Heavy flavour physics

Lecture 2

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IFJ PAN, Kraków
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Contents

Lecture 2

- Flavour sector beyond the SM
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- CKM matrix and types of CP violation
- Measurements of CKM angles β and α

Flavour sector beyond the SM

Yukawa mechanism in the lepton sector

- in the SM the lepton Yukawa matrices can be diagonalized independently due to the global G_l symmetry of the Lagrangian, and therefore there are no FCNC

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i D_R^j H + Y_u^{ij}\bar{Q}_L^i U_R^j H_c + Y_e^{ij}\bar{L}_L^i E_R^j H + \text{h.c.}$$

$$\mathcal{G}_q = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}, \qquad \mathcal{G}_\ell = SU(3)_{L_L} \otimes SU(3)_{E_R}$$

- however, the discovery that neutrinos oscillate (and are massive) implies that Lepton Flavour is not conserved

- the level of neutral Lepton Flavour Violation depends on the mechanism to generate neutrino masses (for instance **seesaw mechanism**)

- it could be just a copy of the quark sector, but it may be different due to the properties of the right-handed neutrino

Seesaw mechanism

Simplification: one family: ν_L and ν_R

- total mass term: Dirac and Majorana mass

$$\mathcal{L}_{mass} = -m(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) - \frac{1}{2} M(\nu_R^T C \nu_R + \bar{\nu}_R C \bar{\nu}_R^T)$$

- diagonalization of the mass matrix:

  → Majorana mass eigenstates of the neutrinos

  for $M >> m$ we get

$$m_1 \approx \frac{m^2}{M} \quad m_2 \approx M$$

- one very heavy, practically right handed neutrino
- one very light, practically left handed neutrino

At energies small compared to M, Majorana mass term for left handed neutrino:

$$\mathcal{L}_{mass} = -\frac{1}{2}\frac{m^2}{M}\left(\nu_L^T C \nu_L + \bar{\nu}_L C \bar{\nu}_L{}^T\right)$$

Majorana mass is small if $M >> m$

Seesaw mechanism

- In case of three families: **Neutrino Mixing**
- Compact notation for the Leptons:

$$\mathcal{N}_{L/R} = \begin{bmatrix} \nu_{e,L/R} \\ \nu_{\mu,L/R} \\ \nu_{\tau,L/R} \end{bmatrix} \qquad \mathcal{E}_{L/R} = \begin{bmatrix} e_{L/R} \\ \mu_{L/R} \\ \tau_{L/R} \end{bmatrix}$$

- Dirac masses are generated by the Higgs mechanism: (as for the quarks)

$$\mathcal{L}^{N}_{DM} = -\mathcal{N}_L m^N \mathcal{N}_R + h.c. \qquad \mathcal{L}^{E}_{DM} = -\mathcal{E}_L m^E \mathcal{E}_R + h.c.$$

- m^N: Dirac mass matrix for the neutrinos, m^E: (Dirac) mass matrix for e, μ, τ

- Right handed neutrinos → Majorana mass term:

$$\mathcal{L}_{MM} = -\frac{1}{2}\left(N_R^T M C N_R + \bar{N}_R M C \bar{N}_R^T\right)$$

- M: (symmetric) **Majorana Mass Matrix**
- this term is perfectly $SU(2)_L \otimes U(1)$ invariant

Implementation of the seesaw mechanism:

- assume that all eigenvalues of M are large

Effective theory at low energies → *only light, practically left handed neutrinos*

- effect of right handed neutrino: Majorana mass term for the light neutrinos

$$\mathcal{L}_{mass} = -\frac{1}{2}\left(N_L^T m^T M^{-1} m C N_L + \bar{N}_L m^T M^{-1} m C \bar{N}_L^T\right)$$

Lepton mixing: PMNS matrix

- we know there are FCNC in the lepton sector (analogous to the quark sector) because we have observed neutrino oscillations
- therefore the Yukawa couplings in lepton sector do contain also a mixing matrix

Pontecorvo Maki Nakagawa Sakata Matrix

- almost like CKM: Three Euler angles θ_{ij}

$$U_{12} = \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad U_{13} = \begin{bmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{bmatrix}, \quad U_{23} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}$$

- a Dirac phase δ and two Majorana phases α_1 and α_2

$$U_\delta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta_{13}} \end{bmatrix} \quad U_\alpha = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1} & 0 \\ 0 & 0 & e^{-i\alpha_2} \end{bmatrix}$$

- PNMS parametrization: $V_{\mathrm{PMNS}} = U_{23} U_\delta^\dagger U_{13} U_\delta U_{12} U_\alpha$
- V_{PMNS} is unitary like the CKM matrix
- left handed neutrinos are Majorana
  $\rightarrow$ *no freedom to rephase these fields!*

$$\theta_{12}[^\circ] = 33.36^{+0.81}_{-0.78}$$
$$\theta_{23}[^\circ] = 40.0^{+2.1}_{-1.5} \text{ or } 50.4^{+1.3}_{-1.3}$$
$$\theta_{13}[^\circ] = 8.66^{+0.44}_{-0.46}$$
$$\delta_{\mathrm{CP}}[^\circ] = 300^{+66}_{-138}$$

No hierarchy observed!

Lepton mixing: PMNS matrix

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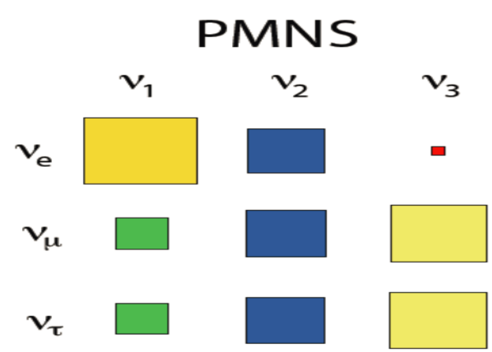


No hierarchy observed!

Lepton Flavour Violation

FCNC processes in the leptonic sector:

$$\tau \to \mu\gamma \quad \mu \to e\gamma \quad \tau \to eee \text{ etc.}$$

$$\nu_\tau \to \nu_e\gamma \quad \nu_\tau - \nu_e \text{ mixing}$$

Lepton Flavour Violation:

- right handed neutrinos are Majorana fermions:
  - → no conserved quantum number corresponding to the rephasing of the right handed neutrino fields
- lepton flavour violation could feed via conserved B-L into baryon number violation
- if neutrinos are **Dirac particles**, expect **very small** (far from experimental sens.) **LFV**
- however, if neutrinos are **Majorana particles** and something like the **seesaw mechanism** is at work, **large values** (close to exp. sens.) are favoured
- in general, **any extension of the SM with new states at the TeV scale generates large charged LFV**

Many flavour related open questions

- Our understanding of Flavour is unsatisfactory:
  - $\rightarrow$ 22 (out of 27) free parameters of the SM originate from the Yukawa Sector (including Lepton Mixing)
  - $\rightarrow$ Why is the CKM Matrix hierarchical?
  - $\rightarrow$ Why is CKM so different from the PMNS?
  - $\rightarrow$ Why are quark masses (except top) so small compared with electroweak VEV?
  - $\rightarrow$ Why do we have three families?
- Why is CP Violation in flavour-diagonal processes not observed? (e.g. electric dipol moments of electron and neutron)
- Where is the CP violation needed to explain the matter-antimatter asymmetry of the Universe?

Strong CP remains mysterious

- flavour diagonal CP Violation is well hidden

$\rightarrow$ e.g electric dipole moment of the neutron:

$$
\begin{aligned}
d_e &\sim e\,\frac{\alpha_s}{\pi}\,\frac{G_F^2}{(16\pi^2)^2}\,\frac{m_t^2}{M_W^2}\,\mathrm{Im}\Delta\,\mu^3 \\
&\sim 10^{-32}\,e\,cm \quad \text{with } \mu \sim 0.3\,\mathrm{GeV} \\
d_{\mathrm{exp}} &\leq 3.0\times 10^{-26}\,e\,cm
\end{aligned}
$$

Many open questions

Standard Model

- does **not describe neutrino masses**
- does not have **a good DM candidate**
- **cannot explain the baryon asymmetry** in the Universe
- no explanation for the **flavour structure**
- does **not include gravity**
- suffers from **fine tuning issues in the Higgs sector**

Possible extensions

- SUSY, extra dimensions, hidden sectors, …..
- in general, the diagonalization of the mass matrix will not give diagonal Yukawa couplings $\rightarrow$ **large FCNC**

Needed

- precision measurements of flavour observables are generically sensitive to additions to the Standard Model
- precise measurements of the Higgs boson properties
- precise measurements of FCNC

Experimental facilities

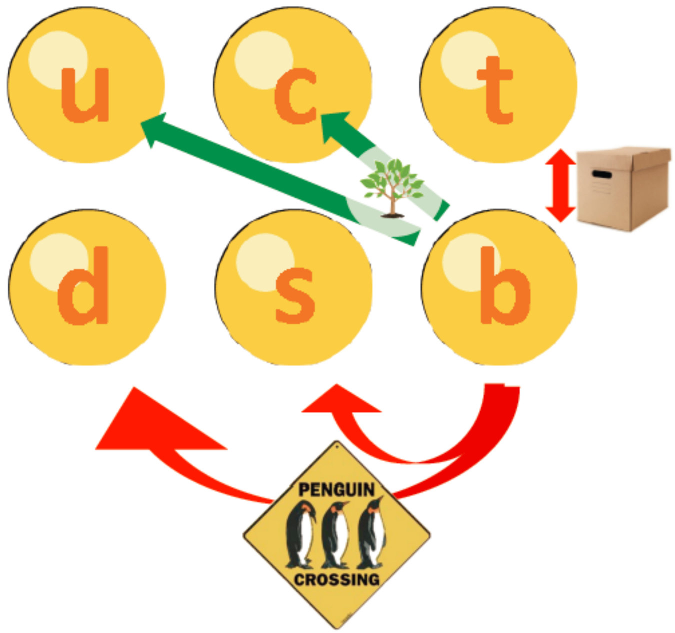
Heavy flavour physics

- 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

    $\rightarrow$ *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

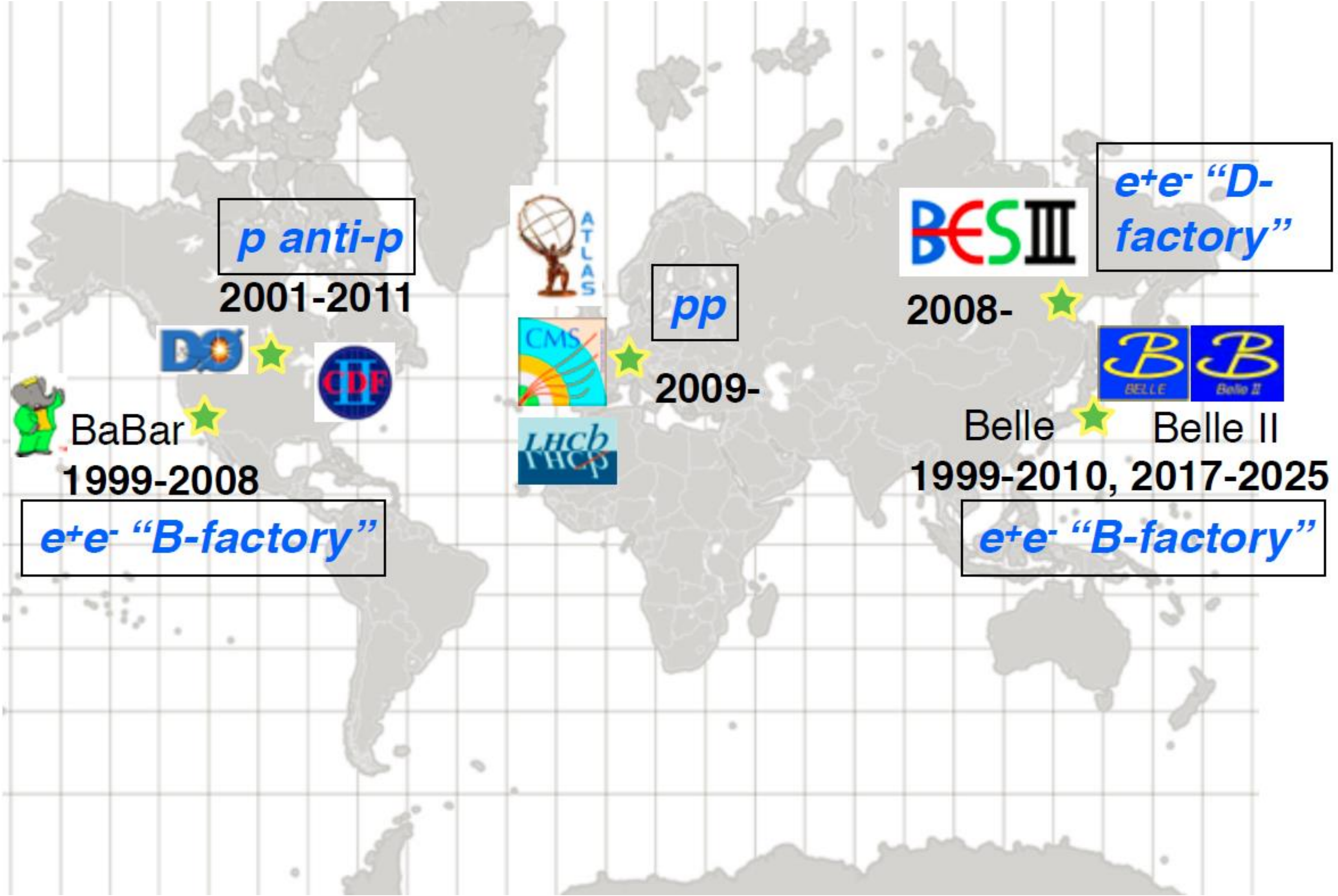
Rich phenomenology with beauty quarks

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



- 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

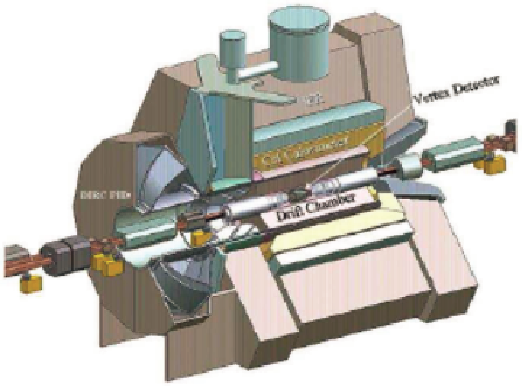
Where are *B* and *D* mesons produced



Flavour physics experiments

B-factories (BaBar & Belle)

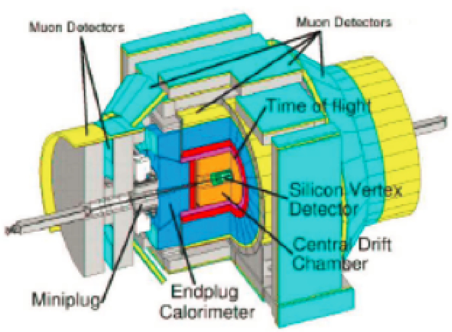
- e^+e^- experiment at SLAC / KEK
- Dedicated B-physics experiment



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

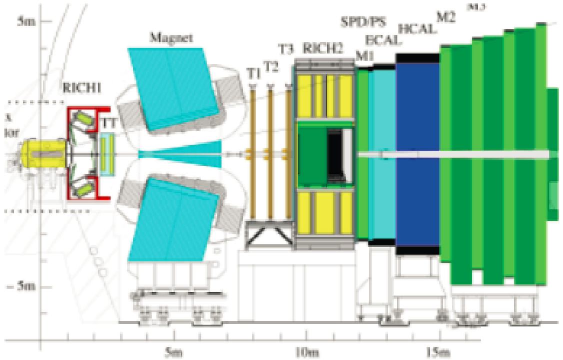
- Proton colliders @ CERN / Tevatron
- 4π multi purpose detectors

CDF II Detector



LHCb

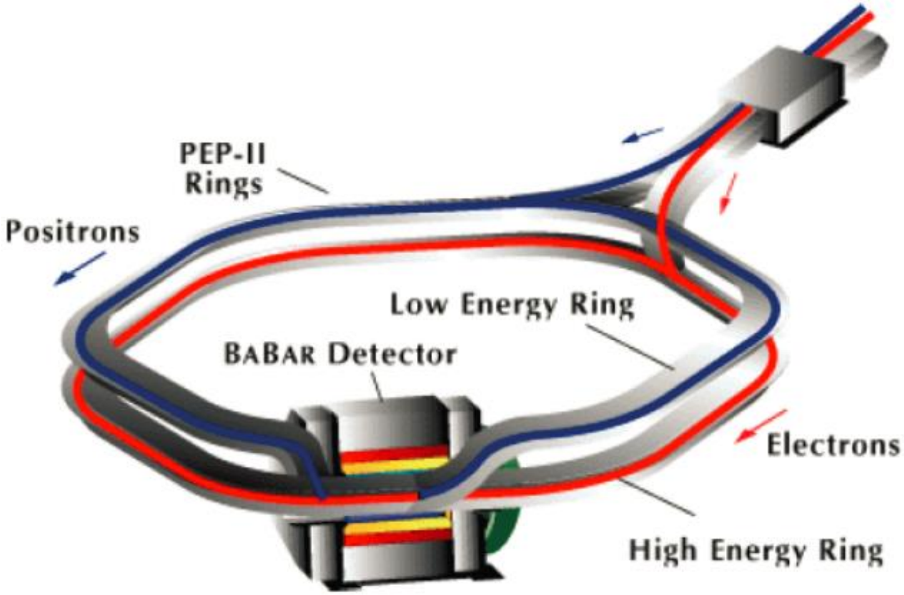
- Proton colliders @ CERN
- Dedicated B-physics experiment

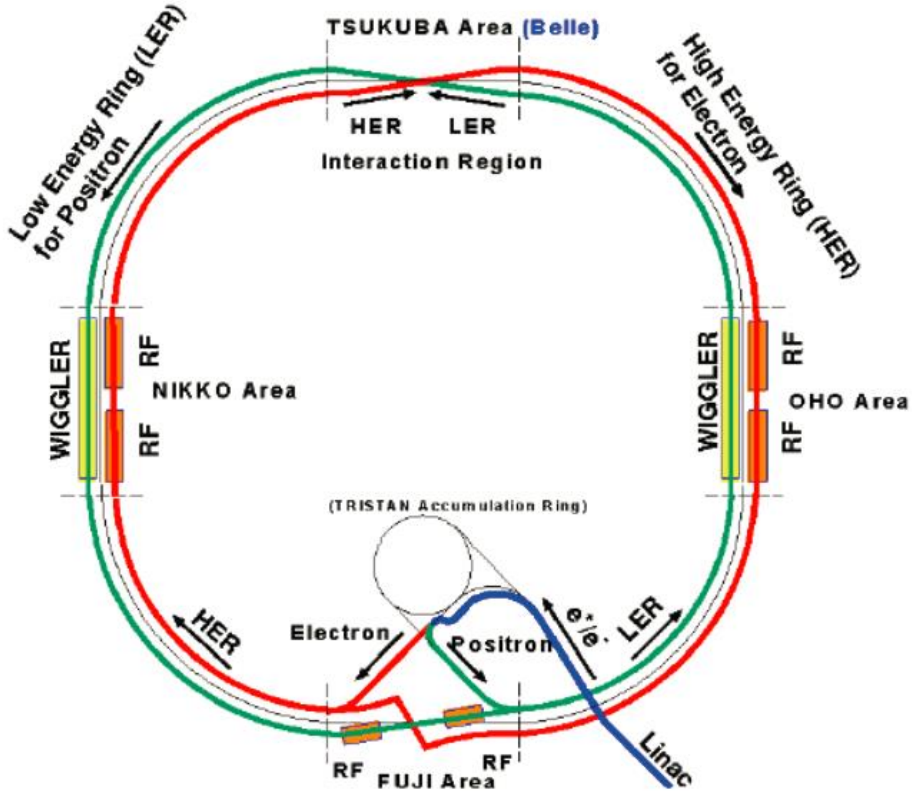


e^+e^-: Asymmetric B factories

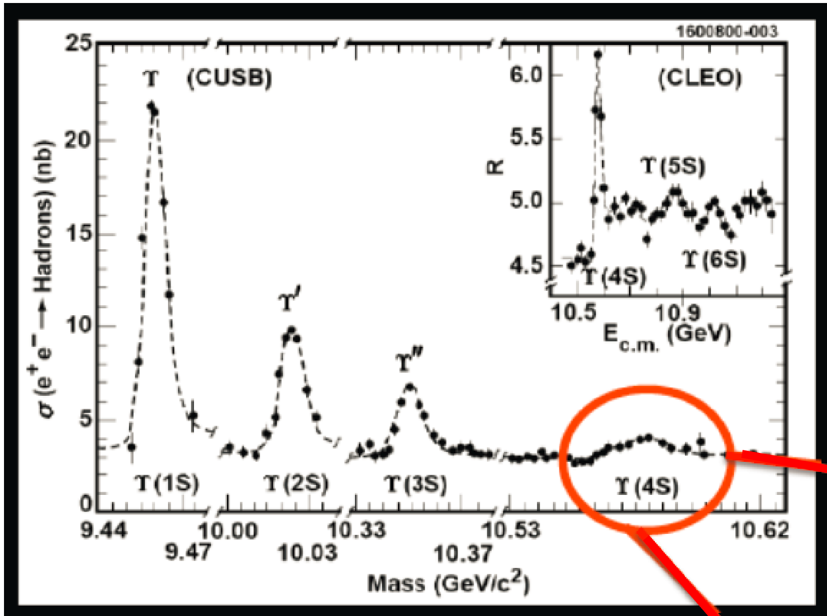
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

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





Y(4S) resonance



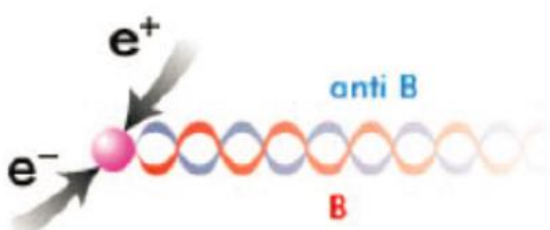
Cleanest way to produce B mesons in e^+e^- collisions: at centre-of-mass energy = mass of Y(4S)

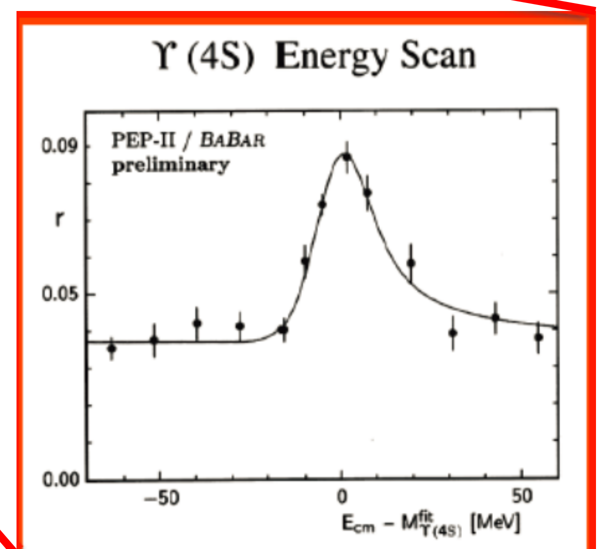
$\sqrt{s}$ = 10.58 GeV

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}

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





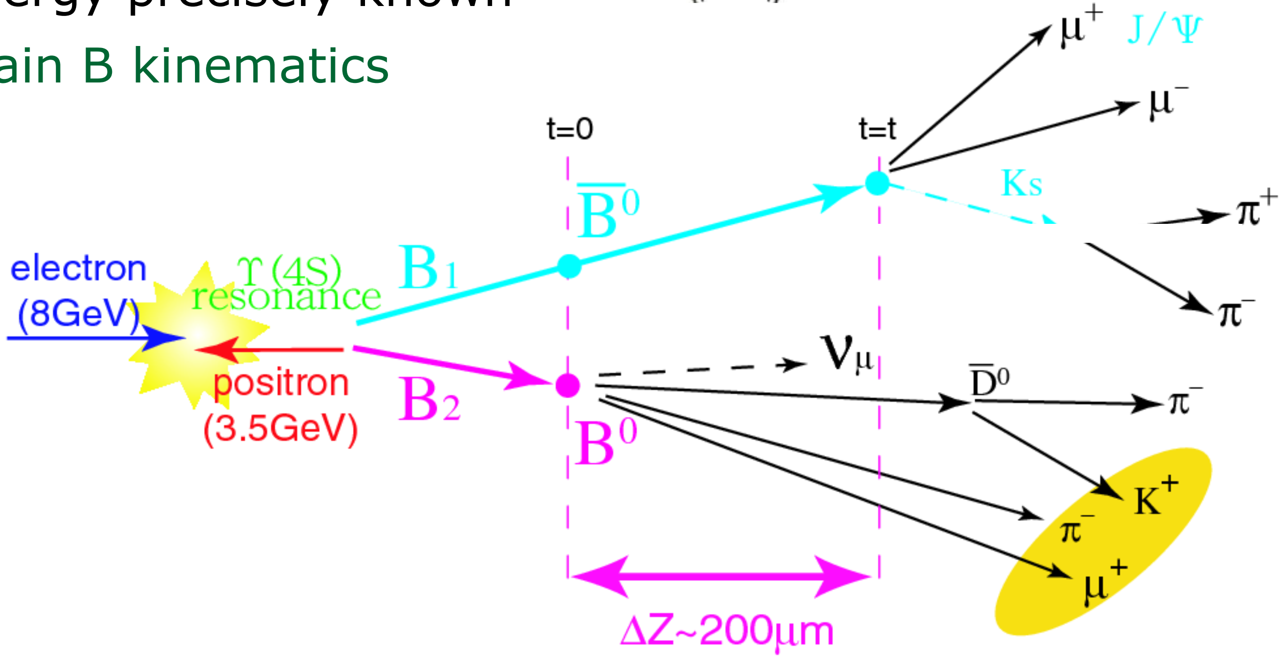
BB pair is produced in a coherent state
→ two B mesons evolve until one decays

Kinematics at e^+e^- colliders

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

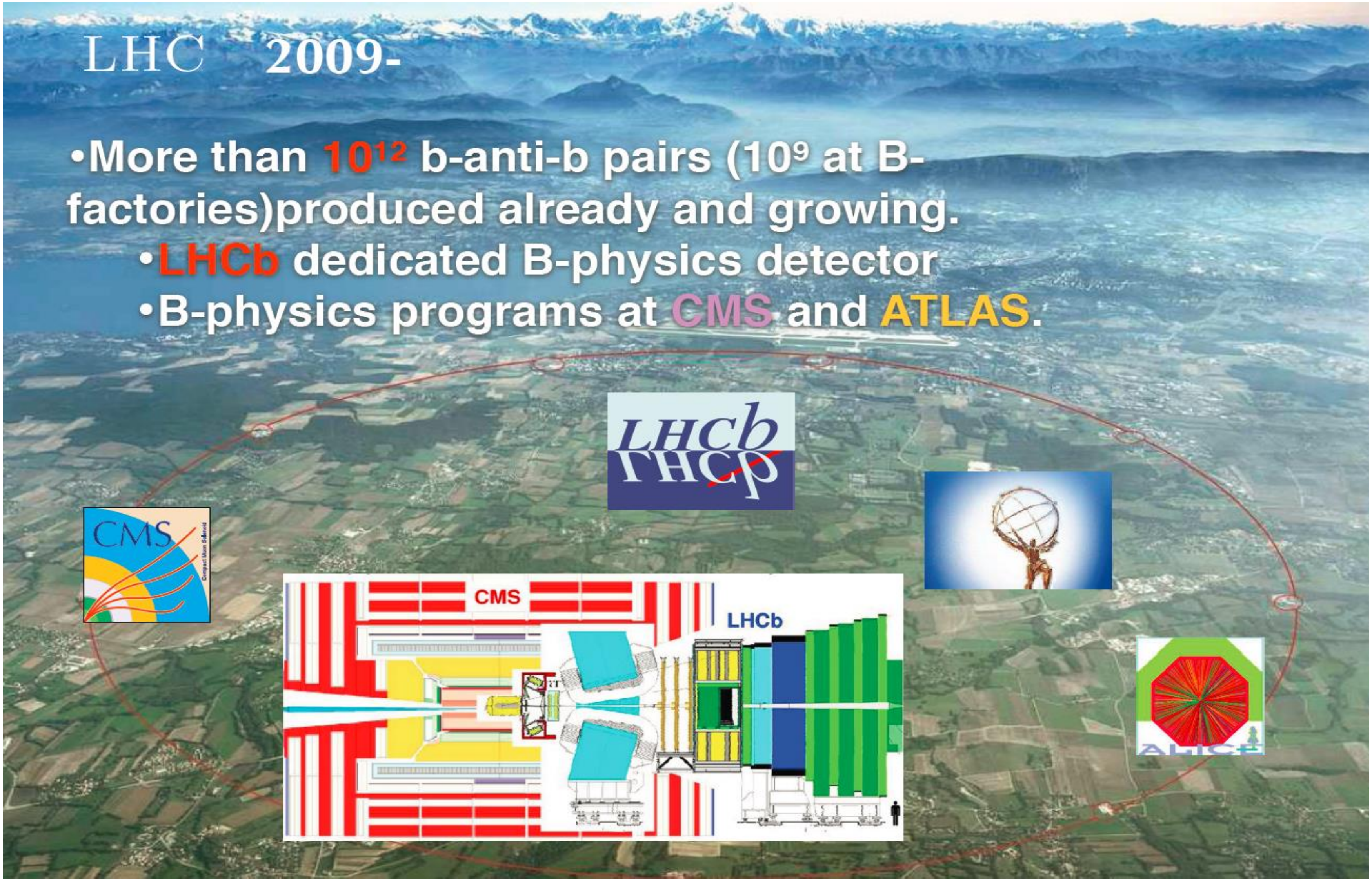
$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

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

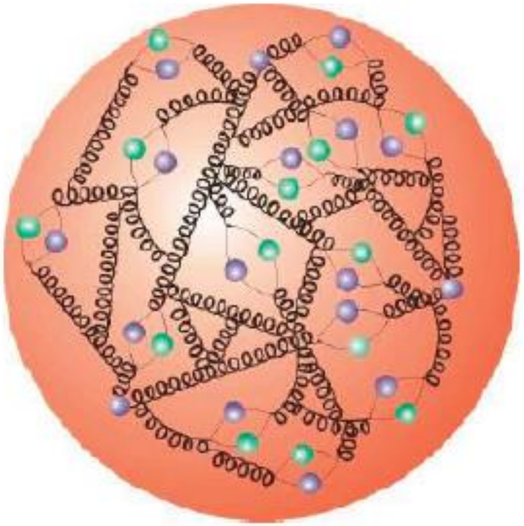


- To measure t require B meson to be moving
  $\rightarrow$ e^+e^- at threshold with asymmetric collisions

bb(bar) production at *pp* collider



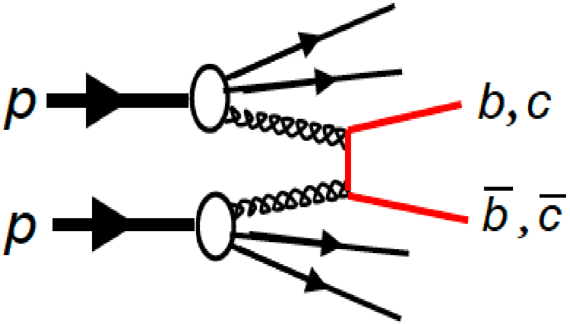
Proton collisions



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

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

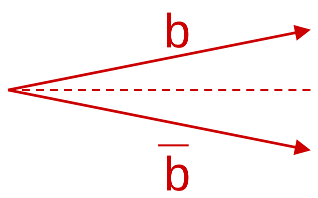
x_i = Bjorken x (fractional momentum) of parton



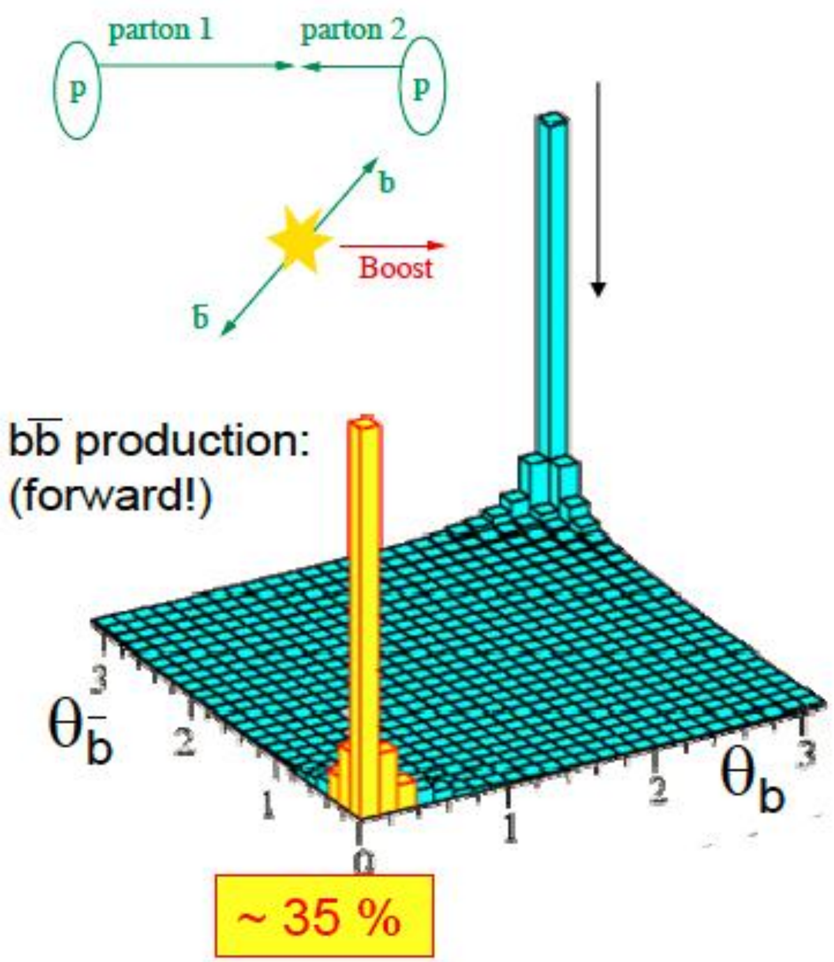
- Energy of particular collision unknown, but distributions known
  - hadron colliders „scan” a wide energy range
  - average s’ ~ 0.1 s
  - dominant process @ LHC: gluon fusion

Event kinematics

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



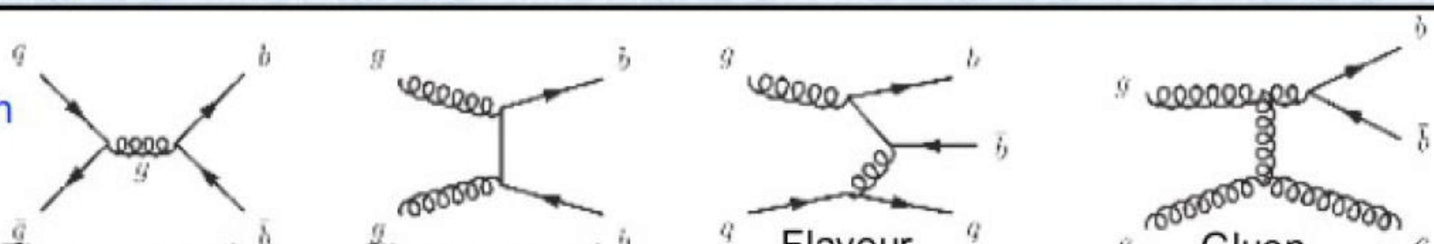
- B hadron mass ~ 5 GeV
  - asymmetric x-values
  - strongly boosted (βγ~100)
  - average flight length ~ 7mm
- Boost allows time dependent analyses of fast B_s mixing
- B hadron admixture:
  - 40% B^0
  - 40% $B^{\pm}$
  - 10% B_s
  - 10% Λ_b
  - <1% others (B_c, B^*, B^{**}, …)



b production at hadron colliders

	$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ **PEP-II, KEK-B**	$p\bar{p} \rightarrow b\bar{b}X \quad (\sqrt{s} = 2\ \mathrm{TeV})$ **TeVatron**	$pp \rightarrow b\bar{b}X \quad (\sqrt{s} = 14\ \mathrm{TeV})$ **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



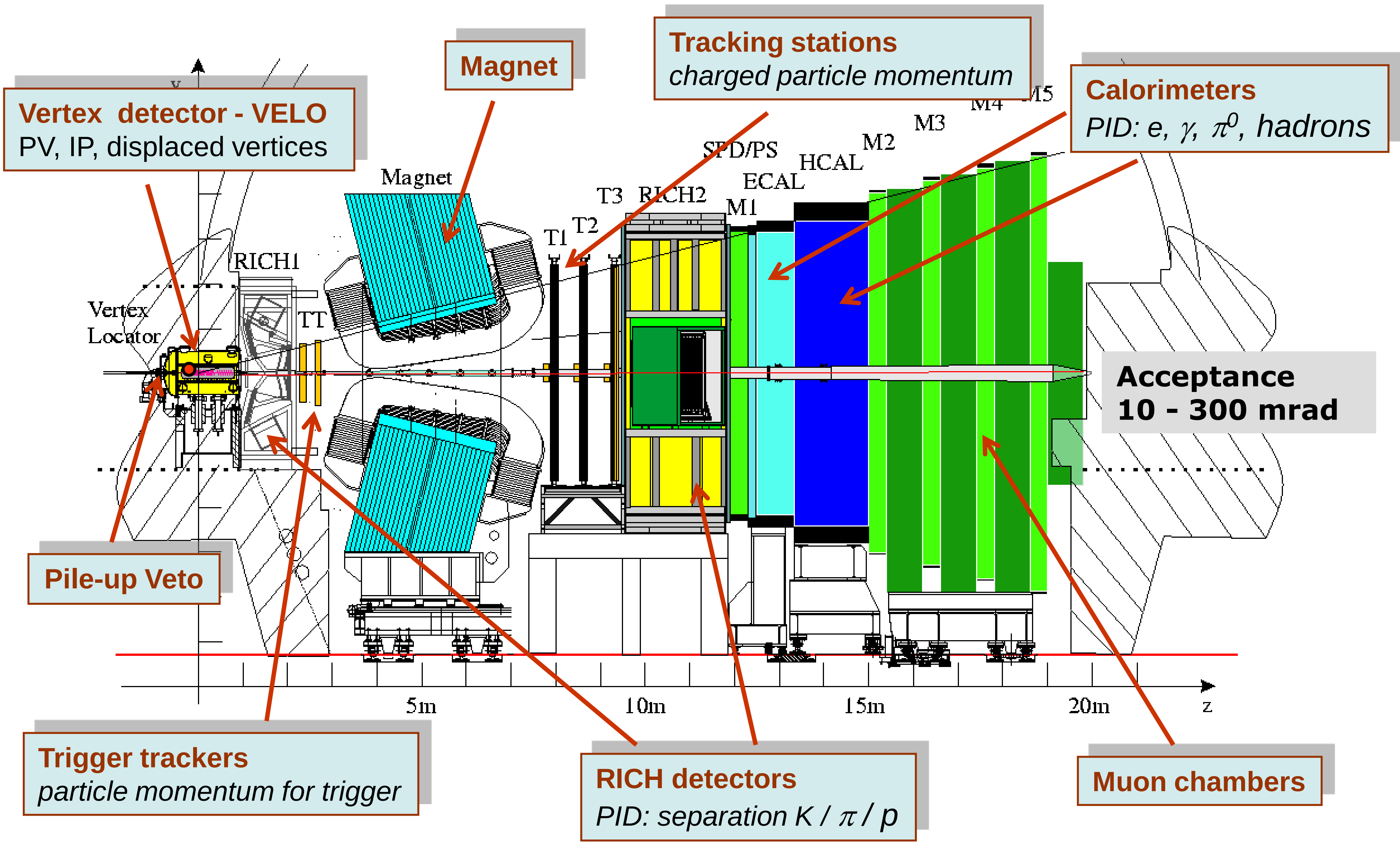
Flavour creation (quark annihilation)

Flavour creation (gluon fusion)

Flavour excitation

Gluon splitting

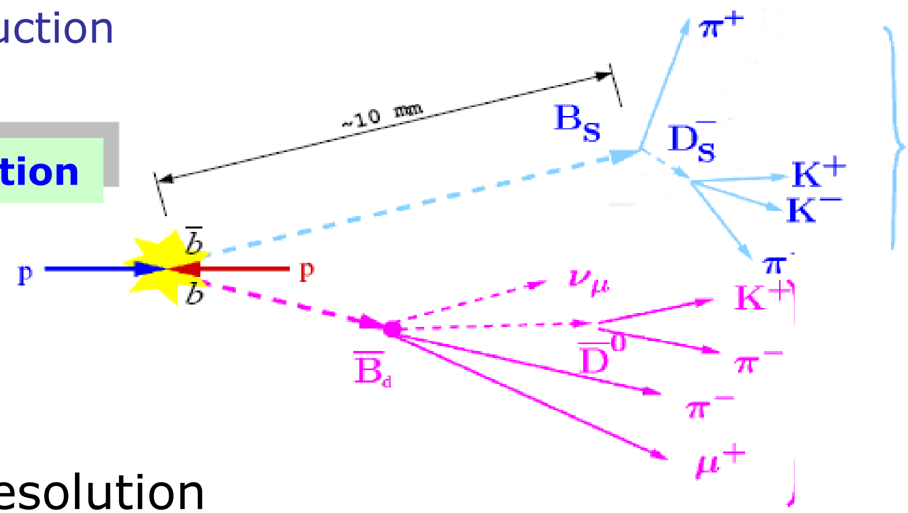
LHCb - single arm spectrometer



Detector requirements

Good decay vertex resolution
- proper time resolution
- background reduction

example of B production



signal B

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

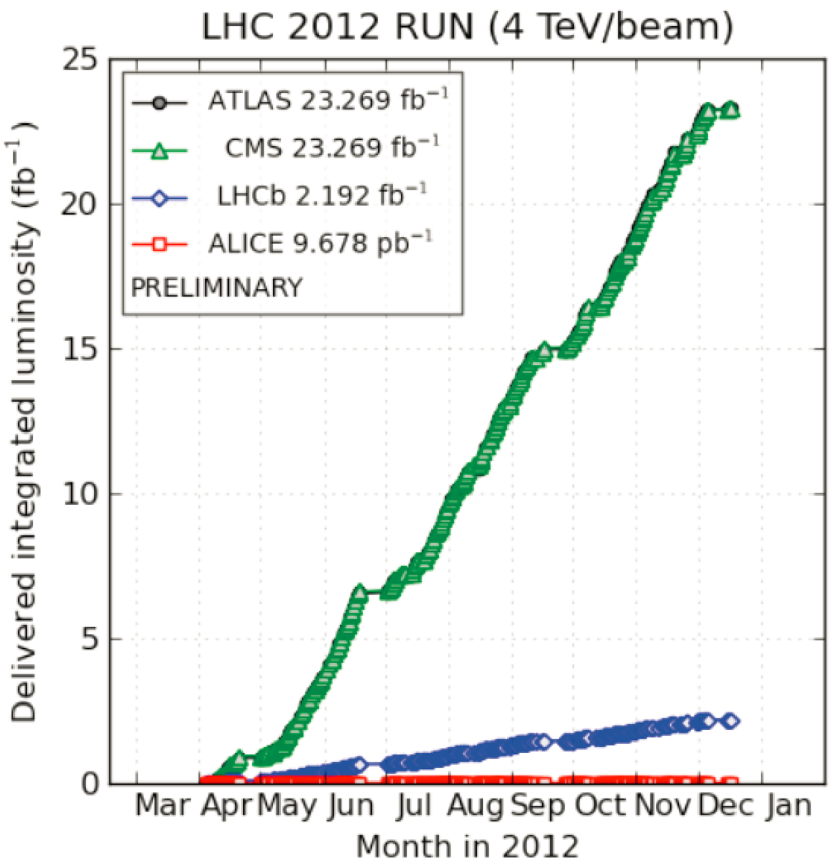
ATLAS / CMS

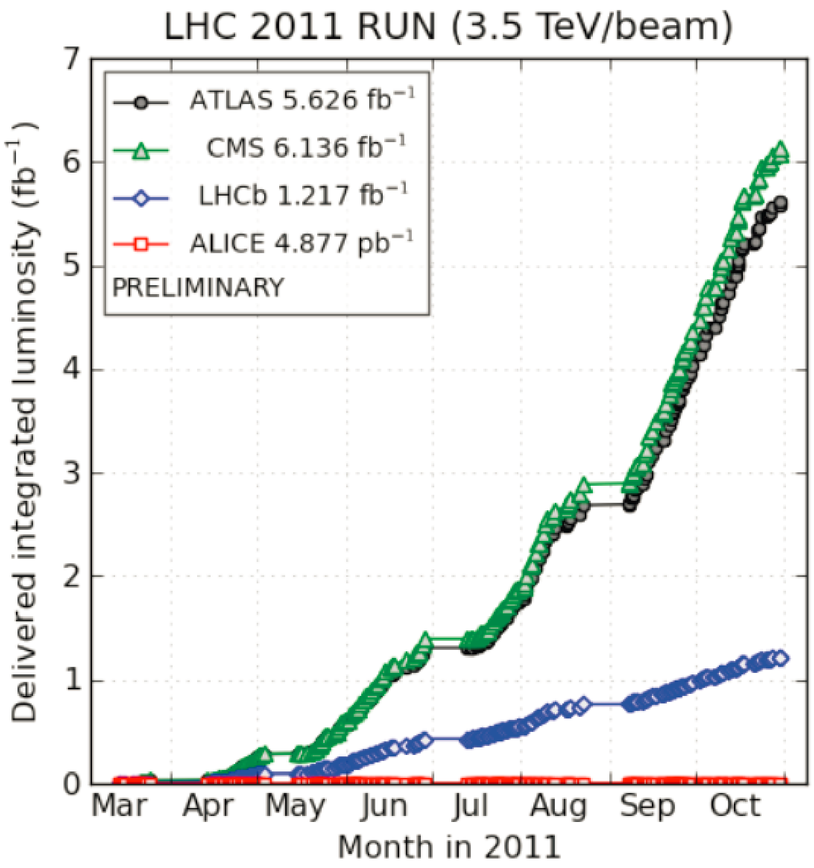
- Central detectors, $|\eta|<2.5$
- **High Luminosity ($>10^{34}cm^{-2}s^{-1}$)**
  → high pileup ~20
- Trigger
  - Relatively low rate (~200-400Hz)
  - High PT muon triggers
- Analysis
  - Mostly modes with dimuons
  - Limited flavour tagging
- Particle identification
  - Excellent muon ID
  - Limited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

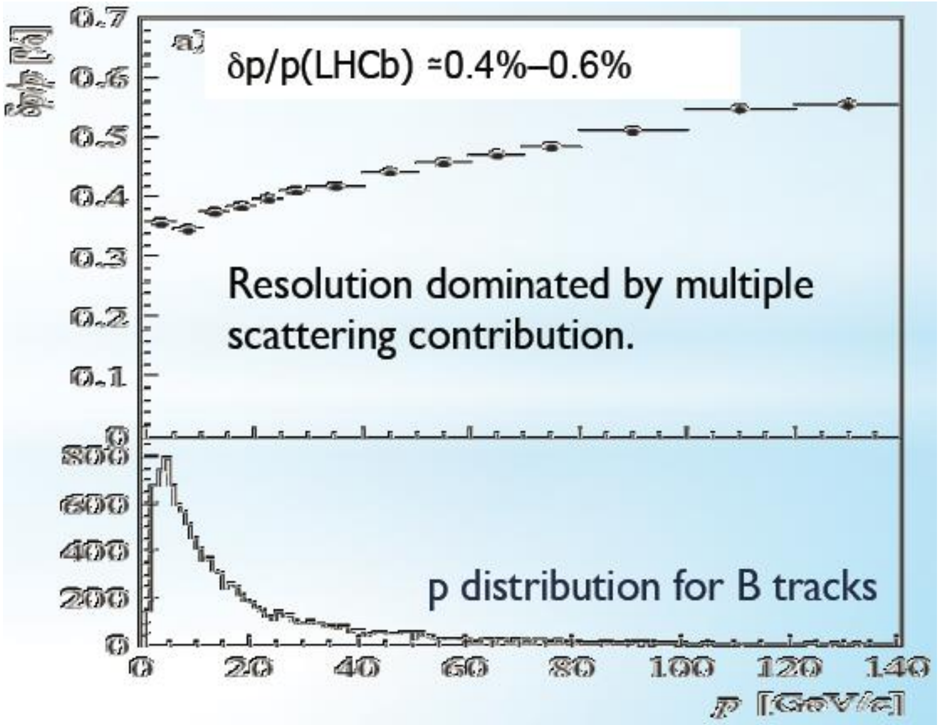
Key issues for B physics: *data statistics*





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

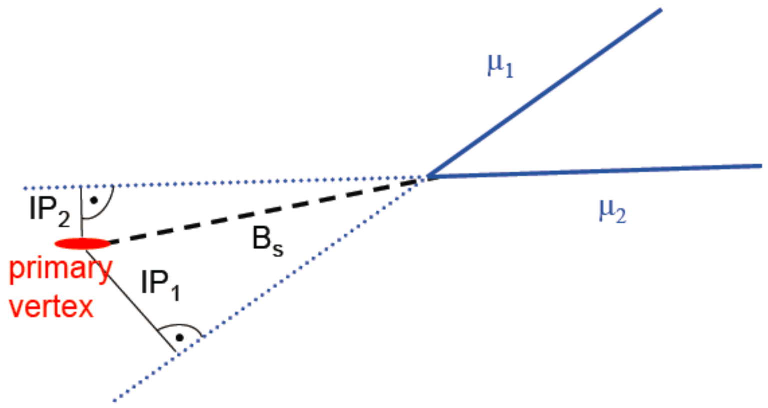
Key issues for B physics: *momentum and mass resolution*



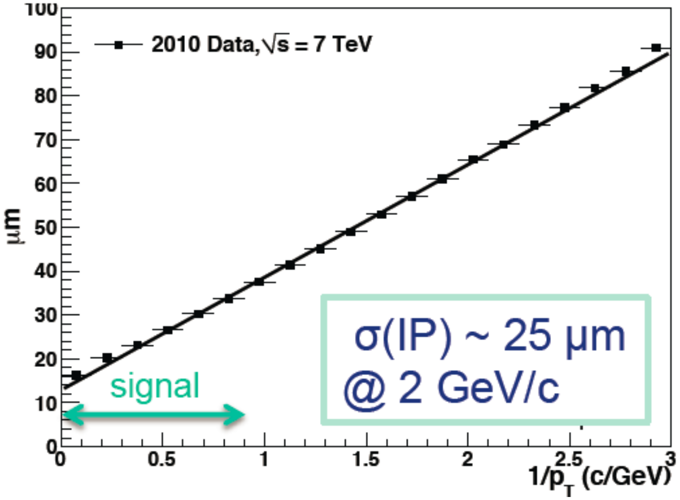
	momentum resolution	mass resolution $J/\psi \to \mu\mu$
LHCb	δp/p = 0.4-0.6 %	13 MeV
CMS	δpt/pt = 1-3 %	40 MeV
ATLAS	δpt/pt = 5-6 %	71 MeV

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

Impact parameter (IP):



IP resolution vs 1/pT

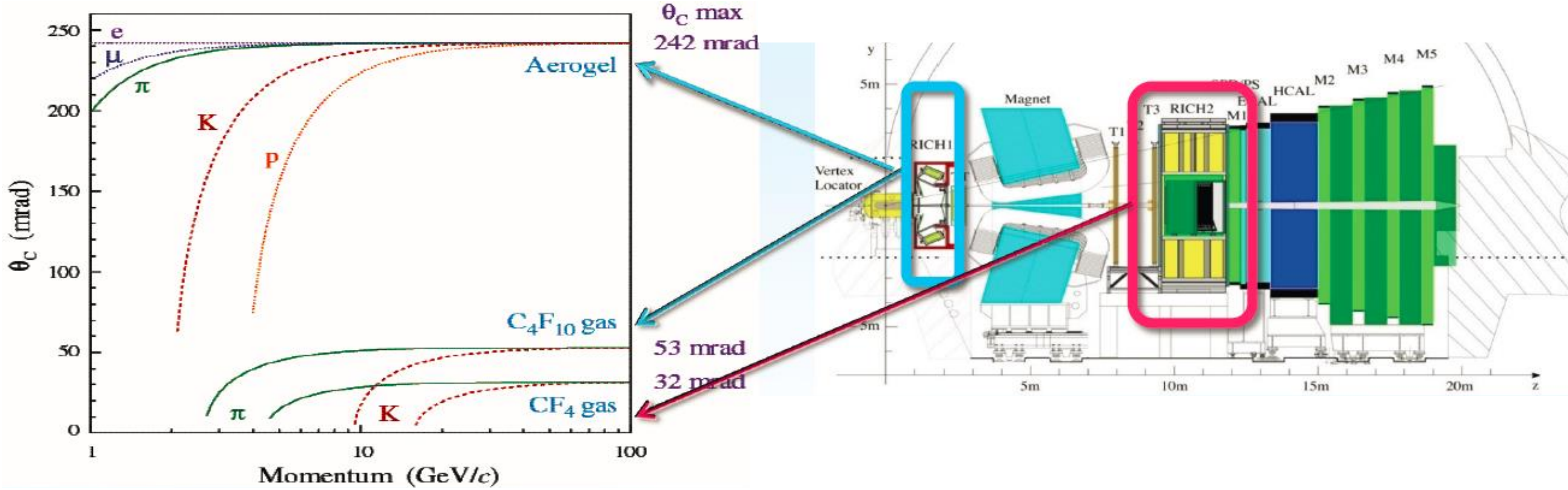


Primary vertex resolutions (25 tracks):

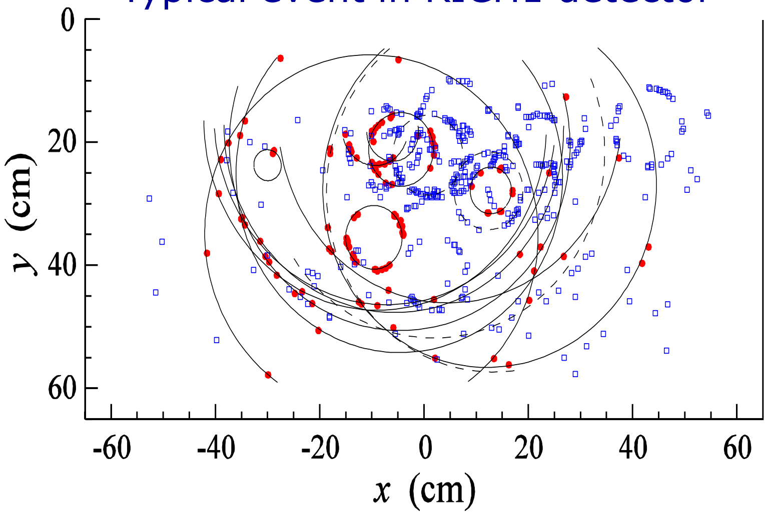
	LHCb [μm]	ATLAS [μm]	CMS [μm]
σ(x)	15.8	60	20-40
σ(y)	15.2	60	20-40
σ(z)	76	100	40-60

	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

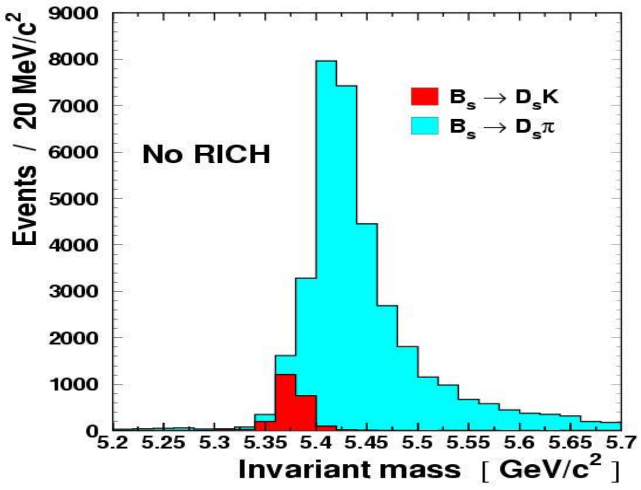
RICH2

- carbon tetrafluoride CF_4

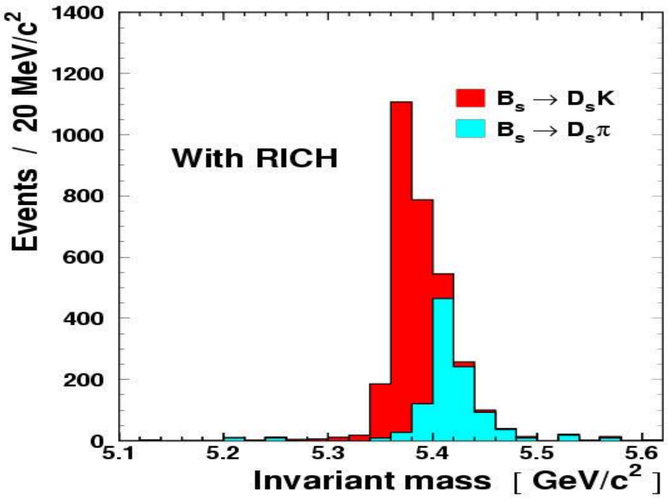
  n(CF_4) = 1.0005 → 16 - 100 GeV

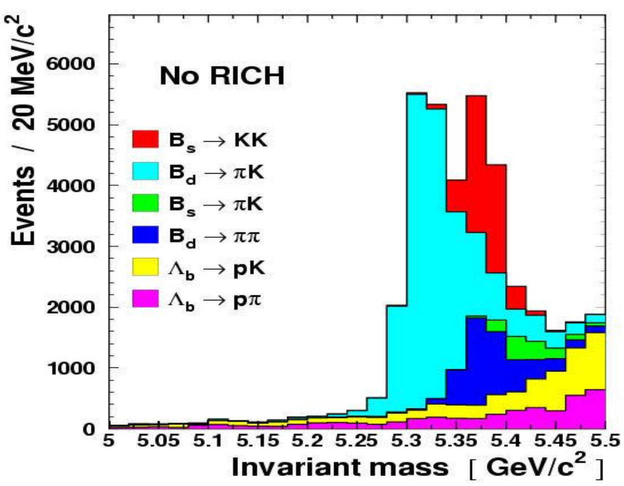
Key issues for B physics: *particle identification*

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

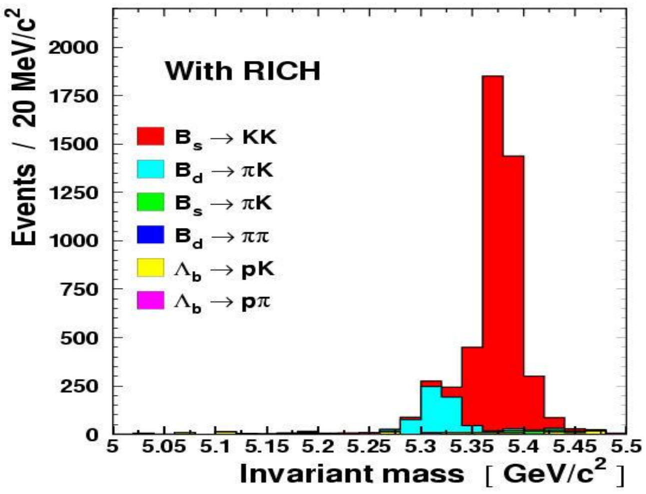


$B_s \to D_s K$





$B_s \to KK$



Key issues for B physics: *trigger system*

Challenge is

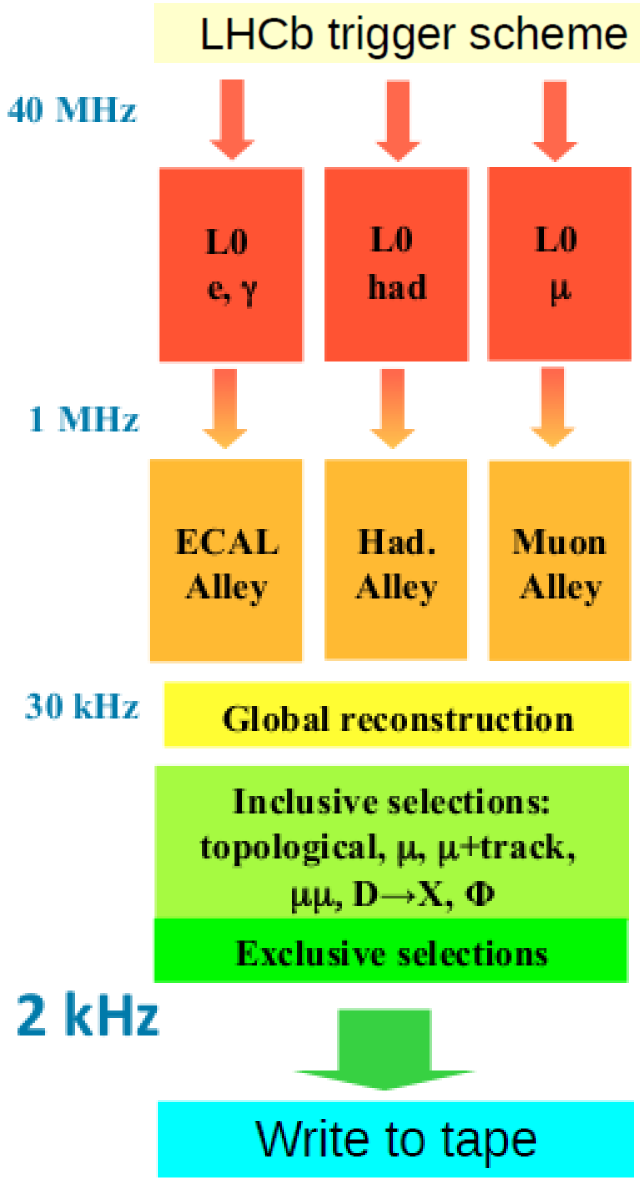
- to efficiently select most interesting B decays
- while maintaining manageable data rates

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

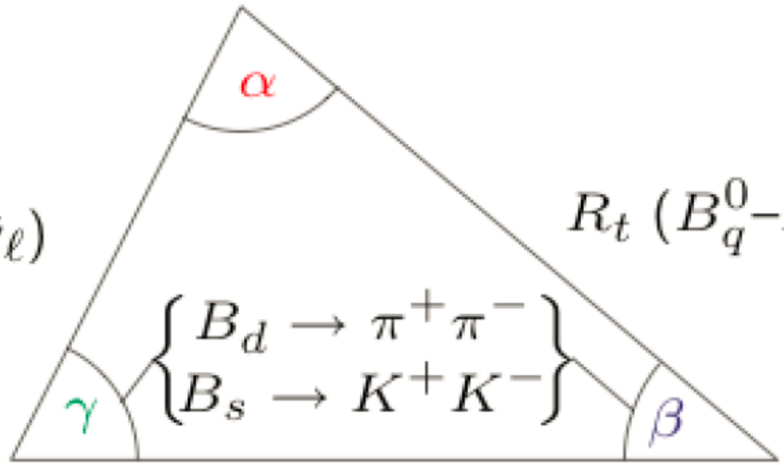
CKM matrix and types of CP violation

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)



$B \to \pi K$ (penguins)

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

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

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

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

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:

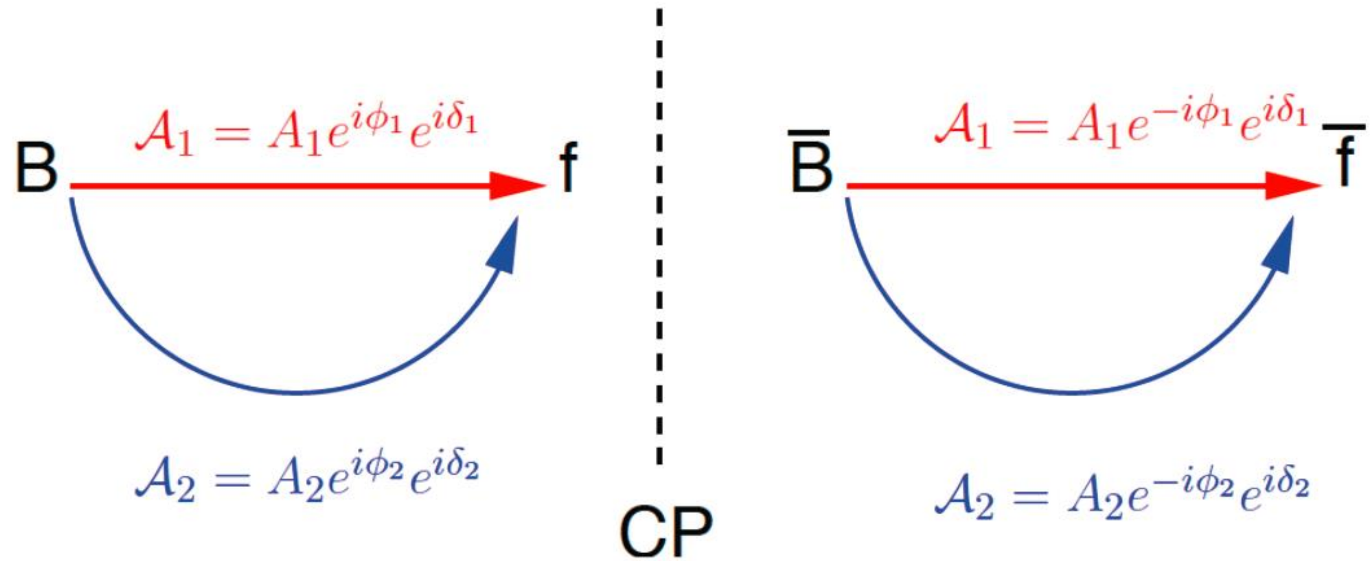
$$|\mathcal{A}_1 + \mathcal{A}_2|^2 = (\mathcal{A}_1 + \mathcal{A}_2)(\mathcal{A}_1^* + \mathcal{A}_2^*) = |\mathcal{A}_1^* + \mathcal{A}_2^*|^2$$

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

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



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

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

A_1 i A_2 need to have different weak phases ϕ and different strong phases δ

Strong phases are notoriously difficult to compute

Phases and CP-Violation

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

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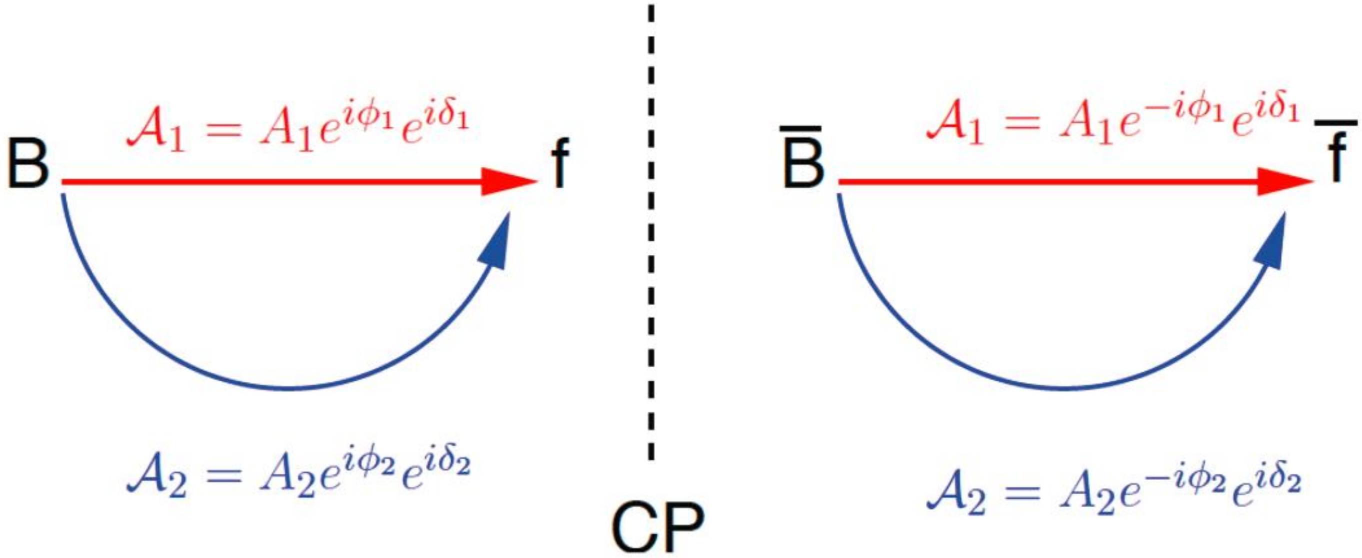

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A_1 i A_2 need to have different weak phases ϕ and different strong phases δ

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**:

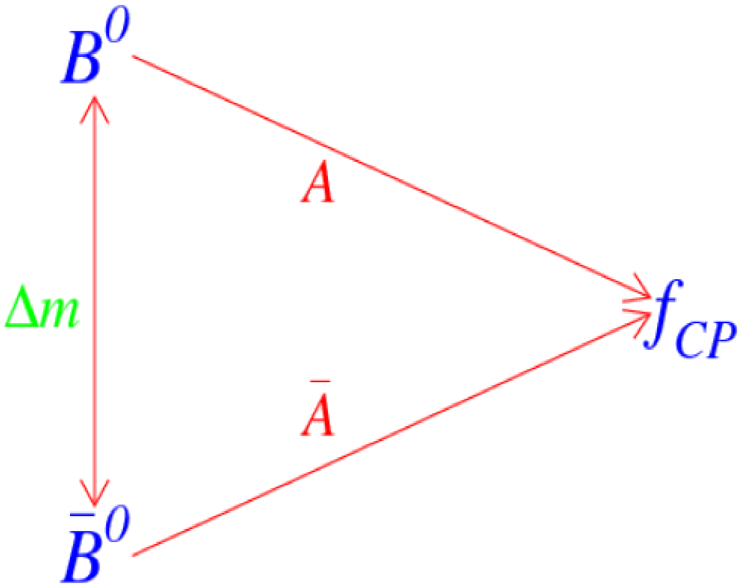
$$|\frac{q}{p}| \neq 1$$

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

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

3) CP violation in interference between mixing and decay:

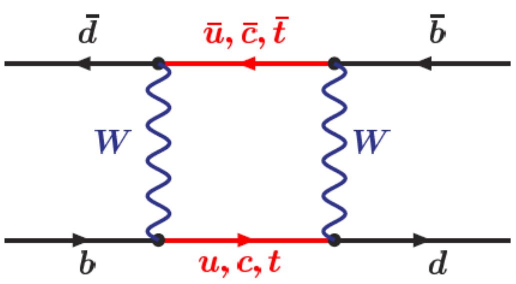
$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

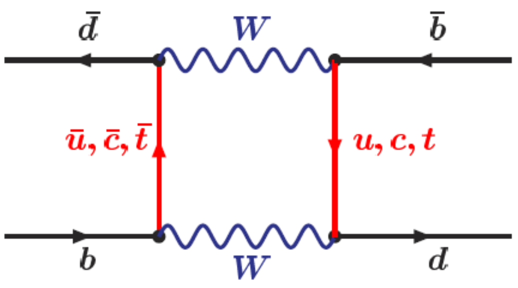


3 types of CP-Violation: In mixing

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

Mixing occurs via box diagrams: ΔF = 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:

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

$\Delta\Gamma \sim 0$ 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

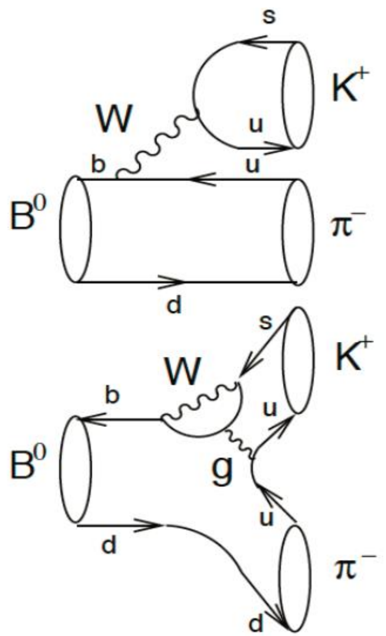
2) Direct CP violation condition: |A(bar) / A| ≠ 1

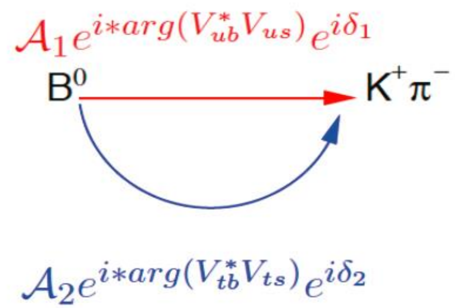
- need *A* and *A(bar)* to consist of (at least) two parts with different weak (φ) and strong (δ) phases
- often realised by „tree” and „penguin” diagrams

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

TREE

PENGUIN





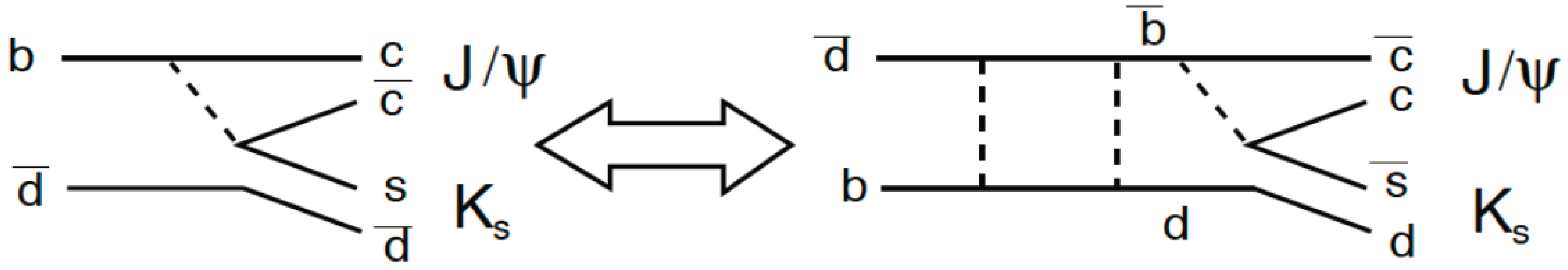
$$A = |T|e^{i(\delta_T-\phi_T)}+|P|e^{i(\delta_P-\phi_P)} \qquad \overline{A} = |T|e^{i(\delta_T+\phi_T)}+|P|e^{i(\delta_P+\phi_P)}$$

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

3 types of CP-Violation: In interference

3) CP violation in interference between mixing and decay

Same final state through decay & mixing + decay



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

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

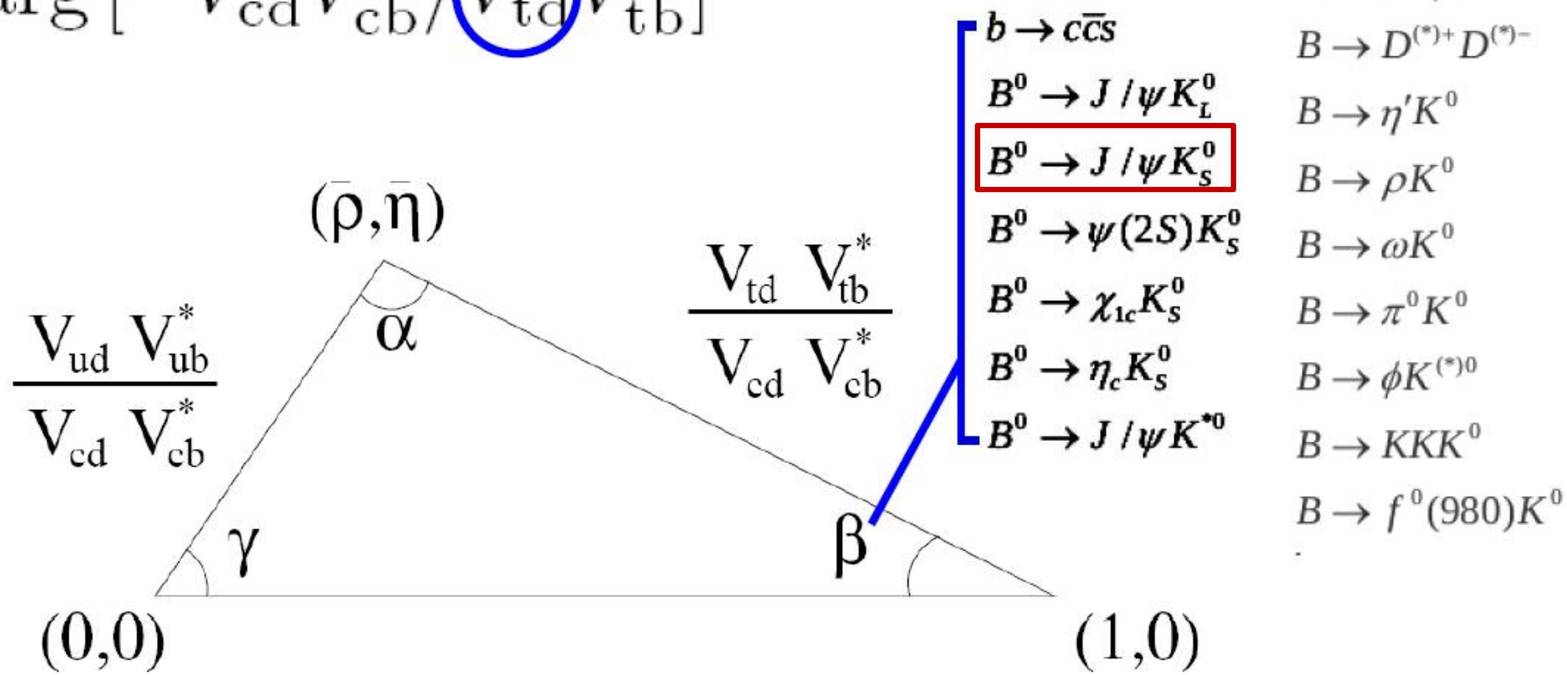
$\Delta\delta = \pi/2 \Leftarrow$ mixing introduce second phase difference

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

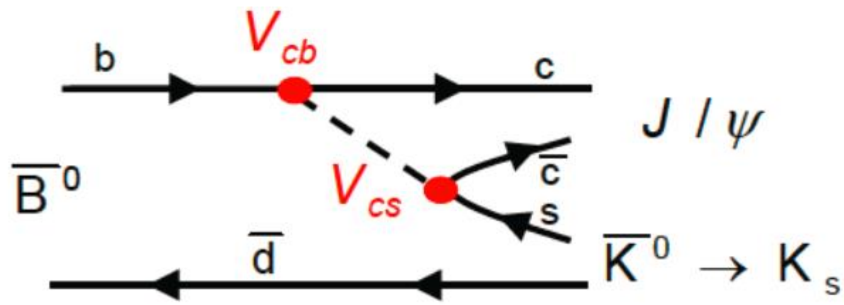
$$\beta \equiv \arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$$



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

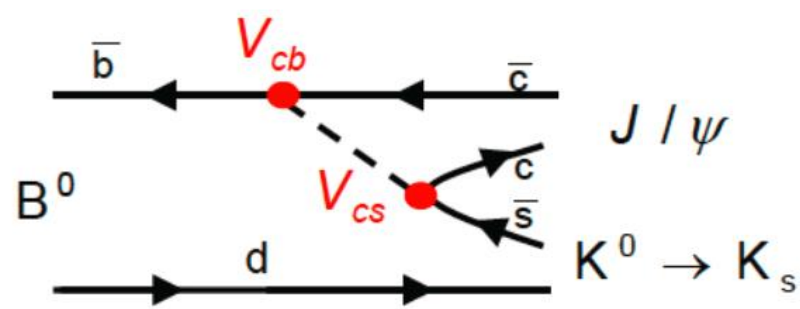
$B^0 \to J/\psi\ K_s$ — CP ⇒ $\bar{B}^0 \to J/\psi\ K_s$

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



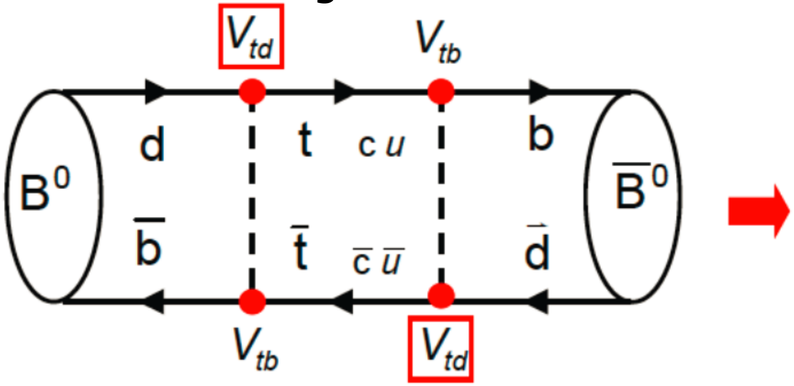
$\to$ here the CKM elements contributing are $V_{cb}V^*_{cs}$ that in Wolfenstein CKM parametrisation have no phase

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



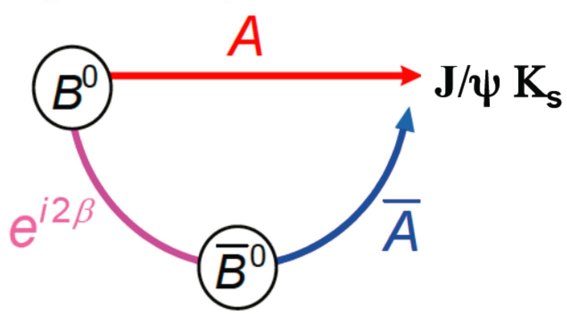
sin(2*β*): Golden decay $B^0 \rightarrow J/\psi\ K_s$

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



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

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



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

$\rightarrow$ requires knowledge of production flavour of the *B*

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

The colour-suppressed tree dominates

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

$\to$ CKM-suppressed pollution by penguins - **golden channel**

• $|A(bar)| = |A| \Rightarrow$ no direct CP violation

• C = 0 & S = $-\eta_{CP}$ sin(2β)

$\to$ sine term has a non-zero coefficient $\to$ 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 $e^+e^- \to Y(4S) \to B^0B^0(bar)$?

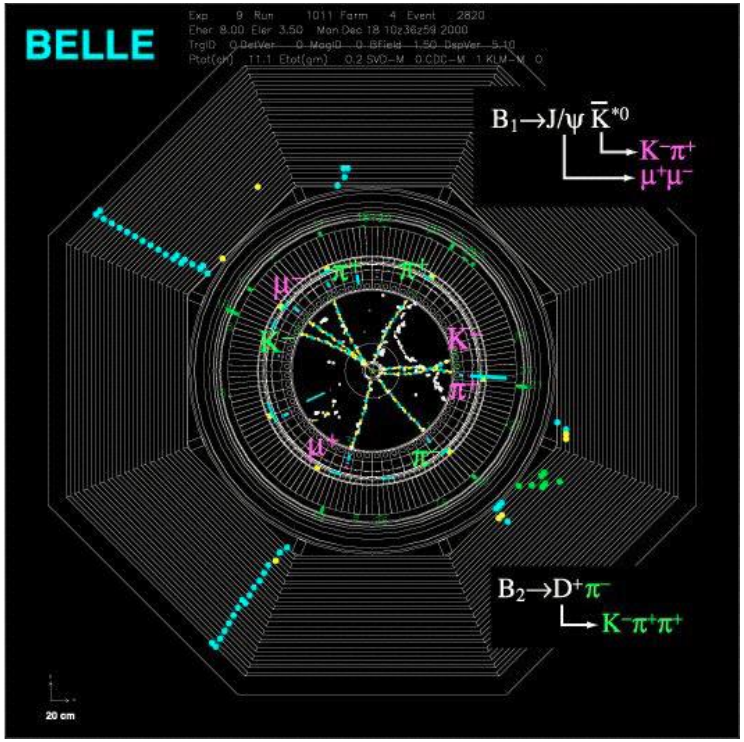
• the answer: asymmetric-energy B factory (e.g. Belle)

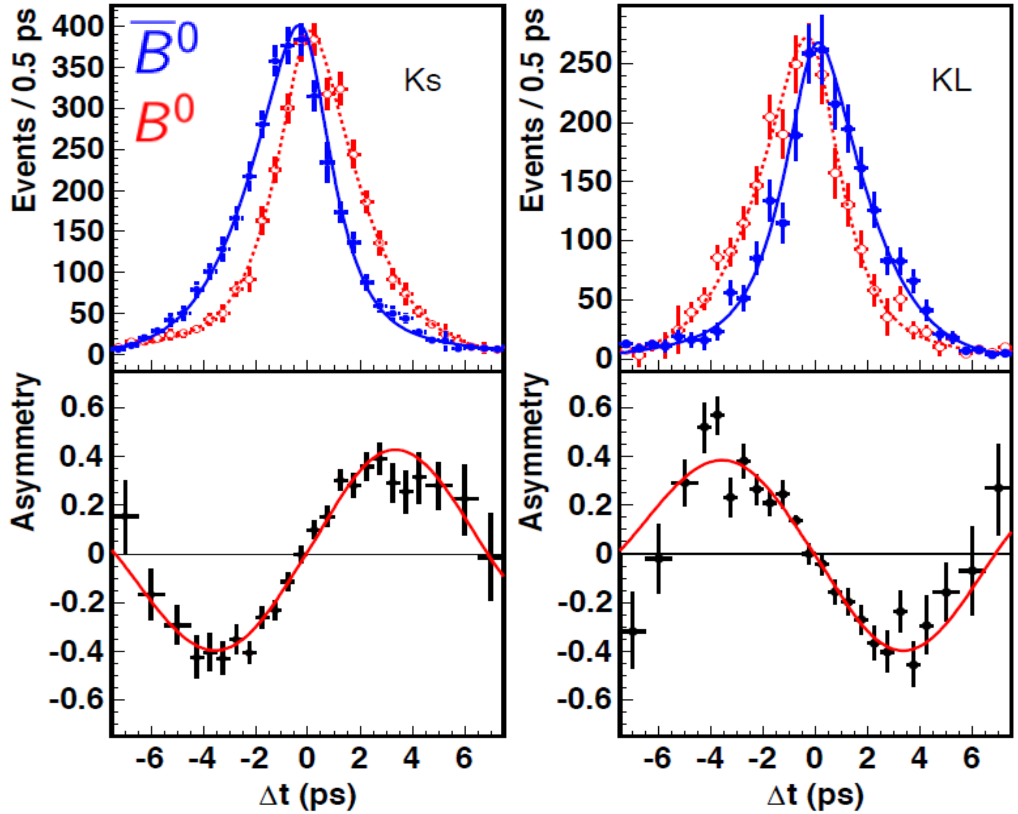
• key points

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

$\to$ *B* mesons are moving in LAB frame

sin(2β): Belle measurement

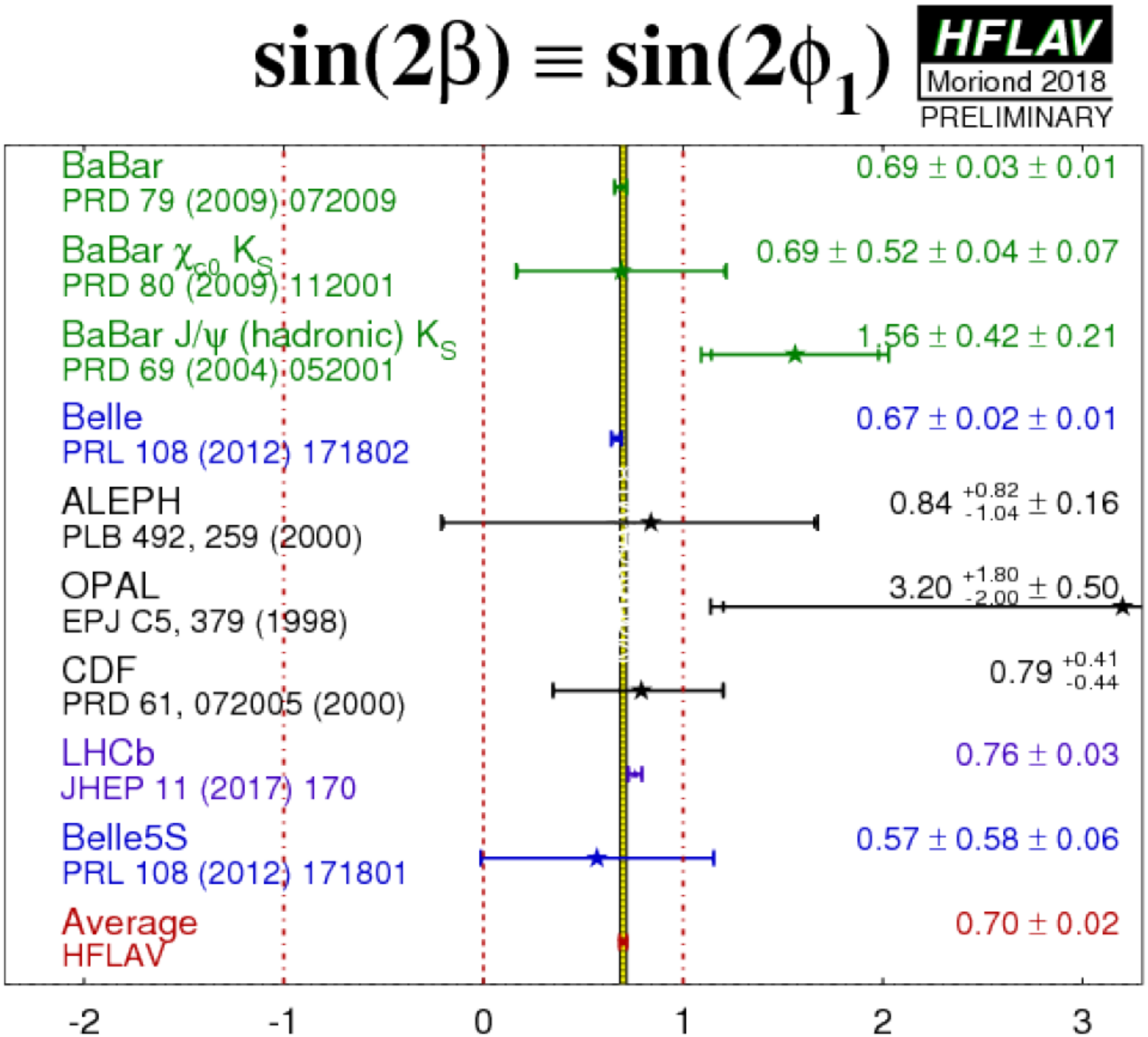




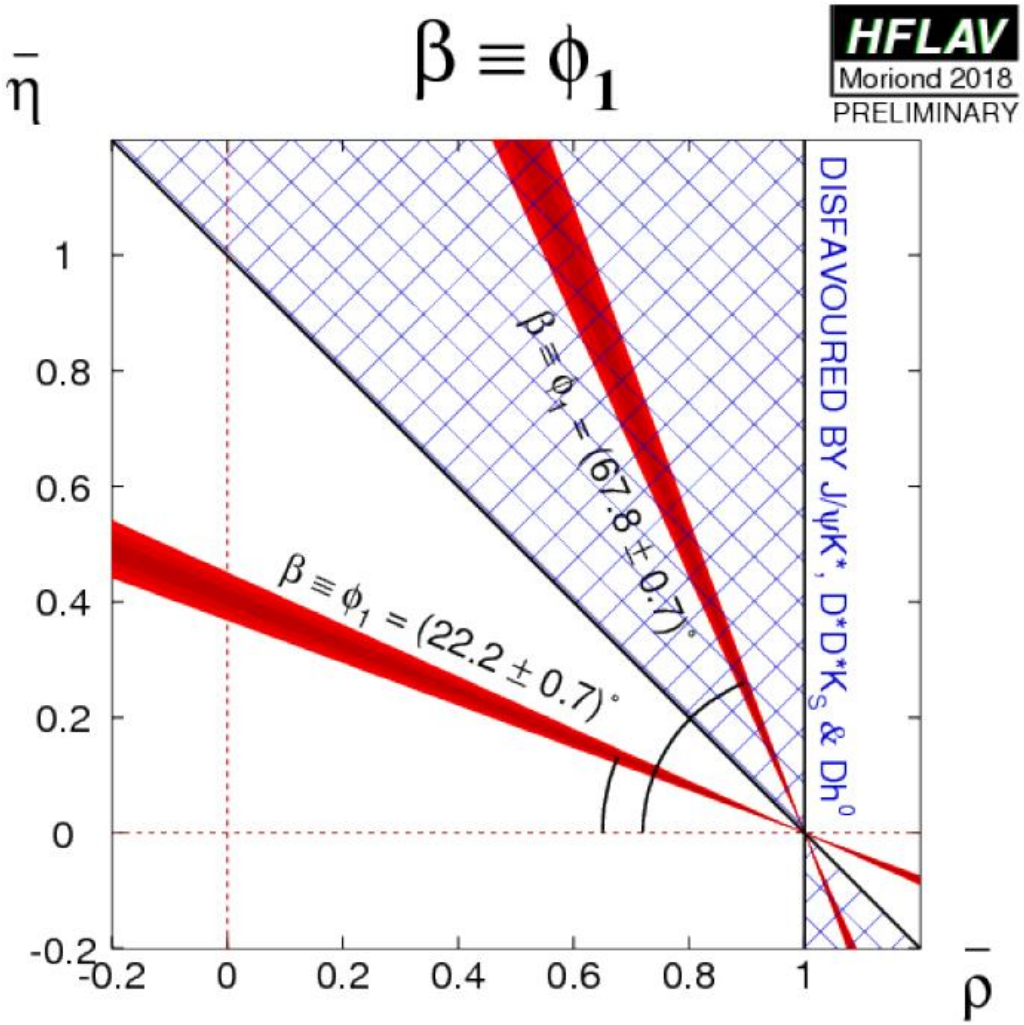
What do we have to do to measure $A_{CP}(t)$?

- 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



$\beta = (22.2 \pm 0.7)°$

2nd CKM measurement: α angle

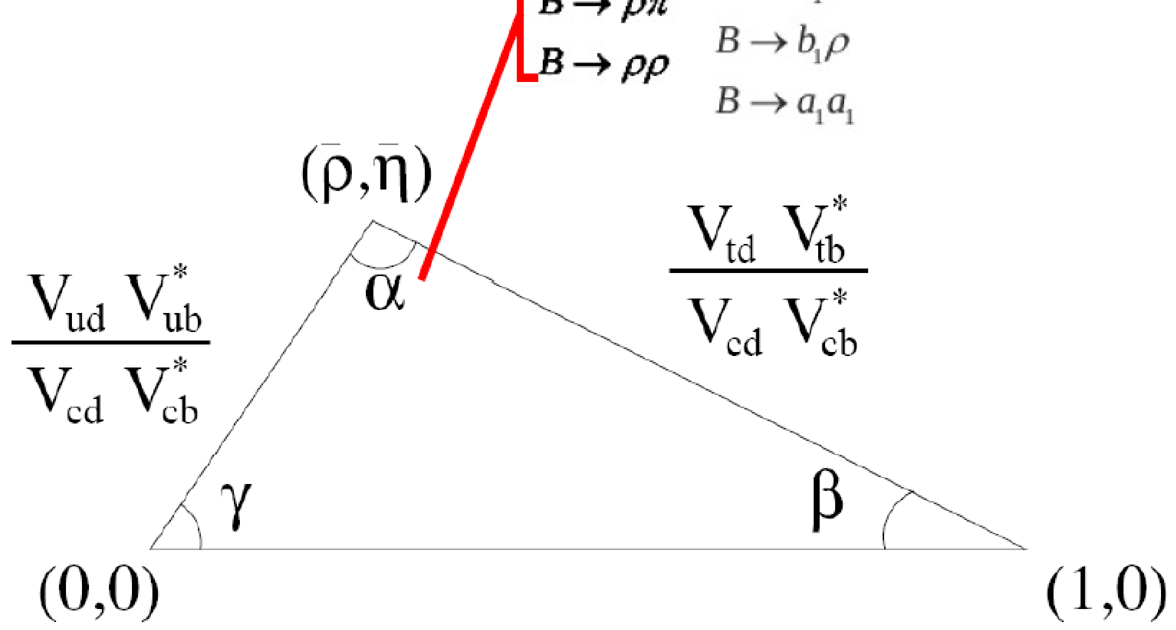
b → uu(bar)d transitions with possible loop contributions. Extract α using:

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

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

$b \to u\bar{u}d$
$B \to \pi\pi$
$B \to \rho\pi$
$B \to \rho\rho$

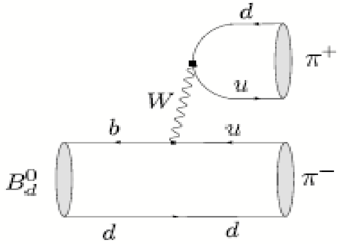
$B \to a_1\pi$
$B \to a_1\rho$
$B \to b_1\pi$
$B \to b_1\rho$
$B \to a_1 a_1$



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 = $+\eta_{CP} \sin(2\alpha)$

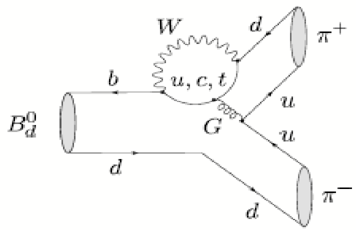


- $b \to du(bar)u$ penguin transitions contribute to same final states

  $\to$ „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

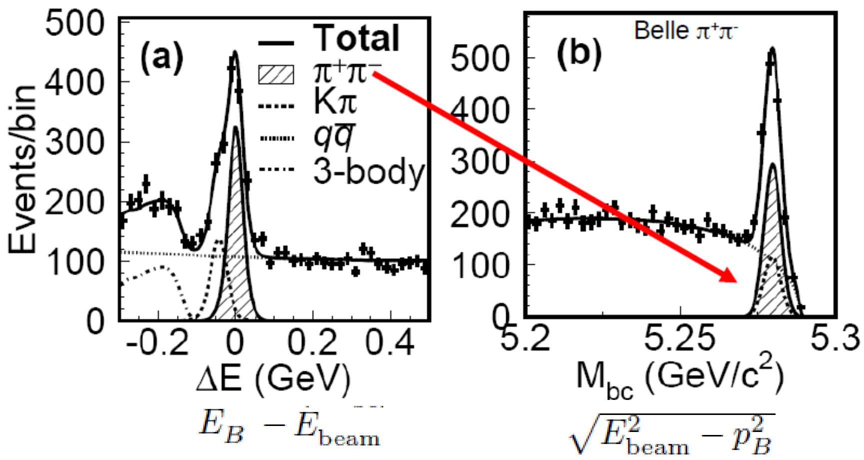
  $\to$ correct for penguin effect (isospin analysis)

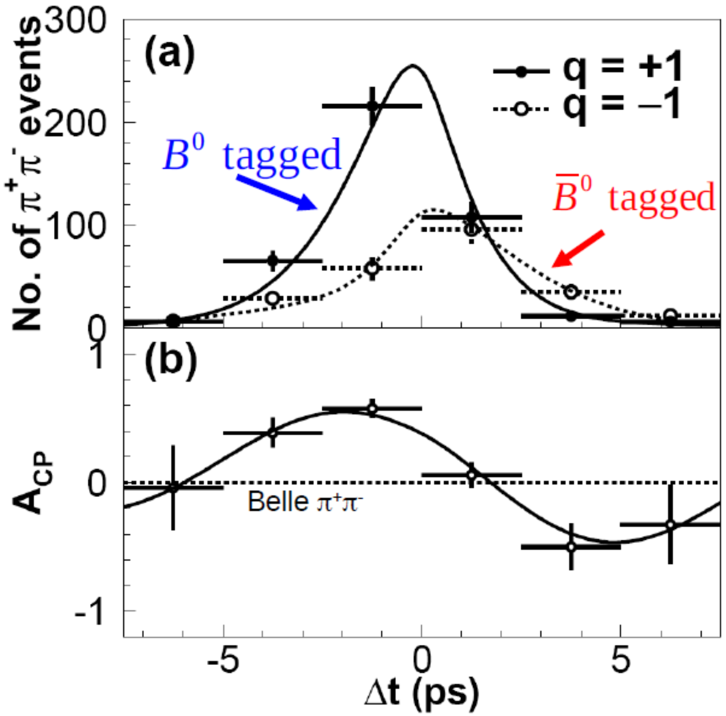
$$C_{hh} \propto \sin(\delta)$$
$$S_{hh} = \sqrt{1 - C_{hh}^2} \sin(2\alpha_{eff})$$
$$\delta = \delta_P - \delta_T$$

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(5×10^{-6})





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

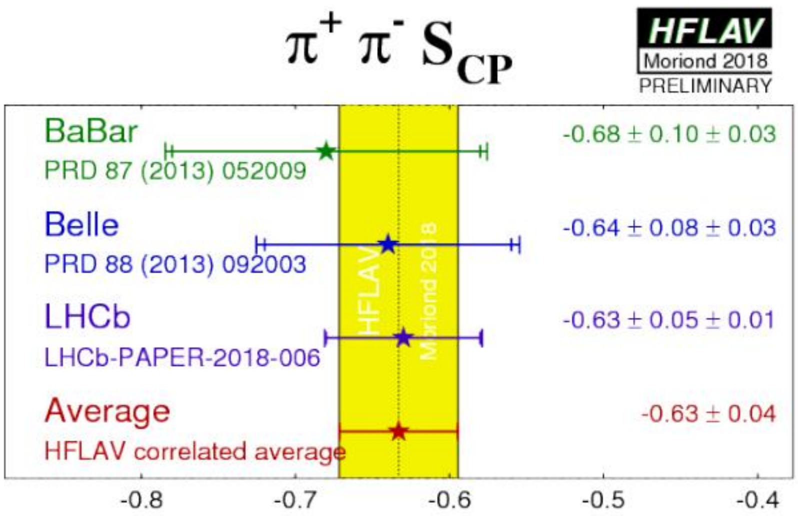
→ BR ~ 1.5×10^{-6}

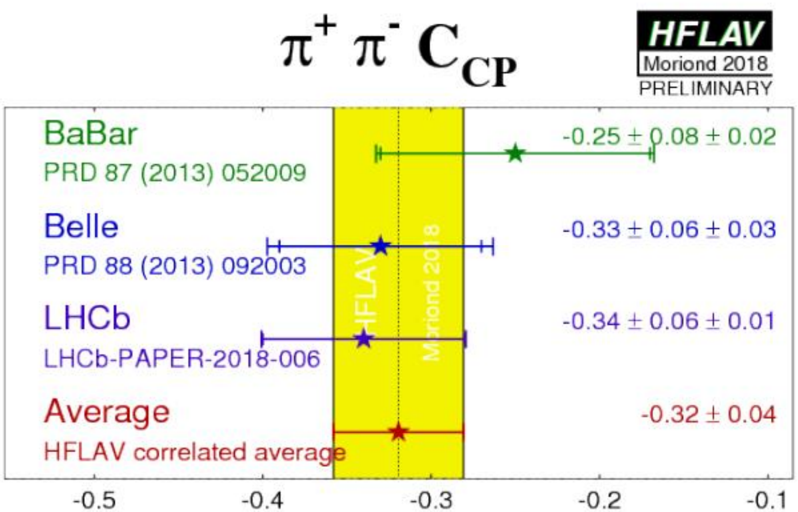
→ no tracks in the fnal state to provide vertex info

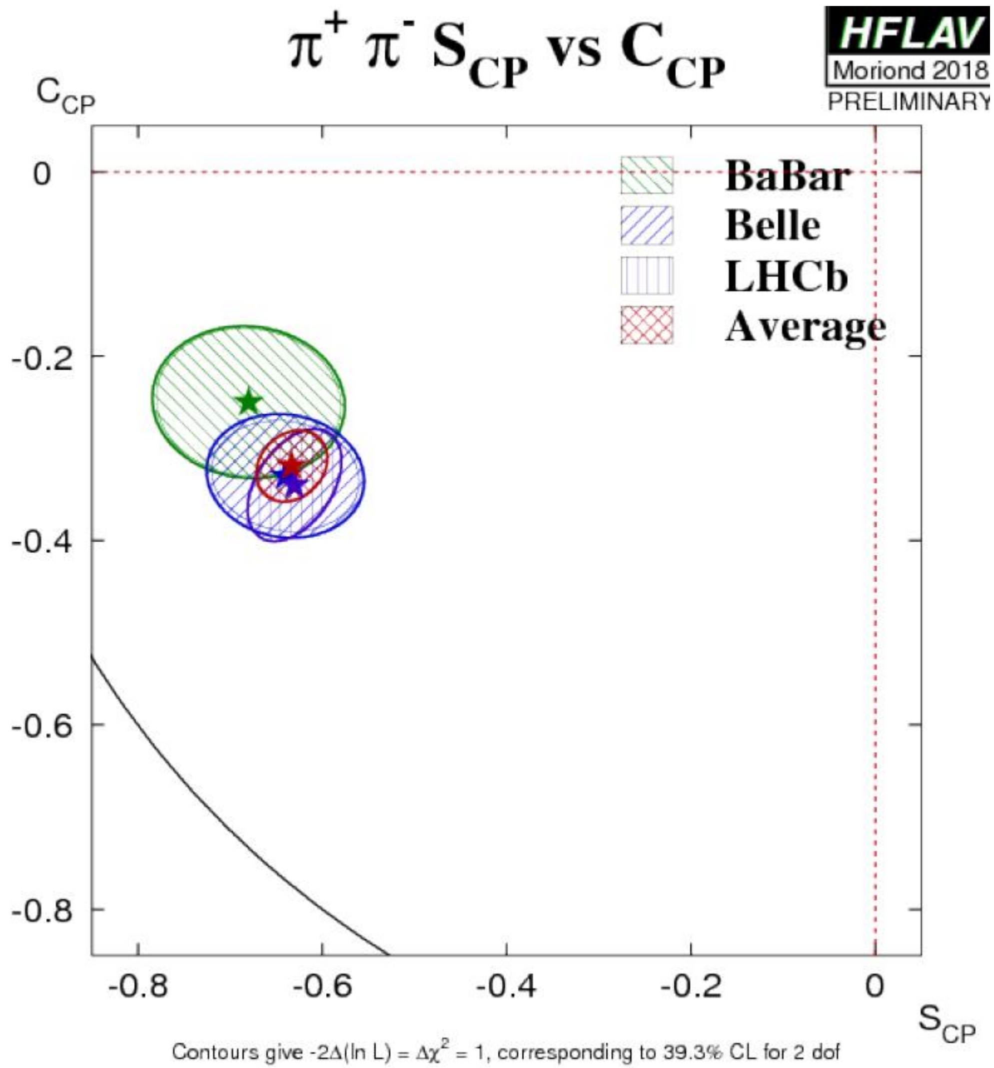
→ $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ has a large ΔE resolution

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

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





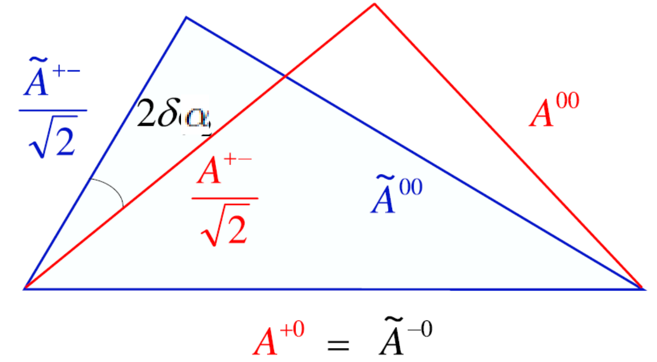


Measurement of α: *Isospin analysis*

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

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

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



- $B \to \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ 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

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

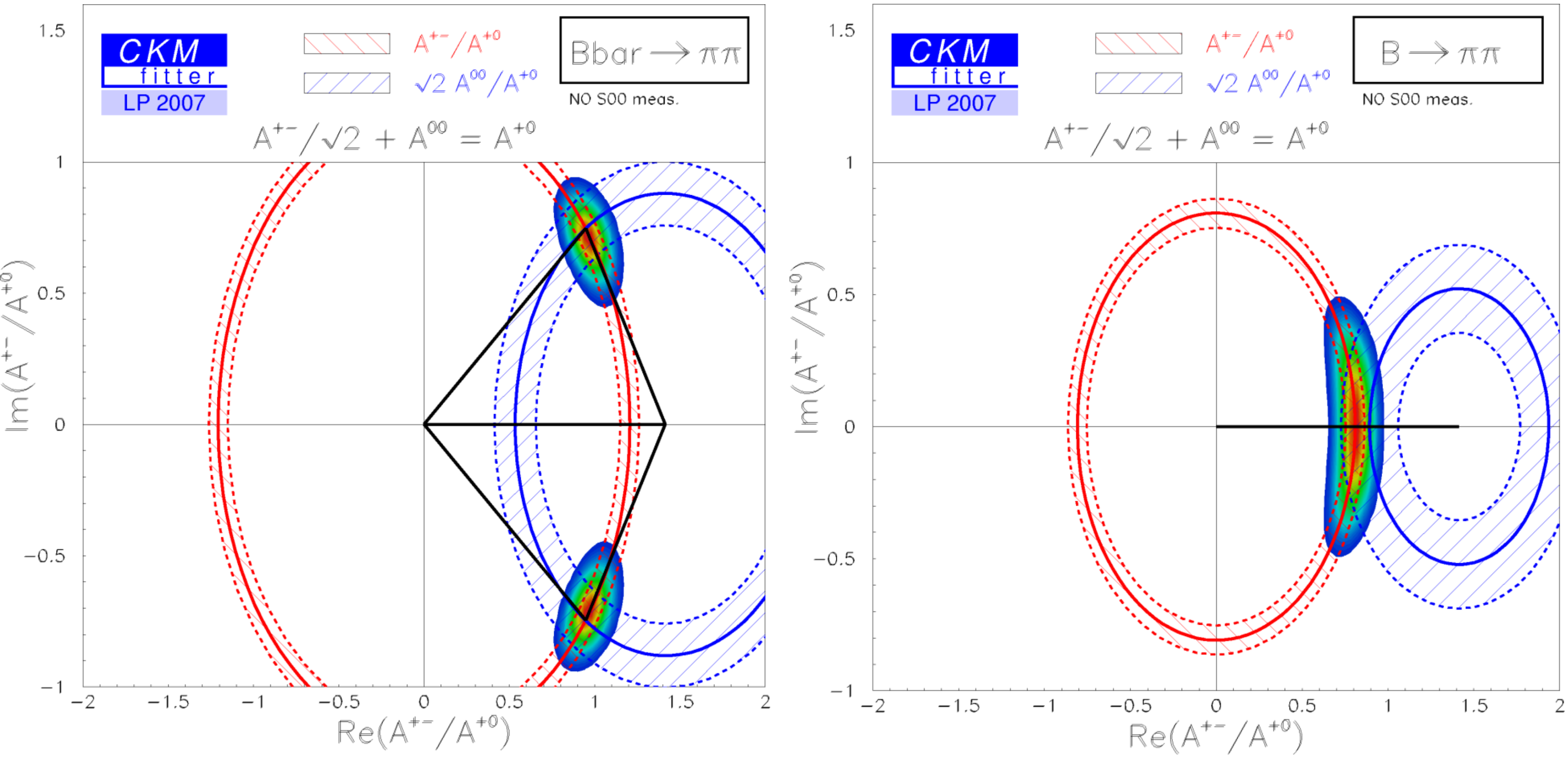
  $\rightarrow$ $\pi^+\pi^0$ is a pure I = 2 state (ΔI = 3/2) and it gets contribution only from the tree diagram

  $\rightarrow$ 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: $B^0 \rightarrow \rho\rho$

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

  L=0,1,2 partial waves:

  $\rightarrow$ longitudinal: CP-even state

  $\rightarrow$ transverse: mixed CP states

- isospin analysis:

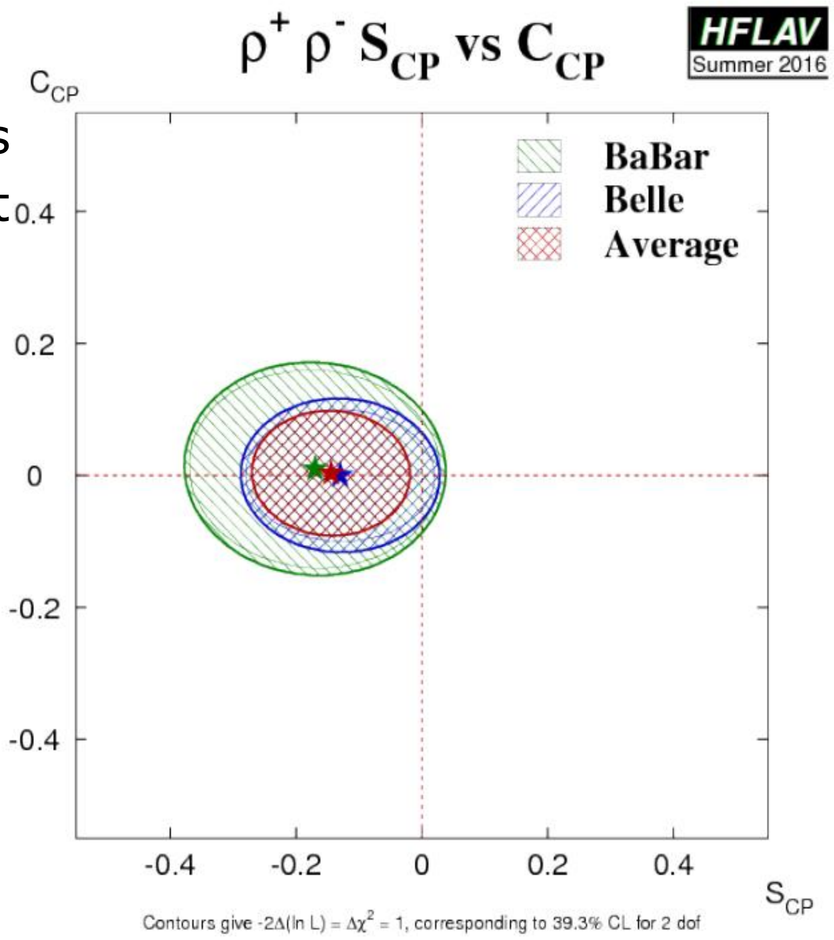
  $\rightarrow$ possible contribution from $\rho^0\rho^0$

- 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:

  $\rightarrow$ almost a pure CP-even state



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

$\alpha = (93.3 \pm 5.6)°$