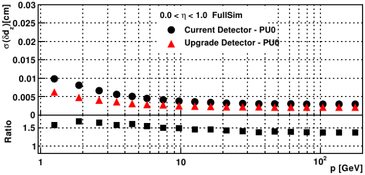
# Tracker upgrade → Phase 1

- Pixel detector will be replaced
- One additional layer, closer to the beampipe ⇒ improved track resolution and efficiency
- New readout chip ⇒ better efficiency to high rate / high PU
- Less material, new cooling, new powering scheme, . . .




- Substantial improvement for low-momentum tracks

# TRIGGER UPGRADE → PHASE 1

- New electronics (based on Virtex7 FPGAs) for all the trigger sub-systems: Calorimeter, Muon, Global
- Improved algorithms for PU mitigation and isolation
- Trigger inputs split to allow full commissioning of the new trigger in parallel with the operating legacy system

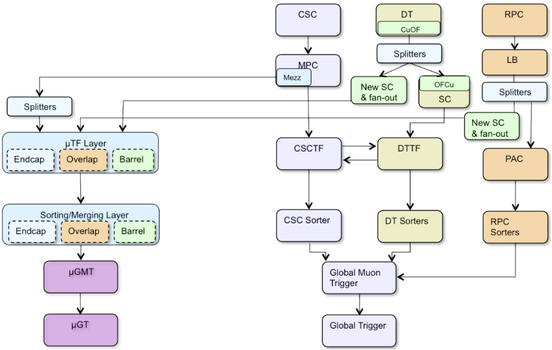



Figure: Muon trigger

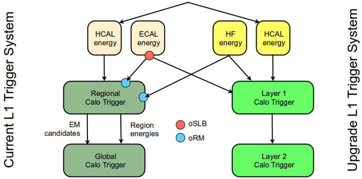
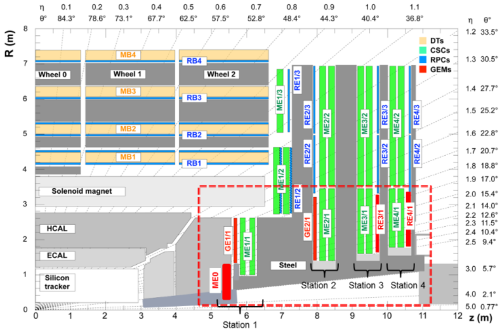


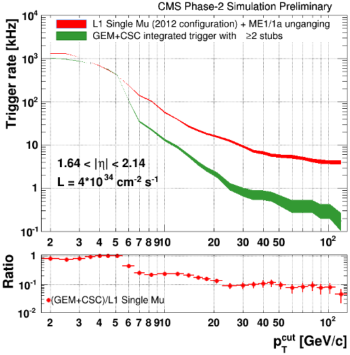

Figure: Calo trigger

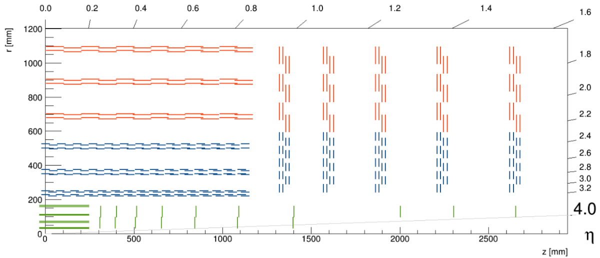
- Muon system:
  - ▷ New electronics to merge the information of the DT and RPC detectors at the chamber level
  - ▷ Improvement of $p_T$ assignment with new LUTs at track-finding level

- Improve trigger and and performances + provide redundancy
  - ▷ Complete muon stations in the $1.6 < |\eta| < 2.4$ region
  - ▷ Add GEM detectors in first 2 stations ⇒ increase $p_T$ resolution
  - ▷ Add RPCs in last 2 stations ⇒ improve timing resolution to reduce background
- Considering increase of the muon coverage to $2.2 < |\eta| < 4.0$ with one GEM tagging station (ME0) coupled with the extended pixel tracker

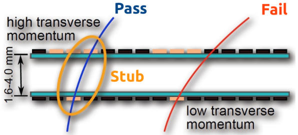


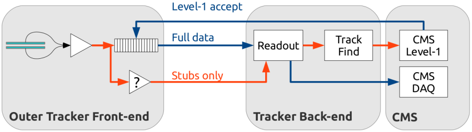

Example of single μ trigger rate reduction with GEM1/1 station





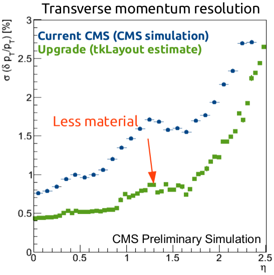

- Inner tracker
  - ▷ Pixel tracker with similar configuration (4 layers) as Phase 1
  - ▷ Thin (100 $\mu$m) sensors with small (30 × 100 $\mu$m) pixels
- Outer tracker
  - ▷ High granularity ⇒ efficient track reconstruction with high (∼140) PU
  - ▷ Two closely-spaced sensors readout by one same front-end 40 MHz ["$p_T$-modules"]
    - 2S (Strip-Strip) $p_T$-modules
    - SP (Strip-Pixel) $p_T$-modules
- Tracks inputs to L1 trigger ⇒ tracking trigger



- Clear $p_T$ resolution improvements
- Matching muon with tracking trigger inputs at L1 trigger
  - ▷ Improved precision of $p_T$ measurement
  - ▷ Large rate reduction without increasing the trigger thresholds

Single μ resolution $p_T$=10 GeV/c




Single μ resolution $p_T$=100 GeV/c