
Heavy flavour physics

Lecture 2

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Contents

Lecture 2

- Experimental facilities
- CKM matrix and types of CP violation
- Measurements of CKM angles β and α

Experimental facilities

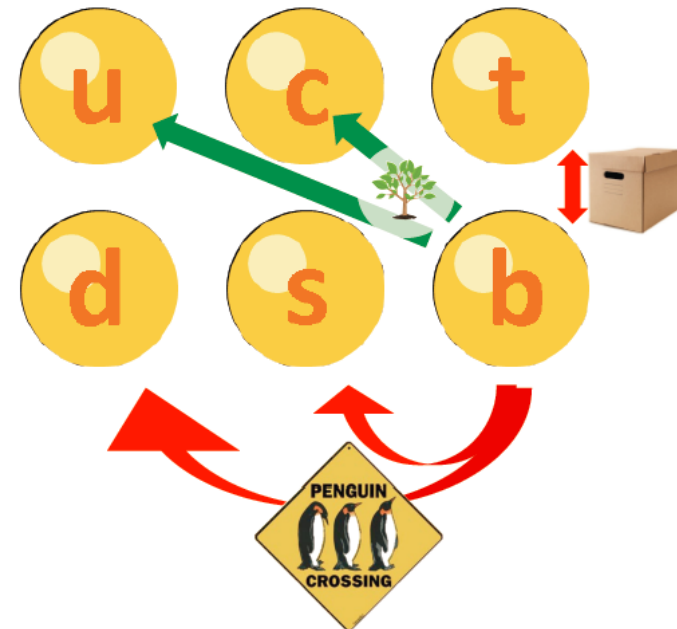
Heavy flavour physics

- Focus in these lecture will be on
 - flavour changing interactions of **charm** and **beauty quarks**
- But quarks feel the strong interaction and hadronize
 - various different beauty hadrons
 - many possible decays to different final states
 - *hadronization introduces great complications,*
BUT also increases the observability of CP violation effects
- Many aspects of flavour physics left out in this lecture
 - neutrino physics: have own phenomenology
 - light quark flavour physics
 - charged lepton physics
 - top-flavour physics: different, as the top does not hadronize

Rich phenomenology with beauty quarks

- The beauty quark ...

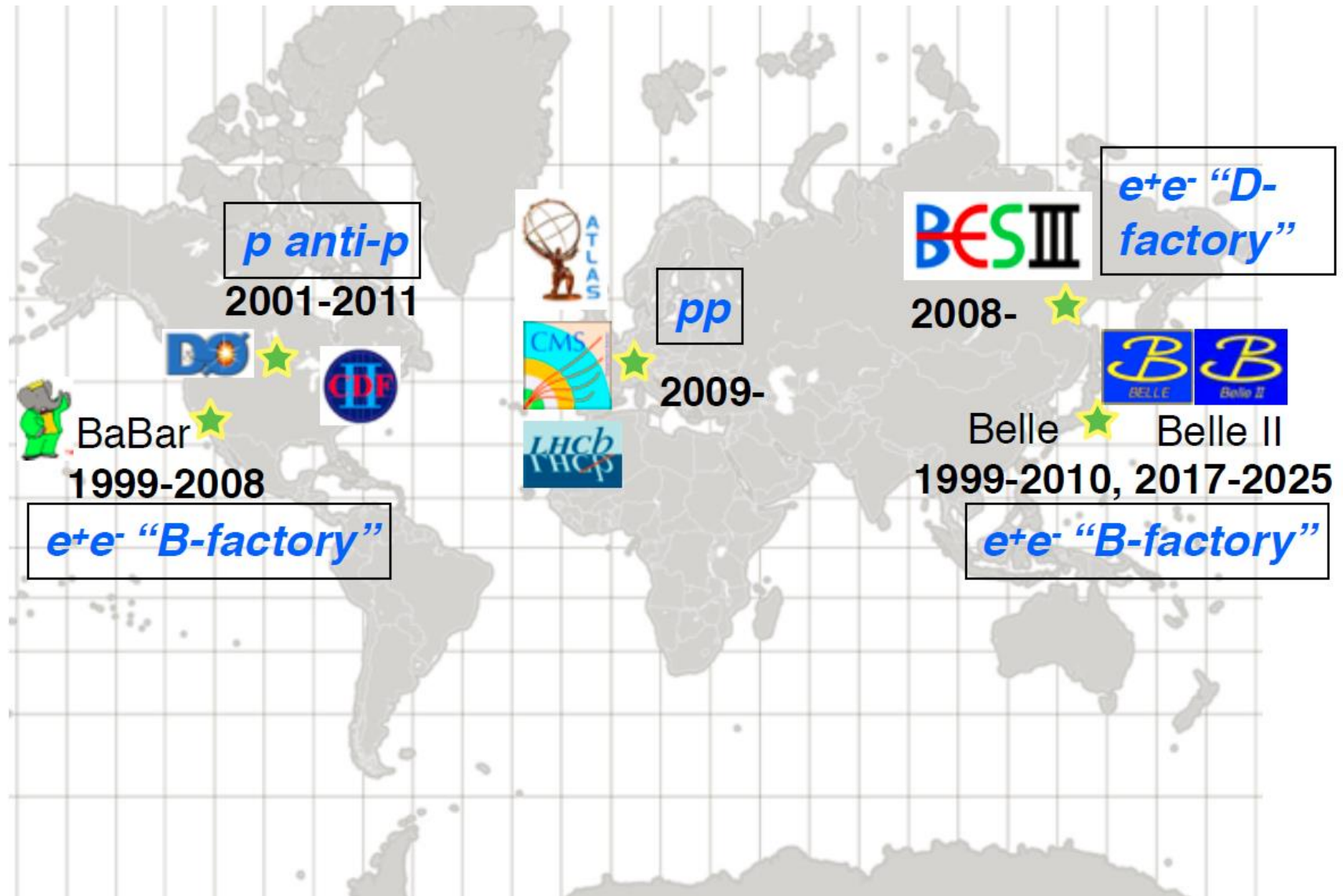
- is the heaviest quark that forms hadronic bound states
 - high mass: many accessible final states
- must decay outside the 3rd family
 - all decays are CKM suppressed
 - long lifetime of B meson ($\sim 1.6\text{ps}$)



- Beauty-decays:

- dominant decay process: „tree”
 - $b \rightarrow c$ transition
- very suppressed „tree” $b \rightarrow u$ transition
- FCNC „penguin” $b \rightarrow s$ and $b \rightarrow d$ transitions
- flavour oscillations ($b \rightarrow t$ „box” diagrams)
- CP violation – expect large CP asymmetries in some B decays

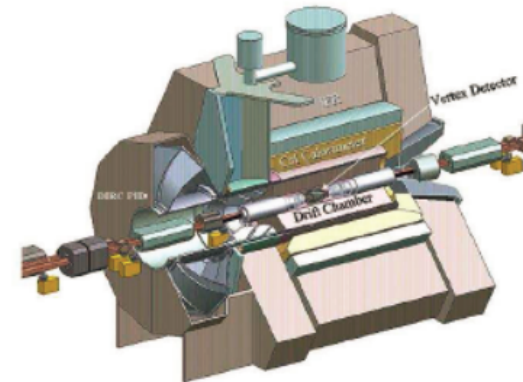
Where are B and D mesons produced



Flavour physics experiments

B-factories (BaBar & Belle)

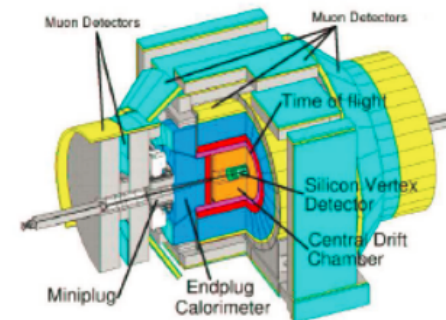
- e^+e^- experiment at SLAC / KEK
- Dedicated B-physics experiment



General purpose detectors (ATLAS, CMS, CDF, D0)

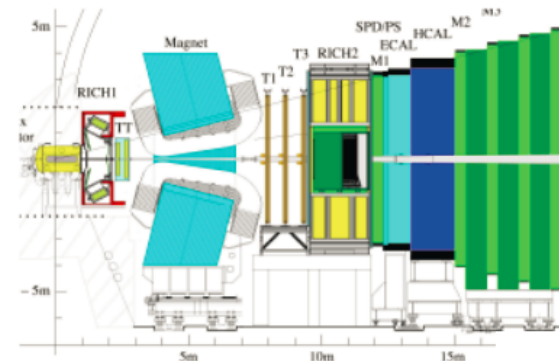
- Proton colliders @ CERN / Tevatron
- 4π multi purpose detectors

CDF II Detector



LHCb

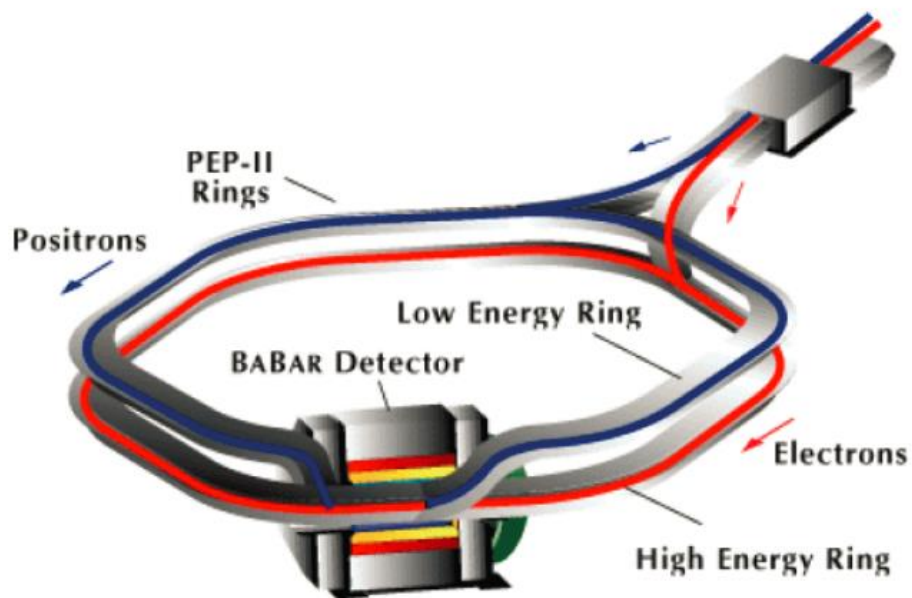
- Proton colliders @ CERN
- Dedicated B-physics experiment



e^+e^- : Asymmetric B factories

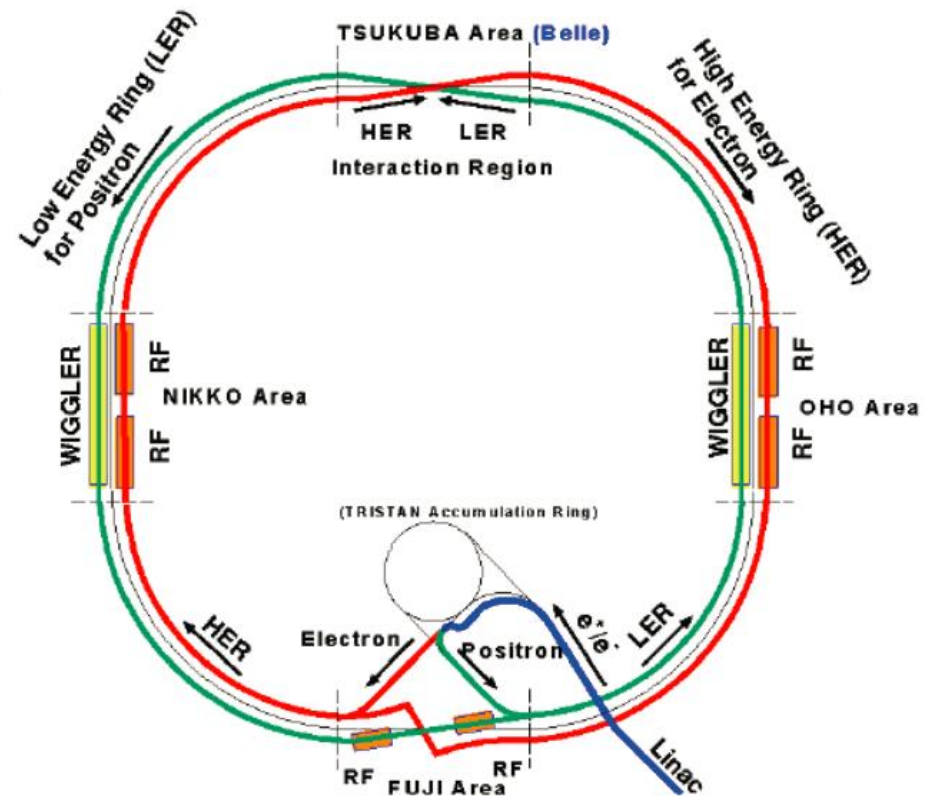
PEP-II at SLAC

9.0 GeV e^- on 3.1 GeV e^+

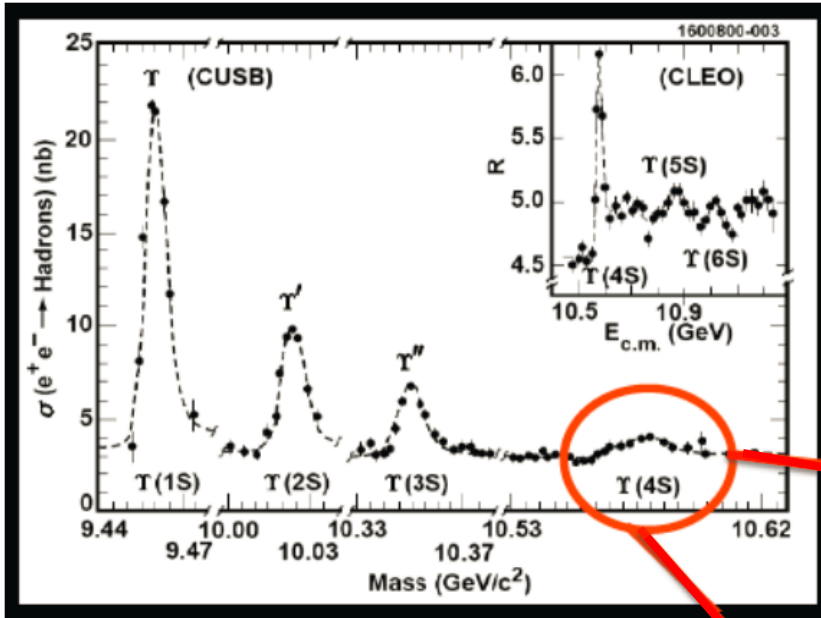


KEKB at KEK

8.0 GeV e^- on 3.5 GeV e^+



Y(4S) resonance



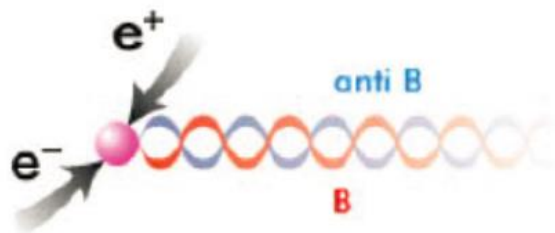
Cleanest way to produce B mesons in e^+e^- collisions: at centre-of-mass energy = mass of Y(4S)

$$\sqrt{s} = 10.58 \text{ GeV}$$

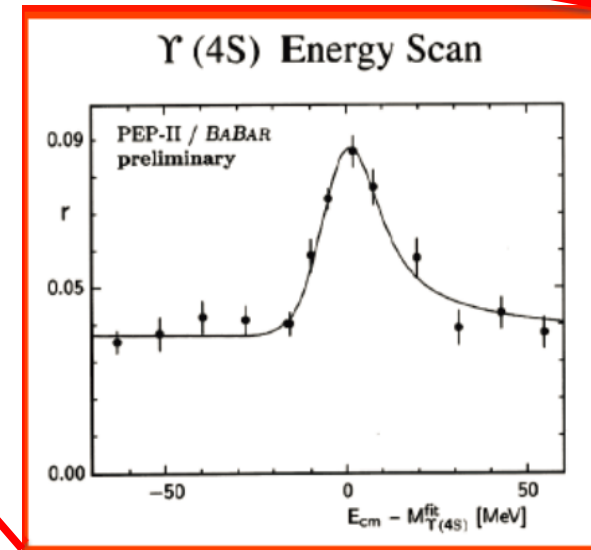
Y(4S) is bound bb -state that decays to $\sim 100\%$ to B^+B^- or $B^0\bar{B}^0$ pairs

$$\sim 1.1\text{M } B\bar{B} \text{ pairs per fb}^{-1}$$

$$\sigma_{bb} / \sigma_{\text{continuum}} \sim 1/3$$



BB pair is produced in a coherent state
 \rightarrow two B mesons evolve until one decays

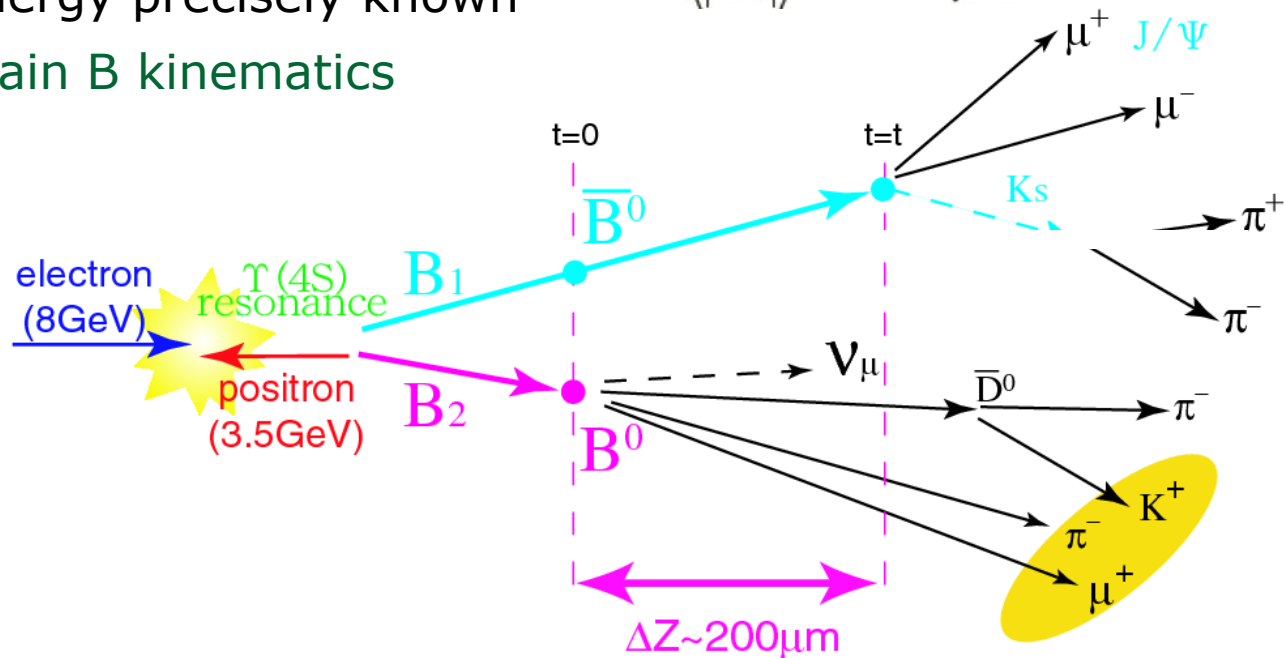


Kinematics at e^+e^- colliders

- Symmetric collider: B-mesons produced almost at rest
→ short lifetime make flight distance unmeasurably small
- Asymmetric collider (KEKB, PEP-II)
→ with boost $\beta\gamma \sim 0.6$
- Beam energy precisely known
→ constrain B kinematics

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

$$\langle |\Delta z| \rangle \approx 200 \mu\text{m}$$

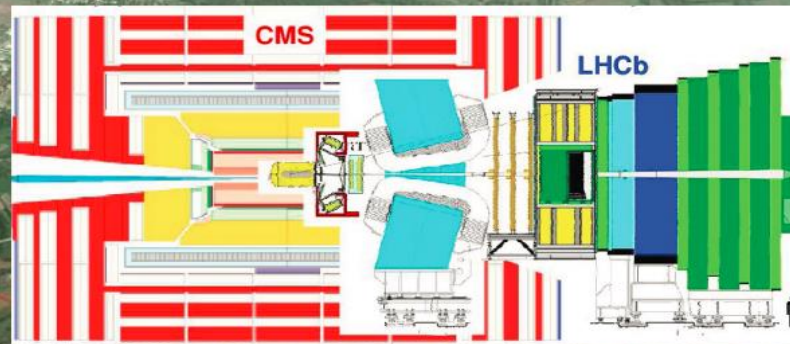


- To measure t require B meson to be moving
→ e^+e^- at threshold with asymmetric collisions

bb(bar) production at *pp* collider

LHC 2009-

- More than 10^{12} b-anti-b pairs (10^9 at B-factories) produced already and growing.
- **LHCb** dedicated B-physics detector
- B-physics programs at **CMS** and **ATLAS**.



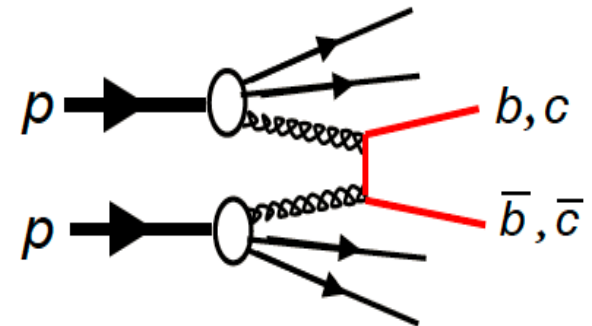
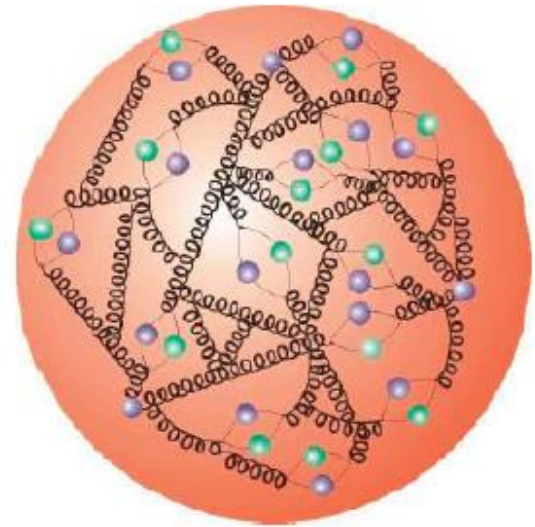
Proton collisions

- Protons are complicated objects
 - valence & sea quarks, gluons
- Available energy of „proton” collision depends on partons

$$s' = x_1 \cdot x_2 \cdot s$$

x_i = Bjorken x (fractional momentum) of parton

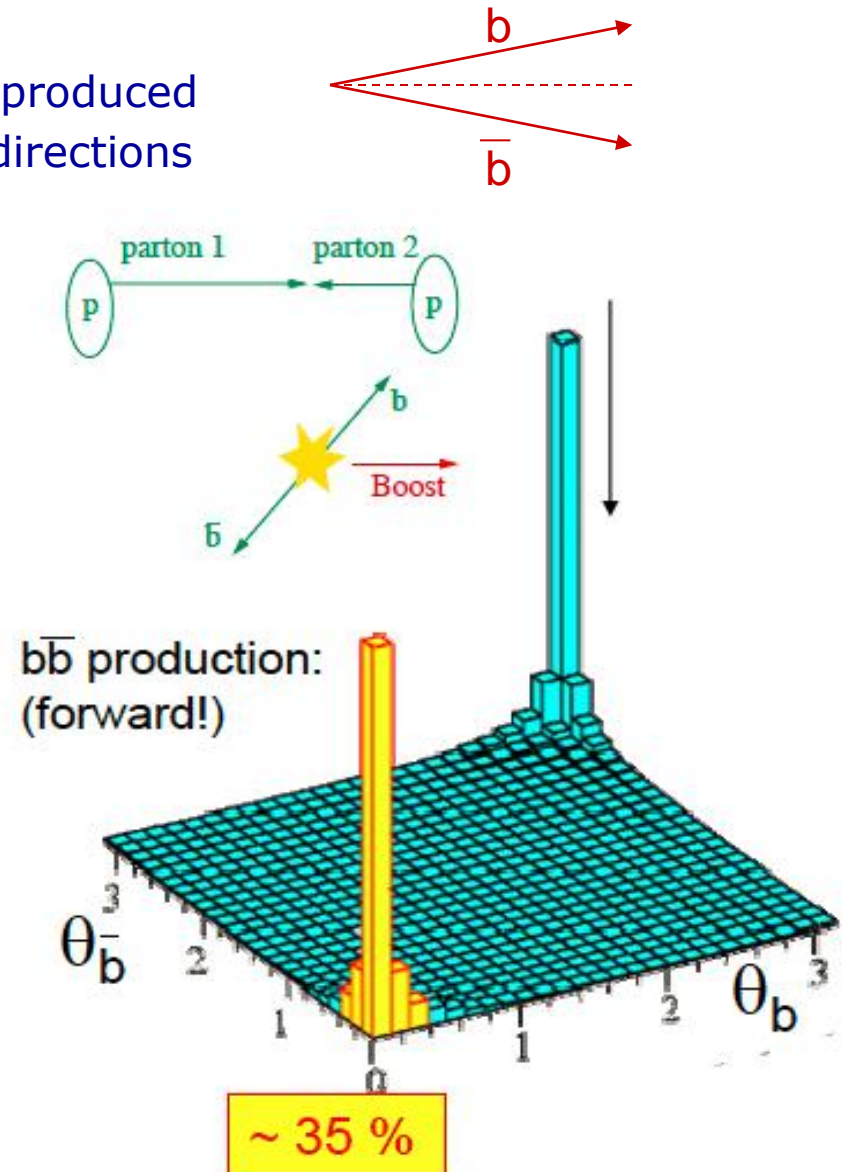
- Energy of particular collision unknown, but distributions known
 - hadron colliders „scan” a wide energy range
 - average $s' \sim 0.1 s$
 - dominant process @ LHC: gluon fusion



Event kinematics

In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions

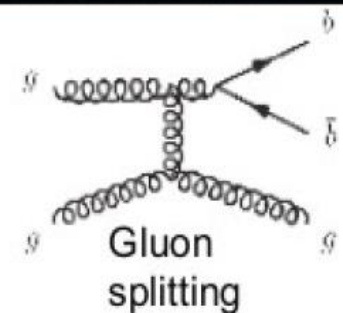
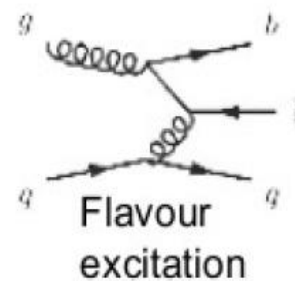
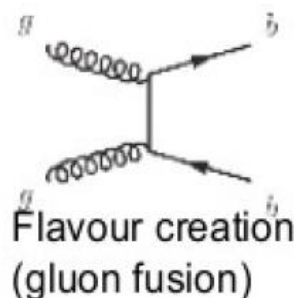
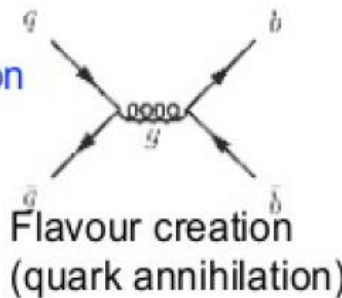
- B hadron mass ~ 5 GeV
 - asymmetric x-values
 - strongly boosted ($\beta\gamma \sim 100$)
 - average flight length ~ 7 mm
- Boost allows time dependent analyses of fast B_s mixing
- B hadron admixture:
 - 40% B^0
 - 40% B^\pm
 - 10% B_s
 - 10% Λ_b
 - $<1\%$ others (B_c, B^*, B^{**}, \dots)



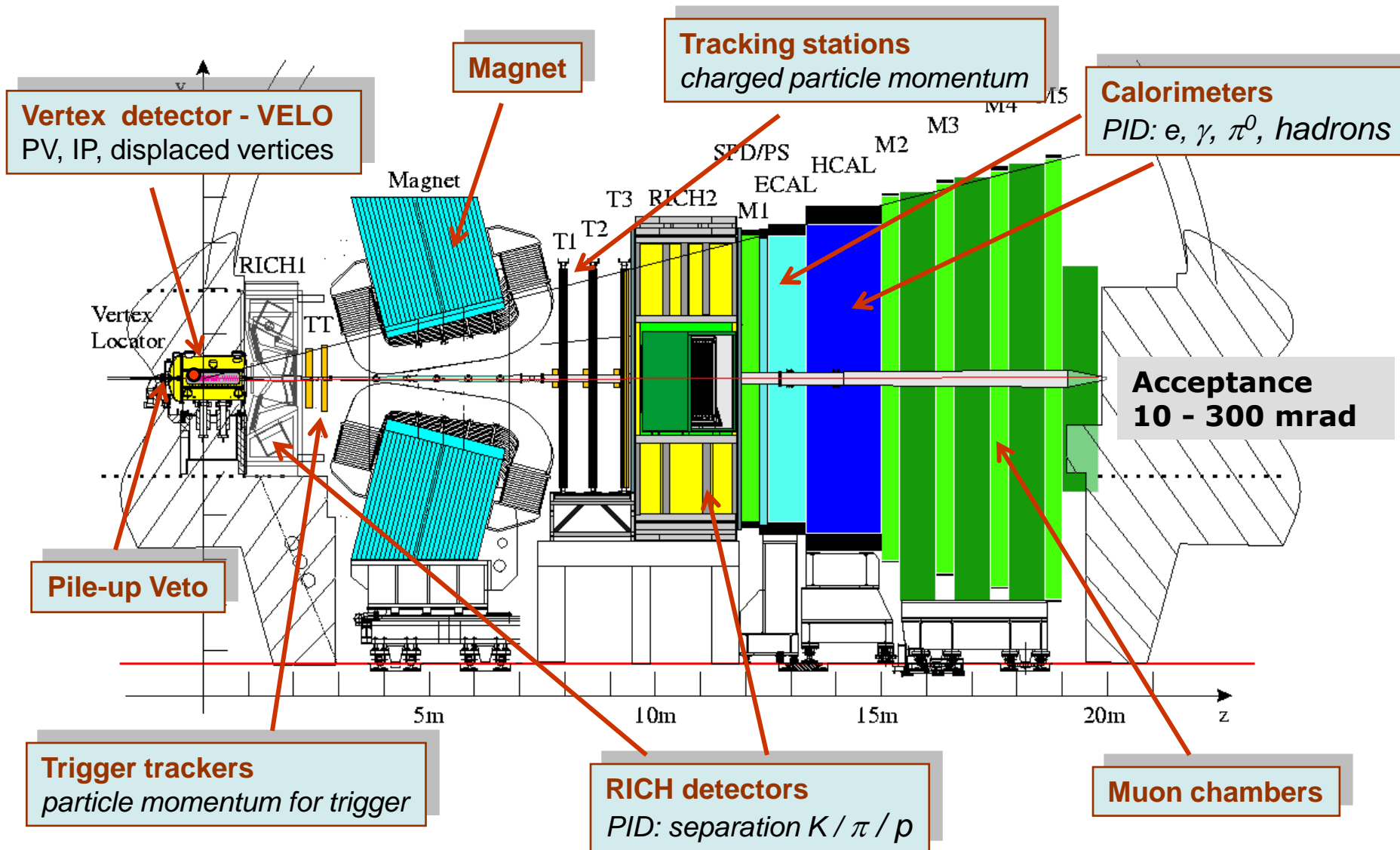
b production at hadron colliders

	$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ PEP-II, KEK-B	$p\bar{p} \rightarrow b\bar{b}X$ ($\sqrt{s} = 2$ TeV) TeVatron	$pp \rightarrow b\bar{b}X$ ($\sqrt{s} = 14$ TeV) LHC
prod	1 nb	$\sim 100 \mu\text{b}$	$\sim 500 \mu\text{b}$
typ. $b\bar{b}$ rate	10 Hz	~ 100 kHz	~ 500 kHz
purity	$\sim 1/4$	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s (10%), B_c ($< 1\%$), b-baryons (10%)	
B boost	small, $\beta\gamma \sim 0.56$	large, decay vertices are displaced	
event structure	$B\bar{B}$ pair alone	many particles non-associated to $b\bar{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\bar{B}^0$ mixing	coherent	incoherent \rightarrow flavour tagging dilution	

bb production
at hadron
colliders



LHCb - single arm spectrometer

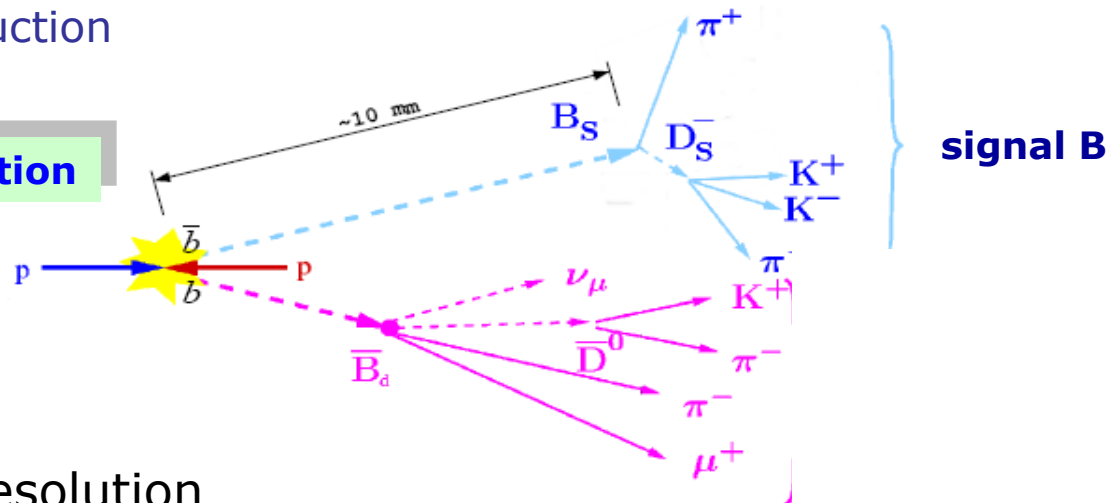


Detector requirements

Good decay vertex resolution

- proper time resolution
- background reduction

example of B production



Good tracking resolution

- proper tracking and good momentum resolution

Particle identification in the wide momentum range (2 - 100 GeV/c)

- background reduction if kinematic separation not sufficient

Fast and efficient trigger system

- selection of interesting events from large background

Fast data acquisition system

LHC flavour physics programme

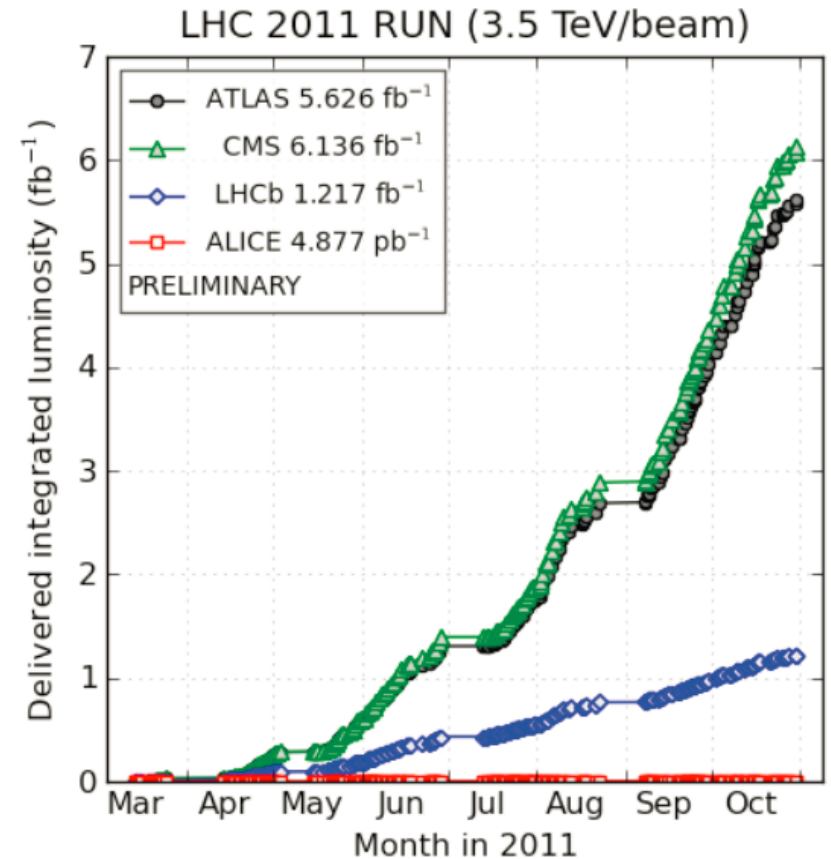
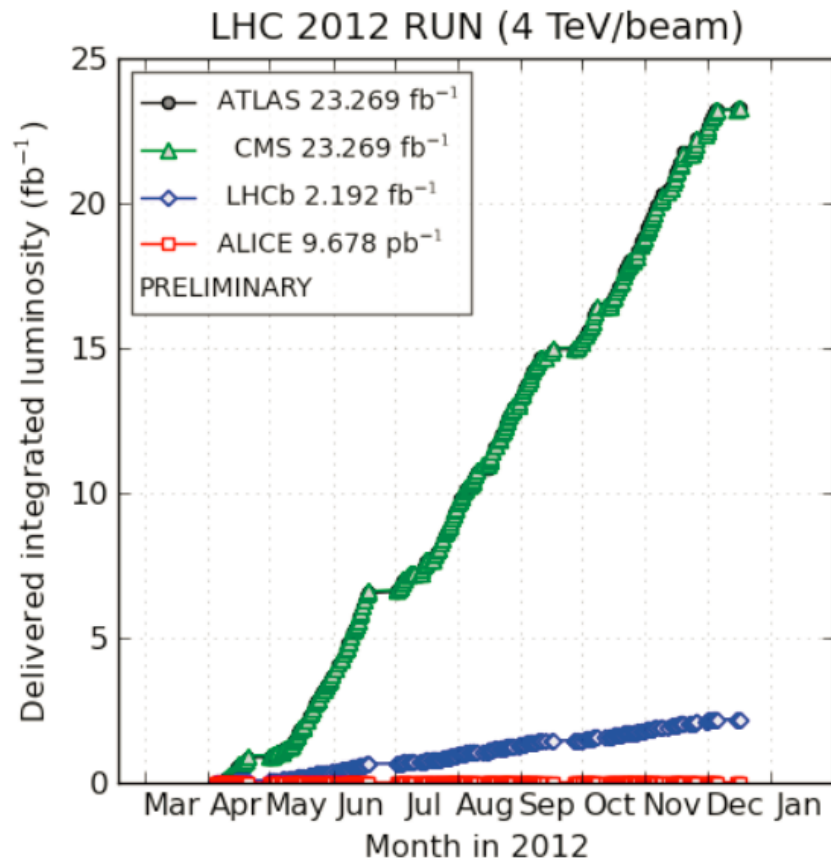
ATLAS / CMS

- Central detectors, $|\eta| < 2.5$
- **High Luminosity ($> 10^{34} \text{cm}^{-2} \text{s}^{-1}$)**
→ **high pileup ~ 20**
- Trigger
 - Relatively low rate ($\sim 200\text{-}400\text{Hz}$)
 - High PT muon triggers
- Analysis
 - Mostly modes with dimuons
 - Limited flavour tagging
- Particle identification
 - Excellent muon ID
 - Limited K / π separation

LHCb

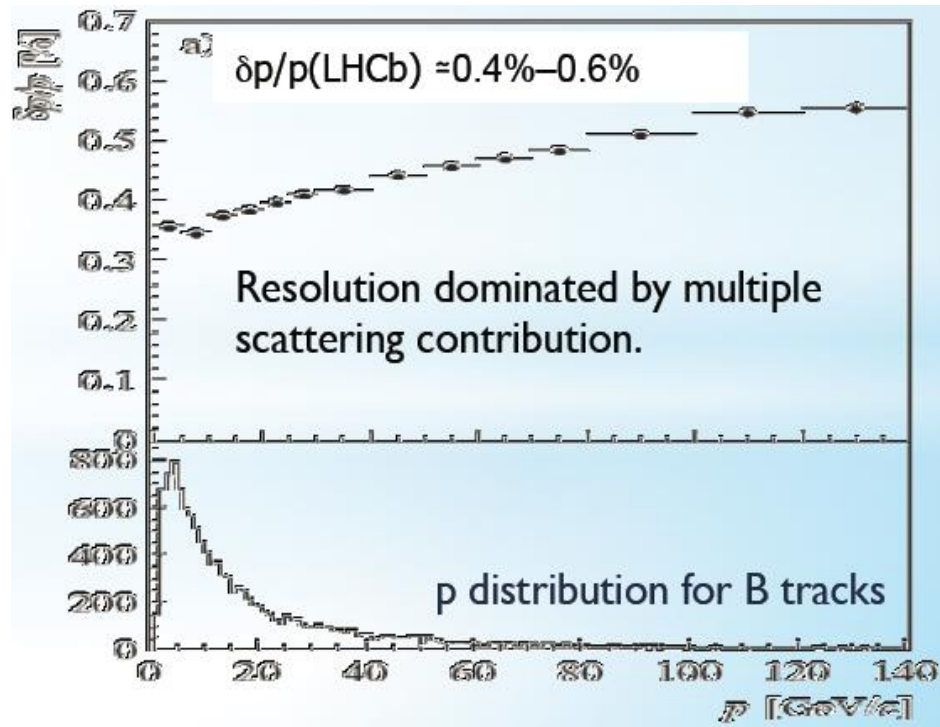
- Forward spectrometer, $1.9 < \eta < 5$
- **Lower Luminosity ($4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$)**
→ pileup ~ 1.5
- Trigger
 - **High trigger rate ($\sim 2\text{kHz}$)**
 - **Muon & hadron** triggers, softer thresholds
 - **Large bandwidth for charm**
- Analysis
 - Hadronic and low M modes accessible
 - Excellent flavour tagging & σ_t
- Particle identification
 - Excellent muon ID
 - Dedicated RICH PID (K / π)

Key issues for B physics: *data statistics*



Full dataset (Run I): ATLAS = CMS = 10 * LHCb

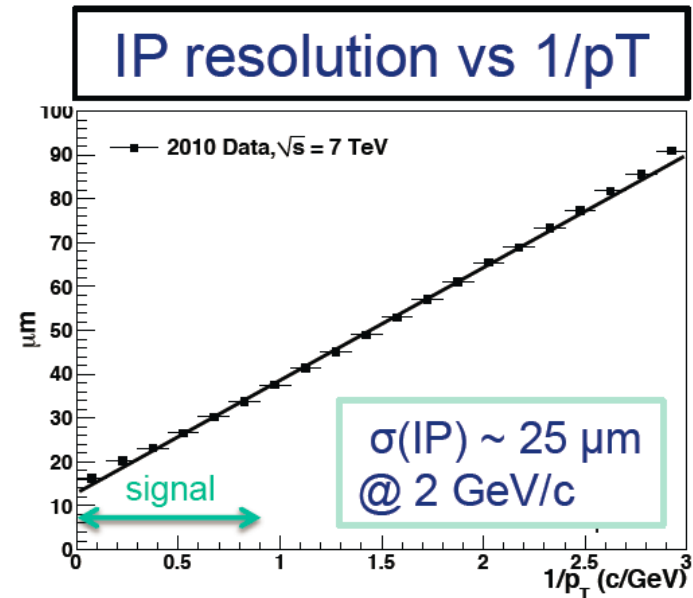
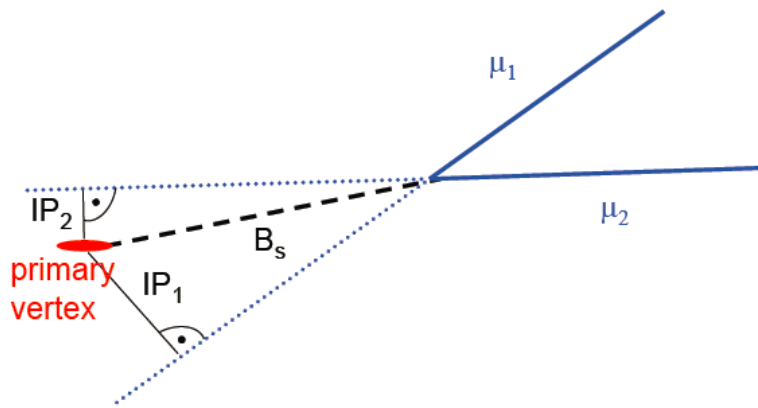
Key issues for B physics: *momentum and mass resolution*



	momentum resolution	mass resolution $J/\psi \rightarrow \mu\mu$
LHCb	$\delta p/p = 0.4-0.6\%$	13 MeV
CMS	$\delta p_t/p_t = 1-3\%$	40 MeV
ATLAS	$\delta p_t/p_t = 5-6\%$	71 MeV

Key issues for B physics: *IP and PV resolution*

Impact parameter (IP):

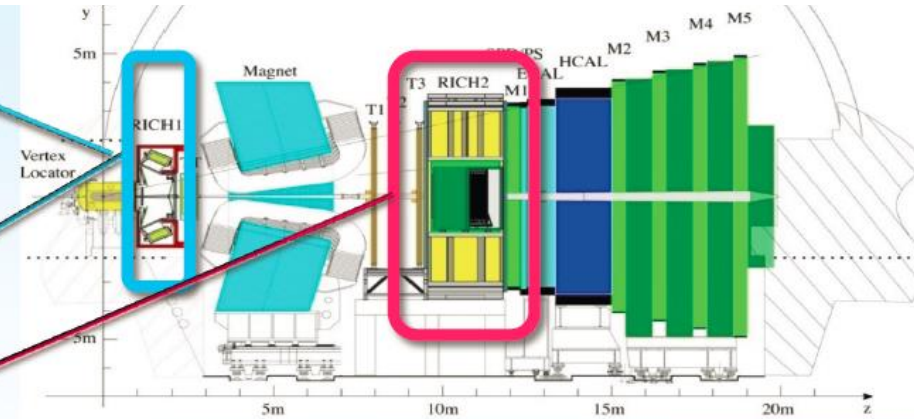
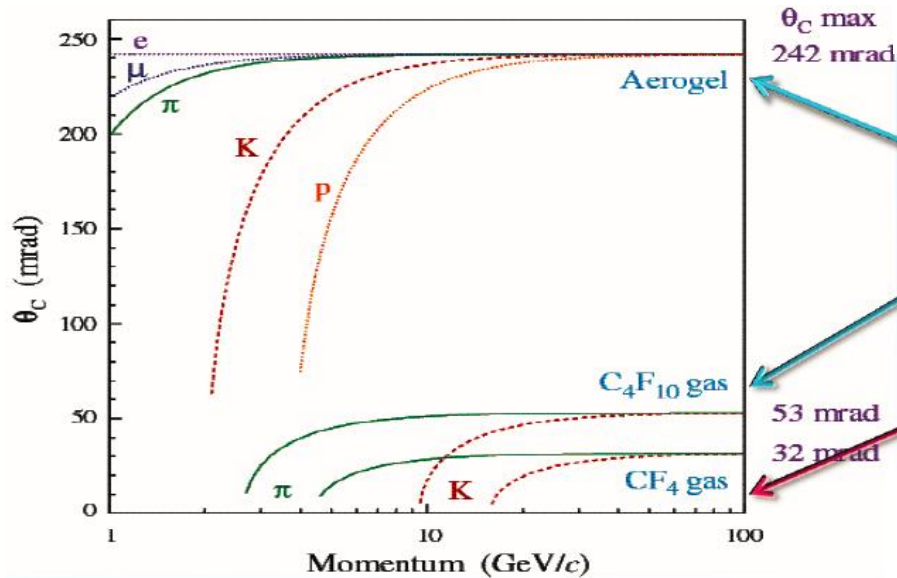


Primary vertex resolutions (25 tracks):

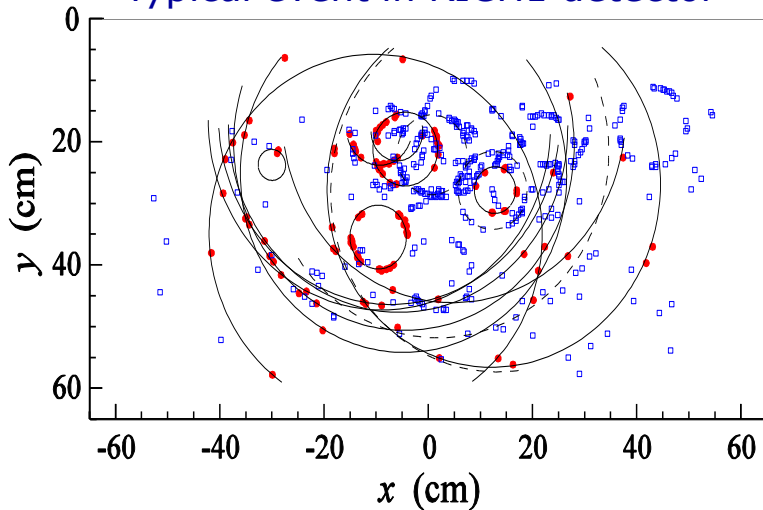
	LHCb [μm]	ATLAS [μm]	CMS [μm]
$\sigma(x)$	15.8	60	20-40
$\sigma(y)$	15.2	60	20-40
$\sigma(z)$	76	100	40-60

	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~ 100 fs	~ 70 fs	87 fs	45 fs

Key issues for B physics: *particle identification*



Typical event in RICH1 detector



RICH1

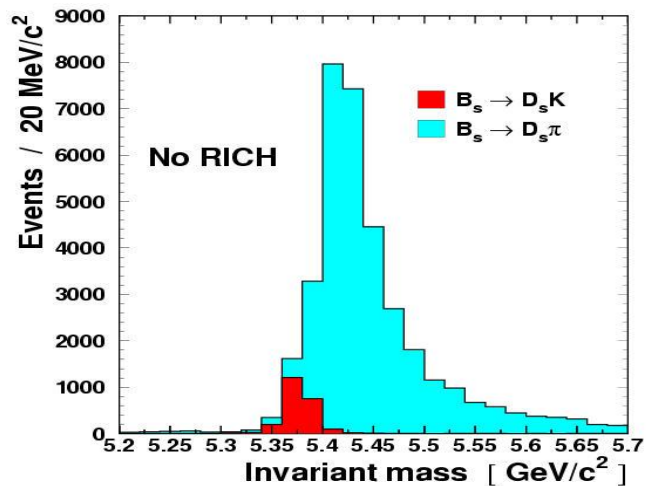
- aerogel (silicate foam) + C_4F_{10}
- $n(\text{aerogel}) = 1.03$
→ 2 - 10 GeV - slowest particles
- $n(C_4F_{10}) = 1.0014$
→ 10 - 60 GeV

RICH2

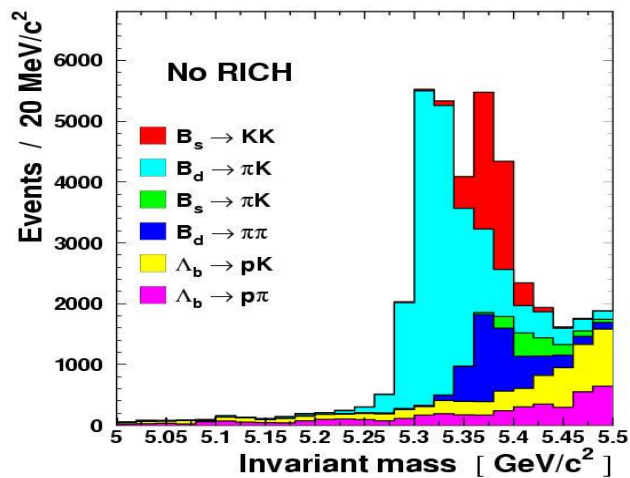
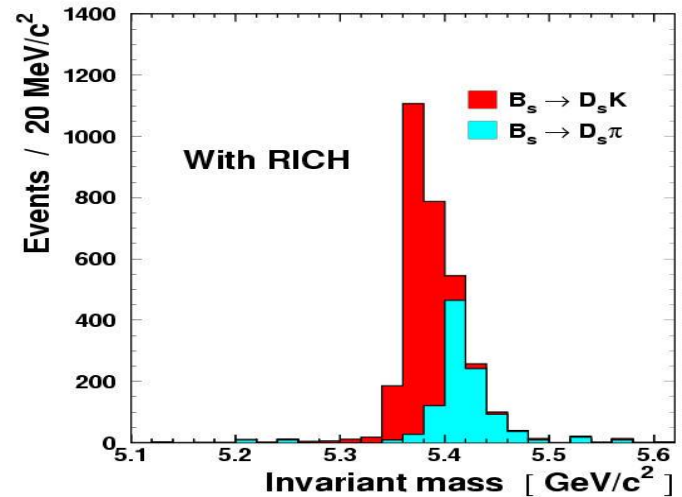
- carbon tetrafluoride CF_4
- $n(CF_4) = 1.0005$ → 16 - 100 GeV

Key issues for B physics: *particle identification*

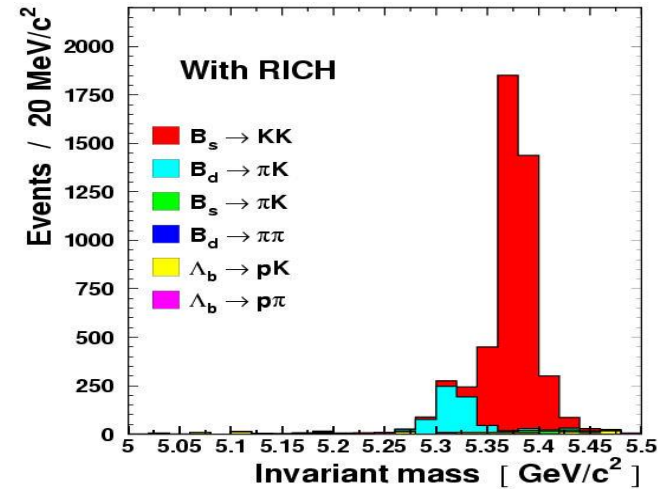
- Results of the simulation of B decays showing the necessity of particle ID



$B_s \rightarrow D_s K$



$B_s \rightarrow KK$



Key issues for B physics: *trigger system*

Challenge is

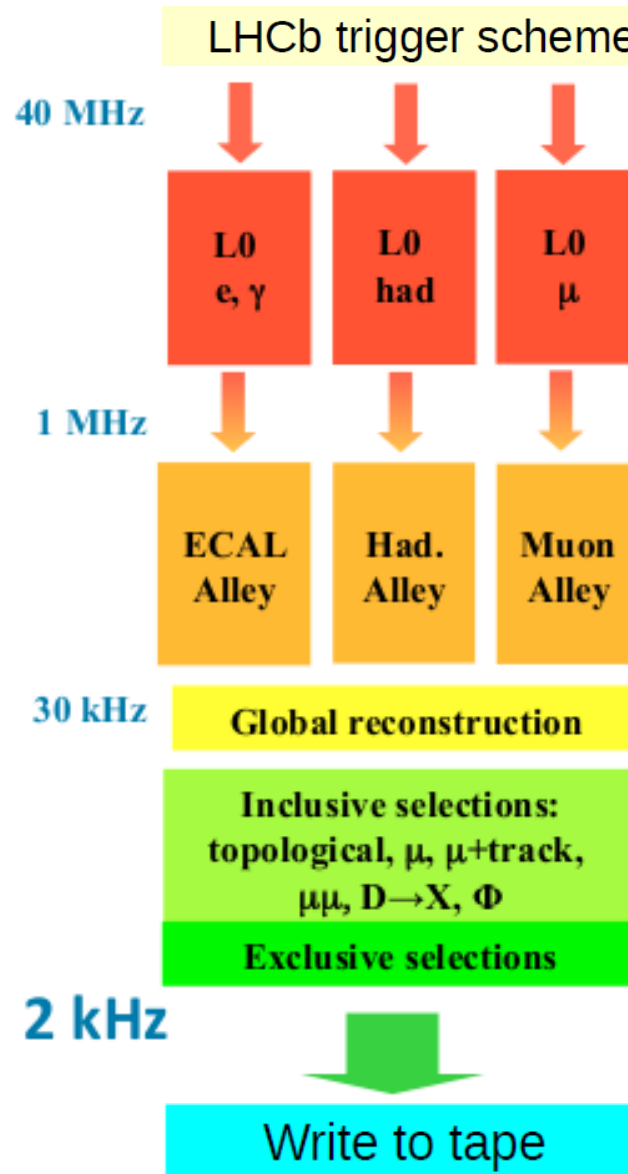
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- „minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



L0 – high p_T signals in calorimeters & muon chambers

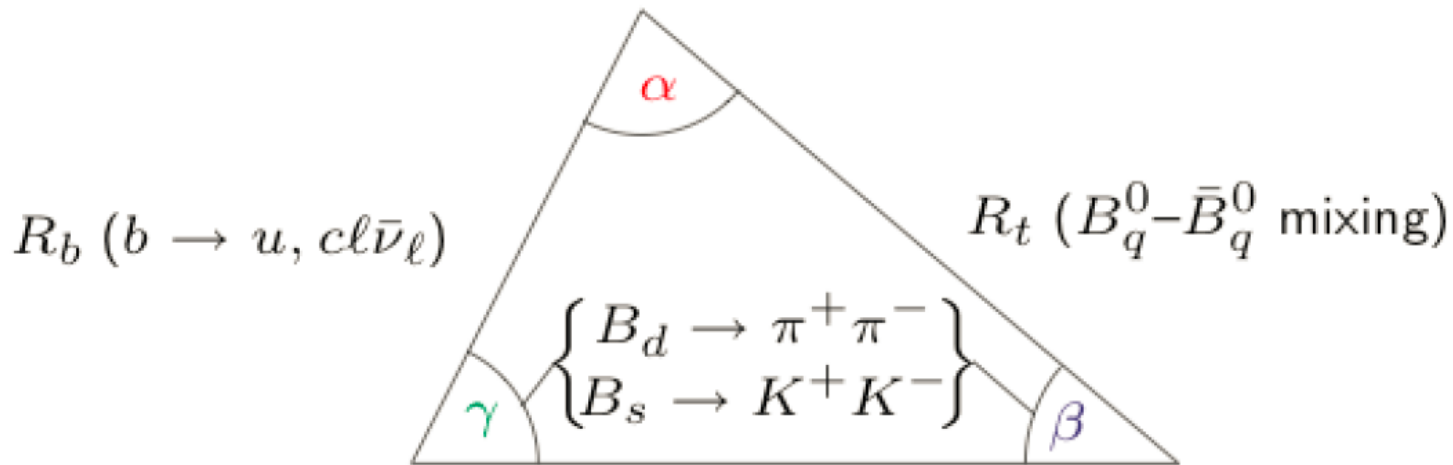
HLT1 – associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

CKM matrix and types of CP violation

Over-constraining the Unitarity Triangle

$B \rightarrow \pi\pi$ (isospin), $B \rightarrow \rho\pi$, $B \rightarrow \rho\rho$



$B \rightarrow \pi K$ (penguins)

$B_d \rightarrow \psi K_S$ ($B_s \rightarrow \psi\phi : \phi_s \approx 0$)

$\left. \begin{array}{l} B_u^\pm \rightarrow K^\pm D \\ B_d \rightarrow K^{*0} D \\ B_c^\pm \rightarrow D_s^\pm D \end{array} \right\} \text{only trees}$

$B_d \rightarrow \phi K_S$ (pure penguin)

$\left. \begin{array}{l} B_d \rightarrow D^{(*)\pm} \pi^\mp : \gamma + 2\beta \\ B_s \rightarrow D_s^\pm K^\mp : \gamma + \phi_s \end{array} \right\} \text{only trees}$

Phases and CP-Violation

CP violation: $|\mathcal{A}(B \rightarrow f)|^2 \neq |\mathcal{A}(\bar{B} \rightarrow \bar{f})|^2$

Within weak interaction, moving from particle to antiparticle, system amplitudes are complex conjugated

No CP violation if:

- There is only one amplitude contributing to the decay: $|\mathcal{A}|^2 = |\mathcal{A}^*|^2$
- The sum of two amplitudes, where both are complex conjugated, by moving from particle to antiparticle system:

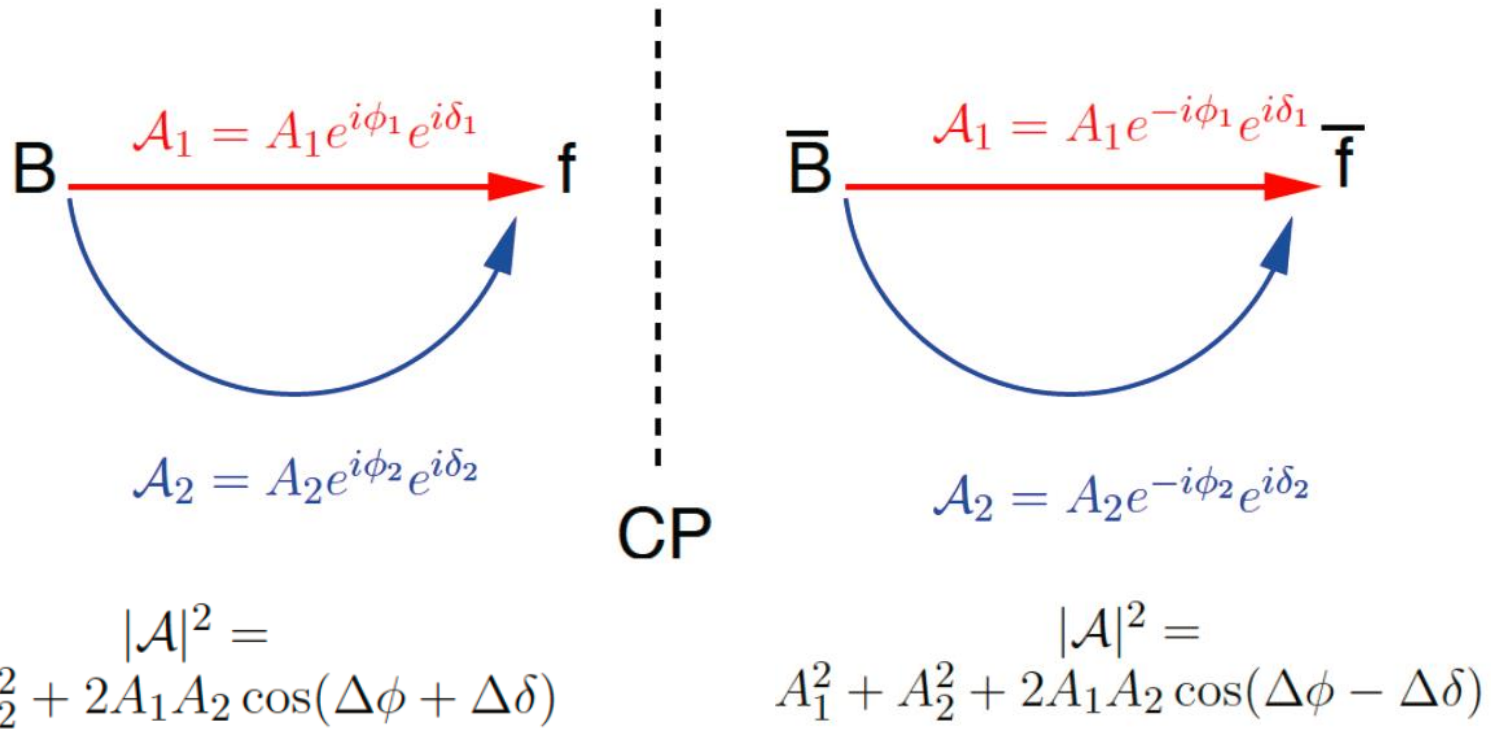
$$|\mathcal{A}_1 + \mathcal{A}_2|^2 = (\mathcal{A}_1 + \mathcal{A}_2)(\mathcal{A}_1^* + \mathcal{A}_2^*) = |\mathcal{A}_1^* + \mathcal{A}_2^*|^2$$

For CP violation one needs two complex amplitudes, where **one of them is complex conjugated and one is not** by moving from particle to antiparticle system

Phases and CP-Violation

CP violation: interplay of weak (ϕ) and strong (δ) phases

$$\mathcal{A}_{CP} \propto \Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})$$



A_1 i A_2 need to have **different weak phases ϕ** and **different strong phases δ**
 Strong phases are notoriously difficult to compute

Categories of CP violation

Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}$$

1) Indirect CP violation, or CPV in **mixing**:

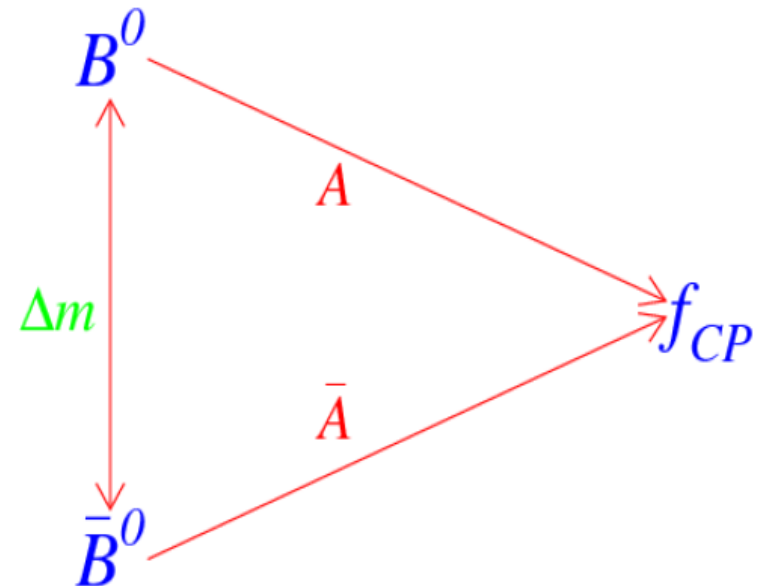
$$\left| \frac{q}{p} \right| \neq 1$$

2) Direct CP violation, or CPV in **decays**:

$$\left| \frac{\bar{A}}{A} \right| \neq 1$$

3) CP violation in interference between mixing and decay:

$$\Im \left(\frac{q}{p} \frac{\bar{A}}{A} \right) \neq 0$$



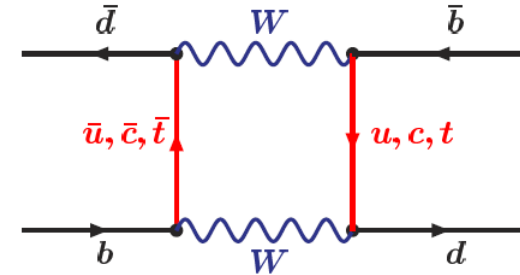
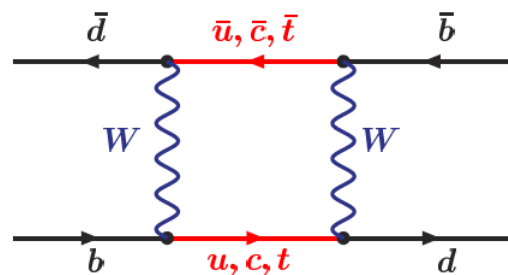
3 types of CP-Violation: In mixing

1) CP violation in mixing: CP eigenstates \neq mass eigenstates

Mixing occurs via box diagrams: $\Delta F = 2$ transitions

- **SM predictions for**

- neutral kaon system
- neutral D meson system
- B_d^0 system
- B_s^0 system



The 4 different neutral meson systems have very different mixing properties

- In case of a CP eigenstate: time evolution of the neutral mesons generates a „strong phase“ $\sim \sin(\Delta m t)$

- **CP asymmetries become time dependent:** $A_{CP}(t) = \frac{C \cos(\Delta m t) - S \sin(\Delta m t)}{\cosh(\Delta \Gamma t/2) + D \sinh(\Delta \Gamma t/2)}$

$$C^2 + S^2 + D^2 = 1$$

- Two eigenstates:

$$\Delta m = m_1 - m_2 \quad \Delta \Gamma = \Gamma_1 - \Gamma_2$$

$\Delta \Gamma \sim 0$ for B_d $\Delta \Gamma$ not negligible for B_s

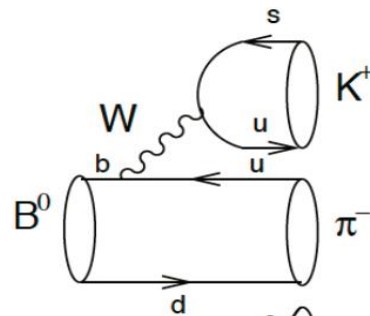
direct CP violation $\rightarrow C \neq 0$
 CP violation in interference $S \neq 0$

3 types of CP-Violation: In decays

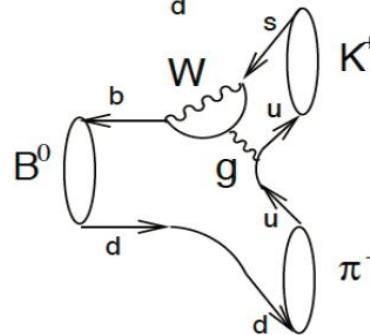
2) Direct CP violation condition: $|A(\bar{A}) / A| \neq 1$

- need A and $A(\bar{A})$ to consist of (at least) two parts with different weak (ϕ) and strong (δ) phases
- often realised by „tree” and „penguin” diagrams

TREE

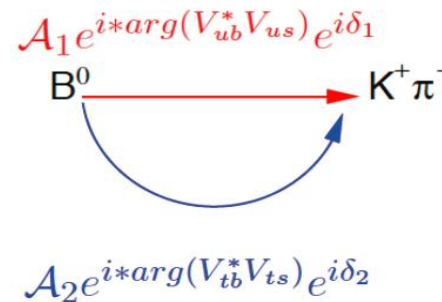


PENGUIN



Example: $B \rightarrow K\pi$

(weak phase difference is γ)



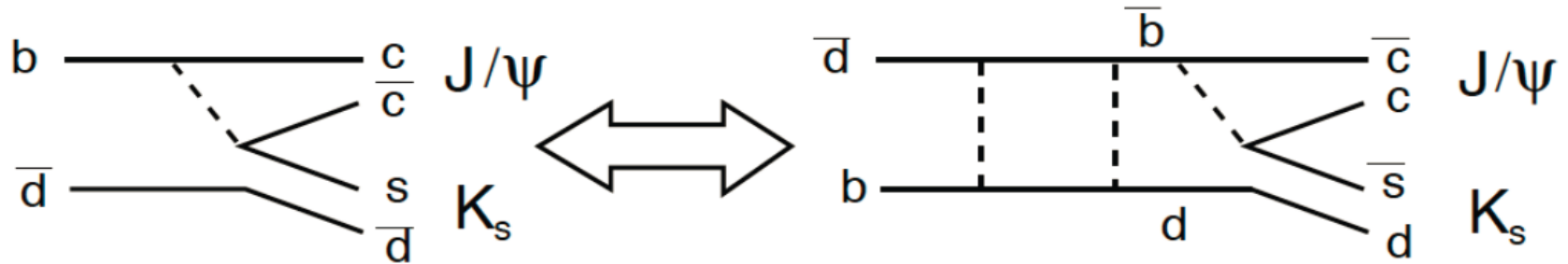
$$A = |T|e^{i(\delta_T - \phi_T)} + |P|e^{i(\delta_P - \phi_P)} \quad \bar{A} = |T|e^{i(\delta_T + \phi_T)} + |P|e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2|T||P|\sin(\delta_T - \delta_P)\sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2|T||P|\cos(\delta_T - \delta_P)\cos(\phi_T - \phi_P)}$$

3 types of CP-Violation: In interference

3) CP violation in interference between mixing and decay

Same final state through decay & mixing + decay



$$\mathcal{A}_1 = \mathcal{A}_{mix}(B^0 \rightarrow B^0) * \mathcal{A}_{decay}(B^0 \rightarrow J/\Psi K_s)$$

$$= \cos\left(\frac{\Delta mt}{2}\right) * A * e^{i\omega}$$

$$\mathcal{A}_2 = \mathcal{A}_{mix}(B^0 \rightarrow \bar{B}^0) * \mathcal{A}_{decay}(\bar{B}^0 \rightarrow J/\Psi K_s)$$

$$= i \sin\left(\frac{\Delta mt}{2}\right) * e^{+i\phi} * A * e^{-i\omega}$$

$\Delta\phi = \phi - 2\omega$ (assume no CP violation in mixing and in decay)

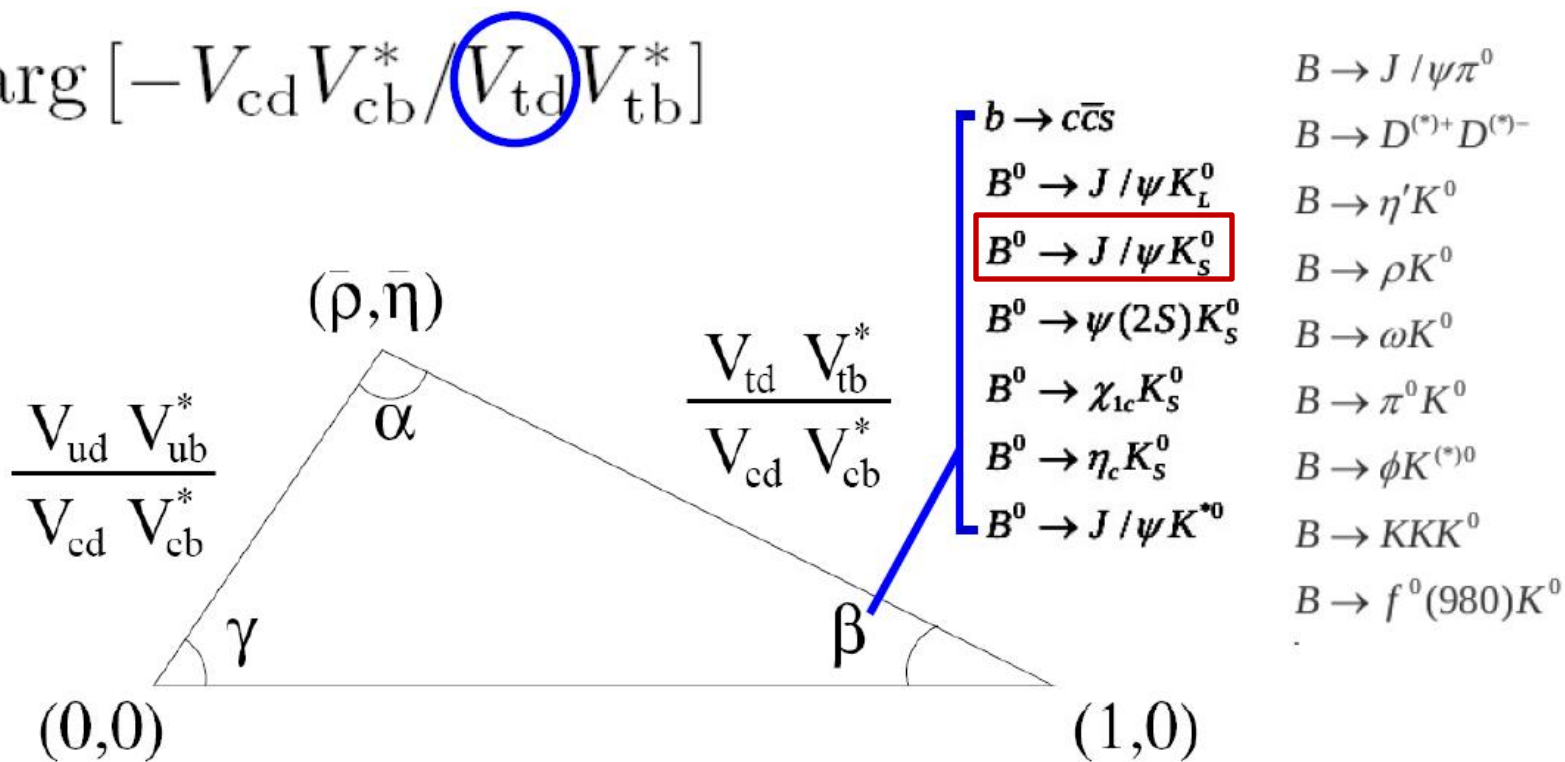
$\Delta\delta = \pi/2 \Leftarrow$ mixing introduce second phase difference

Measurements of CKM angles

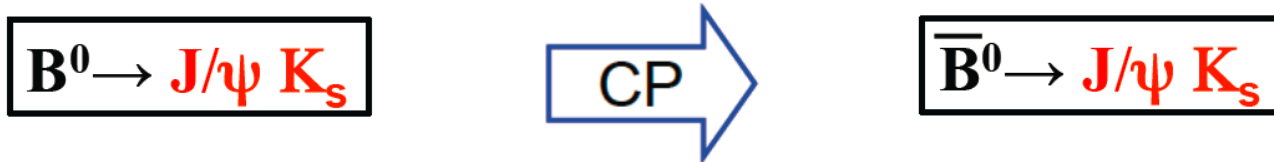
1st CKM measurement: $\sin(2\beta)$

- Theoretically cleaner (SM uncertainties $\sim 10^{-2}$ to 10^{-3})
 → tree dominated decays to charmonium + K^0 final states

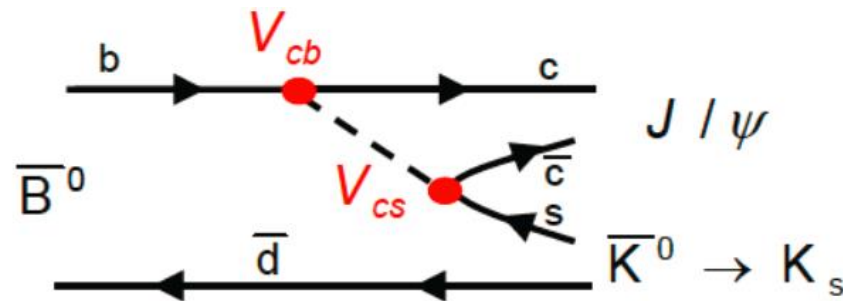
$$\beta \equiv \arg \left[-V_{cd} V_{cb}^* / \underbrace{V_{td} V_{tb}^*}_{\text{circled}} \right]$$



$\sin(2\beta)$: Golden decay $B^0 \rightarrow J/\psi K_s$

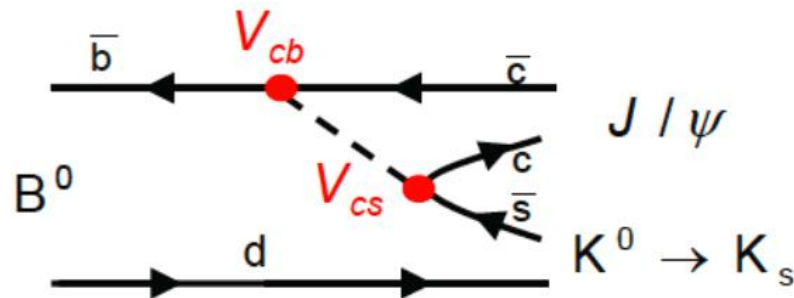


- Leading-order tree decays to $c\bar{c}s$ final states



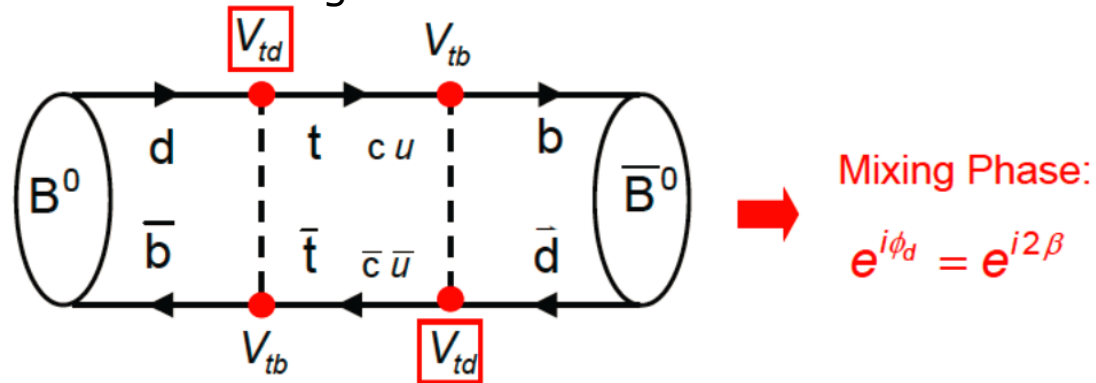
→ here the CKM elements contributing are $V_{cb}V_{cs}^*$ that in Wolfenstein CKM parametrisation have no phase

- The CP conjugated case is also leading to (about) the same final state:

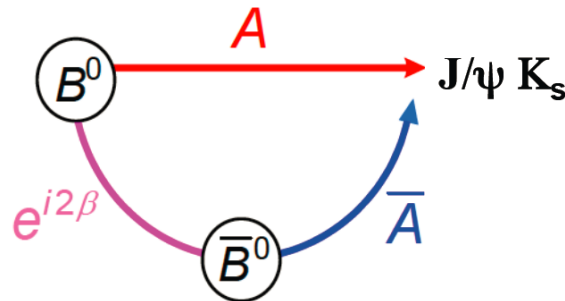


$\sin(2\beta)$: Golden decay $B^0 \rightarrow J/\psi K_s$

- Because both B and $B(\text{bar})$ can decay to this common final state, this can interfere with the oscillation diagram:



$$\Gamma(B^0 \rightarrow J/\psi K_s)(t) \neq \Gamma(\bar{B}^0 \rightarrow J/\psi K_s)(t)$$



$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B}^0 \rightarrow J/\psi K_s) - \Gamma(B^0 \rightarrow J/\psi K_s)}{\Gamma(\bar{B}^0 \rightarrow J/\psi K_s) + \Gamma(B^0 \rightarrow J/\psi K_s)} = \sin(2\beta) \sin(\Delta m t)$$

→ requires knowledge of production flavour of the B

$\sin(2\beta)$: Golden decay $B^0 \rightarrow J/\psi K_S$

The colour-suppressed tree dominates

→ subleading $b \rightarrow sc(\bar{b})c$ penguin has (predominantly) the same weak phase

→ CKM-suppressed pollution by penguins - **golden channel**

- $|A(\bar{b})| = |A| \Rightarrow$ no direct CP violation

- $C = 0$ & $S = -\eta_{CP} \sin(2\beta)$

→ sine term has a non-zero coefficient → there is CP violation in the interference between mixing and decay amplitudes in $cc(\bar{b})s$ decays

- reasonable branching fraction & experimentally clean signature

How can we measure decay time in $e^+e^- \rightarrow Y(4S) \rightarrow B^0\bar{B}^0$?

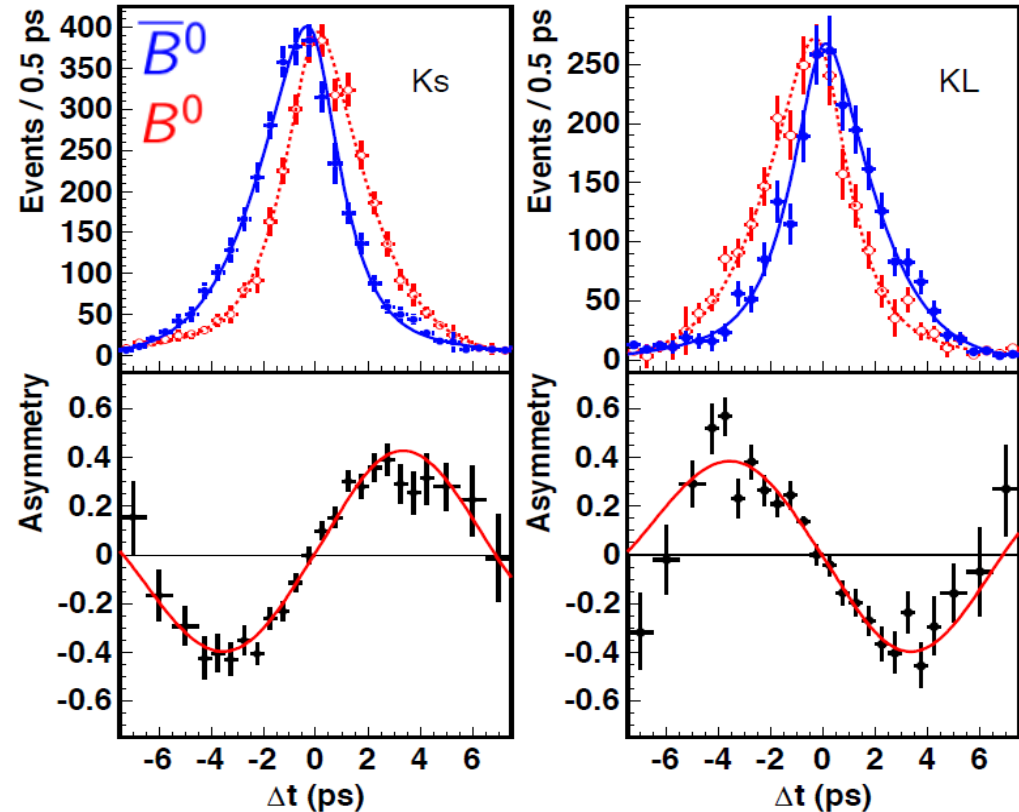
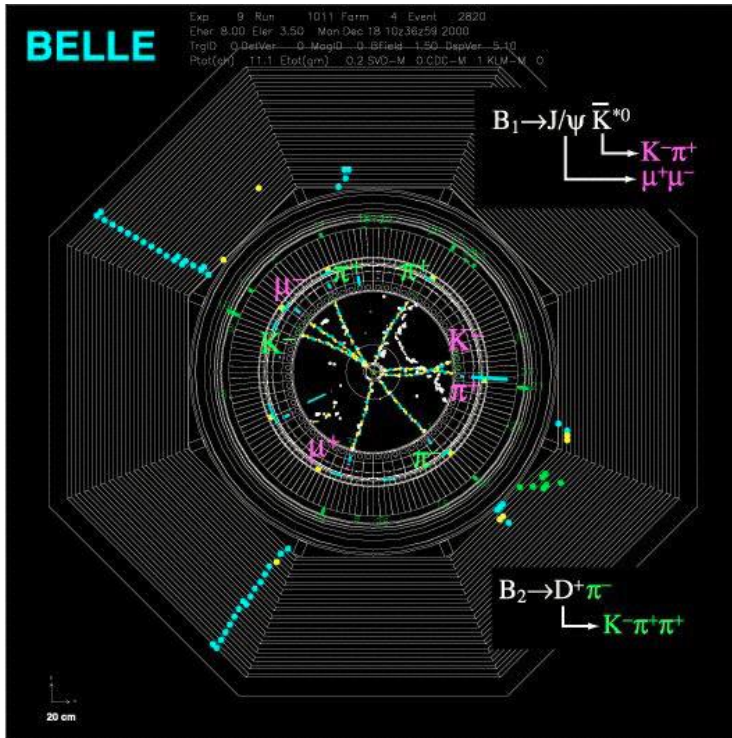
- the answer: asymmetric-energy B factory (e.g. Belle)

- key points

→ $Y(4S) \rightarrow B^0\bar{B}^0$ produces coherent pairs

→ B mesons are moving in LAB frame

sin(2β): Belle measurement



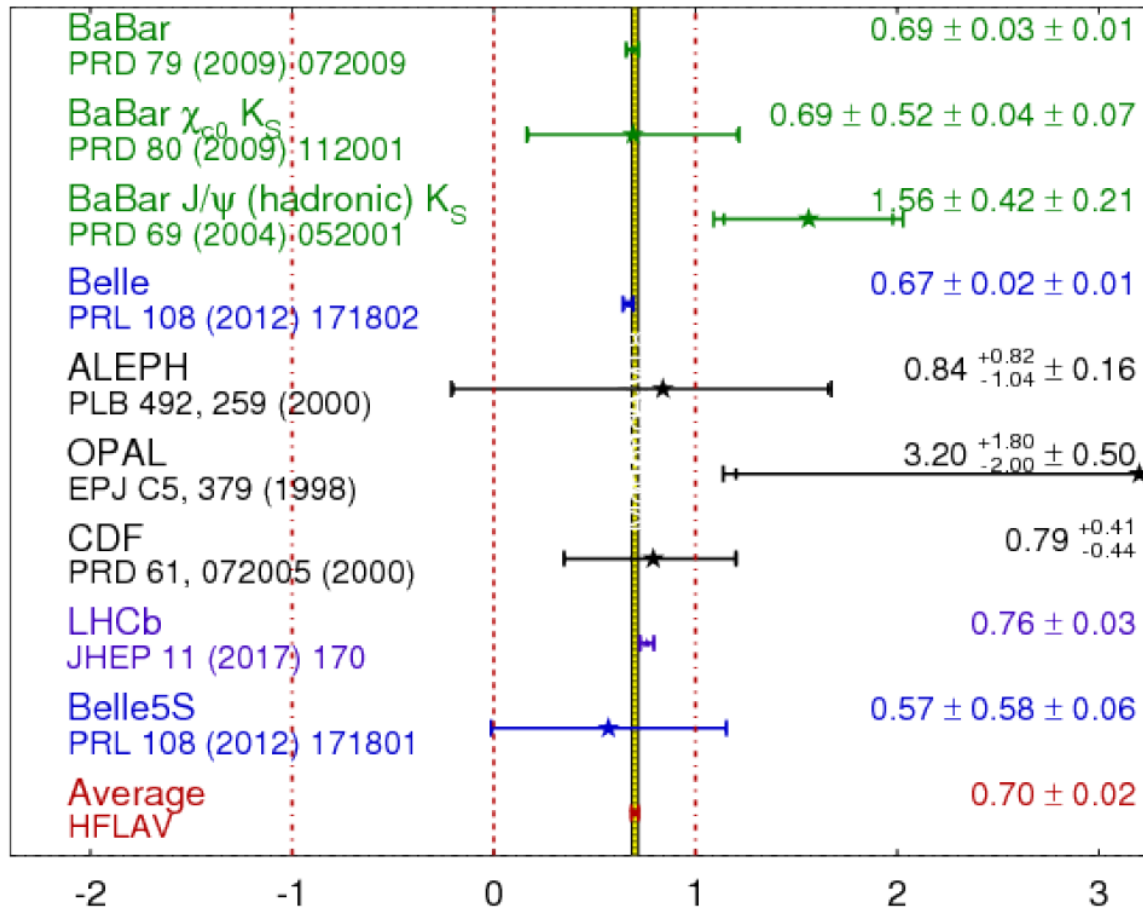
What do we have to do to measure $A_{CP}(t)$?

- step 1: produce and detect $B^0 \rightarrow f_{CP}$ events
- step 2: separate B^0 from $B^0(\text{bar})$
- step 3: measure the decay time t

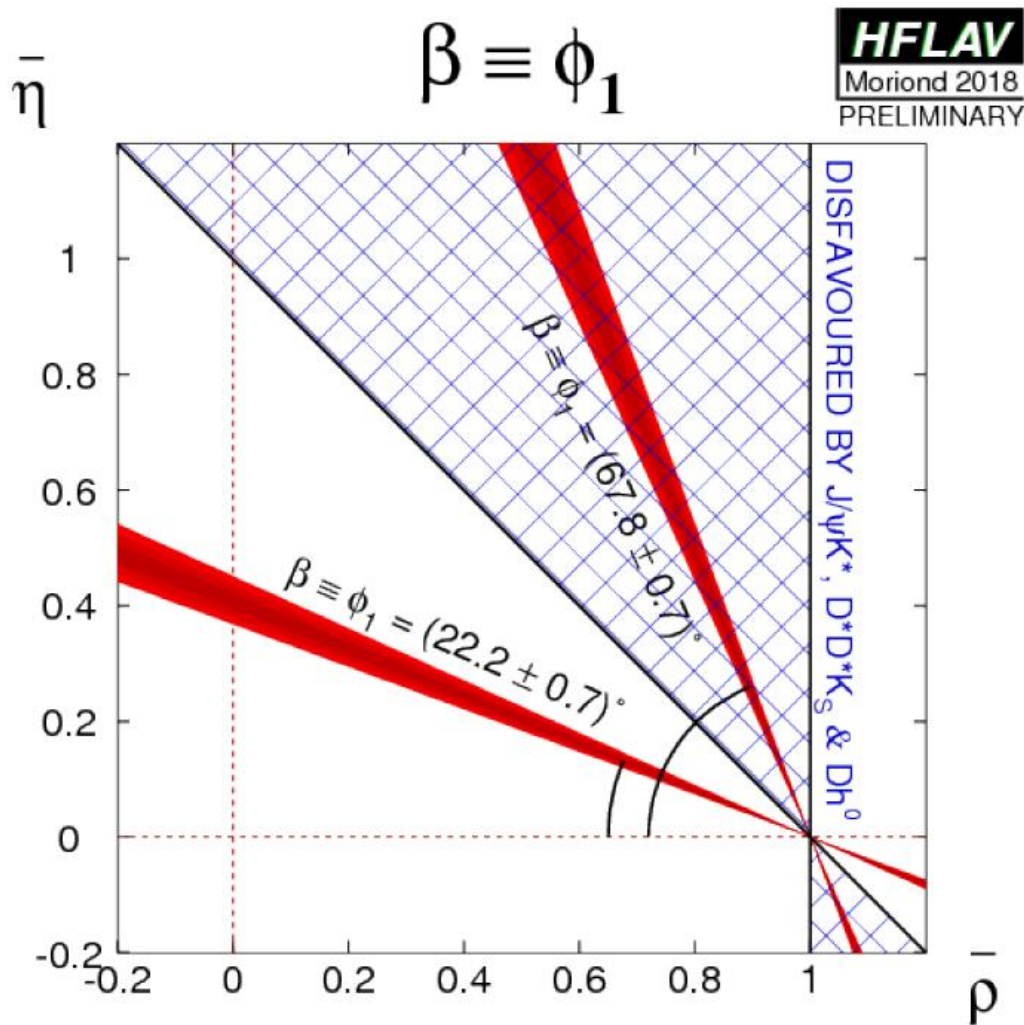
sin(2β): Compilation of results

$$\sin(2\beta) \equiv \sin(2\phi_1)$$

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$\sin(2\beta)$: Compilation of results



$$\beta = (22.2 \pm 0.7)^\circ$$

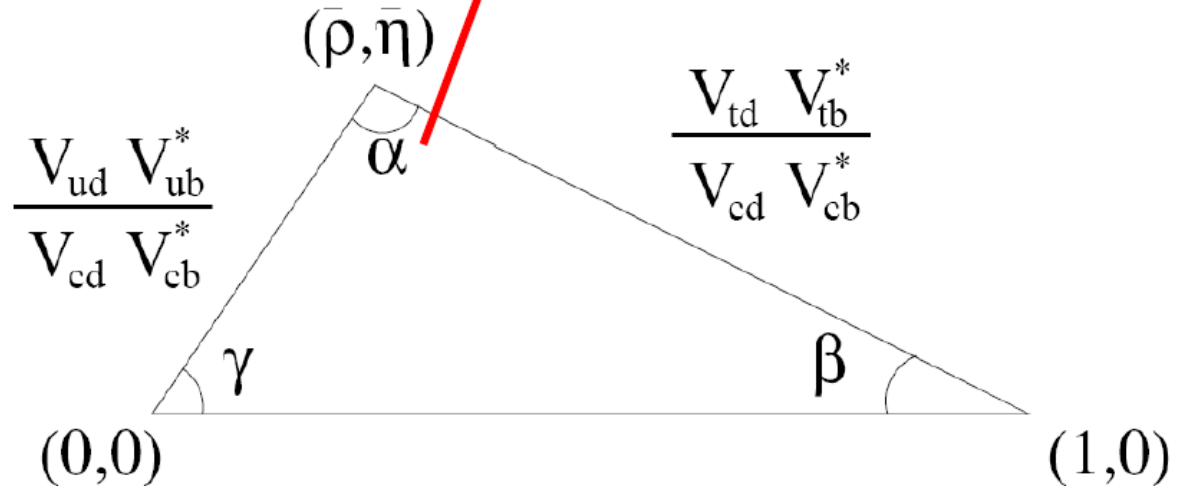
2nd CKM measurement: α angle

$b \rightarrow uu(\text{bar})d$ transitions with possible loop contributions. Extract α using:

- SU(2) isospin relations
- SU(3) flavour related processes

$$\alpha \equiv \arg \left[-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right]$$

- $b \rightarrow u\bar{u}d$ $B \rightarrow a_1\pi$
- $B \rightarrow \pi\pi$ $B \rightarrow a_1\rho$
- $B \rightarrow \rho\pi$ $B \rightarrow b_1\pi$
- $B \rightarrow \rho\rho$ $B \rightarrow b_1\rho$
- $B \rightarrow a_1a_1$



Measurement of α

- Time-dependent CP violation in modes dominated by $b \rightarrow uu(\text{bar})d$ tree diagrams probes α (or $\pi - (\beta + \gamma)$)

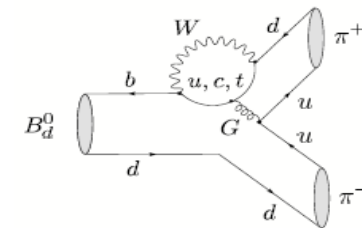
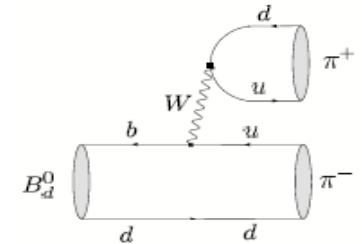
$$\rightarrow C = 0 \ \& \ S = +\eta_{CP} \sin(2\alpha)$$

- $b \rightarrow du(\text{bar})u$ penguin transitions contribute to same final states

\rightarrow „penguin pollution”

$\rightarrow C \neq 0 \Leftrightarrow$ direct CP violation can occur

$\rightarrow S \neq +\eta_{CP} \sin(2\alpha)$



In this case the penguin diagram is not CKM suppressed so it spoils the clean measurement of the CP violation effect

- Two approaches (optimal approach combines both)
 - \rightarrow try to use modes with small penguin contribution
 - \rightarrow correct for penguin effect (isospin analysis)

$$C_{hh} \propto \sin(\delta)$$

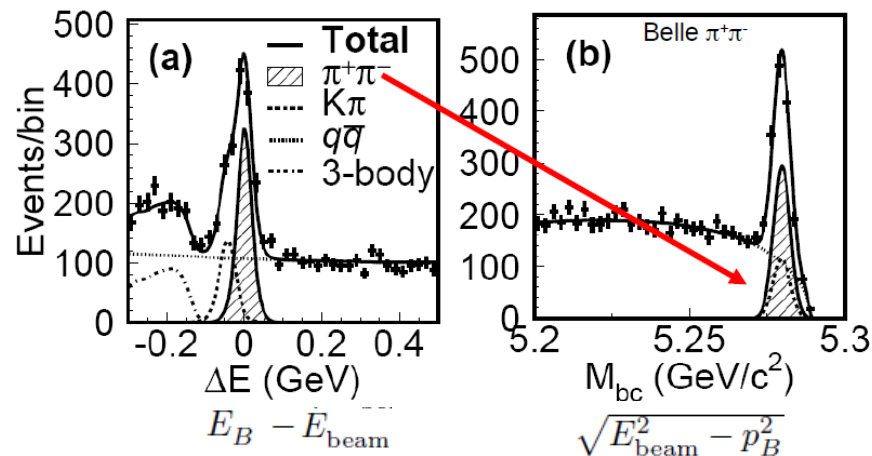
$$S_{hh} = \sqrt{1 - C_{hh}^2} \sin(2\alpha_{\text{eff}})$$

$$\delta = \delta_P - \delta_T$$

Measurement of α : $B^0 \rightarrow \pi\pi$

$B^0 \rightarrow \pi\pi$

- easy to isolate signal for $\pi^+\pi^-$ and $\pi^+\pi^0$ as these modes are relatively clean and have relatively large BR $\sim O(5 \times 10^{-6})$



- much harder to isolate $\pi^0\pi^0$

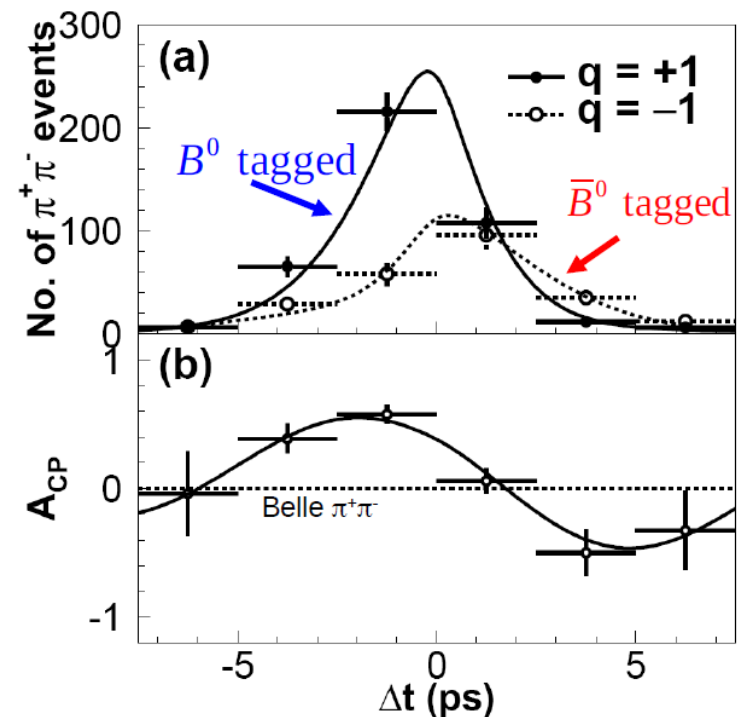
→ BR $\sim 1.5 \times 10^{-6}$

→ no tracks in the final state to provide vertex info

→ $B^0 \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma$ has a large ΔE resolution

- possible to separate flavour tags to measure C

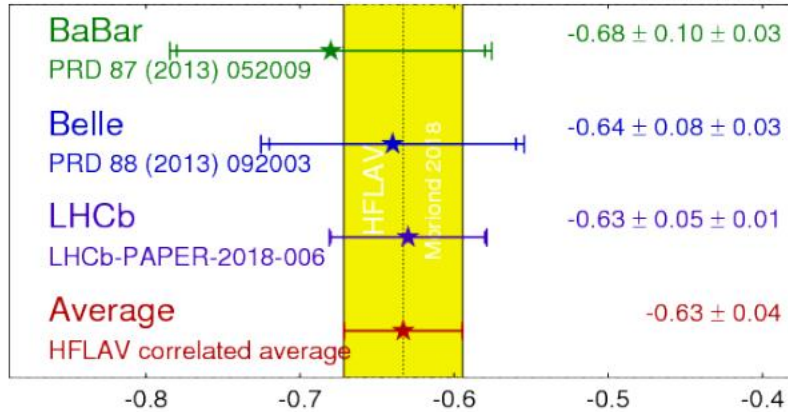
- this completes set of information required for an isospin analysis



Measurement of α : $B^0 \rightarrow \pi^+\pi^-$

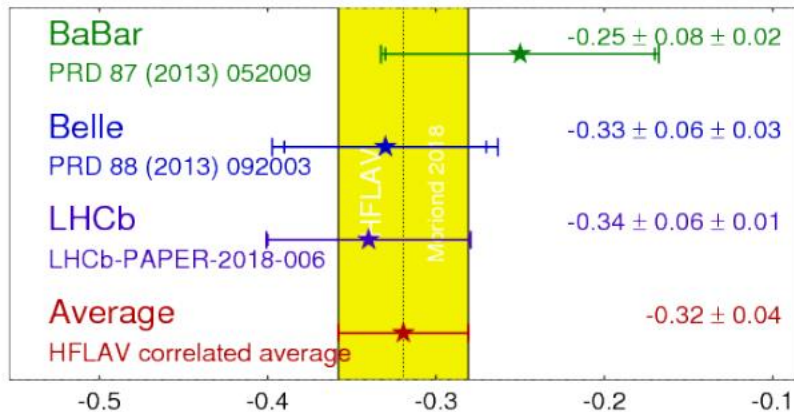
$\pi^+ \pi^- S_{CP}$

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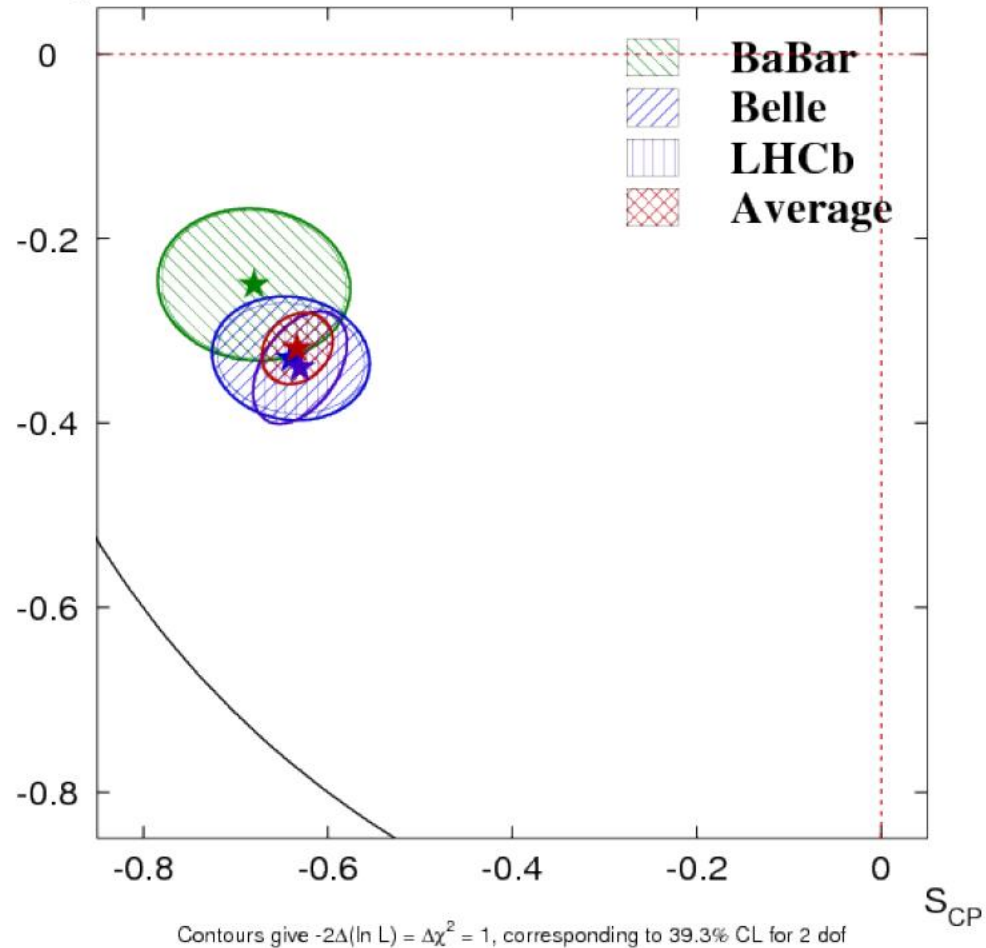
$\pi^+ \pi^- C_{CP}$

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$\pi^+ \pi^- S_{CP}$ vs C_{CP}

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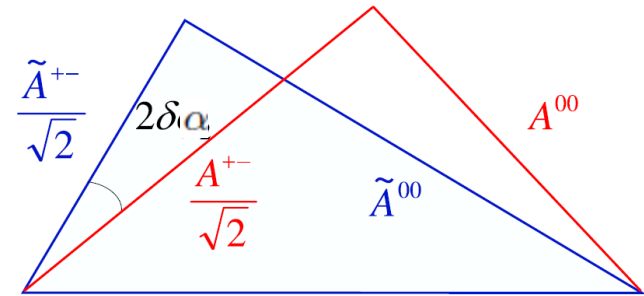


Measurement of α : *Isospin analysis*

Use triangle construction to find difference ($\delta\alpha$) between „ α_{eff} ” and α

- requires measurement of rates and asymmetries of $B^+ \rightarrow \pi^+ \pi^0$ & $B^0 \rightarrow \pi^0 \pi^0$

$$\delta\alpha = \alpha_{\text{eff}} - \alpha \qquad \tilde{A} = e^{i2\alpha} \bar{A}$$



$$A^{+0} = \tilde{A}^{-0}$$

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{+0}$$

- $B \rightarrow \pi^+ \pi^-, \pi^+ \pi^0, \pi^0 \pi^0$ decays are connected by isospin relations
- $\pi\pi$ states can have $I = 2$ or $I = 0$

→ the gluonic penguins contribute only to the $I = 0$ state ($\Delta I = 1/2$)

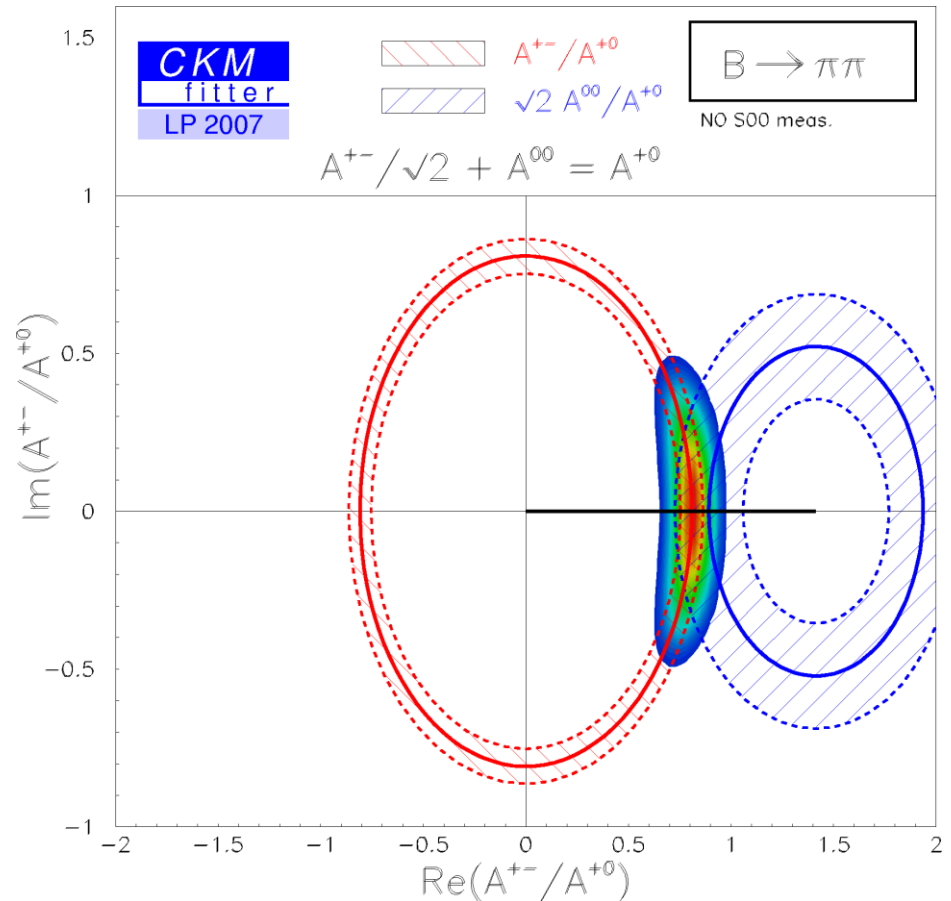
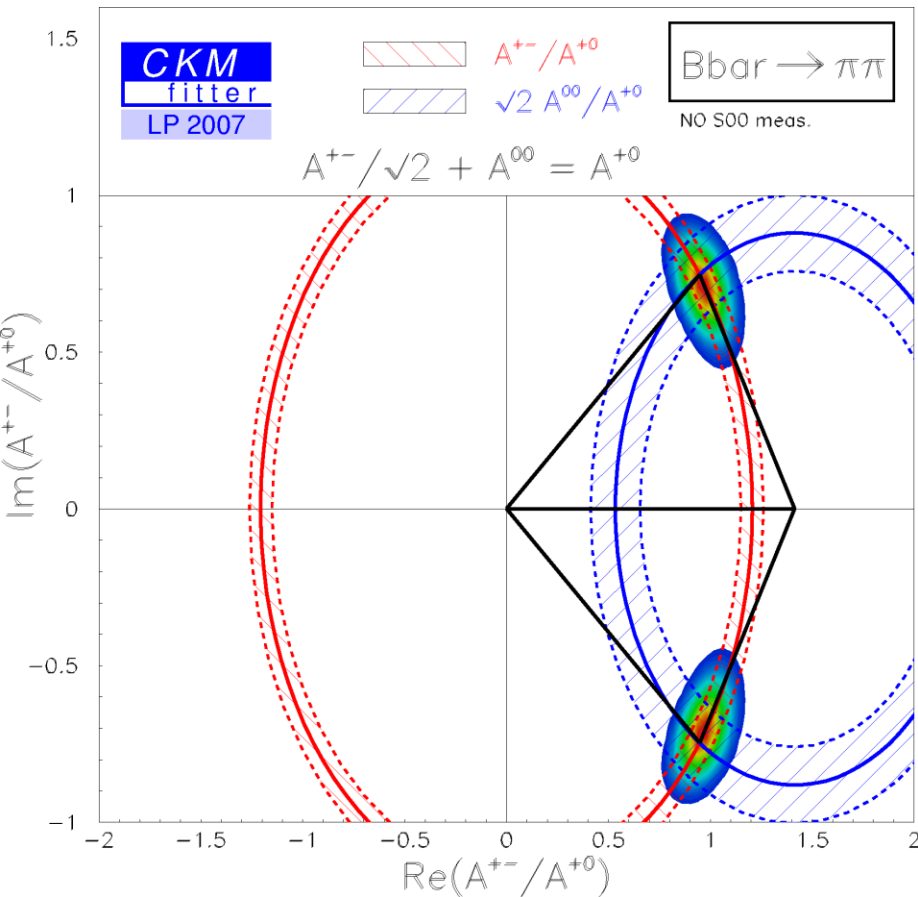
→ $\pi^+ \pi^0$ is a **pure $I = 2$** state ($\Delta I = 3/2$) and it gets contribution only from the **tree diagram**

→ **triangular relations** allow for the determination of the phase difference induced on α

Both $\text{BR}(B^0)$ and $\text{BR}(B^0(\text{bar}))$ have to be measured in all the $\pi\pi$ channels

Measurement of α : *Isospin analysis*

There are SU(2) violating corrections to consider, for example electroweak penguins ($\sim 5\%$), but these are much smaller than current experimental accuracy and eventually they can be incorporated into the isospin analysis



Measurement of α : $B^0 \rightarrow \rho\rho$

- **vector-vector modes**: angular analysis required to determine the CP content

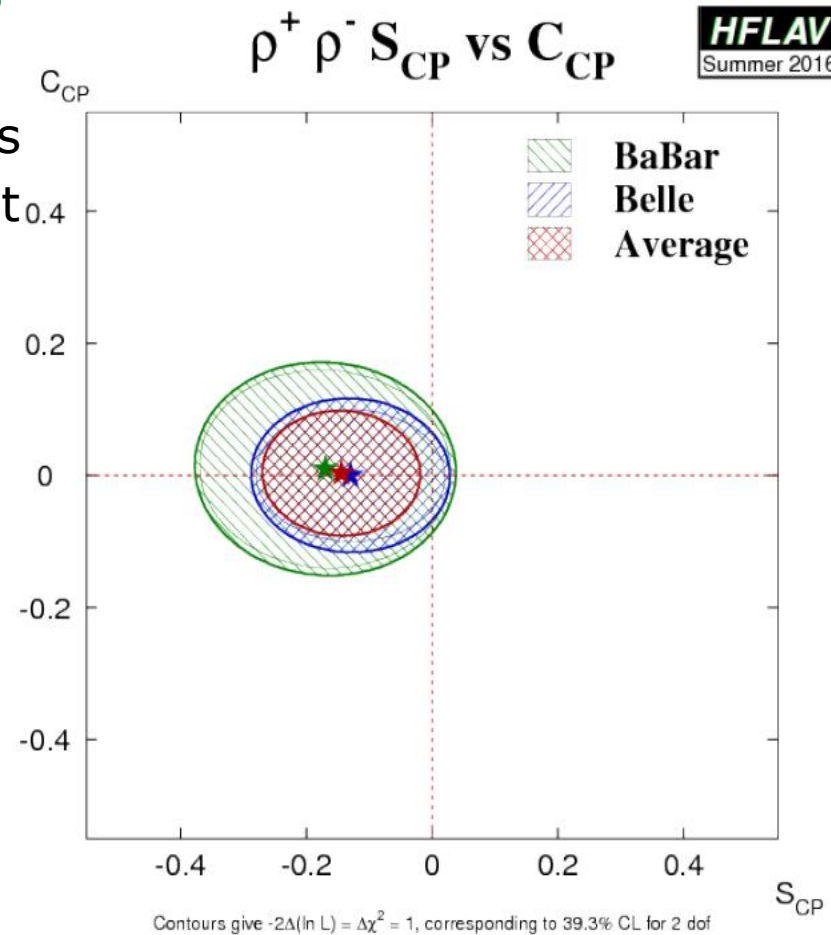
L=0,1,2 partial waves:

- longitudinal: CP-even state
- transverse: mixed CP states

- isospin analysis:
 - possible contribution from $\rho^0\rho^0$
- wide ρ resonance

But

- BR 5 times larger with respect to $\pi\pi$
- **penguin pollution smaller than in $\pi\pi$**
- ρ are almost 100% polarized:
 - almost a pure CP-even state



from $\pi\pi, \rho\rho, \pi\rho$ combined

$$\alpha = (93.3 \pm 5.6)^\circ$$