LHCPhysics

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INFN

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on behalf of the CMS Collaboration

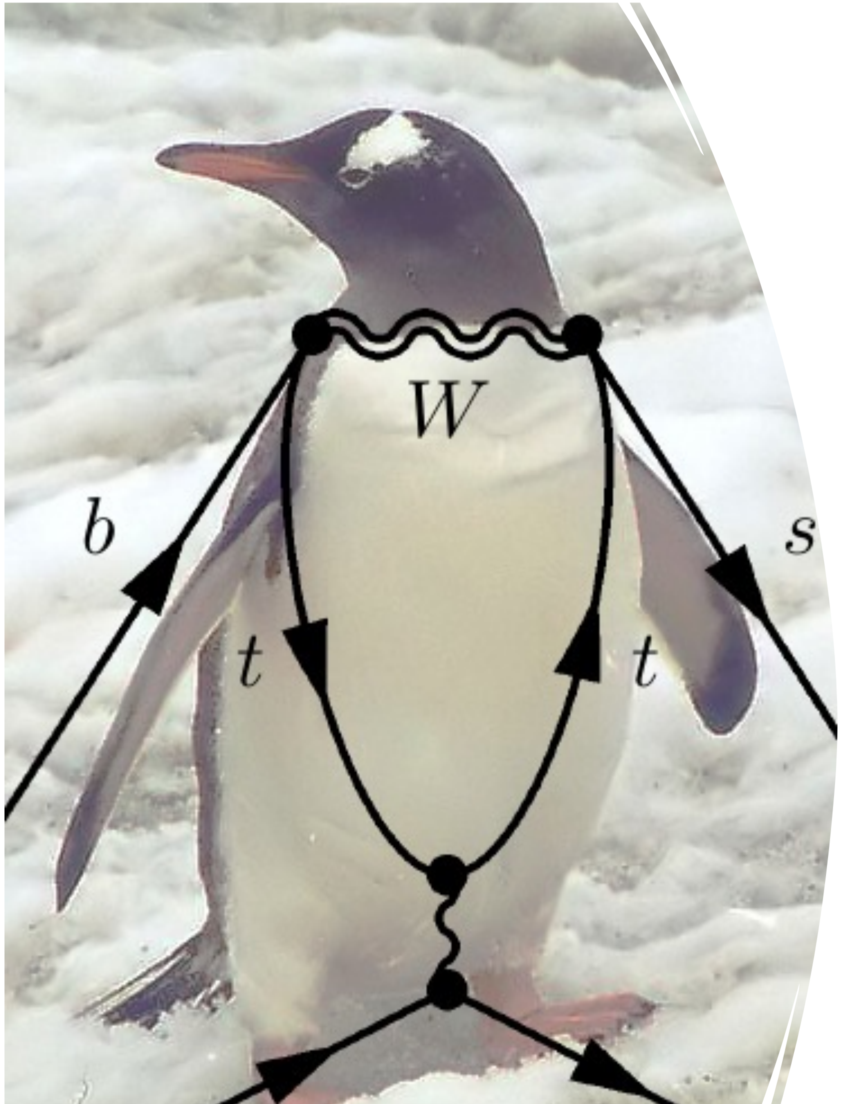
Results on CP violation and lifetimes from CMS

CMS

Compact Muon Solenoid

Introduction and outline

- The LHC allows to test SM predictions and look for new physics in many ways
  - Direct evidence of new particles and signatures
  - Indirect evidence from SM deviations in rare decays and precision measurements –> two such results by CMS are reported in this talk
- Branching fraction and lifetime for **B_s -> $\mu^+\mu^-$**
  - BPH-21-006, accepted by PLB
  - 140 fb^{-1} at 13 TeV
- Search for CP violation in **B_s -> J/ψ Φ** decays
  - PLB 816 (2021) 136188
  - 96.4 fb^{-1} at 13 TeV -> 48500 fully reconstructed B_s decays
- More b-physics results can be found here https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/



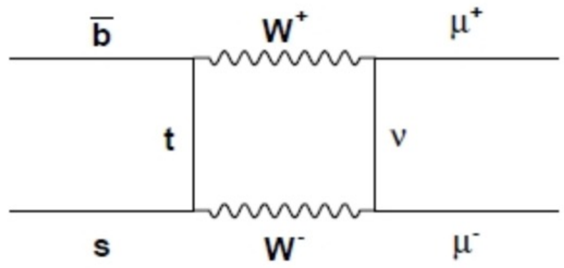
https://upload.wikimedia.org/wikipedia/commons/c/c5/Penguin_diagram.JPG

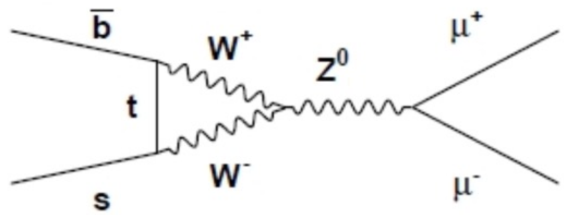
Branching fraction and lifetime for $B_s \to \mu^+\mu^-$

- $B_s \to \mu^+\mu^-$ is highly suppressed in the SM and is theoretically very clean and easy to calculate. In addition it has a very clean experimental signature
  - An ideal place to look for potential BSM contributions!
- Some hints of deviations from SM have been observed in b-> s l l processes
  - the global fits of rare b hadron decay data show a strong preference for a BSM physics scenario over the SM (*)

(*) W. Altmannshofer and P. Stangl, *Eur. Phys. J. C* **81** (2021) 952

Analysis strategy





B production fraction ratio (external)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}} \frac{f_u}{f_s},$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to J/\psi\phi(1020)) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B_s^0 \to J/\psi\phi(1020)}} \frac{\varepsilon_{B_s^0 \to J/\psi\phi(1020)}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0 \to \mu^+\mu^-}} \frac{f_u}{f_d},$$

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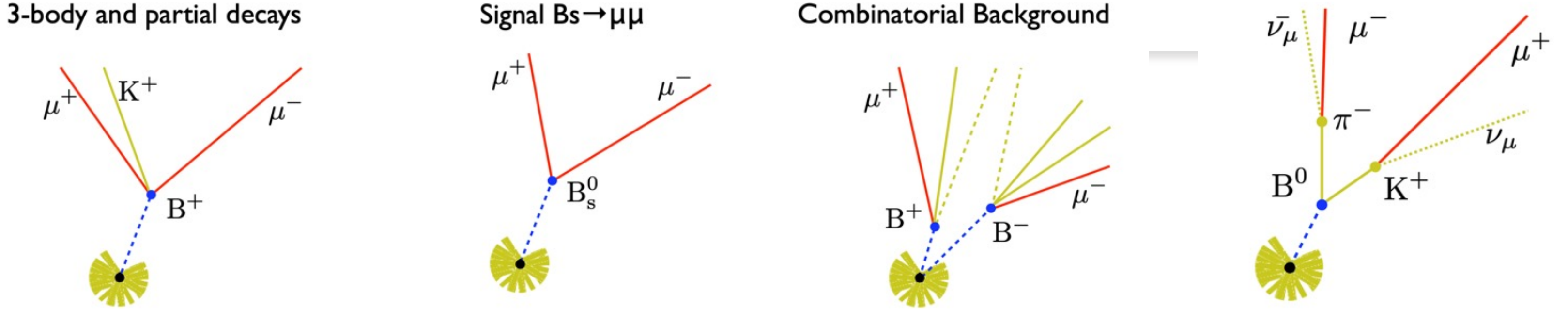
- Normalization to well known decay channels
  - Many systematics cancel out
  - No need to input the (poorly known) $b\bar{b}$ cross section

- Blind analysis. Simultaneous unbinned ML fits in multiple categories.
- Multi-variate analysis (intentionally loose selection in order to give more inputs to MVA)

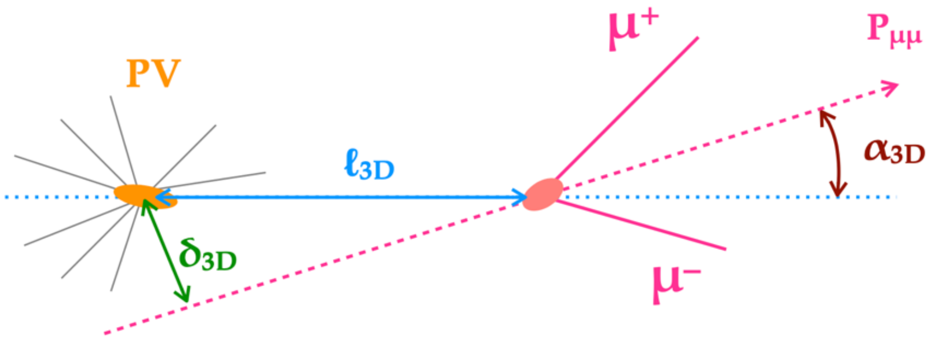
Signal and backgrounds

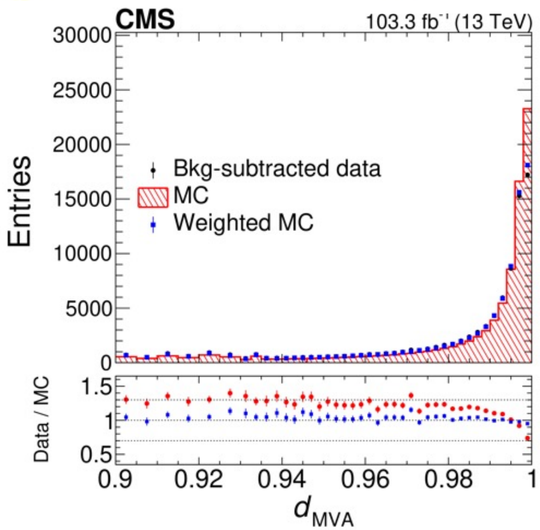
- Combinatorial and peaking backgrounds from muons originating from the same B meson decay, or different B mesons, and fake muons

3-body and partial decays | Signal Bs→μμ | Combinatorial Background



Thanks to Dmytro Kovalskyi for the drawings





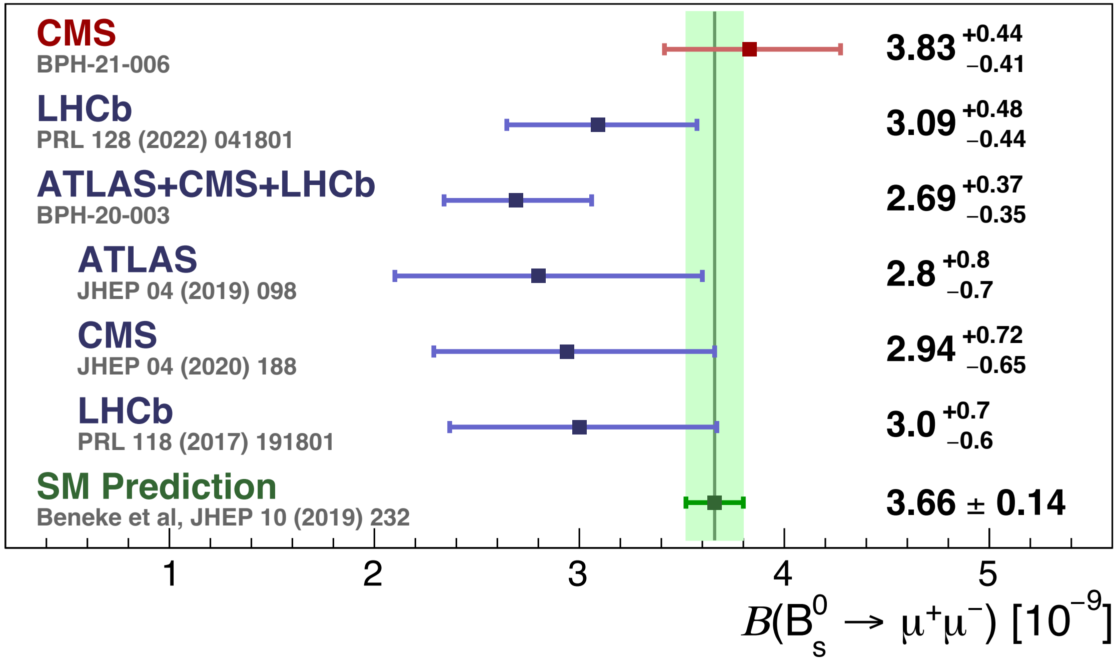
Multivariate analysis used to suppress the dominant backgrounds.

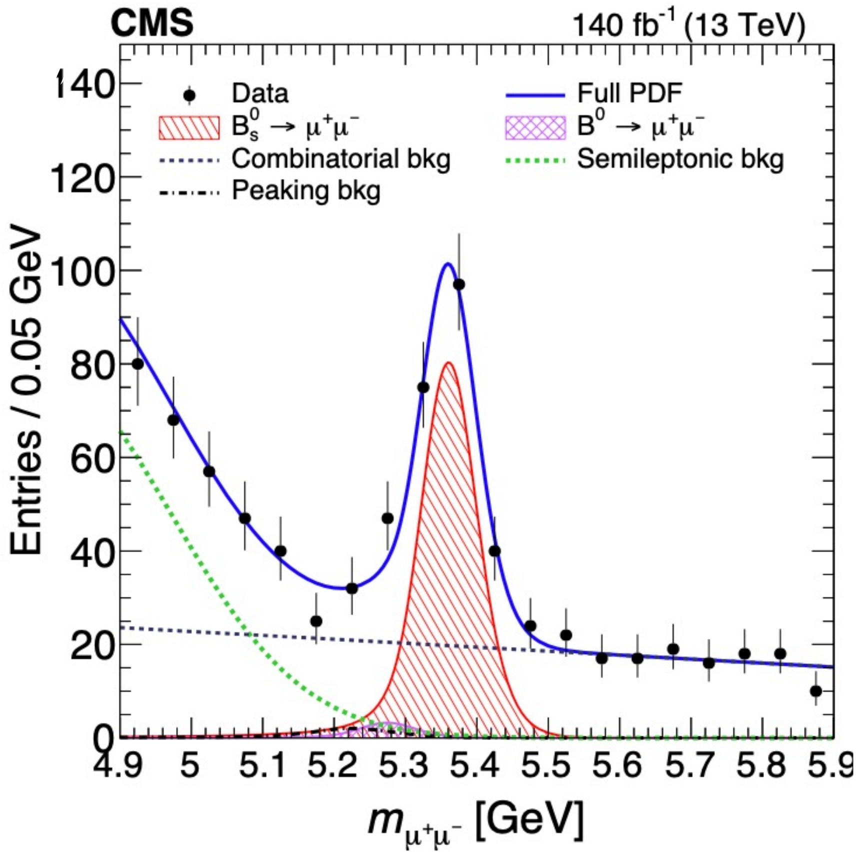
Trained with signal MC and mass sideband data with the XGBoost package

Use B→J/ψK events to model B→μμ decays in Data and MC

Branching fractions

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\mathrm{stat})\ ^{+0.19}_{-0.16}\,(\mathrm{syst})\ ^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9}$$





No evidence for $\mathrm{B^0} \to \mu^+\mu^-$

$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\%\ \mathrm{CL},$$

Lifetime

- In absence of CP violation, only the heavier mass eigenstate (CP odd) can decay to $\mu^+\mu^-$ (CP odd too).
- Any significant deviation of the measuremer from the expected value for the heavier eigenstate $\tau_{\mathrm{H}} = 1.624 \pm 0.009\,\mathrm{ps}$ would indicate a BSM physics contribution !

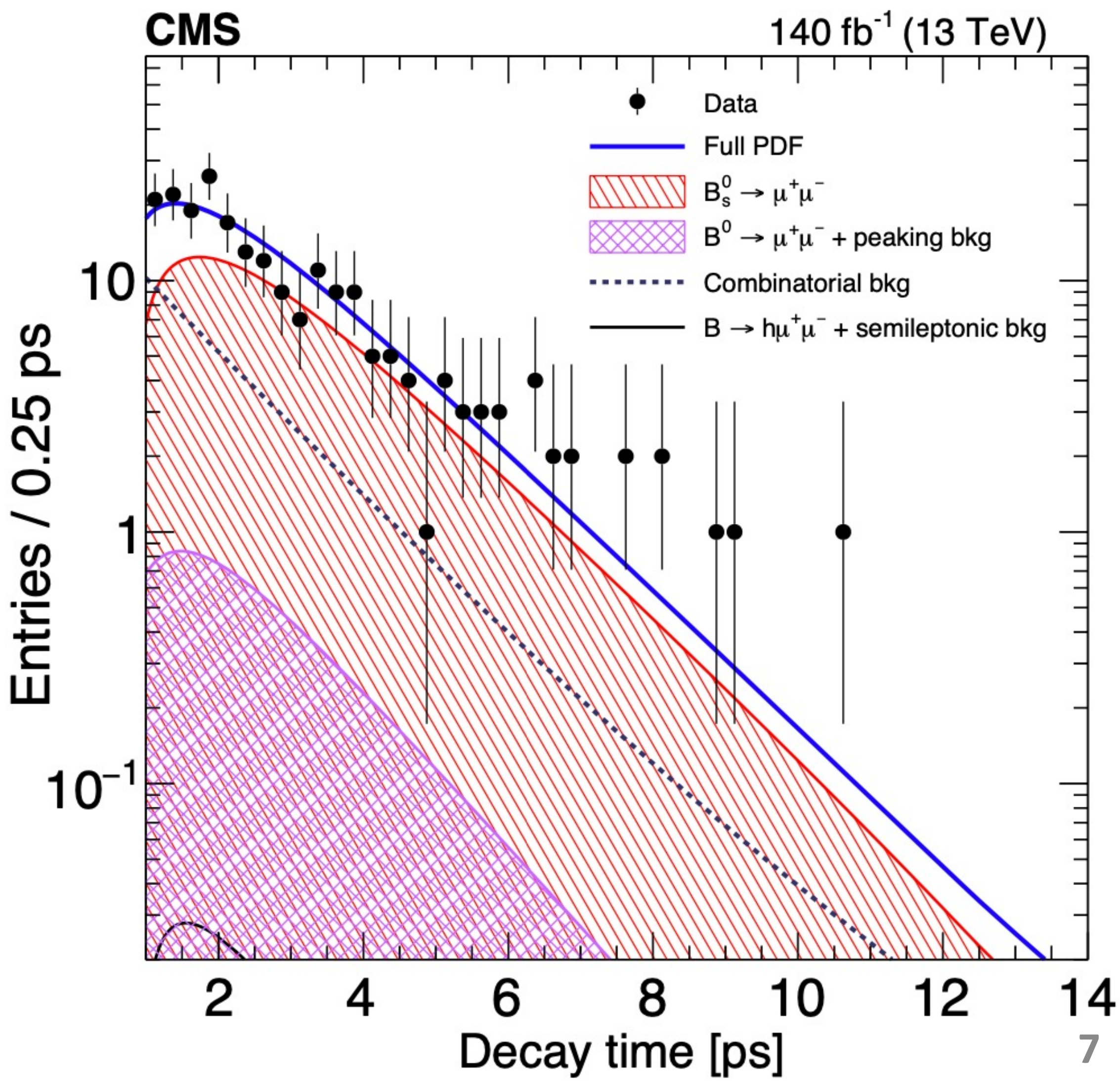
$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\mathrm{stat})\,^{+0.04}_{-0.04}\,(\mathrm{syst})\,\mathrm{ps}.$$

Most precise value to date!

World average: (1.624 ± 0.009) ps (*)
SM prediction: (1.616 ± 0.010) ps

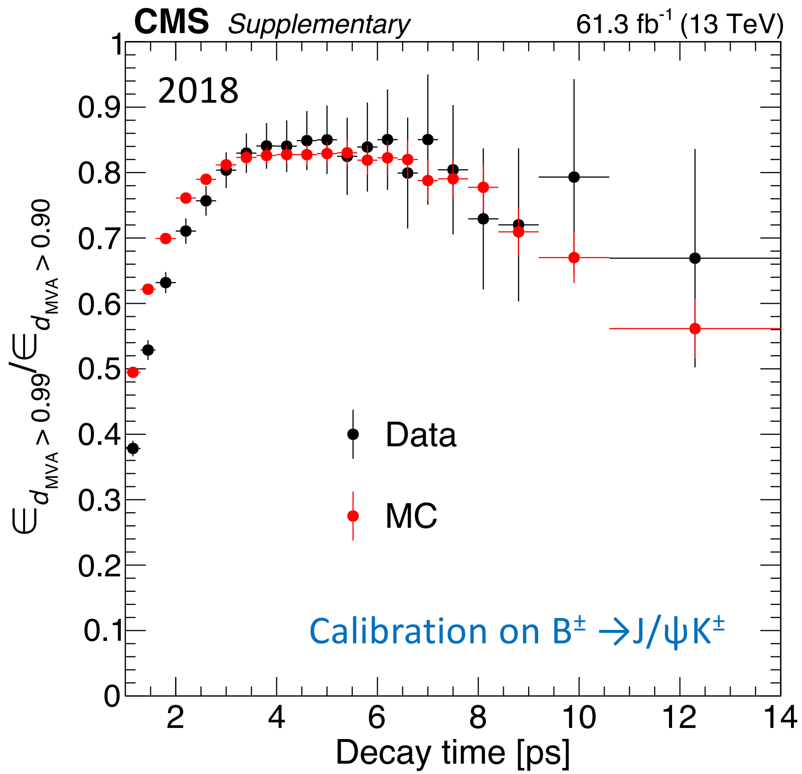
(*) PDG 2022, R.L. Workman et al.

UML fit projection on the decay time axis for the signal region 5.28 < $m_{\mu+\mu-}$ < 5.48 GeV.



Systematics on the lifetime

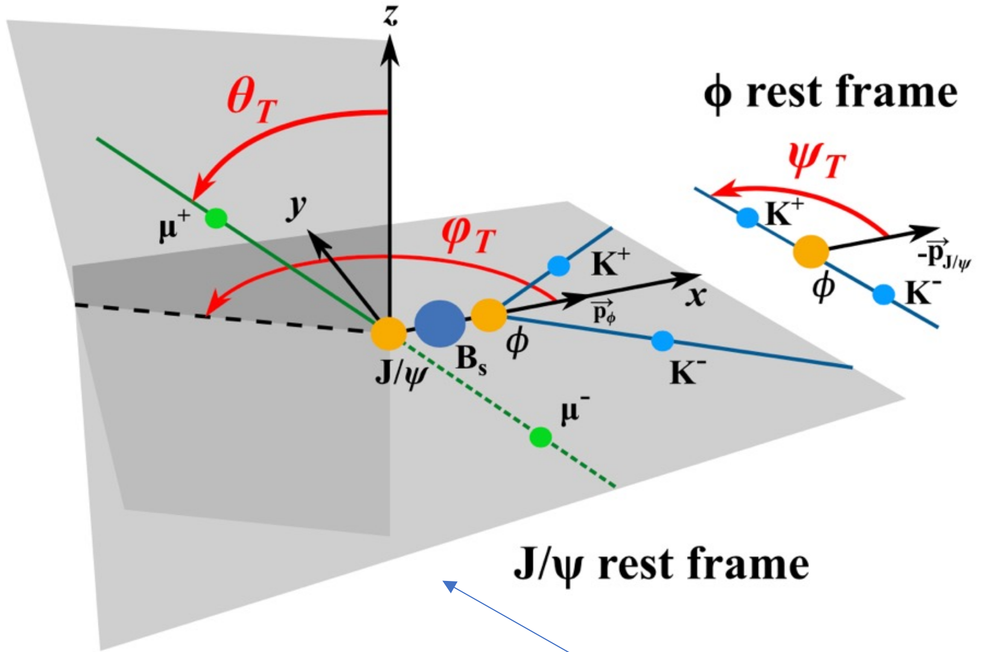
- Dominant systematics come from a strong correlation between MVA (mainly the pointing angle and its uncertainty) and the decay time (hard to model well)



Effect	2016a	2016b	2017	2018
Lifetime fit bias	0.04	0.04	0.05	0.04
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Efficiency modeling		0.01		
Lifetime dependence		0.01		
Total	0.11	0.07	0.05	0.04

The effective B_s lifetime measurement in $B_s \rightarrow \mu^+\mu^-$ has now achieved a precision comparable with the lifetime difference between the heavy and light B_s mass eigenstates -> sensitivity to potential BSM physics effects in the effective lifetime!

CP violation in $B_s \to J/\psi\ \Phi$



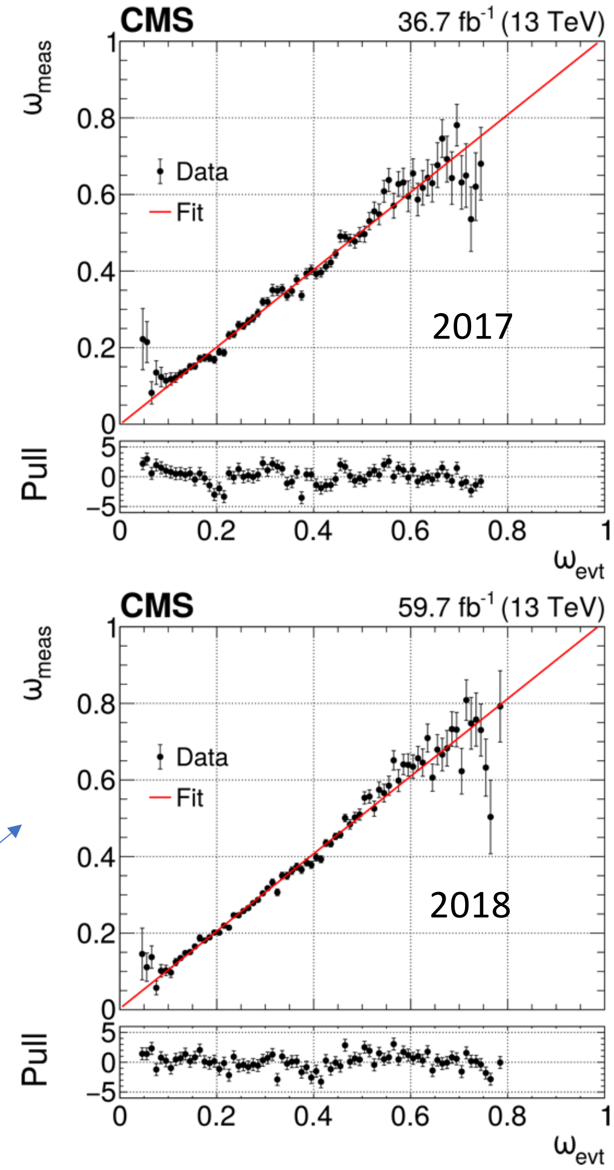
Improved measurement of ϕ_s and $\Delta\Gamma_s$!

Vector-vector final state: angular analysis needed to separate CP-even and CP-odd contributions

- $B_s \to J/\psi\ \Phi$: a golden channel to measure φ_s and $\Delta\Gamma_s$
- $\varphi_s = -2\beta_s = -2\ arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
- SM prediction known to a great precision:
  - $\varphi_s = -36.82\ ^{+0.60}_{-0.86}$ mrad (CKMFitter); $\varphi_s = -37.0 \pm 1.0$ mrad (UTFit)
- BSM particles can modify the phase
- $\Delta\Gamma_s$ is less well known in the SM: (0.091 ± 0.013) ps^{-1}

Analysis strategy

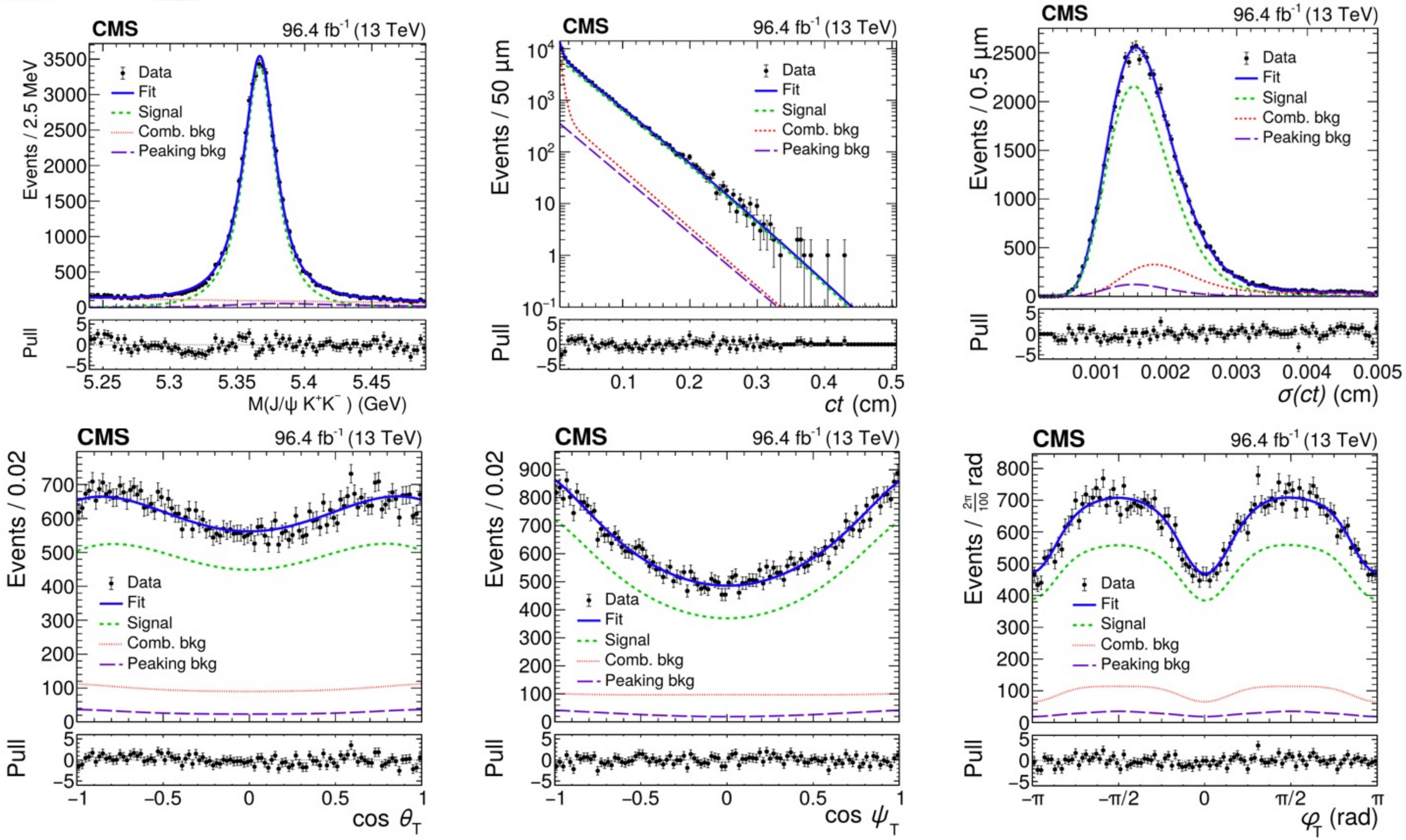
- Novel opposite-side μ tagger and trigger to select data
- Exploitation of semileptonic b->μX decays to tag the flavour
- Deep Neural Network to reduce the mistag fraction.
- Training on simulation; calibration on self-tagged $B^{\pm}$ -> $J/\psi\ K^{\pm}$ data.
- Tagging efficiency ≈50% both in 2017 and 2018 data



Per-event mistag probability ω_{evt} based on $B^{\pm} \to J/\psi K^{\pm} \to \mu^{+}\mu^{-}K^{\pm}$ decays

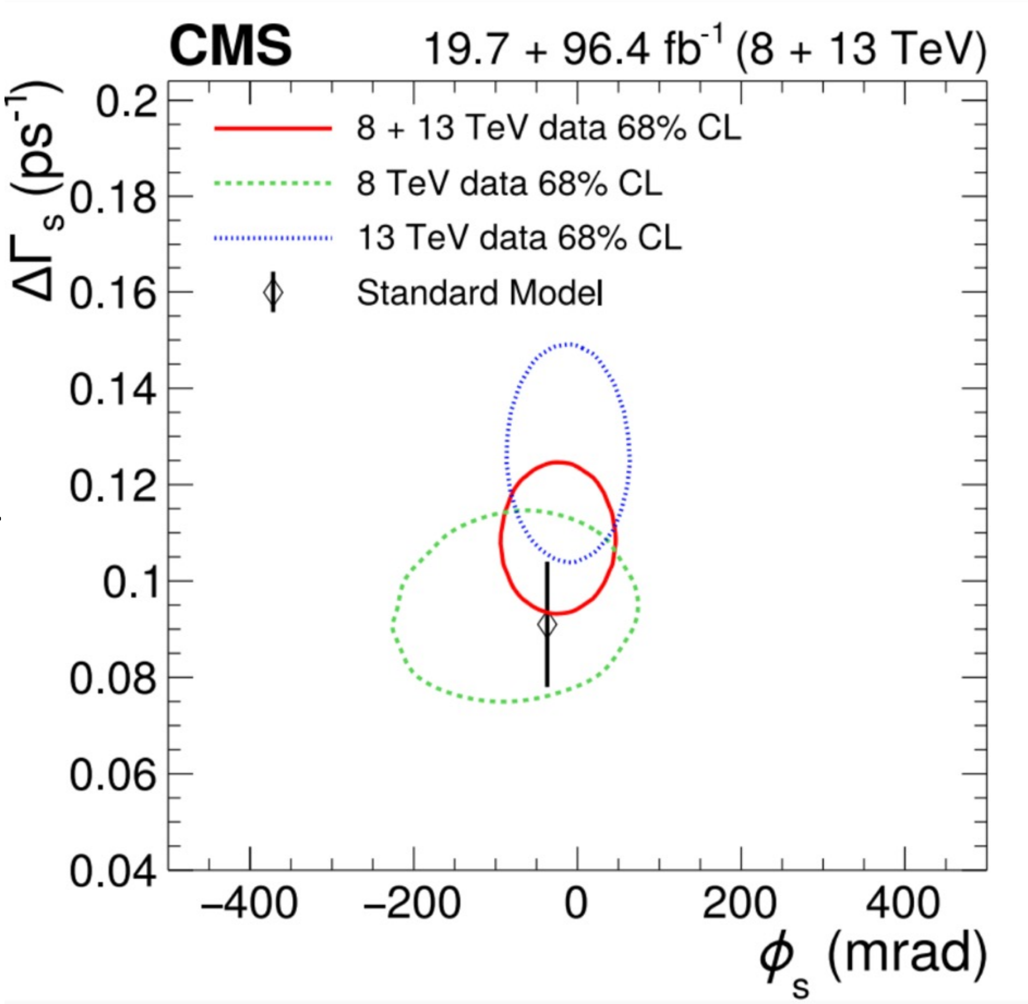
Fit results

Many observables measured simultaneously



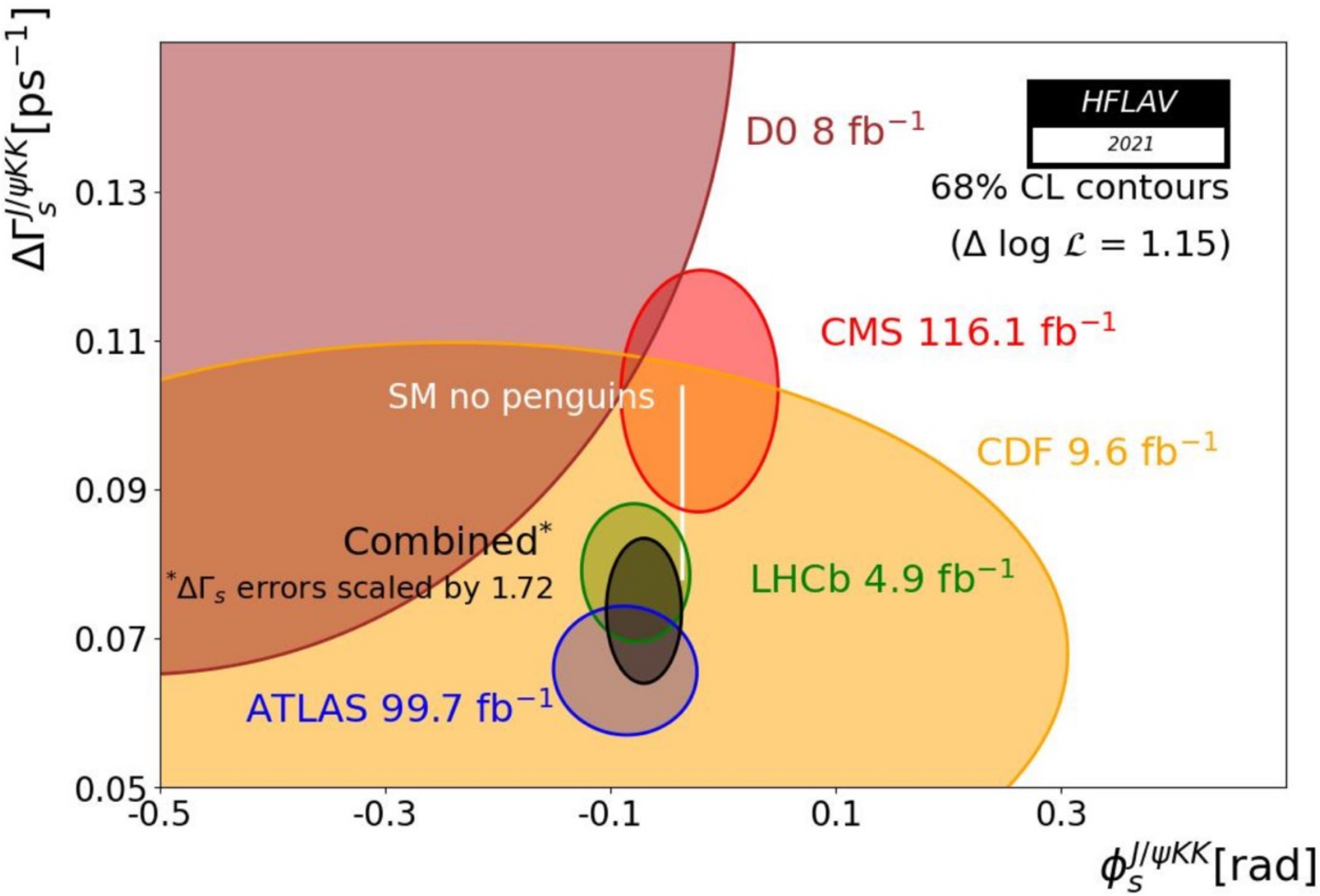
8 TeV + 13 TeV combination

- Run 1 + partial Run 2 (116.1 fb^{-1})
- **φ_s = −21 ± 44 (stat) ± 10 (syst) mrad**
  $\Delta\Gamma_s$= 0.1032 ± 0.0095 (stat) ± 0.0048 (syst) ps^{-1}
- Greatly improved φ_s over the 8 TeV measurement because of statistics and the new tagging strategy in the Run 2 data analysed.



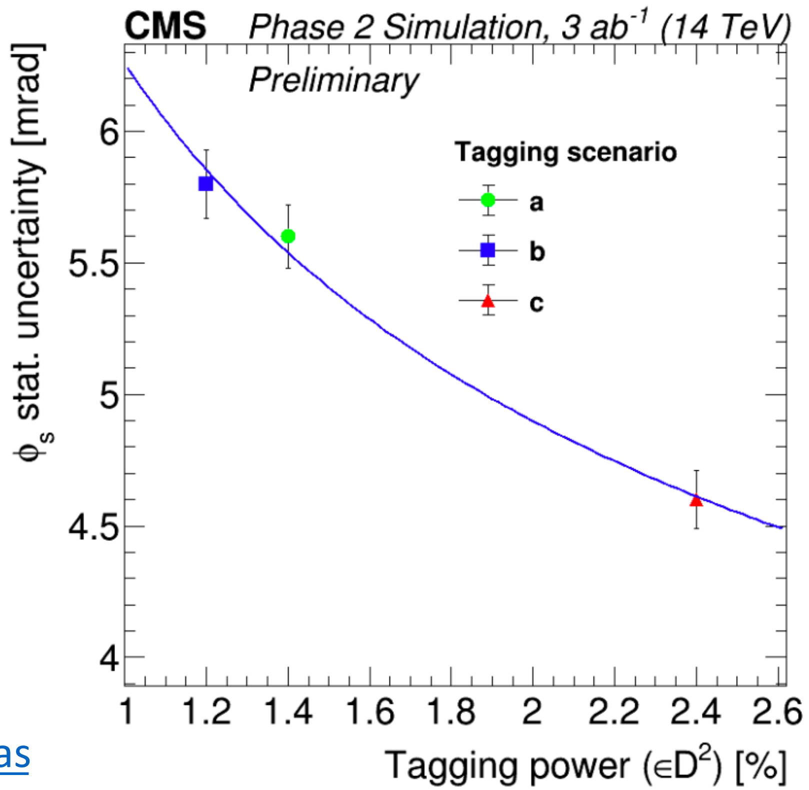
Overview

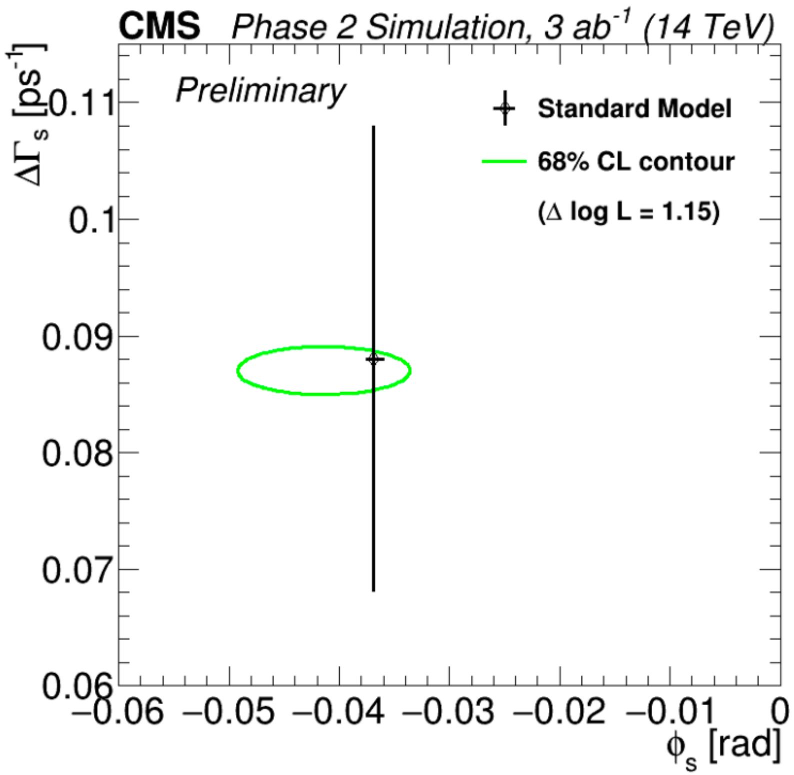
- Results are consistent with SM predictions and no CPV in the interference between mixing and decay.
- Also, the first measurement by CMS of Δm_s and $|\lambda|$



Projections for HL-LHC

- How will CMS improve on Φ_s with more data?
- With 3 ab^{-1} of data, the statistical uncertainty on Φ_s will be 5-6 mrad.
- This means the current world-average uncertainty will be reduced by a factor 5!





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Conclusions

- Precision tests and search for SM deviations in rare decays are a powerful tool to search for New Physics at the LHC!
  - They allow to probe energy scales not directly accessible yet
- B_s decays to $\mu^+\mu^-$ and $J/\psi\ \Phi$ provide a clean environment to look for deviations from the SM predictions
  - CMS reported updated improved measurements that are consistent with SM expectations
- More statistics is being collected at a new unprecedented center-of-mass energy
- CMS is ready to provide new interesting measurements!