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**

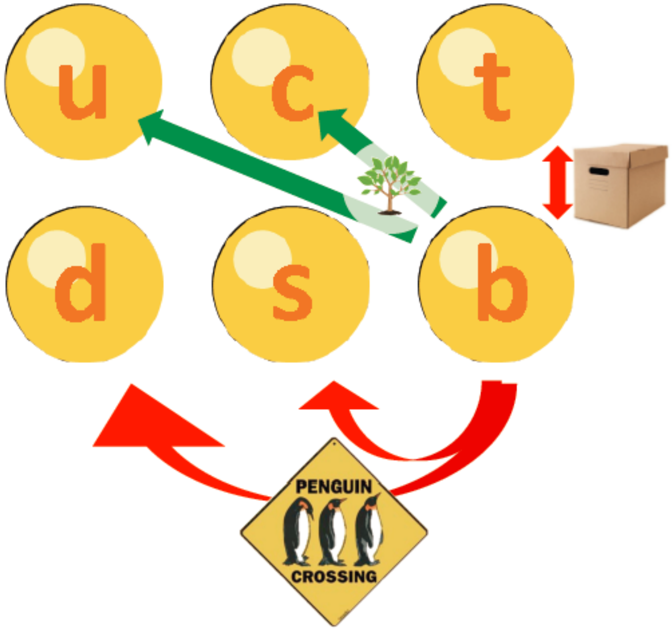
- But quarks feel the strong interaction and hadronize
  - various different beauty hadrons
  - many possible decays to different final states

    → *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

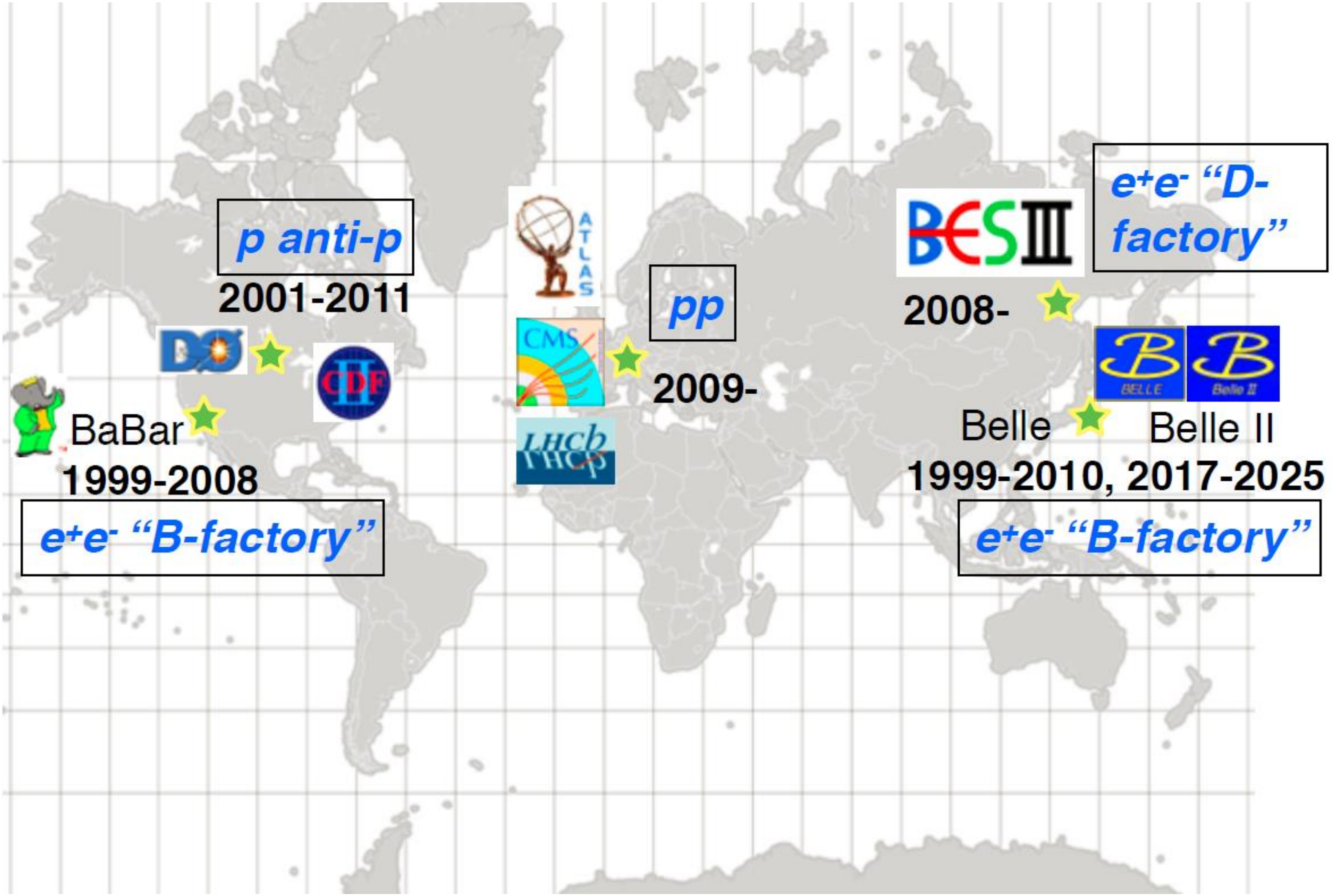
Rich phenomenology with beauty quarks

- 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 (~1.6ps)



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

Where are *B* and *D* mesons produced



p anti-p

2001-2011

BaBar

1999-2008

e⁺e⁻ "B-factory"

pp

2009-

e⁺e⁻ "D-factory"

2008-

Belle

Belle II

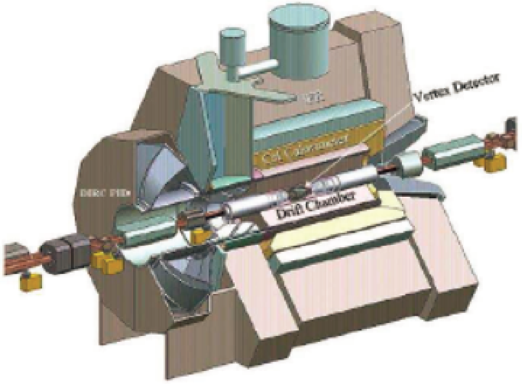
1999-2010, 2017-2025

e⁺e⁻ "B-factory"

Flavour physics experiments

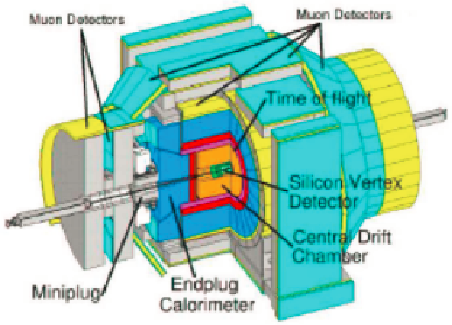
B-factories (BaBar & Belle)

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



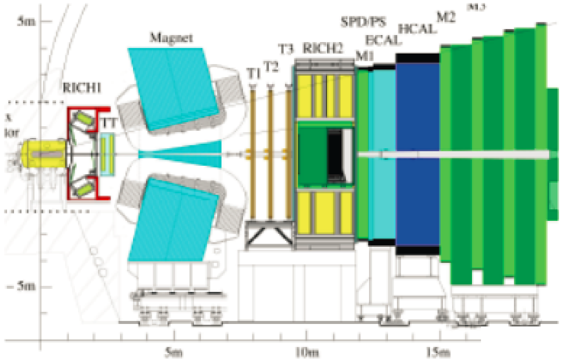
General purpose detectors (ATLAS, CMS, CDF, D0)

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


CDF II Detector

LHCb

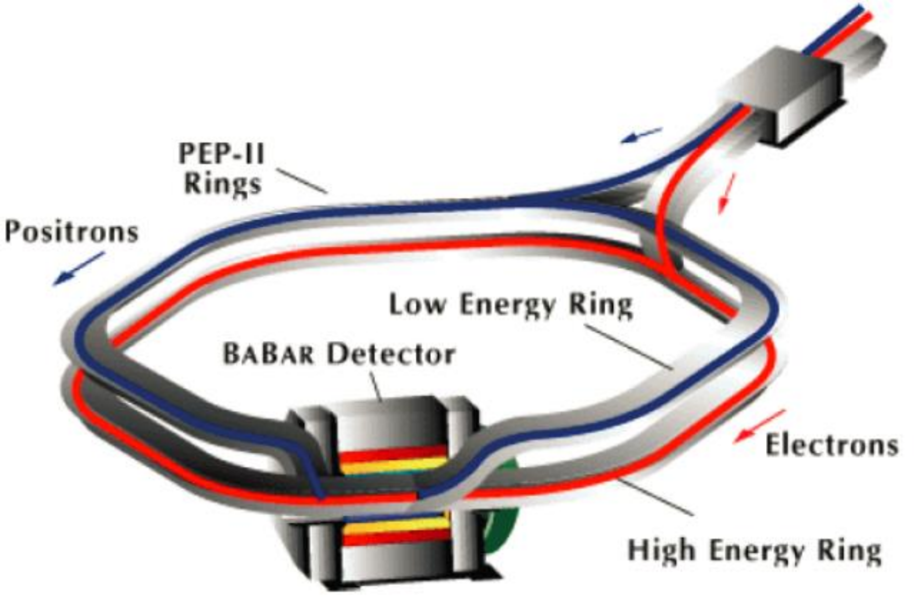
- Proton colliders @ CERN
- Dedicated B-physics experiment

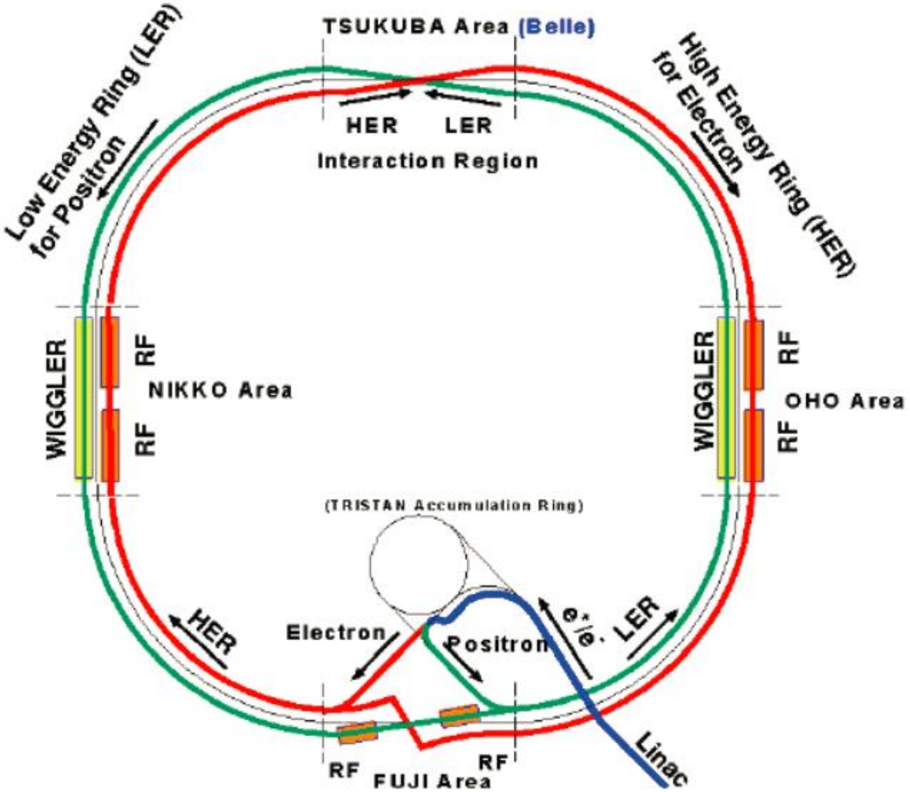


e^+e^-: Asymmetric B factories

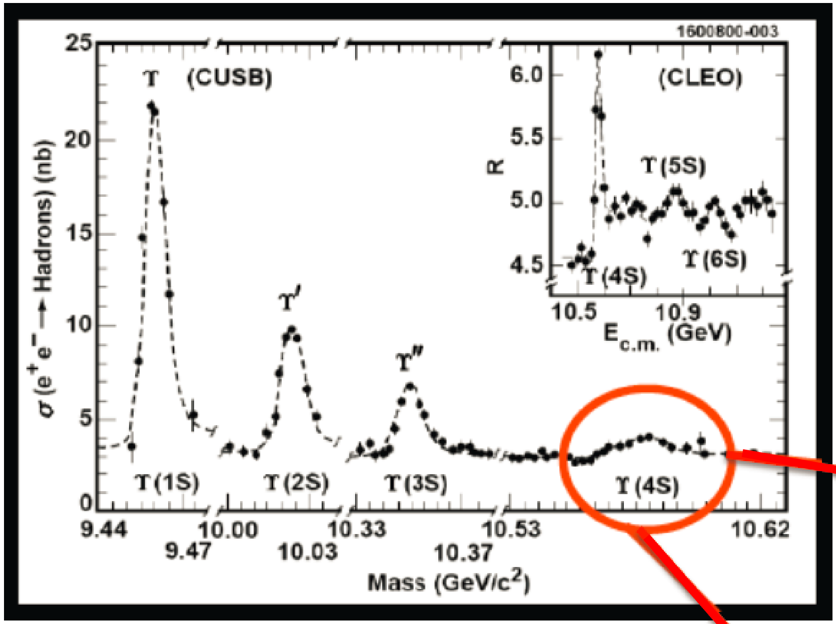
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





Y(4S) resonance



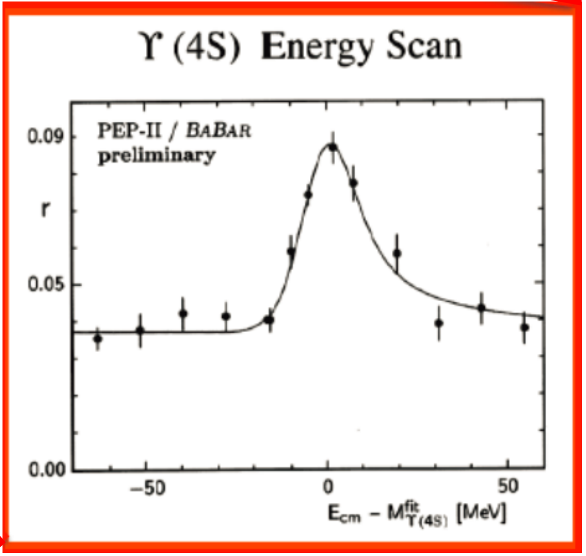
Cleanest way to produce B mesons in e^+e^- collisions: at centre-of-mass energy = mass of Y(4S)

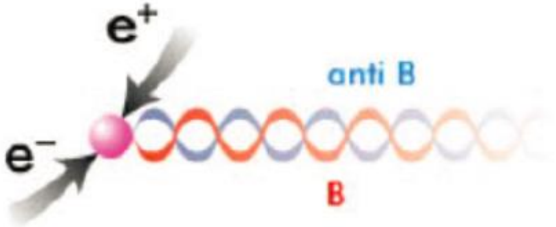
$\sqrt{s} = 10.58$ GeV

Y(4S) is bound bb-state that decays to ~100% to B^+B^- or B^0B^0(bar) pairs

~1.1M BB(bar) pairs per fb^{-1}

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


Υ (4S) Energy Scan



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

Kinematics at e⁺e⁻ colliders

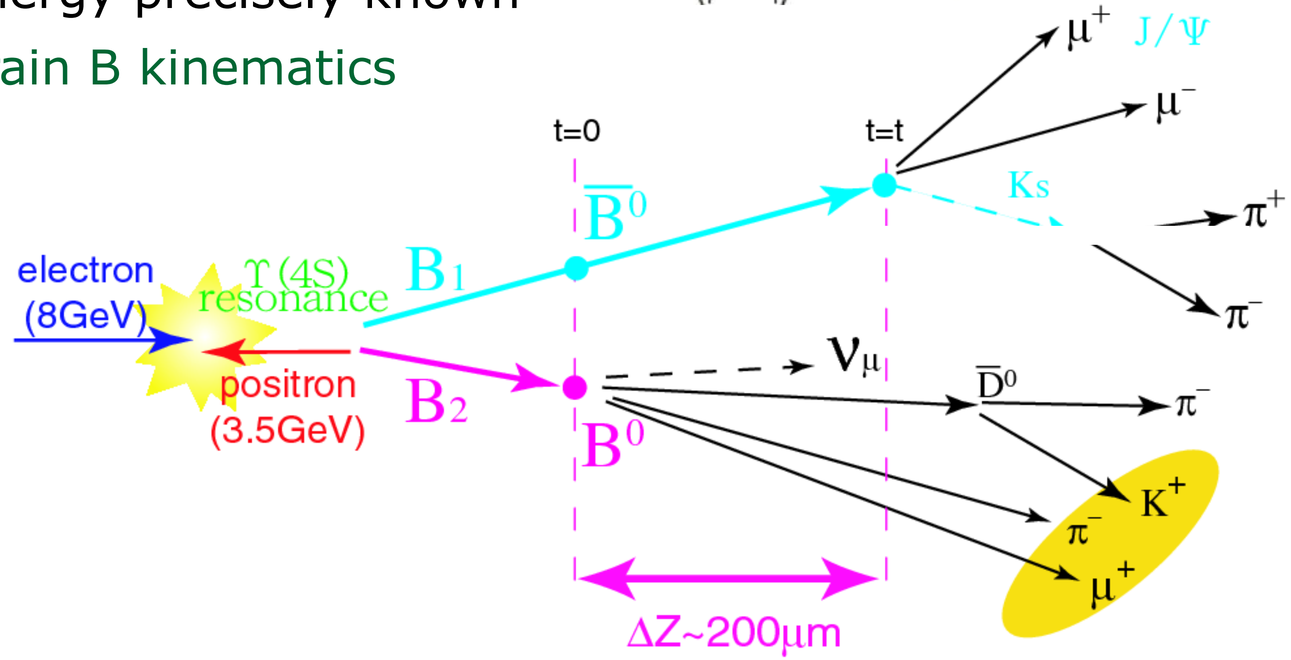
- Symmetric collider: B-mesons produced almost at rest
  → short lifetime make flight distance unmeasurably small

- Asymmetric collider (KEKB, PEPII)
  → with boost $\beta\gamma$ ~ 0.6

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

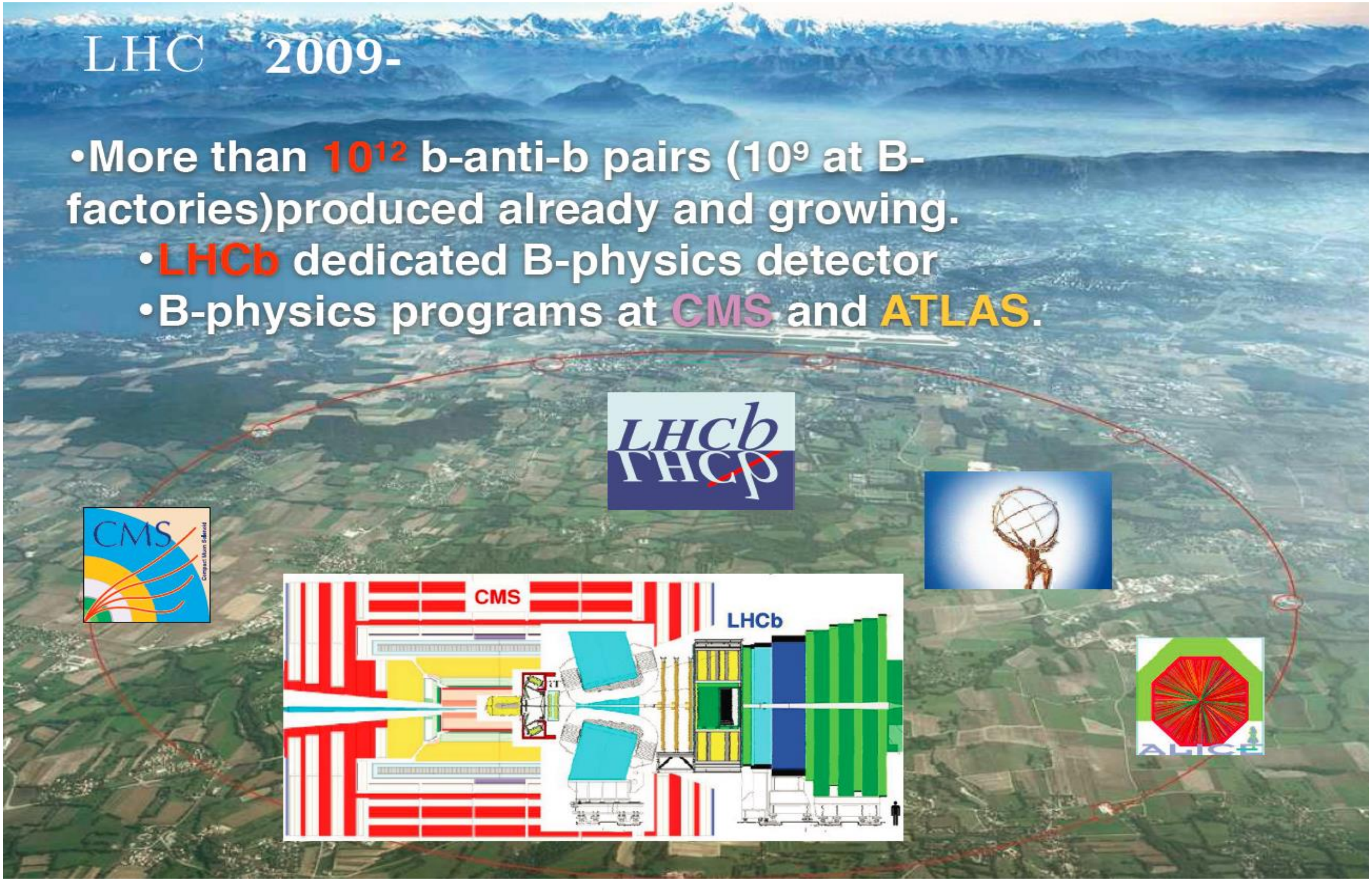
$$\langle |\Delta z| \rangle \approx 200\ \mu m$$

- Beam energy precisely known
  → constrain B kinematics



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

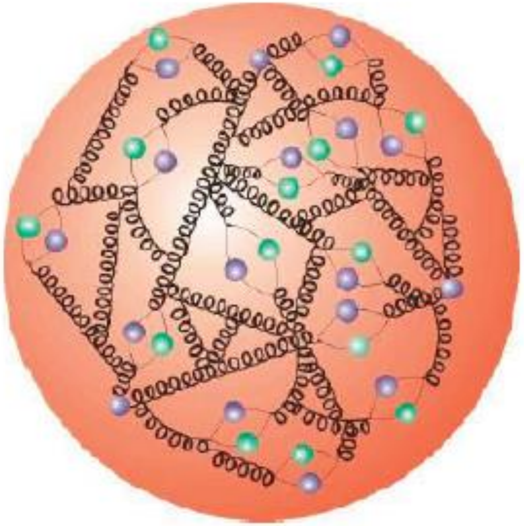
bb(bar) production at *pp* collider



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

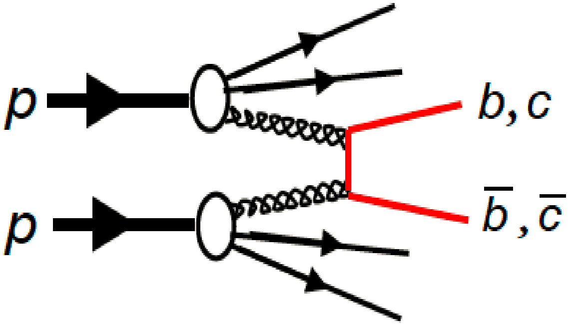


- Protons are complicated objects
  - valence & sea quarks, gluons

- Available energy of „proton" collision depends on partons

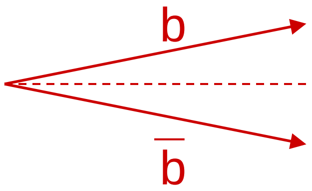
$$s' = x_1 \cdot x_2 \cdot s$$

x_i = Bjorken x (fractional momentum) of parton



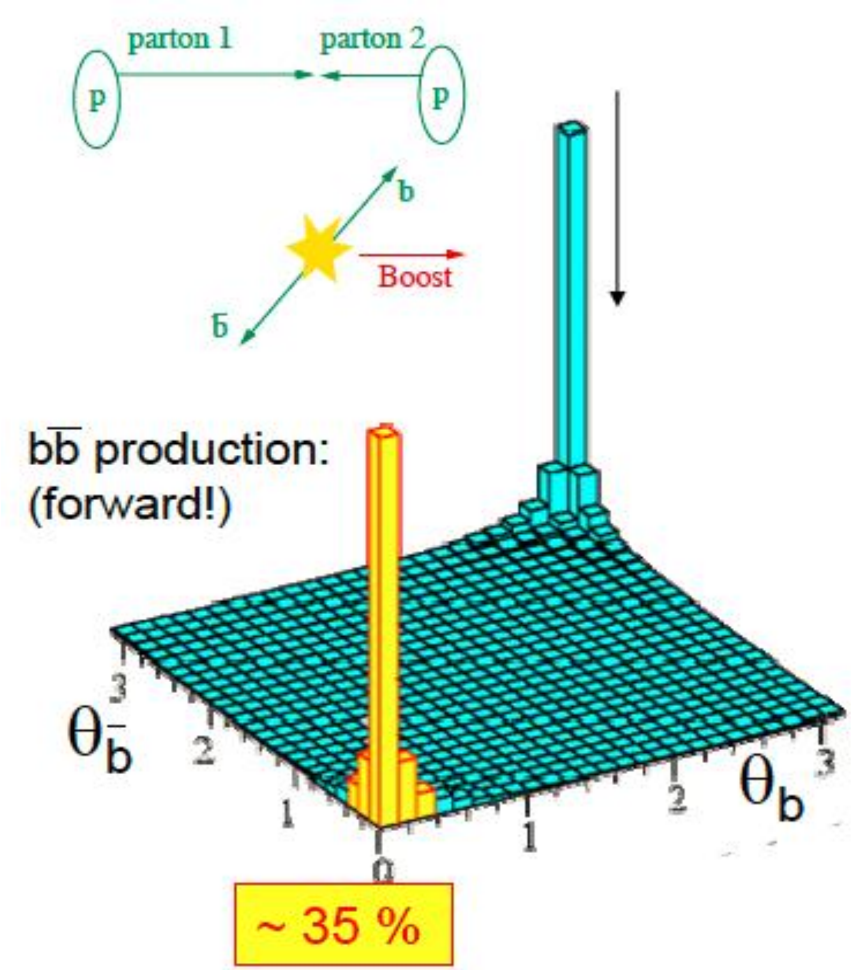
- Energy of particular collision unknown, but distributions known
  - hadron colliders „scan" a wide energy range
  - average s' ~ 0.1 s
  - dominant process @ LHC: gluon fusion

Event kinematics

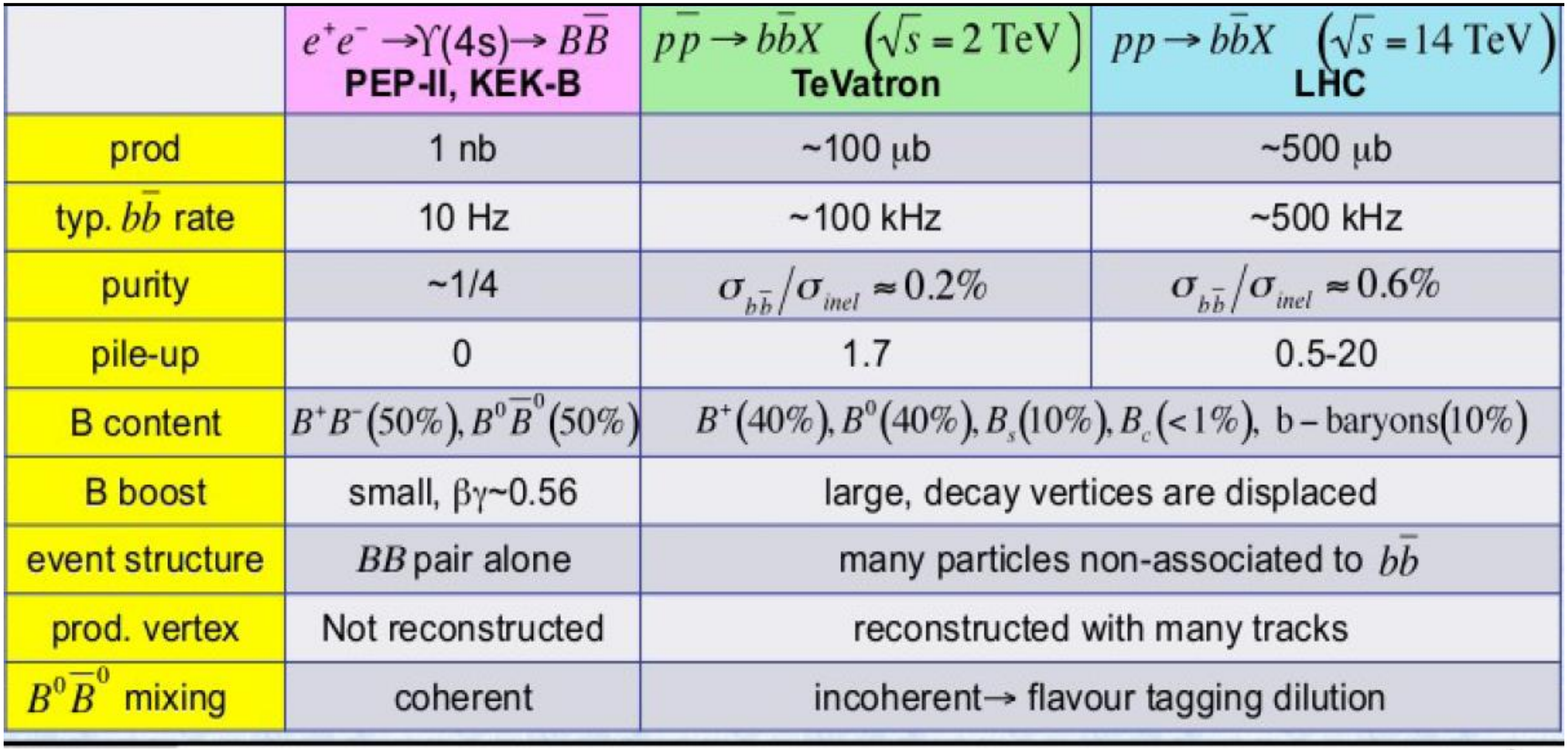


In high energy collisions, bb(bar) pairs produced predominantly in forward or backward directions

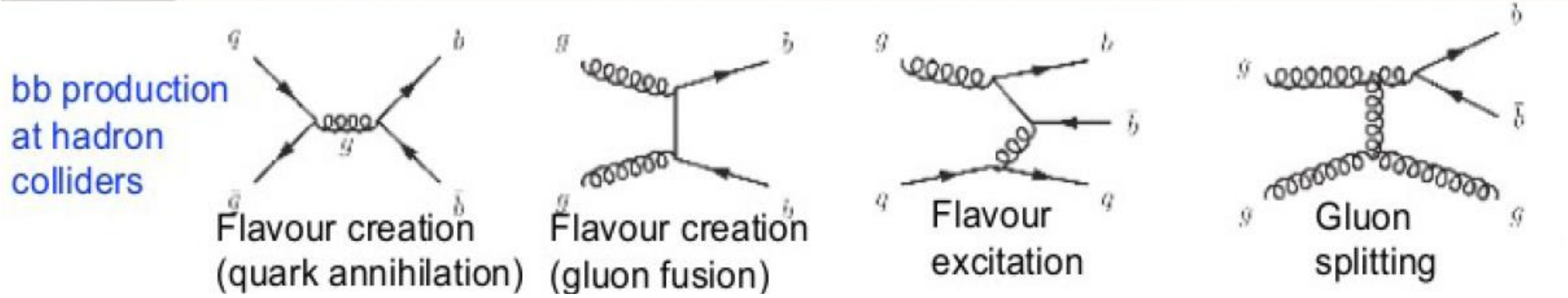
- B hadron mass ~ 5 GeV
  - asymmetric x-values
  - strongly boosted (βγ~100)
  - average flight length ~ 7mm
- Boost allows time dependent analyses of fast B_s mixing
- B hadron admixture:
  - 40% B^0
  - 40% $B^{\pm}$
  - 10% B_s
  - 10% Λ_b
  - <1% others (B_c, B^*, B^{**}, …)



b production at hadron colliders



	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$ **PEP-II, KEK-B**	$p\bar{p} \to b\bar{b}X \quad \left(\sqrt{s} = 2\ \mathrm{TeV}\right)$ **TeVatron**	$pp \to b\bar{b}X \quad \left(\sqrt{s} = 14\ \mathrm{TeV}\right)$ **LHC**
prod	1 nb	~100 μb	~500 μb
typ. $b\bar{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~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, βγ~0.56	large, decay vertices are displaced	
event structure	BB 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→ flavour tagging dilution	



bb production at hadron colliders

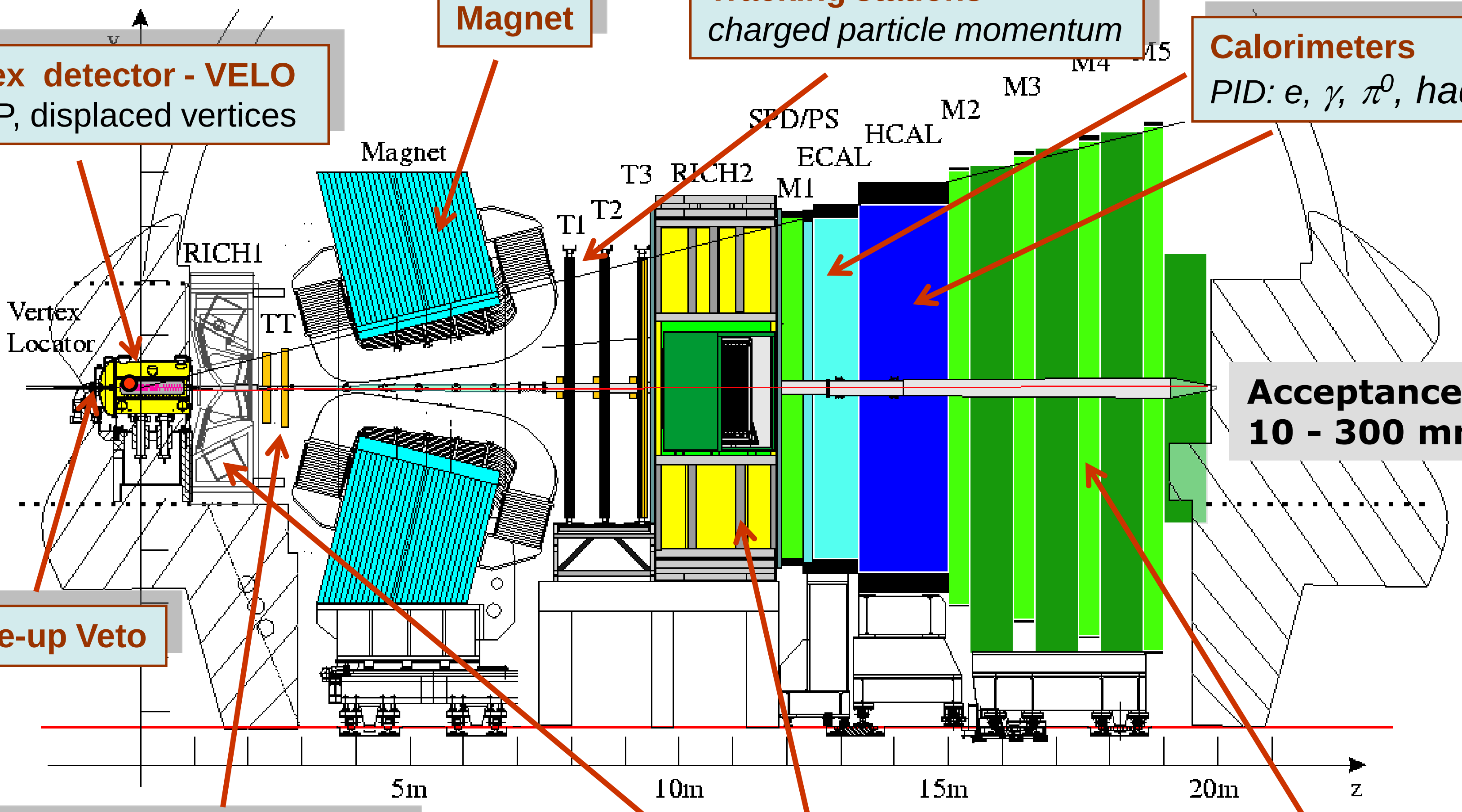
Flavour creation (quark annihilation)

Flavour creation (gluon fusion)

Flavour excitation

Gluon splitting

LHCb - single arm spectrometer



Vertex detector - VELO
PV, IP, displaced vertices

Magnet

Tracking stations
charged particle momentum

Calorimeters
PID: e, γ, π^0, hadrons

Acceptance
10 - 300 mrad

Pile-up Veto

Trigger trackers
particle momentum for trigger

RICH detectors
PID: separation K / π / p

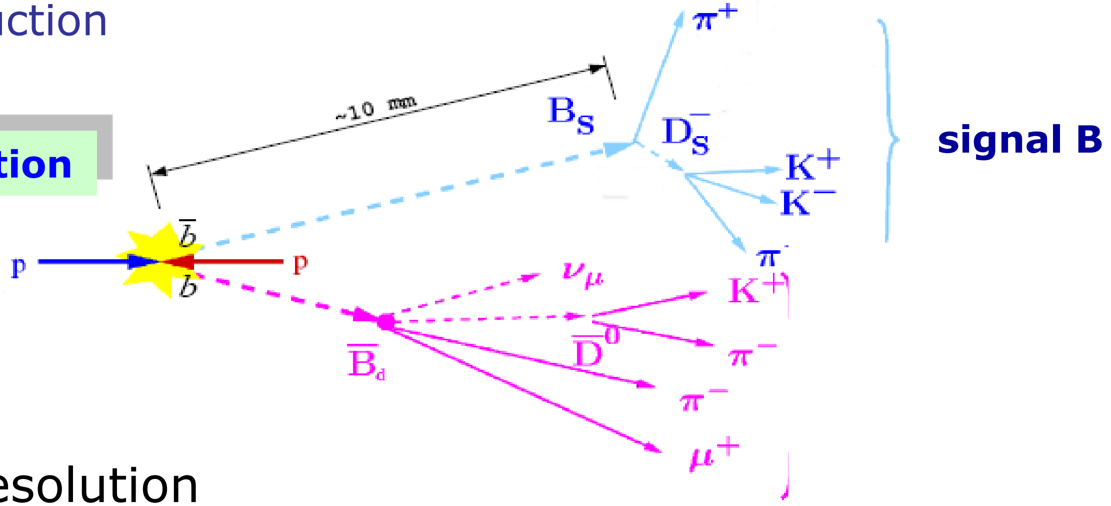
Muon chambers

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 aquisition system

LHC flavour physics programme

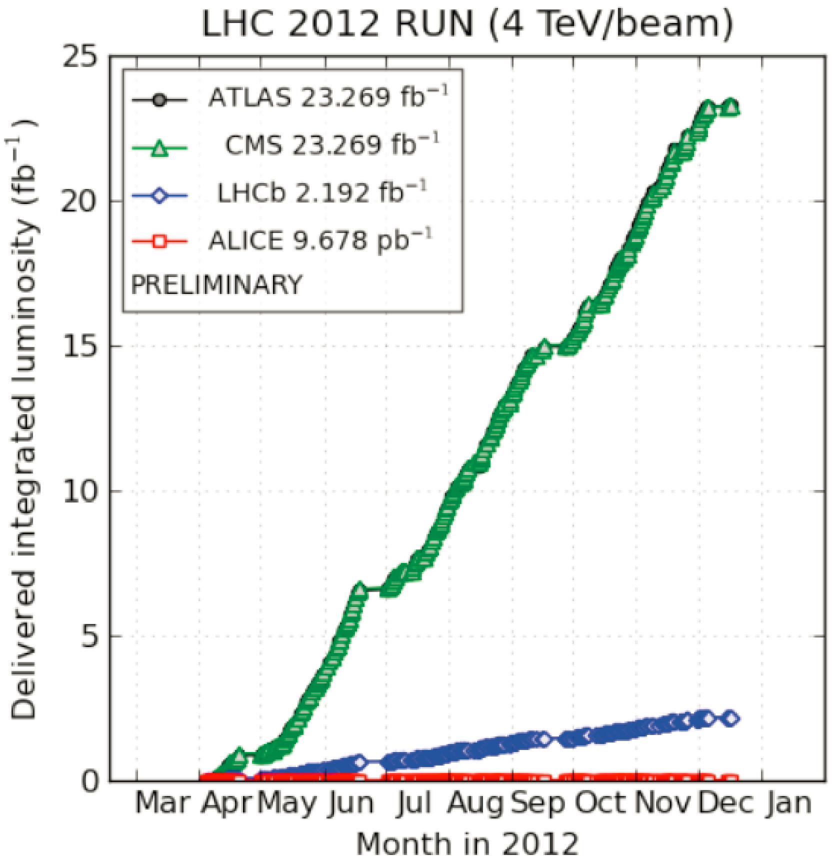
ATLAS / CMS

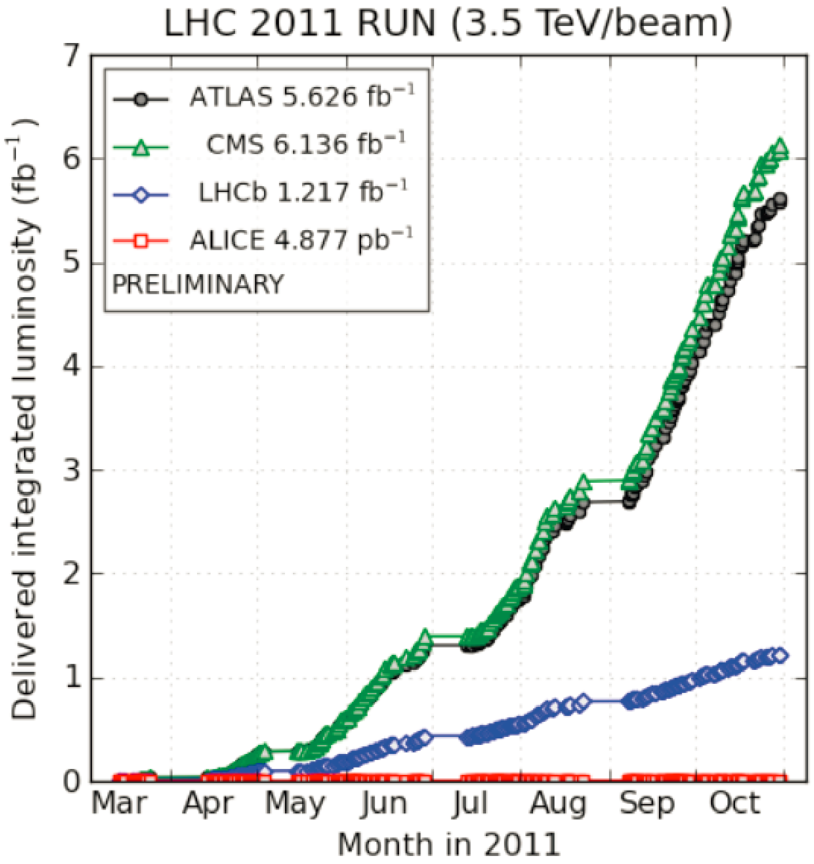
- Central detectors, $|\eta|<2.5$
- **High Luminosity ($>10^{34}cm^{-2}s^{-1}$)**
  → high pileup ~20
- Trigger
  - Relatively low rate (~200-400Hz)
  - High PT muon triggers
- Analysis
  - Mostly modes with dimuons
  - Limited flavour tagging
- Particle identification
  - Excellent muon ID
  - Limited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

LHCb

- Forward spectrometer, $1.9< \eta < 5$
- Lower Luminosity ($4x10^{32}cm^{-2}s^{-1}$)
  → pileup ~1.5
- Trigger
  - **High trigger rate** (~2kHz)
  - 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)

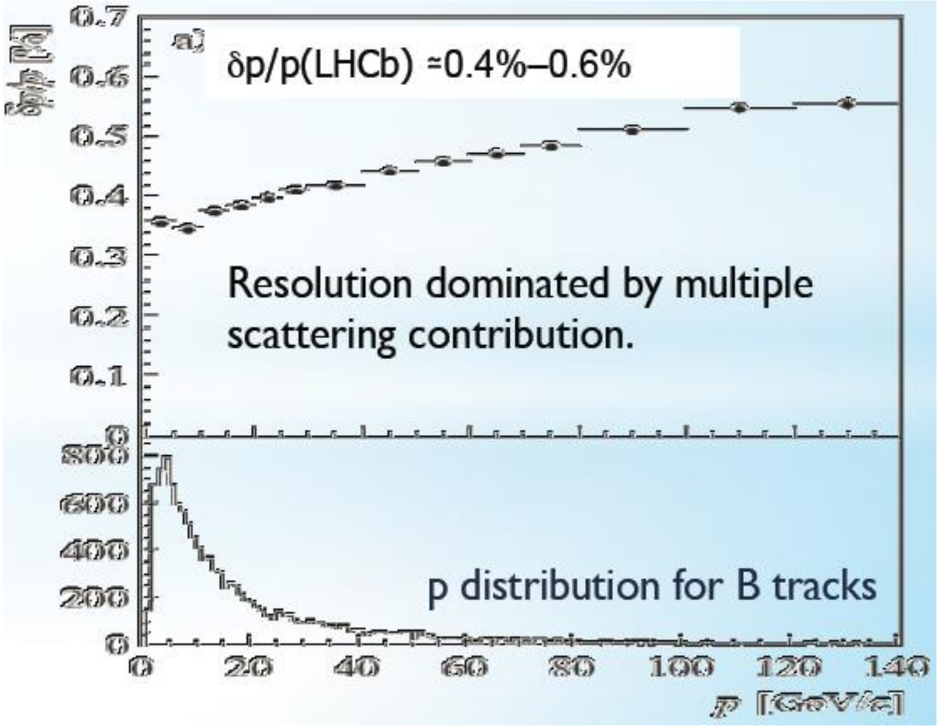
Key issues for B physics: *data statistics*





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

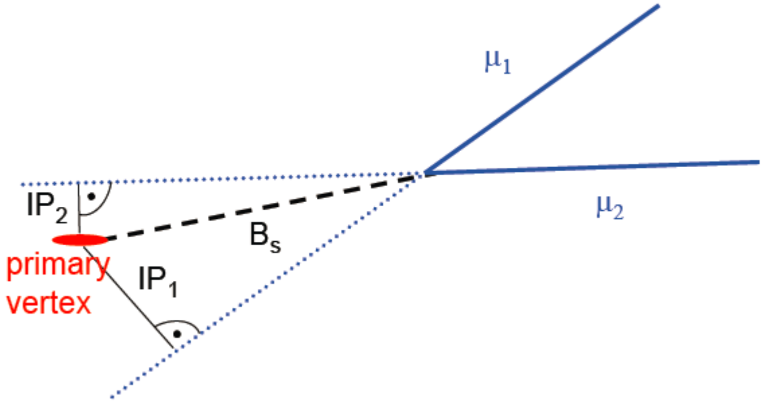
Key issues for B physics: *momentum and mass resolution*



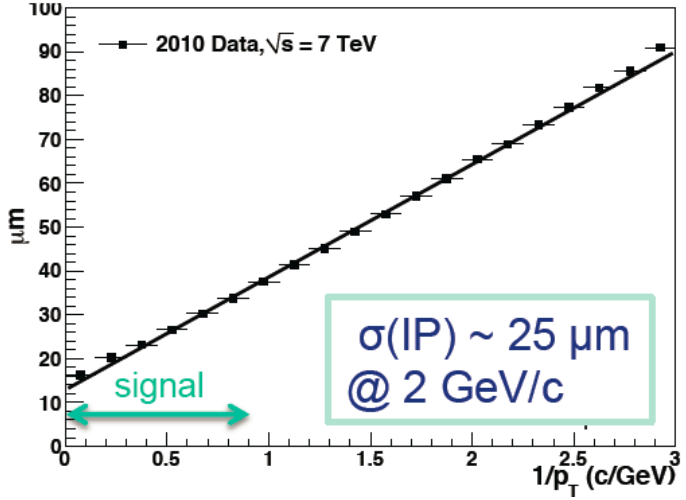
	momentum resolution	mass resolution J/ψ→μμ
LHCb	δp/p = 0.4-0.6 %	13 MeV
CMS	δpt/pt = 1-3 %	40 MeV
ATLAS	δpt/pt = 5-6 %	71 MeV

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

Impact parameter (IP):



IP resolution vs 1/pT

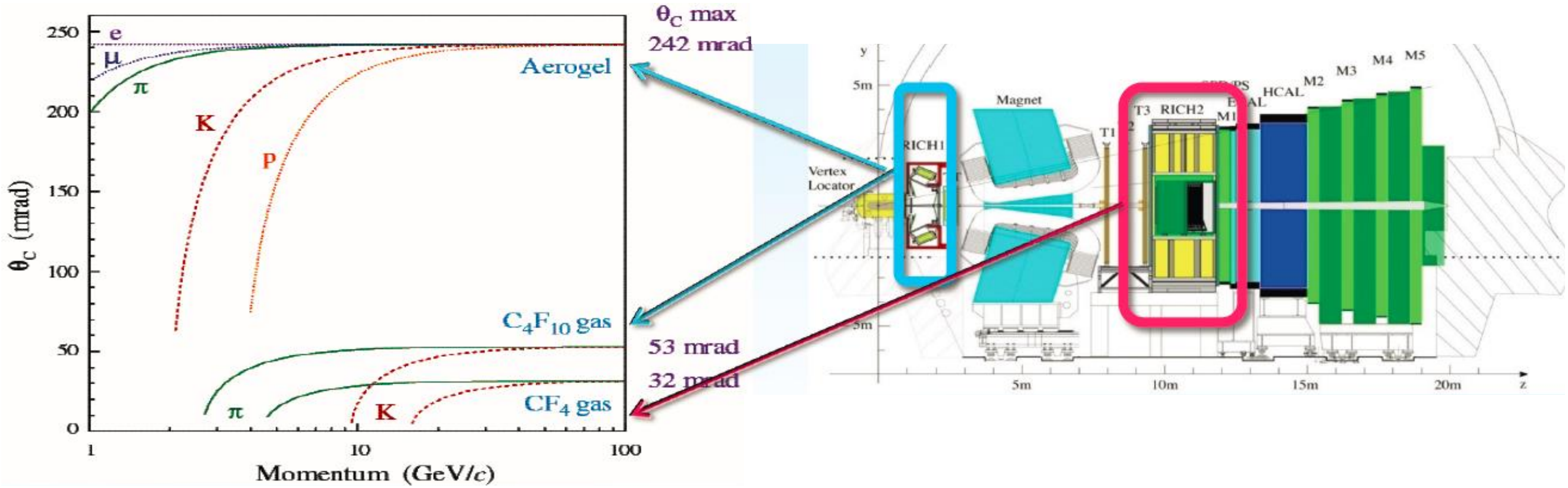


Primary vertex resolutions (25 tracks):

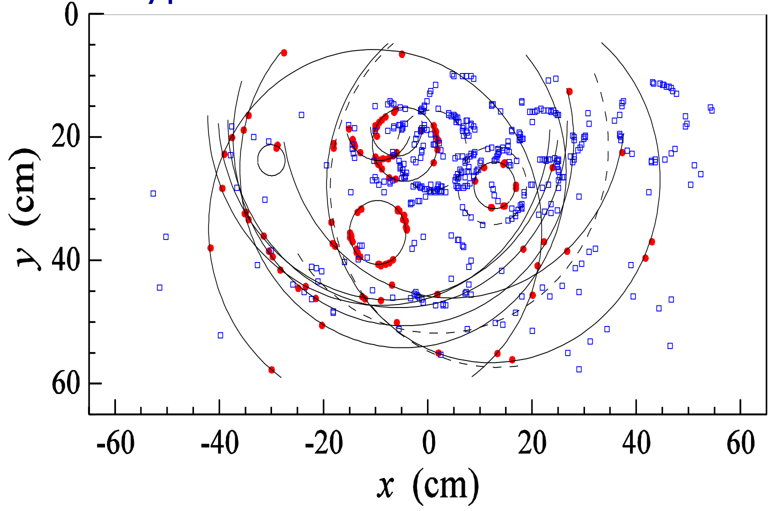
	LHCb [μm]	ATLAS [μm]	CMS [μm]
σ(x)	15.8	60	20-40
σ(y)	15.2	60	20-40
σ(z)	76	100	40-60

	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(aerogel) = 1.03

  → 2 - 10 GeV - slowest particles

  $n(C_4F_{10}) = 1.0014$

  → 10 - 60 GeV

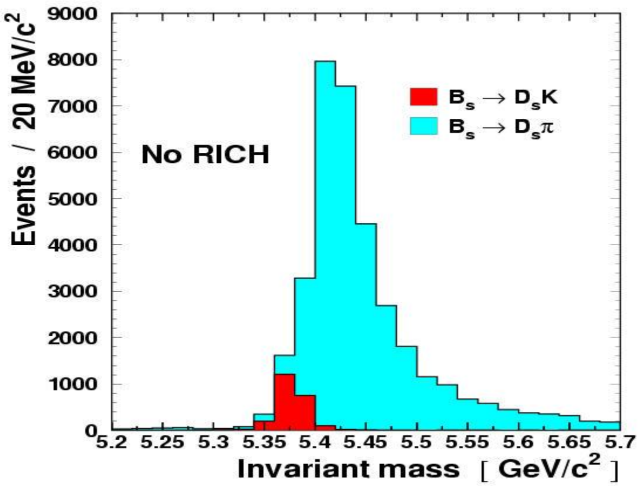
RICH2

- carbon tetrafluoride CF_4

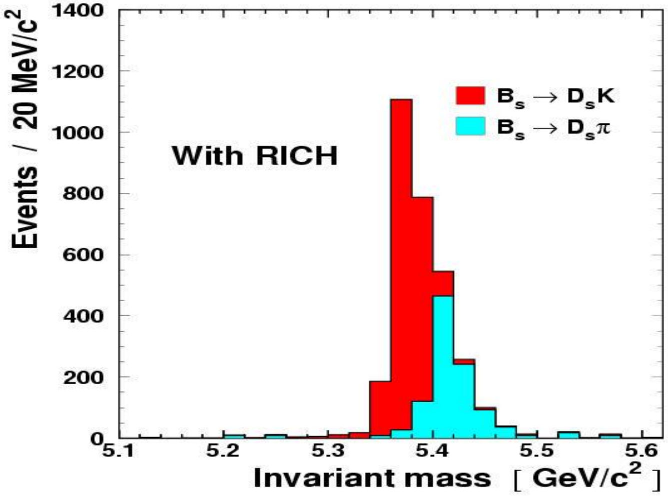
  $n(CF_4) = 1.0005$ → 16 - 100 GeV

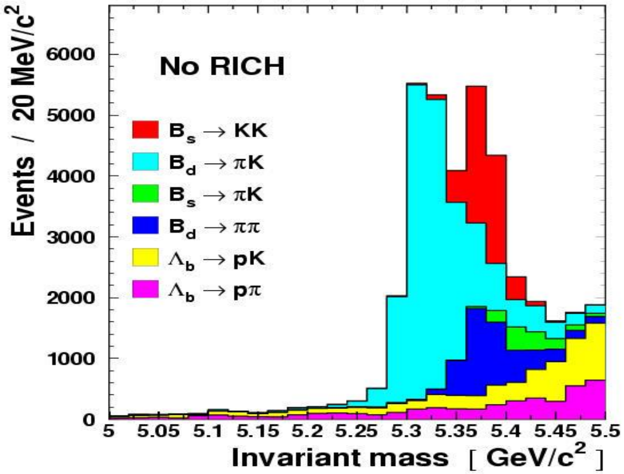
Key issues for B physics: *particle identification*

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

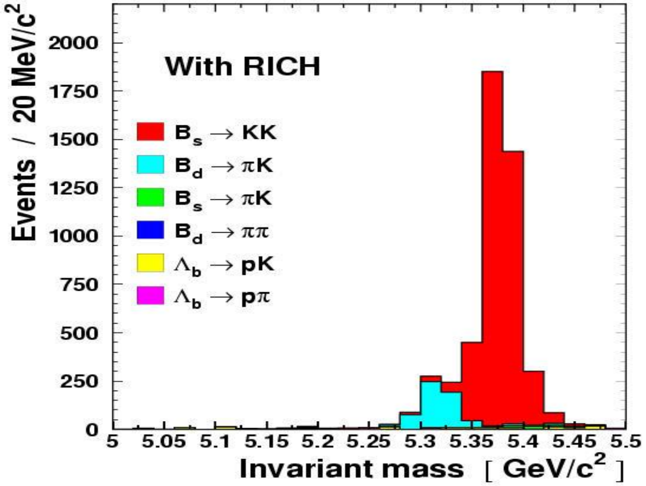


$B_s \to D_s K$





$B_s \to KK$



Key issues for B physics: *trigger system*

Challenge is

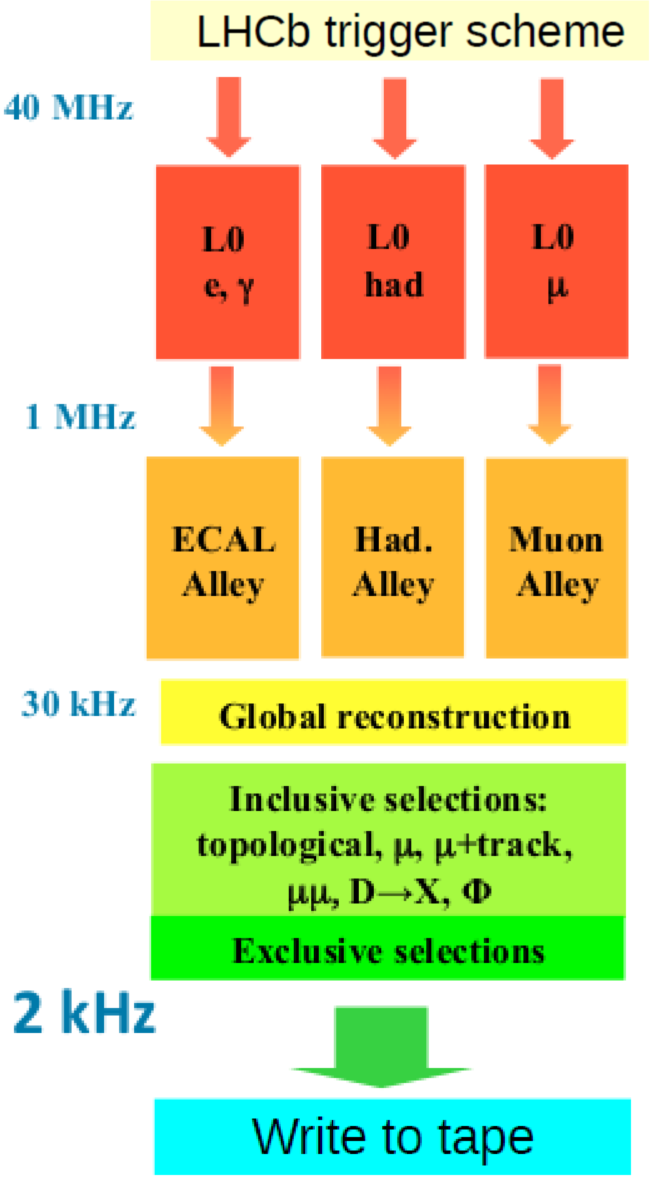
- to efficiently select most interesting B decays
- while maintaining manageable data rates

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

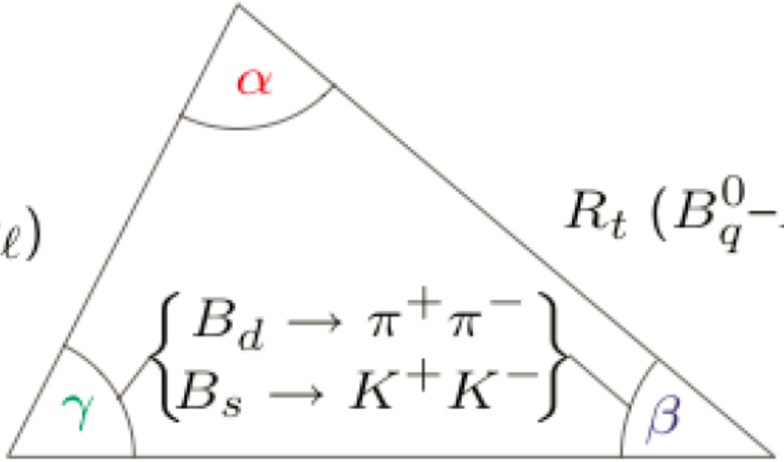
HLT1 – associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

CKM matrix and types of CP violation

Over-constraining the Unitarity Triangle

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



R_b $(b \to u, c\ell\bar{\nu}_\ell)$

R_t $(B_q^0\text{–}\bar{B}_q^0$ mixing)

$$\begin{Bmatrix} B_d \to \pi^+\pi^- \\ B_s \to K^+K^- \end{Bmatrix}$$

$B \to \pi K$ (penguins)

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

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

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

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

Phases and CP-Violation

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

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:

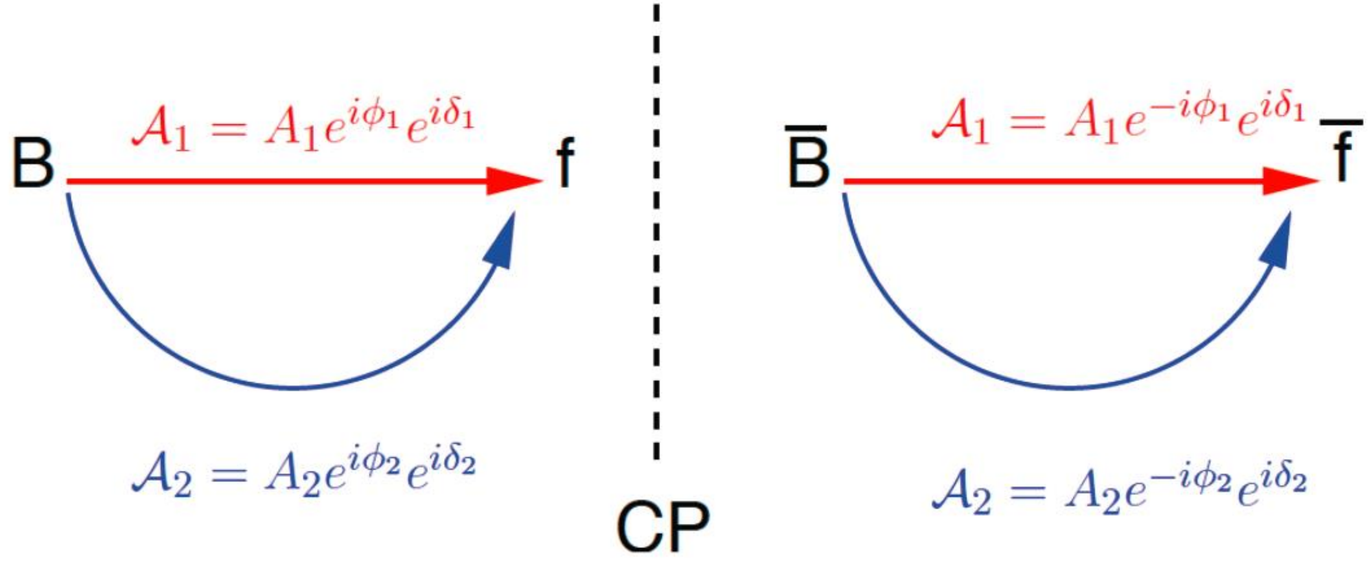
$$|\mathcal{A}_1 + \mathcal{A}_2|^2 = (\mathcal{A}_1 + \mathcal{A}_2)(\mathcal{A}_1^* + \mathcal{A}_2^*) = |\mathcal{A}_1^* + \mathcal{A}_2^*|^2$$

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

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



$$\mathcal{A}_1 = A_1 e^{i\phi_1} e^{i\delta_1}$$

$$\mathcal{A}_2 = A_2 e^{i\phi_2} e^{i\delta_2}$$

$$\mathcal{A}_1 = A_1 e^{-i\phi_1} e^{i\delta_1}$$

$$\mathcal{A}_2 = A_2 e^{-i\phi_2} e^{i\delta_2}$$

$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi - \Delta\delta)$$

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:

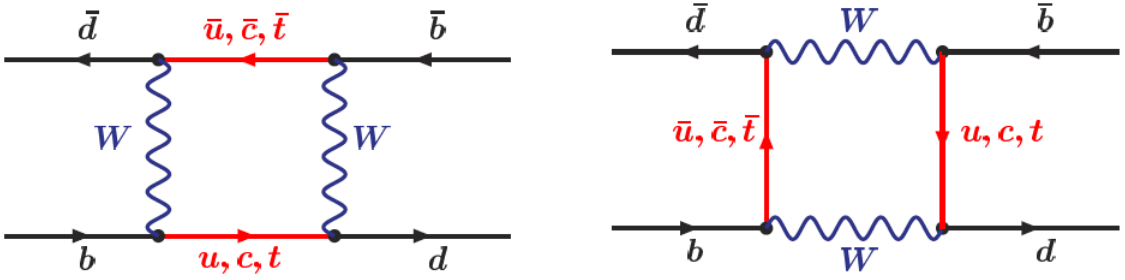
$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

$$\begin{tikzcd}
B^0 \arrow[dr, "A"] \arrow[dd, leftrightarrow, "\Delta m"'] & \\
 & f_{CP} \\
\bar{B}^0 \arrow[ur, "\bar{A}"'] &
\end{tikzcd}$$

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" ~sin(*Δmt*)

- CP asymmetries become time dependent:

$$\mathcal{A}_{CP}(t) = \frac{C\cos(\Delta m\, t) - S\sin(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + D\sinh(\Delta\Gamma\, t/2)}$$

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

- Two eigenstates:

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

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

direct CP violation → $C \neq 0$

CP violation in interference $S \neq 0$

3 types of CP-Violation: In decays

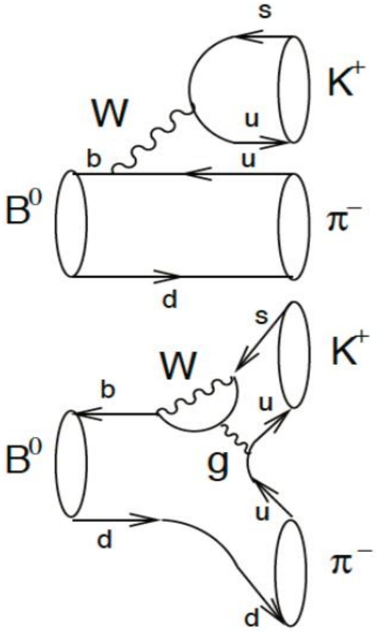
2) Direct CP violation condition: |A(bar) / A| ≠ 1

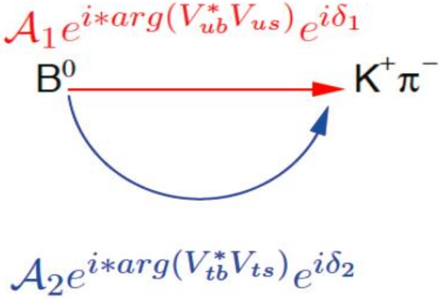
- need *A* and *A(bar)* to consist of (at least) two parts with different weak (φ) and strong (δ) phases
- often realised by „tree" and „penguin" diagrams

Example: *B* → *Kπ*
(weak phase difference is *γ*)

TREE

PENGUIN





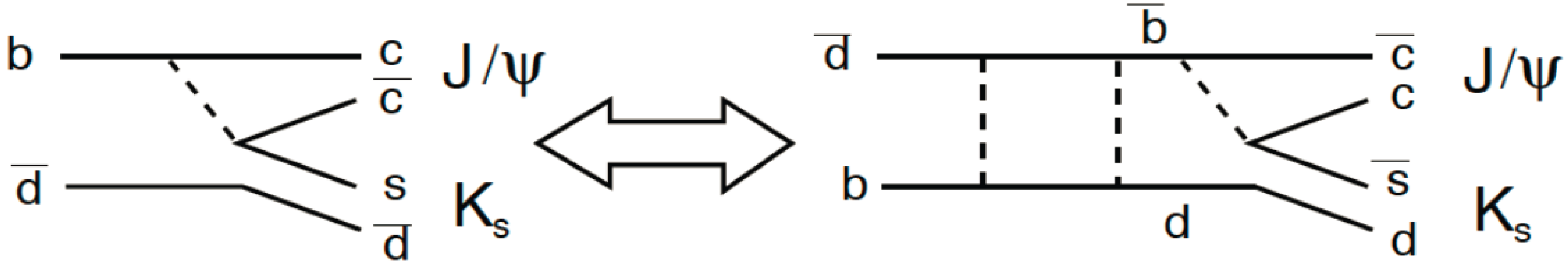
$$A = |T|e^{i(\delta_T-\phi_T)}+|P|e^{i(\delta_P-\phi_P)} \qquad \overline{A} = |T|e^{i(\delta_T+\phi_T)}+|P|e^{i(\delta_P+\phi_P)}$$

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

3 types of CP-Violation: In interference

3) CP violation in interference between mixing and decay

Same final state through decay & mixing + decay



$$\begin{aligned}
\mathcal{A}_1 &= \mathcal{A}_{mix}(B^0 \to B^0) * \mathcal{A}_{decay}(B^0 \to J/\Psi K_s) \\
&= \cos(\frac{\Delta m t}{2}) * A * e^{i\omega} \\
\mathcal{A}_2 &= \mathcal{A}_{mix}(B^0 \to \bar{B}^0) * \mathcal{A}_{decay}(\bar{B}^0 \to J/\Psi K_s) \\
&= i \sin(\frac{\Delta m t}{2}) * e^{+i\phi} * A * e^{-i\omega}
\end{aligned}$$

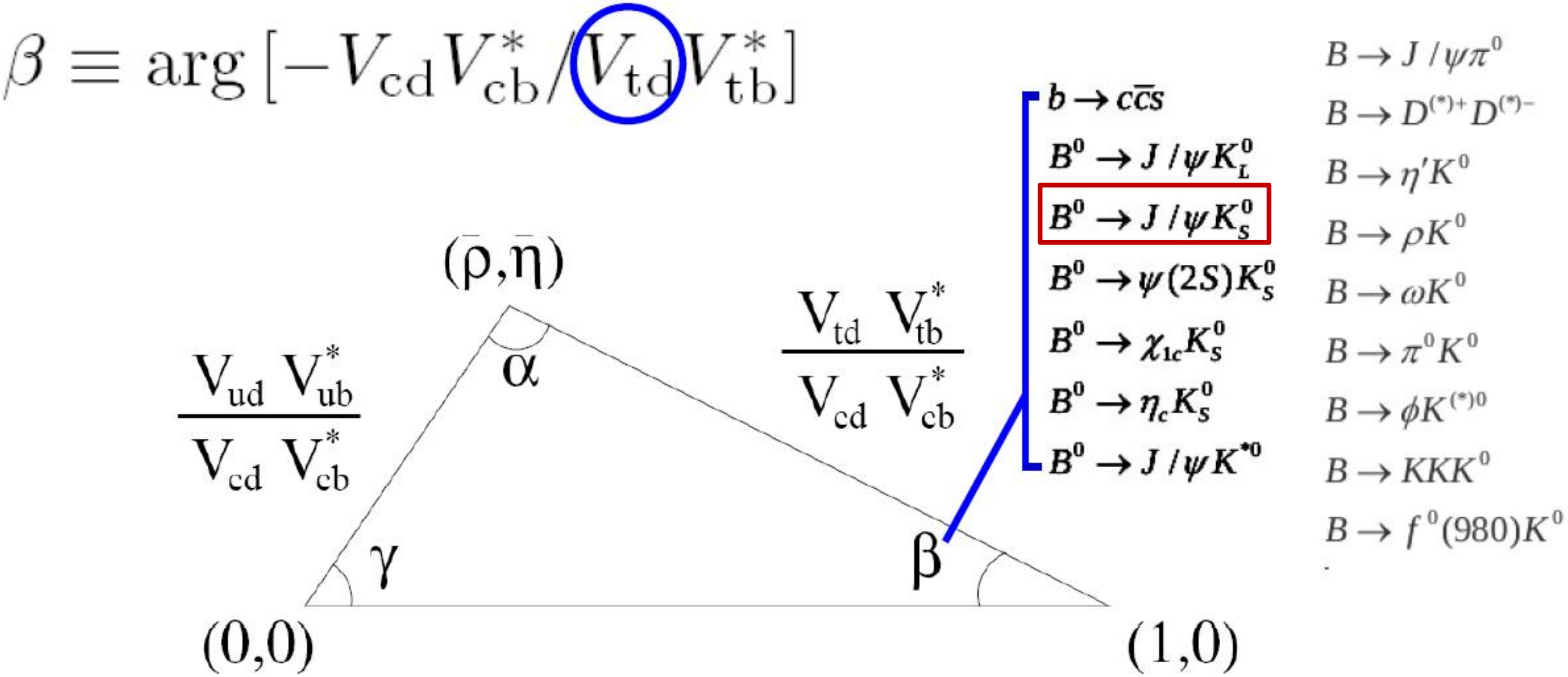
$\Delta\phi = \phi - 2\omega$ (assume no CP violation in mixing and in decay)

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

Measurements of CKM angles

1st CKM measurement: sin(2*β*)

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



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

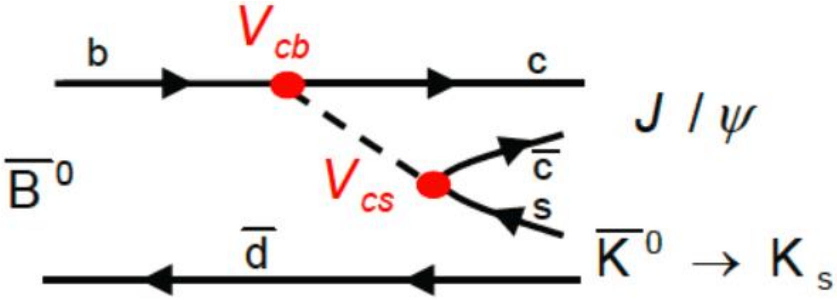
$b \to c\bar{c}s$
$B^0 \to J/\psi K_L^0$
$B^0 \to J/\psi K_S^0$
$B^0 \to \psi(2S)K_S^0$
$B^0 \to \chi_{1c}K_S^0$
$B^0 \to \eta_c K_S^0$
$B^0 \to J/\psi K^{*0}$

$B \to J/\psi\pi^0$
$B \to D^{(*)+}D^{(*)-}$
$B \to \eta' K^0$
$B \to \rho K^0$
$B \to \omega K^0$
$B \to \pi^0 K^0$
$B \to \phi K^{(*)0}$
$B \to KKK^0$
$B \to f^0(980)K^0$

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

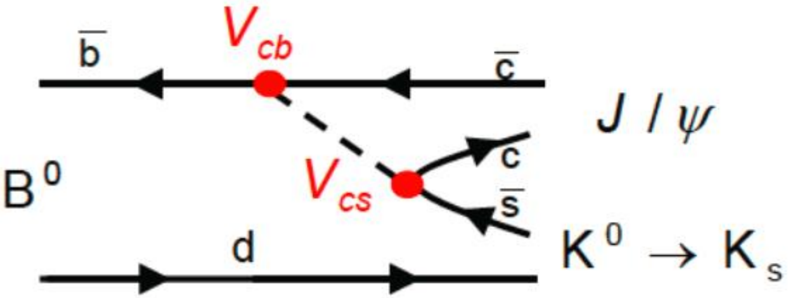
$\boxed{B^0 \to J/\psi\ K_s} \xrightarrow{CP} \boxed{\bar{B}^0 \to J/\psi\ K_s}$

- Leading-order tree decays to cc(bar)s final states



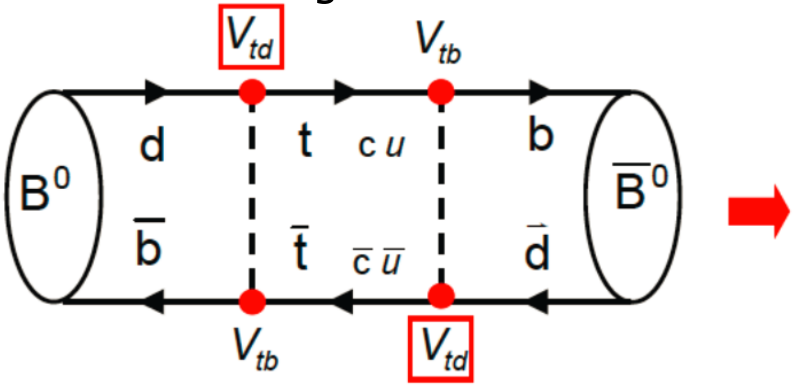
→ here the CKM elements contributing are $V_{cb}V^*_{cs}$ that in Wolfenstein CKM parametrisation have no phase

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



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

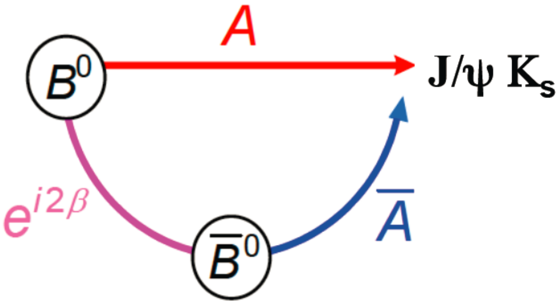
- Because both *B* and *B(bar)* can decay to this common final state, this can interfere with the oscillation diagram:



Mixing Phase:

$e^{i\phi_d} = e^{i2\beta}$

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



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

→ requires knowledge of production flavour of the *B*

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

The colour-suppressed tree dominates

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

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

- $|A(bar)| = |A| \Rightarrow$ no direct CP violation
- C = 0 & S = $-\eta_{CP}$ sin(2β)

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

- reasonable branching fraction & experimentally clean signature

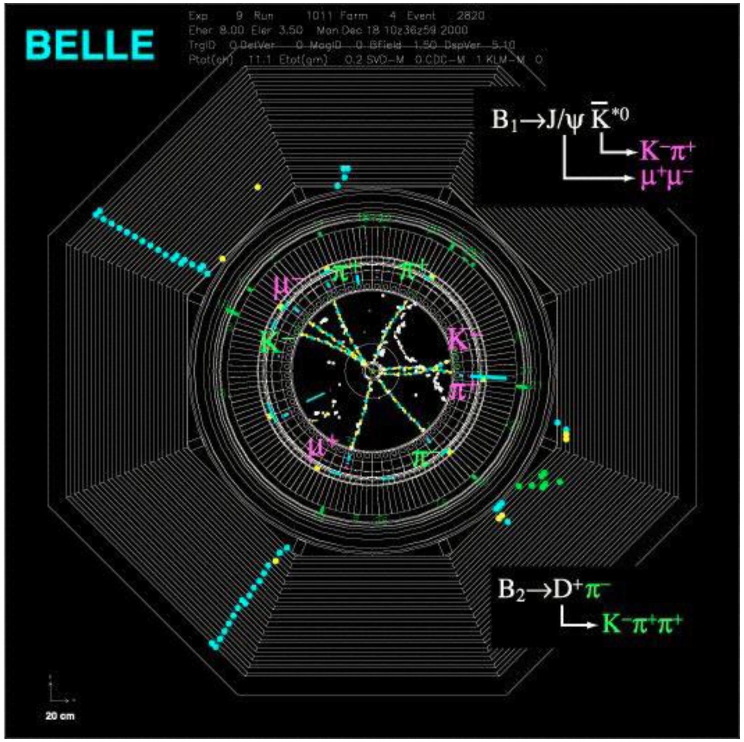
How can we measure decay time in $e^+e^- \to Y(4S) \to B^0B^0(bar)$?

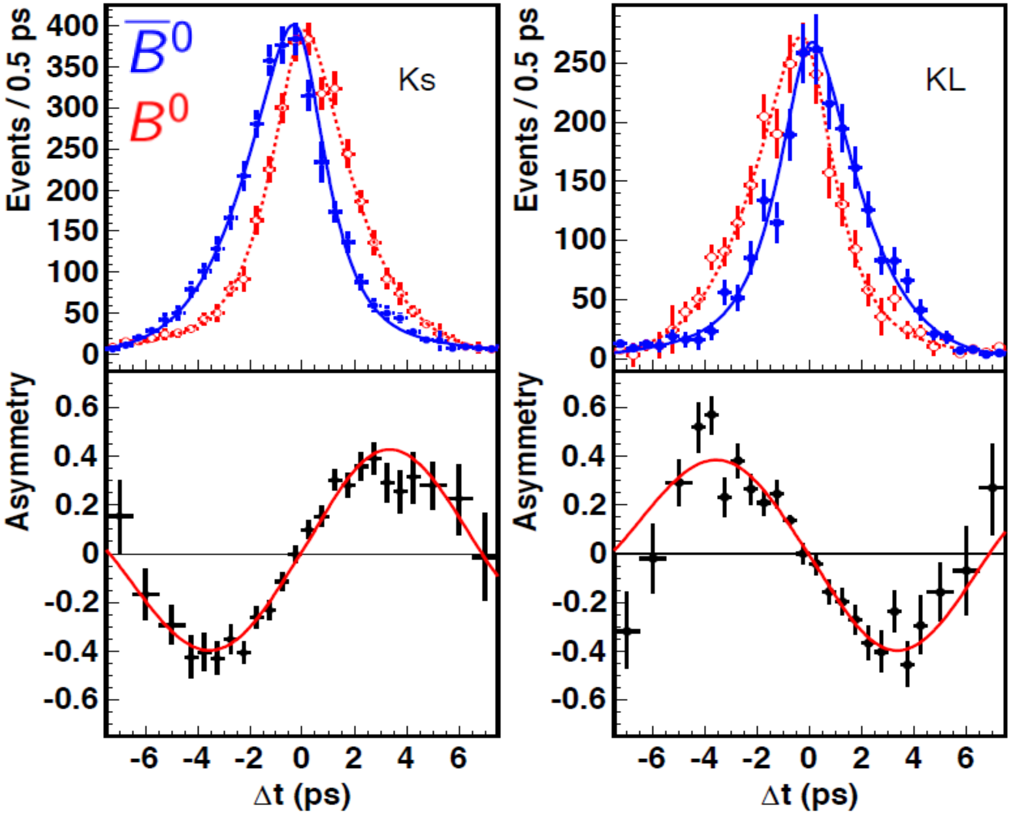
- the answer: asymmetric-energy B factory (e.g. Belle)
- key points

→ $Y(4S) \to B^0B^0(bar)$ produces coherent pairs

→ B mesons are moving in LAB frame

sin(*2β*): Belle measurement

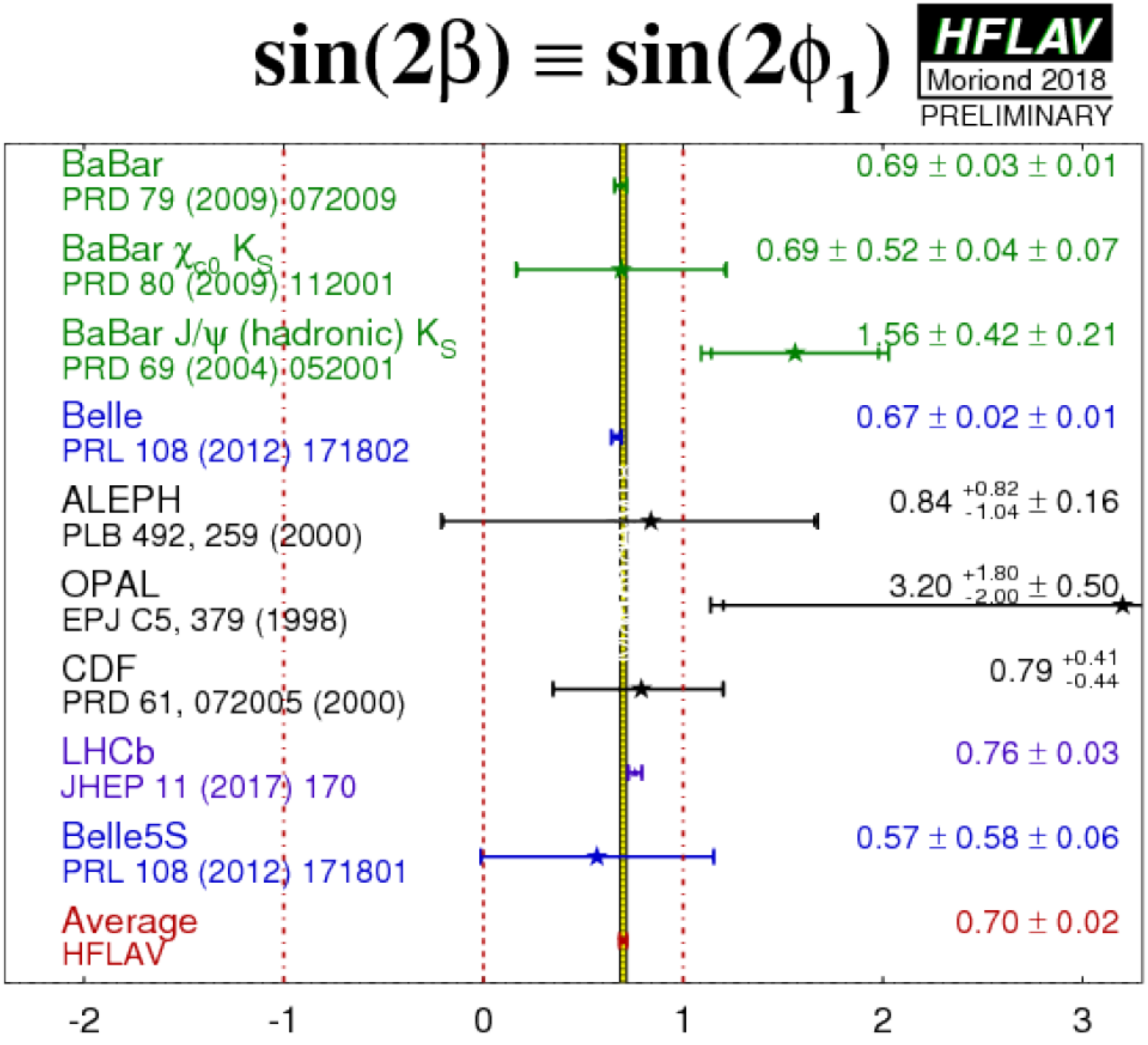




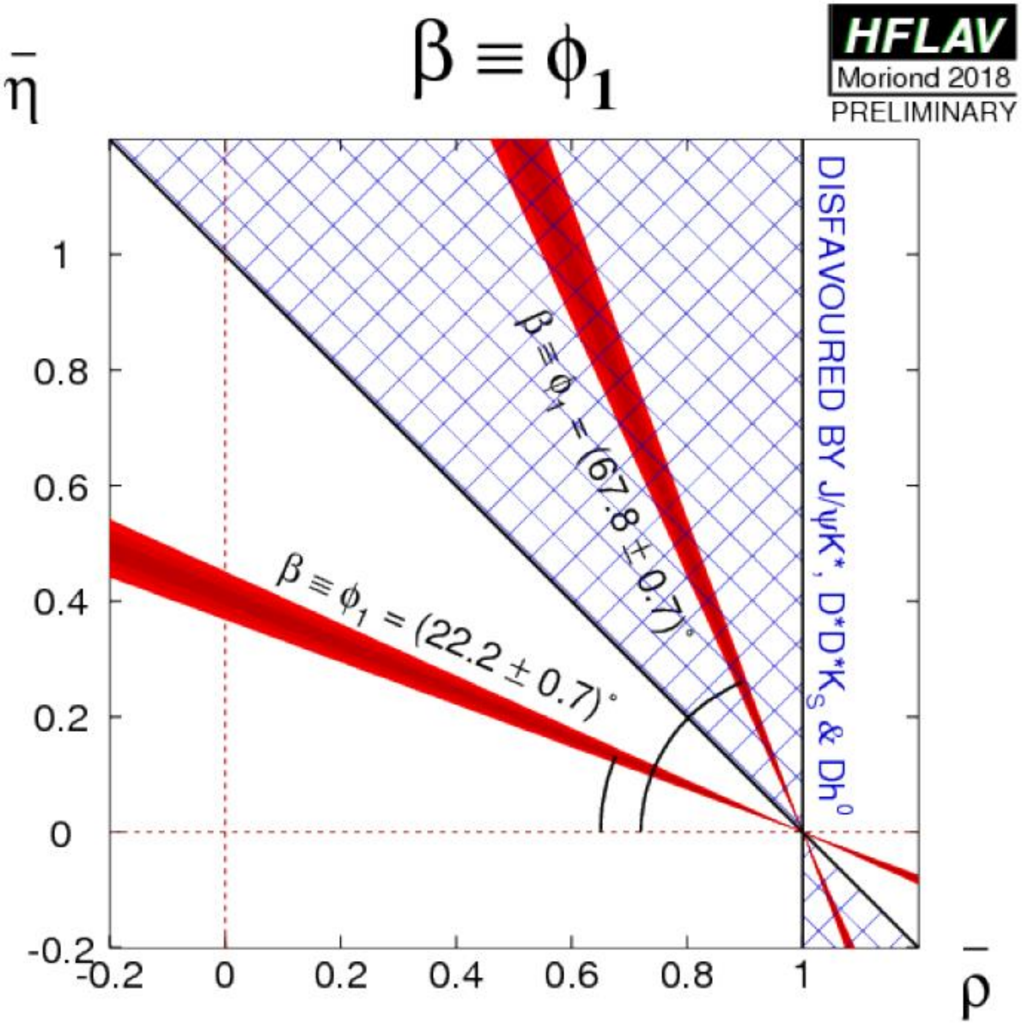
What do we have to do to measure $A_{CP}(t)$?

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

sin(*2β*): Compilation of results



sin(2β): Compilation of results



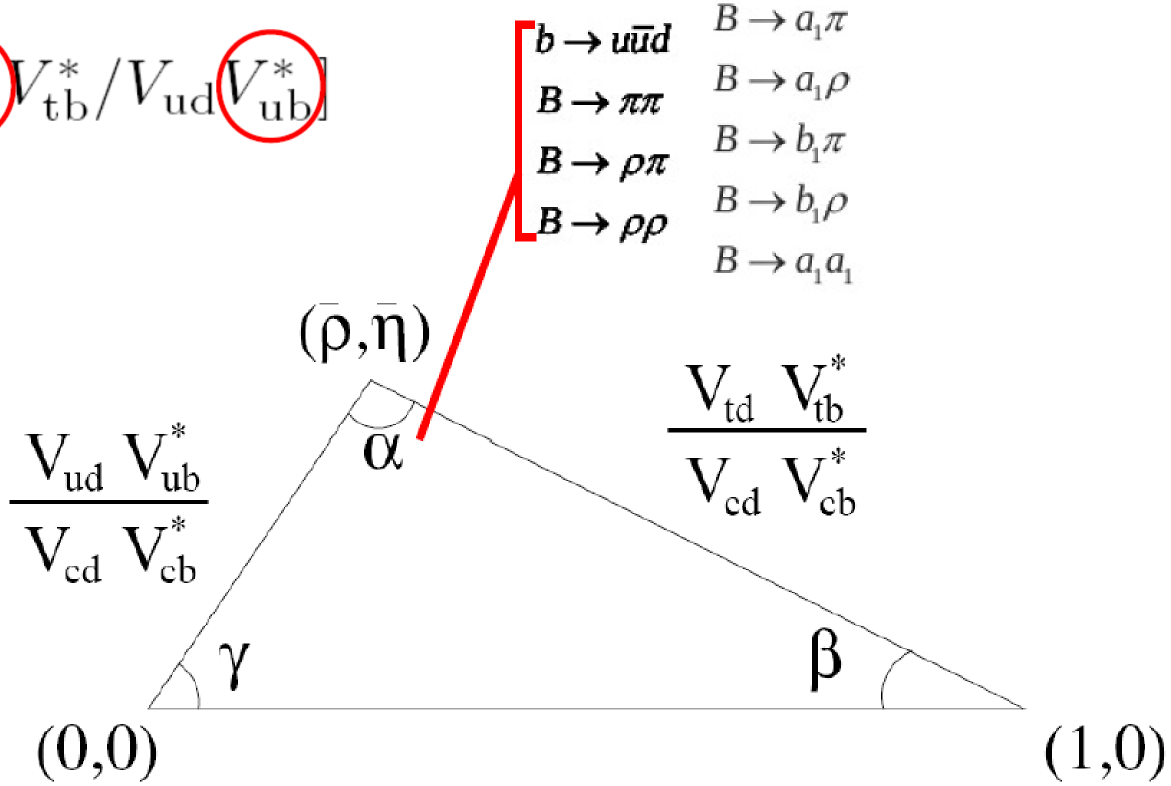
$\boldsymbol{\beta}$ **= (22.2 ± 0.7)°**

2nd CKM measurement: α angle

b → uu(bar)d transitions with possible loop contributions. Extract α using:

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

$$\alpha \equiv \arg\left[-V_{\mathrm{td}}V^*_{\mathrm{tb}}/V_{\mathrm{ud}}V^*_{\mathrm{ub}}\right]$$



$b \to u\bar{u}d$

$B \to \pi\pi$

$B \to \rho\pi$

$B \to \rho\rho$

$B \to a_1\pi$

$B \to a_1\rho$

$B \to b_1\pi$

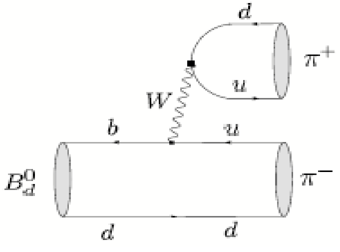
$B \to b_1\rho$

$B \to a_1 a_1$

Measurement of α

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

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

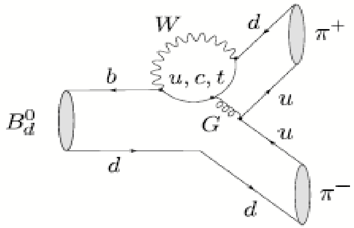


- $b \to du(bar)u$ penguin transitions contribute to same final states

  $\to$ „penguin pollution”

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

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



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)

  $\to$ try to use modes with small penguin contribution

  $\to$ correct for penguin effect (isospin analysis)

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

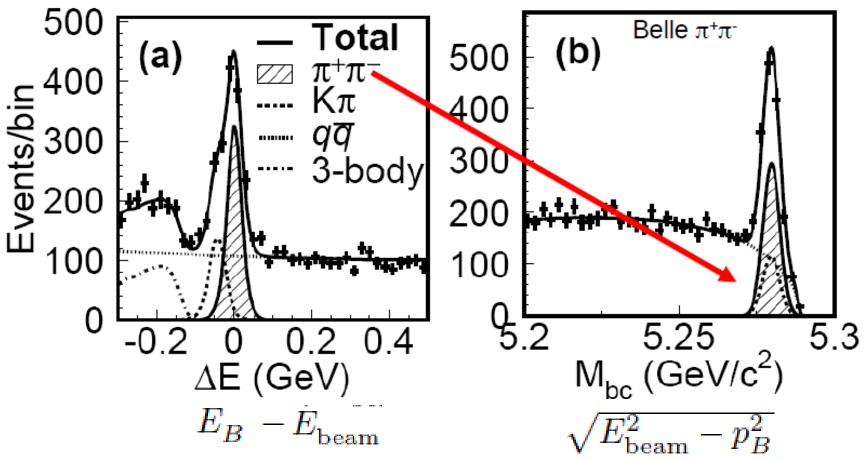
$$S_{hh} = \sqrt{1 - C_{hh}^2}\,\sin(2\alpha_{\text{eff}})$$

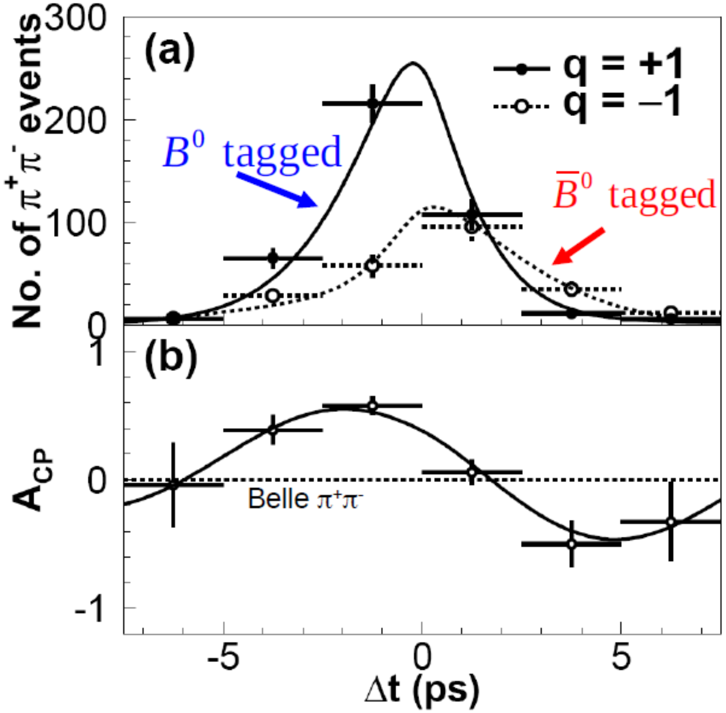
$$\delta = \delta_P - \delta_T$$

Measurement of α: $B^0 \to \pi\pi$

$B^0 \to \pi\pi$

- easy to isolate signal for $\pi^+\pi^-$ and $\pi^+\pi^0$ as these modes are relatively clean and have relatively large BR ~ $O(5\times10^{-6})$





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

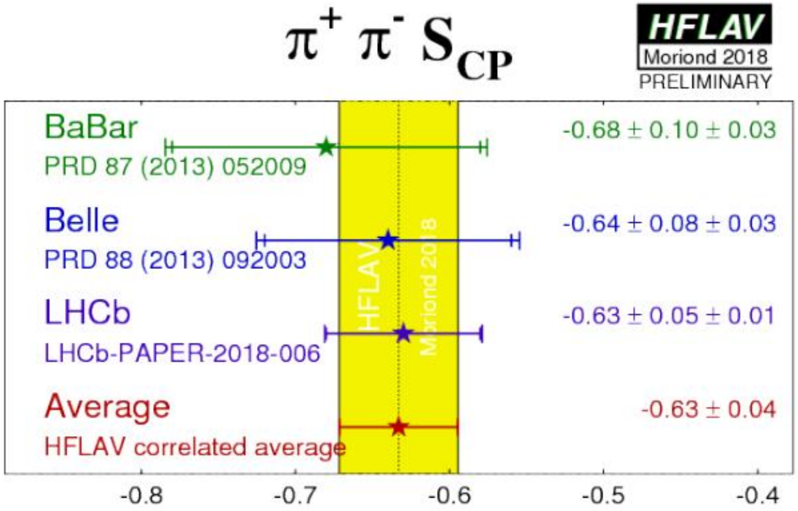
→ BR ~ 1.5×10^{-6}

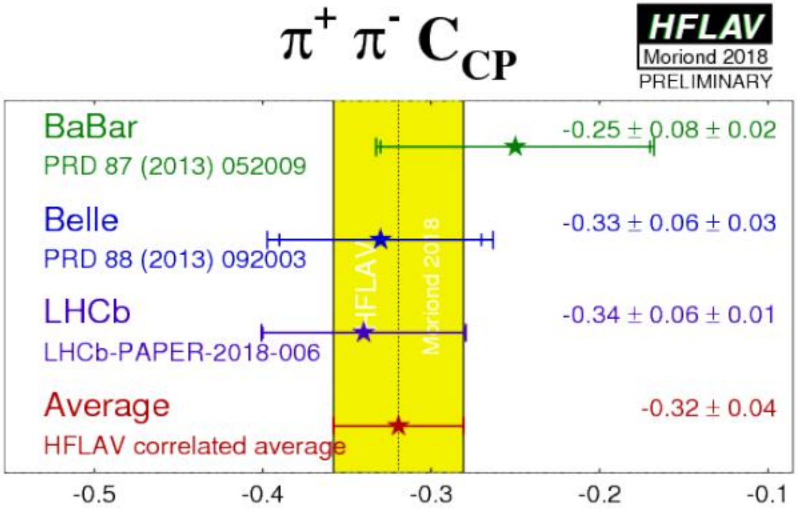
→ no tracks in the final state to provide vertex info

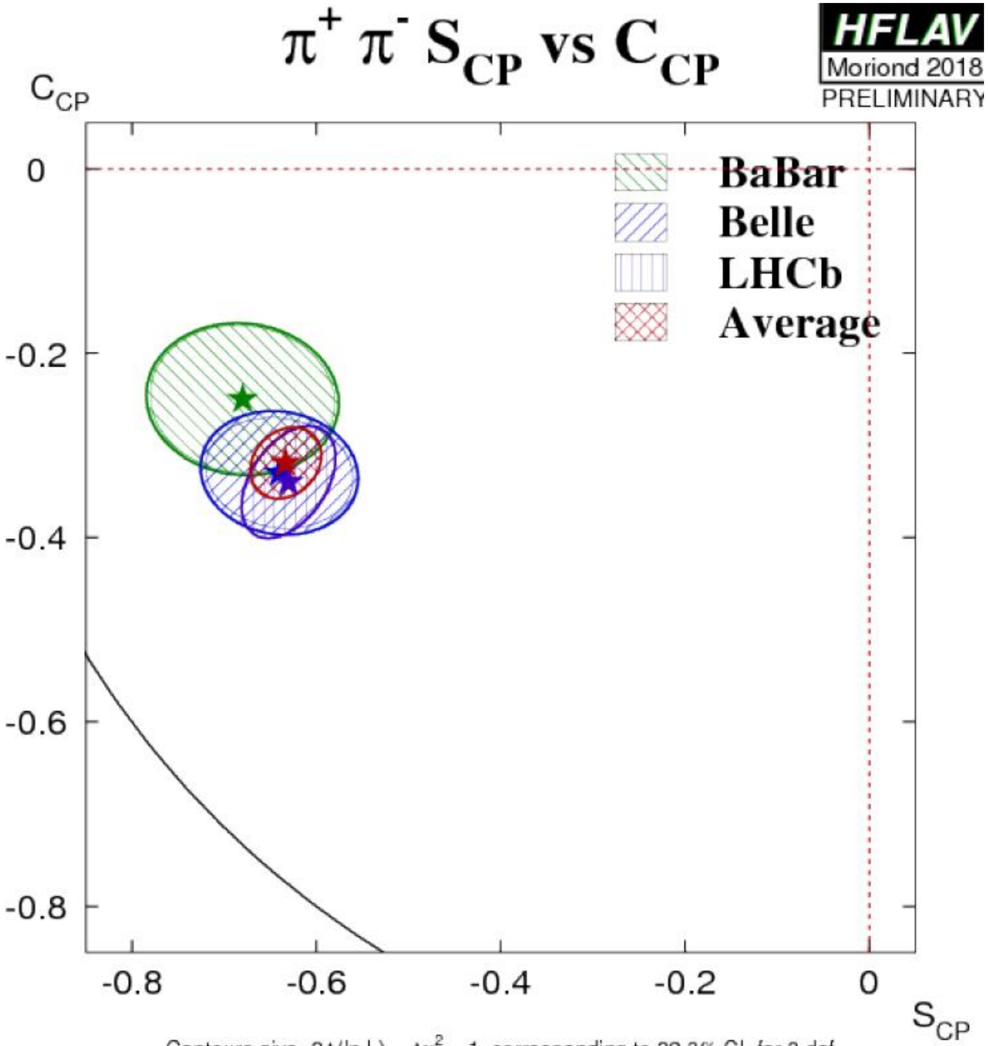
→ $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ has a large ΔE resolution

- possible to separate flavour tags to measure C
- this completes set of information required for an isospin analysis

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







Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 39.3% CL for 2 dof

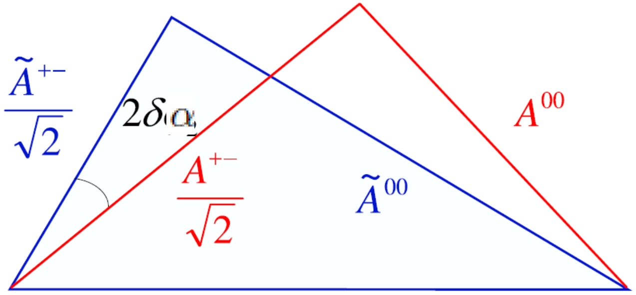
Measurement of α: *Isospin analysis*

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

$\delta\alpha = \alpha_{eff} - \alpha$

$$\widetilde{A} = e^{i2\gamma}\bar{A}$$

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



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

- $B \to \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ decays are connected by isospin relations

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

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

- $\pi\pi$ states can have I = 2 or I = 0

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

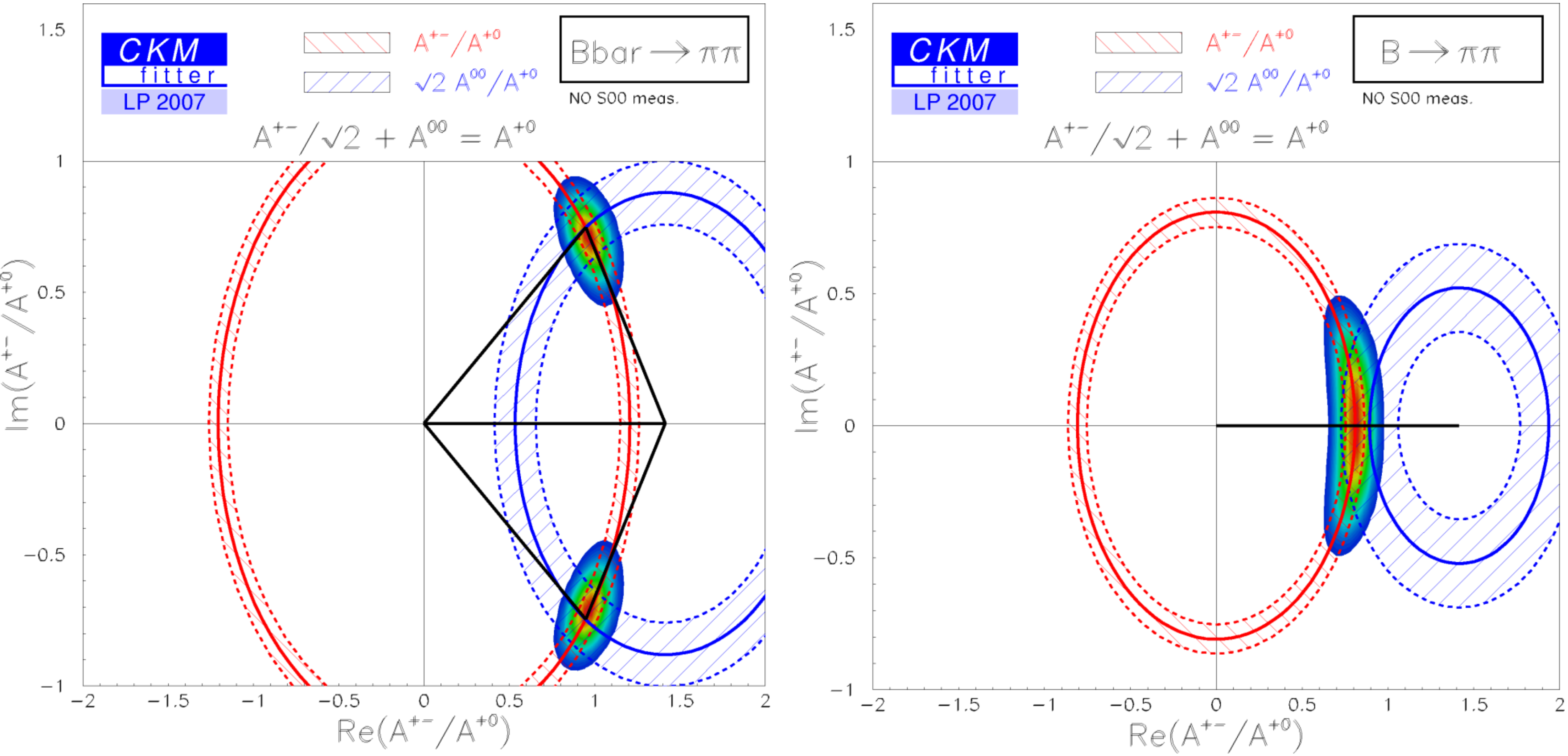
→ $\pi^+\pi^0$ is a pure I = 2 state (ΔI = 3/2) and it gets contribution only from the tree diagram

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

Both BR(B^0) and BR(B^0(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 (~5%), but these are much smaller than current experimental accuracy and eventually they can be incorporated into the isospin analysis



Measurement of α: $B^0 \to \rho\rho$

- vector-vector modes: angular analysis reaquired to determine the CP content

  L=0,1,2 partial waves:

  → longitudinal: CP-even state

  → transverse: mixed CP states

- isospin analysis:

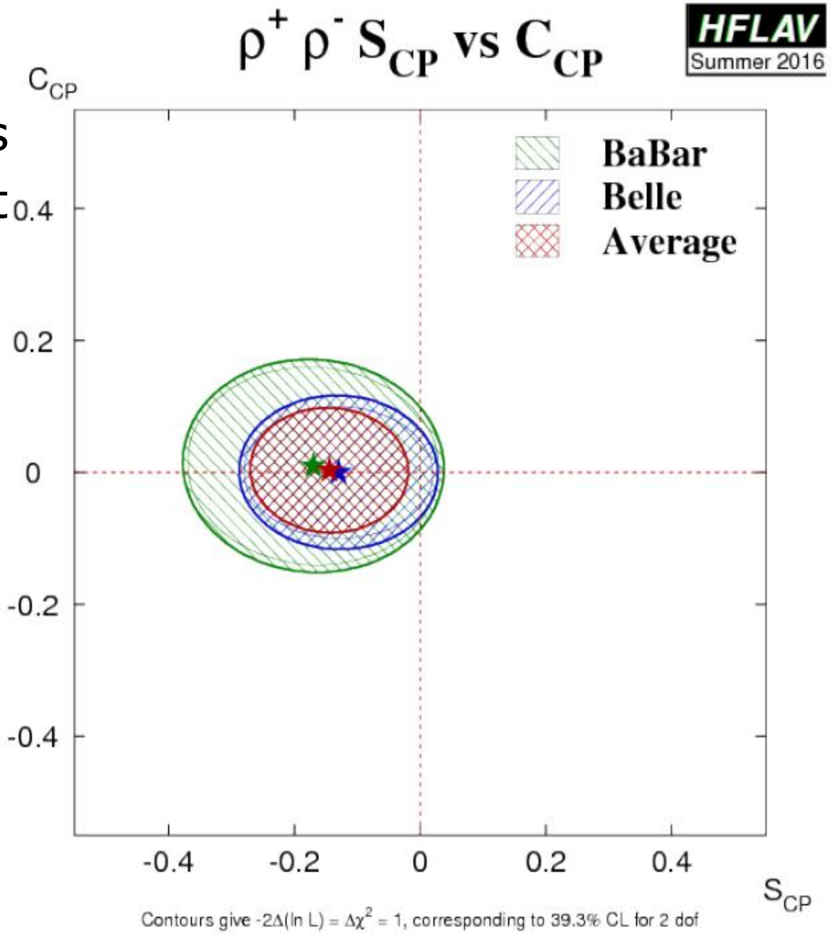
  → possible contribution from $\rho^0\rho^0$

- 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

α = (93.3 ± 5.6)°