PRECISION MEASUREMENT OF THE CP-VIOLATING PHASE φ_s AT LHCb

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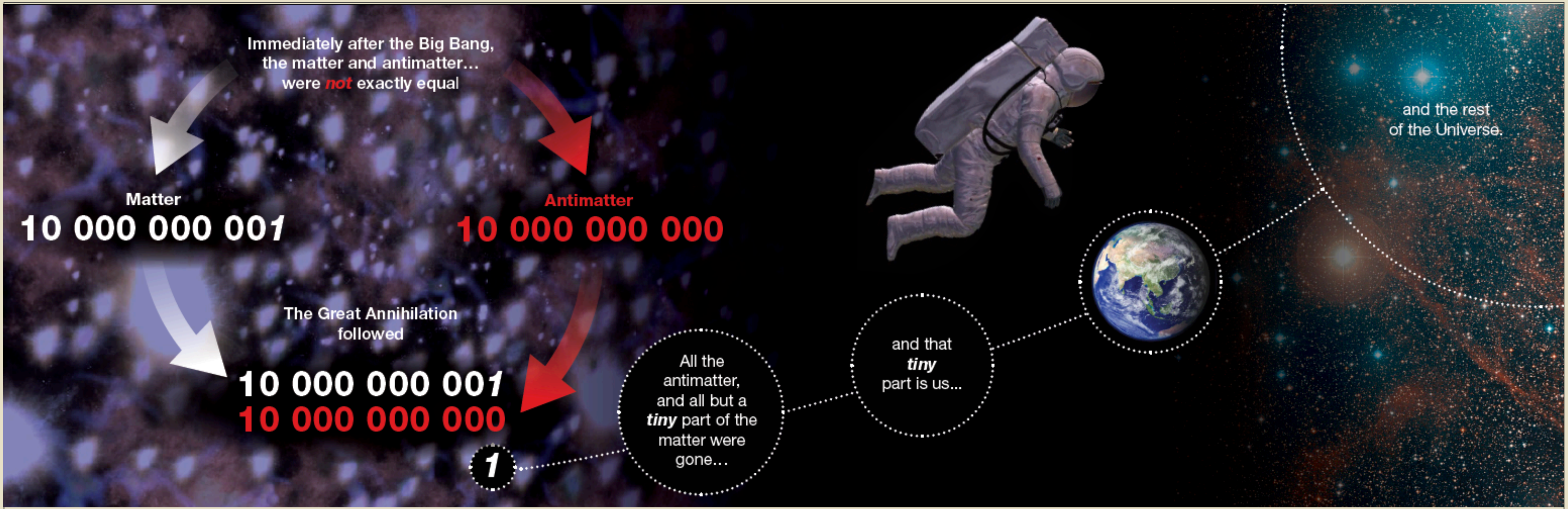
On behalf of the LHCb Collaboration

CERN SEMINAR

CERN, 7th May 2019



Sakharov Conditions

[A. D. Sakharov, JETP Lett.5, 24 (1967)]

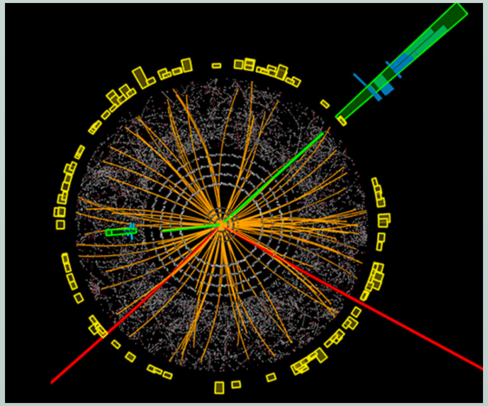
1. Baryon Number Violation
2. **C and CP violation**
3. Interactions out of thermal equilibrium

[Rev. Mod. Phys. 88, 015004 (2016)]

- Baryon asymmetry of the Universe: $n_b/n_\gamma \sim 10^{-10}$
- CP violation in the SM does not account for it
- There must be **New Physics** and **new sources of CP violation**

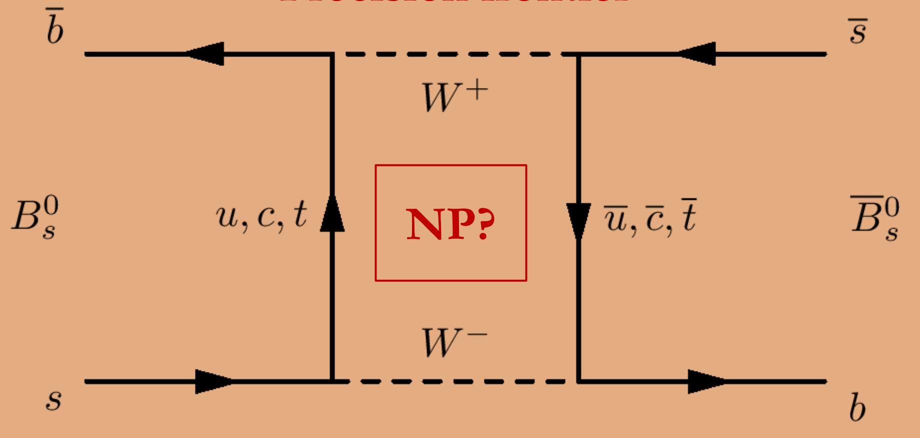
How to find New Physics at the LHC

High energy frontier



Direct observation: require E>mc^2 for direct production → few TeV

Precision frontier



Indirect effects: new particle effect loop processes → up to O(100 TeV)

See e.g. [L. Silvestrini: arXiv.1905.00798]

- Most HEP direct discoveries have been preceeded by indirect evidence first!
- If we don't see New Physics directly at the LHC can indirect evidence guide us where to look (or what to build) next?

Flavour physics: a history of success

1956 — **Parity violation**
T. D. Lee
C. N. Yang and
C. S. Wu et al.

1963 — **Cabibbo mixing**
N. Cabibbo

1964 — **Strange particles: CP violation in K meson decays**
J. W. Cronin,
V. L. Fitch et al.

1970 — **Branching ratio of $K^0 \to \mu\mu$ and prediction of the charm quark**
Glashow et al.

1973 — **The CKM matrix**
M. Kobayashi and
T. Maskawa

1987 — **Observation of the $B^0 - \overline{B}^0$ oscillations and extrapolation of the top mass**
Argus collaboration

1999 — **First observation of direct CP violation**
NA48 and KTeV collaborations

2001 — **Observation of CP violation in the B^0 system**
Babar and Belle collaborations

2006 — **Observation of the $B_s^0 - \overline{B}_s^0$ oscillations**
CDF collaboration

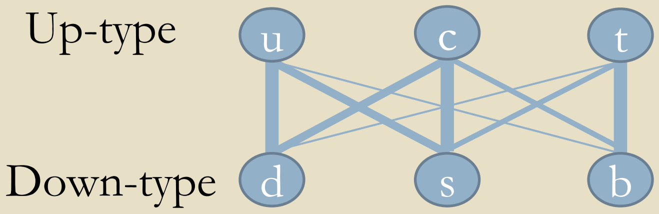
2019 — **Observation of CP violation in D^0 meson decays**
LHCb collaboration

?

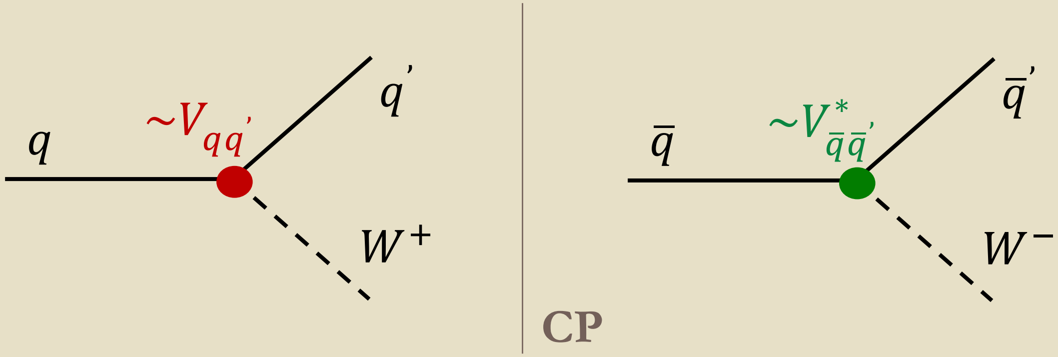
Quark transitions

In the SM quarks can change flavour by emission of a $W^{\pm}$ boson
- So must also change charge

(i.e. from up-type to down-type or vice-versa)



- The probability for such a transition is governed by the elements of the 3×3 unitary **CKM matrix**



Mass eigenstates

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{} \cdot \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

Flavour eigenstates

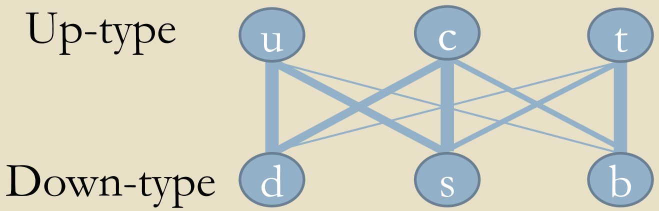
Cabibbo-Kobayashi-Maskawa Matrix (V_{CKM})
3x3 unitary complex matrix

Quark transitions II

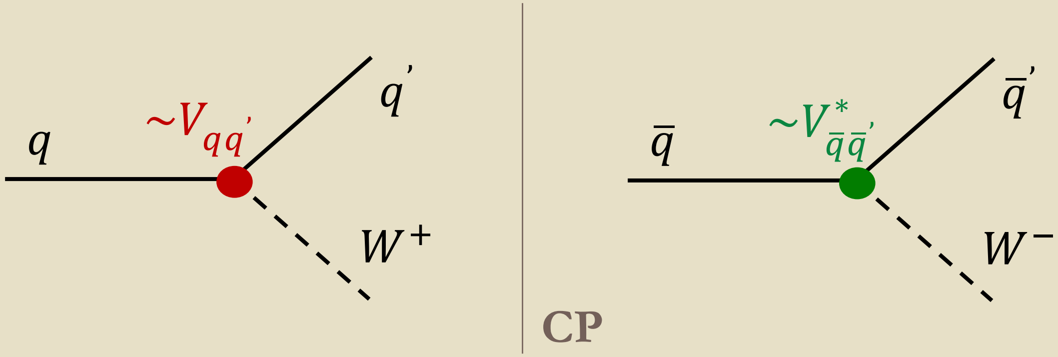
In the SM quarks can change flavour by emission of a $W^{\pm}$ boson

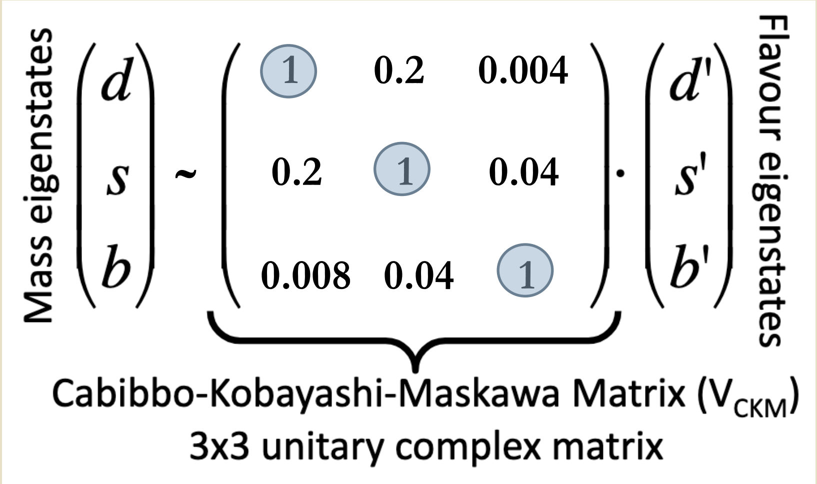
- So must also change charge

(i.e. from up-type to down-type or vice-versa)



- The probability for such a transition is governed by the elements of the 3×3 unitary **CKM matrix**
- It exhibits a clear hierarchy





CP violation in the Standard Model

- **Wolfenstein parameterisation**: CKM matrix described by 4 parameters λ, A, ρ, η

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5\left[1-2(\rho+i\eta)\right]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)(1-\lambda^2/2)\right] & -A\lambda^2+A\lambda^4\left[1-2(\rho+i\eta)\right]/2 & 1-A^2\lambda^4/2 \end{pmatrix}}_{\text{Wolfenstein parametrisation}} + \mathcal{O}(\lambda^6)$$

$$\lambda = \sin(\theta_c) \approx 0.22, \quad \eta \approx 0.3$$

- 3 quark generations allow for a CP violating phase: η is the **only CPV source in the SM**
- But η is small → where did the anti-matter go?
- Test the consistency of CKM picture within SM experimentally

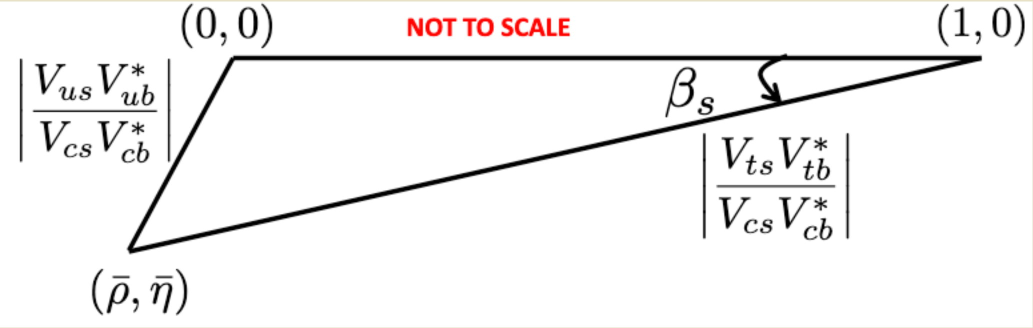
Unitarity triangle

Unitarity $V_{\text{CKM}} \cdot V_{\text{CKM}}^{\dagger} = I$ imposes several conditions which give rise to “unitarity” triangles

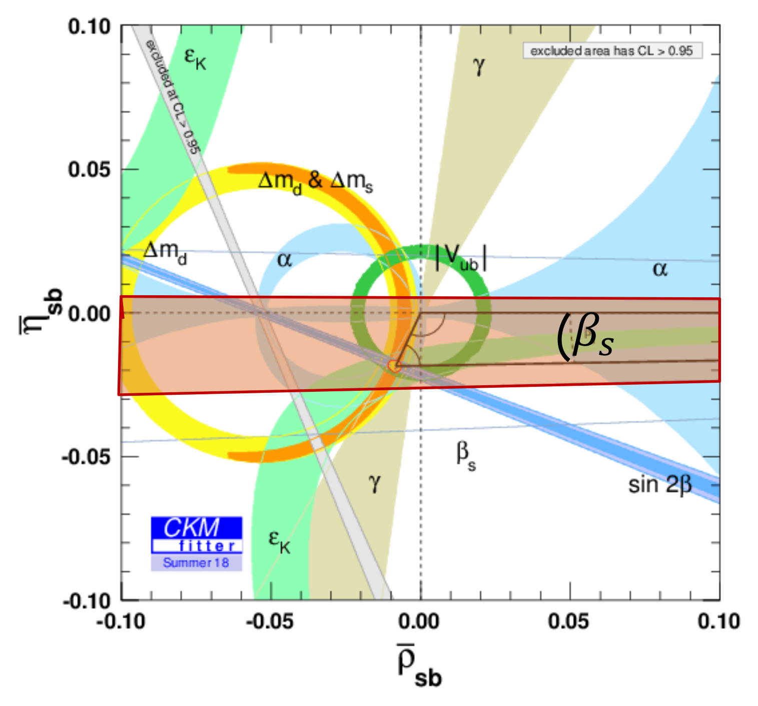
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity condition from 2nd and 3rd columns:

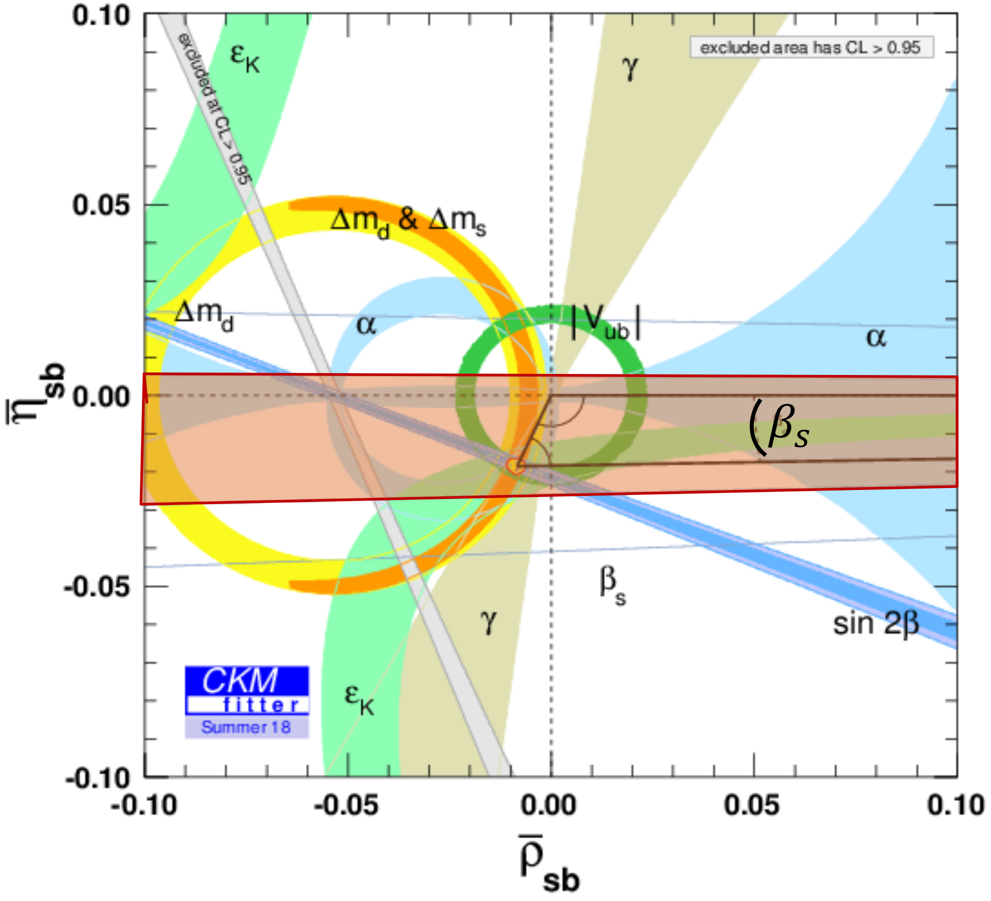
$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$



[CKM Fitter]



[CKM Fitter]

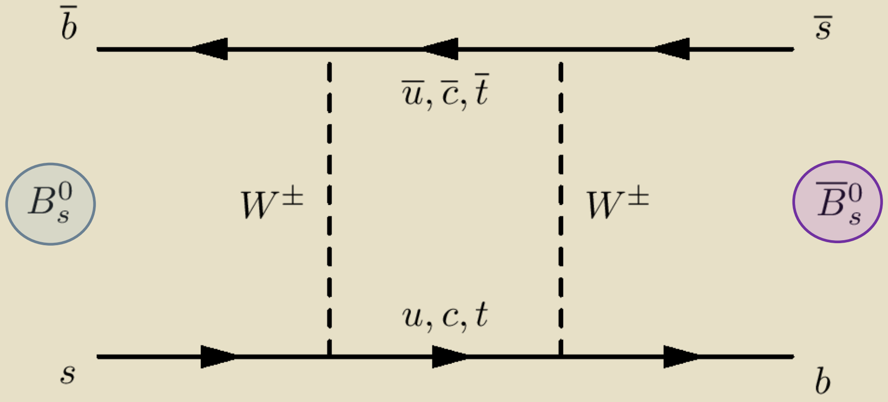


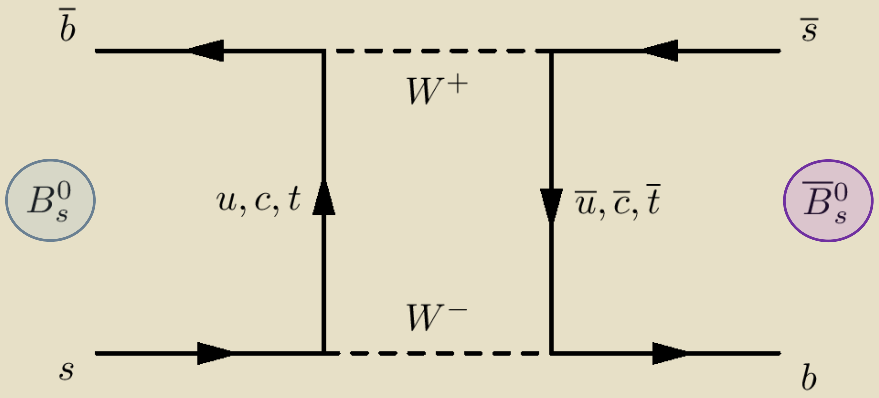
The CKM fit: a lot of room for NP

- The SM works so remarkably well that we have to make **more and more precise measurements**
- **O(20%) NP contributions to most loop-level processes (FCNC) are still allowed**
  - See e.g. J. Charles at al arXiv:1309.2293 [hep-ph]
- Interesting comparison of tree-level vs higher-order observables. In the latter, unknown particles could contribute.

B flavour mixing

- Neutral B_s^0 mesons can **oscillate** between their particle and anti-particle states





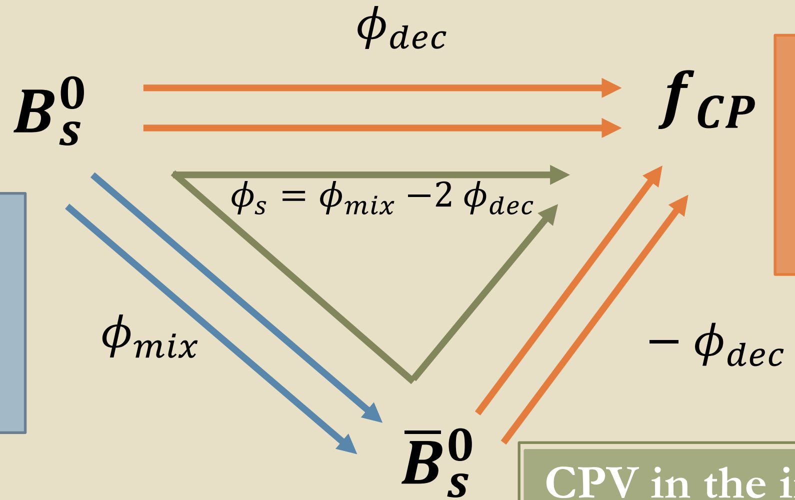
The physical mass eigenstates (L,H) are admixtures of the weak eigenstates:

$$|B_L> = p\,|B_s^0> \; + q\,|\bar{B}_s^0>$$
$$|B_H> = p\,|B_s^0> - q\,|\bar{B}_s^0>$$

- with **mass difference** $\Delta m = m_H - m_L$ and **decay-width difference** $\Delta\Gamma = \Gamma_L - \Gamma_H$
- flavor at production (t=0) could be different from flavour at decay time t

CP violation

- Must have **two interfering amplitudes** with different strong (δ) and weak (φ) phases
- For a B_s^0 decay to a **CP eigenstate *f***, CP-violating effects depend on $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$



CPV in mixing

- $P(B_s^0 \to \bar{B}_s^0) \neq P(\bar{B}_s^0 \to B_s^0)$
- $|q/p| \neq 1$

CPV in decay

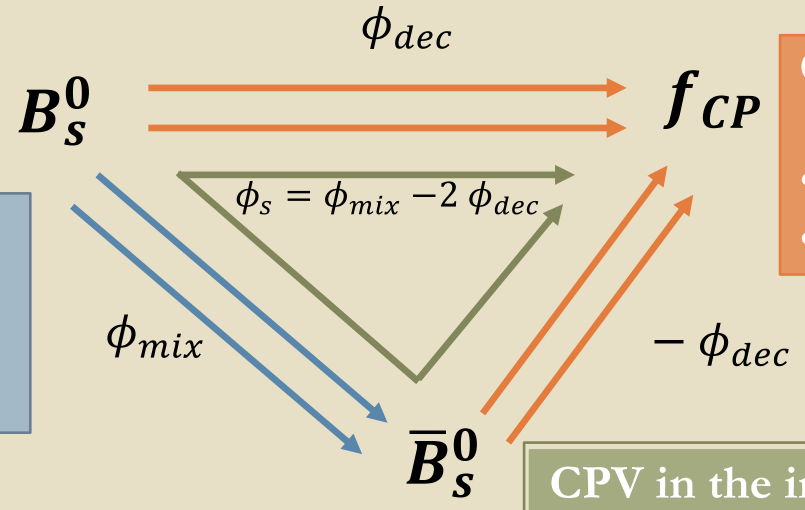
- $P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$
- $|\bar{A}_f/A_f| \neq 1$

CPV in the interference between decay and mixing

- $P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$
- $\arg(\lambda_f) \neq 0$

CP violation

- Must have **two interfering amplitudes** with different strong (δ) and weak (φ) phases
- For a B_s^0 decay to a **CP eigenstate *f***, CP-violating effects depend on $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$



CPV in mixing

- $P(B_s^0 \to \bar{B}_s^0) \neq P(\bar{B}_s^0 \to B_s^0)$
- $|q/p| \neq 1$

CPV in decay

- $P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$
- $|\bar{A}_f/A_f| \neq 1$

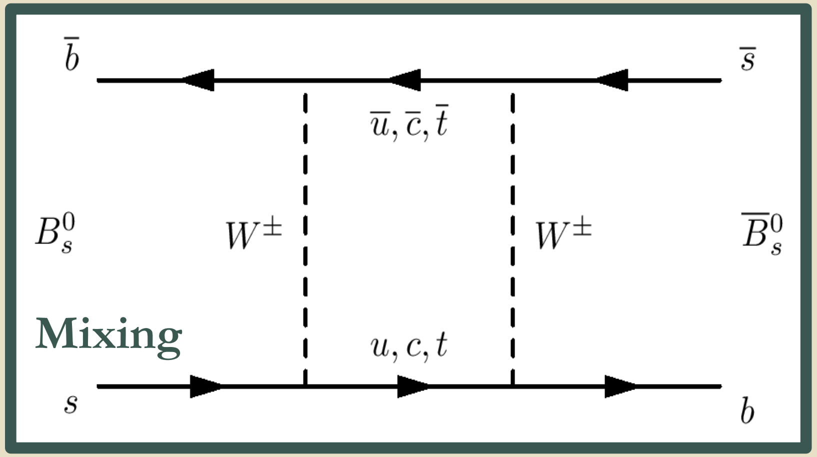
CPV in the interference between … **mixing**

- $P(B_s^0 \to f)$ … $f)$
- $\arg(\lambda_f)$ …

Today new results on this CPV

CPV in B_s^0 mixing and decays

[Fleischer, PRD 60 (1999) 073008]
[Ciuchini et al., PRL 95 (2005) 221804]
[Faller et al., PRD 79 (2009) 014005, 014030]
[Jung, PRD 86 (2012) 053008]
[Jung, Schacht, PRD 91 (2015) 034027]
[De Bruyn, Fleischer, JHEP 03 (2015) 145]



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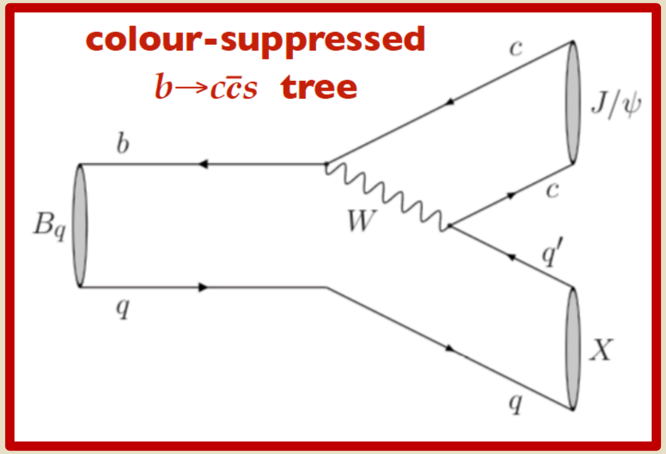

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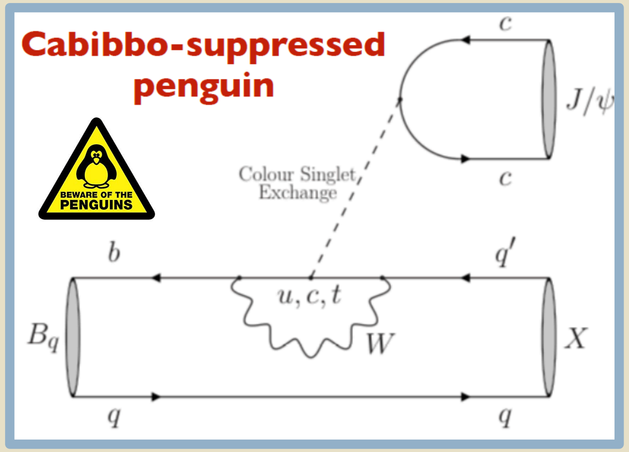
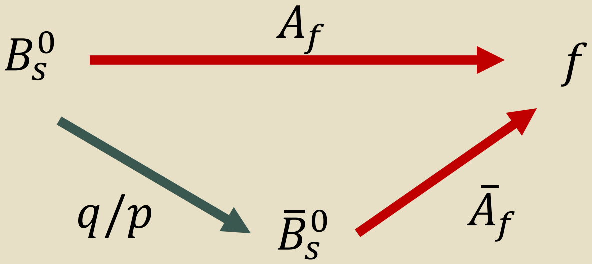


$$B_{H,L} = pB_s^0 \pm q\bar{B}_s^0$$

Golden mode: $B_s^0 \to J/\psi(\to \mu\mu)\phi(\to KK)$

+ smaller weak exchange (E) and penguin annihilation (PA) diagrams



MEASURABLE PHASE

CPV due to mixing-decay interference

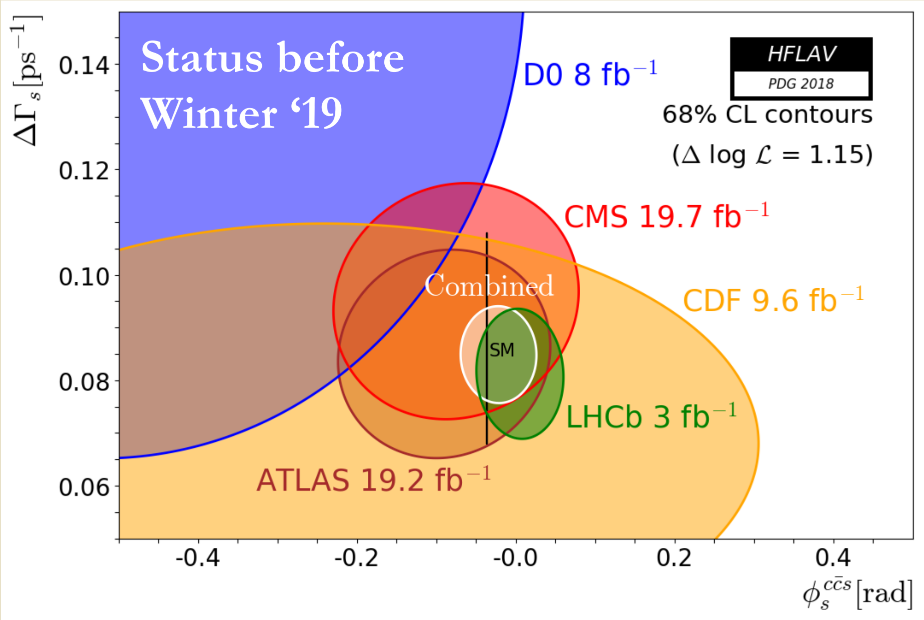
$$\varphi_s = \arg\left(\lambda_{f(c\bar{c}s)}\right) = \underbrace{\varphi_s^{SM}}_{-2\beta_s} + \Delta\varphi_s^{peng} + \Delta\varphi_s^{NP}$$

GLOBAL FIT PREDICTION

$$\varphi_s^{SM} = -0.03686^{+0.00096}_{-0.00068}\ \text{rad}$$

[CKMFitter]

φ_s before Winter 2019



GLOBAL FIT PREDICTION

$$\varphi_s^{SM} = -0.03686^{+0.00096}_{-0.00068} \text{ rad}$$

[CKMFitter]

- **Golden channel exploited by LHCb, ATLAS, CMS**: $B_s^0 \to J/\psi\phi$
- LHCb also measured many other channels

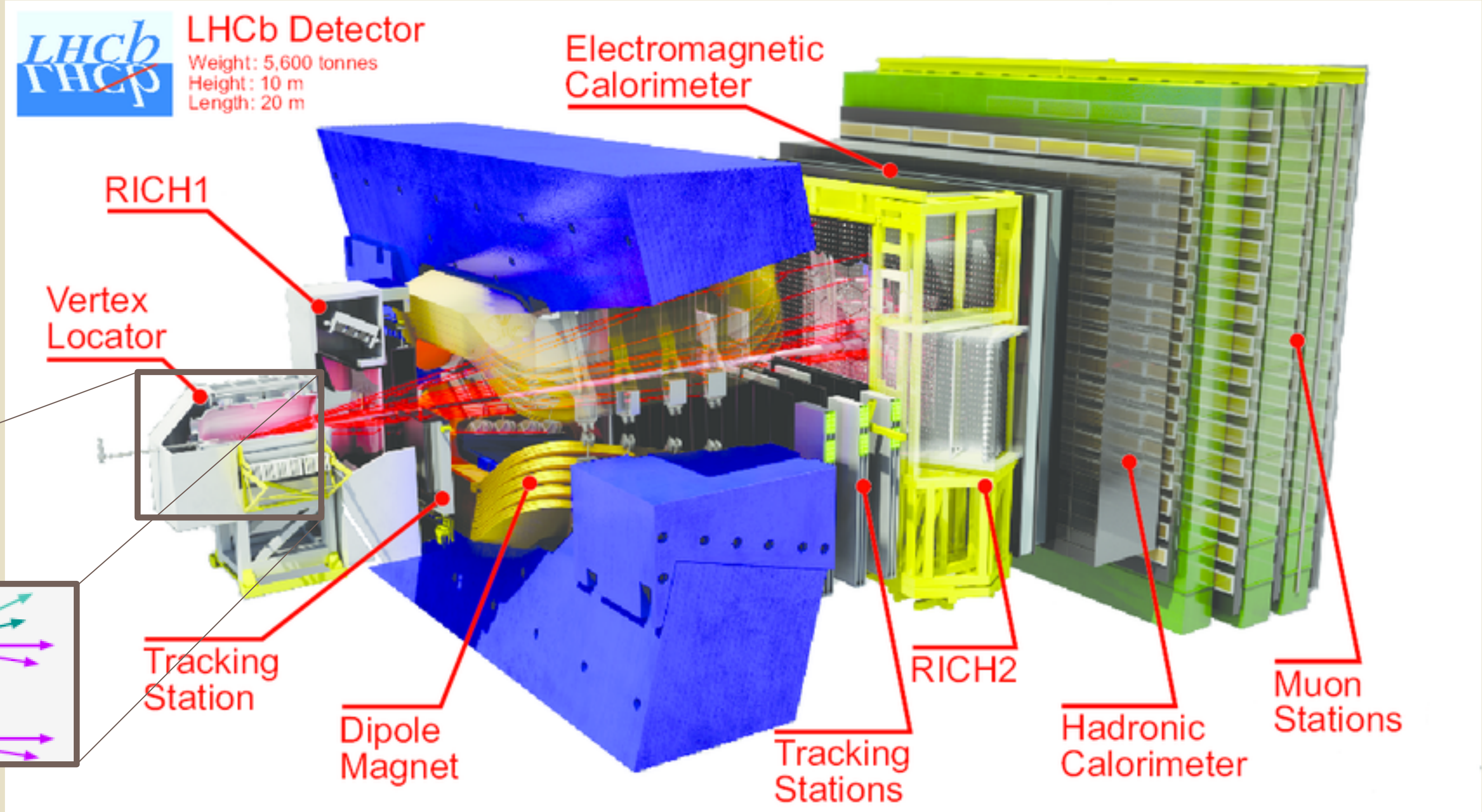
- World average (dominated by LHCb) consistent with predictions;
- Exp. uncertainty (31 mrad) almost a factor of 30 larger than uncert. of indirect determination when penguin pollution is ignored.

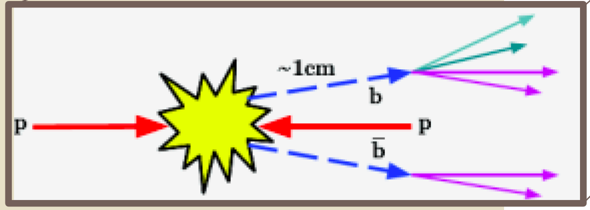
$$\varphi_s^{c\bar{c}s} = -0.021 \pm 0.031 \text{ rad}$$
$$\Delta\Gamma_s = 0.090 \pm 0.005 \text{ ps}^{-1}$$

[HFLAV 2018]

The LHCb detector

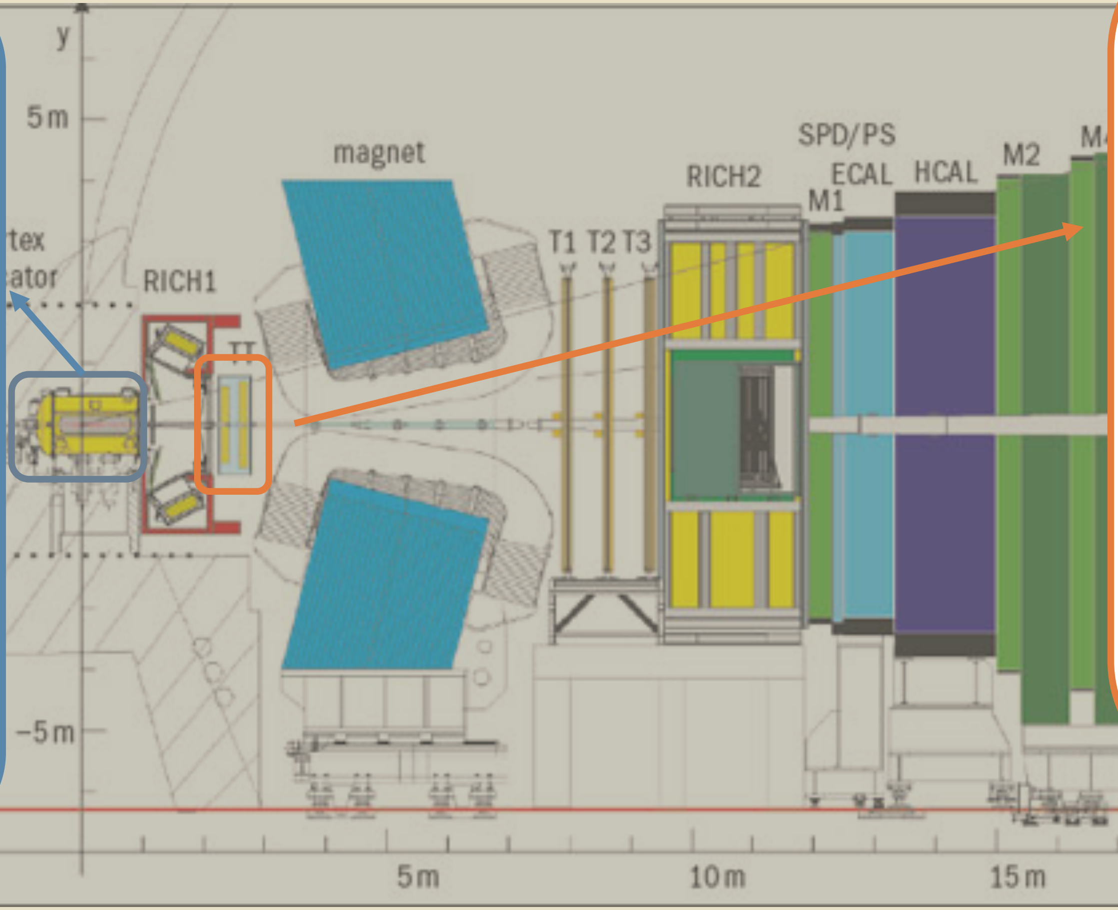
- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2,5]$





LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015)1530022

The tracker upstream the magnet

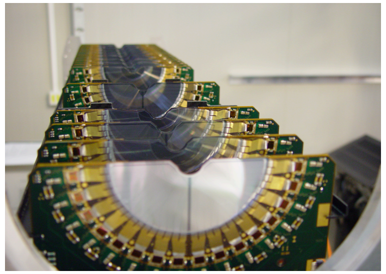


The VErtex LOcator

- 42 silicon micro-strip stations with R-Φ sensors
- 2 retractable halves, 7 mm from beam.

Decay time res ~45 fs

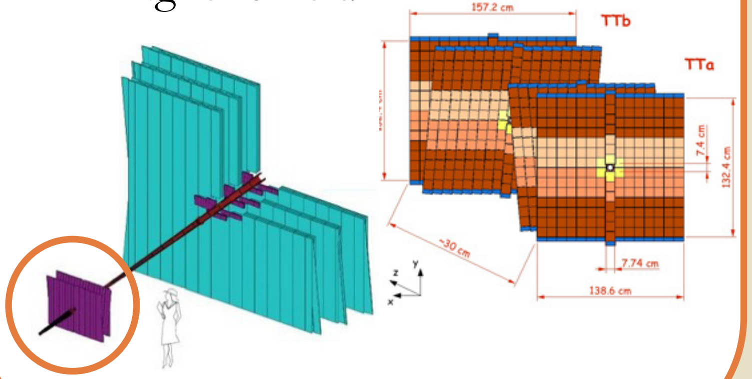
IP res ~20 μm



Performance of the LHCb Vertex Locator
JINST 9 (2014) 09007

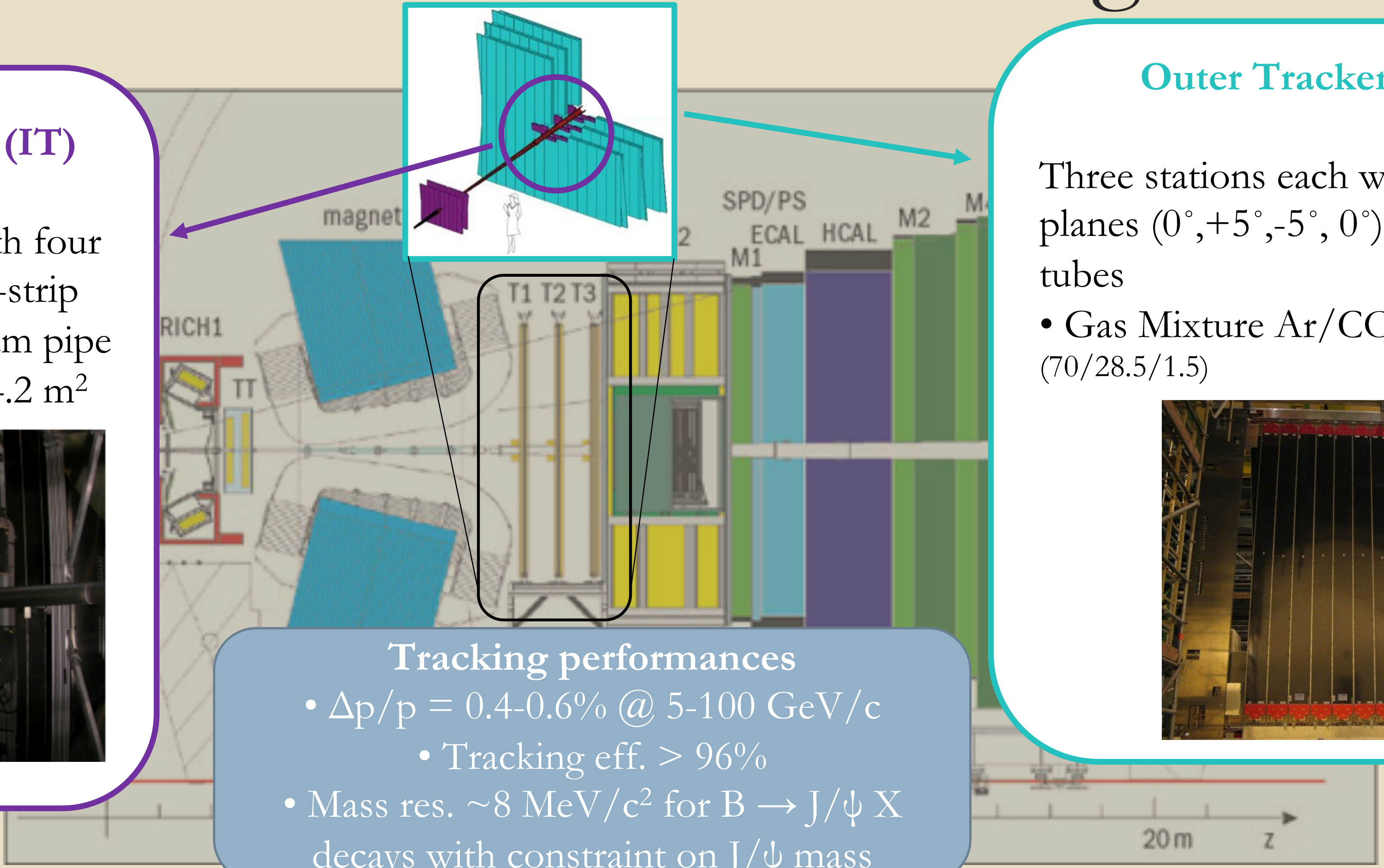
Tracker Turicensis (TT)

- Four planes (0°,+5°,-5°, 0°) of silicon micro-strip sensor
- Total silicon area of 8 m^2
- Already sensitive to the magnetic field



LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

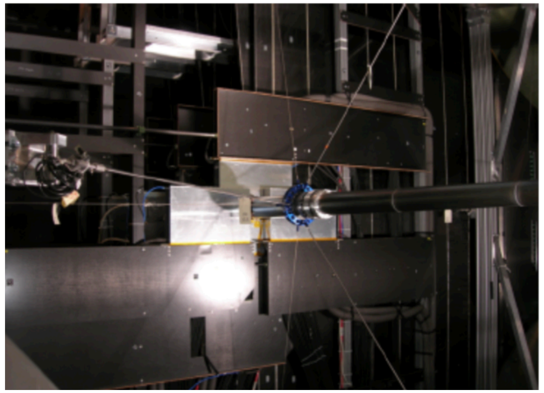
The tracker downstream the magnet



The Inner Tracker (IT)

Three stations each with four planes of silicon micro-strip sensors around the beam pipe

- Total silicon area of 4.2 m^2



Outer Tracker (OT)

Three stations each with four planes (0˚,+5˚,-5˚, 0˚) of straw tubes

- Gas Mixture $Ar/CO_2/O_2$ (70/28.5/1.5)

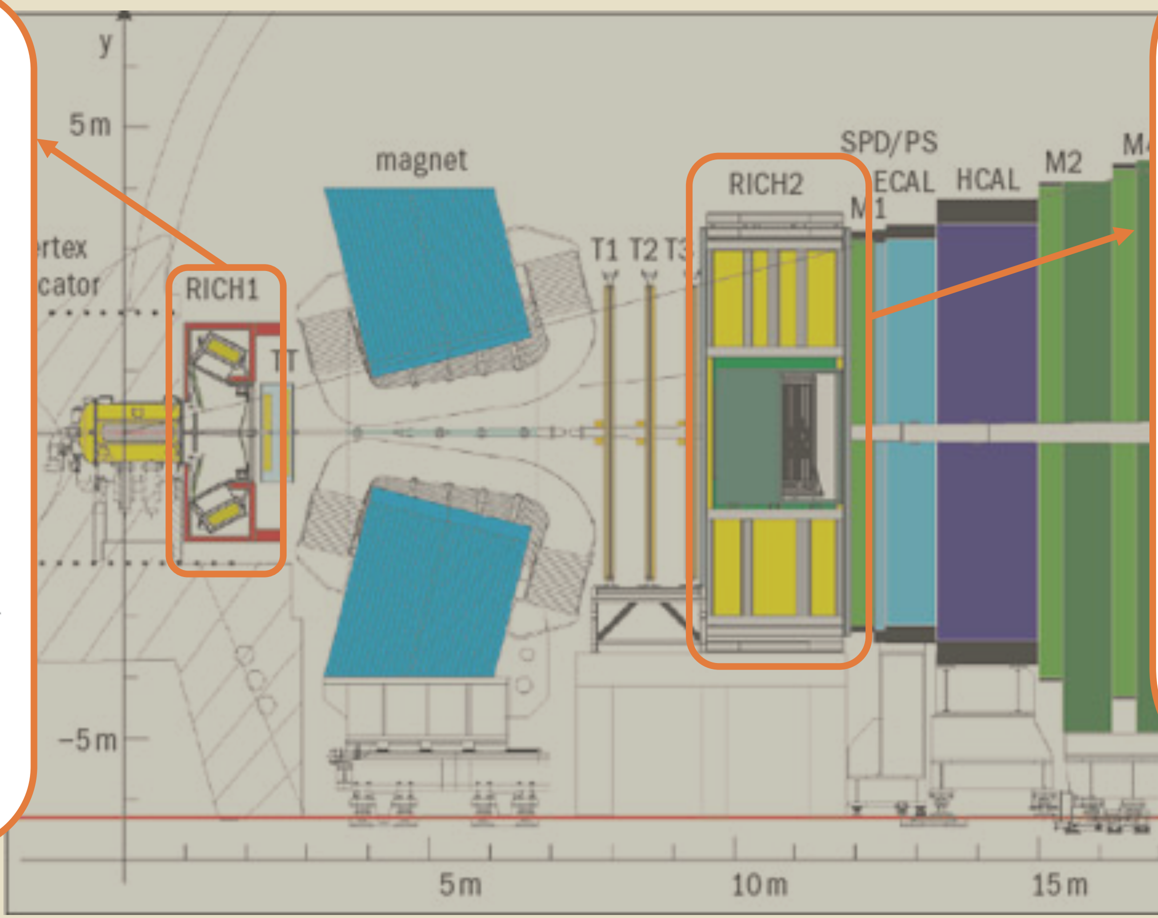
Tracking performances

- $\Delta p/p$ = 0.4-0.6% @ 5-100 GeV/c
- Tracking eff. > 96%
- Mass res. ~8 MeV/c^2 for $B \rightarrow J/\psi X$ decays with constraint on J/ψ mass

Performance of the LHCb Outer Tracker; JINST 9 (2014) P01002

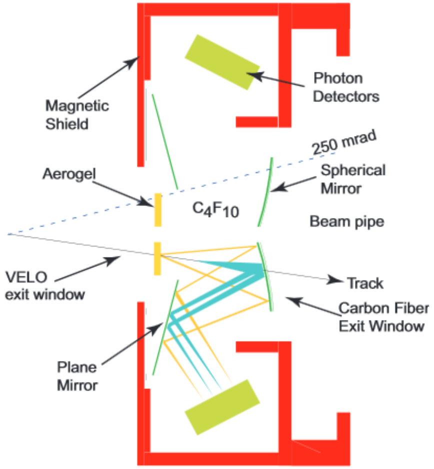
Performance of the LHCb RICH detector ad the LHC
Eur.Phys.J. C73 (2013) 2431

Particle identification



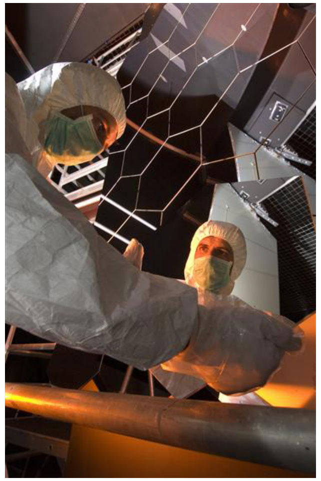
RICH 1

- Upstream of the magnet
- C_4F_{10} radiator
- $2<p<40$ GeV/c



RICH 2

- Downstream of the magnet
- CF10 radiator
- $15<p<100$ GeV/c
- 15-120 mrad

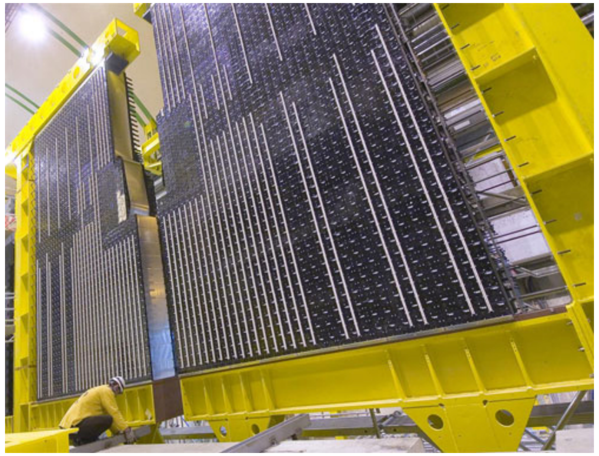


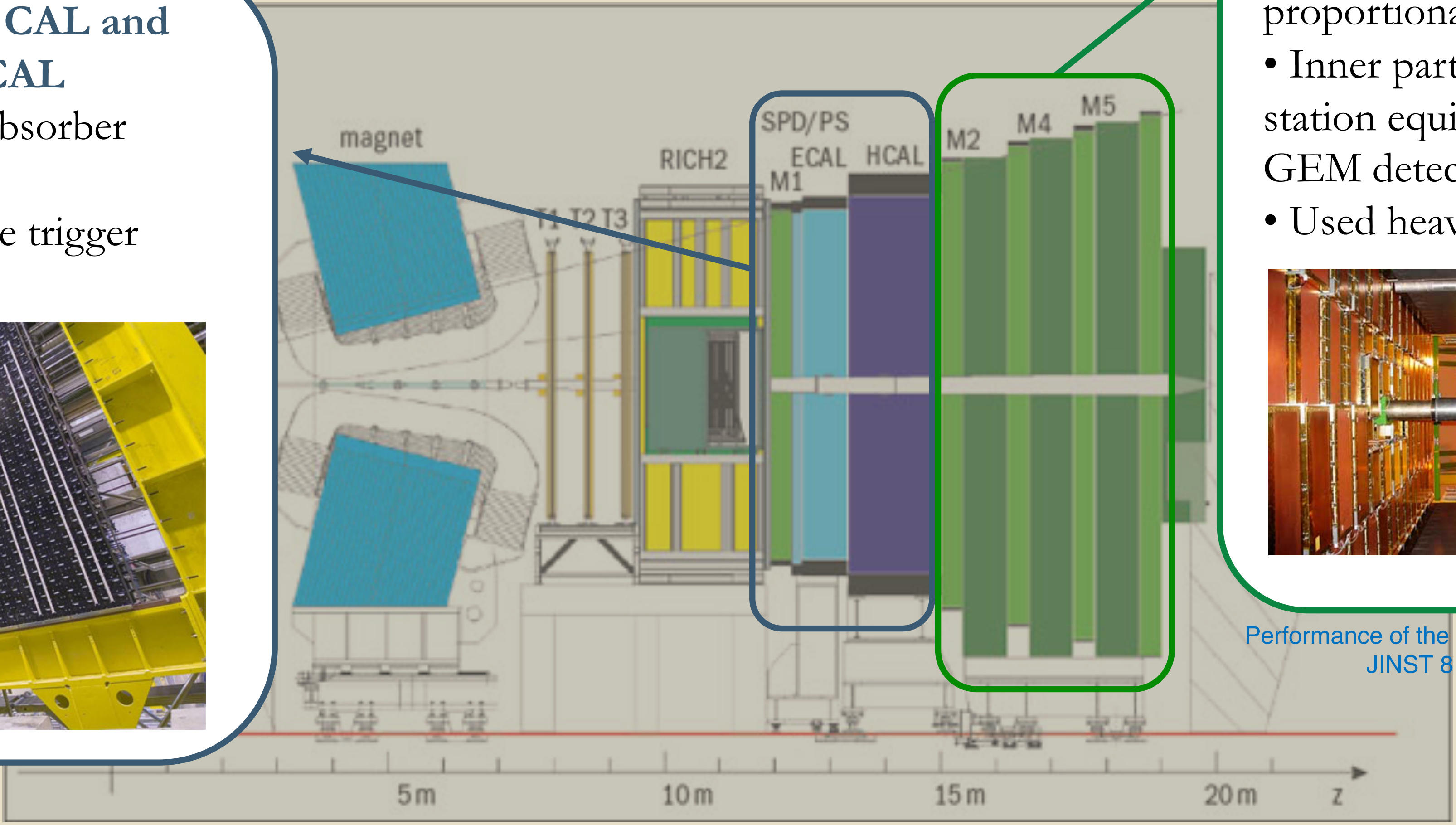
Particle identification

Electromagnetic CAL and Hadronic CAL

Scintillator planes + absorber material planes

- Used in the hardware trigger (L0) selection





Muon Chambers

5 stations, each equipped with 276 multi-wire proportional chambers

- Inner part of the first station equipped with 12 GEM detectors
- Used heavily in trigger

Performance of the Muon Identification system
JINST 8 (2013) P10020

LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

Particle identification

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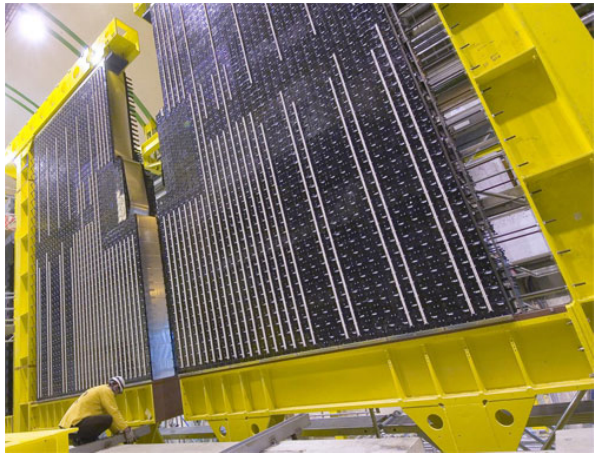

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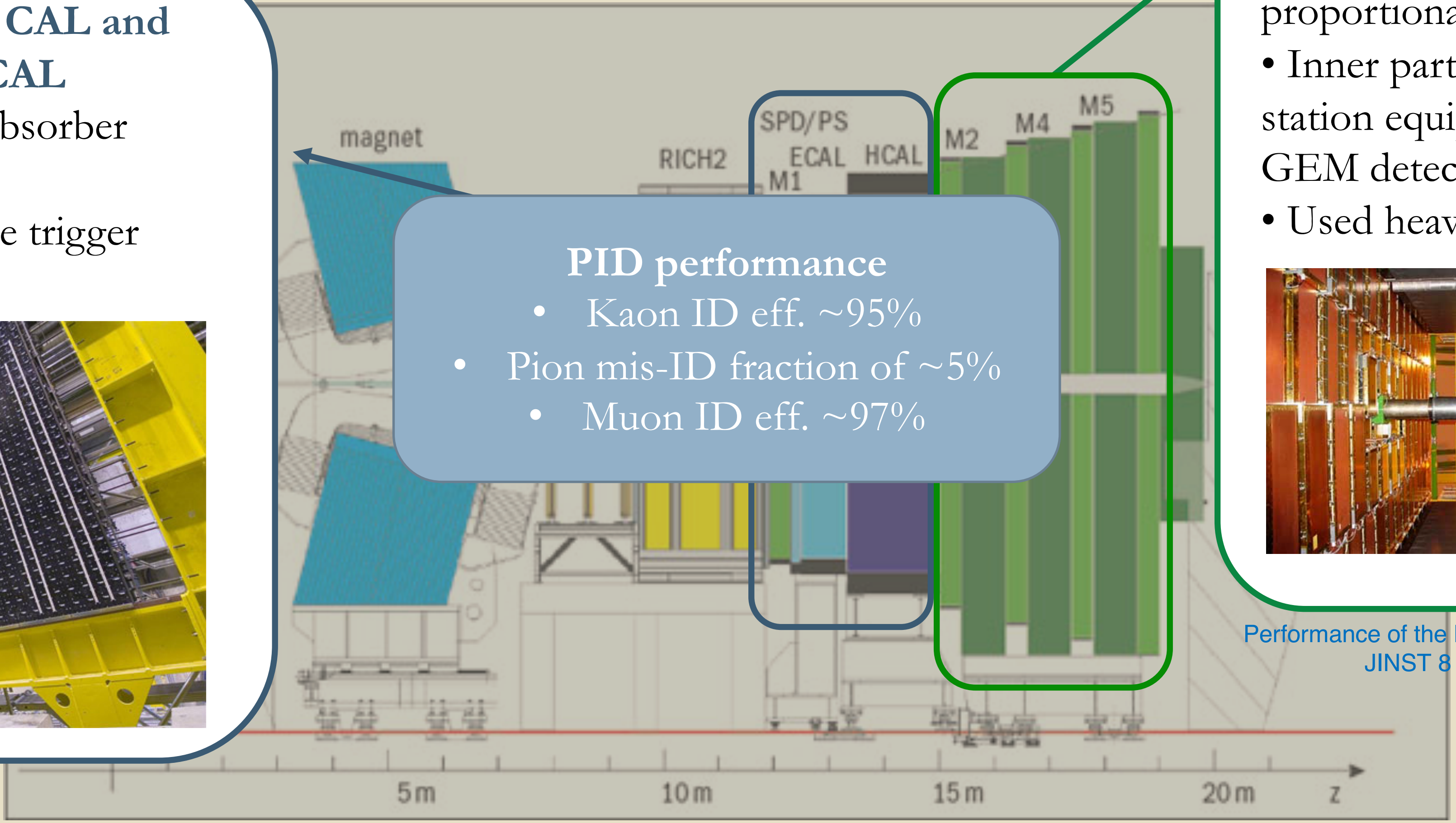

PID performance

- Kaon ID eff. ~95%
- Pion mis-ID fraction of ~5%
- Muon ID eff. ~97%

Muon Chambers

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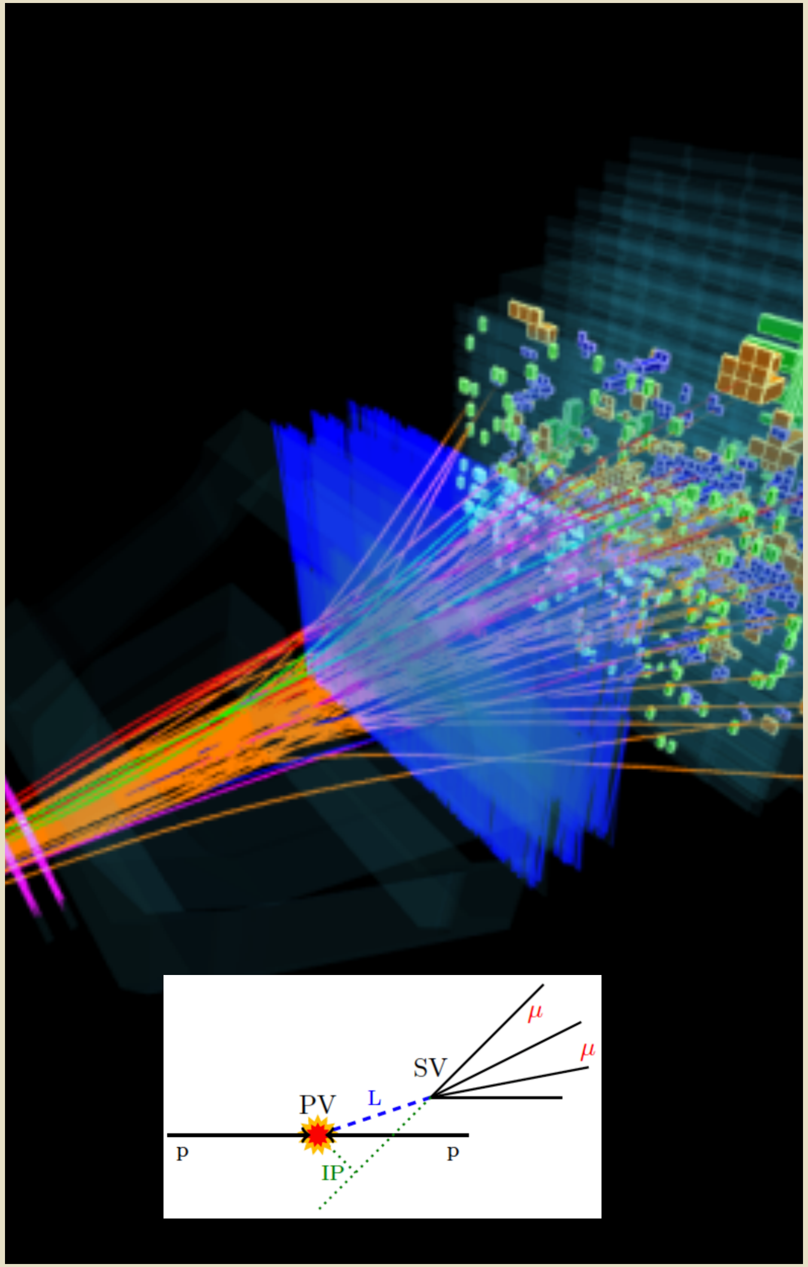
Performance of the Muon Identification system
JINST 8 (2013) P10020



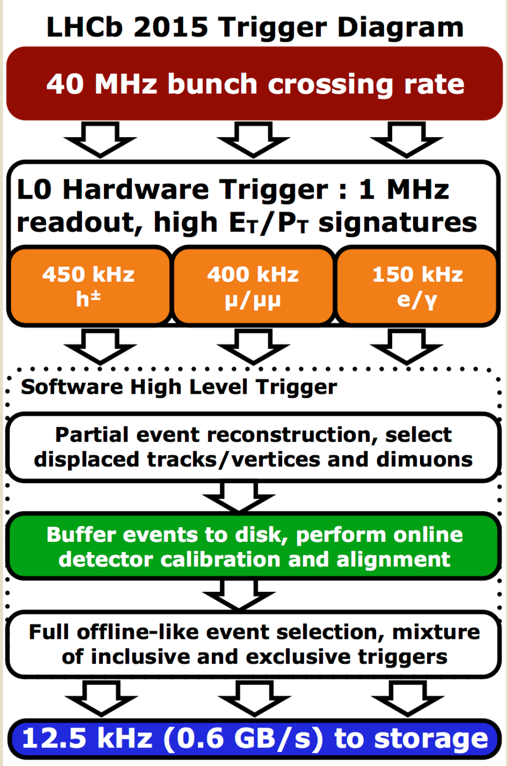
Trigger principles

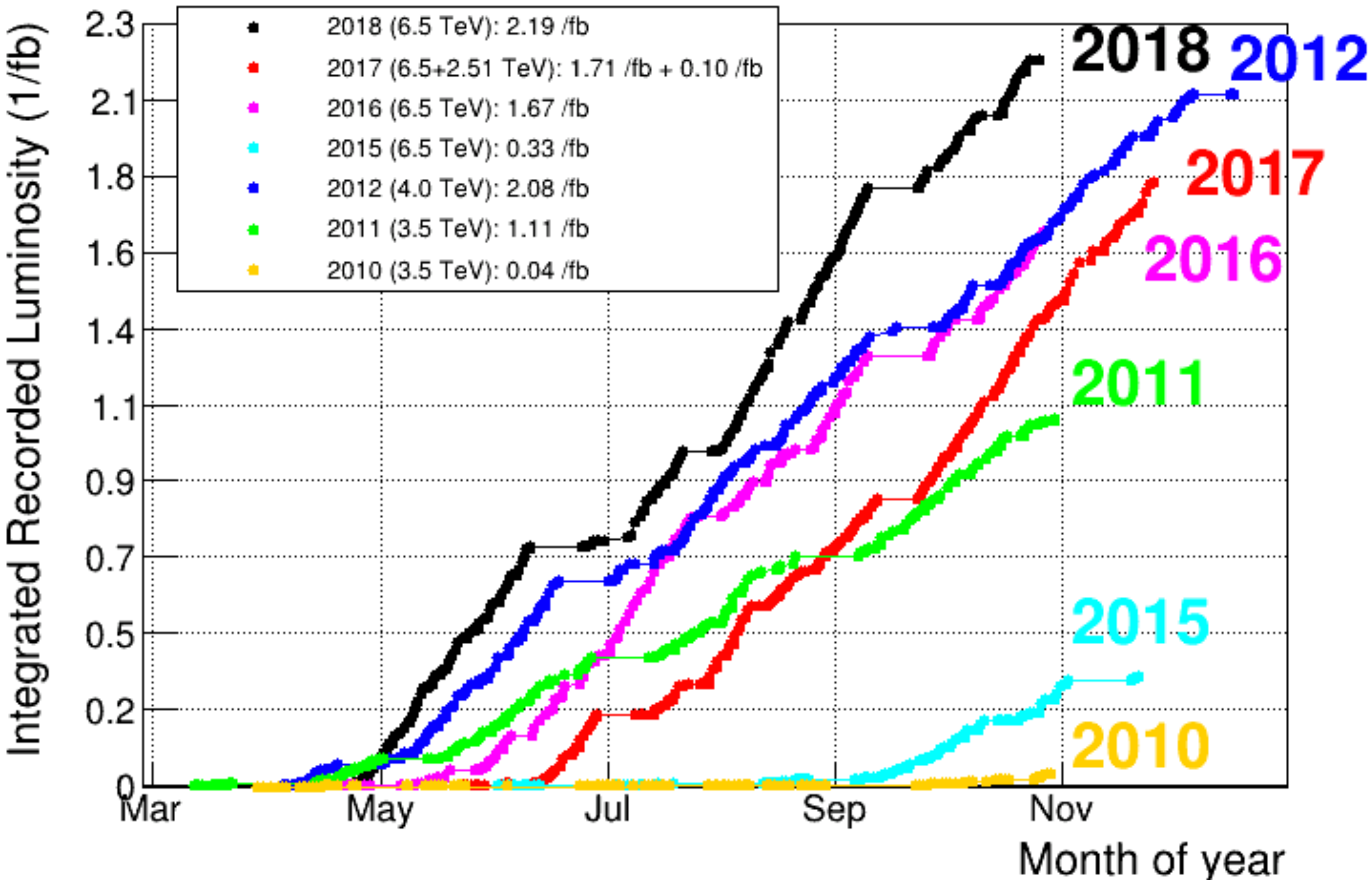
BEAUTY SIGNATURES

- Mass $m(B^{+}) = 5.28\ \mathrm{GeV/c^2}$
- Daughter p_T $\mathcal{O}(1\ \mathrm{GeV/c})$
- Lifetime $\tau(B)\sim 1.5$ ps
- Flight distance $\sim$1 cm
- Detached secondary vertex

Since Run II the detector is calibrated and aligned online:

- **Same reconstruction online and offline**
- No need of offline data processing





INTEGRATED RECORDED LUMINOSITY

The full LHCb data set is about 9fb^{-1}

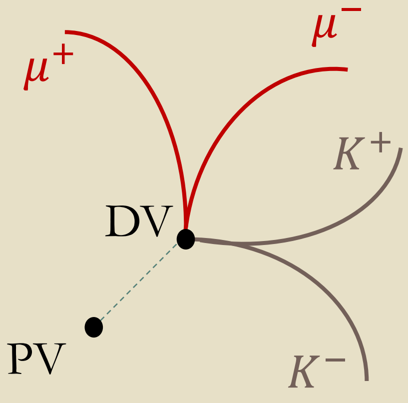
THANKS LHC!!

2015: 0.3 fb^{-1}
2016: 1.6 fb^{-1}
2017: 1.7 fb^{-1}
2018: 2.1 fb^{-1}

Large number of beauty hadrons:
$\sigma_{b\bar{b}}(7\text{ TeV}) = 72.0 \pm 0.3 \pm 6.8\ \mu\text{b}$
$\sigma_{b\bar{b}}(13\text{ TeV}) = 154.3 \pm 1.5 \pm 14.3\ \mu\text{b}$
[PRL 118 (2017) 052002]

Decay channels discussed today

$B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$

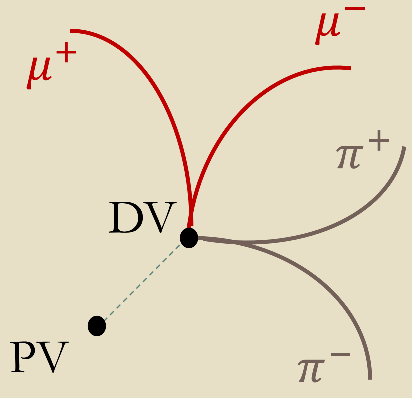


In $B_s^0 \to J/\psi KK$ the final state is a mixture of CP-even (L = 0, 2) and CP-odd (L = 1 + S-wave) components:

- $|B_L> = p\,|B_s^0> \, + q\,|\bar{B}_s^0> \;\approx\;$ CP – even
- $|B_H> = p\,|B_s^0> - q\,|\bar{B}_s^0> \;\approx\;$ CP – odd

Requires an **angular analysis** and allows to obtain $\Delta\Gamma_s$ and Γ_s

$B_s^0 \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$



Rich resonant and non-resonant structure in the $\pi^+\pi^-$ mass spectrum.

Mainly CP-odd: requires an amplitude analysis to check the effect of the small CP-even component and it allows to measure Γ_H

Measuring φ_s

Definition of time-dependent CP asymmetry: $A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to f) - \Gamma(B_s^0 \to f)}{\Gamma(\bar{B}_s^0 \to f) + \Gamma(B_s^0 \to f)} = \eta_f \sin\varphi_s \sin(\Delta m_s\, t)$

Experimentally it becomes: $A_{CP}(t) = \eta_f \cdot e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1 - 2\omega) \cdot \sin\varphi_s \cdot \sin(\Delta m_s\, t)$

Critical requirements:

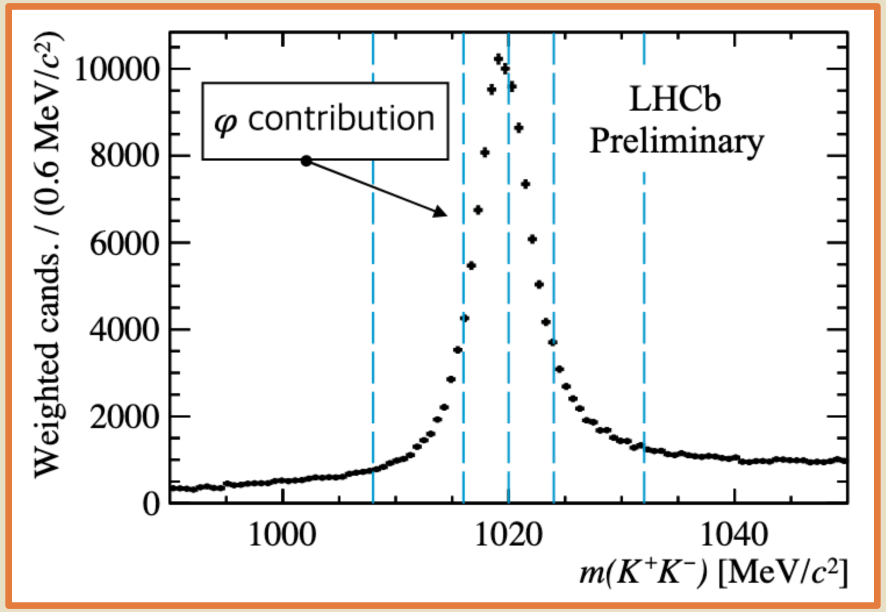
- CP eigenvalue of the final state η_f → angular analysis
- Excellent decay-time resolution $\boldsymbol{\sigma_t}$~45 fs
- Tagging of meson flavour @ production: probability of getting the wrong tag $\boldsymbol{\omega}$

+ in the fit need to model decay-time efficiency $\boldsymbol{\varepsilon(t)}$ (due to selection and reconstruction) and angular efficiency $\boldsymbol{\varepsilon(\Omega)}$

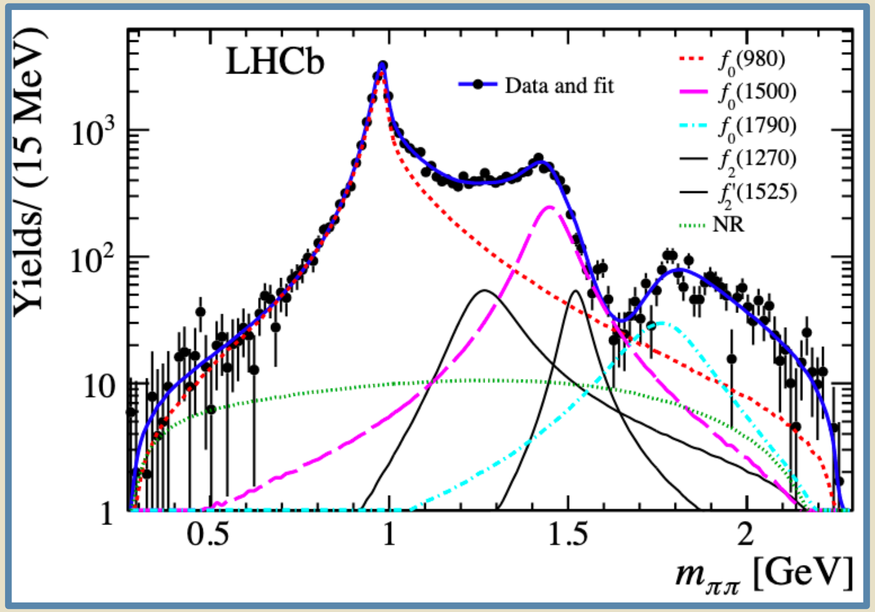
First harvest of LHCb Run 2 data

- New results obtained analysing 2015 (0.3 fb^{-1}) and 2016 (1.6 fb^{-1}) data presented at Moriond EW '19
- $B_s^0 \to J/\psi K^+K^-$ [LHCb-PAPER-2019-013] and $B_s^0 \to J/\psi\pi^+\pi^-$ [arXiv:1903.05530]
- **Not just an update:** Run I strategy duly rediscussed and various methods carefully scrutinized and validated
- Simultaneous fit to the signal decay time and 3 helicity angles

in 6 bins in $m(K^+K^-)$



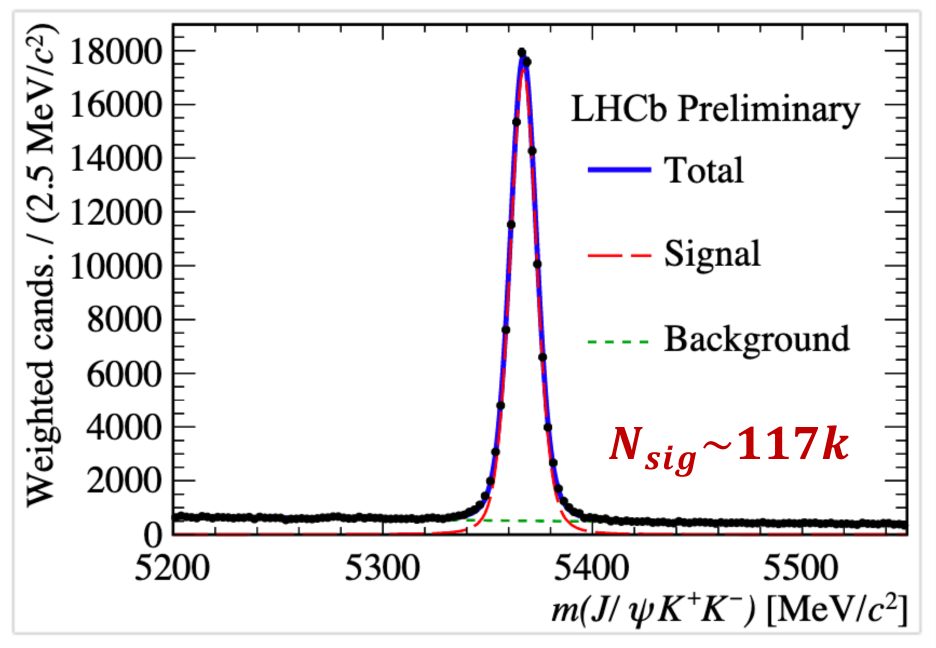
and $m(\pi^+\pi^-)$

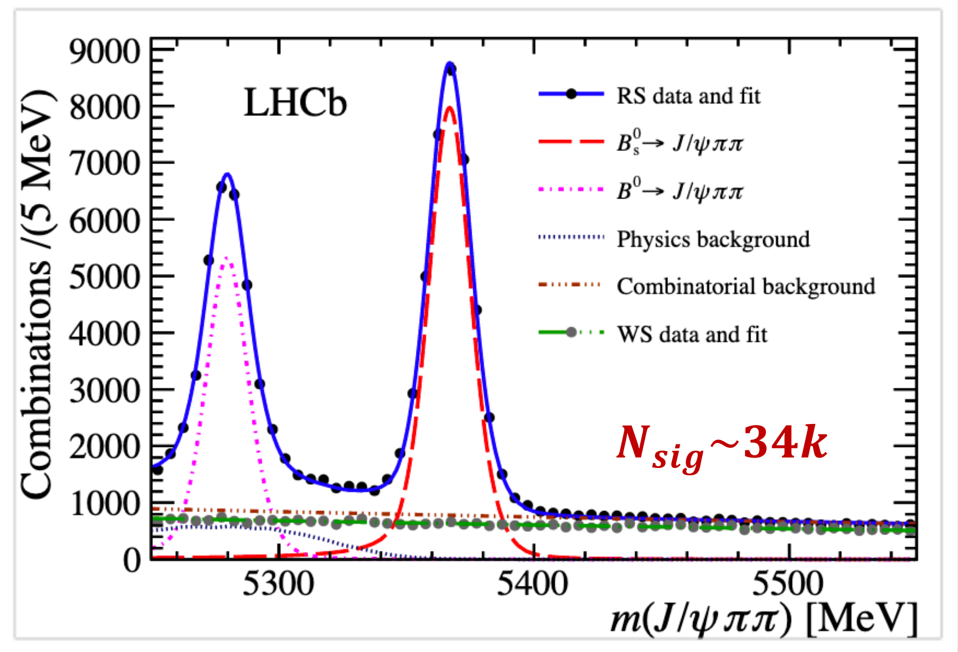


Selection and mass fit

New: Boosted decision tree is trained to select signal candidates

[LHCb-PAPER-2019-013]





[arXiv:1903.05530]

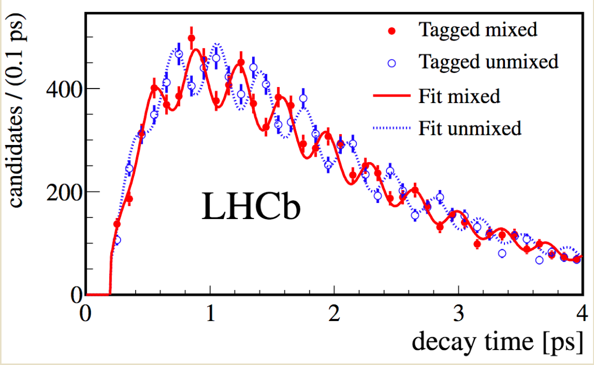
- Injected negative weighted MC to subtract $\Lambda_b^0 \to J/\psi pK$
- Signal width is a function of per-candidate mass error to account for correlation with $\cos(\theta_\mu)$

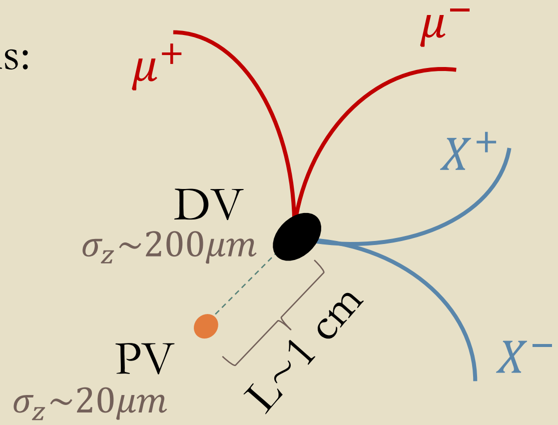
- Use the wrong sign (WS) combination ($\pi^\pm\pi^\pm$) to determine the shape of the combinatorial background

Decay-time resolution

Fundamental to resolve fast $B_s^0 - \bar{B}_s^0$ oscillations:

[New J. Phys. 15 (2013) 053021]





$$t = \frac{L \cdot m}{p}$$ decay time

decay-time resolution

$$\sigma_t^2 = \left(\frac{m}{p}\right)^2 \sigma_L^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$

$\sim 200\mu m$

$\sigma_p \ /p \sim 0.4\%$

The first contribution is ~20 times larger than the second, they become comparable only at several B lifetimes

How to determine σ_t in data?

- Since the resolution of the secondary vertex is dominating, we reconstruct fake $B_s^0 \to \mu\mu hh$ with all tracks coming from the PV (prompt J/ψ + 2 random PV kaons or pions) and without using selections on decay time
- By definition for these candidates $t = 0 \pm \sigma_t$
- Method **validated in MC comparing prompt and signal resolutions**

Decay-time resolution

Fundamental to resolve fast $B_s^0 - \bar{B}_s^0$ oscillations:

$$t = \frac{L \cdot m}{p} \quad \text{decay time}$$

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$\sim 200\mu m$ $\qquad$ $\sigma_p\ /p \sim 0.4\%$

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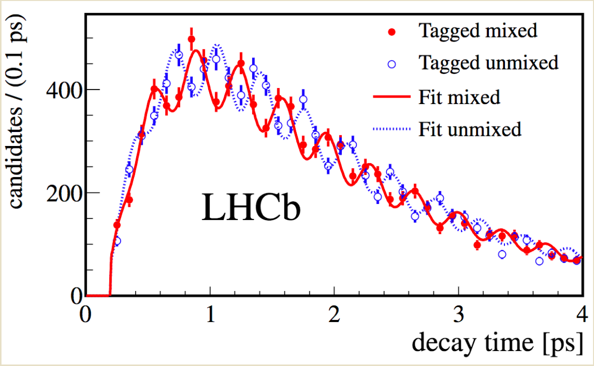

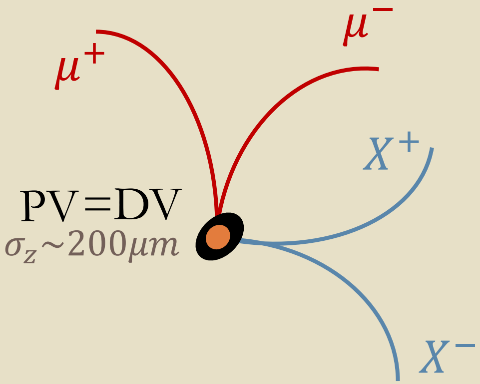

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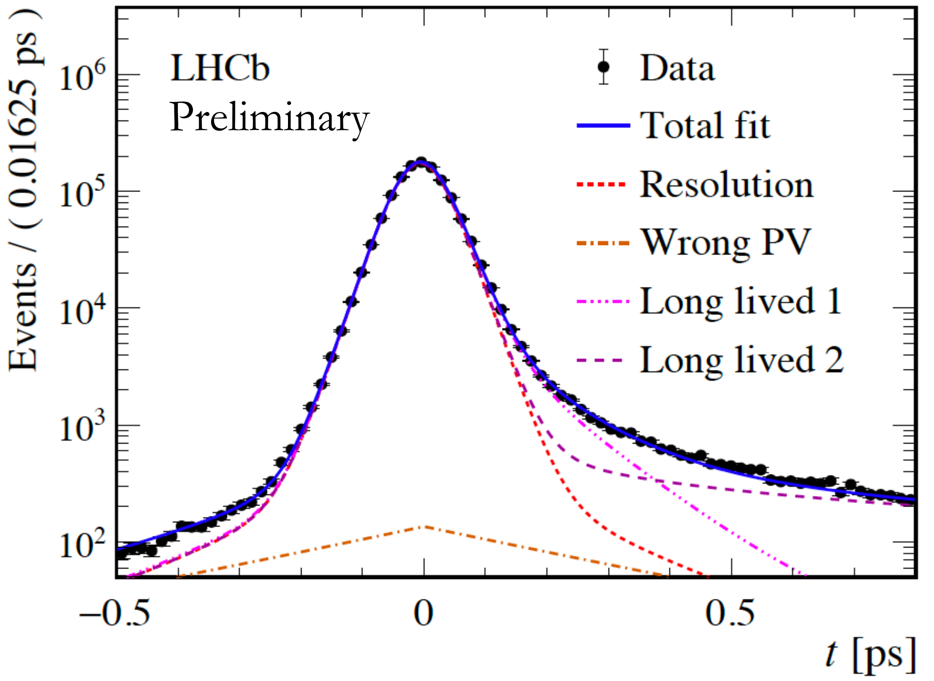
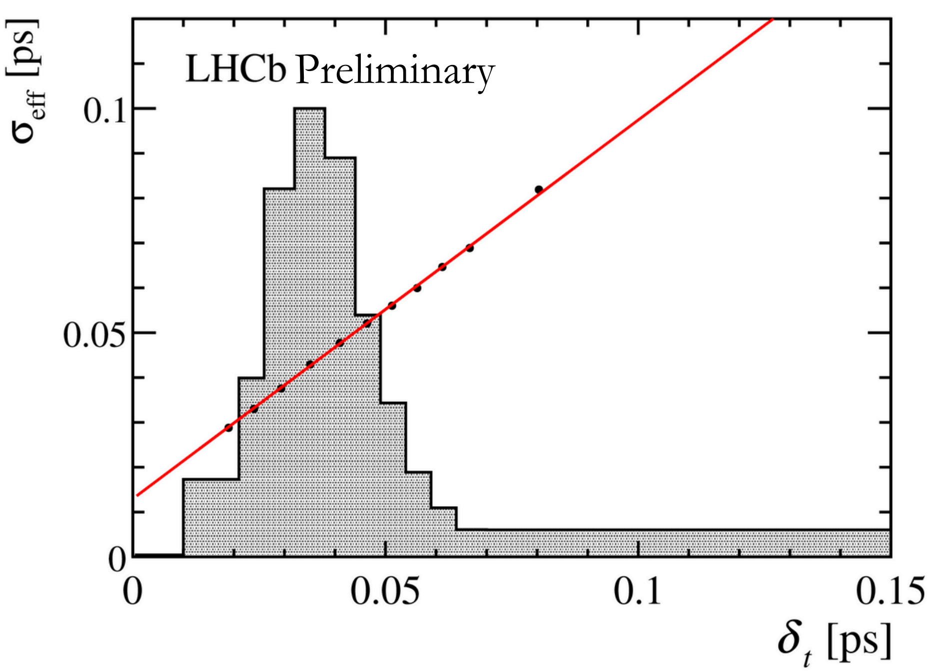
Decay-time resolution

[LHCb-PAPER-2019-013]



Fitting σ_{eff} in diff. bin of the **event-by-event decay-time uncertainty** $\boldsymbol{\delta_t}$



[LHCb-PAPER-2019-013]

$$\sigma_{eff} = \sqrt{(-2/\Delta m_s^2) lnD}, \text{ with } D = \sum_{i-1}^{3} f_i e^{-\sigma_i^2 \Delta m_s^2/2}$$

σ_{eff}= 45.5 fs

$B_s^0 \rightarrow J/\psi K^+ K^-$

σ_{eff}= 41.5 fs

$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

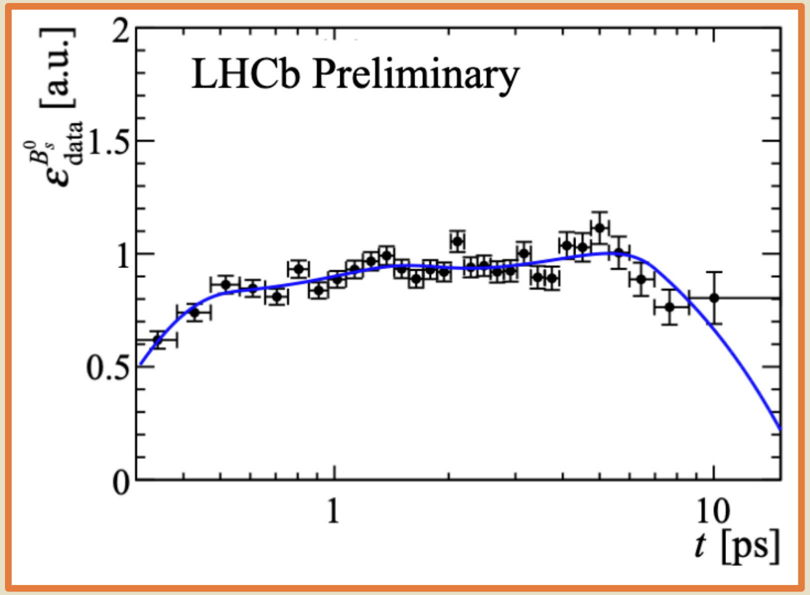
Decay-time efficiency

Use ~550k $B^0 \to J/\psi K^*(892)^0$ as a data control channel (thanks to its well known lifetime $\tau_{B^0} = \frac{1}{\Gamma_d} = 1.520 \pm 0.004$ ps).

Efficiency obtained fitting simultaneously B^0 data and $B^0 - B_s^0$ data-corrected simulations fixing known lifetimes and resolutions:

$$\varepsilon_{B_s^0}^{data}(t) = \varepsilon_{B^0}^{data}(t) \times \frac{\varepsilon_{B_s^0}^{MC}(t)}{\varepsilon_{B^0}^{MC}(t)}$$

Small correction to account for differences between signal and control channels



[LHCb-PAPER-2019-013]

By product: measure directly $\Gamma_s - \Gamma_d$ in $B_s^0 \to J/\psi K^+K^-$ and $\Gamma_H - \Gamma_d$ in $B_s^0 \to J/\psi \pi^+\pi^-$ being independent on the value and uncertainty of Γ_d

Interesting for comparisons with HQE where Γ_s / Γ_d is precisely predicted.

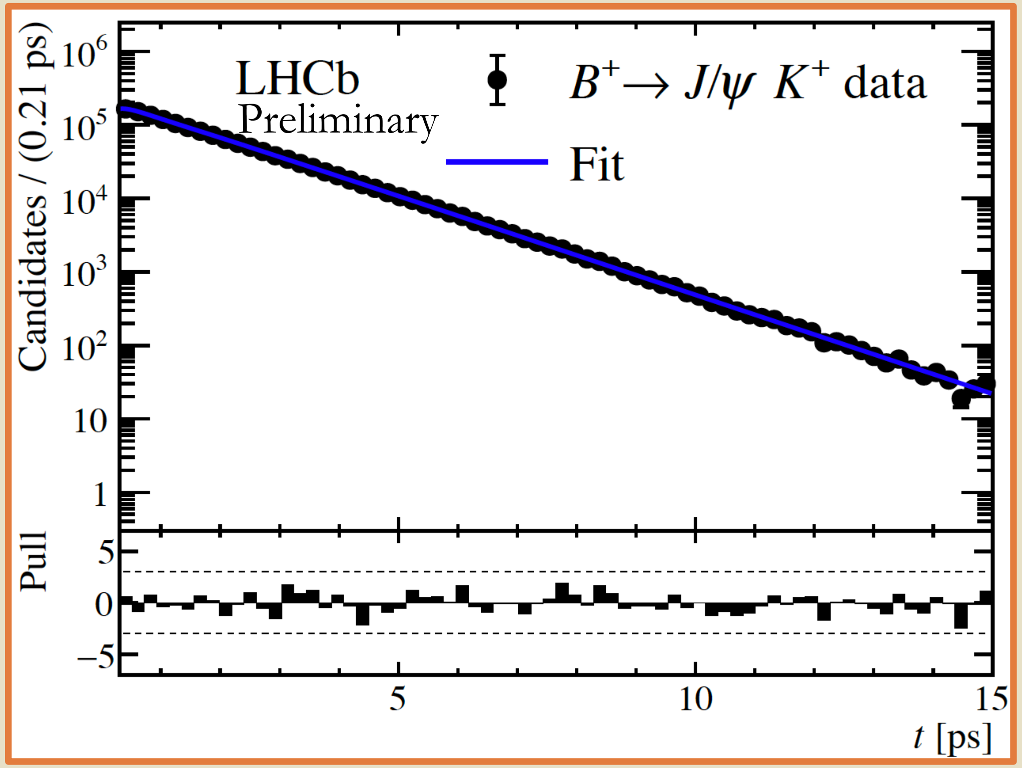
Decay-time efficiency II

Strategy validated using $B^0 \to J/\psi K^*(892)^0$ and $B^+ \to J/\psi K^+$ data control channels

E.g. $B^+ \to J/\psi K^+$

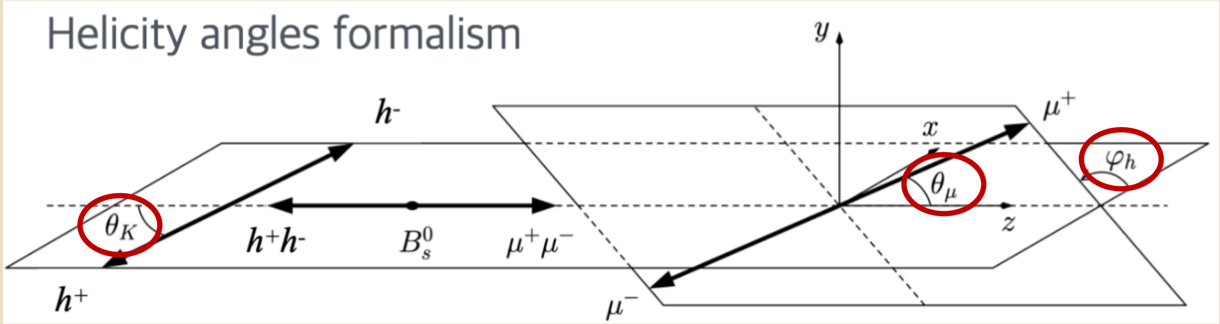
- Determine the B^+ lifetime using $B^0 \to J/\psi K^{*0}$ as control channel
- Replace the B_s^0 MC in the efficiency determination with B^+ MC and determine the efficiency
- Fit B^+ decay time distribution in data with this efficiency

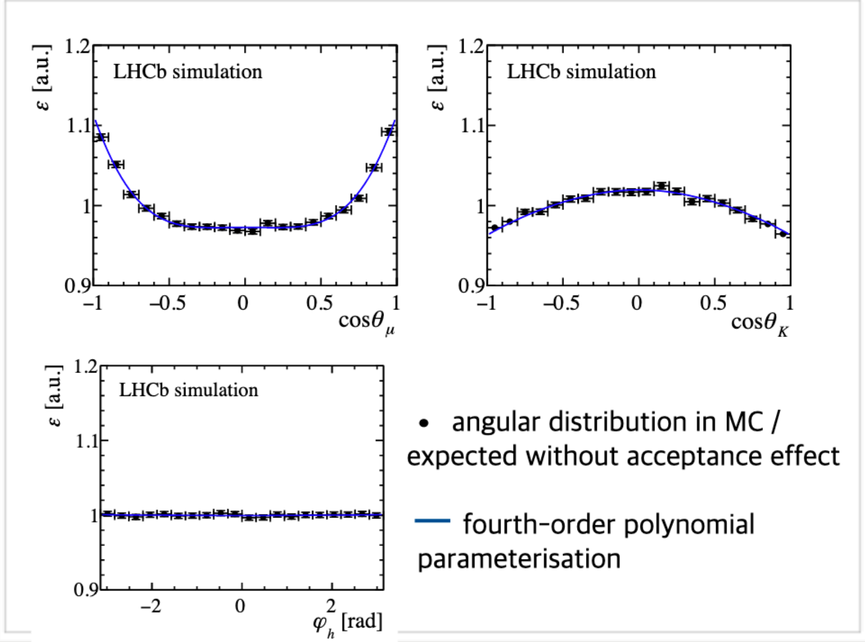
✓ $\Gamma_u - \Gamma_d = -0.0478 \pm 0.0013\ \text{ps}^{-1}$ (stat only)
vs $(\Gamma_u - \Gamma_d)^{\text{PDG}} = -0.0474 \pm 0.0023\ \text{ps}^{-1}$



[LHCb-PAPER-2019-013]

Angular efficiency





[LHCb-PAPER-2019-013]

- Kinematic selection and detector acceptance are causing non uniform efficiency as function of decay angles
- Efficiency taken from MC after iterative reweighting

✓ **Checks done in control data**:

- Measurement of $B^0 \to J/\psi K^{*0}$ polarisation amplitudes in agreement with world average
- Correctly retrieved muon helicity distribution (expected $1 - \cos^2\theta_\mu$ dependence) in $B^+ \to J/\psi K^+$ decays

Flavour tagging

[LHCb-PAPER-2019-013]
[arXiv:1903.05530]

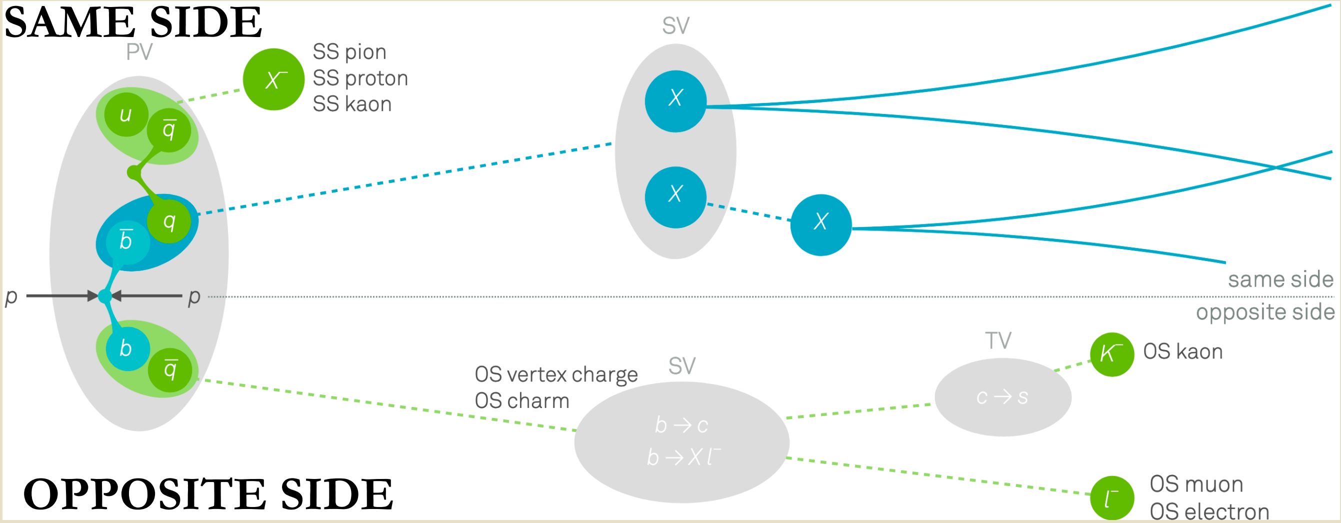
- Two tagging algorithms are used: **opposite side** and **same side**. For each algorithm true mistag probability is calibrated assuming linear dependency with estimated one
  $$\omega = p_0 + p_1(\eta - < \eta >)$$
- Tagging power is given as tagging efficiency times dilution squared $\varepsilon_{tag} D^2$ with $D = (1 - 2\omega)$

$\boxed{\varepsilon_{tag} D^2 = 4.73 \pm 0.34\ \%}$ Run1 was $\approx 3.73\ \%$

$\boldsymbol{B_s^0 \to J/\psi K^+ K^-}$

$\boxed{\varepsilon_{tag} D^2 = 5.06 \pm 0.38\ \%}$ Run1 was $\approx 3.89\ \%$

$\boldsymbol{B_s^0 \to J/\psi \pi^+ \pi^-}$



~30% relative improvement of tagging power

- **More tagging power = better exploitation of data!**

Flavour tagging

[LHCb-PAPER-2019-013]
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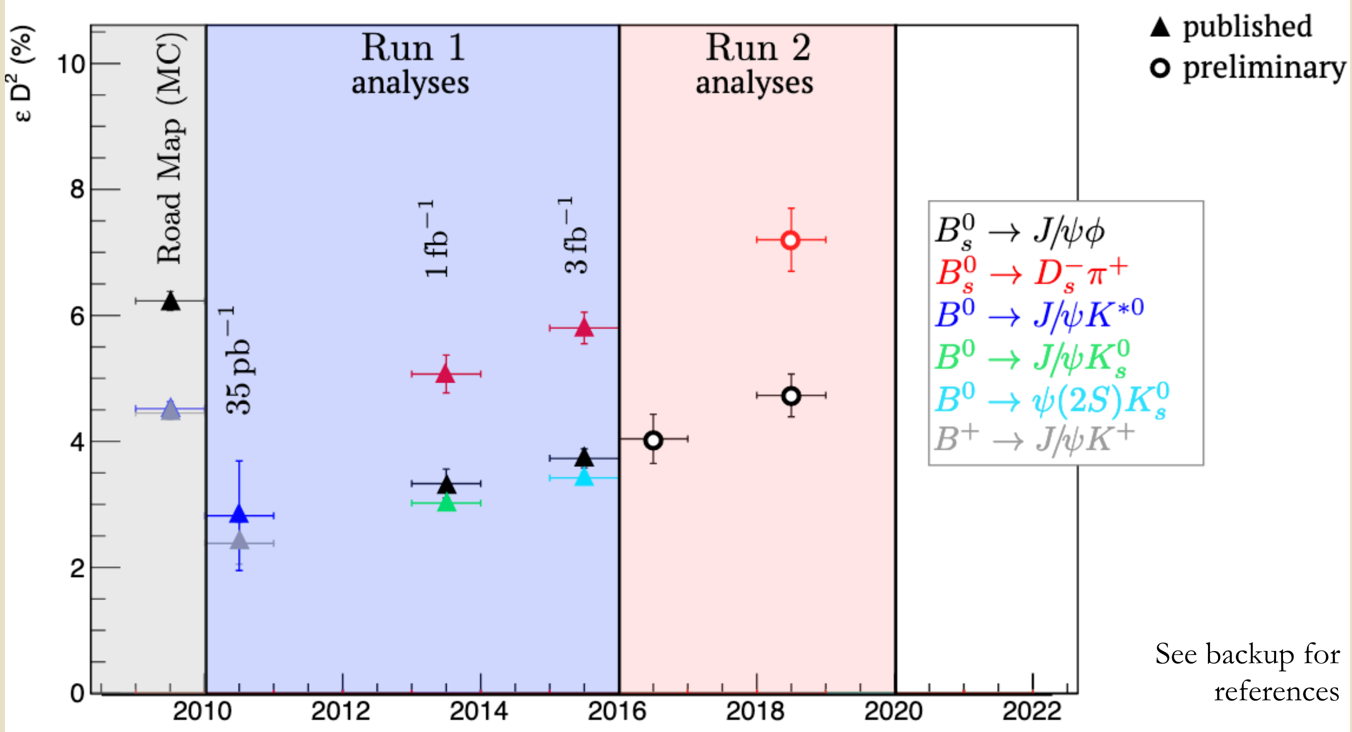
$B_s^0 \to J/\psi\pi^+\pi^-$

Courtesy of S. Akar



See backup for references

- **More tagging power = better exploitation of data!**

[LHCb-PAPER-2019-013]

Systematics for $B_s^0 \to J/\psi K^+ K^-$

φ_s mainly affected by Time res. & Ang. Acc., $\Delta\Gamma_s$ ($|\lambda|$) by Mass factorisation (& Ang. Acc.), $\Gamma_s - \Gamma_d$ by Time eff.

Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass width parametrisation	0.0006	0.0005	-	-	0.05	0.009	-	0.0002	0.001
Mass factorisation	0.0002	0.0004	0.004	$\boxed{0.0037}$	0.01	0.004	0.0007	$\boxed{0.0022}$	0.016
Multiple candidates	0.0006	0.0001	0.0011	0.0011	0.01	0.002	0.0003	0.0001	0.001
Fit bias	0.0001	0.0006	0.001	-	0.02	0.033	-	0.0003	0.001
$C_{\rm SP}$ factors	-	0.0001	0.001	0.0010	0.01	0.005	-	0.0001	0.002
Time res.: applicability of prompt	-	-	-	-	-	0.001	-	-	0.001
Time res.: t bias	-	-	$\boxed{0.0032}$	0.0010	0.08	0.001	0.0002	0.0003	0.005
Time res.: wrong PV	-	-	-	-	-	0.001	-	-	0.001
Ang. acc.: MC sample size	0.0003	0.0004	0.0011	0.0018	-	0.004	-	-	0.001
Ang. acc.: BDT correction	0.0020	0.0011	0.0022	0.0043	0.01	0.008	0.0001	0.0002	0.001
Ang. acc.: low-quality tracks	0.0002	0.0001	0.0005	0.0014	-	0.002	0.0002	0.0001	-
Ang. acc.: t & σ_t dependence	0.0008	0.0012	0.0012	0.0007	0.03	0.006	0.0002	0.0010	0.003
Dec.-time eff.: statistical	0.0002	0.0003	-	-	-	-	$\boxed{0.0012}$	0.0008	-
Dec.-time eff.: kin. weighting	-	-	-	-	-	-	0.0002	-	-
Dec.-time eff.: p.d.f. weighting	-	-	-	-	-	-	0.0001	0.0001	-
Dec.-time eff.: $\Delta\Gamma_s = 0$ sim.	0.0001	0.0002	-	-	-	-	0.0003	0.0005	-
Length scale	-	-	-	-	-	-	-	-	0.004
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.10	0.037	0.0015	0.0026	0.018

[arXiv:1903.05530]

Systematics for $B_s^0 \to J/\psi\pi^+\pi^-$

$\Gamma_H - \Gamma_d$ mainly affected by Background, φ_s and $|\lambda|$ by Resonance modelling

Source	$\Gamma_{\rm H} - \Gamma_{B^0}$ [fs^{-1}]	$\lvert\lambda\rvert$ [$\times 10^{-3}$]	ϕ_s [mrad]
t acceptance	2.0	0.0	0.3
τ_{B^0}	0.2	0.5	0.0
Efficiency $(m_{\pi\pi}, \Omega)$	0.2	0.1	0.0
t resolution width	0.0	4.3	4.0
t resolution mean	0.3	1.2	0.3
Background	$\boxed{3.0}$	2.7	0.6
Flavour tagging	0.0	2.2	2.3
Δm_s	0.3	4.6	2.5
$\Gamma_{\rm L}$	0.3	0.4	0.4
B_c^+	0.5	-	-
Resonance parameters	0.6	1.9	0.8
Resonance modelling	0.5	$\boxed{28.9}$	$\boxed{9.0}$
Production asymmetry	0.3	0.6	3.4
Total	3.8	29.9	11.0

1) Using reweighted WS samples in the fit
2) Vary the background yields by $\pm 1\sigma$

1) Vary Barrier factor
2) Replace NR by $f_0(500)$
3) Solution II
4) Add $\rho(770)$

[LHCb-PAPER-2019-013]
[arXiv:1903.05530]

Results using 2015-2016 data

$B_s^0 \to J/\psi K^+ K^-$

$$\varphi_s = -0.083 \pm 0.041 \pm 0.006 \text{ rad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0773 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1}$$

$B_s^0 \to J/\psi \pi^+ \pi^-$

$$\varphi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad}$$
$$|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$$
$$\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}$$

$$\Gamma_s = 0.6538 \pm 0.0024 \pm 0.0015 \pm 0.0017 \text{ (input } \Gamma_\mathrm{d}) \text{ ps}^{-1}$$

Combining the above + Run 1: $B_s^0 \to J/\psi KK$, $B_s^0 \to J/\psi \pi\pi$, $B_s^0 \to J/\psi KK$ high mass, $B_s^0 \to D_s D_s$, $B_s^0 \to \psi(2S)\varphi$

$$\varphi_s = -0.041 \pm 0.025 \text{ rad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$

Correlations between the parameters and between the systematic uncertainties are taken into account.

Overview of LHCb combination

Preliminary

Combination of all LHCb (Run1 and 2) results

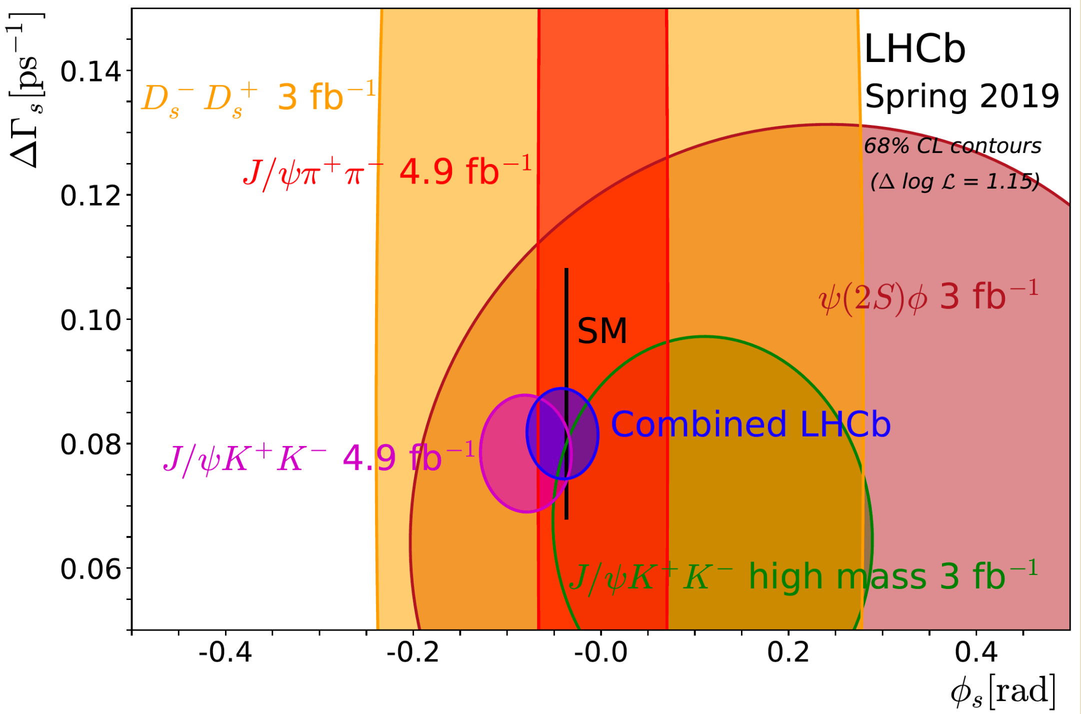
$$\varphi_s = -0.041 \pm 0.025 \text{ rad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$

φ_s 0.1 σ away from SM
consistent with Standard Model

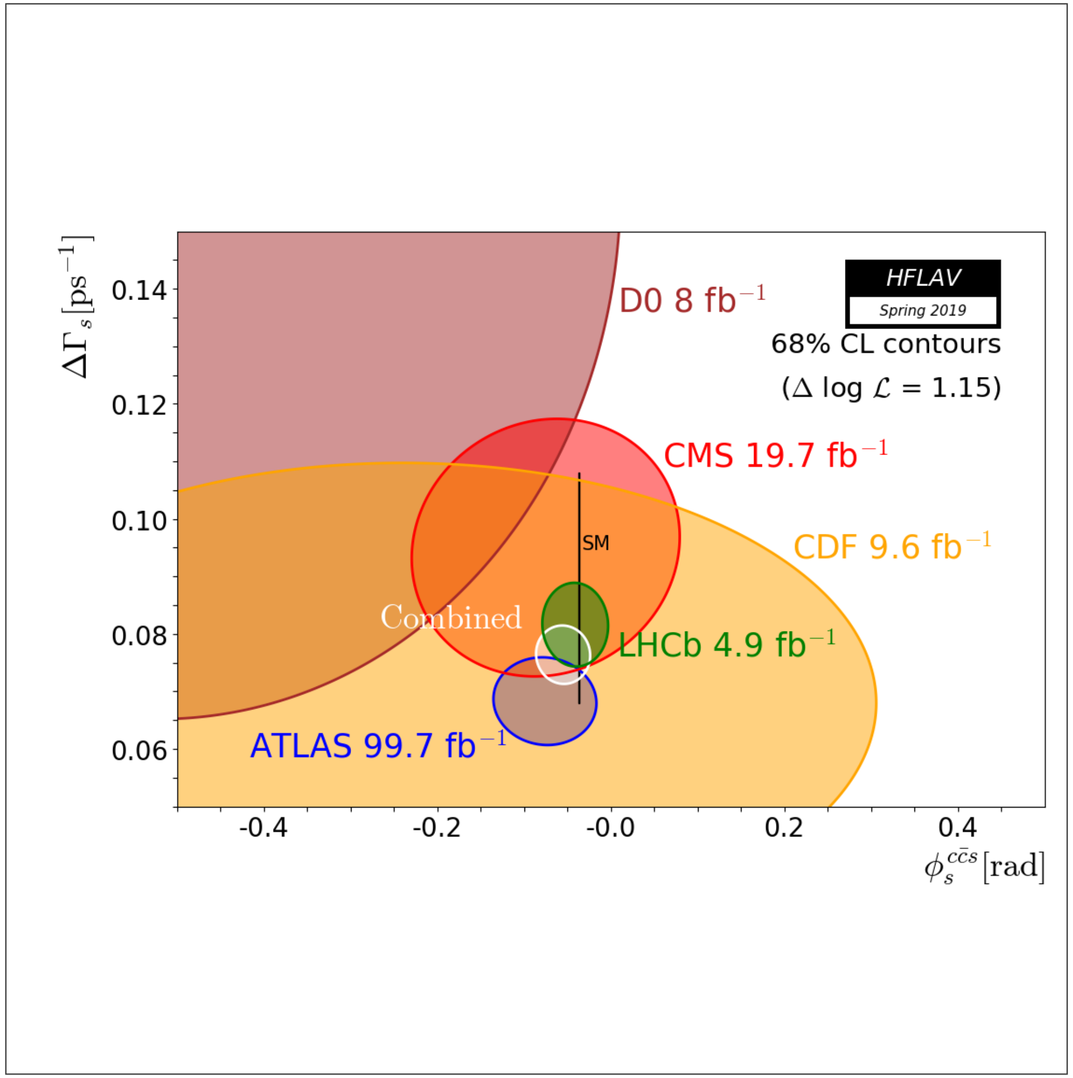
φ_s 1.6 σ away from 0
consistent with no CPV in interference

|λ| consistent with 1
consistent with no direct CPV

$\Gamma_s - \Gamma_d$ consistent with HQE prediction



[LHCb-PAPER-2019-013]



Preliminary

New HFLAV combination

At Moriond EW '19 also ATLAS presented preliminary results exploiting 2015-2017 data using $B_s^0 \to J/\psi K^+K^-$.

ATLAS combination with Run 1 results is:

$$\varphi_s = -0.076 \pm 0.034 \pm 0.019 \text{ rad}$$
$$\Gamma_s = 0.669 \pm 0.001 \pm 0.001 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004 \pm 0.003 \text{ ps}^{-1}$$

[ATLAS-CONF-2019-009]

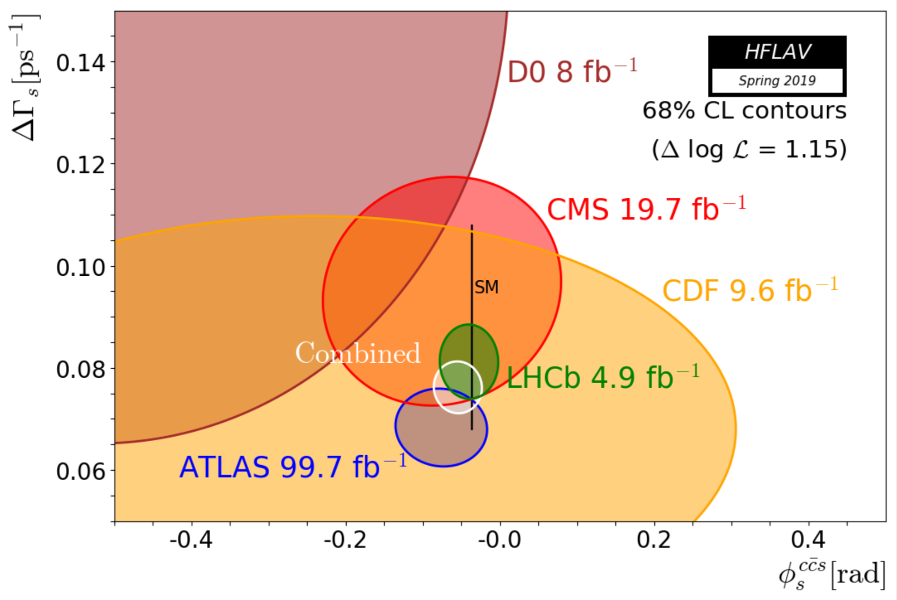
The preliminary HFLAV combination is:

$$\varphi_s = -0.055 \pm 0.021 \text{ rad}$$
$$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1}$$

[HFLAV PRELIMINARY]

Some considerations on the combination

- **Combination among the experiments is getting more and more interesting**
  - Entering in a regime where **penguin pollution** constraints are similar to the precision of the combination
- Strength of LHCb: **versatility** and possibility to measure φ_s also with many other channels, in particular $B_s^0 \to J/\psi\pi^+\pi^-$

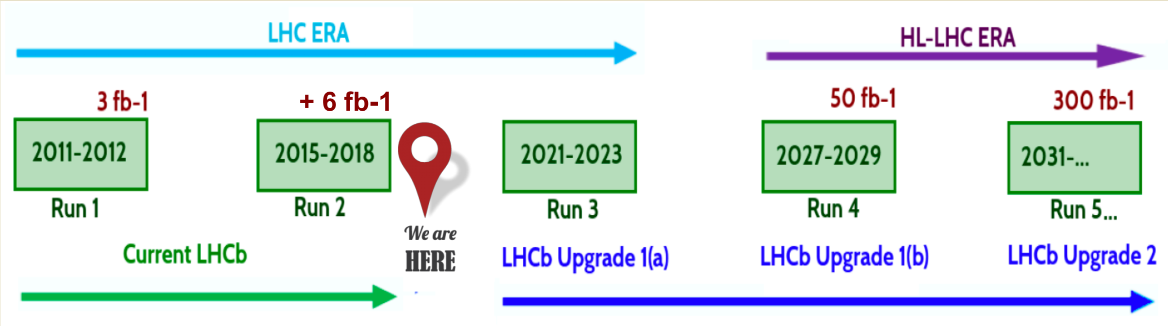


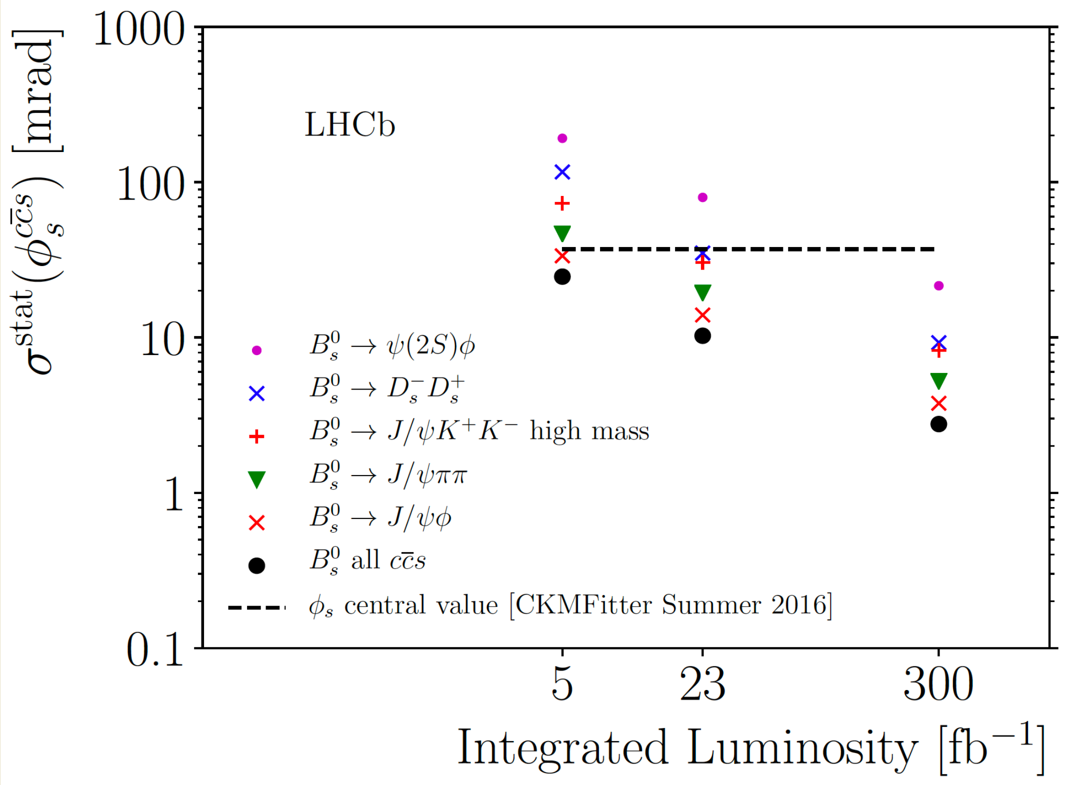
The value of Γ_s **shows tension** between LHCb and ATLAS:

- HFLAV (not including Run 2): $\Gamma_s^{HFLAV} = 0.6629 \pm 0.0018\ \mathrm{ps}^{-1}$
- LHCb Run 2: $\Gamma_s^{LHCb} = 0.6538 \pm 0.0033\ \mathrm{ps}^{-1}$ → $\boldsymbol{-2.4\ \sigma}$ **from WA**
- ATLAS Run 2: $\Gamma_s^{ATLAS} = 0.669 \pm 0.0014\ \mathrm{ps}^{-1}$ → $\boldsymbol{+2.7\ \sigma}$ **from WA**

⇒ Tension between ATLAS and LHCb of >4 σ

Prospects for the future





[LHCB-PUB-2018-009]

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgrade 1
- Same performances as in Run I
  - Assumed tagging power 4%
- Additional modes planned: $J/\psi \to ee, \eta' \to \rho^0\gamma$ or , $\eta' \to \eta\pi\pi$ or $\gamma\gamma$ as cross cheks

300/fb: $\boldsymbol{\sigma^{STAT}(\varphi_s)}$ ~ 4 mrad from $B_s^0 \to J/\psi KK$ only

- Vital FT performance maintains or improves
- **$\boldsymbol{\varphi_s}$ expected to be statistically limited**

Impact of Upgrade I and II very important for $\boldsymbol{\varphi_s}$!

Control of penguin pollution

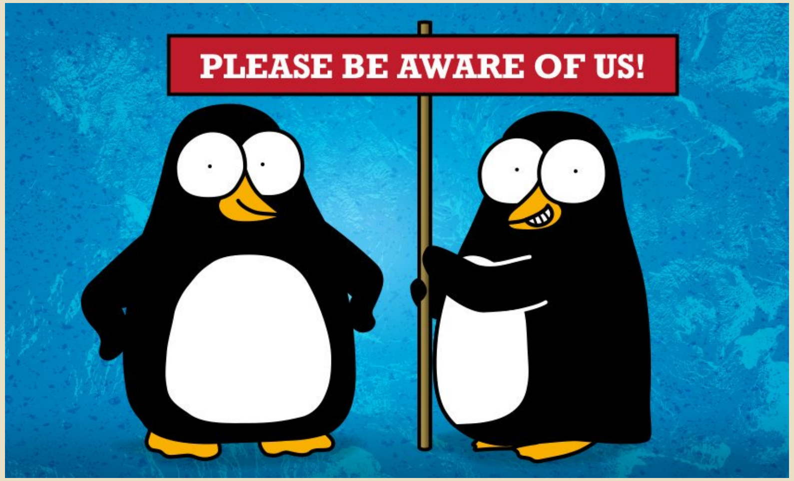
- U-spin or SU(3) flavour symmetry to constrain size of penguin with b→c$\bar{c}$d (related by s-d spectator exchange)
- Penguin pollution and/or CP violation **could be different for each polarisation state**, f ∈ (0, ⊥, ∥, S)

  → no sign yet of dependence in $B_s^0 \to J/\psi$ KK (also in Run 2) so penguins are small

- **SU(3)$_F$: $B_s^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi \rho^0$ are b→c$\bar{c}$d transitions**.

$$\Delta\phi_{s,0}^{J/\psi\,\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ {}^{+0.004}_{-0.009}\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\,\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\,\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$

[JHEP 11 (2015) 082]



Precision of ~10 mrad
To be compared with the current precision of HFLAV of **21 mrad**

Fundamental to update these analyses, expected sensitivity **at 300/fb is 1.5 mrad** (statistically limited)
+ adding $B_s^0 \to J/\psi\omega$ and $B^0 \to J/\psi\varphi$ (E + PA diagrams only)

Conclusions and remarks

- Interest in precision flavour measurements is stronger than ever

  ⇒ If no direct evidence of NP pops out of the LHC, flavour physics can play a key role.

- All results in this sector in **good agreement with SM**, need to go to even **higher precision**: x2 statitics already available in Run 2.

- **Good prospects for the precision measurements in the Upgrade** phase of LHCb. Considering all modes:

$$\boxed{300/\text{fb}: \sigma^{STAT}(\varphi_s) \sim 3\text{ mrad}}$$

  statistically limited.

"And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!"

BACKUP

Historical record of indirect discoveries

GIM Mechanism

Observed branching ratio $K^0 \rightarrow \mu\mu$

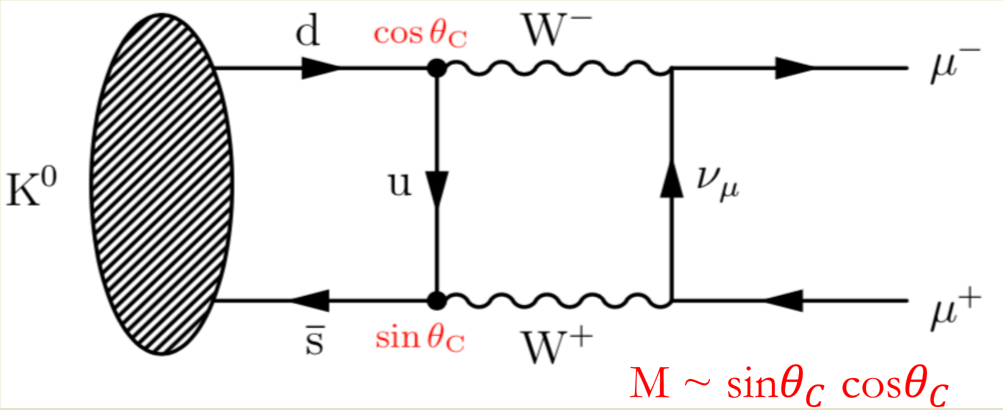
$$\frac{BR(K_L \rightarrow \mu^+\mu^-)}{BR(K_L \rightarrow all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

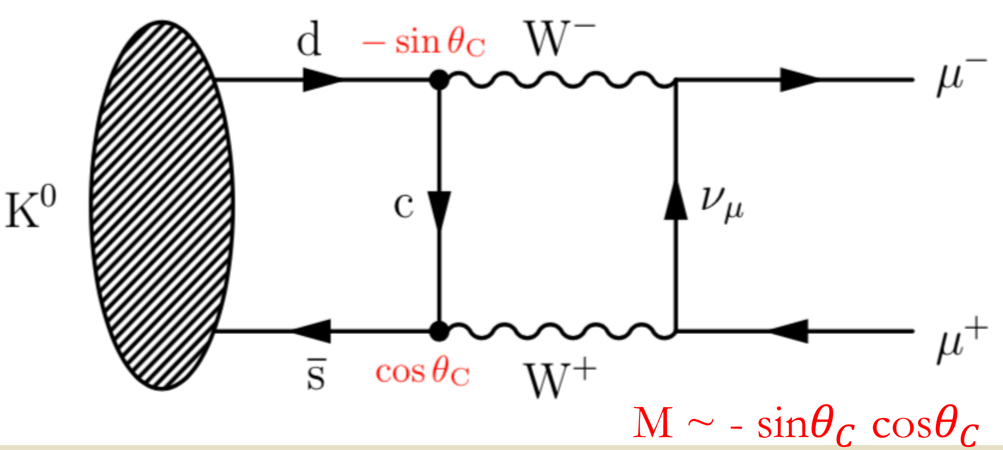
In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopoulos, Maiani (1970):

Prediction of a 2nd up-type quark (1972), additional Feynman graph cancels the «u box graph»

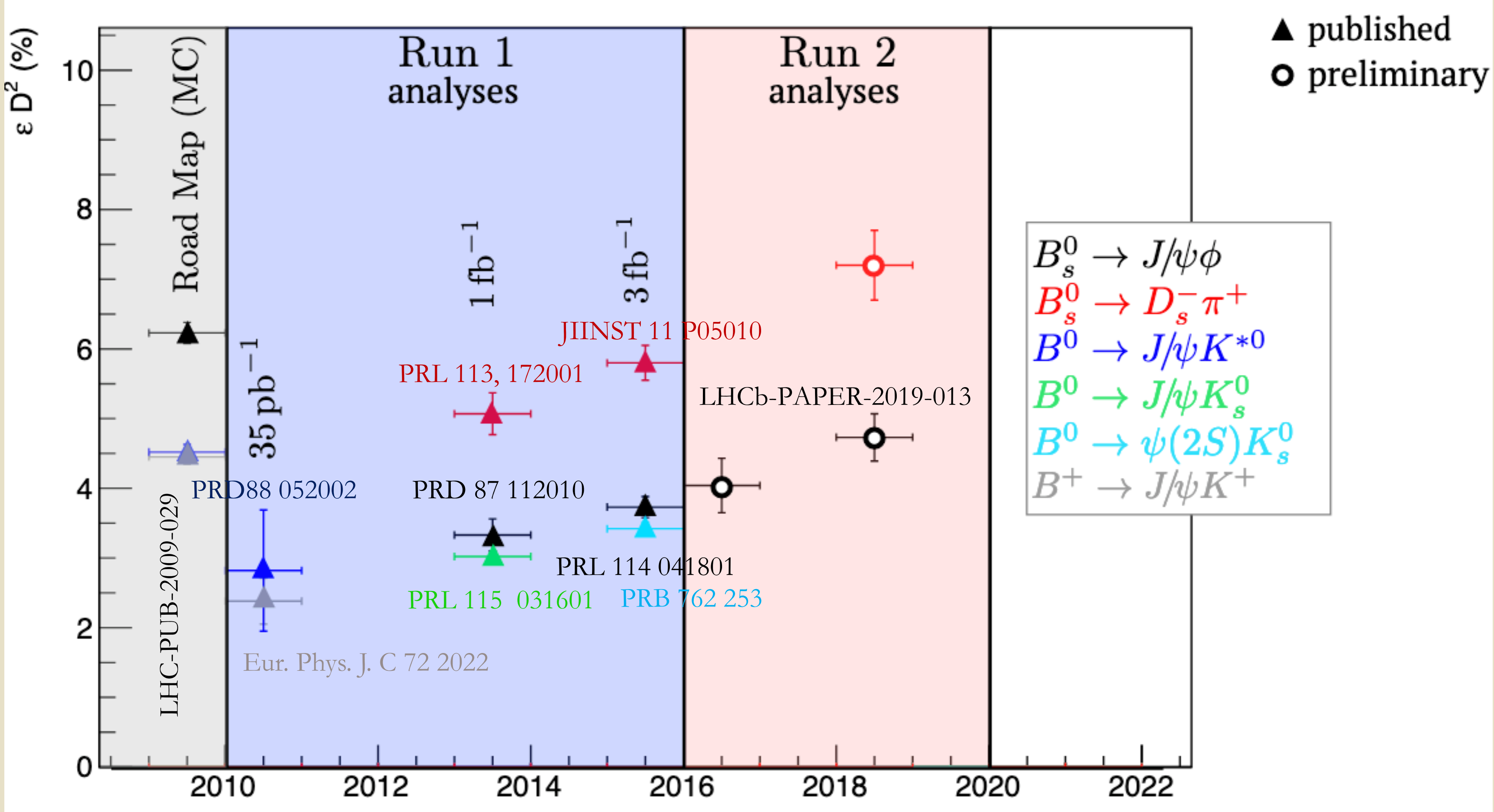
But also e.g. CPV $K^0 \rightarrow \pi\pi$ that brought to CKM and 3rd generation, B mixing that brought to top mass extrapolation



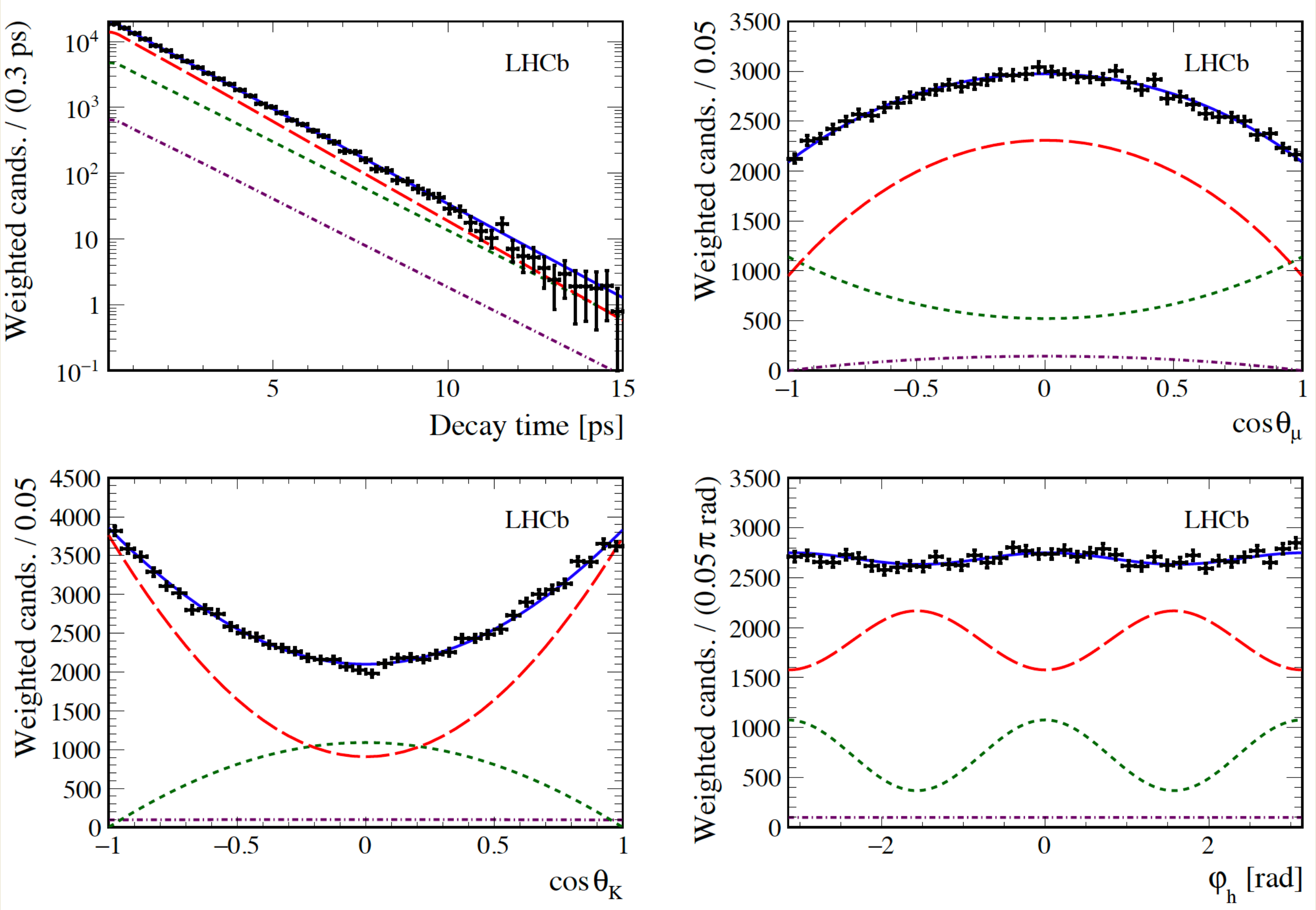


Flavour tagging - references

Courtesy of S. Akar



Fit projections $B_s^0 \rightarrow J/\psi KK$



FULL LIST OF FITTED VARIABLES $B_s^0 \to J/\psi KK$

Table 4: Parameter estimates for the nominal fit. The first uncertainty is statistical and the second systematic.

Parameter	Value
ϕ_s [rad]	$-0.080 \pm 0.041 \pm 0.006$
$\lvert\lambda\rvert$	$1.006 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0772 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.705 \pm 0.059 \pm 0.018$
$\lvert A_\perp\rvert^2$	$0.2457 \pm 0.0040 \pm 0.0019$
$\lvert A_0\rvert^2$	$0.5186 \pm 0.0029 \pm 0.0024$
$\delta_\perp - \delta_0$	$2.64 \pm 0.13 \pm 0.10$
$\delta_\parallel - \delta_0$	$3.061^{+0.084}_{-0.073} \pm 0.037$

Table 5: The correlation matrix including the statistical and systematic correlations between the parameters.

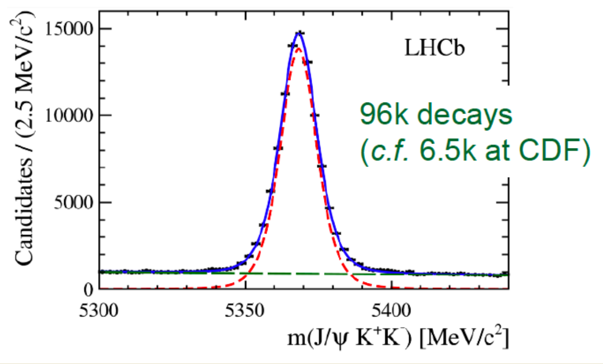
	ϕ_s	$\lvert\lambda\rvert$	$\Gamma_s - \Gamma_d$	$\Delta\Gamma_s$	Δm_s	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\perp$	$\delta_\parallel$
ϕ_s	1.00	0.16	-0.05	0.02	0.01	-0.03	0.00	0.04	-0.01
$\lvert\lambda\rvert$		1.00	0.06	-0.09	0.07	0.05	-0.02	0.09	0.02
$\Gamma_s - \Gamma_d$			1.00	-0.46	0.07	0.35	-0.24	0.04	0.05
$\Delta\Gamma_s$				1.00	-0.06	-0.65	0.46	-0.10	-0.02
Δm_s					1.00	0.01	0.01	0.61	-0.00
$\lvert A_\perp\rvert^2$						1.00	-0.64	0.07	0.09
$\lvert A_0\rvert^2$							1.00	-0.03	-0.02
$\delta_\perp$								1.00	0.24
$\delta_\parallel$									1.00

LHCb in the φ_s game

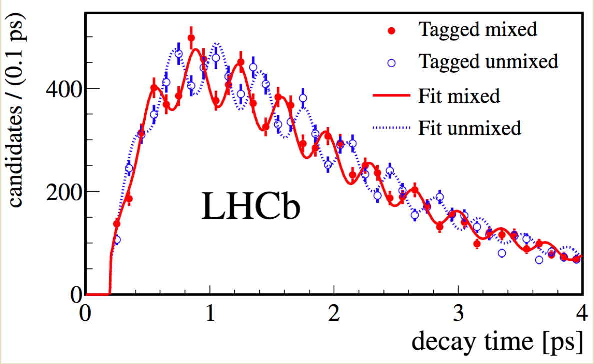
LHCb optimised with φ_s as a key goal. In particular it brings to the game:

High signal yields and high purity

[PRL 114 (2015) 041801]



Excellent decay-time resolution

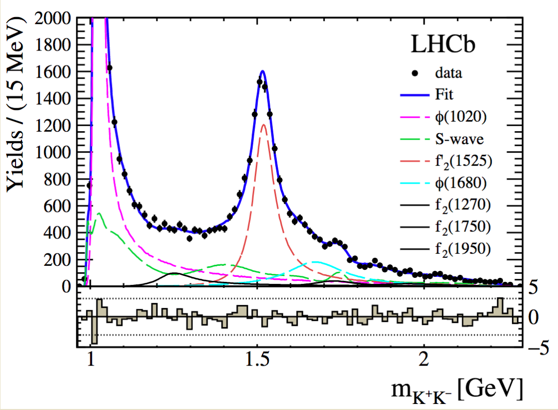


[New J. Phys. 15 (2013) 053021]

And in addition new modes and analysis techniques:

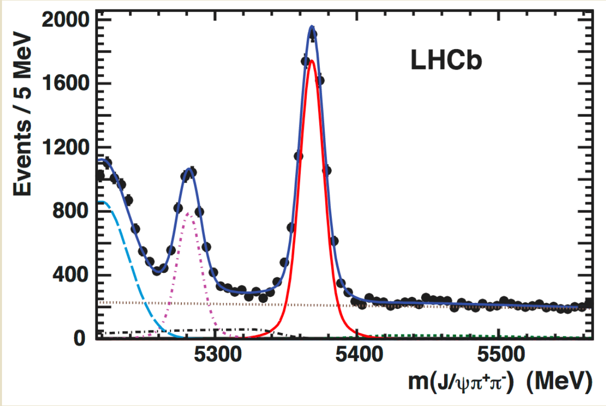
Inclusion of $J/\psi KK$ decays above the φ

[JHEP 08 (2017) 037]



Inclusion of $J/\psi\pi\pi$ decays:
Simpler analysis wrt $J/\psi\varphi$

[PLB 713 (2012) 378]

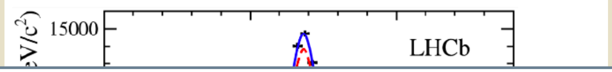


LHCb entered the game

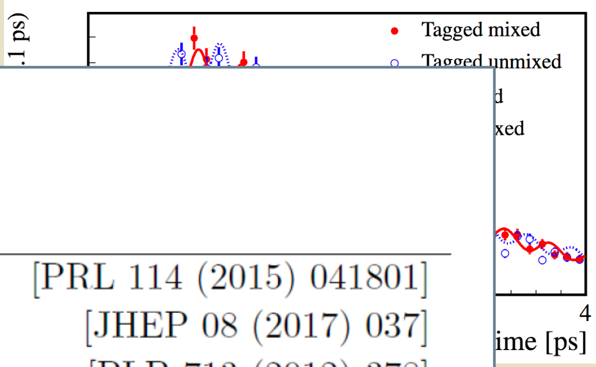
LHCb optimised with φ_s as a key goal. In particular it brings to the game:

Enormous signal yields

[PRL 114 (2015) 041801]



Excellent proper time resolution



[New J. Phys. 15 (2013) 053021]

LHCb Run I results:

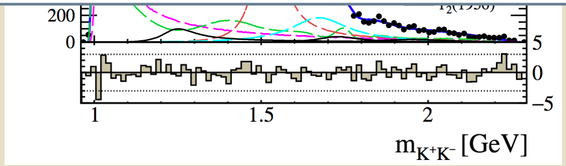
$J/\psi K^+K^-$ in ϕ region	$-58 \pm 49 \pm 6$ mrad	[PRL 114 (2015) 041801]
$J/\psi K^+K^-$ in high mass K^+K^- region	$119 \pm 107 \pm 34$ mrad	[JHEP 08 (2017) 037]
$J/\psi \pi^+\pi^-$	$70 \pm 68 \pm 8$ mrad	[PLB 713 (2012) 378]
Overall	1 ± 37 mrad	

Other measurements:

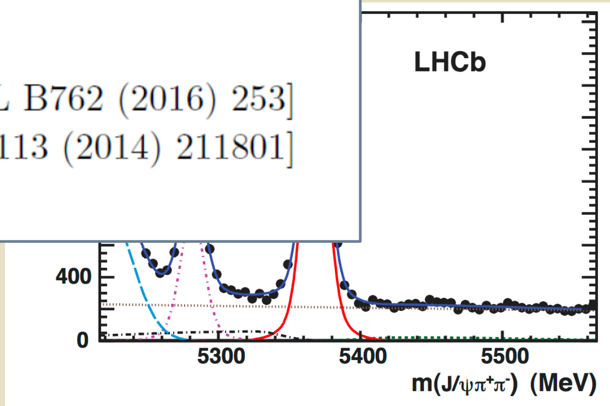
$\psi(2S)\phi$	$230^{+290}_{-280} \pm 20$ mrad	[PRL B762 (2016) 253]
$D_s^+D_s^-$	$20 \pm 170 \pm 20$ mrad	[PRL 113 (2014) 211801]

And in add

Inclusion of J/ψ
decays above the



analysis



[JHEP 08 (2017) 037]

[PLB 713 (2012) 378]

ATLAS systematics

Table 5: Summary of systematic uncertainties assigned to the physical parameters of interest.

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	1.7×10^{-2}	0.4×10^{-3}	0.3×10^{-3}	0.2×10^{-3}	0.2×10^{-3}	2.3×10^{-3}	1.9×10^{-2}	2.2×10^{-2}	2.2×10^{-3}
Acceptance	0.7×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.8×10^{-3}	0.7×10^{-3}	2.4×10^{-3}	3.3×10^{-2}	1.4×10^{-2}	2.6×10^{-3}
ID alignment	0.7×10^{-3}	0.1×10^{-3}	0.5×10^{-3}	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	1.0×10^{-2}	7.2×10^{-3}	$<10^{-4}$
S–wave phase	0.2×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.3×10^{-3}	$<10^{-4}$	0.3×10^{-3}	1.1×10^{-2}	2.1×10^{-2}	8.3×10^{-3}
Background angles model:									
Choice of fit function	1.8×10^{-3}	0.8×10^{-3}	$<10^{-4}$	1.4×10^{-3}	0.7×10^{-3}	0.2×10^{-3}	8.5×10^{-2}	1.9×10^{-1}	1.8×10^{-3}
Choice of p_T bins	1.3×10^{-3}	0.5×10^{-3}	$<10^{-4}$	0.4×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	1.0×10^{-3}
Choice of mass interval	0.4×10^{-3}	0.1×10^{-3}	0.1×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	1.3×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	2.3×10^{-3}
Dedicated backgrounds:									
B_d^0	2.3×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.2×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1.0×10^{-2}	2.3×10^{-2}	2.1×10^{-3}
Λ_b	1.6×10^{-3}	0.4×10^{-3}	0.2×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.8×10^{-3}	1.4×10^{-2}	2.9×10^{-2}	0.8×10^{-3}
Fit model:									
Time res. sig frac	1.4×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.5×10^{-3}	0.6×10^{-3}	0.6×10^{-3}	1.2×10^{-2}	3.0×10^{-2}	0.4×10^{-3}
Time res. p_T bins	3.3×10^{-3}	1.4×10^{-3}	0.1×10^{-2}	$<10^{-4}$	$<10^{-4}$	0.5×10^{-3}	6.2×10^{-3}	5.2×10^{-3}	1.1×10^{-3}
Total	1.8×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.2×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	9.7×10^{-2}	2.0×10^{-1}	0.1×10^{-1}

Penguin pollution roadmap

- With increasing precision crucial to understand penguin pollution
- Can use U-spin and SU(3) related modes, where penguin not suppressed, to determine its size [S. Faller, R. Fleischer, M. Jung, T. Mannel, arXiv:0809.0842]

Golden modes: $b \to c\bar{c}s$ amplitude ($i = 0, \parallel, \perp$)

$$A'_i(b \to c\bar{c}s) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}'_i \left[1 + \epsilon a'_i e^{i\theta'} e^{i\gamma}\right]$$

$a'_i e^{i\theta'}$: Penguin/Tree ratio in $b \to c\bar{c}s$ where $\lambda \equiv |V_{us}| \approx 0.226, \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.054, \gamma$ unitarity triangle angle.

Control modes: $b \to c\bar{c}d$ amplitude

$$A_i(b \to c\bar{c}d) = -\lambda \mathcal{A}_i \left[1 + a_i e^{i\theta} e^{i\gamma}\right]$$

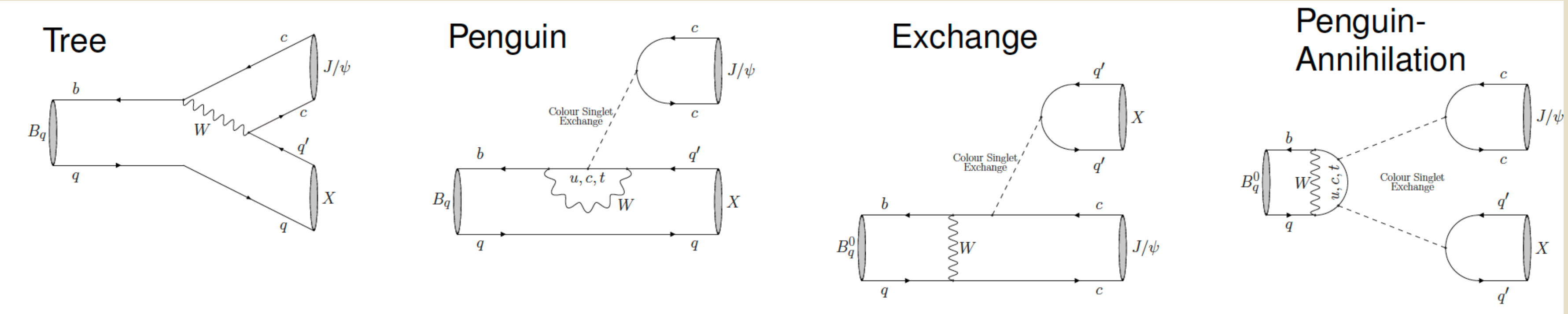
$a'_i e^{i\theta'}$: Penguin/Tree ratio in $b \to c\bar{c}d$

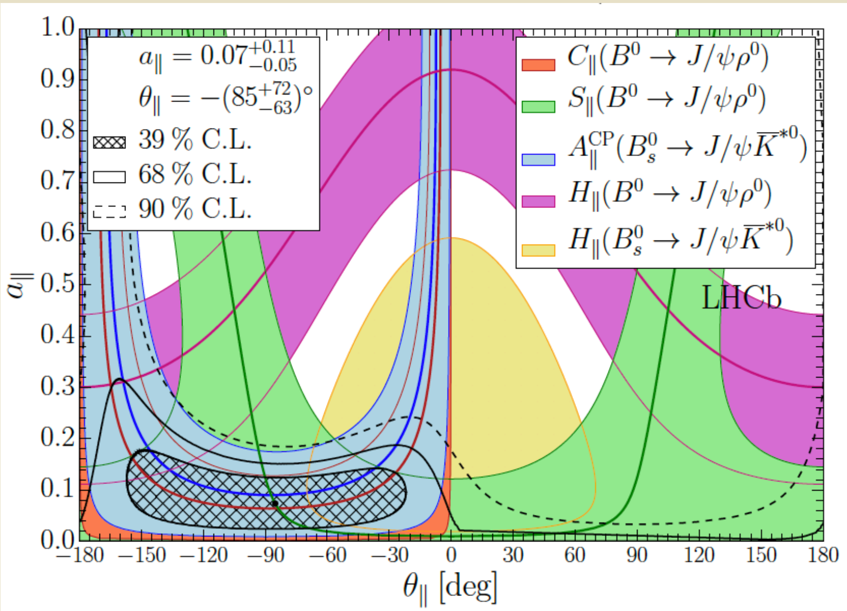
Overall λ factor, BF is suppressed

Absence of ϵ, penguin effects are magnified.

SU(3): $a'_i = a_i, \theta'_i = \theta_i$. Extract $\boldsymbol{\Delta\varphi_s^{peng}(a_i, \theta_i)}$ **and** $\boldsymbol{\Delta\beta^{peng}(a_i, \theta_i)}$ from t to CP parameters and BF.

Penguin pollution roadmap φ_s





De Bruyn, Fleischer, JHEP 03 (2015) 145

Studied at LHCb with 3 fb^{-1}:

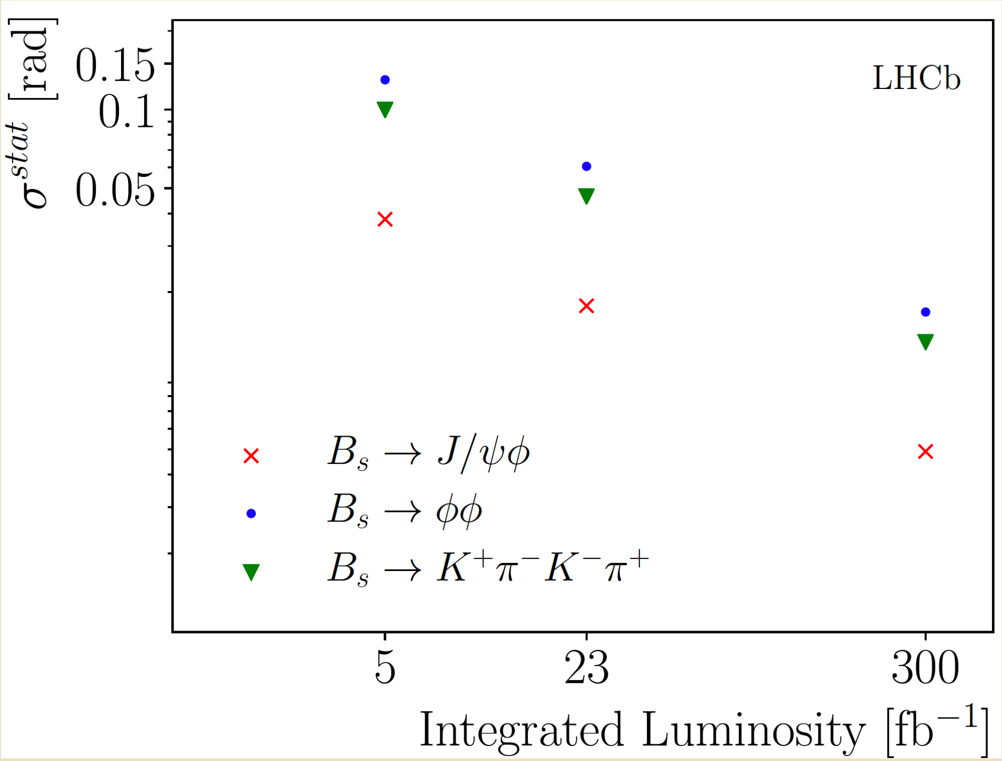
- $B^0 \to J/\psi\rho$ (BF, C and S) [JHEP11(2015)082]
- $B_s^0 \to J/\psi K^{*0}$ (BF and C), has no PA and E [PLB742(2015)38-49]

Measure penguin phase shift for each polarisation state,f ∈ (0, ⊥, ∥, S) [JHEP 11 (2015) 082]

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ {}^{+0.004}_{-0.009}\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$

Small penguin shift ~0.06° wrt experimental precision $\boldsymbol{\sigma(\varphi_s)\sim 1.7^\circ}$!!

Side note: φ_s from penguin decays



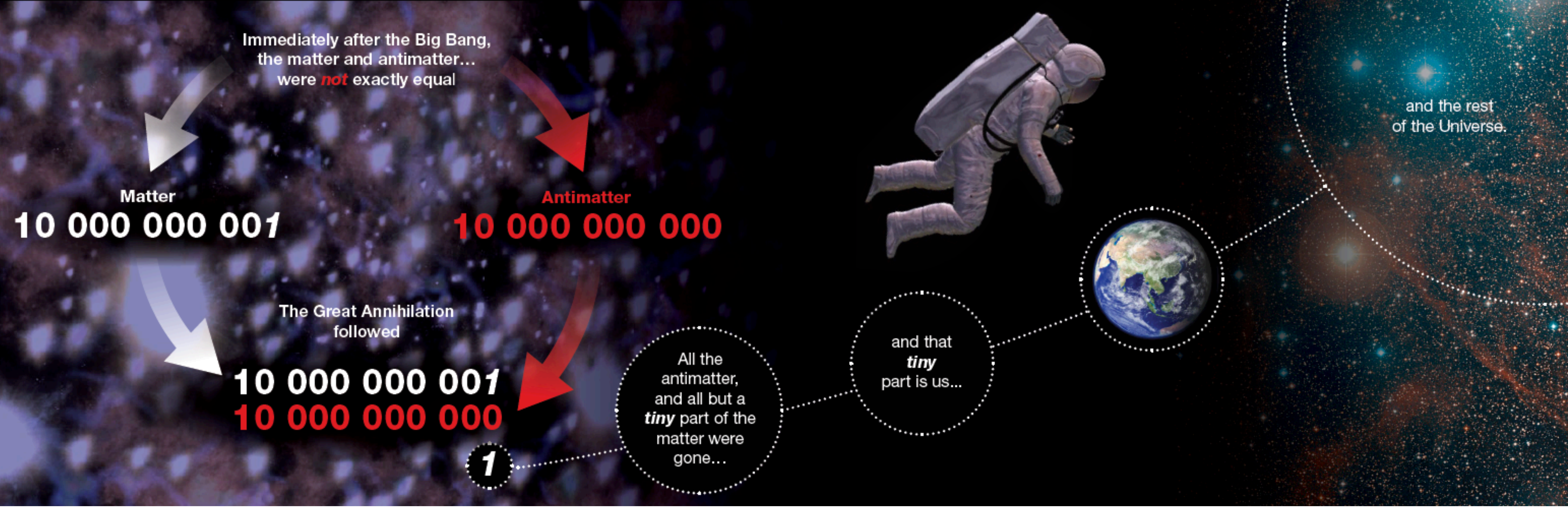
[LHCB-PUB-2018-009]

- Include gain in trigger after Upgrade 1

300/fb: $\boldsymbol{\sigma^{STAT}(\varphi_s)} \sim$ 11 mrad from $B_s^0 \to \phi\phi$

300/fb: $\boldsymbol{\sigma^{STAT}(\varphi_s)} \sim$ 9 mrad from $B_s^0 \to K\pi K\pi$

- $B_s^0 \to \phi\phi$ will remain stat. limited
- Limiting syst for $B_s^0 \to K\pi K\pi$ <30 mrad from MC (important to exploit rapid MC production) and modelling resonances.



Sakharov Conditions

[A. D. Sakharov, JETP Lett.5, 24 (1967)]

1. Baryon Number Violation
2. **C and CP violation**
3. Interactions out of thermal equilibrium

[Rev. Mod. Phys. 88, 015004 (2016)]

- Baryon asymmetry of the Universe: $n_b/n_\gamma \sim 10^{-10}$
- CP violation in the SM does not account for it
- There must be **New Physics** and **new sources of CP violation**