Measurement of CP-violating phase ϕ_s in the LHCb experiment

11/12/2019, mini-simposio fisica delle alte energie

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Introduction: **the problem of matter-antimatter asymmetry**

Problem: our Universe is made almost entirely from matter…
So where is the antimatter ?

Necessary ingredient: violation of the CP simmetry (CPV) !

$\boldsymbol{V_{qq'} \neq V^{*}_{\overline{q}\overline{q}'}}$ $\Rightarrow$ The **only CPV source** in the SM !
Not enough to explain the matter-antimatter asymmetry.
⇓
Possible existance of new CPV sources not described by the SM
⇓
Perform many mesurements of CP violation to test the SM

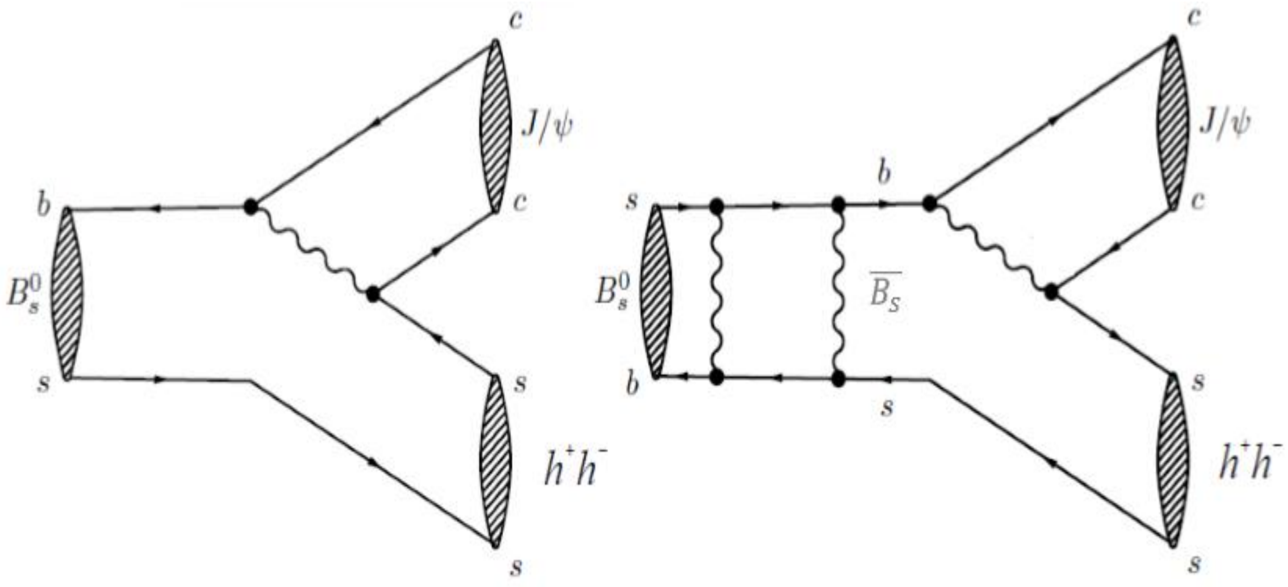
Mass eigenstates

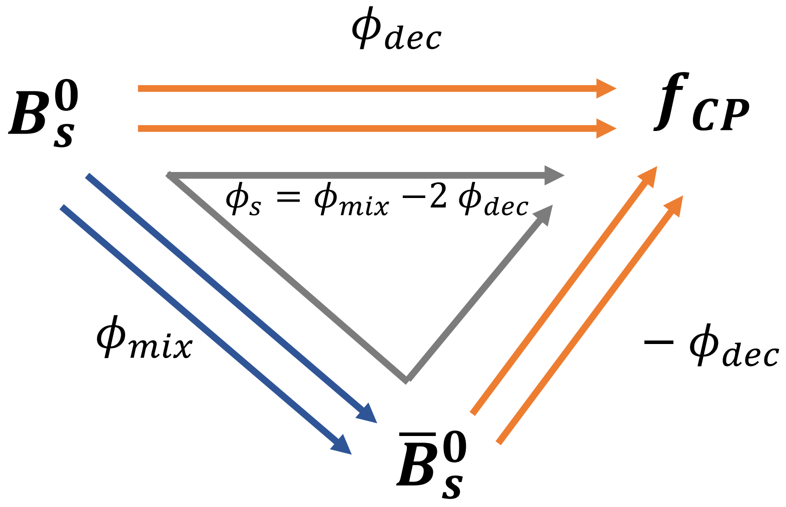
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

Flavour eigenstates

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

Introduction: **CP violation in the Standard Model**

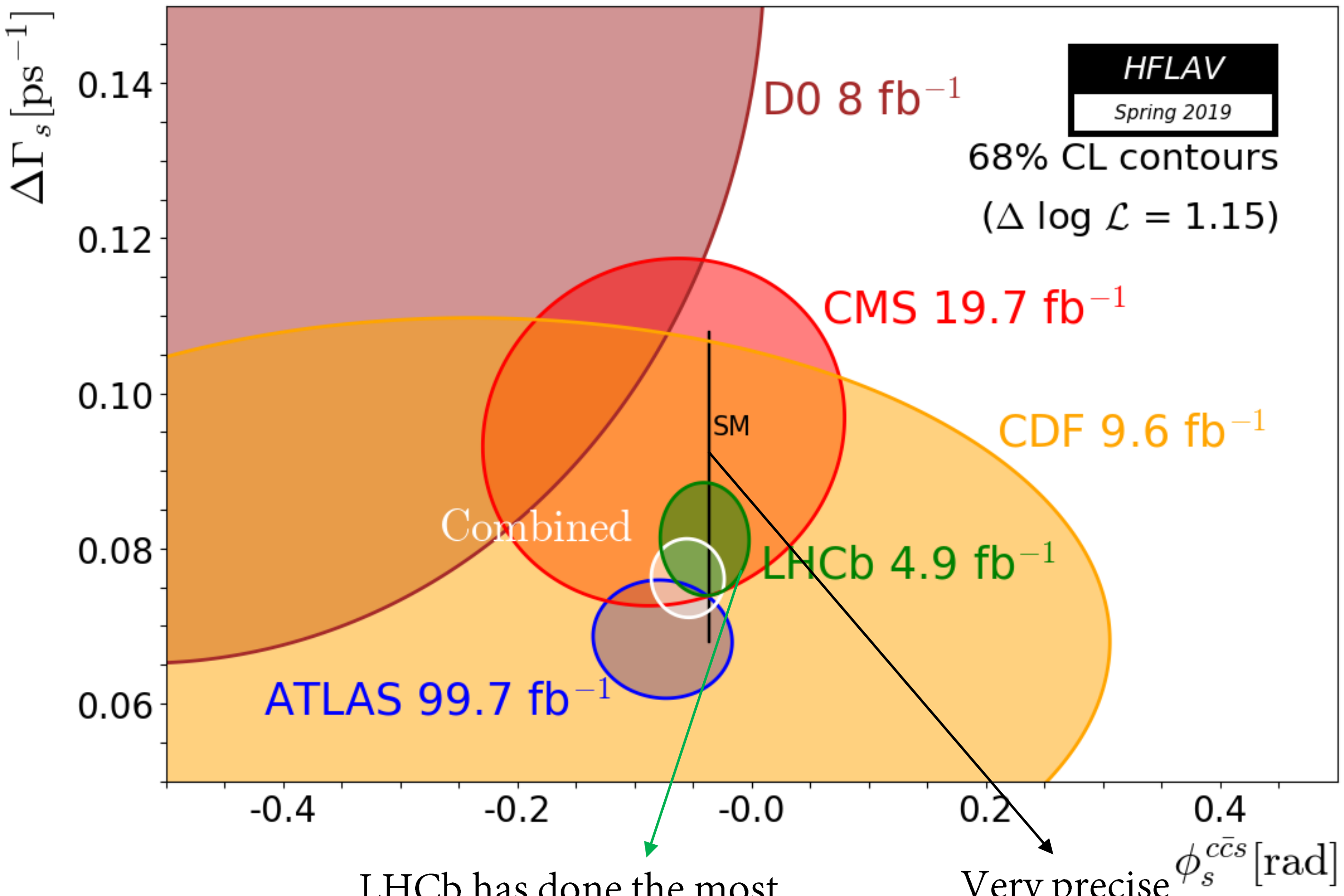




Theory prediction: $\boldsymbol{\phi_s^{SM} \approx -0.03686^{+0.00096}_{-0.00068}}$ **rad**

Very precise so **perfect to search for new sources of CP violation !**

Measurement of ϕ_s: state of the art



LHCb has done the most precise measurement until now

Very precise prediction

LHCb: $\boldsymbol{\phi_s = -0.040 \pm 0.025}$ rad

Combined: $\boldsymbol{\phi_s = -0.055 \pm 0.021}$ rad

Decay channels for ϕ_s measurement at LHCb

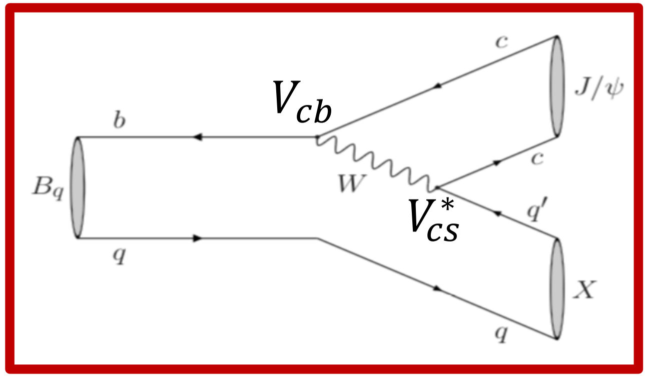
$B_s^0 \to J/\psi K^+K^-$

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

$B_s^0 \to D_s D_s$

$B_s^0 \to \psi(2S)\phi$

The decay investigated by me is $\boldsymbol{B_s \to J/\psi\pi^+\pi^-}$



Measurement of ϕ_s: analysis strategy

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

Theoretical distribution

Experimental effects

$$\frac{d\Gamma}{dt\,dm_{hh}\,d\Omega} \sim \sum_{k=1}^{10} f(\Omega, m_{hh})\, h_k(t|B_s) \oplus G(t, \sigma_t)\, \epsilon(t,\Omega)(1-2\omega)$$

σ_t → resolution

ϵ → efficiency

ω → B_s o $\overline{B_s}$

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

Measurement of ϕ_s: where? The LHCb experiment

Single arm spectrometer designed for high precision flavour physics measurements!

Most important features:

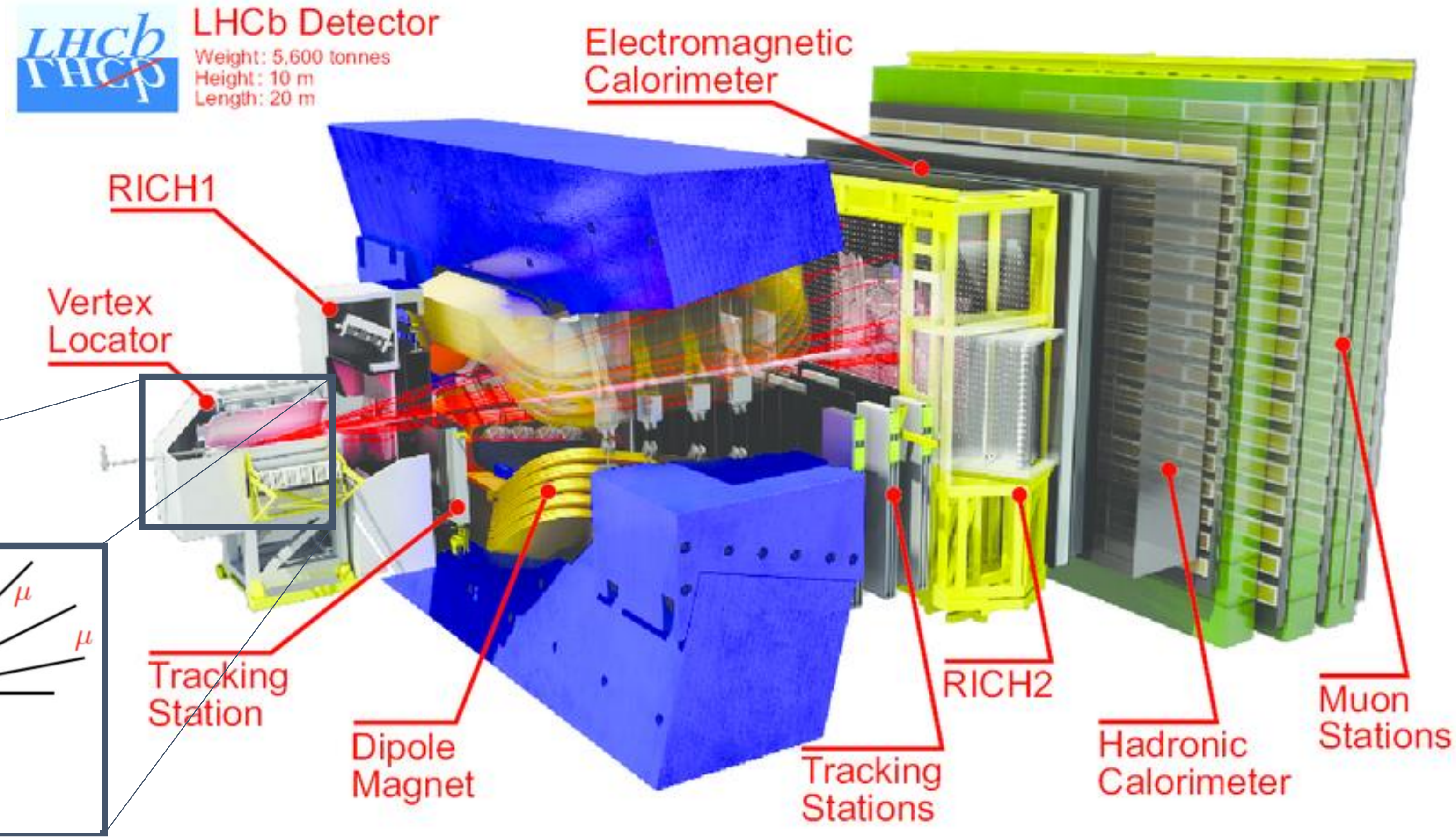
- **Decay time resolution ~45 fs**
- **PV resolution ~70 μm along collision axis**
- **Δp/p = 0.4-0.6% @ 5-100 GeV/c**
- **Excellent particle identification**

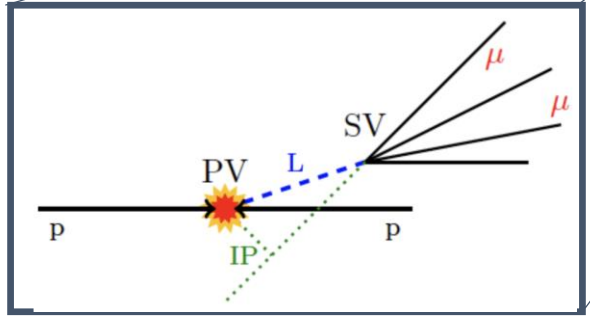
Large number of beauty hadrons:

$\sigma_{b\bar{b}}$(7 TeV) = 72.0 ± 0.3 ± 6.8 μb

$\sigma_{b\bar{b}}$(13 TeV) = 154.3 ± 1.5 ± 14.3 μb

[PRL 118 (2017) 052002]





Measurements of ϕ_s using $B_s^0 \to J/\psi\pi^+\pi^-$ channel

Analysis already done with 2015-2016 data.

Current value with this channel

To be improved to test SM ← $\phi_s = -0.057 \pm 0.060 \pm 0.011$ rad → NO CPV

[https://arxiv.org/pdf/1903.05530.pdf]

My work: **Addition of 2017 2018 data** to gain a **factor 3 of statistical power**.

- **Candidates selection**
- **Measurement of decay time resolution**
- **Flavour tagging performances**

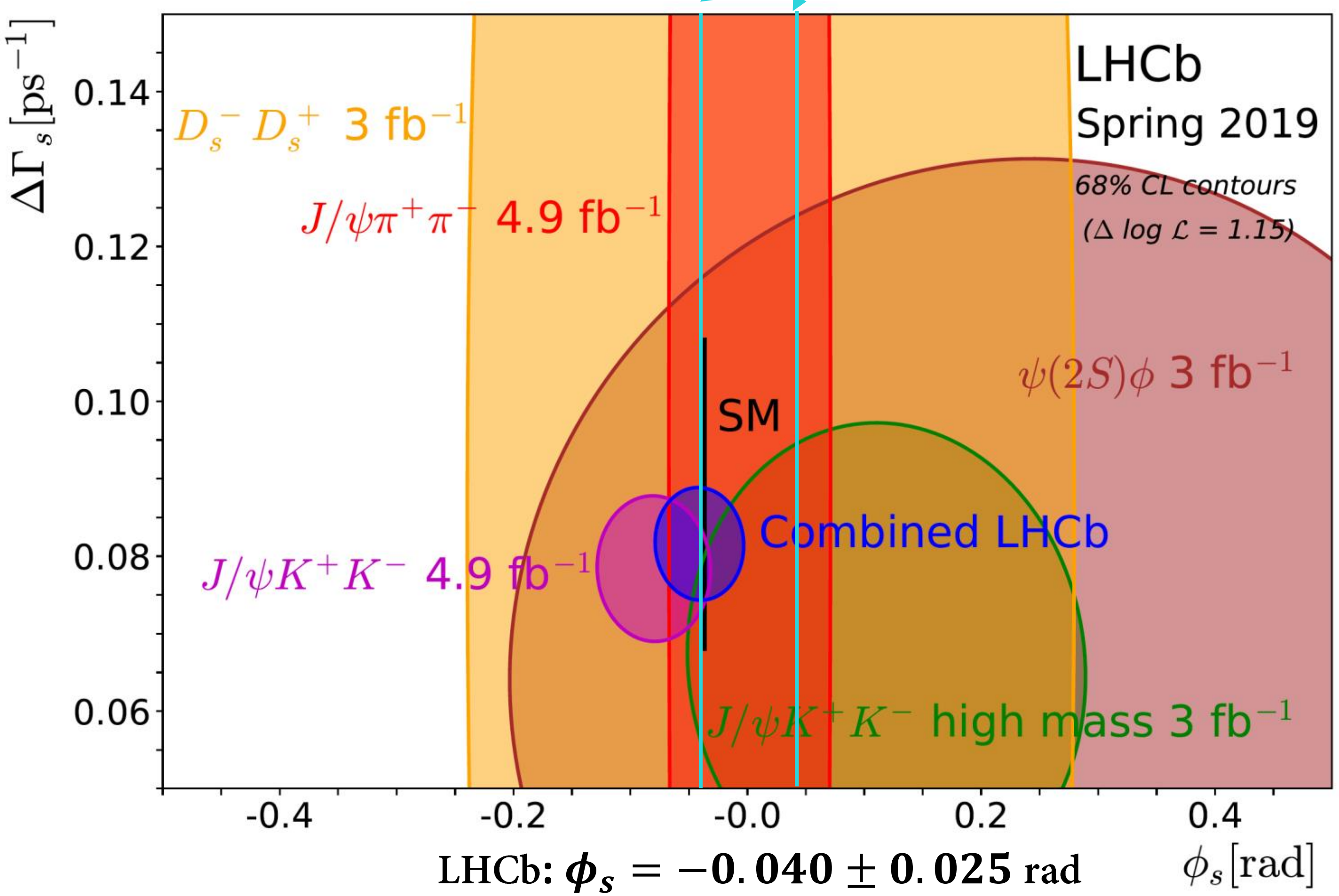
} Done in Cagliari

- Study of angular and time acceptances
- Final fit to determine φ_s

} Will be done from Tsinghua University

Expected precision of ϕ_s in $B_s^0 \to J/\psi\pi\pi$ analysis with full RUN2 data

Extrapolated precision for Run 2



LHCb: $\boldsymbol{\phi_s = -0.040 \pm 0.025}$ rad

Preliminary results

Number of candidates:

- 2015: 4700 ± 90
- 2016: 31300 ± 200
- 2017: 27500 ± 200
- 2018: 38200 ± 250

$\phi_s = -0.057 \pm 0.060 \pm 0.011$ rad
[https://arxiv.org/pdf/1903.05530.pdf]

This analysis with **data from 2015 to 2018**:
$\phi_s = xxx \pm 0.036 \pm xxx$ rad

NB: $\varphi_s^{SM} \approx -0.03686^{+0.00096}_{-0.00068}$ rad

Very important improvement expected on $\boldsymbol{\phi_s}$ precision using RUN2 data using just this channel !

BACKUP

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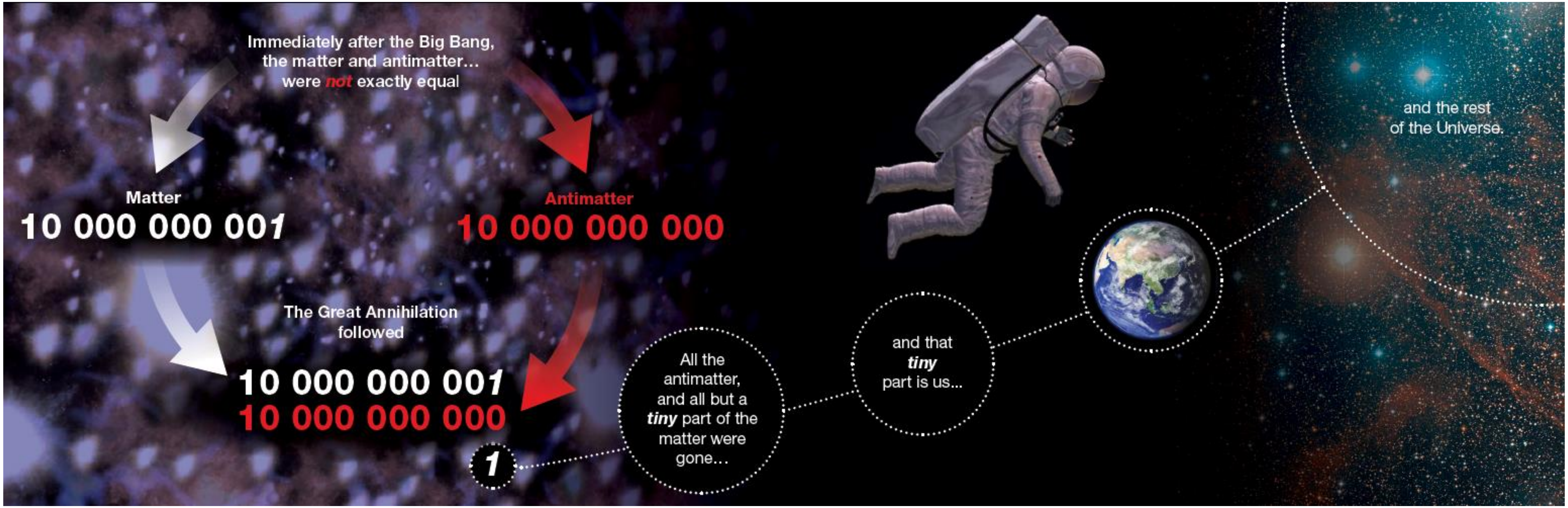


Sakharov Conditions

[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)]

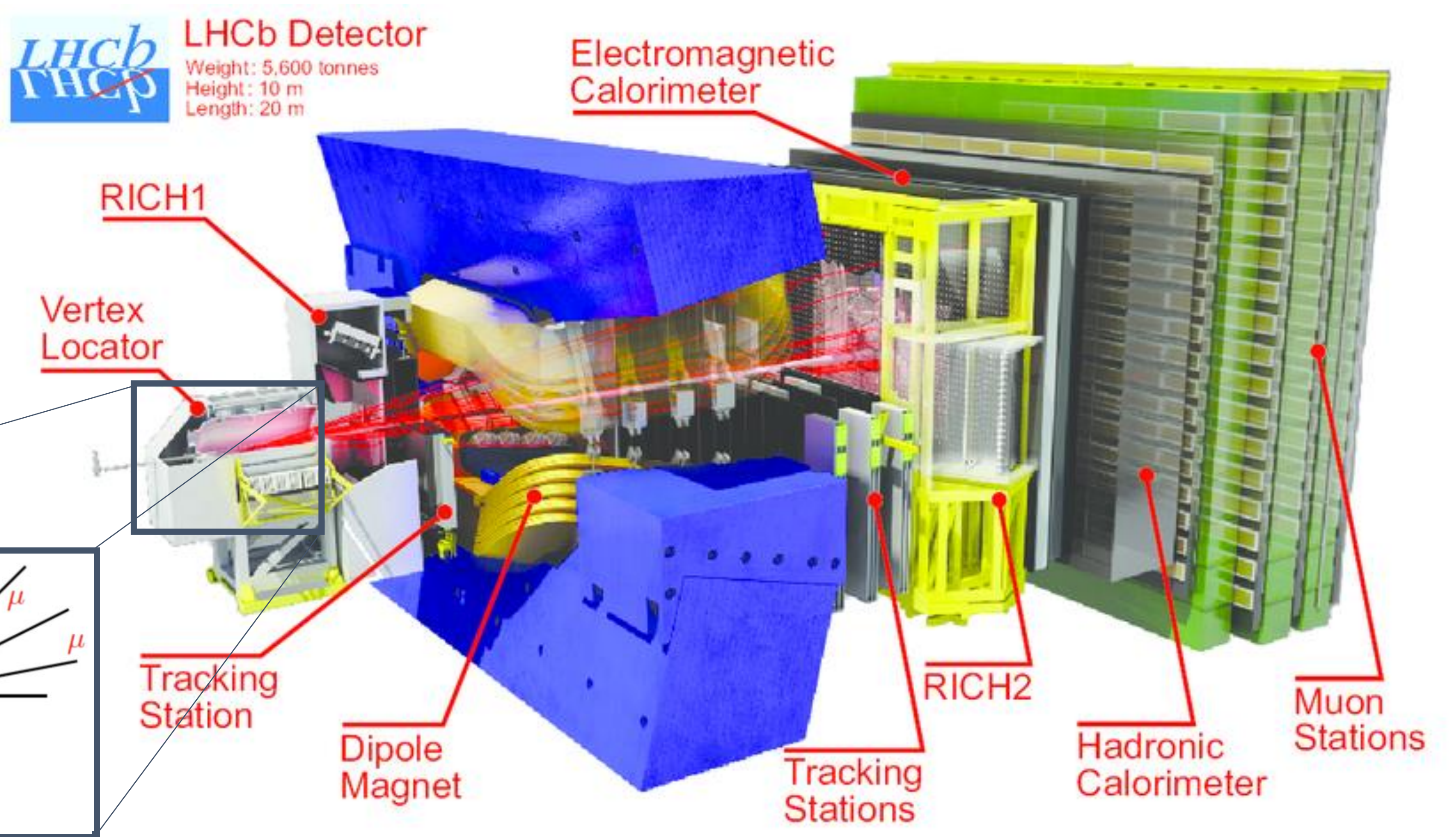
- Baryon asymmetry of the Universe: $n_b/n_\gamma \sim 10^{-10}$
- CP violation in the SM does not account for it
- There must be **New Physics** and **new sources of CP violation**

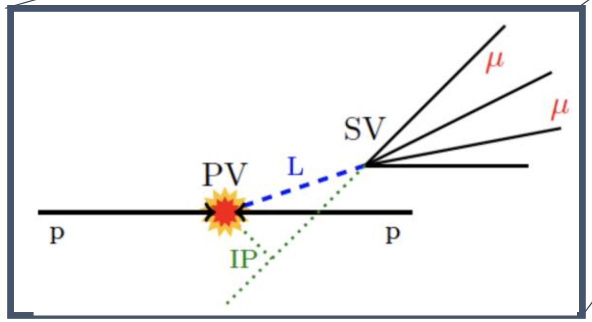
BACKUP

Single arm spectrometer designed for high precision flavour physics measurements !

Most important featurs:

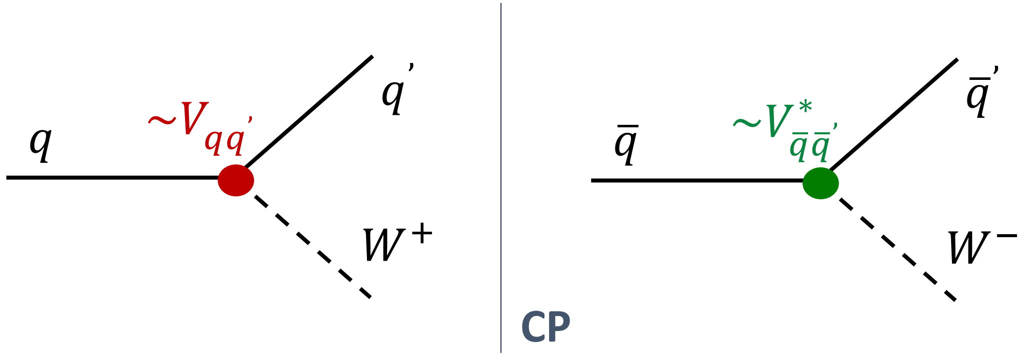
- **Decay time resolution ~45 fs**
- **PV resolution ~70 μm along collision axis**
- **Δp/p = 0.4-0.6% @ 5-100 GeV/c**
- **Tracking eff. > 96%**
- **Mass res. ~8 MeV/c^2 for B $\longrightarrow$ J/ψ X decays**
- **Kaon ID eff. ~95%**
- **Pion mis-ID fraction of ~5%**
- **Muon ID eff. ~97%**

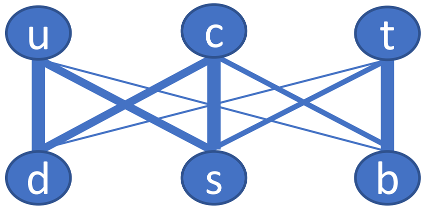




Introduction: **CP violation in the Standar Model**

In the Standard Model (SM) quark can transform into another quark thanks to the weak interaction:





The probability for such a transition depends on the elements of Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$\underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{Mass eigenstates}} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix} \cdot \underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{Flavour eigenstates}}$$

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

If $V_{qq'} \neq V^*_{\bar{q}\bar{q}'} \Rightarrow$ There is CPV

This is the **only CPV source** in the SM !
But **it is not enough** to explain the matter-antimatter asymmetry.
⇓
It is possible that there are new CPV sources not described by the SM
⇓
Perform many mesurements of CP violation to test the SM

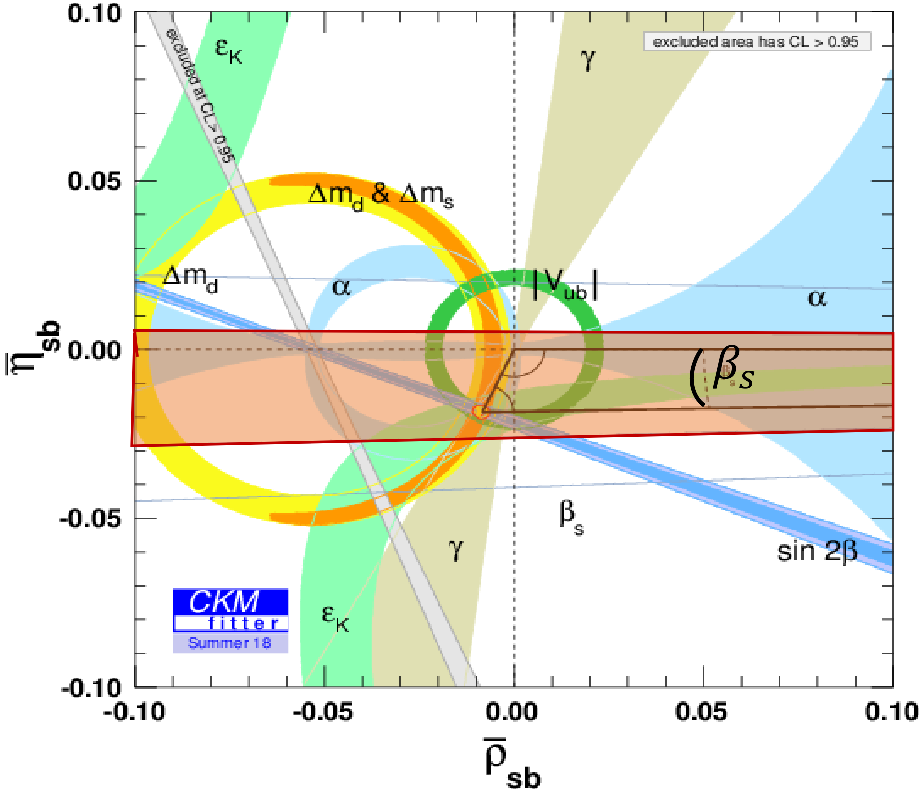
Introduction: **CP violation in the Standard Model**

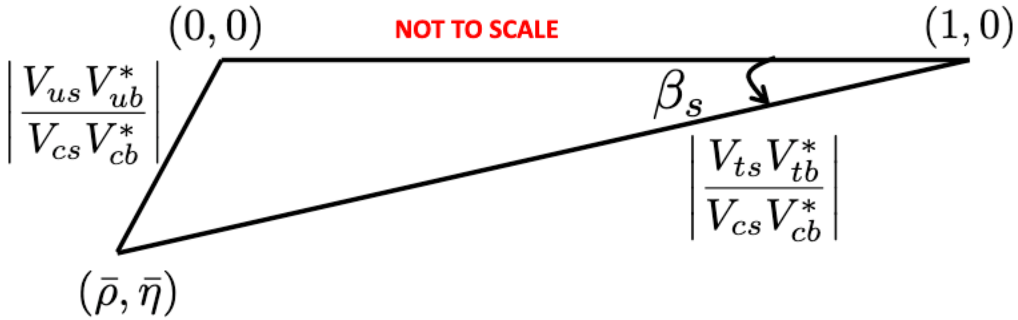
Asking for conservation of probability $\Rightarrow \boldsymbol{V_{CKM}V_{CKM}^{\dagger} = 1}$

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

Unitarity condition from 2nd and 3rd columns:

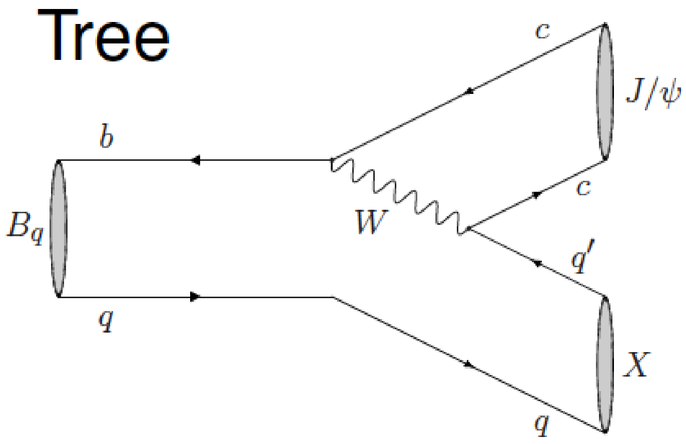
$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

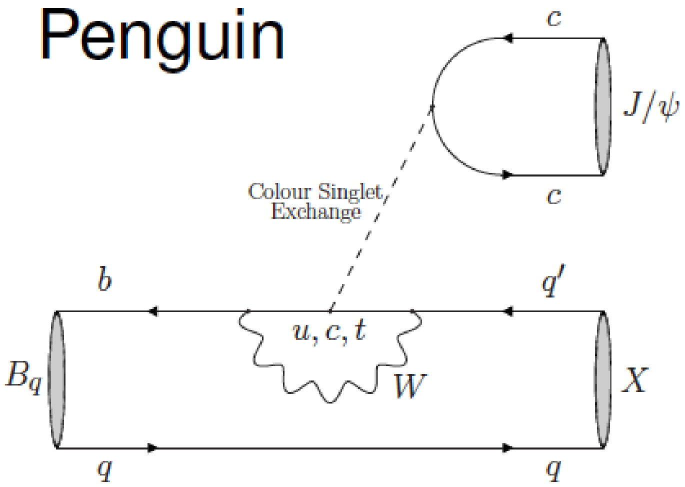




The area of triangle gives information about the magnitude of CP violation !

Control of penguin pollution





$$\phi_s = \phi_s^{SM} + \Delta\phi_s^{peng} + \Delta\phi_s^{NP}$$

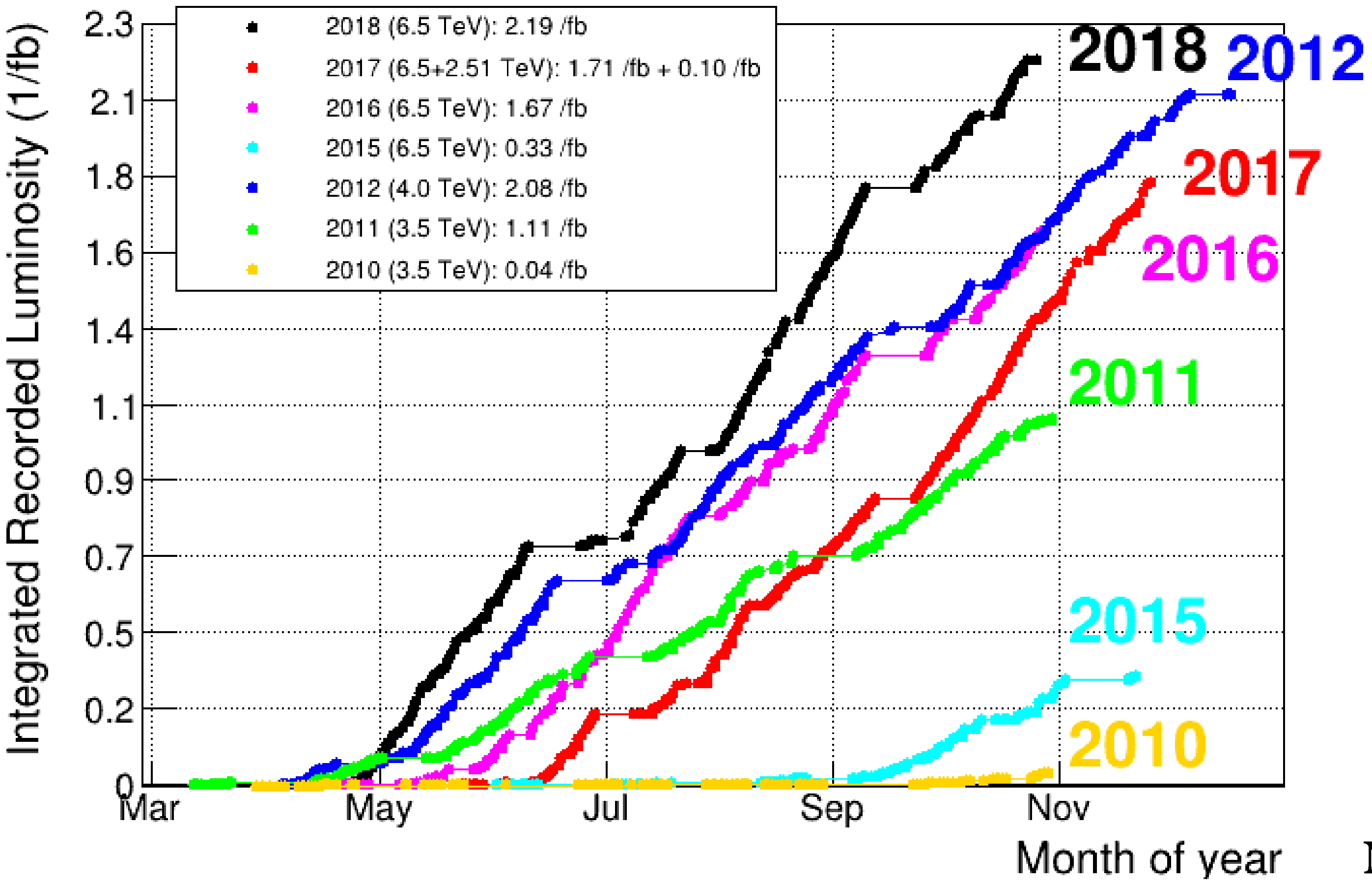
$-2\beta_s$

Important channels:

- $B_s^0 \rightarrow J/\psi\, K^*$
- $B^0 \rightarrow J/\psi \rho^0$

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

Analysis: **data available until now at LHCb**



Large number of beauty hadrons:

$\sigma_{b\bar{b}}(7\ \mathrm{TeV}) = 72.0 \pm 0.3 \pm 6.8\ \mu\mathrm{b}$

$\sigma_{b\bar{b}}(13\ \mathrm{TeV}) = 154.3 \pm 1.5 \pm 14.3\ \mu\mathrm{b}$

[PRL 118 (2017) 052002]

Measurement made with **2015 and 2016 data**

$$\varphi_s = -0.057 \pm 0.060 \pm 0.011\ \mathrm{rad}$$

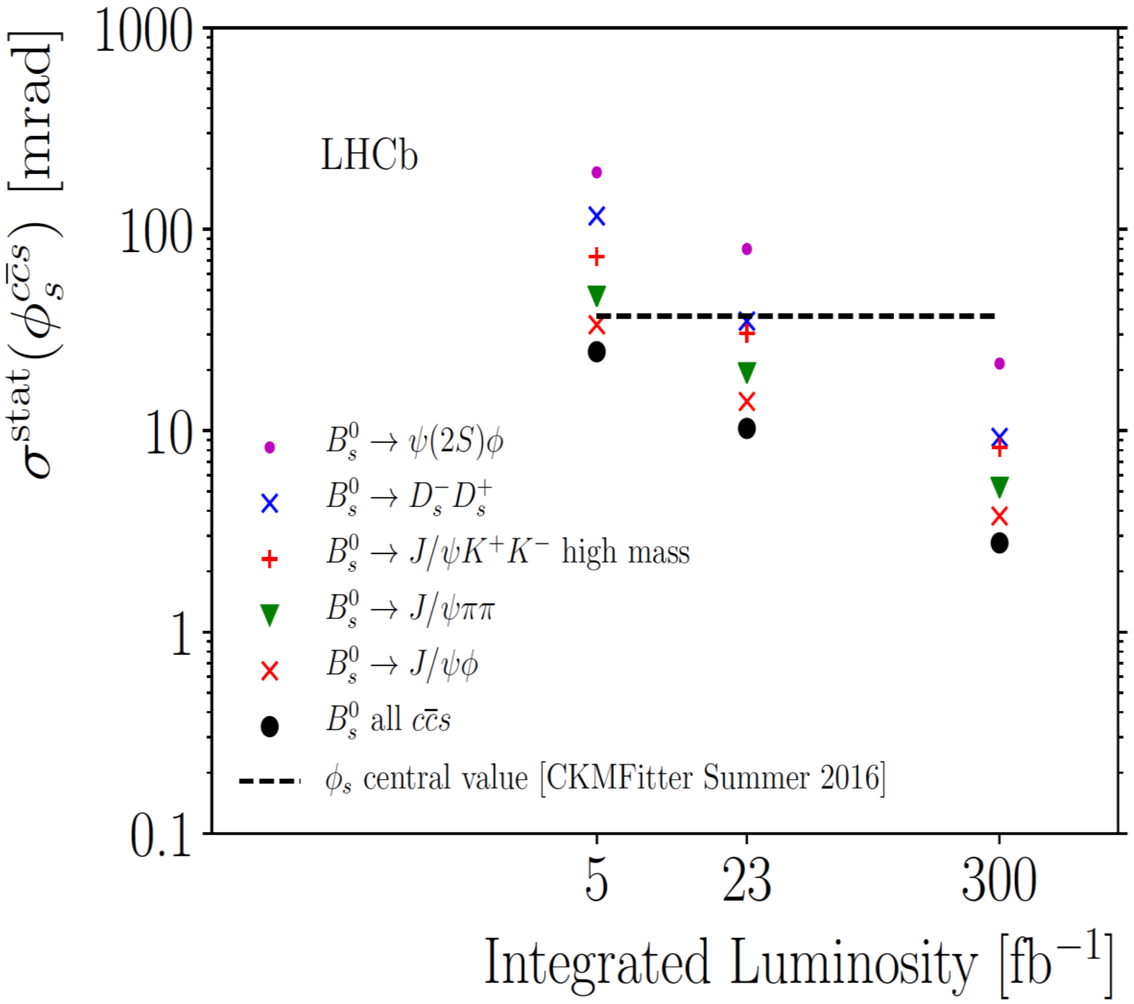
[https://arxiv.org/pdf/1903.05530.pdf]

Scaling considering lumi **from 2015 to 2018:**

$$\varphi_s = -0.057 \pm 0.035 \pm 0.011\ \mathrm{rad}$$

NB: $\varphi_s^{SM} \approx -0.03686^{+0.00096}_{-0.00068}$ rad

New measurements are fundamental to test the SM



[LHCB-PUB-2018-009]

Prospects for the future

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

NB: $\phi_s^{SM} \approx -0.03686^{+0.00096}_{-0.00068}$ rad

The CKM matrix can be described by 4 parameters: λ, A, ρ, η

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

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

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

η is the **only CPV source** in the SM !

But **it is not enough** to explain the matter-antimatter asymmetry.

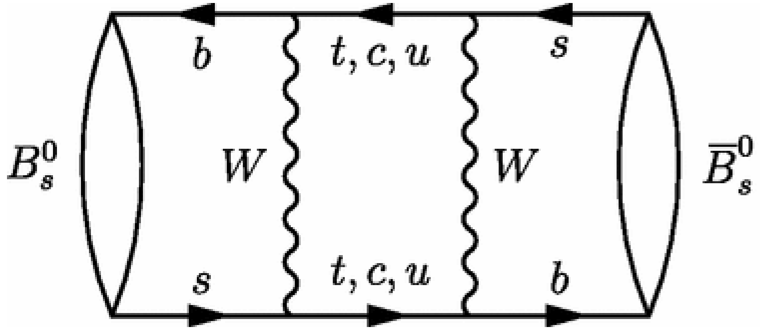
$\Downarrow$

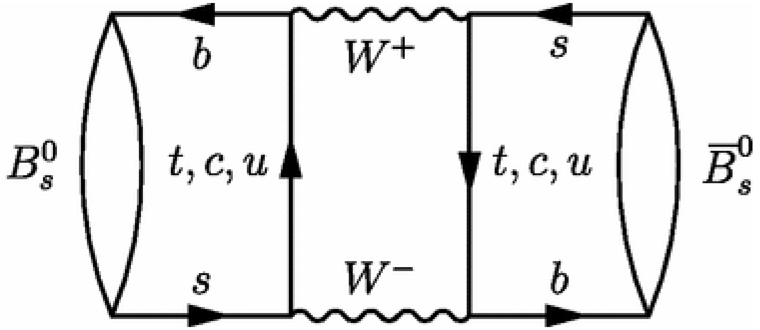
It is possible that there are new CPV sources not described by the SM

$\Downarrow$

Test the consistency of CKM within SM experimentally

Theoretical introduction: mixing of neutral mesons





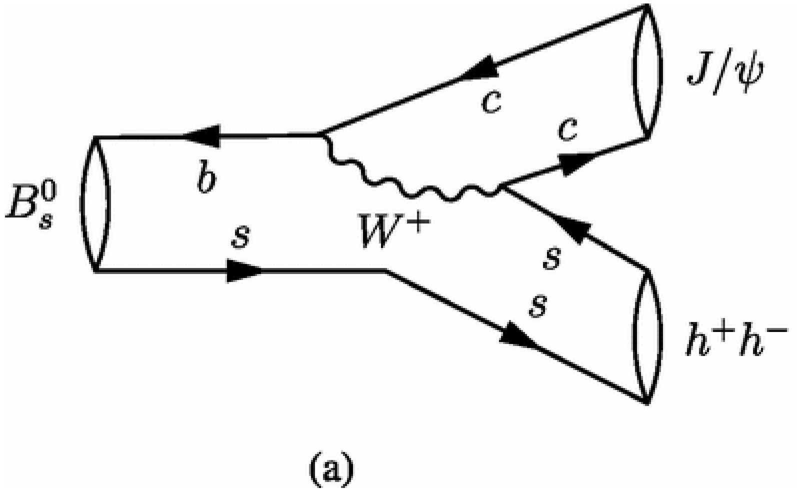
Mixing phenomena:
during its time evolution a B_s^0 can tranform into its antiparticle.
Therefore the hamiltonian eigenstates are different from the interaction states and are known as mass eigenstates B_L and B_H and they can be written as their linear combination:

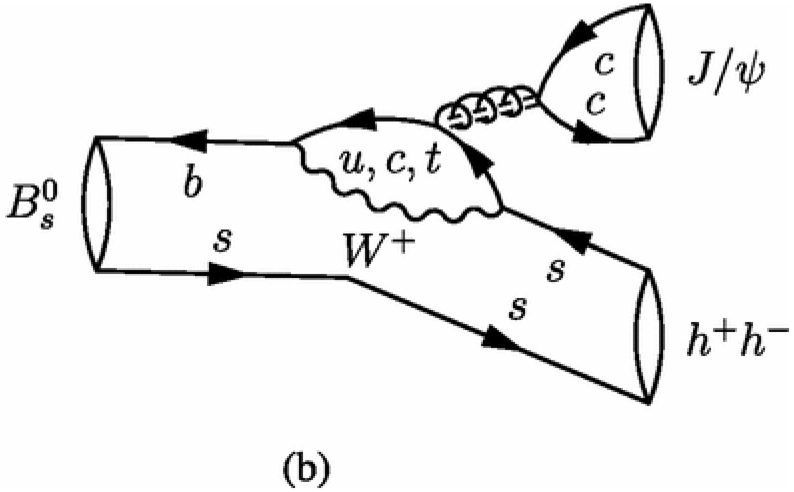
$$|B_H\rangle \propto p\,|B_q^0\rangle + q\,|\overline{B}_q^0\rangle$$
$$|B_L\rangle \propto p\,|B_q^0\rangle - q\,|\overline{B}_q^0\rangle$$

$$|B_q^0(t)\rangle \propto \frac{1}{2p}\left(|B_L(t)\rangle + |B_H(t)\rangle\right)$$
$$|\overline{B}_q^0(t)\rangle \propto \frac{1}{2q}\left(|B_L(t)\rangle - |B_H(t)\rangle\right)$$

where $|B_{H/L}(t)\rangle = e^{-iM_{H/L}\,t}\,e^{-\Gamma_{H/L}\,t/2}\,|B_{H/L}\rangle$ with $\Gamma_q = \frac{\Gamma_L+\Gamma_H}{2} \equiv \frac{1}{\tau}$,

Theoretical outline: Direct CP violation in $B_s^0 \to J/\psi hh$ decay



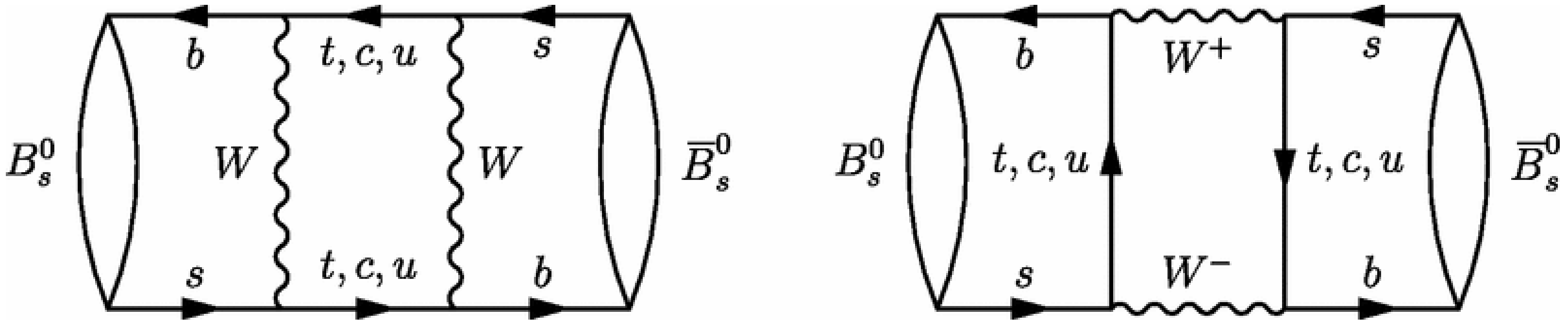


Tree diagram
(dominant)

Penguin diagram
(deleted)

CP violation in decay: $B \to f$ probability is different from that of $\bar{B} \to \bar{f}$
Due to a phase arising from interference of two diagrams

Theoretical outline: CP violation in mixing



CP violation in mixing: $B \rightarrow \bar{B}$ probability different from that of $\bar{B} \rightarrow B$
Due to different phasis arising from interference of two diagrams

$$|B(t)\rangle = \quad g_+(t)\ |B\rangle + \frac{q}{p} g_-(t)\ |\bar{B}\rangle$$
$$|\bar{B}(t)\rangle = \frac{p}{q} g_-(t)\ |B\rangle + \quad g_+(t)\ |\bar{B}\rangle$$

No violation if $^q/_p \sim 1$, true for B_s^0 for which $|\,^q/_p\,| = 1.0003 \pm 0.0014$

HFLAV arXiv:1612.0723

Theoretical outline: CP violation in interference between mixing and decay

Interference between mixing and decay is due to different decay rate between $B_s^0 \to f$ and $B_s^0 \to \overline{B_s^0} \to \bar{f}$

Arising from a phase parameter $\phi_s = -2\arg\left({}^{-V_{ts}V_{tb}^*}/{}_{V_{cs}V_{cb}^*}\right)$ (SM, ignoring penguin contributions)

Very accurate ⟵ $2\arg\left({}^{-V_{ts}V_{tb}^*}/{}_{V_{cs}V_{cb}^*}\right) = -0.03686^{+0.00096}_{-0.00068}$ rad

Parameter very sensitive to new physics effects, as the presence of a new particle in the box diagram