Measurement of the mixing-induced CP-violating observables in $B_s \to \phi\gamma$

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LAPP

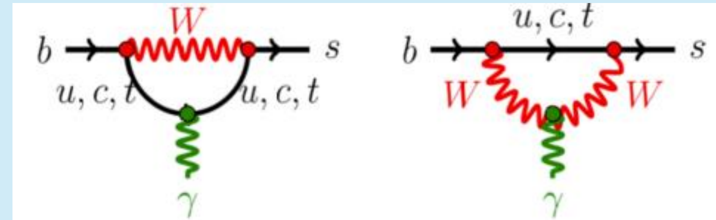
GDR-InF Annual Workshop 2022

Why $B_s \to \phi\gamma$?

- γ: Left-handed + Right-handed
  - Enhancement?

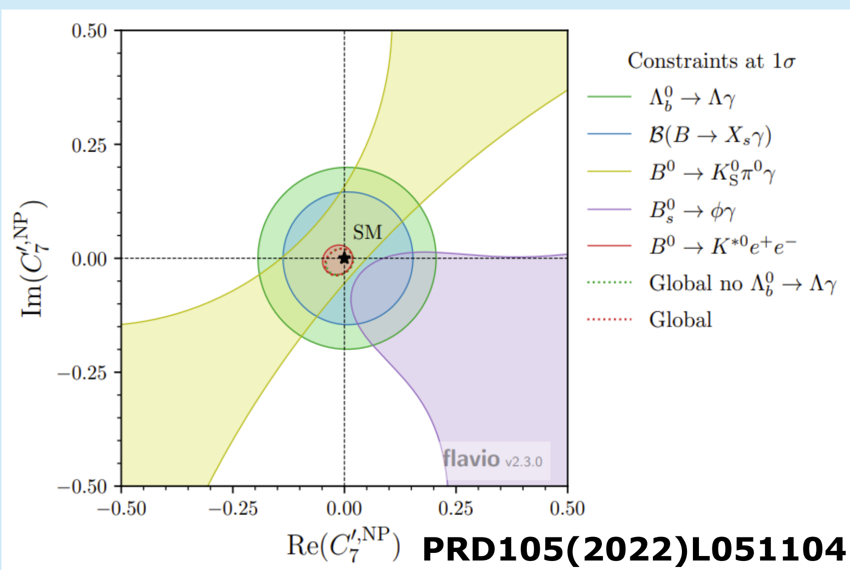
✓Effect on mixing-induced CP asymmetries

✓Sensitive to the NP



$$\mathcal{H}_{\rm rad} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_{7R}\mathcal{O}_{7R} + C_{7L}\mathcal{O}_{7L})$$

$$\Gamma(t)^{\pm} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}^{\Delta} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \mathcal{C}\cos(\Delta m_s t) \mp \mathcal{S}\sin(\Delta m_s t)\right]$$



PRD105(2022)L051104

Mixing-induced A_{CP}:

$$\mathcal{S} = \frac{2\mathcal{Im}[\frac{q}{p}(A_L \bar{A}_L^* + A_R \bar{A}_R^*)]}{|A_L|^2 + |\bar{A}_L|^2 + |A_R|^2 + |\bar{A}_R|^2}$$

- In the SM, with LO:

$$\mathcal{S}_{O7} = -2\frac{m_s}{m_b}\sin(\phi_s - \phi_s) = 0$$

Experiment status

- Tagged and untagged time-dependent result with LHCb Run1 data. [PRL 118, 021801 (2017), PRL 123, 081802 (2019)]
  - $A^{\Delta} = -0.669^{+0.364}_{-0.398}(stat.) \pm 0.170(syst.) \pm 0.096(ext.)$
  - $\mathcal{S} = 0.427 \pm 0.304(stat.) \pm 0.111(syst.) \pm 0.008(ext.)$
  - $\mathcal{C} = 0.106 \pm 0.289(stat.) \pm 0.109(syst.) \pm 0.013(ext.)$

- Expected improvements
  - Larger data sample Run1 + Run2 (~5 times to Run1)
  - Higher efficiency in event selections (cut-based → BDT)
  - Better flavour tagging performance (new tagging tech)
  - Better control in systematics.

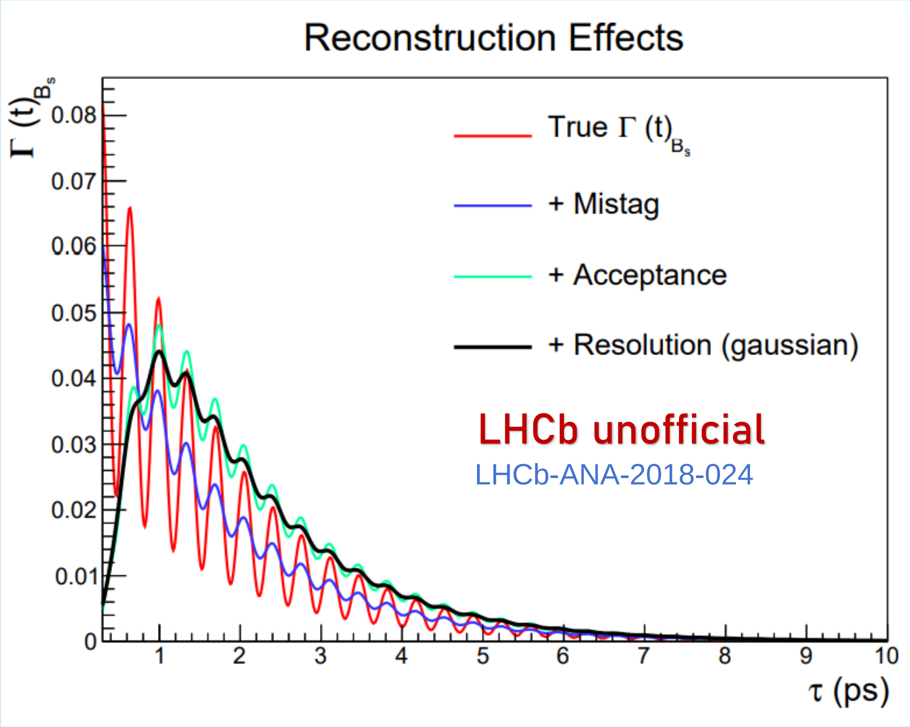
Formalism and Analysis strategy

- **The decay time PDF:**

$$F(t,q|\omega,\sigma_t) = \Gamma(t',q|\omega) \otimes R_{acc}(t,t'|\sigma_t)$$

➢ $\Gamma(t',q|\omega) = e^{-\Gamma_s t'}\left[\cosh\left(\frac{\Delta\Gamma_s t'}{2}\right) - A^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t'}{2}\right) + q(1-2\omega)\mathcal{C}\cos(\Delta m_s t') - q(1-2\omega)\mathcal{S}\sin(\Delta m_s t')\right]$

➢ $R_{acc}(t,t'|\sigma_t) = \epsilon_{acc}(t)R(t,t'|\sigma_t)$



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Start

Event selection:
Stripping-HLT-offline selection

Mass fit:
Data with sWeight for time fit.

Time acceptance ϵ_{acc}:
➢ Control channel $B_d \to K^*\gamma$

Time resolution $R(t,t'|\sigma_t)$:
➢ Double-Gaussian model

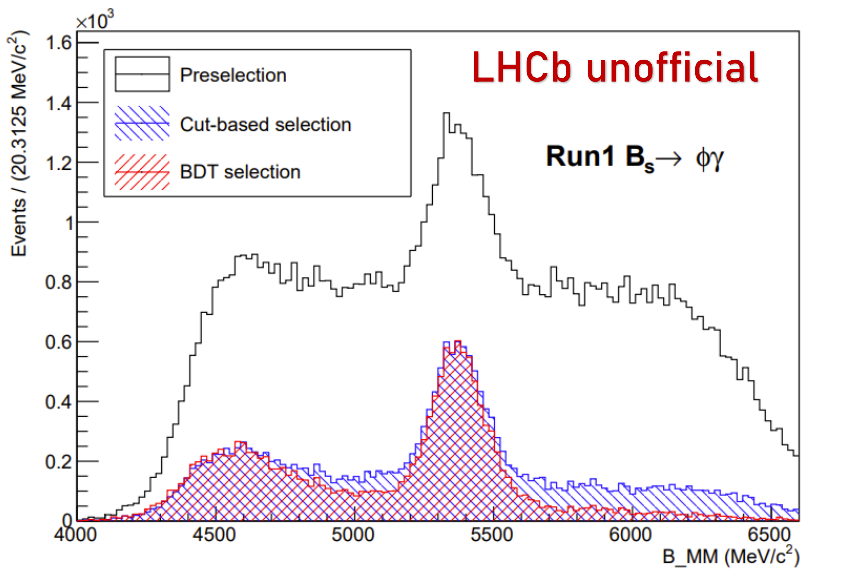
Flavour Tagging (FT):
➢ Mistag rate ω calibration

Time fit:
Extract A^{Δ}, $\mathcal{C}$, $\mathcal{S}$

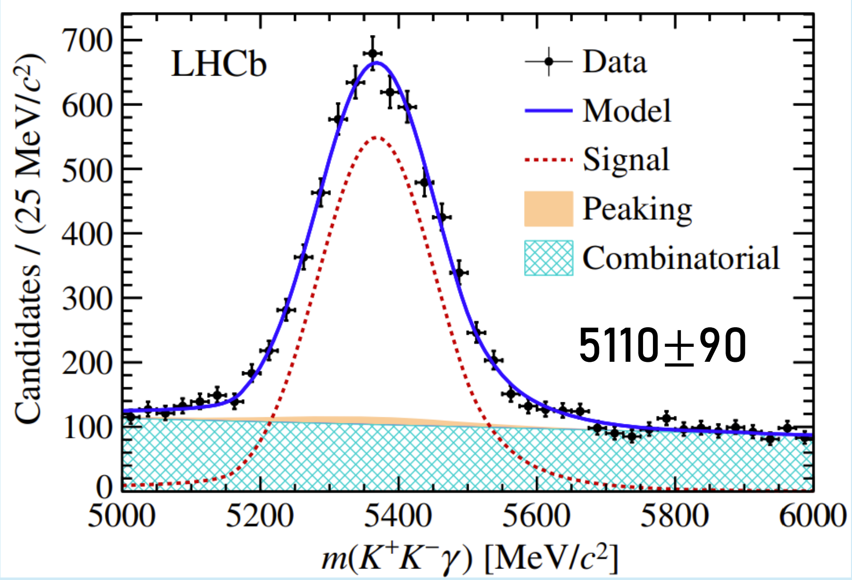
Event selection and Mass Fit

- Selections
  - Cuts: Tracks $\chi^2_{IP} > 55$, $p_T(B) > 3$ GeV/c, $\Delta M(\phi) < 15$ Mev/c^2

➢ Improvement in selection (BDT)
  - ➢ Input samples: RSB-data(BKG), Signal MC(Signal)
  - ➢ Features used: pT, χ^2_{IP}, η, θ_{DIRA}, Min($\Delta\chi^2_{vtx}$)



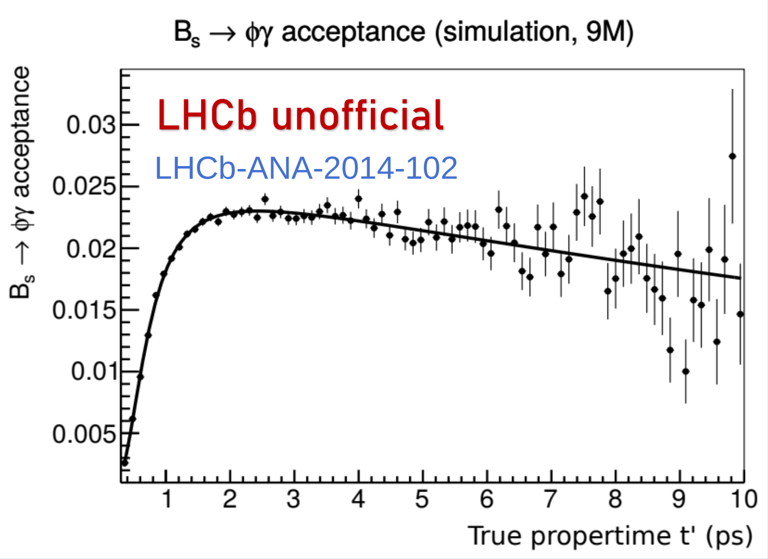
~13% increase in signal



PRL 123, 081802 (2019)

Time acceptance

- Time acceptance model
  - $\epsilon_{acc}(t) = e^{-\alpha t} \frac{[a(t-t_0)]^n}{1+[a(t-t_0)]^n}, t \geq t_0$
  - a, n: Low decay times
  - α: High decay times.
  - t_0: Efficiency 0 time point



- Simultaneous fit (Sig+Con MC)
  - a, n: Fixed as same value for both channels
  - t_0, α: a global offset between MC and data is allowed, same for both channel

Update for new stripping version:
- ➢ Simultaneous fit on signal data + control data + signal MC + control MC.
- ➢ Acceptance ratio between signal and control channel is fixed.

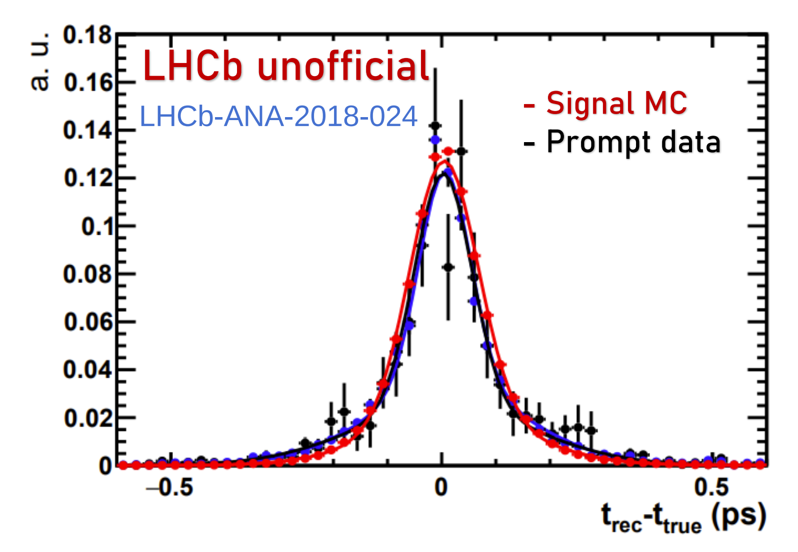
Time resolution

- Double-Gaussian Model

Decay time uncertainty from kinematic fit

$$R(\Delta t; f, \mu, s_1, s_2|\sigma_t) = f G_1(\Delta t; \mu, s_1\sigma_t) + (1-f)G_2(\Delta t; \mu, s_2\sigma_t)$$

- Data-MC consistency check
  - Using prompt $\phi\gamma$ data and MC sample



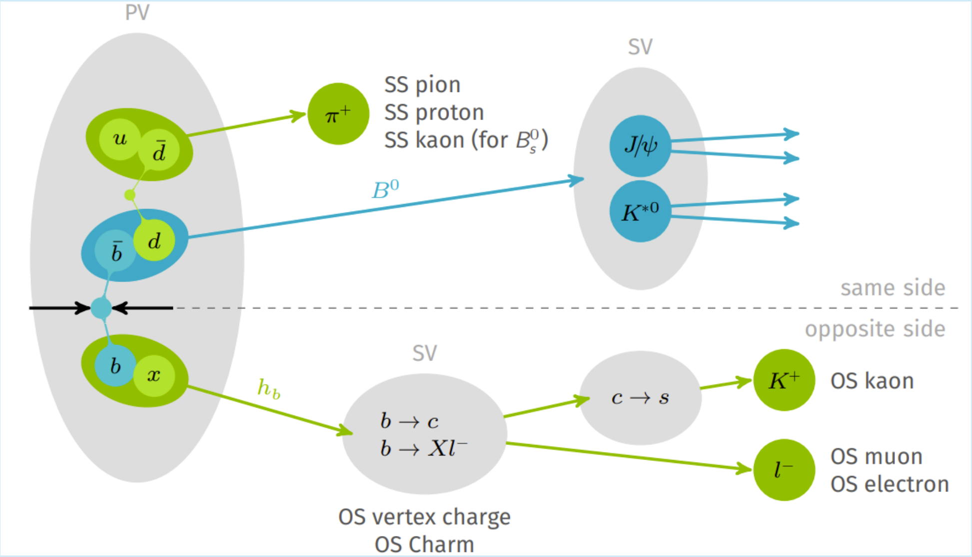
For better controlling systematics [LHCb-TALK-2022-041, CERN-OPEN-99-030]

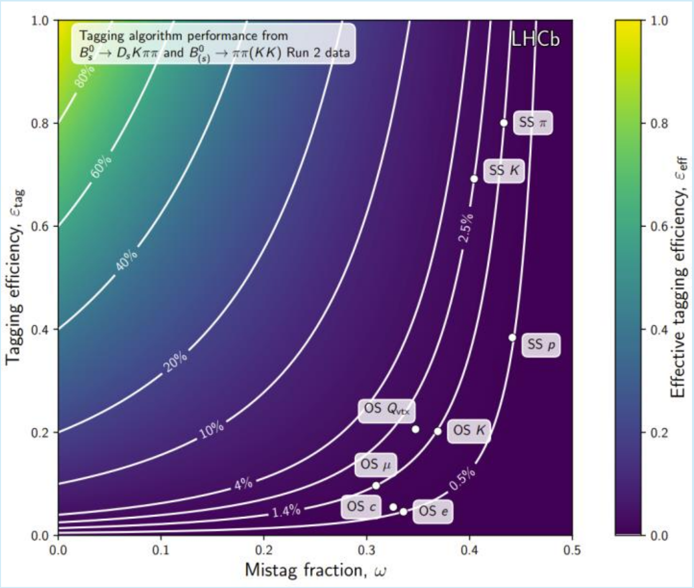
- ➢ Model resolution ⇒ Model dilution
- ➢ $D = e^{-\frac{1}{2}\sigma_D^2 \Delta m^2}$ ⇒ Effective single Gaussian resolution
- ➢ Numerically: $D = \frac{1}{N}\sum \cos(\Delta m t)$
- ➢ Calibrated σ_t with σ_D in decay time uncertainty bins.

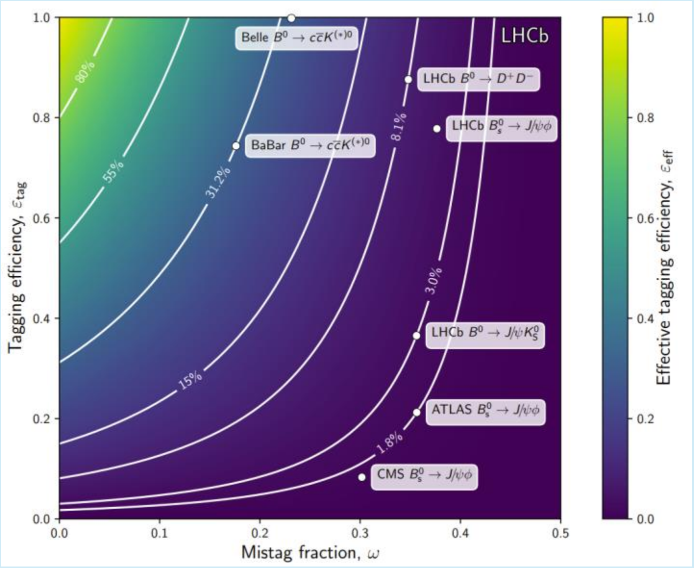
$$R(t')\otimes \sin(\Delta m t') = \sin(\Delta\, m t)\int_{-\infty}^{+\infty} dt' R(t') \cos(\Delta m t') = D \sin(\Delta m t)$$

Flavour Tagging (FT)

- Tagging at LHCb
  - OS tagger + SS tagger
  - $\epsilon_{tag} = \frac{N_{tag}}{N_{tag}+N_{untag}}$, $\omega = \frac{N_{wrong}}{N_{tag}}$
  - $\epsilon_{eff} = \epsilon_{tag}(1-2\omega)^2 \propto 1/\sigma_{stat}^2$
  - “Classic”
    - Choose taggers + Combine







LHCb-FIGURE-2020-002

FT Calibration

Calibration strategy

- OS tagger: OSCharm, OSElectronLatest, OSKaonLatest, OSVtxCh, OSMuonLatest; SS tagger: SSKaonLatest
- Control sample: OS: $B_u^+ \to J/\psi K^+$; SS: $B_s \to D_s^- \pi^+$ [**Run1** and Run2 MC & Data]

Calibration procedure

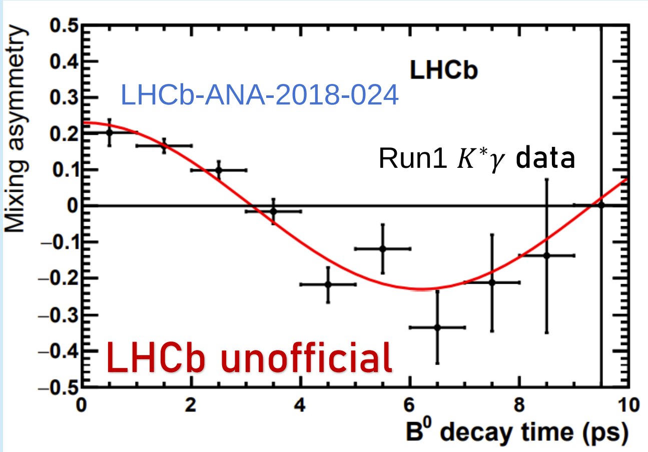
Calibrate taggers independently → Combine the taggers → Reweight (nPVs, nTracks, B_eta, B_PT) to signal → Calibrate combined tagger

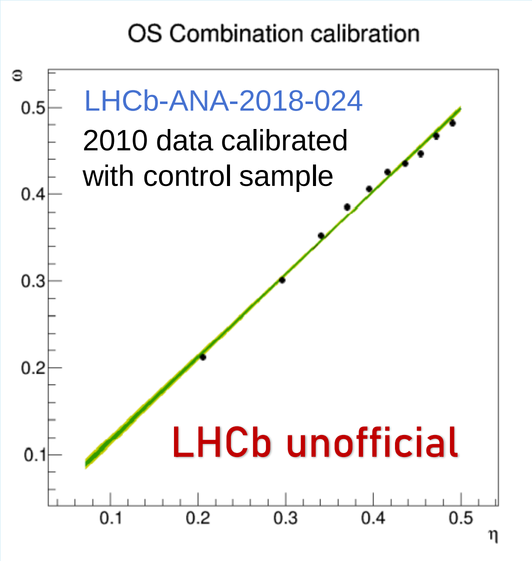
Calibration model

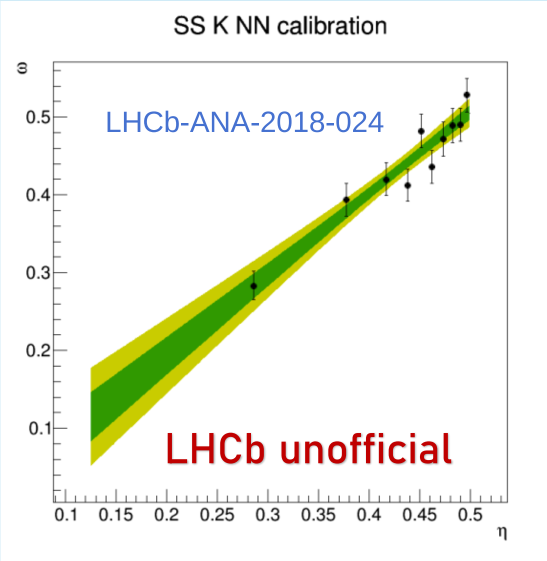
- $\omega(\eta) = p0 + p1(\eta - \langle\eta\rangle)$,
  $\omega(\eta)$ is the true mistag rate, η is the mistag rate predicted by tagging algorithm, p0 and p1 are the calibration parameters.
- Unbinned method:
  $\mathrm{PDF}(\mathrm{a}|\eta) = (1 - \mathrm{a})\omega(\eta) + \mathrm{a}[1 - \omega(\eta)]$, $\mathrm{a} = 0, 1$(wrong, right tagged)

FT Calibration

- Tagging performance of Run1 data
  - SS $\epsilon_{eff} = 2.26\%$
  - OS $\epsilon_{eff} = 2.84\%$
  - Combination $\epsilon_{eff} = 4.88\%$







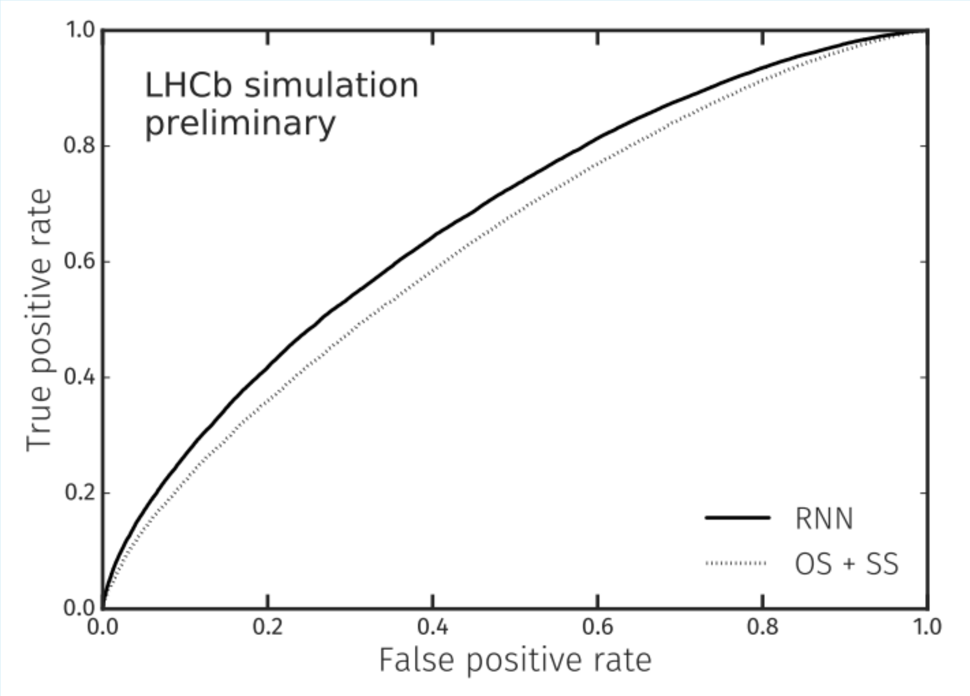
- ϵ_{eff} of Run2 is expected to be better
  - Optimized FT Alg
  - Better trained model

~20% ϵ_{eff} increase between J/ψϕ Run1 and 201516 analysis

[EPJC 79 (2019) 706] [PRL 114 (2015) 041801]

Inclusive Flavour Tagging (IFT)

- Combine info of all non-signal tracks into the tag decision
  - Tagging efficiency ~100%
  - Support one single framework rather than 8 separate taggers

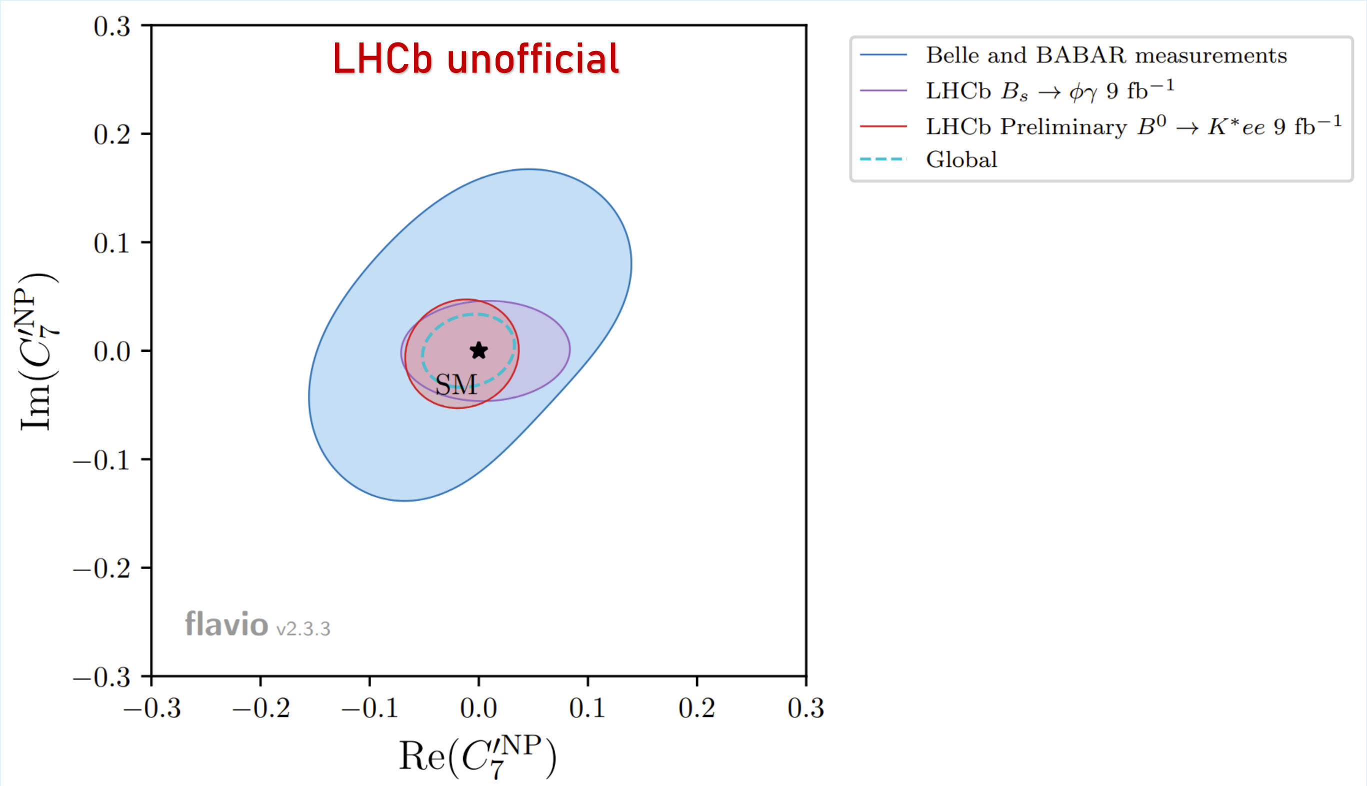


- IFT is now ready for test and check on Run2 data.
- Expected to increase B_s ϵ_{eff} by ~8%.

➢ Decrease the σ_{stat} by ~4%

pos.sissa.it/321/230/pdf

Expected Constraint on C7'



- Constraint on C7' with expected Run1 + Run2 $B_s \to \phi\gamma$ precision.
  - Improvement in selections and tagging power are included.
  - Assuming the systematics are at same level as Run1 analysis.
  - Assuming the mean value of S and A^{Δ} are same as SM predictions.
- Good constraint on C7', competitive with $B^0 \to K^*ee$.

Summary and outlook

- As one of the sensitive antennae to the NP, $B_s \to \phi\gamma$ is expected to provide better constraints on theory.
- The mixing-induced CPV observables $A^{\Delta}, \mathcal{C}, \mathcal{S}$ are expected to have significant improved precision
  - Whole Run1 and Run2 data
  - Optimized selections, time description, FT performance
  - Analysis note is under preparation[stay tuned…]

- Other possibilities with $b \to s\gamma$
  - CPV when having more resonances, inclusive $B_s \to hh\gamma$ (need amplitude/angular parameters)
  - Virtual γ process, like $B_s \to \phi ee$ (angular observables + time-dependent CP observables)[arXiv:2210.11995]
- Promising Run3
  - High luminosity, software/detector upgrade (better performance…)


THANKS FOR LISTENING
ANY QUESTIONS?
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