910 Scientists
64 Institutes
16 countries

CP violation in charmless two-body B decays at LHCb

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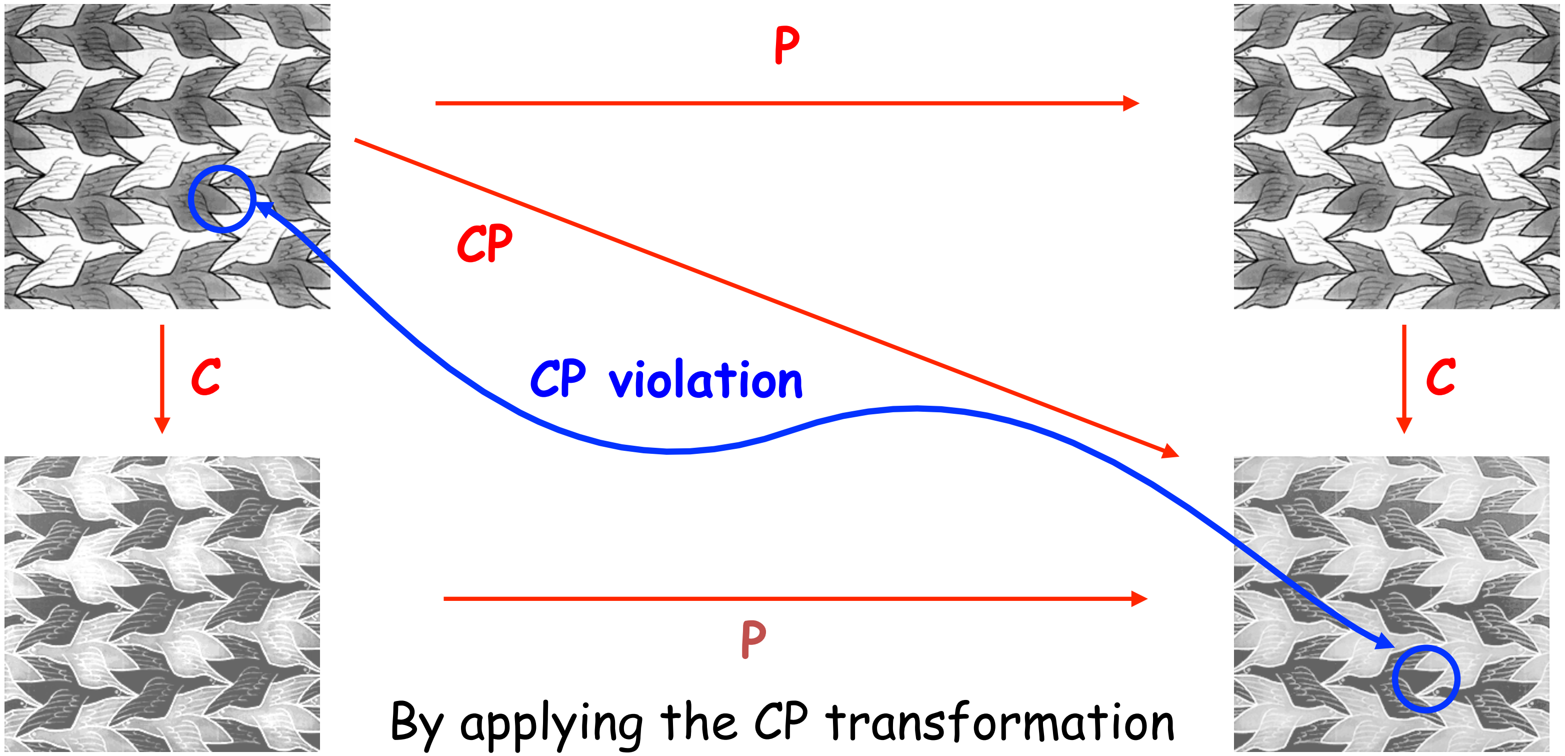
On behalf of LHCb Collaboration

INFN
Istituto Nazionale di Fisica Nucleare

LHC Seminar – CERN, 5th November 2013

CP violation

Physics laws are not invariant under the combined application of charge conjugation (C) and parity (P) transformations



By applying the CP transformation the initial state is reproduced, apart from a little detail…

Some history

CP violation and flavour physics have always been land for discovery

1963 N. Cabibbo, Phys. Rev. Lett. 10 (1963) 531 **Dirac Medal 2010**

1964 Christenson et al., Phys.Rev.Lett. 13 (1964) 138 **First evidence of CP violation Nobel Prize 1980**

Cartoon presented by N. Cabibbo at the Berkeley conference in 1966

Some history

1963	N. Cabibbo, Phys. Rev. Lett. 10 (1963) 531	**Dirac Medal 2010**
1964	Christenson et al., Phys. Rev. Lett. 13 (1964) 138	**First evidence of CP violation Nobel Prize 1980**
1970	Glashow et al., Phys. Rev. D2 (1970) 1285-1292	**Prediction of the existence of the charm quark**
1973	Kobayashi and Maskawa, Prog. Theor. Phys. 49 (1973) 652	**Nobel Prize 2008**
1987	ARGUS collaboration, Phys.Lett.B 192 (1987) 245	**Observation of B^0-$\overline{B}^0$ mixing Extrapolations of top quark mass**

Some history

1970	Glashow et al., Phys. Rev. D2 (1970) 1285-1292	**Prediction of the existence of the charm quark**
1973	Kobayashi and Maskawa, Prog. Theor. Phys. 49 (1973) 652	**Nobel Prize 2008**
1987	ARGUS collaboration, Phys.Lett.B 192 (1987) 245 Phys. Lett. B465, 335 (1999)	**Observation of B^0-$\bar{B}^0$ mixing** **Extrapolations of top quark mass**
1999	NA48 Collaboration, Phys. Lett. B465, 335 (1999) KTeV Collaboration, Phys. Rev. Lett. 83, 22 (1999)	**First observation of direct CP violation**
2001	BaBar collaboration, Phys. Rev. Lett. 87 (2001) 091801 Belle collaboration, Phys. Rev. Lett. 87 (2001) 091802	**Observation of CP violation in B^0 system**

Some history

1987	ARGUS collaboration, Phys.Lett.B 192 (1987) 245	**Observation of B^0-$\overline{B}^0$ mixing Extrapolations of top quark mass**
1999	NA48 Collaboration, Phys. Lett. B465, 335 (1999) KTeV Collaboration, Phys. Rev. Lett. 83, 22 (1999)	**First observation of direct CP violation**
2001	BaBar collaboration, Phys. Rev. Lett. 87 (2001) 091801 Belle collaboration, Phys. Rev. Lett. 87 (2001) 091802	**Observation of CP violation in B^0 system**
2006	CDF Collaboration, Phys. Rev. Lett. 97 (2006) 242003	**Observation of B_s^0-$\overline{B}_s^0$ mixing**
2012	LHCb collaboration, Phys. Rev. Lett. 110, 101802 (2013)	**Observation of D^0–$\overline{D}^0$ mixing**
2013		

CP violation in the Standard Model

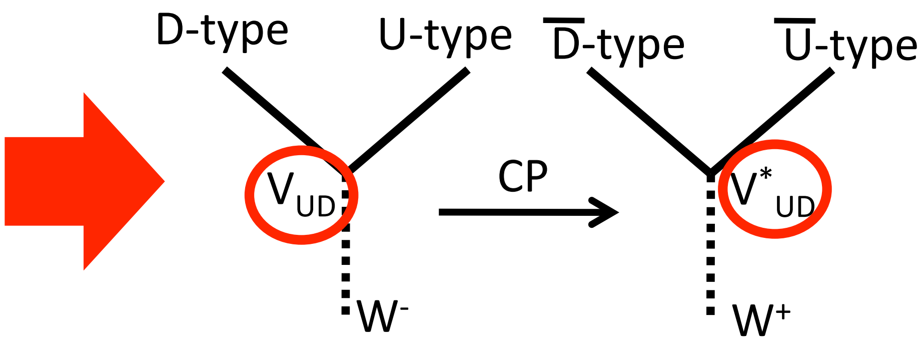
- Within the SM only weak interactions violate CP
  - Flavour eigenstates of quarks are a mixture of mass eigenstates

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



The presence of complex phases in the amplitudes of weak processes is responsible for CP violation

The CKM matrix

Wolfenstein parameterization of the CKM matrix
Expansion in powers of $\lambda = \sin(\theta_C) \approx 0.225$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\underline{\lambda^3}(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\underline{\lambda^5}\left[1-2(\rho+i\eta)\right] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\underline{\lambda^3}\left[1-(\rho+i\eta)\left(1-\frac{1}{2}\lambda^2\right)\right] & -A\lambda^2+\frac{1}{2}A\underline{\lambda^4}\left[1-2(\rho+i\eta)\right] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}\left(\lambda^6\right)$$

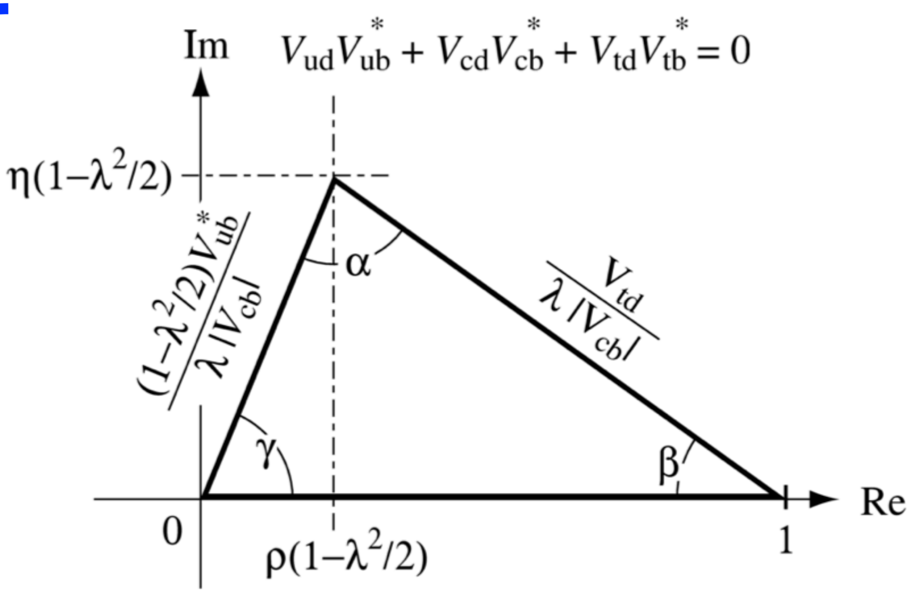
Immediate view of the strength of transitions where the imaginary CP violating term appears

Unitary triangles

- Unitary conditions $V_{CKM}V_{CKM}^{+} = I$ can be represented as **triangles in the complex plan**

$$
\begin{aligned}
\underbrace{V_{ud}V_{us}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{cd}V_{cs}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{td}V_{ts}^*}_{\mathcal{O}(\lambda^5)} &= 0, \\
\underbrace{V_{us}V_{ub}^*}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs}V_{cb}^*}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{ts}V_{tb}^*}_{\mathcal{O}(\lambda^2)} &= 0, \\
\boxed{\underbrace{V_{ud}V_{ub}^*}_{(\rho+i\eta)A\lambda^3} + \underbrace{V_{cd}V_{cb}^*}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{(1-\rho-i\eta)A\lambda^3} = 0,} \\
\underbrace{V_{ud}^*V_{cd}}_{\mathcal{O}(\lambda)} + \underbrace{V_{us}^*V_{cs}}_{\mathcal{O}(\lambda)} + \underbrace{V_{ub}^*V_{cb}}_{\mathcal{O}(\lambda^5)} &= 0, \\
\underbrace{V_{cd}^*V_{td}}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs}^*V_{ts}}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{cb}^*V_{tb}}_{\mathcal{O}(\lambda^2)} &= 0, \\
\underbrace{V_{ud}^*V_{td}}_{(1-\rho-i\eta)A\lambda^3} + \underbrace{V_{us}^*V_{ts}}_{-A\lambda^3} + \underbrace{V_{ub}^*V_{tb}}_{(\rho+i\eta)A\lambda^3} &= 0.
\end{aligned}
$$

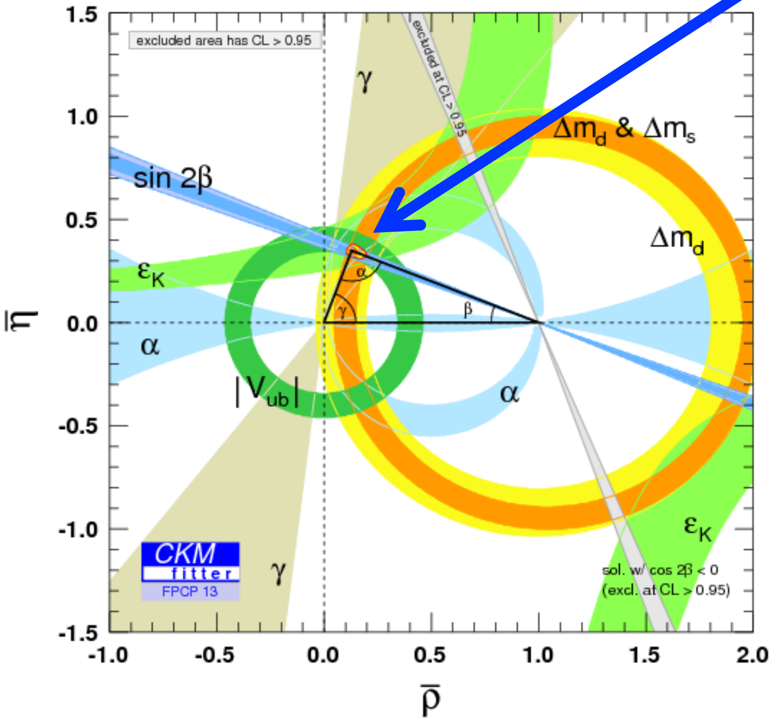
The Unitary Triangle

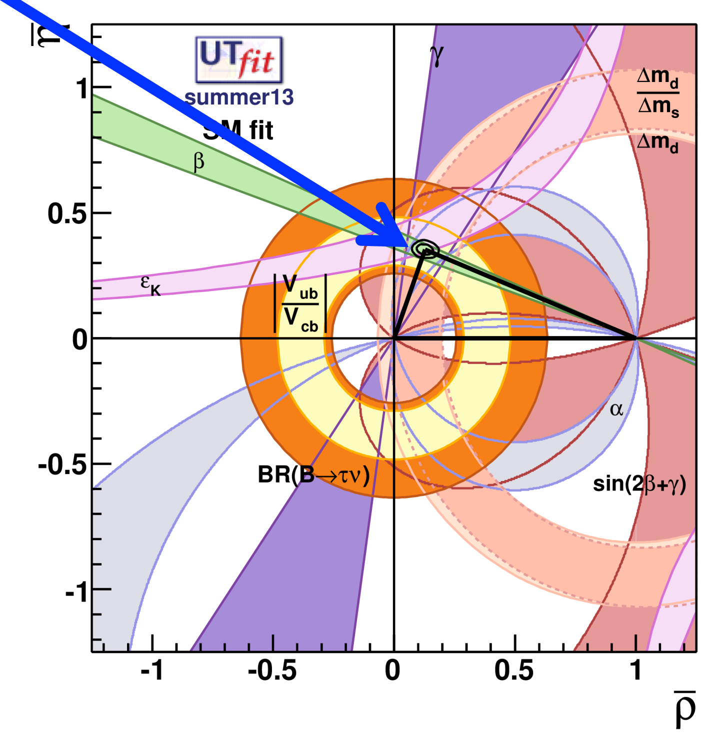


Relevant as its sides are all of the same magnitude

The Unitary Triangle

- Remarkable agreement between all the measurements of the UT sides and angles





- Better precision in the measurements is needed to look for discrepancies

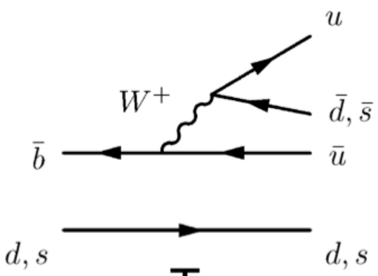
Charmless two-body *B* decays

- Rich set of decays of *b* hadrons
  - I will treat only a subset of neutral B^0 and B_s^0 decays into two charged light mesons ($B \to h^+h'^-$)
- Great interest in studying CP violation in these decays
  - Sensitive to **CKM matrix** elements
  - Can reveal **physics beyond the SM**
  - **Benchmark for flavour symmetries** (**SU(3) flavour**) used to deal with QCD contributions

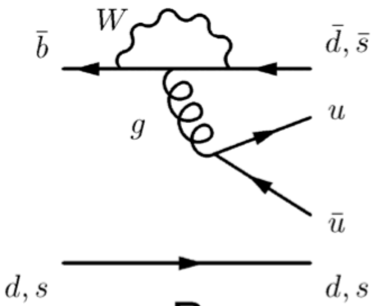
[R. Fleischer, PLB 459 (1999) 306]
[M. Gronau and J. Rosner, PLB 482 (2000) 71]
[H.J. Lipkin, PLB 621 (2005) 126]
[R. Fleischer, EPJ C52 (2007) 267]
[M. Ciuchini *et al.*, JHEP 1210 (2012) 029]

Decay diagrams

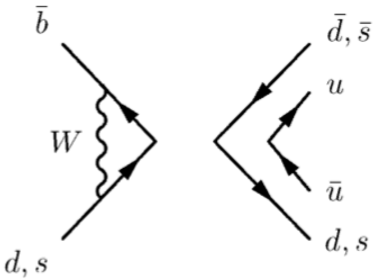
- $B \to h^+ h'^-$ decays receive contributions from different decay diagrams
  - Tree (T), strong penguin (P), penguin annihilation (PA), electroweak penguin (P_{EW}), exchange (E)
  - Relevant observables are direct and mixing-induced **CP asymmetries** as well as **branching ratios**



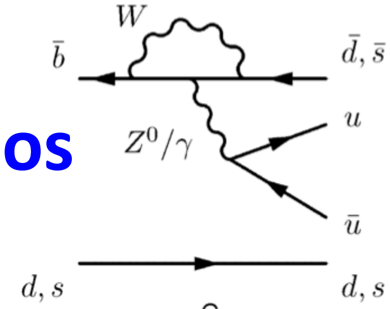
T



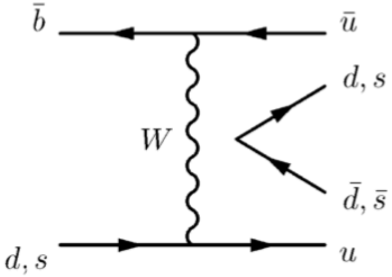
P



PA



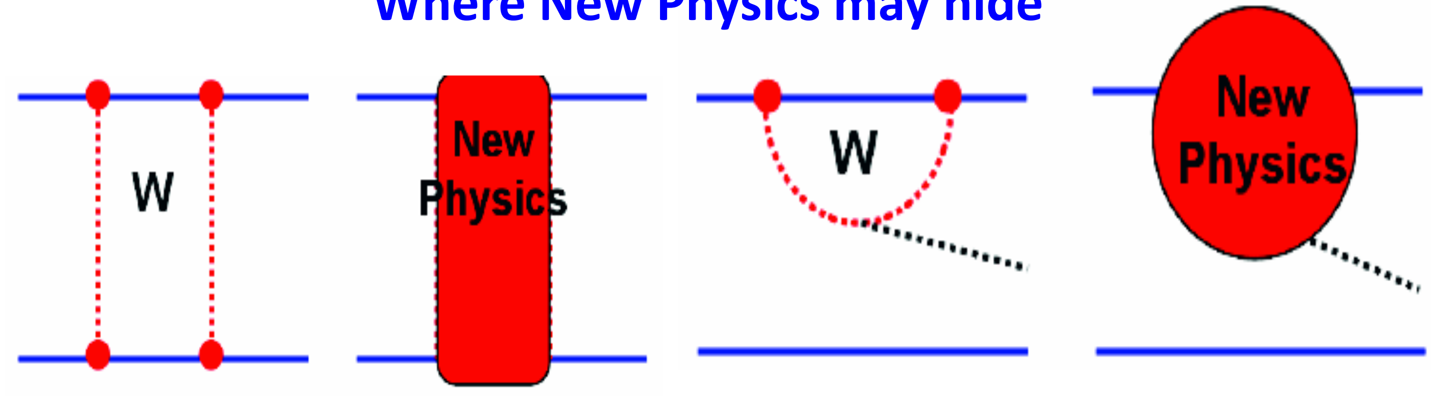
P^C_{EW}



E

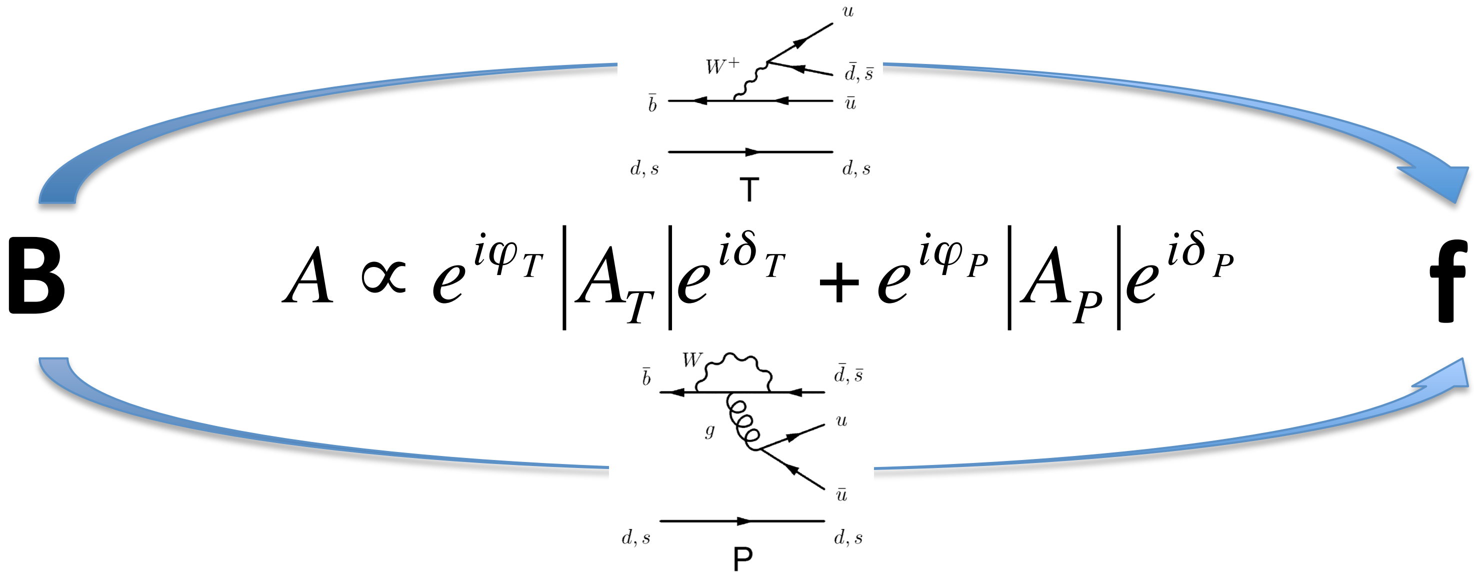
New physics in B→$h^+h'^-$ decays

Where New Physics may hide



- Penguin and box diagrams are suitable places where **new particles** may appear as virtual contributions
- **Discrepancies** with respect to SM predictions can reveal the presence of new particles
  - The SM value of the angle γ can be determined with very high precision using decays dominated by tree diagrams

Direct CP violation

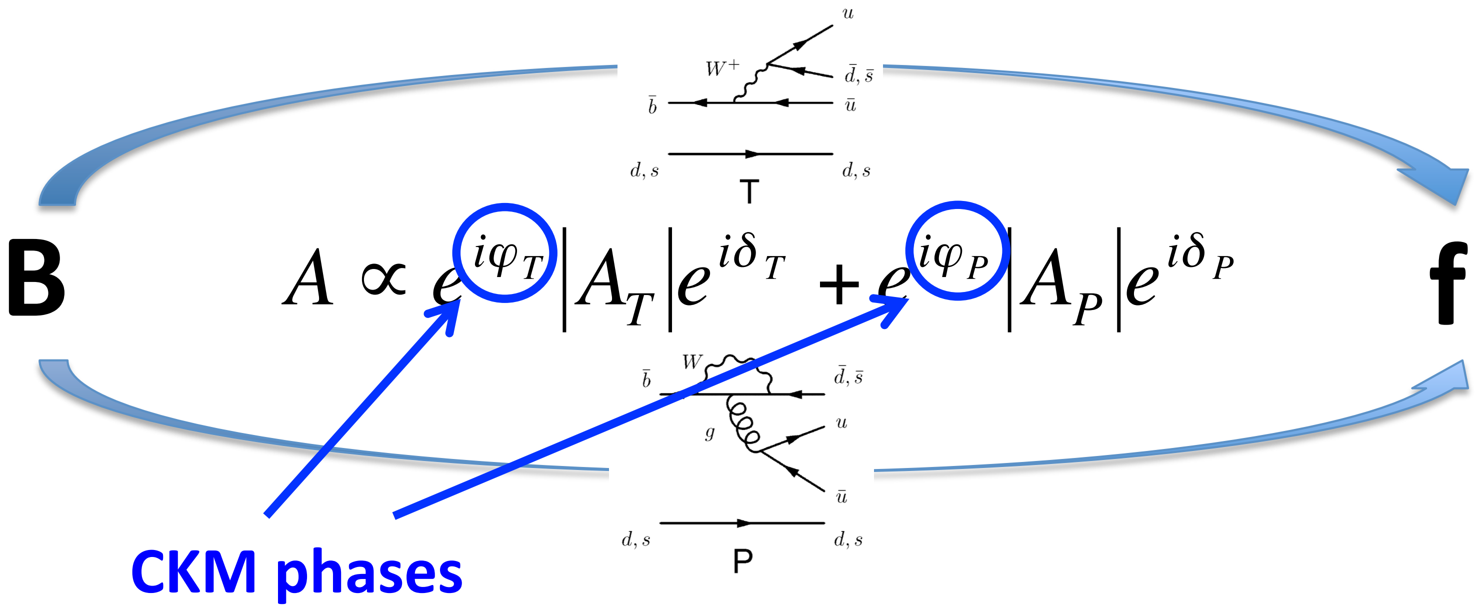


B

$$A \propto e^{i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

f

Direct CP violation



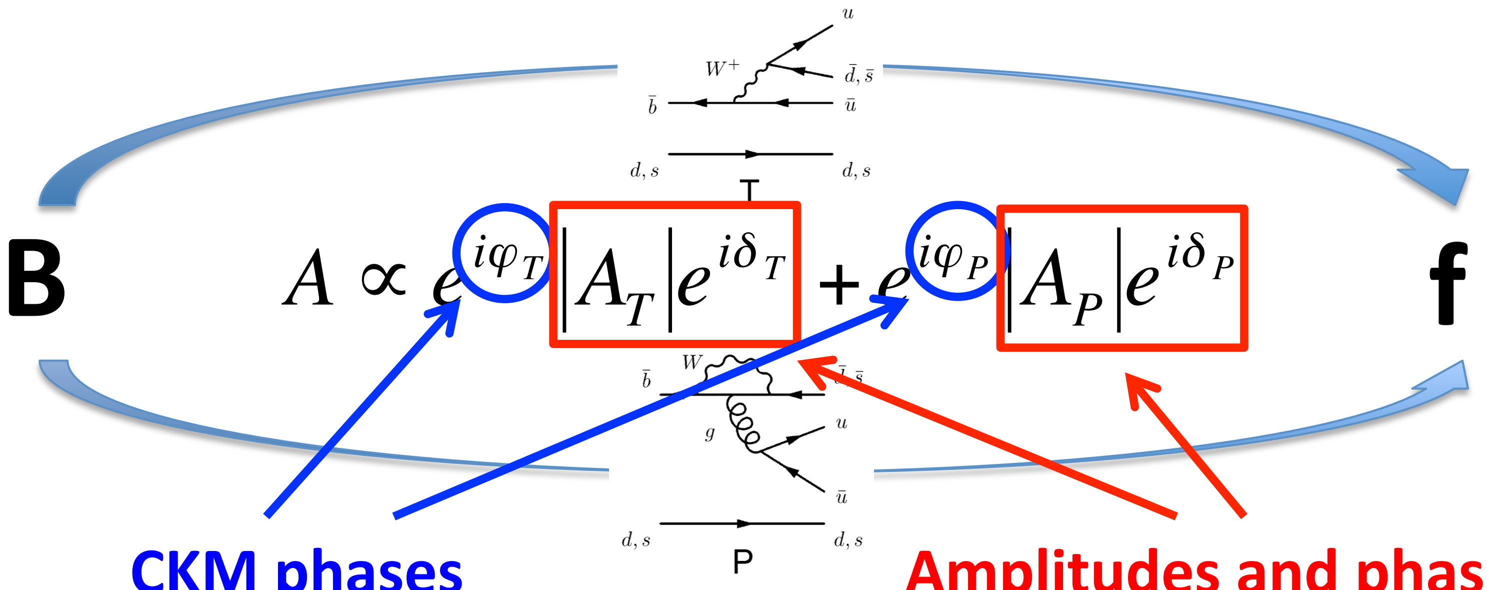
B

$$A \propto e^{i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

f

CKM phases

Direct CP violation

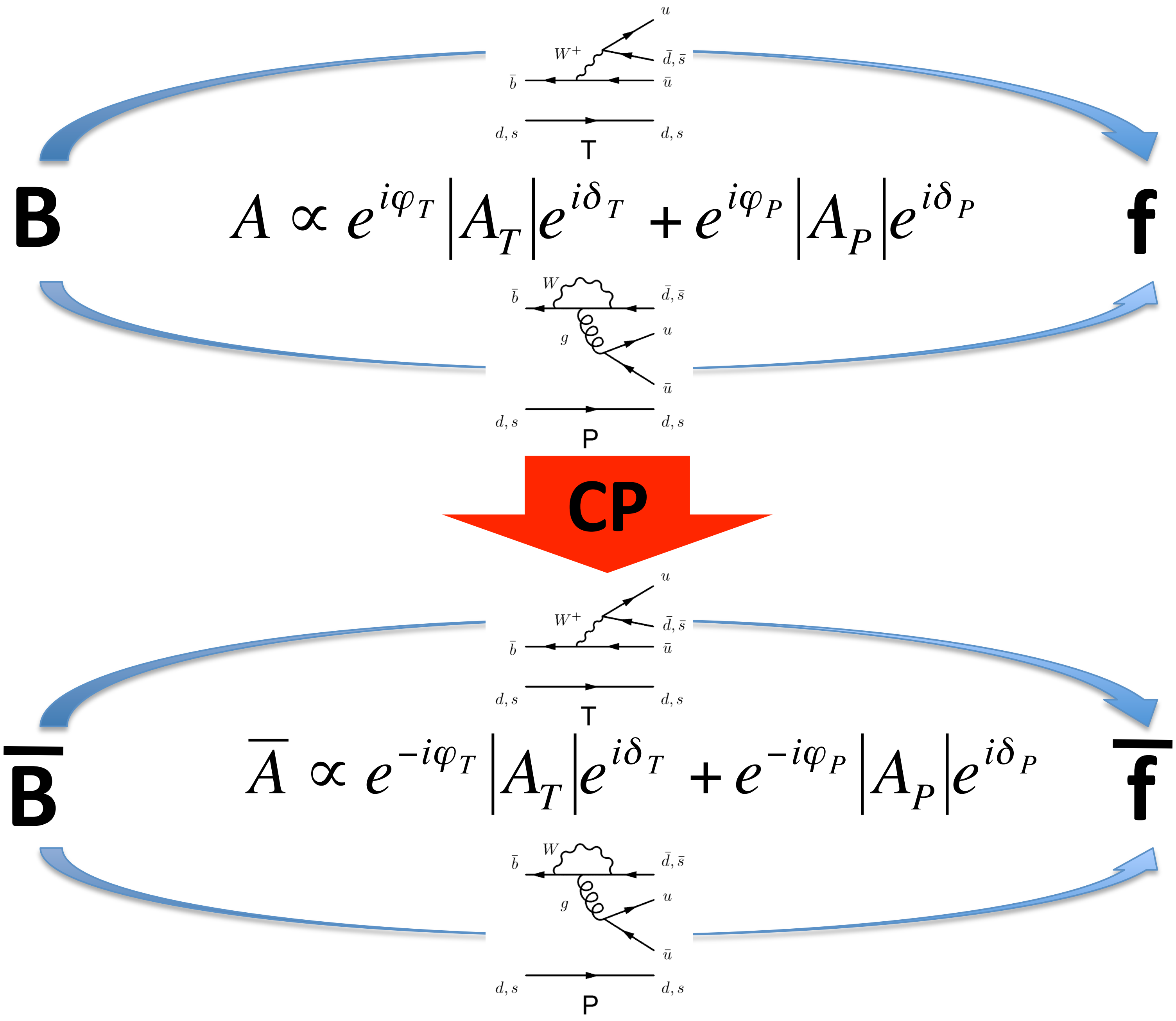


$$A \propto e^{i\varphi_T}\boxed{|A_T|e^{i\delta_T}} + e^{i\varphi_P}\boxed{|A_P|e^{i\delta_P}}$$

CKM phases

Amplitudes and phases due to QCD interaction among quarks

Direct CP violation



B

$$A \propto e^{i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

f

CP

$\bar{B}$

$$\bar{A} \propto e^{-i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{-i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

$\bar{f}$

Direct CP violation

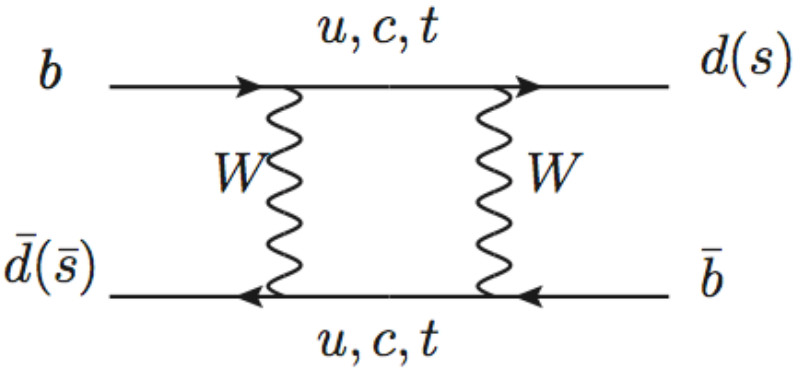
Direct CP asymmetry

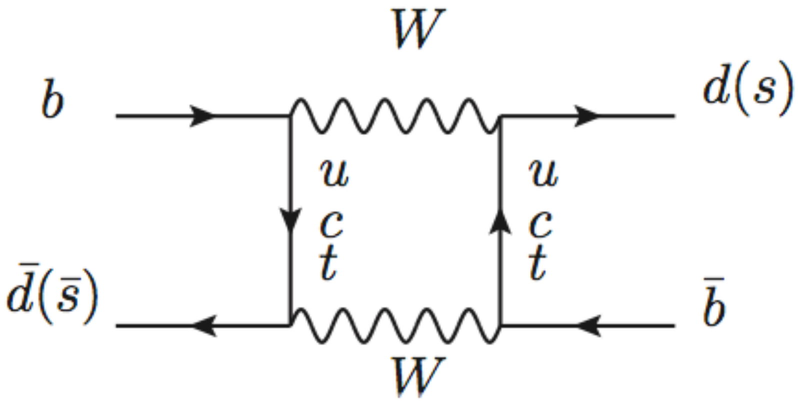
$$\boxed{A_{CP} = \frac{\left|\overline{A}\right|^2 - \left|A\right|^2}{\left|\overline{A}\right|^2 + \left|A\right|^2} \propto \left|A_T\right|\left|A_P\right| \sin\left(\varphi_T - \varphi_P\right) \sin\left(\delta_T - \delta_P\right)}$$

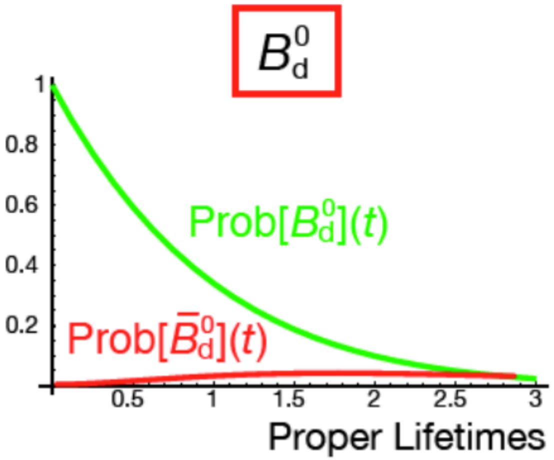
Direct CP violation manifests itself in the interference between tree and penguin decay amplitudes

Mixing diagrams

- Neutral B^0 and B_s^0 mesons can oscillate between their particle and anti-particle state

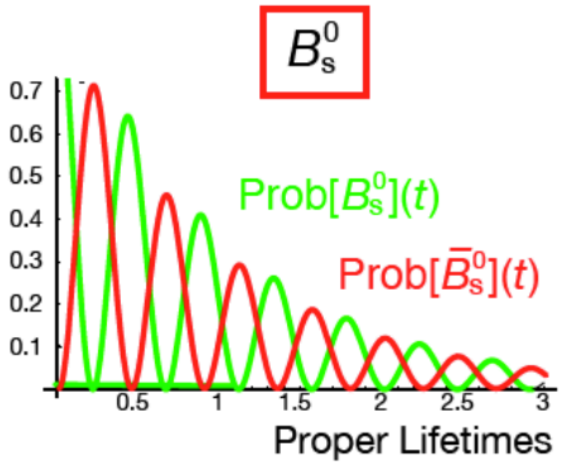






LHCb: Phys.Lett.B719(2013)318

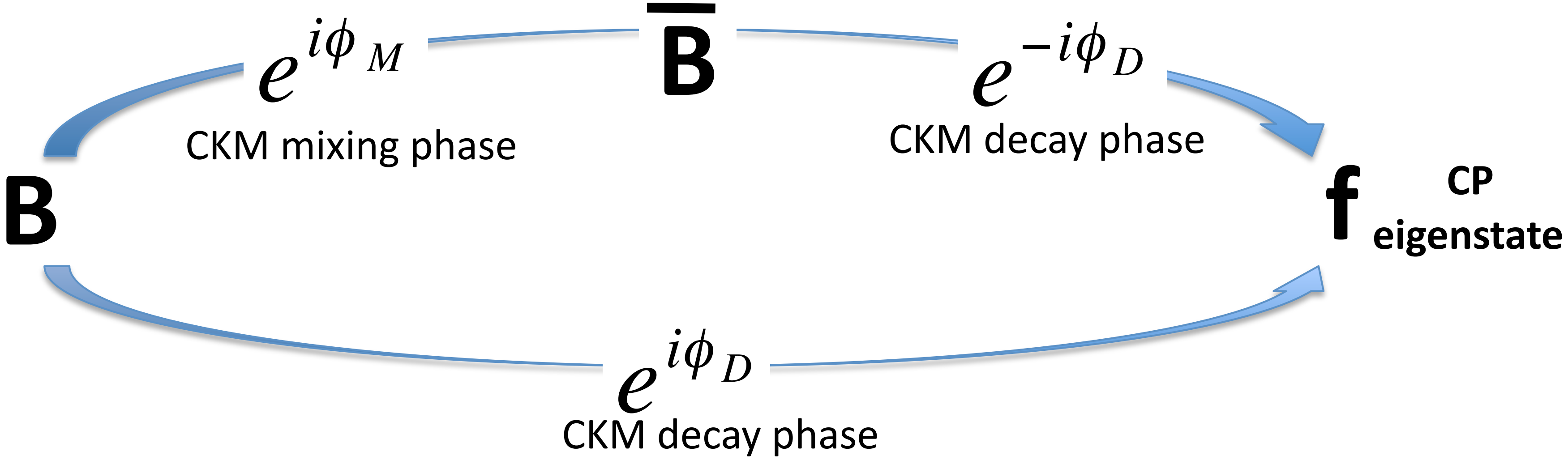
$\Delta m_d = 0.5156 \pm 0.0051 \pm 0.0033\ \mathrm{ps}^{-1}$



LHCb: New J. Phys. 15 053021

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$

Mixing induced CP violation



$e^{i\phi_M}$

CKM mixing phase

$\bar{\mathrm{B}}$

$e^{-i\phi_D}$

CKM decay phase

B

f

CP eigenstate

$e^{i\phi_D}$

CKM decay phase

Mixing induced CP violation manifests itself in the interference between the mixing and decay amplitudes

Time-dependent CP asymmetry

$$\boxed{A_{CP}(t)=\frac{\Gamma_{\bar{B}\to f}(t)-\Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t)+\Gamma_{B\to f}(t)}=\frac{-C_f\cos(\Delta mt)+S_f\sin(\Delta mt)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right)+D_f\sinh\left(\frac{\Delta\Gamma}{2}t\right)}}$$

C_f represents the asymmetry in the decay amplitudes

S_f represents the mixing-induced CP asymmetry

CKM metrology from $B \to h^+h'^-$ decays

- Direct and mixing induced CP asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays are related to the angle γ and to the B^0 and B_s^0 mixing phases

[R. Fleischer, PLB 459 (1999) 306]
[R. Fleischer, EPJ C52 (2007) 267]
[M. Ciuchini *et al.*, JHEP 1210 (2012) 029]

$$C_{\pi^+\pi^-} = -\frac{2d\sin(\vartheta)\sin(\gamma)}{1-2d\cos(\vartheta)\cos(\gamma)+d^2},$$

$$S_{\pi^+\pi^-} = -\frac{\sin(2\beta+2\gamma)-2d\cos(\vartheta)\sin(2\beta+\gamma)+d^2\sin(2\beta)}{1-2d\cos(\vartheta)\cos(\gamma)+d^2},$$

$$C_{K^+K^-} = \frac{2\tilde{d}'\sin(\vartheta')\sin(\gamma)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2},$$

$$S_{K^+K^-} = -\frac{\sin(-2\beta_s+2\gamma)+2\tilde{d}'\cos(\vartheta')\sin(-2\beta_s+\gamma)+\tilde{d}'^2\sin(-2\beta_s)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2},$$

- d, d', θ, θ' are hadronic quantities affected by theoretical uncertainties
  - Interpretation of $C_{\pi\pi}$, $S_{\pi\pi}$, C_{KK} and S_{KK} is not trivial
  - Use of U-spin symmetry to constrain uncertainties

U-spin symmetry

- U-spin symmetry deals with the **invariance of QCD** with respect to the exchange of ***d*** **and** ***s*** **quarks**
  - Broken symmetry due to mass difference between *d* and *s*
- B→h⁺h’⁻ amplitudes are connected by U-spin relations
  - The interplay between observables of different decays can **constrain size of U-spin symmetry breaking**
  - Important tool to **reduce theoretical uncertainties** due to QCD contributions

$$\underbrace{B^0 \to K^+K^-}_{PA+E} \quad d \longleftrightarrow s \quad \underbrace{B_s^0 \to \pi^+\pi^-}_{PA+E}$$

$$\underbrace{B^0 \to \pi^+\pi^-}_{T+P+\frac{2}{3}P_{EW}^C+PA+E} \quad d \longleftrightarrow s \quad \underbrace{B_s^0 \to K^+K^-}_{T+P+\frac{2}{3}P_{EW}^C+PA+E}$$

$$\underbrace{B^0 \to K^+K^-}_{PA+E} \quad d \longleftrightarrow s \quad \underbrace{B_s^0 \to \pi^+\pi^-}_{PA+E}$$

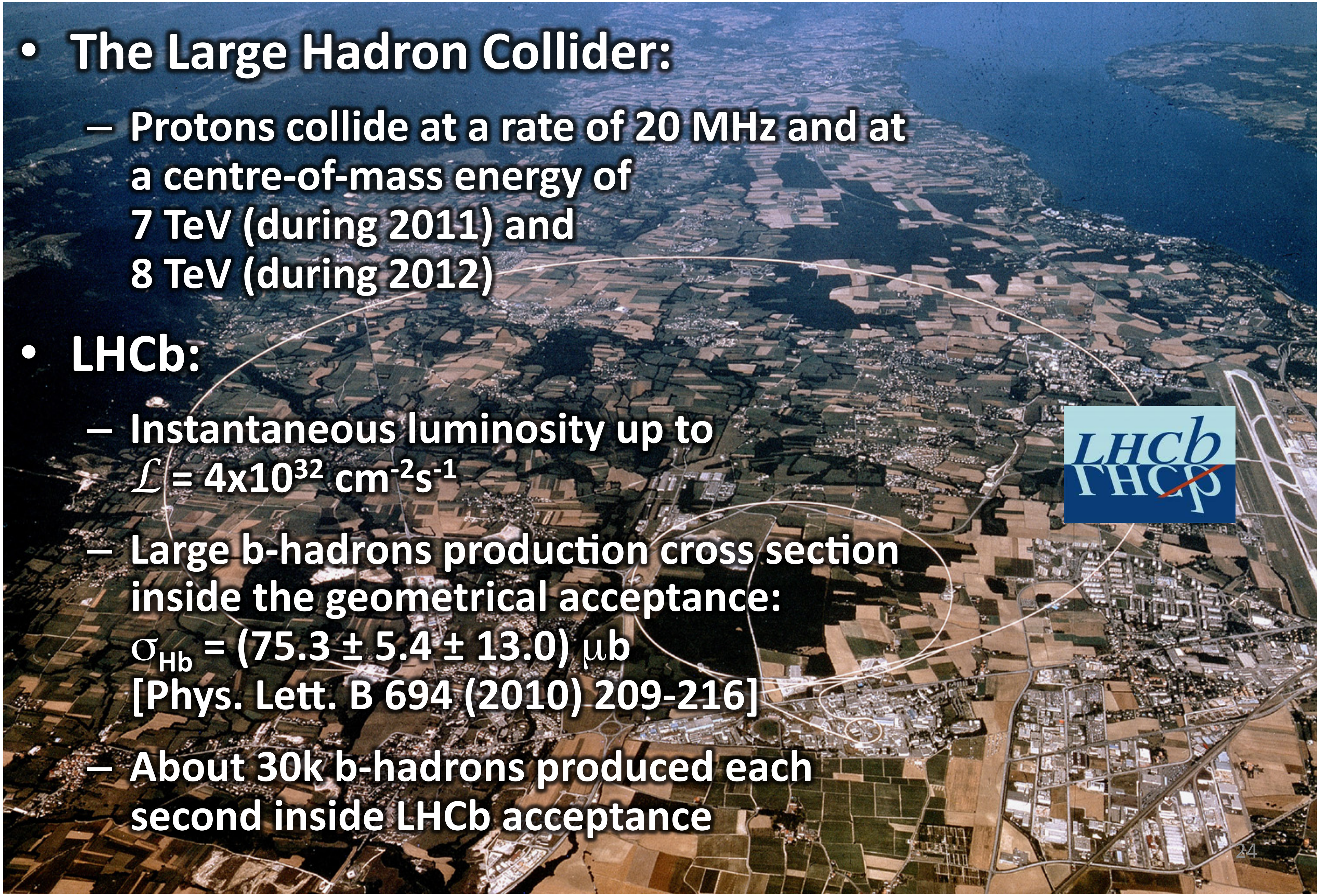
$$\underbrace{B^0 \to K^+\pi^-}_{T+P+\frac{2}{3}P_{EW}^C} \quad d \longleftrightarrow s \quad \underbrace{B_s^0 \to \pi^+K^-}_{T+P+\frac{2}{3}P_{EW}^C}$$

$$\underbrace{B^0 \to K^+\pi^-}_{T+P+\frac{2}{3}P_{EW}^C} \quad d \overset{\text{spect.}}{\longleftrightarrow} s \quad \underbrace{B_s^0 \to K^+K^-}_{T+P+\frac{2}{3}P_{EW}^C+PA+E}$$

$$\underbrace{B^0 \to \pi^+\pi^-}_{T+P+\frac{2}{3}P_{EW}^C+PA+E} \quad d \overset{\text{spect.}}{\longleftrightarrow} s \quad \underbrace{B_s^0 \to \pi^+K^-}_{T+P+\frac{2}{3}P_{EW}^C}$$

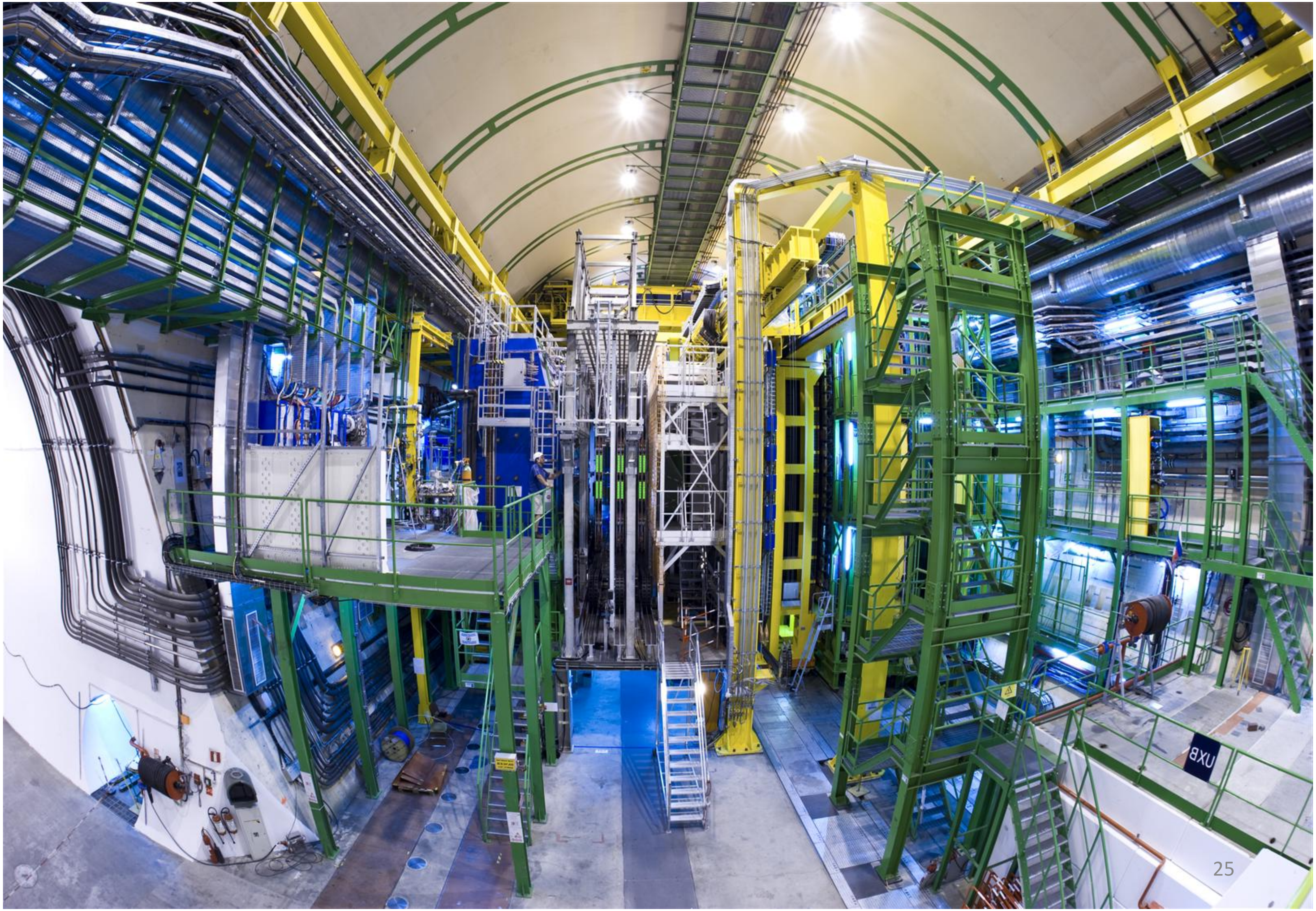
Experimental setup

The most powerful factory of *b* quarks to date…

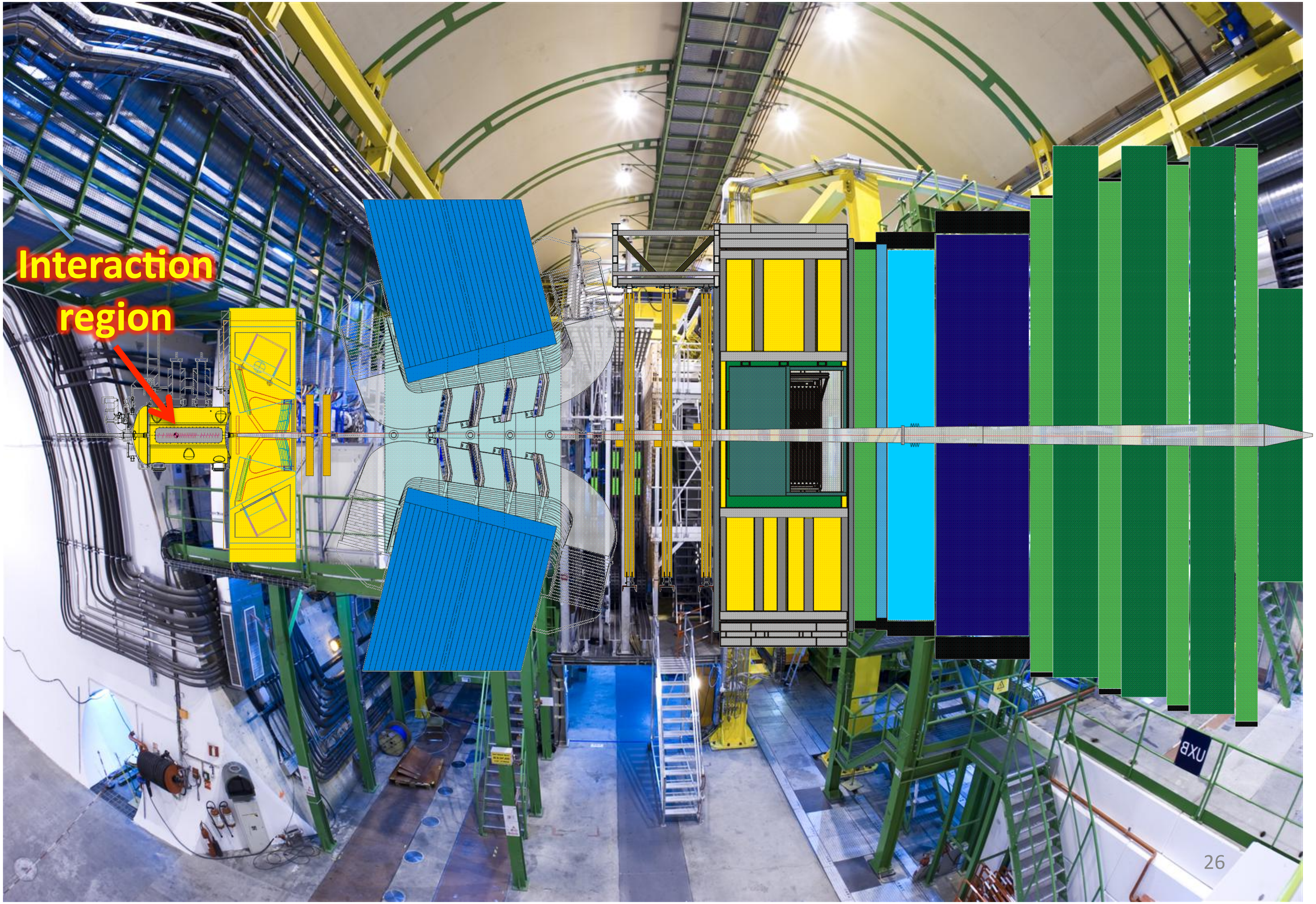


- The Large Hadron Collider:
  - Protons collide at a rate of 20 MHz and at a centre-of-mass energy of
    7 TeV (during 2011) and
    8 TeV (during 2012)
- LHCb:
  - Instantaneous luminosity up to
    $\mathcal{L} = 4\text{x}10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
  - Large b-hadrons production cross section inside the geometrical acceptance:
    $\sigma_{Hb} = (75.3 \pm 5.4 \pm 13.0)\ \mu\text{b}$
    [Phys. Lett. B 694 (2010) 209-216]
  - About 30k b-hadrons produced each second inside LHCb acceptance

The LHCb detector



The LHCb detector



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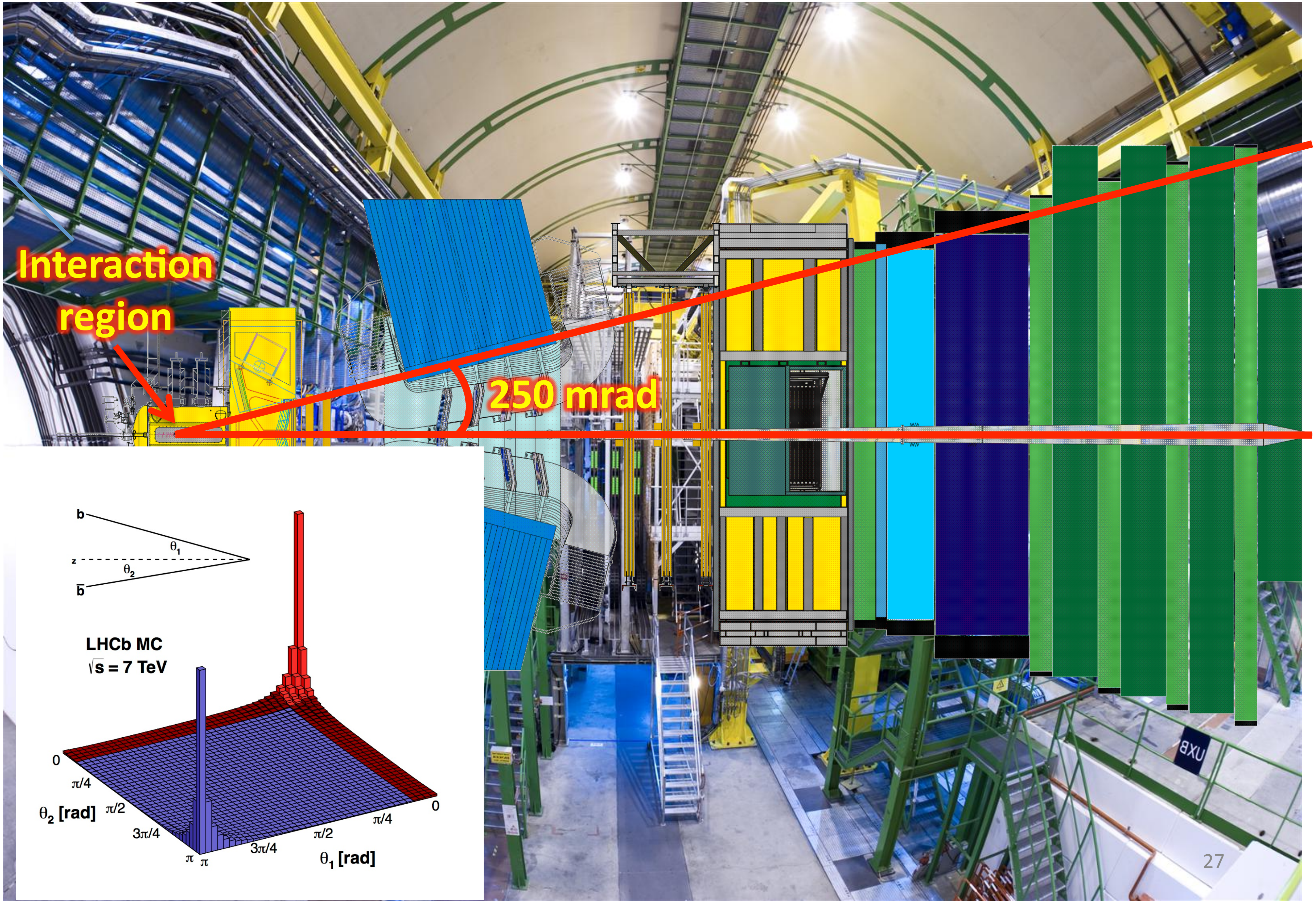

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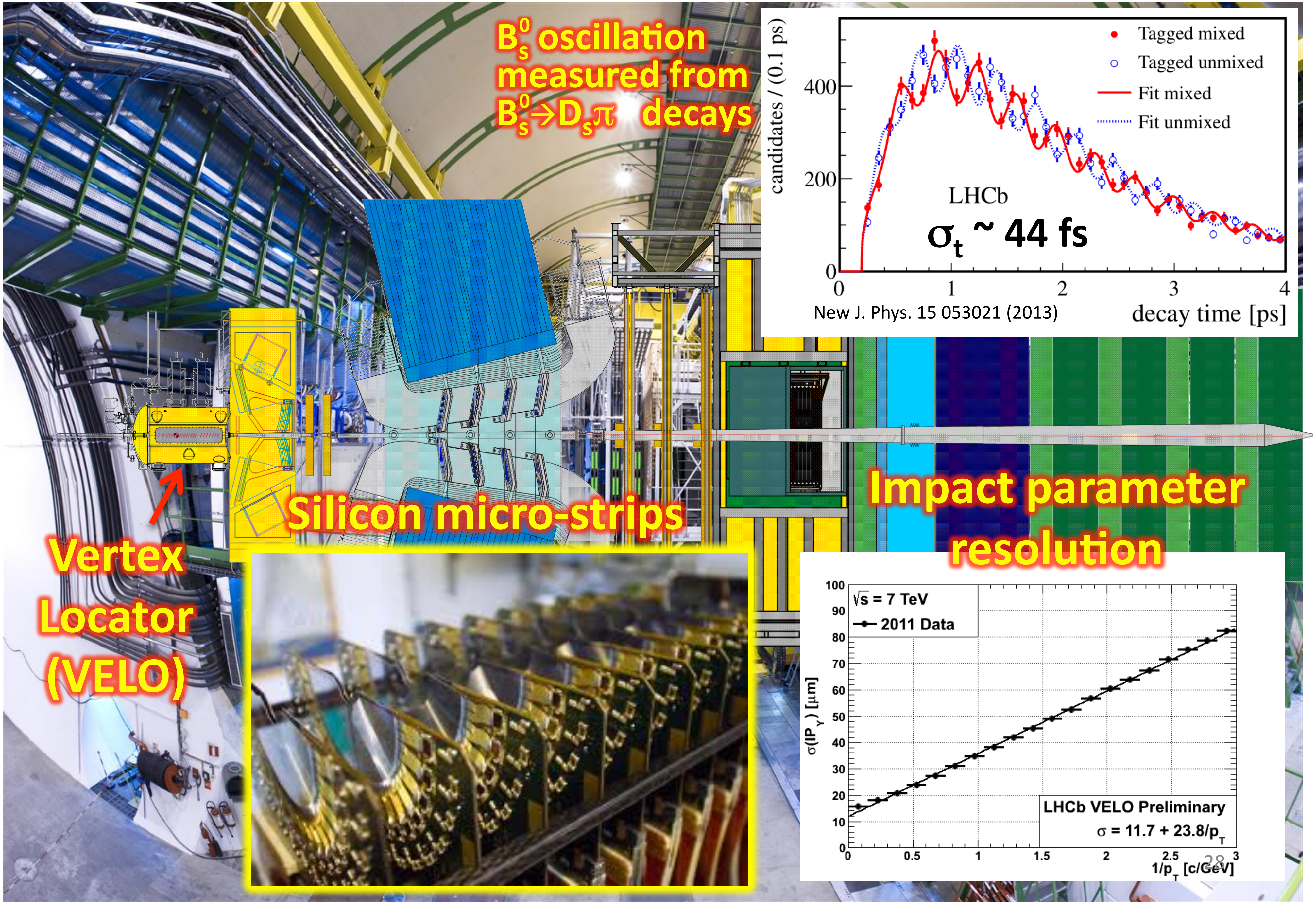


B_s^0 oscillation measured from $B_s^0 \rightarrow D_s\pi$ decays

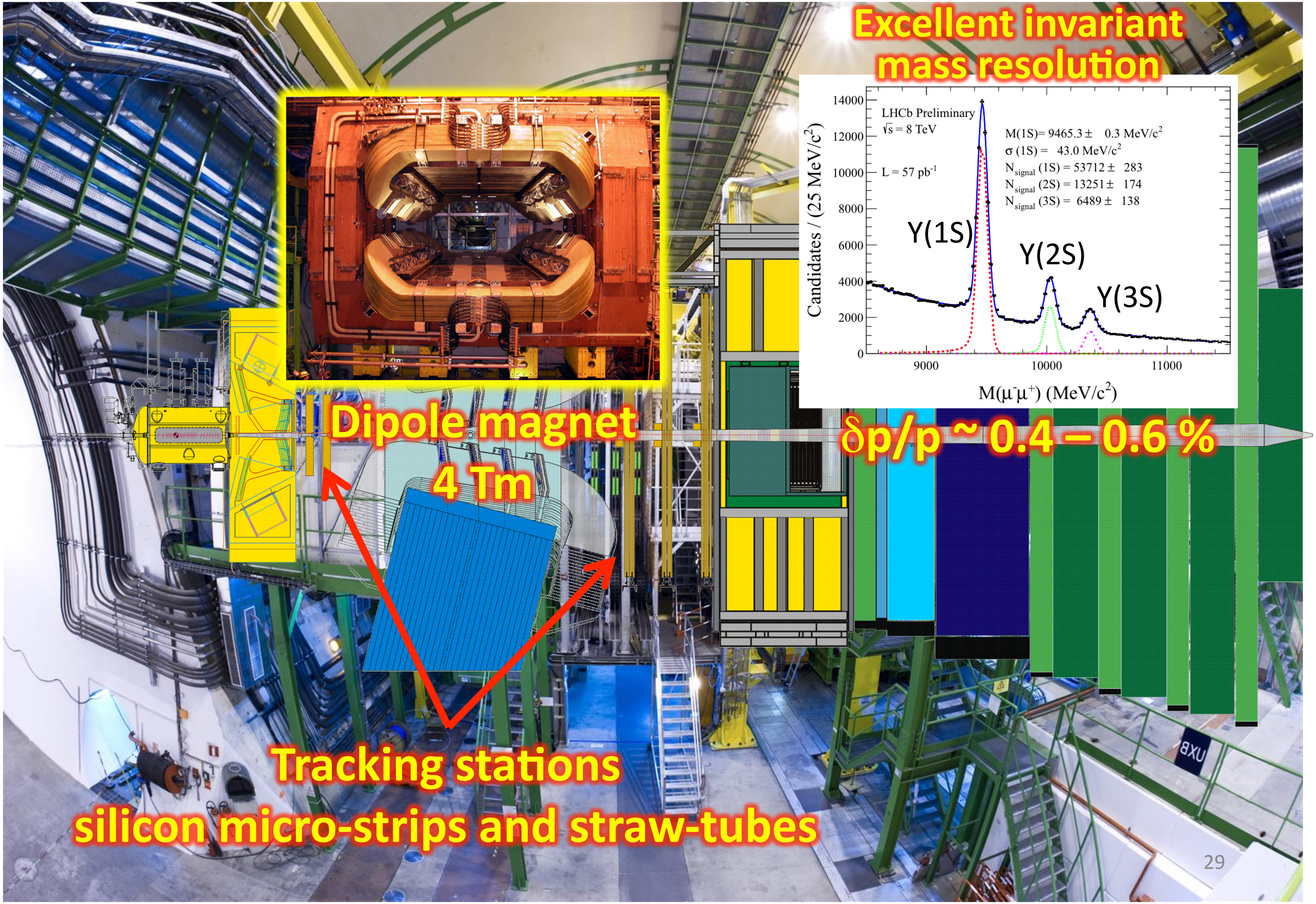
New J. Phys. 15 053021 (2013)

Vertex Locator (VELO)

Silicon micro-strips

Impact parameter resolution

The LHCb detector



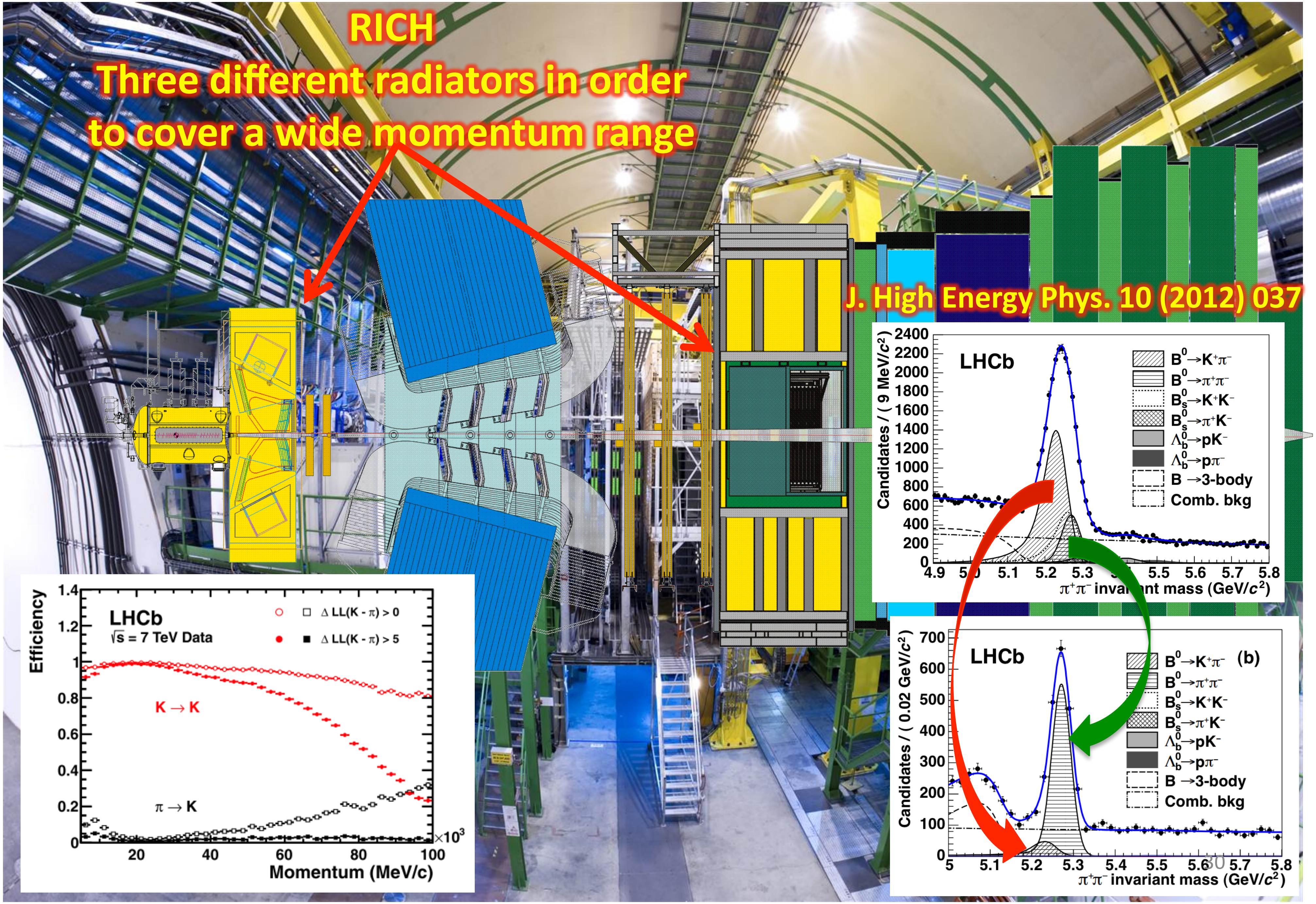
Excellent invariant mass resolution

Dipole magnet
4 Tm

δp/p ~ 0.4 – 0.6 %

Tracking stations
silicon micro-strips and straw-tubes

The LHCb detector

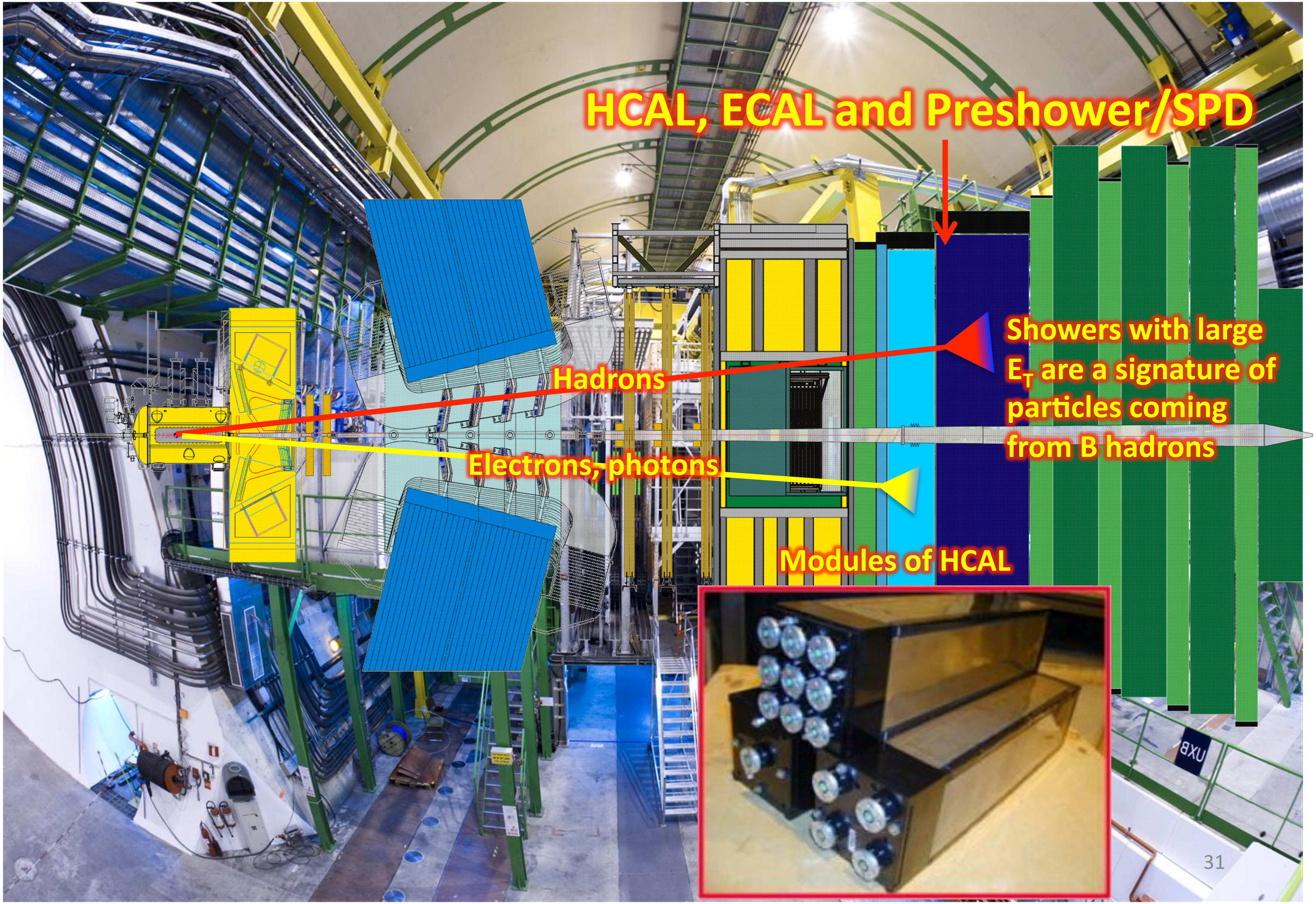


RICH

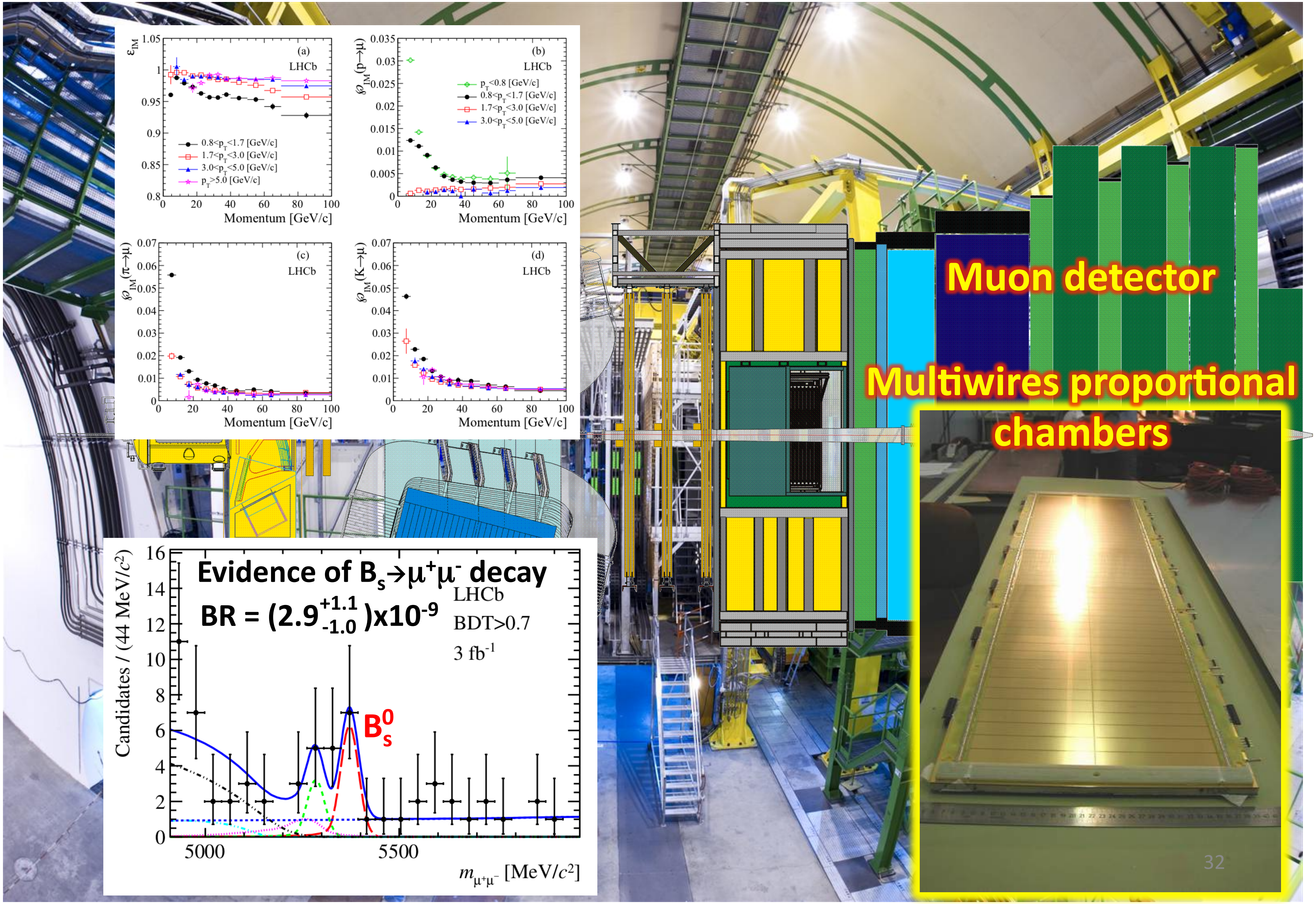
Three different radiators in order to cover a wide momentum range

J. High Energy Phys. 10 (2012) 037

The LHCb detector



The LHCb detector



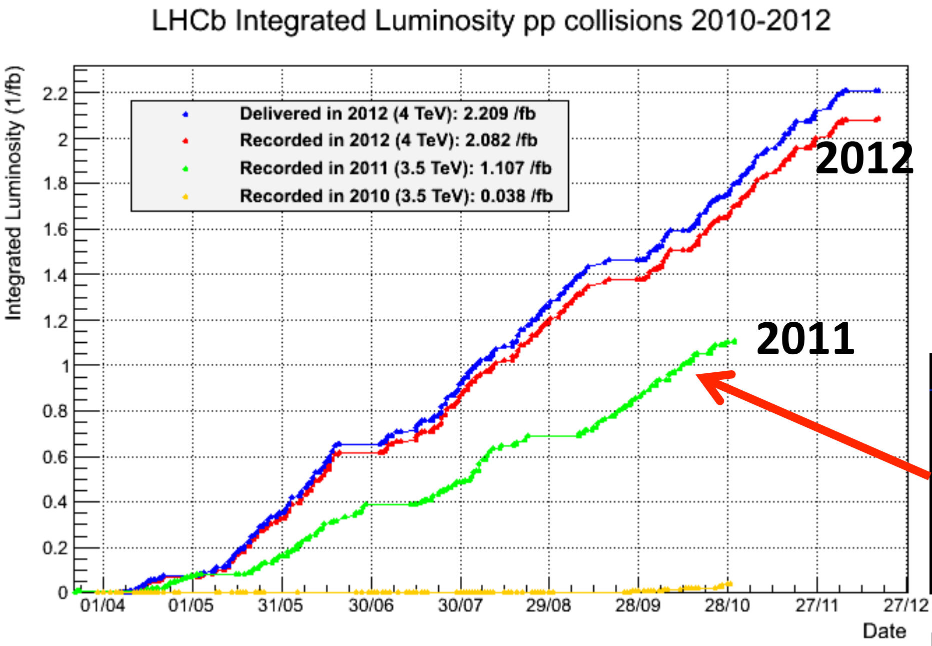
Muon detector

Multiwires proportional chambers

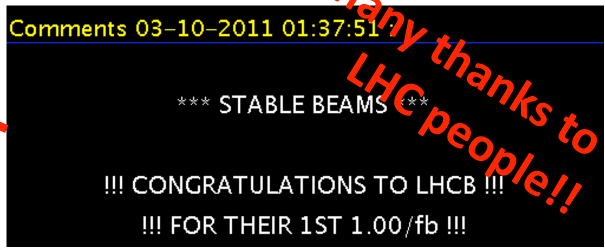
Evidence of $B_s \rightarrow \mu^+\mu^-$ decay

BR = $(2.9^{+1.1}_{-1.0})\times10^{-9}$

The data taking



- Total sample
  - ~ 1.1/fb @ 7 TeV
  - ~ 2.1/fb @ 8 TeV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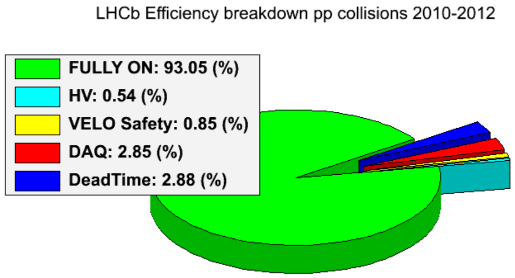
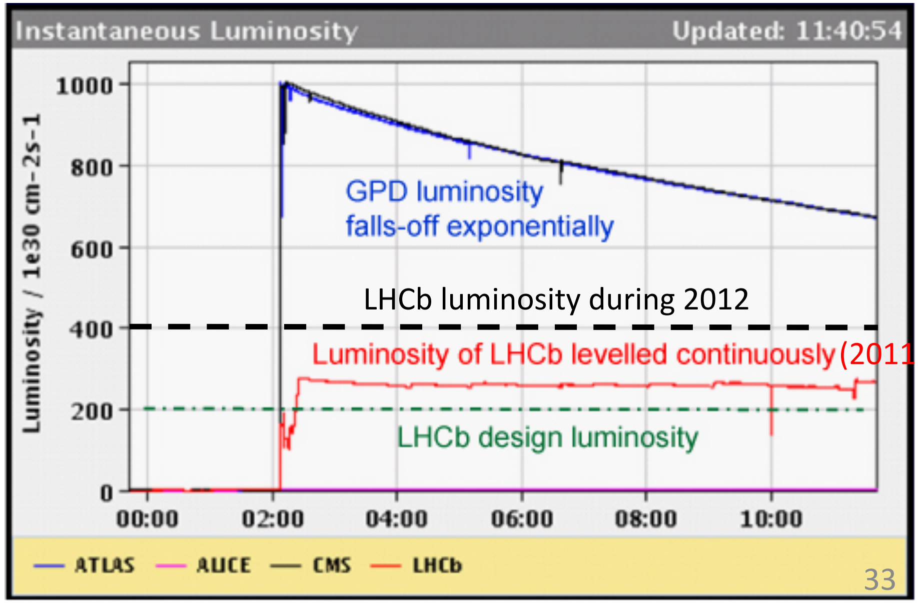
*** STABLE BEAMS ***

!!! CONGRATULATIONS TO LHCB !!!
!!! FOR THEIR 1ST 1.00/fb !!!

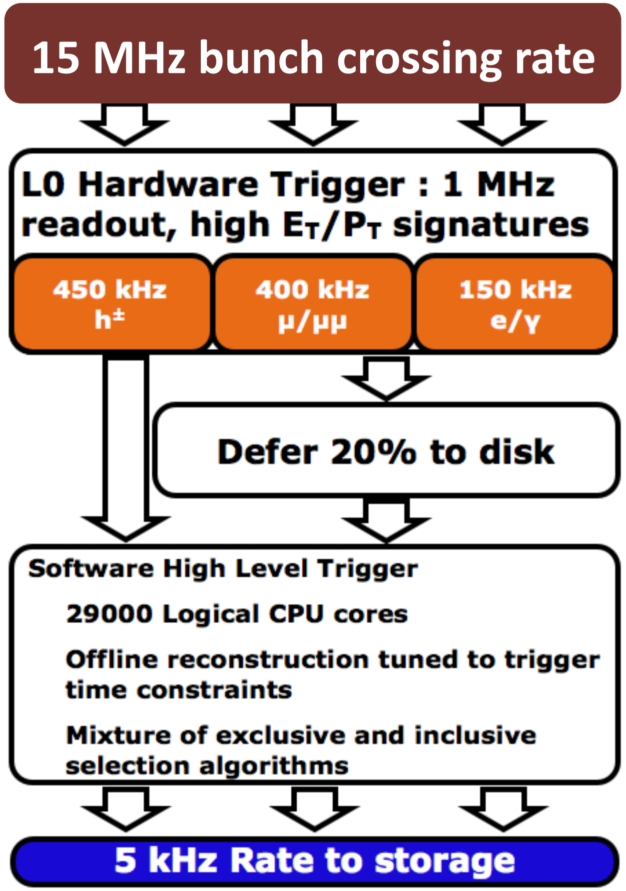
Many thanks to the LHC people!!



- **Excellent efficiency** of the detector:
  - Especially considering the sustained overhead in instantaneous luminosity



The LHCb trigger



15 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Defer 20% to disk

Software High Level Trigger

29000 Logical CPU cores

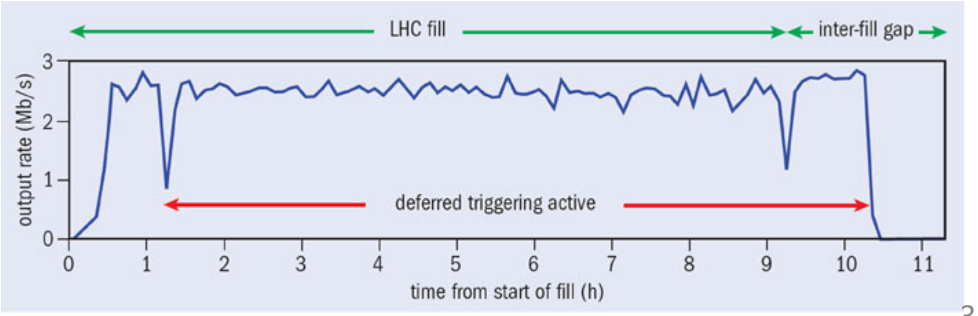
Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

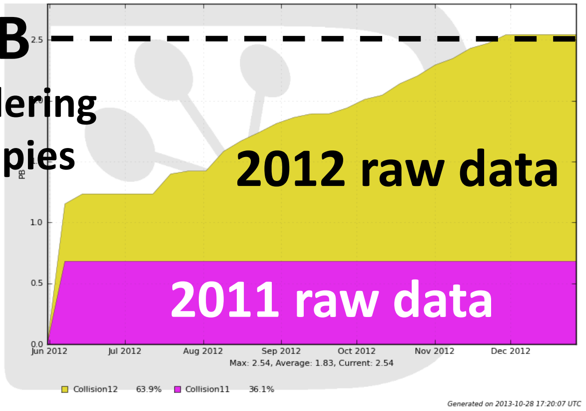
With an average of 60 kB/evt one has 300 MB/s of throughput to storage

- Multiple trigger levels:
  - **Level 0** uses information from fast detectors (calorimeters and muon stations)
  - **Software trigger** perform a **full reconstruction** of the tracks in the event
    - **Dedicated software trigger algorithm for B→$h^+h'^-$ decays**
  - **Deferred trigger**: a fraction of events is stored on the local disk of the online farm and processed in the time between LHC fills



The LHCb distributed computing

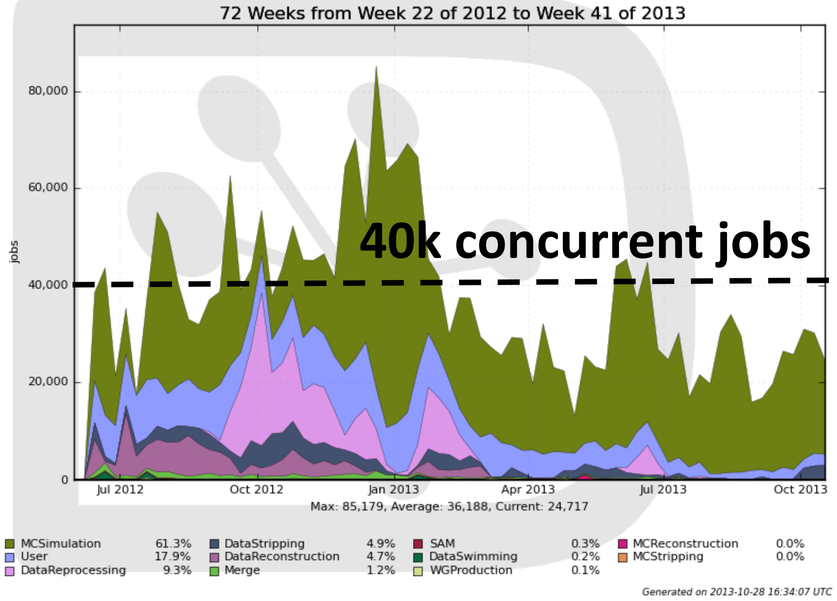
RAW data stored at T0 + T1s

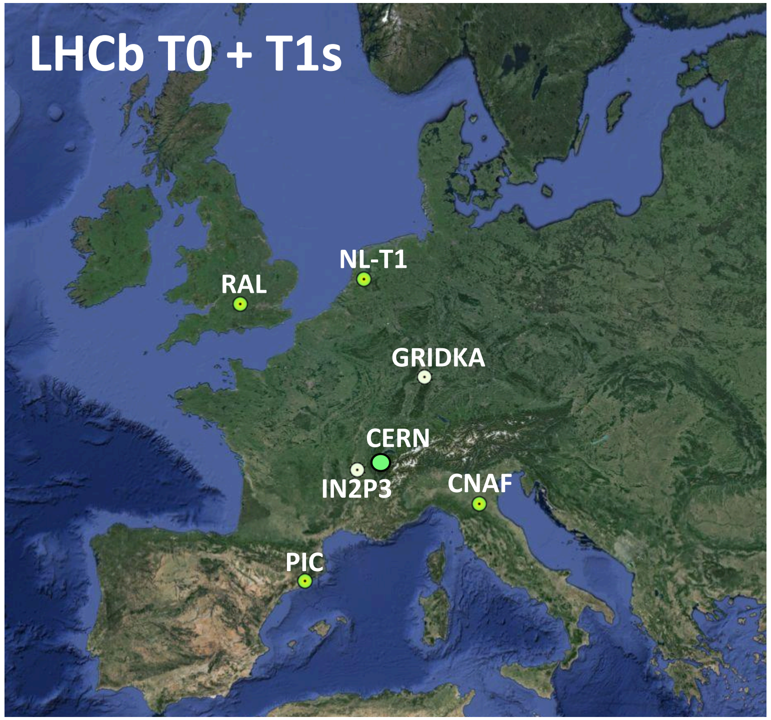


2.5 PB

5 PB considering backup copies

Running jobs





- **Lots of effort to make the data available for users**
  - **Prompt reconstruction**
  - **Stripping (event preselection)**
  - **Re-processing (with updated calibrations)**
  - **Monte Carlo simulation (mainly at T2s)**
  - **User jobs**

Direct CP asymmetries in $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ decays

Phys. Rev. Lett. 110 (2013) 221601

Main steps of the analysis

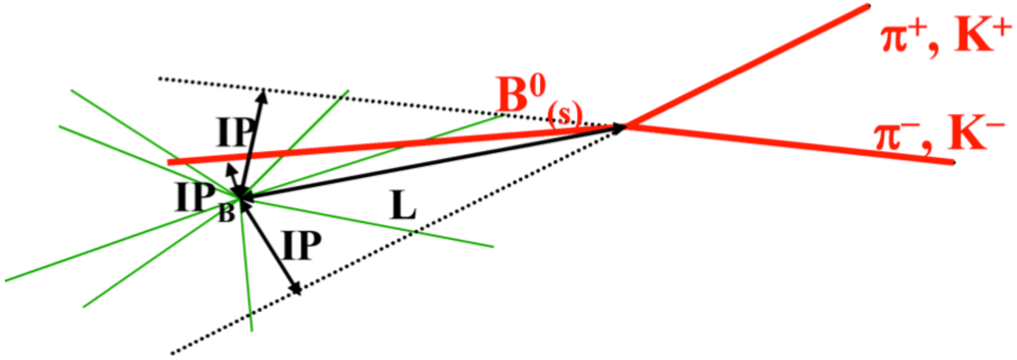
- Event selection
  - **1 fb^{-1}** collected during 2011 at **$\sqrt{s}$ = 7 TeV**
- Calibration of particle identification (**PID**)
- Determination of **raw asymmetries** from invariant mass fits
- Correction to the raw asymmetries
  - **Detection asymmetries**
  - **Production asymmetries**

Event selection

- Event selection is performed in **two steps**:
  - Separation of signal events from combinatorial background events using requirements on kinematic and topological variables
  - Separation of final states using PID criteria:
    - 8 mutually exclusive samples ($\pi^+\pi^-$, $K^+\pi^-$, π^+K^-, K^+K^-, pK^-, pK^+, $p\pi^-$, $p\pi^+$)
- Different values of the requirements have been optimized for the two measurements:
  - **Looser cuts** for $A_{CP}(B^0 \rightarrow K^+\pi^-)$
  - **Tighter cuts** for $A_{CP}(B_s^0 \rightarrow \pi^+K^-)$

Kinematic selection

- Using fast MC toys the **sensitivity on A_{CP}** has been parameterized as a function of the fraction of signal events in the sample and the total number of events
- Signal events are modelled using MC
  - Agreement with data is checked “a posteriori”
- Background events are modelled using signal-free invariant mass sideband



- Choose the combination of cut values giving the **best sensitivity on A_{CP}**

Looser cuts of $A_{CP}(B^0 \rightarrow K^+\pi^-)$

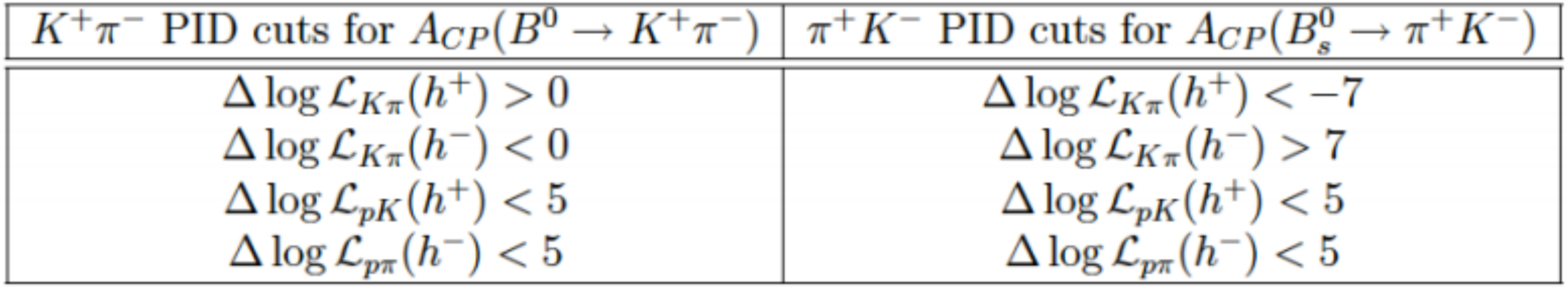
Cut type	Accepted regions
Track p_T [GeV/c]	> 1.1
Track IP [μm]	> 150
Track χ^2/d.o.f.	< 3
$\max(p_T^{h^+}, p_T^{h'^-})$ [GeV/c]	> 2.8
$\max(IP^{h}, IP^{h'^-})$ [μm]	> 300
p_T^B [GeV/c]	> 2.2
$\tau_{\pi\pi}^B$ [ps]	> 0.9

Tighter cuts of $A_{CP}(B^0_s \rightarrow \pi^+K^-)$

Cut type	Accepted regions
Track p_T [GeV/c]	> 1.2
Track IP [μm]	> 200
Track χ^2/d.o.f.	< 3
$\max(p_T^{h^+}, p_T^{h'^-})$ [GeV/c]	> 3
$\max(IP^{h}, IP^{h'^-})$ [μm]	> 400
p_T^B [GeV/c]	> 2.4
$\tau_{\pi\pi}^B$ [ps]	> 1.2

PID selection

- Events passing the kinematic selection are separated into different final states by means of PID requirements
  - Separation between hadrons is performed by means of information provided by **RICH detectors**
- Values of PID cuts are chosen in order to reduce the total amount of mis-identified decays under $B^0 \rightarrow K^+\pi^-$ and $B_s \rightarrow \pi^+K^-$ peaks to the same level of the combinatorial background



$K^+\pi^-$ PID cuts for $A_{CP}(B^0 \rightarrow K^+\pi^-)$	π^+K^- PID cuts for $A_{CP}(B_s^0 \rightarrow \pi^+K^-)$
$\Delta \log \mathcal{L}_{K\pi}(h^+) > 0$	$\Delta \log \mathcal{L}_{K\pi}(h^+) < -7$
$\Delta \log \mathcal{L}_{K\pi}(h^-) < 0$	$\Delta \log \mathcal{L}_{K\pi}(h^-) > 7$
$\Delta \log \mathcal{L}_{pK}(h^+) < 5$	$\Delta \log \mathcal{L}_{pK}(h^+) < 5$
$\Delta \log \mathcal{L}_{p\pi}(h^-) < 5$	$\Delta \log \mathcal{L}_{p\pi}(h^-) < 5$

$\Delta\log\mathcal{L}_{ab}(h) = \log\mathcal{L}_a(h) - \log\mathcal{L}_b(h)$

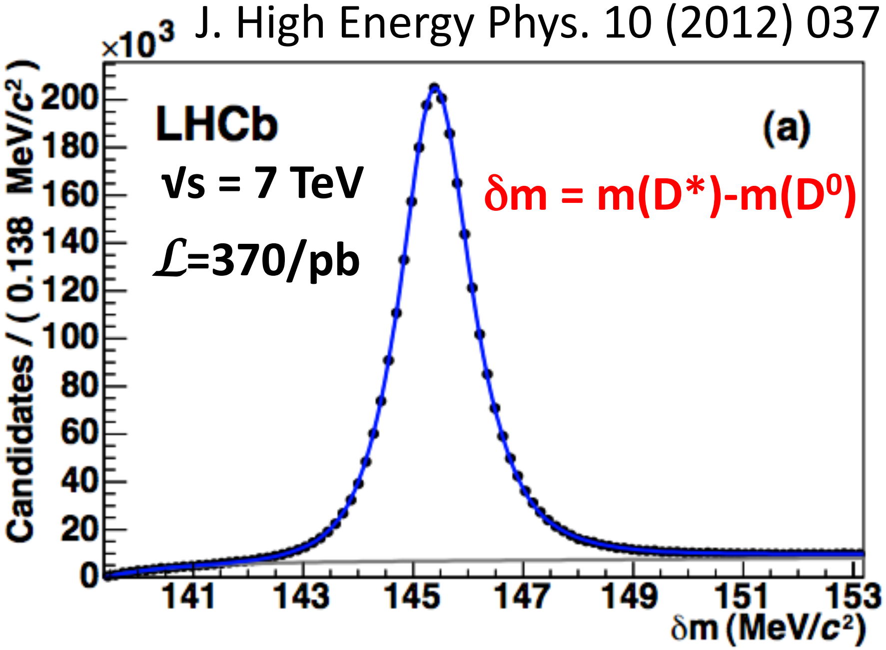
$\log\mathcal{L}_a(h)$ = logarithm of the likelihood of the hypothesis *a* for the particle *h*

The use of harder cuts for the $B_s^0 \rightarrow \pi^+K^-$ will be clear when showing the invariant mass spectra

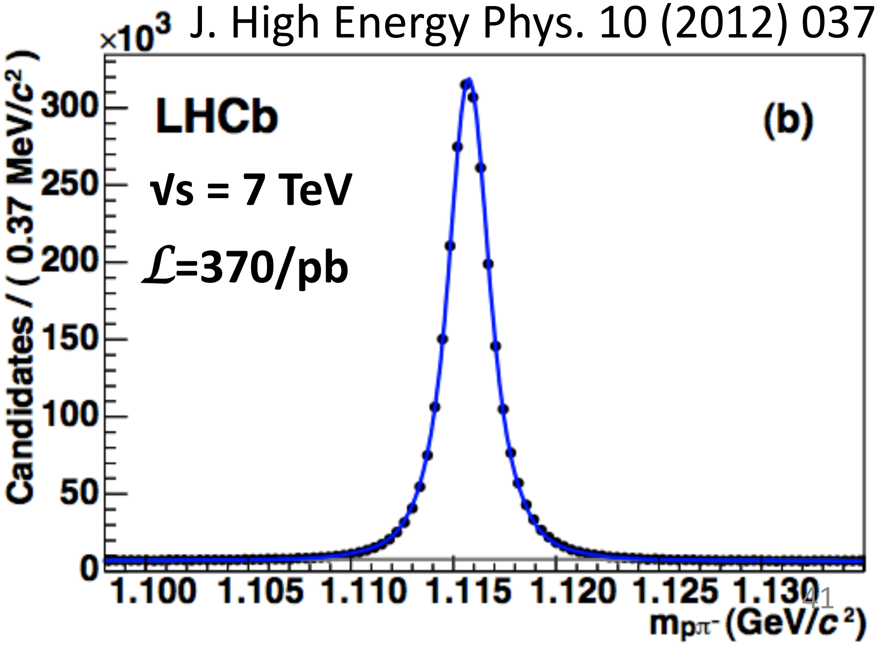
PID calibration

- Crucial aspect of the analysis:
  - Determine the contamination of mis-identified B→hh' decays under signal peaks
- $D^* \rightarrow D^0(K\pi)\pi_s$ and $\Lambda \rightarrow p\pi$ decays are suitable calibration samples:
  - high statistics and pure samples of π, K and p selected without using PID informations
  - $\Delta\log\mathcal{L}$ distributions are extracted from data using sPlot technique to subtract background

J. High Energy Phys. 10 (2012) 037



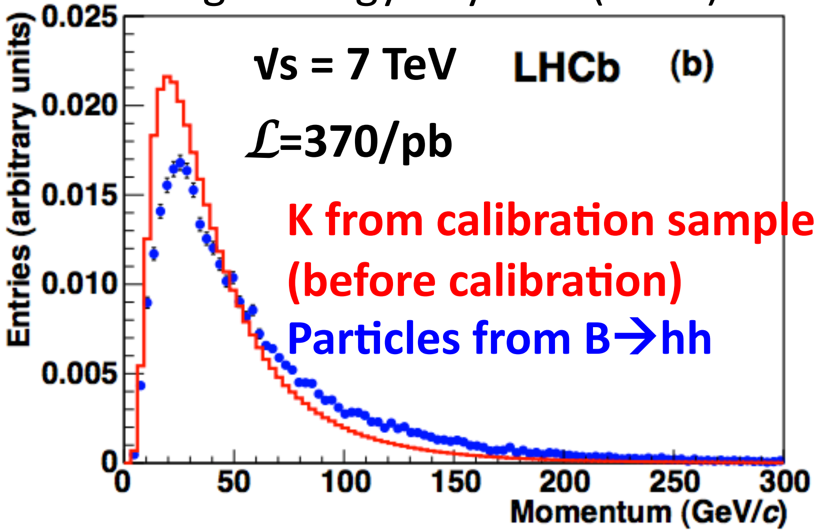
J. High Energy Phys. 10 (2012) 037

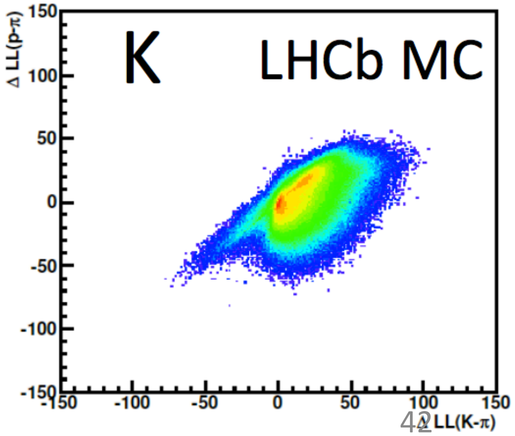


PID calibration

- PID variables depends on the kinematic of particles
  - Momentum distribution of calibration particles is **equalized** to the momentum distribution of particles from B
  - Momentum of particles from B→hh' is determined **from data** using sPlot technique to subtract background
  - PID efficiencies are computed on **reweighted samples**
- Complications:
  - Kinematic correlation between the two daughters of signal B is taken into account
  - Correlation between $\Delta\log\mathcal{L}_{K\pi}$ and $\Delta\log\mathcal{L}_{p\pi}$ is taken into account

J. High Energy Phys. 10 (2012) 037





$\Delta\log\mathcal{L}_{p\pi}$ vs $\Delta\log\mathcal{L}_{K\pi}$

Invariant mass fits

- Raw asymmetries are extracted using unbinned maximum lieklihood fits to the invariant mass spectra

$$A_{RAW} = \frac{N(\overline{B} \to \bar{f}) - N(B \to f)}{N(\overline{B} \to \bar{f}) + N(B \to f)}$$

- All 8 final state samples are fitted simultaneously
  - B→hh' yields related by PID mis-ID probabilities **obtained from calibration procedure**

J. High Energy Phys.10 (2012) 037

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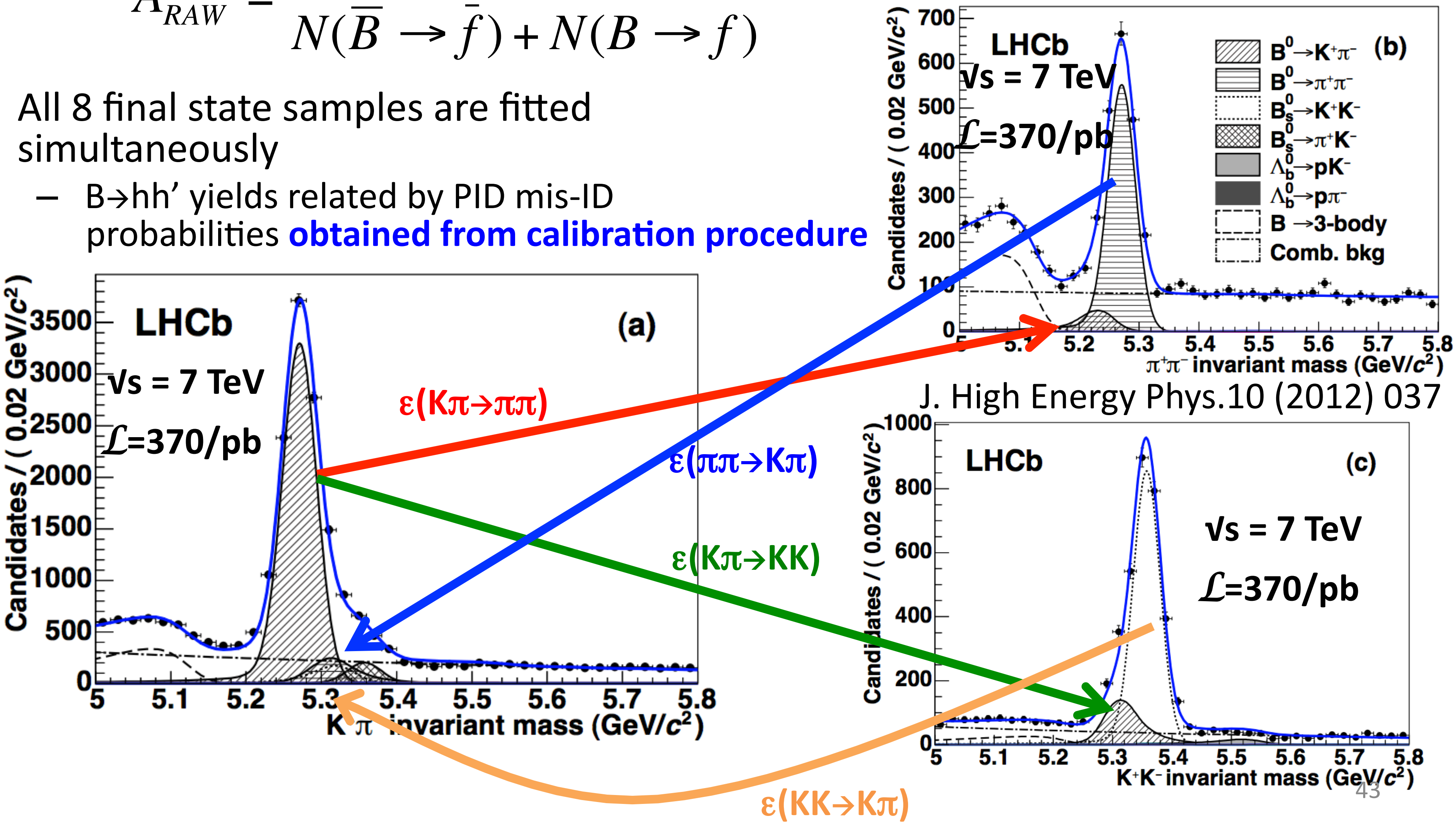
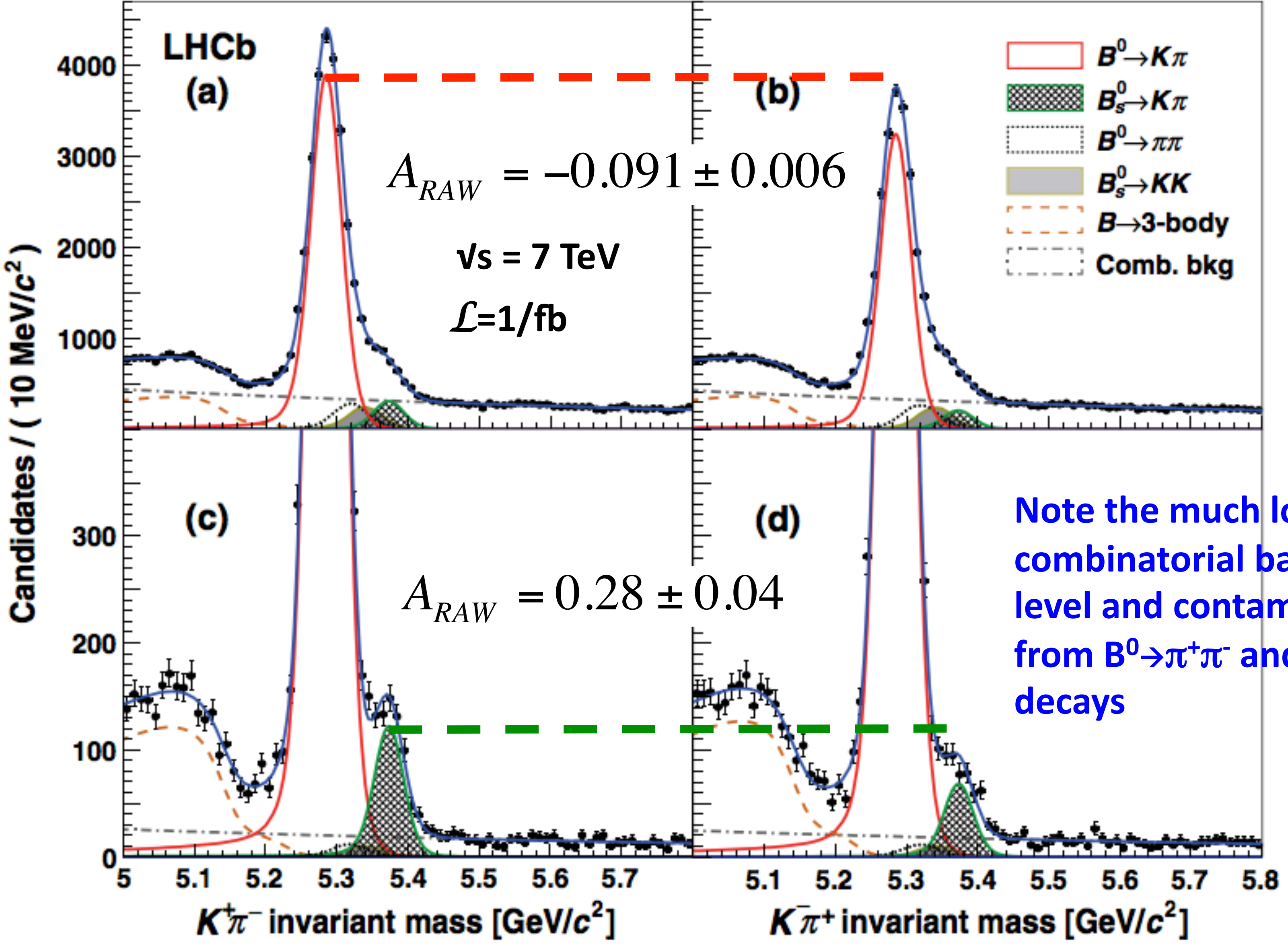


Raw asymmetries

Phys. Rev. Lett. 110 (2013) 221601



$$A_{RAW} = -0.091 \pm 0.006$$

√s = 7 TeV

$\mathcal{L}$=1/fb

$$A_{RAW} = 0.28 \pm 0.04$$

Note the much lower combinatorial background level and contamination from $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays

Correction to raw asymmetries

- $A_{CP}(B^0 \rightarrow K^+\pi^-)$ and $A_{CP}(B_s^0 \rightarrow \pi^+K^-)$ are related to the raw asymmetries by the relation

$$A_{CP} = \boxed{A_{RAW}} - \boxed{A_D} - \kappa\boxed{A_P}$$

Raw asymmetry
From invariant mass fit

Detection asymmetry between
$K^+\pi^-$ and $K^-\pi^+$ pairs

Asymmetry in production rates
of B and B mesons

- κ is a dilution factor that depends on the event selection and on the time evolution of the B meson

For B^0 $\kappa_d = 0.303 \pm 0.005$

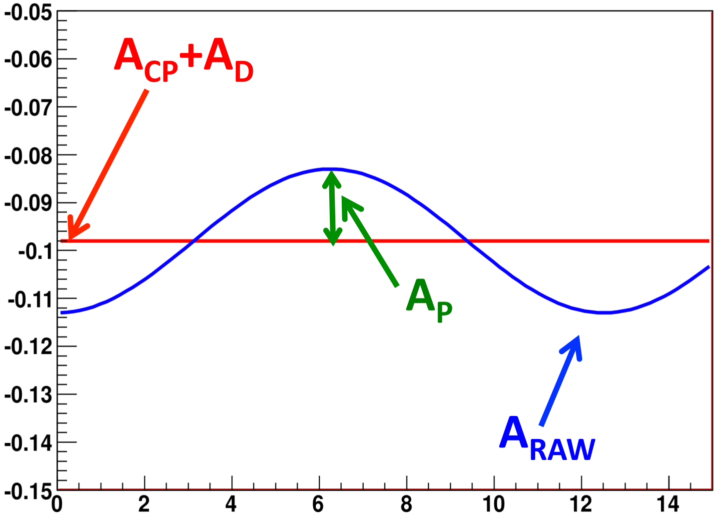
For B_s $\kappa_s = -0.033 \pm 0.003$

Note: fast oscillation of B_s^0 mesons dilutes to a negligible level the correction due to A_P

Production asymmetry

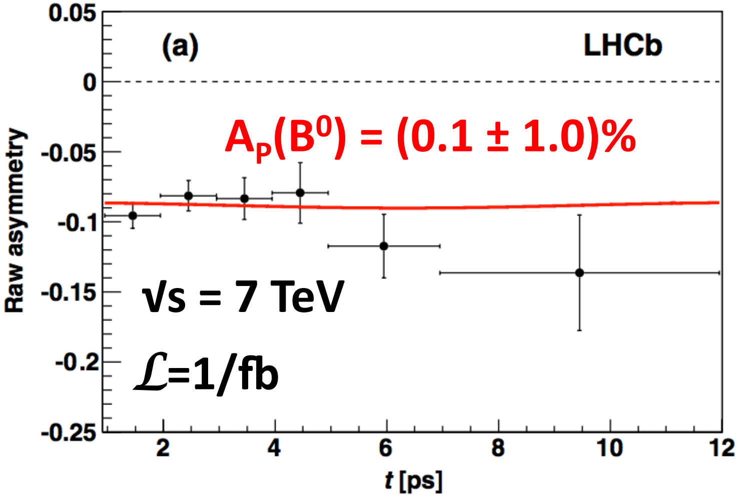
- The time dependent raw asymmetry of $B^0 \rightarrow K^+\pi^-$ and $B^0_s \rightarrow \pi^+K^-$ decay can be written as

$$A_{RAW}(t) = \frac{N_{\bar{B}\rightarrow\bar{f}}(t) - N_{B\rightarrow f}(t)}{N_{\bar{B}\rightarrow\bar{f}}(t) + N_{B\rightarrow f}(t)} \approx A_{CP} + A_D + A_P \cos(\Delta m t)$$

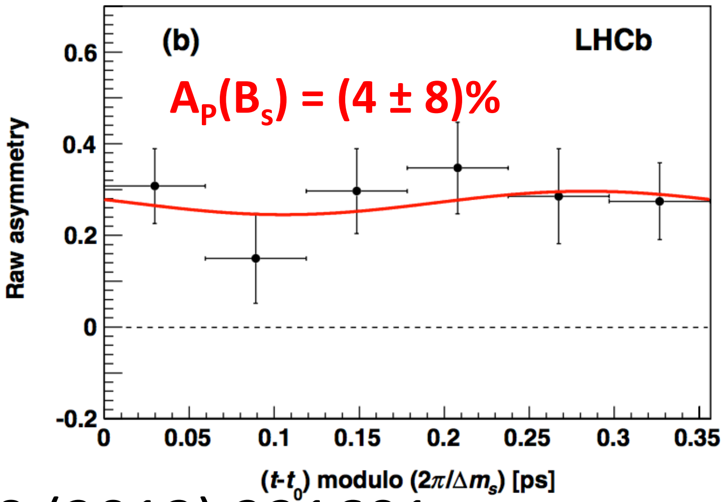


- A_P values for B^0 and B^0_s are obtained from fits to the decay time spectra of B candidates

Loose selection



Tight selection



Phys. Rev. Lett.110 (2013) 221601

Note: points are the raw asymmetry of signals obtained from invariant mass fits in bins of decay time. The curve is the asymmetry projection of the fits to the decay time spectra

Detection asymmetry

- $K^+\pi^-/K^-\pi^+$ can have different reconstruction efficiencies
- $K^+\pi^-/K^-\pi^+$ have different interaction cross section with detector material
- Using $D^* \to D^0(K\pi)\pi_s$ and $D^* \to D^0(KK)\pi_s$ in order to isolate A_D:

$$A^*_{raw}(K\pi) = \cancel{A_{CP}(K\pi)} + A_D(K\pi) + A_D(\pi_s) + A_P(D^*)$$

$$A^*_{raw}(KK) = A_{CP}(KK) + A_D(\pi_s) + A_P(D^*)$$

$$\underline{A_D(K\pi)} = A^*_{raw}(K\pi) - A^*_{raw}(KK) + \boxed{A_{CP}(KK)}$$

Known from
World Average

- Need to consider **different phase** space between B and D decays due to production, decay, trigger, selection

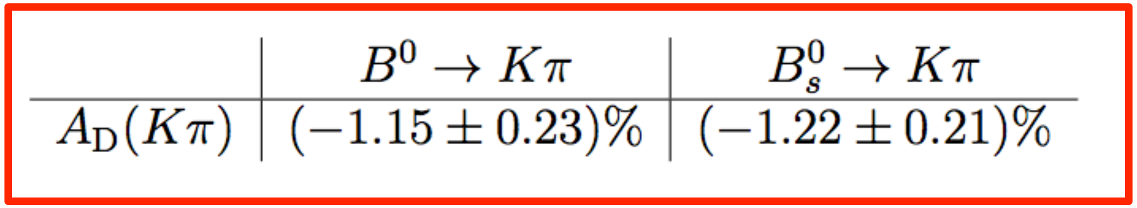
  → Equalize kinematics: from D to B

- **A_{CP}(KK) from World Average** (CDF + B-factories) is transported to the LHCb decay time acceptance, yielding:

$$A_{CP}^{\mathrm{LHCb}}(KK) = (-0.24 \pm 0.18)\%$$

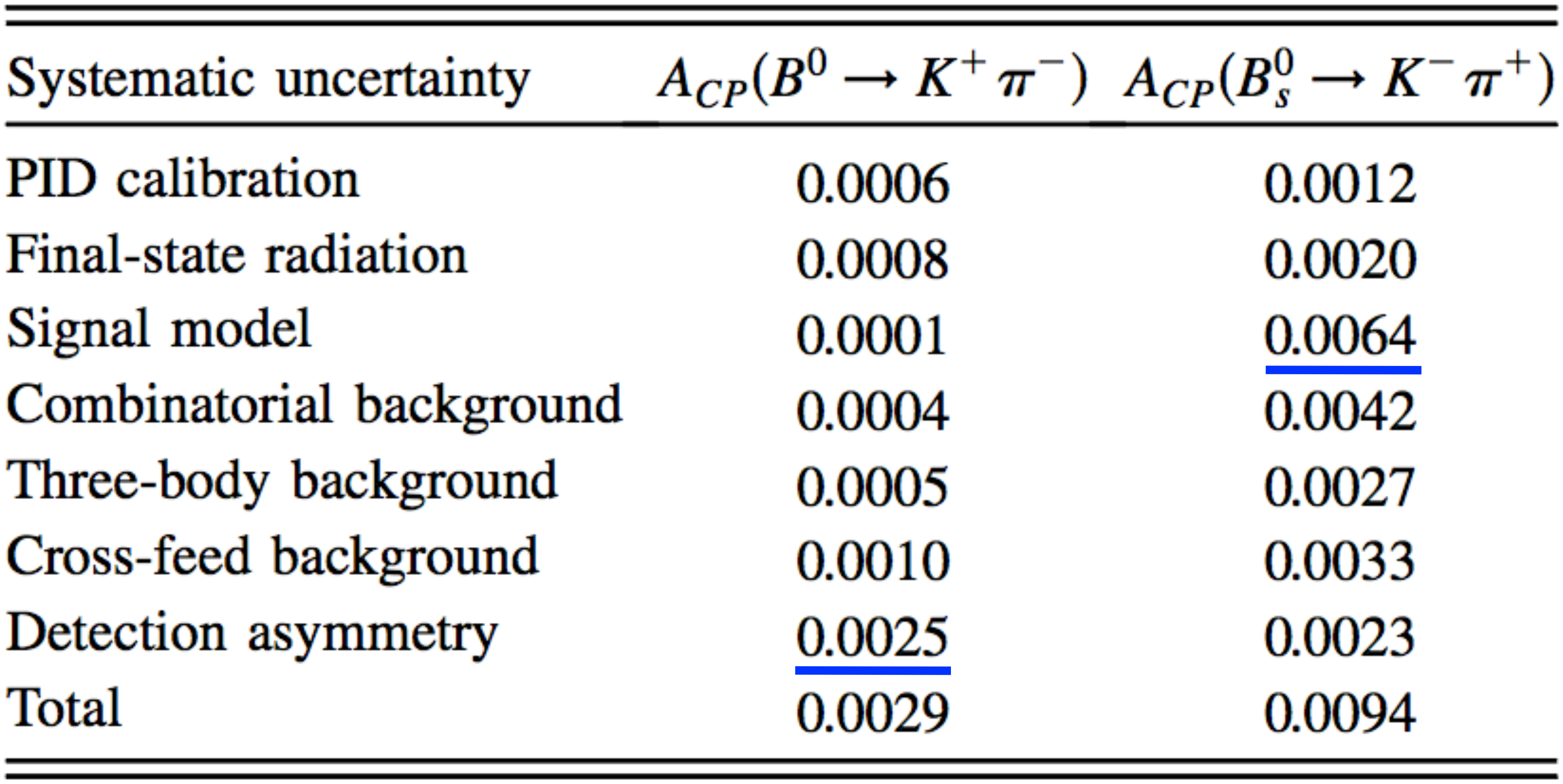
Detection asymmetry

- Build the ratio of normalized signal $B^0_{(s)}\rightarrow K\pi/D^0\rightarrow KK$ and $B^0_{(s)}\rightarrow K\pi/D^0\rightarrow K\pi$ as a function of (p,p_T) and azimuthal angle ϕ
  - Distributions are determined using sPlot technique to subtract the background
- Use this ratio as **per-event weight** for $D^0\rightarrow KK$ and $D^0\rightarrow K\pi$
- Make a posteriori check (i.e. after reweighting) of background subtracted kinematic distributions
- Reweighting is performed also separately for the two different polarities of the dipole magnet
- Perform **χ^2 fits** to the $D^*\rightarrow D^0(KK)\pi$ and $D^*\rightarrow D^0(K\pi)\pi$ **reweighted samples**



	$B^0 \to K\pi$	$B^0_s \to K\pi$
$A_{\rm D}(K\pi)$	$(-1.15 \pm 0.23)\%$	$(-1.22 \pm 0.21)\%$

Systematic uncertainties



Systematic uncertainty	$A_{CP}(B^0 \to K^+\pi^-)$	$A_{CP}(B_s^0 \to K^-\pi^+)$
PID calibration	0.0006	0.0012
Final-state radiation	0.0008	0.0020
Signal model	0.0001	0.0064
Combinatorial background	0.0004	0.0042
Three-body background	0.0005	0.0027
Cross-feed background	0.0010	0.0033
Detection asymmetry	0.0025	0.0023
Total	0.0029	0.0094

Note: since production asymmetries are obtained from fits to the $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$ decay time spectra their uncertainties are statistical in nature and are then propagated to the statistical uncertainties.

Final results

$$A_{CP}\left(B^0 \to K\pi\right) = -0.080 \pm 0.007(\mathrm{stat}) \pm 0.003(\mathrm{syst}),$$

Most precise measurement of this quantity to date, 10.5σ from zero

$$A_{CP}\left(B_s^0 \to K\pi\right) = 0.27 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst}).$$

First observation of CP violation in B_s decays, with significance of 6.5σ

- Test of SM using U-Spin [Phys. Lett. B 621, 126 (2005)]

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

- Using LHCb results for branching ratios [JHEP 10 (2012) 037]

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays

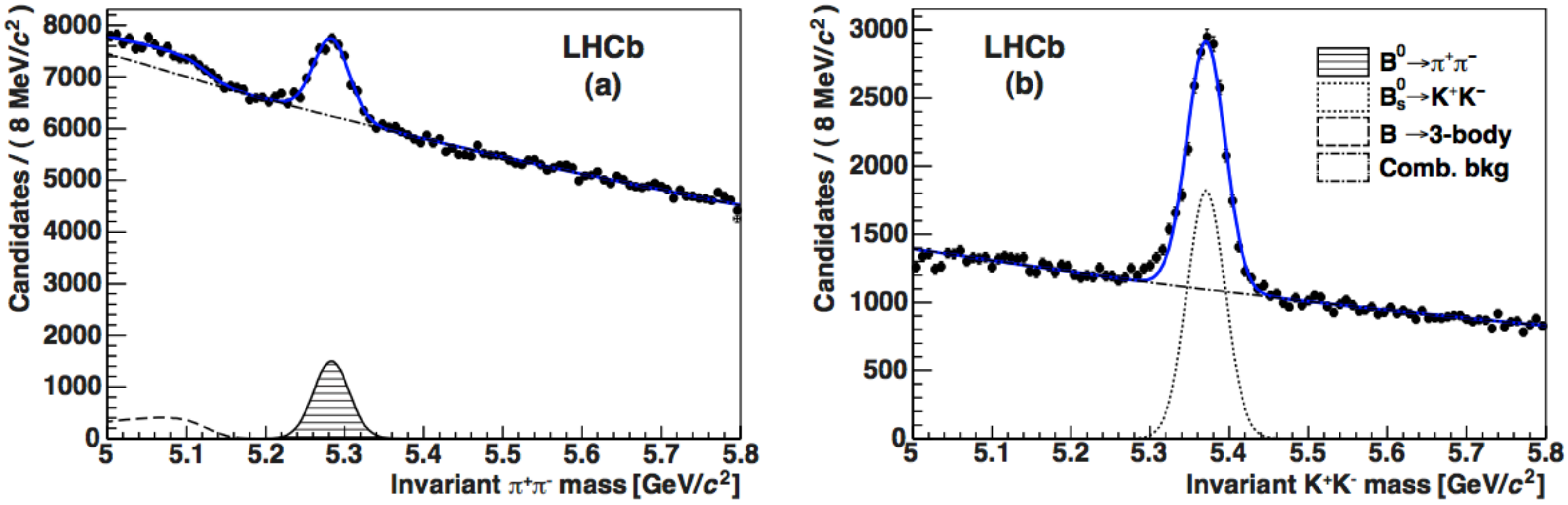
J. High Energy Phys. 10 (2013) 183

Main steps of the analysis

- Event selection
  - 1 fb^{-1} collected during 2011 at √s 7 TeV
- $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ are decays to CP-eigenstates → need time-dependent measurements to observe CP violation
- Determination of **decay time resolution**
- Determination of initial flavour of B mesons
  - Calibration of **flavour tagging**
- 2D fits: invariant mass and tagged decay time

Event selection

- Event selection is based on boosted decision tree (BDT) algorithm
- Selection developed into two steps:
  - In the first steps the PID cuts are applied in order to disentangle $\pi^+\pi^-$, K^+K^-, $K^+\pi^-$ and $K^-\pi^+$ final states
  - Values of PID cuts are optimized in order to reduce the amount of cross-feed background at ~10% level of corresponding signal
  - Two BDT are optimized in order to reject combinatorial background in the $\pi^+\pi^-$ and K^+K^- spectra, respectively
- The optimization is performed in order to maximize S/sqrt(S+B)



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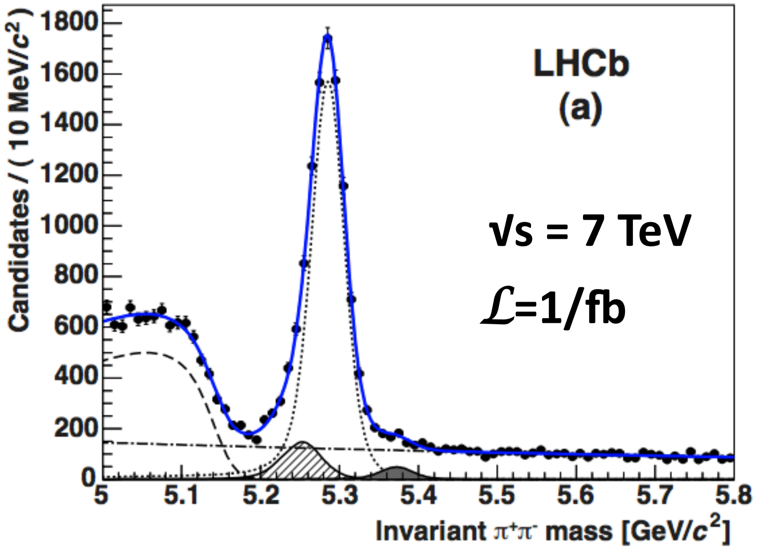
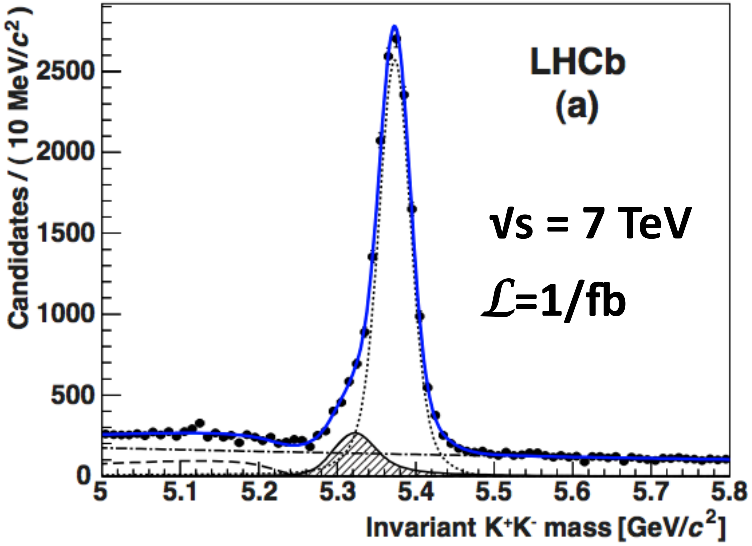
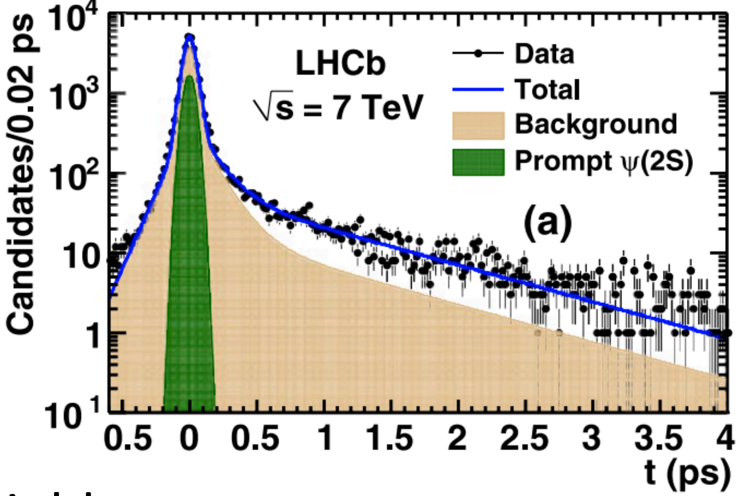




Decay time resolution

- Large samples of **prompt charmonium and bottomonium** states decaying into $\mu^+\mu^-$ have been selected **without** any requirement that **biases the decay time distribution**

Eur. Phys. J. C 72 (2012) 2100



- Using 2D (invariant mass and decay time) it is possible to determine an average decay time resolution
- The comparison with fully simulated events yields to

$$\frac{\sigma_{data}(t)}{\sigma_{MC}(t)} = 1.05 \pm 0.05$$

- This ratio is used to **rescale the decay time resolution** of B→hh' decays estimated from MC
- The error on the decay time resolution has been inflated in order to take into acount the **dependence of σ(t) vs t**
- Finally

$$\sigma(t) = 50 \pm 10\,fs$$

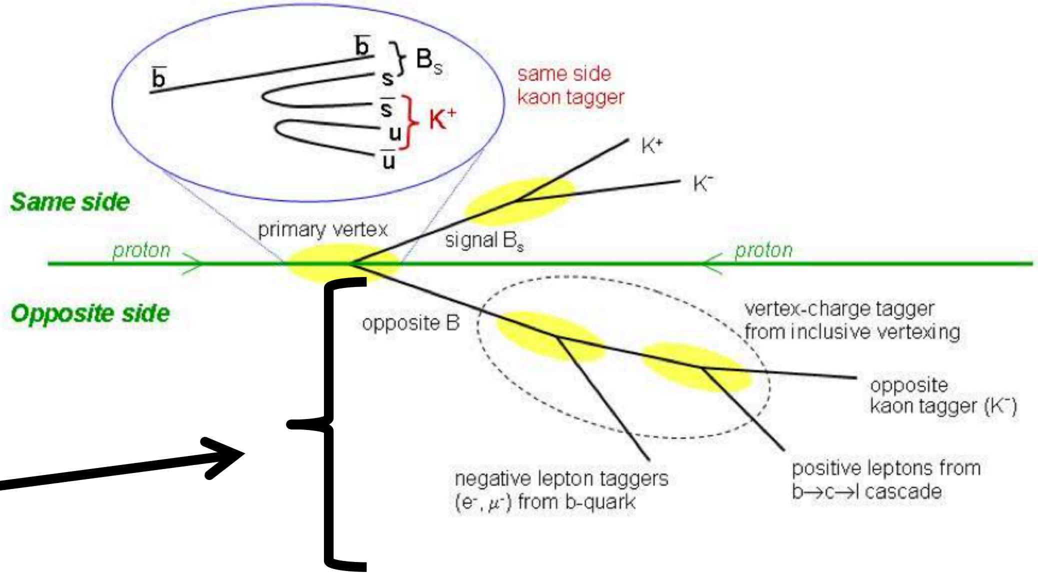
Flavour tagging

- Crucial aspect of the analysis:

$$C_f^{obs} = (1-2\omega)C_f \qquad 1/\sigma(C_f) \propto \varepsilon(1-2\omega)^2$$

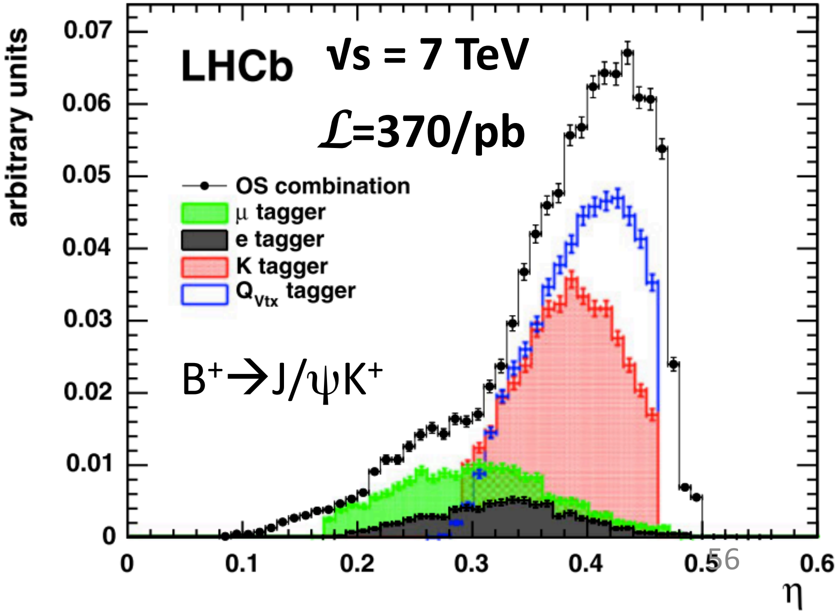
$$S_f^{obs} = (1-2\omega)S_f \qquad 1/\sigma(S_f) \propto \varepsilon(1-2\omega)^2$$

ω = mis-tag fraction ε = tagging efficiency



- In this analysis only **Opposite Side** (OS) taggers are used:
  - Analysing the "other" B in the event it is possible to determine the initial flavour of the signal B
  - For each tagger a mis-tag probability (η) is determined by means of an artificial Nnet
  - In case of multiple decisions a combination is performed in order to get a unique decision and η

Eur. Phys. J. C 72 (2012) 2022



Optimization of flavour tagging

- Using the sPlot technique to subtract background the η distribution of $B \to h^+ h'^-$ decays has been determined

- Data have been divided into subsamples according to the distribution of η in order to achieve the best sensitivity on C_f and S_f
  - Several combination of categories have been studied

Predicted effective tagging power

$$\tilde{\varepsilon}_{eff} = \sum_i \varepsilon_i (1 - 2\eta_i)^2$$

i = interval index

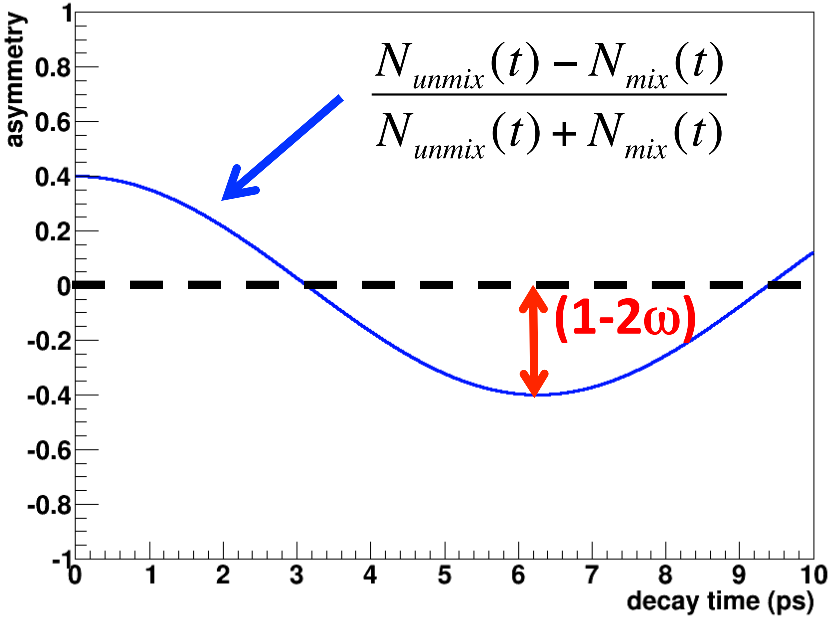
ε_i = tagging efficiency in interval i^th^

η_i = average mistag probability in interval i^th^

Category	Range for η
1	$0.00 - 0.22$
2	$0.22 - 0.30$
3	$0.30 - 0.37$
4	$0.37 - 0.42$
5	$0.42 - 0.47$

Calibration of flavour tagging

- Tagged time-dependent asymmetry of $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays depends on the mistag fraction

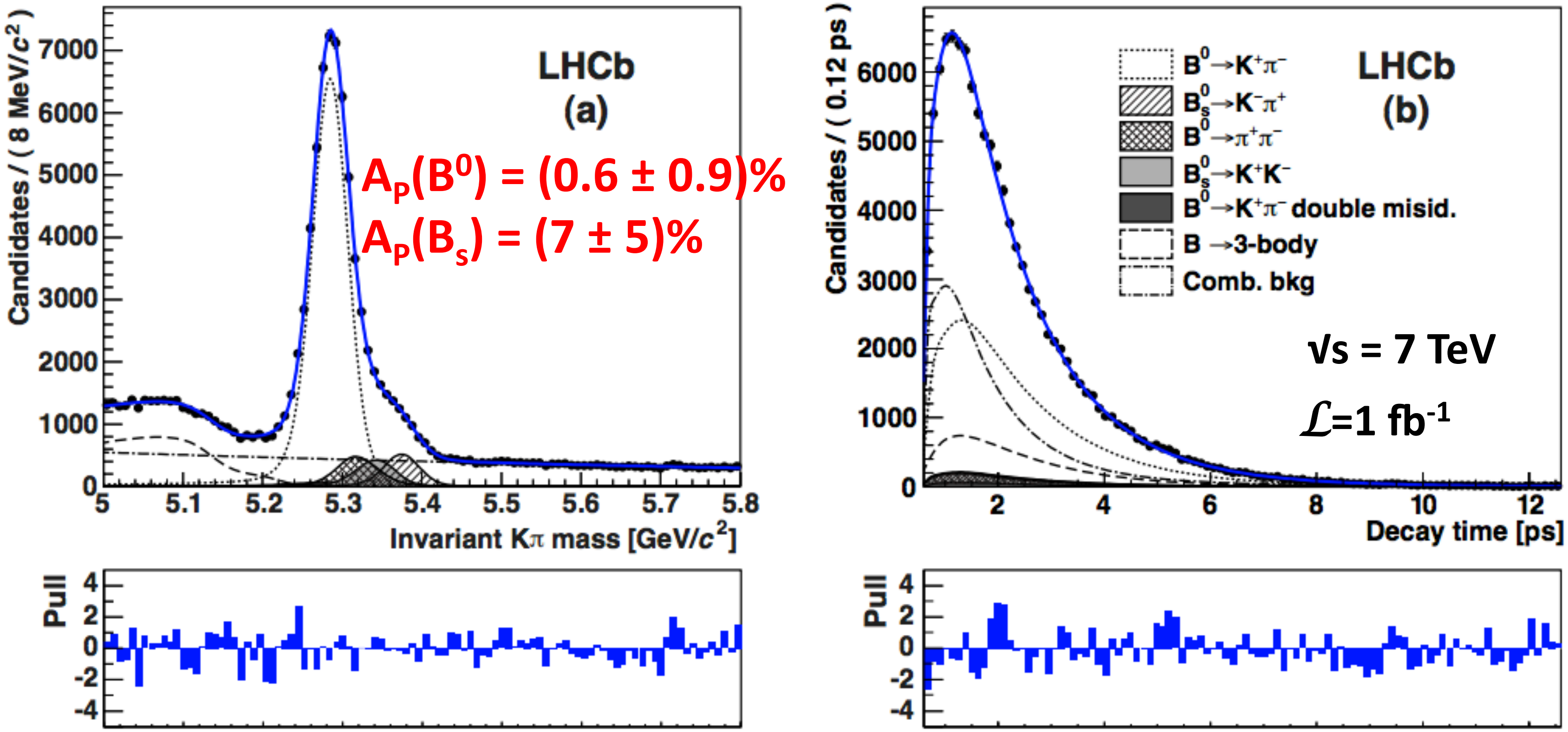


- The time-dependent asymmetry of the untagged subsample is proportional to A_P

- It is possible to calibrate the flavour tagging separately for B and $\overline{B}$

$$\underbrace{\begin{gathered}\varepsilon_k = \varepsilon_k^{\text{tot}}\left(1 - A_k^{\varepsilon}\right), \\ \omega_k = \omega_k^{\text{tot}}\left(1 - A_k^{\omega}\right),\end{gathered}}_{\mathbf{B}} \qquad \underbrace{\begin{gathered}\bar{\varepsilon}_k = \varepsilon_k^{\text{tot}}\left(1 + A_k^{\varepsilon}\right) \\ \bar{\omega}_k = \omega_k^{\text{tot}}\left(1 + A_k^{\omega}\right)\end{gathered}}_{\overline{\mathbf{B}}}$$

Calibration of flavour tagging

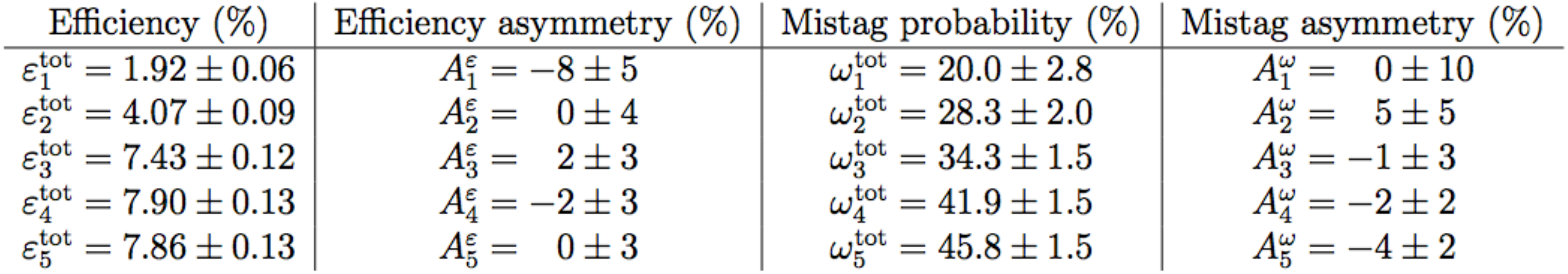


$A_P(B^0) = (0.6 \pm 0.9)\%$

$A_P(B_s) = (7 \pm 5)\%$

$\sqrt{s}$ = 7 TeV

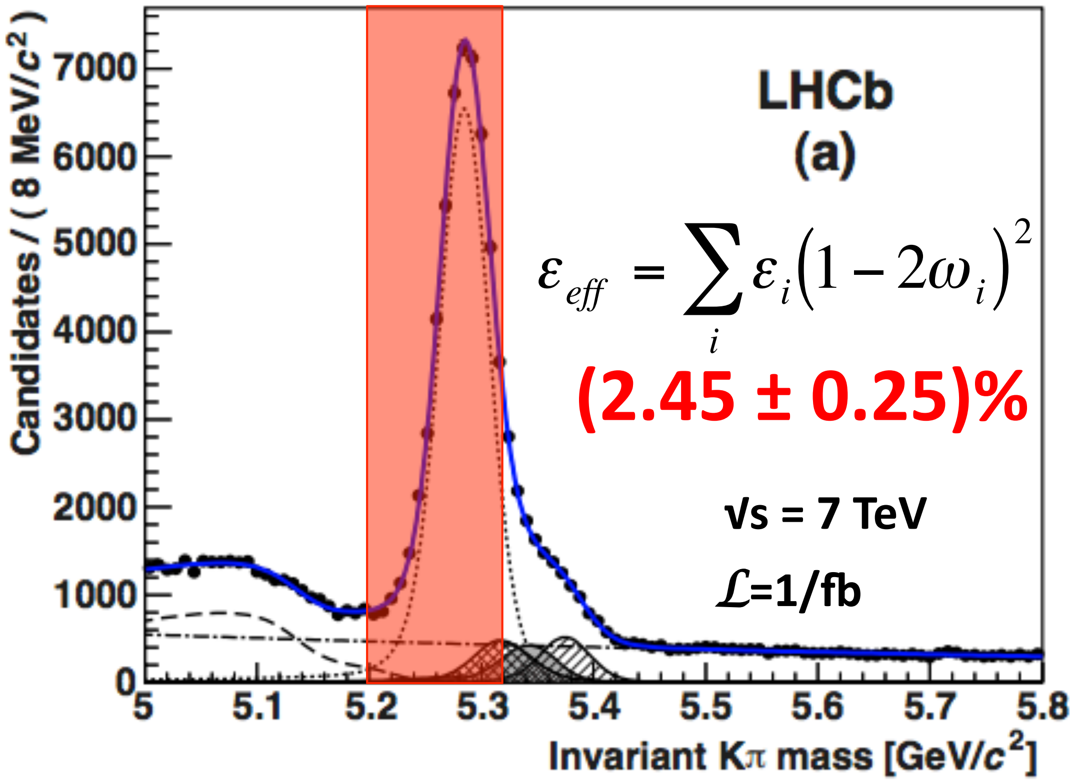
$\mathcal{L}$=1 fb^{-1}



Efficiency (%)	Efficiency asymmetry (%)	Mistag probability (%)	Mistag asymmetry (%)
$\varepsilon_1^{tot} = 1.92 \pm 0.06$	$A_1^{\varepsilon} = -8 \pm 5$	$\omega_1^{tot} = 20.0 \pm 2.8$	$A_1^{\omega} = 0 \pm 10$
$\varepsilon_2^{tot} = 4.07 \pm 0.09$	$A_2^{\varepsilon} = 0 \pm 4$	$\omega_2^{tot} = 28.3 \pm 2.0$	$A_2^{\omega} = 5 \pm 5$
$\varepsilon_3^{tot} = 7.43 \pm 0.12$	$A_3^{\varepsilon} = 2 \pm 3$	$\omega_3^{tot} = 34.3 \pm 1.5$	$A_3^{\omega} = -1 \pm 3$
$\varepsilon_4^{tot} = 7.90 \pm 0.13$	$A_4^{\varepsilon} = -2 \pm 3$	$\omega_4^{tot} = 41.9 \pm 1.5$	$A_4^{\omega} = -2 \pm 2$
$\varepsilon_5^{tot} = 7.86 \pm 0.13$	$A_5^{\varepsilon} = 0 \pm 3$	$\omega_5^{tot} = 45.8 \pm 1.5$	$A_5^{\omega} = -4 \pm 2$

No evidence of different flavour tagging performances between B and $\overline{B}$

Calibration of flavour tagging

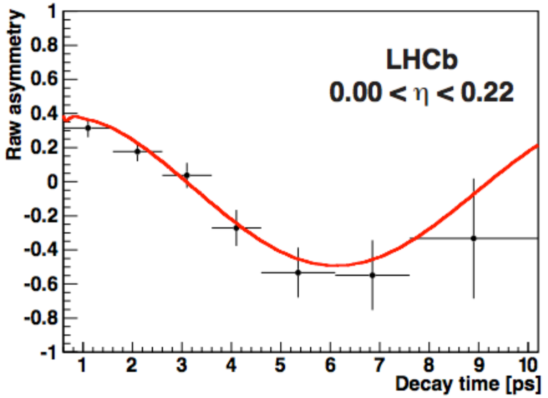


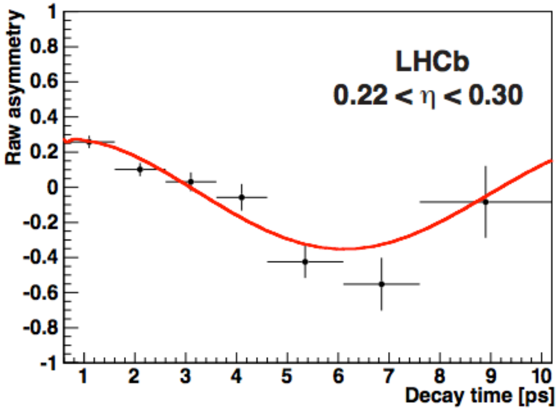
$$\varepsilon_{eff} = \sum_i \varepsilon_i \left(1 - 2\omega_i\right)^2$$

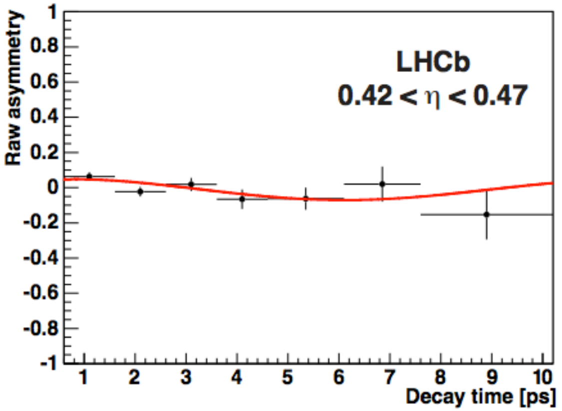
(2.45 ± 0.25)%

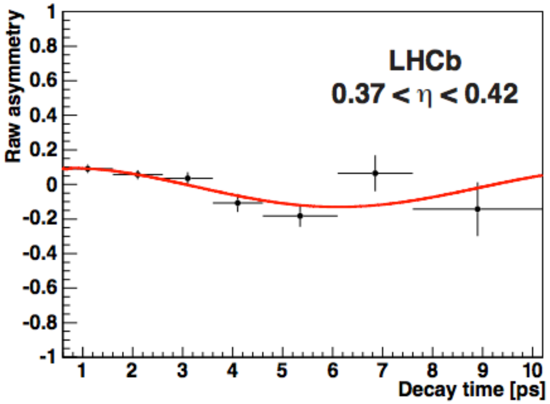
√s = 7 TeV

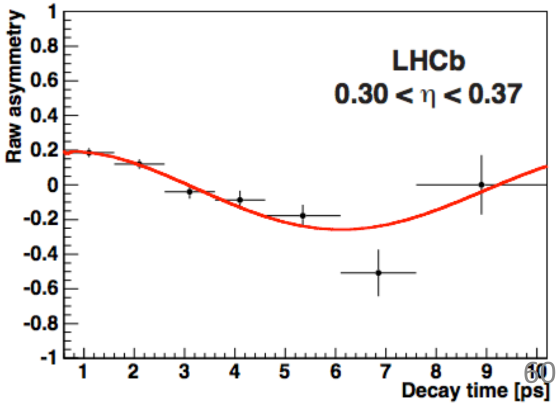
$\mathcal{L}$=1/fb









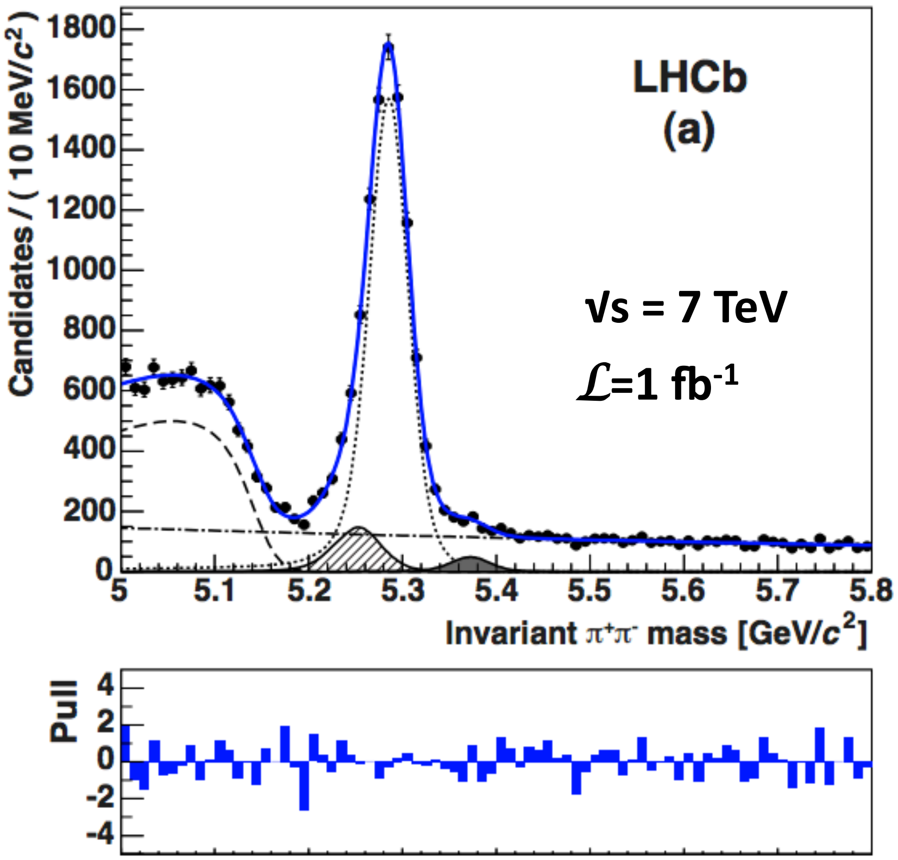


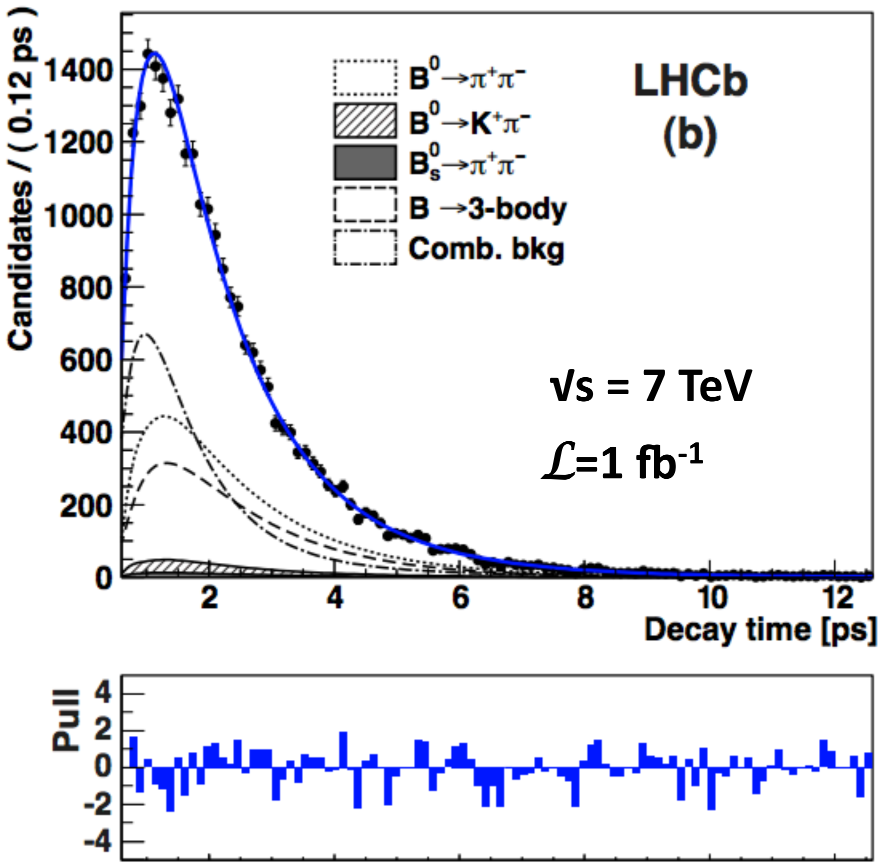
Determination of C_f and S_f

- C_f and S_f are determined from 2D (invariant mass and tagged decay time) fits to the $\pi^+\pi^-$ and K^+K^- spectra

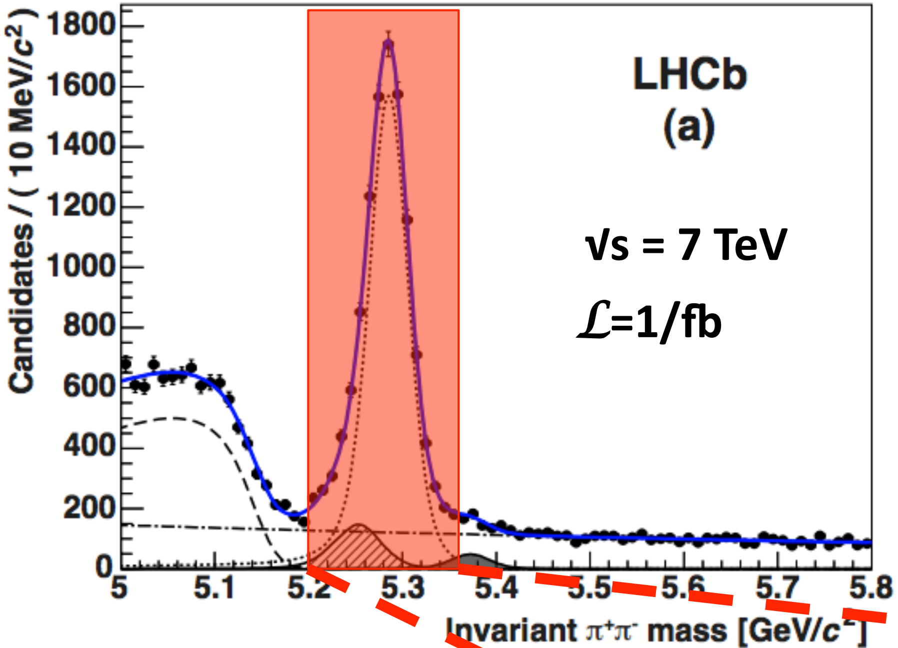
- The flavour tagging parameters and production asymmetries determined from the fits to the $K\pi$ spectra are propagated by multiplying the likelihood with gaussian terms

Fits to the $\pi^+\pi^-$ spectra





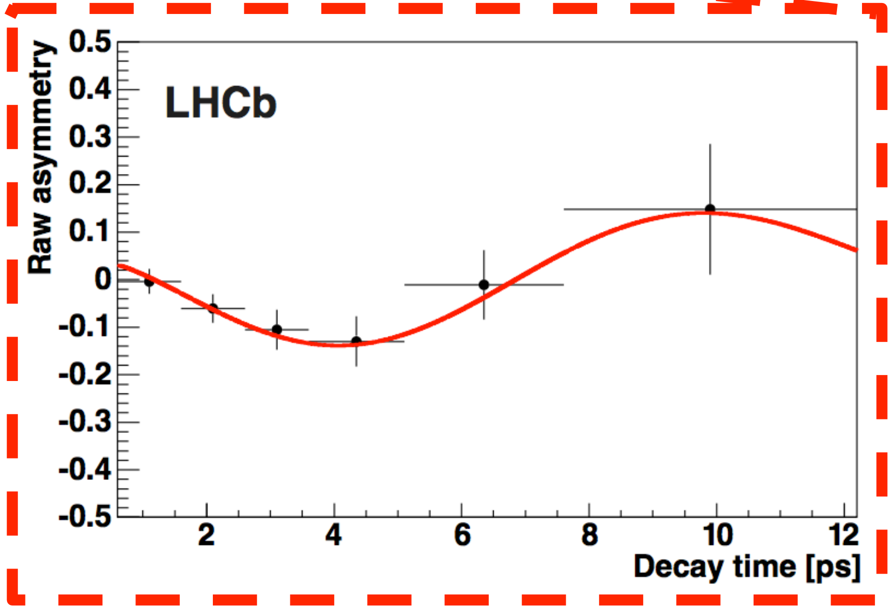
Fits to the $\pi^+\pi^-$ spectra



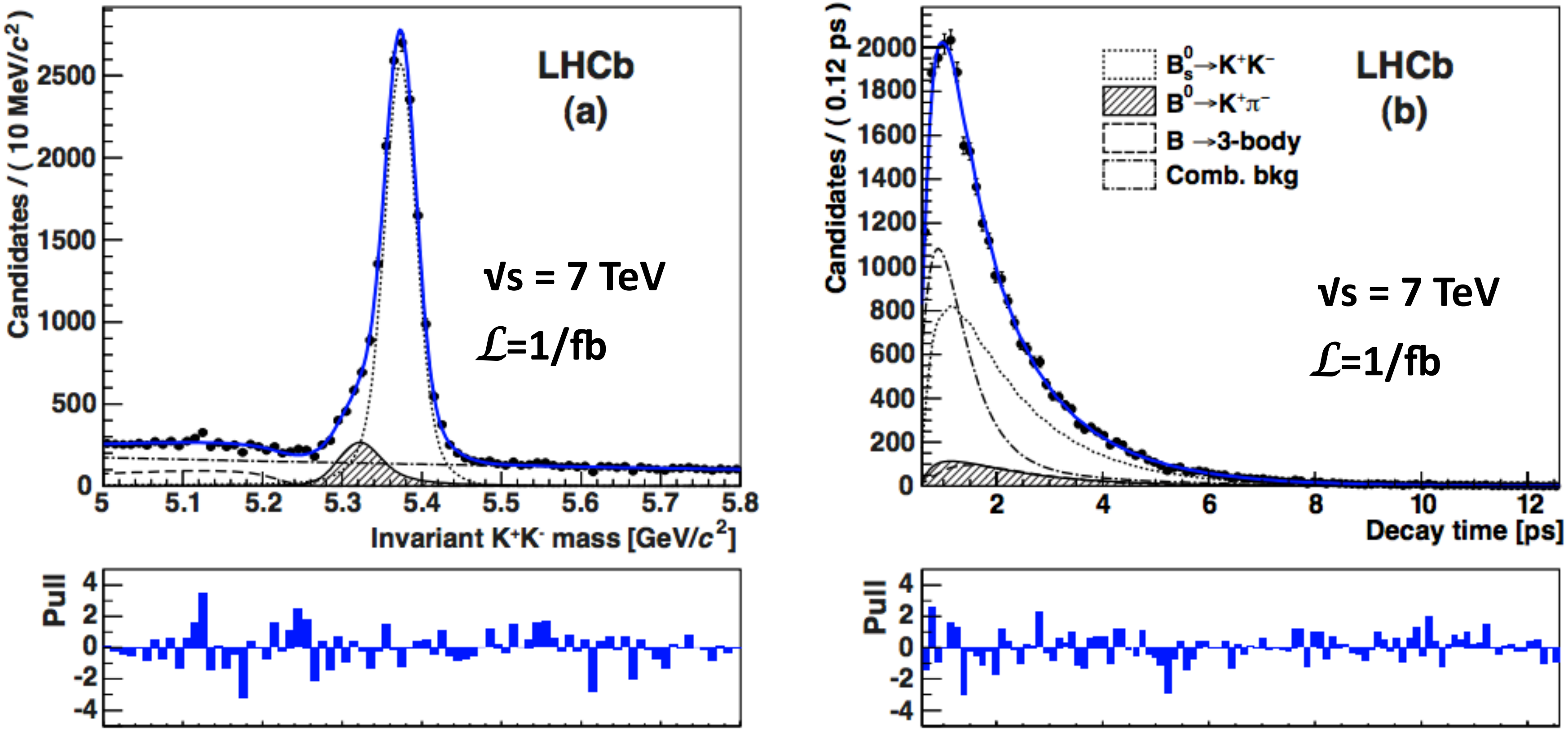
$$C_{\pi\pi} = -0.38 \pm 0.15$$

$$S_{\pi\pi} = -0.71 \pm 0.13$$

$$\rho\left(C_{\pi\pi}, S_{\pi\pi}\right) = 0.38$$



Fits to the K^+K^- spectra



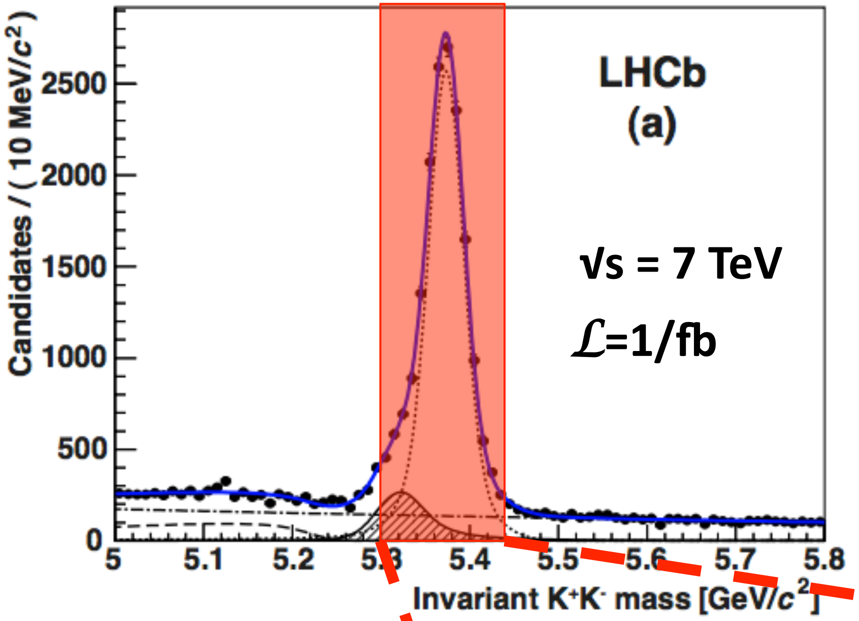
√s = 7 TeV

$\mathcal{L}$=1/fb

√s = 7 TeV

$\mathcal{L}$=1/fb

Fits to the K^+K^- spectra

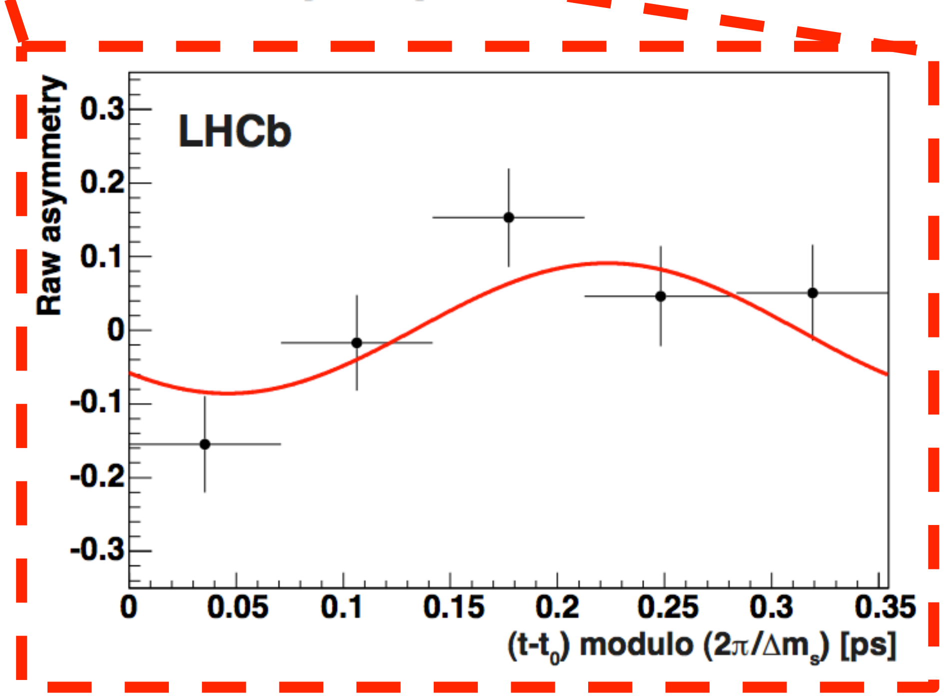


$$C_{KK} = 0.14 \pm 0.11$$

$$S_{KK} = 0.30 \pm 0.12$$

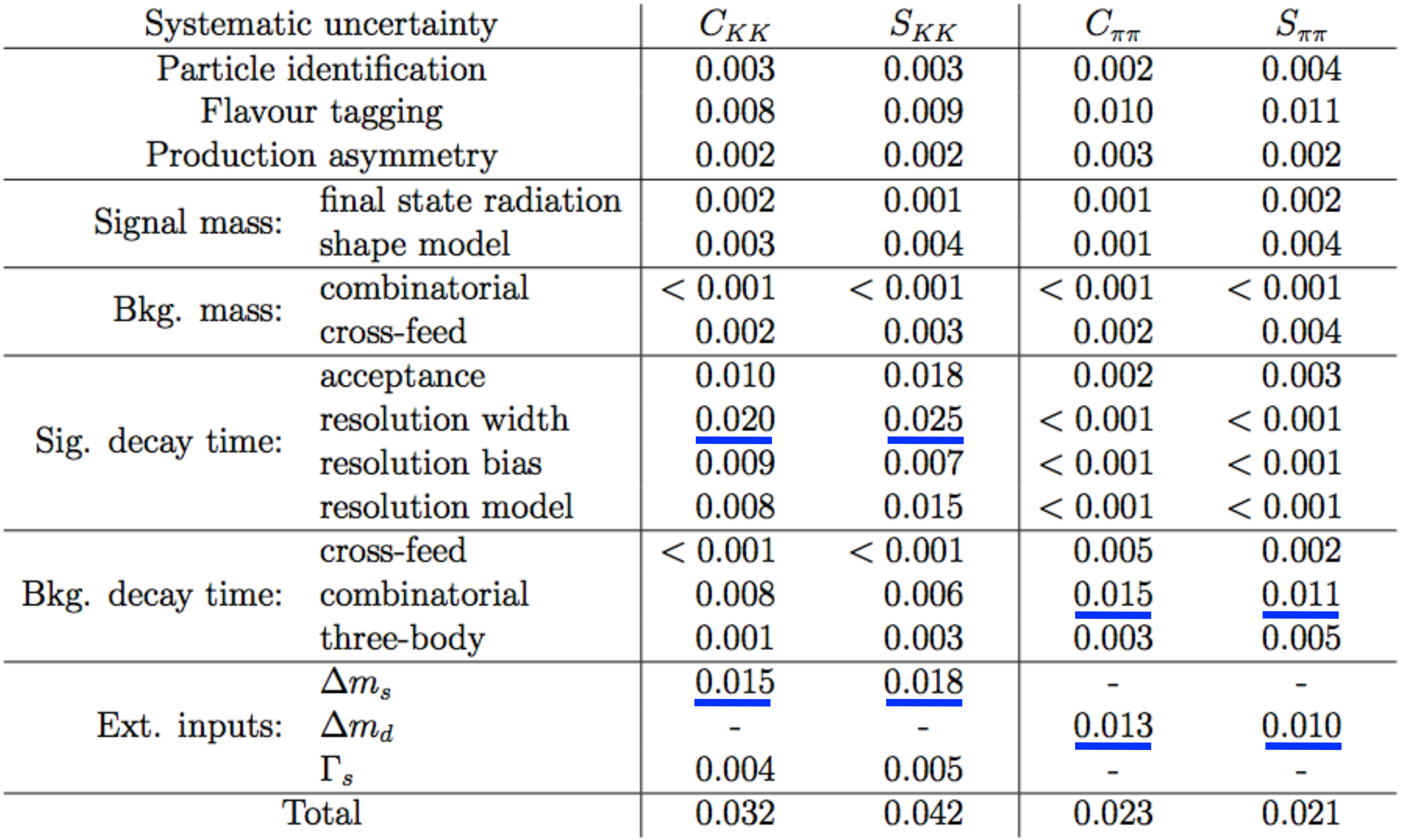
$$\rho\left(C_{KK}, S_{KK}\right) = 0.02$$

arXiv:1308.1428



Note: in order to enhance the visibility of the oscillation, only candidates belonging to the first two tagging categories are used to make this plot

Systematic uncertainties

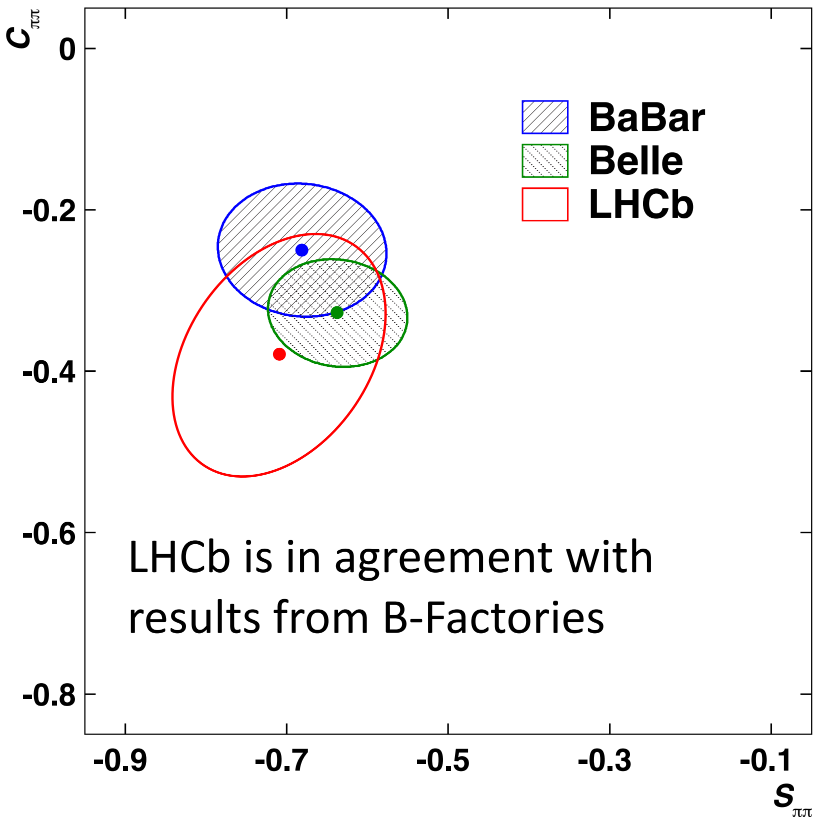


Systematic uncertainty		C_{KK}	S_{KK}	$C_{\pi\pi}$	$S_{\pi\pi}$
Particle identification		0.003	0.003	0.002	0.004
Flavour tagging		0.008	0.009	0.010	0.011
Production asymmetry		0.002	0.002	0.003	0.002
Signal mass:	final state radiation	0.002	0.001	0.001	0.002
	shape model	0.003	0.004	0.001	0.004
Bkg. mass:	combinatorial	< 0.001	< 0.001	< 0.001	< 0.001
	cross-feed	0.002	0.003	0.002	0.004
Sig. decay time:	acceptance	0.010	0.018	0.002	0.003
	resolution width	0.020	0.025	< 0.001	< 0.001
	resolution bias	0.009	0.007	< 0.001	< 0.001
	resolution model	0.008	0.015	< 0.001	< 0.001
Bkg. decay time:	cross-feed	< 0.001	< 0.001	0.005	0.002
	combinatorial	0.008	0.006	0.015	0.011
	three-body	0.001	0.003	0.003	0.005
Ext. inputs:	Δm_s	0.015	0.018	-	-
	Δm_d	-	-	0.013	0.010
	Γ_s	0.004	0.005	-	-
Total		0.032	0.042	0.023	0.021

Final results

- Using 1 fb^{-1} of data collected during 2011 with the LHCb detector, time-dependent CP asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays have been measured

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02,$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02,$$
$$\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.38$$



LHCb is in agreement with results from B-Factories

Final results

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$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02, \qquad C_{KK} = 0.14 \pm 0.11 \pm 0.03,$$

$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02, \qquad S_{KK} = 0.30 \pm 0.12 \pm 0.04,$$

$$\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.38 \qquad \rho(C_{KK}, S_{KK}) = 0.02$$

- The significances of ($C_{\pi\pi}$, $S_{\pi\pi}$) and (C_{KK}, S_{KK}) to differ from (0,0) are determined to be

$$s_{\text{tot}}(\pi\pi) = 5.6\sigma \qquad s_{\text{tot}}(KK) = 2.7\sigma$$

Conclusions…

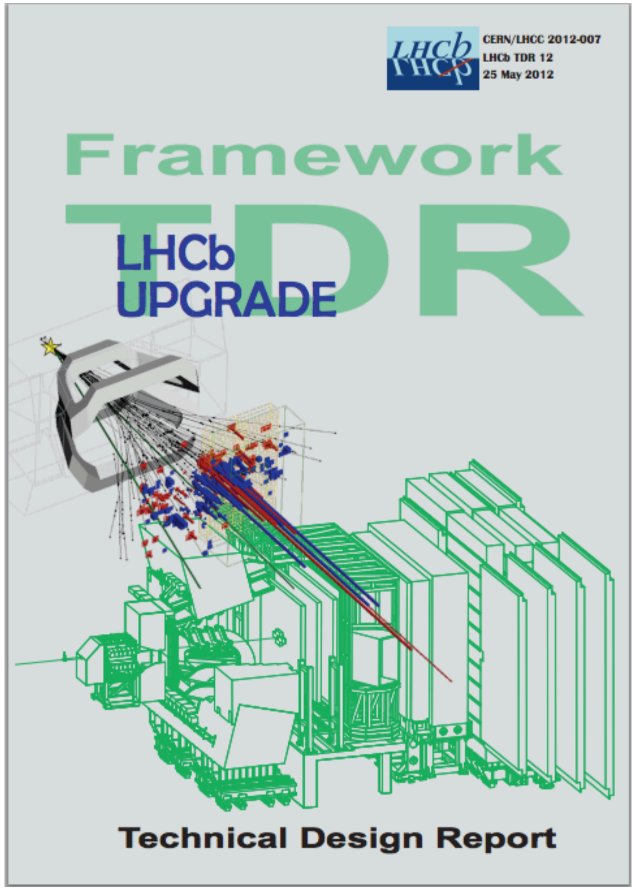
- CP violation and flavour physics play a central rôle in the search for **new discoveries**, today more than ever before
- In the sector of two-body hadronic decays, using an integrated luminosity of 1 fb^{-1} of pp collisions collected during 2011 at √s = 7 TeV, LHCb performed measurements of
  - $A_{CP}(B^0 \rightarrow K^+\pi^-)$
    - Most precise measurement of this quantity to date
    - Observed CP violation with a **statistical significance of 10.5σ**
    - Very precise measurement: stat. error 0.7%, syst. error 0.3%
  - $A_{CP}(B_s^0 \rightarrow \pi^+K^-)$
    - **First observation of CP violation in the decays of B_s mesons**
    - CP violation observed with a **statistical significance of 6.5σ**
  - No evidence of deviation from the SM predictions so far

Conclusions…

- Again using 1 fb^{-1}, LHCb performed measurements of time-dependent CP asymmetries of $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays
  - **$C_{\pi\pi}$ and $S_{\pi\pi}$ are compatible** with previous results from B-factories
  - **C_{KK} and S_{KK} are measured for the first time**
  - No evidence of mixing-induced CP violation in B_s^0 system
- From these measurements, the **CKM phase γ** and the **B_s^0 mixing phase $\phi_M(B_s^0)$** can be determined
  - As penguin (**new physics?**) contributions may be sizeable, it will be interesting to compare γ and $\phi_M(B_s^0)$ with the measurements from tree-level decays and $b \rightarrow c\bar{c}s$ transitions, respectively
  - These quantities can also be used to test U-spin symmetry

Conclusions

- Future plans
  - Determination of γ and B_s^0 mixing phase
  - Update the measurements using the full **3 fb^{-1}** sample
  - Measurements are far from being dominated by systematic uncertainties:
    - Waiting for LHC **Run II** and **LHCb Upgrade**…



CERN/LHCC 2012-007
LHCb TDR 12
25 May 2012

Framework TDR

LHCb UPGRADE

Technical Design Report