Belle II

(Heavy) Flavour Physics **2/2**
CP Violation

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Melbourne
June/July 2016

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ARC Centre of Excellence for Particle Physics at the Terascale

Outline

Part 1: Flavour and Rare decays

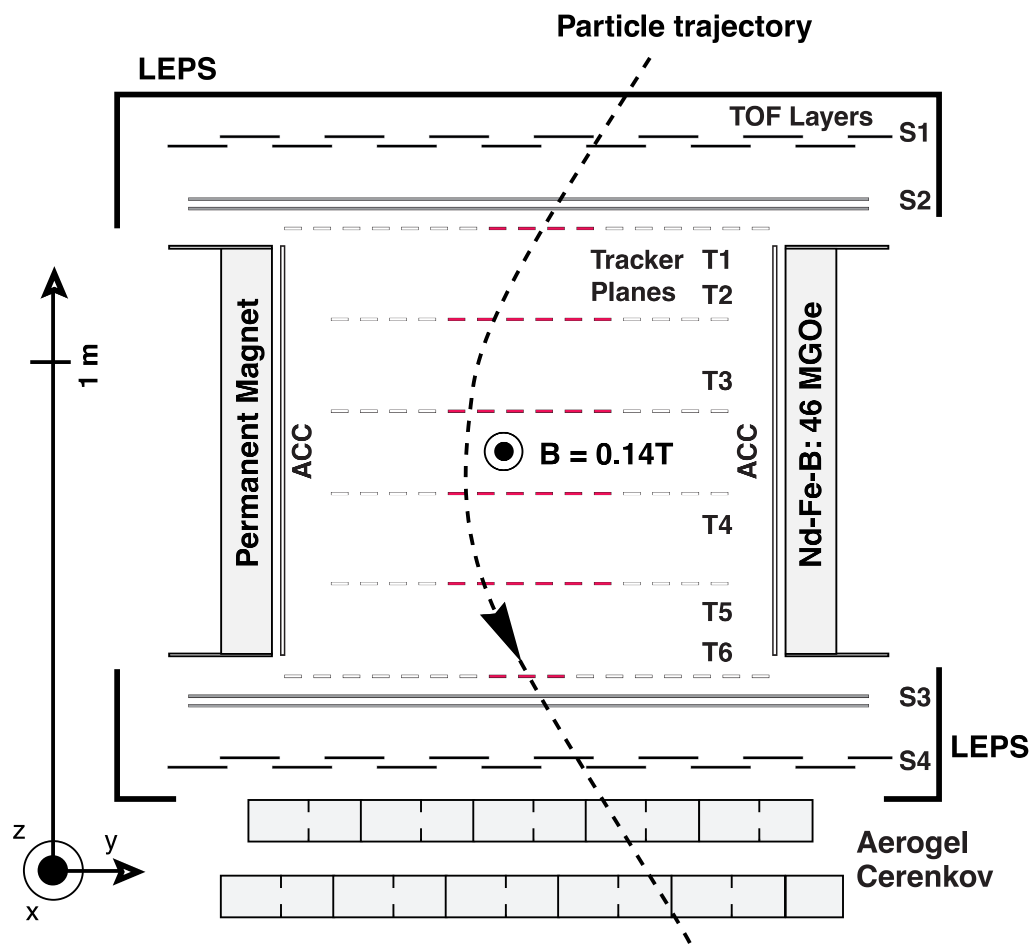
1. What is flavour physics & why is it interesting?
2. Brief history of flavour
3. CKM mechanism
4. Experimental facilities
5. Tree level Decays
6. Flavour Changing Neutral Currents
7. Lepton decays

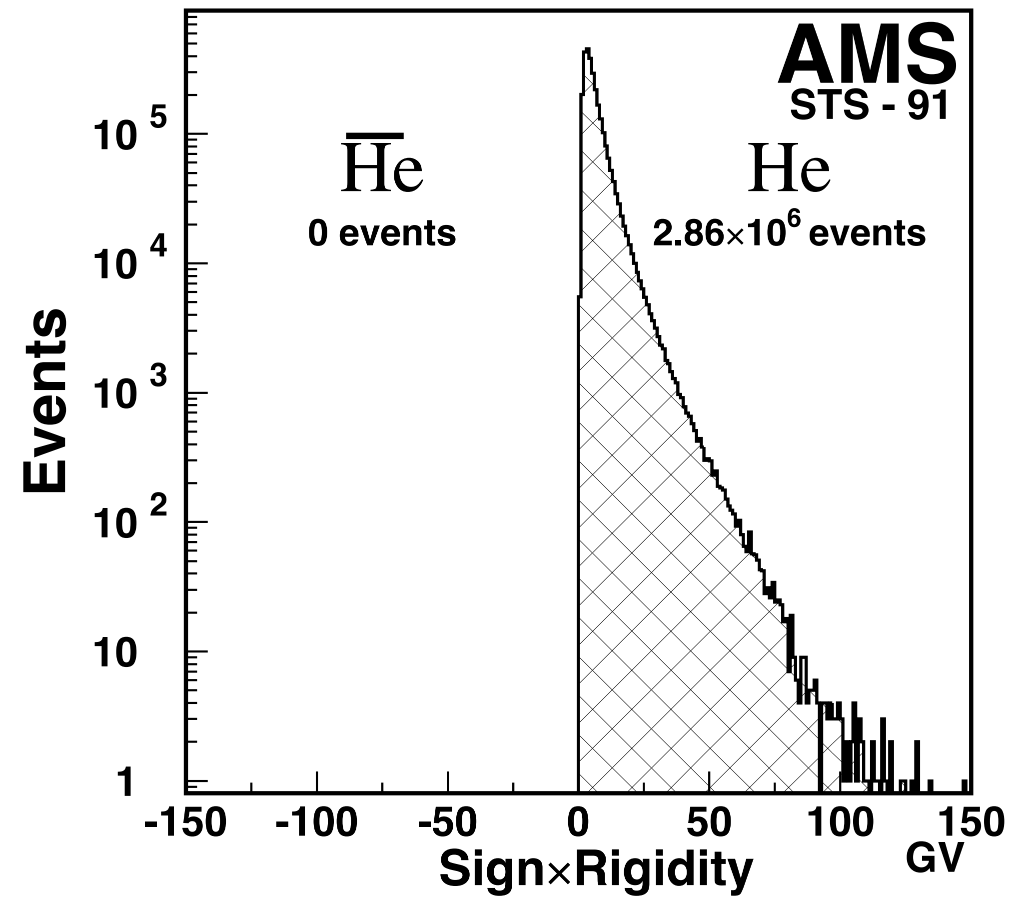
Part 2: CP violation

8. **The Unitarity triangle**
9. **Meson-antimeson oscillations**
10. **Measurements of CP violation**
11. **Global analyses of flavour data & future facilities**

1. CP Violation & the Baryon Asymmetry of the Universe

AMS ca. 2000 & Planck 2015





Determined from power spectrum of the CMB & BBN.

Planck/WMAP/COBE

$$\eta = \frac{n_B}{n_\gamma} = \frac{n_b - b_{\bar{b}}}{n_\gamma} = 6.05(7) \times 10^{-10}$$

Ingredients for Barry O'Genesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

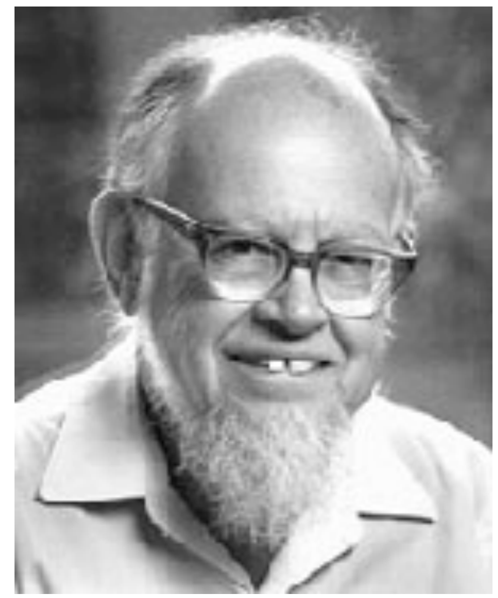
Hierarchy of the CKM Matrix

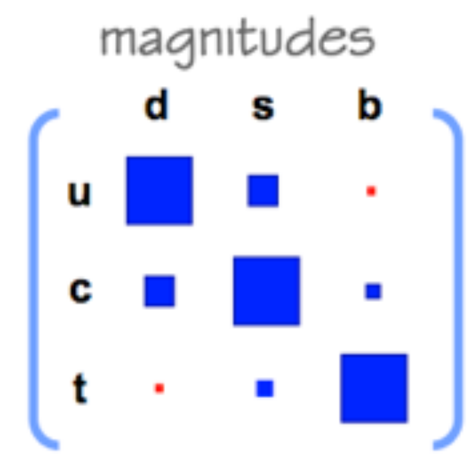
- Wolfenstein Parametrization: Expansion in $\lambda = \sin\theta_C \approx 0.22$

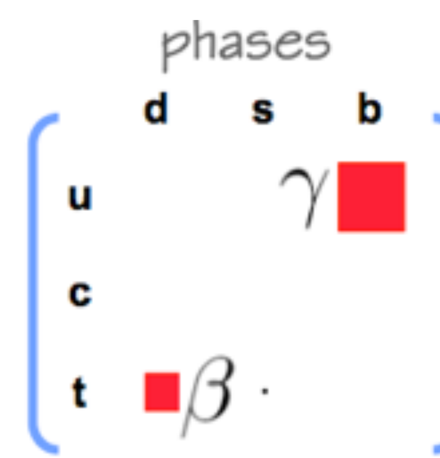
  (4 parameters: $\lambda \approx 0.22$, $A \approx 1$, ρ, η)

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

$$= \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda^2)$$



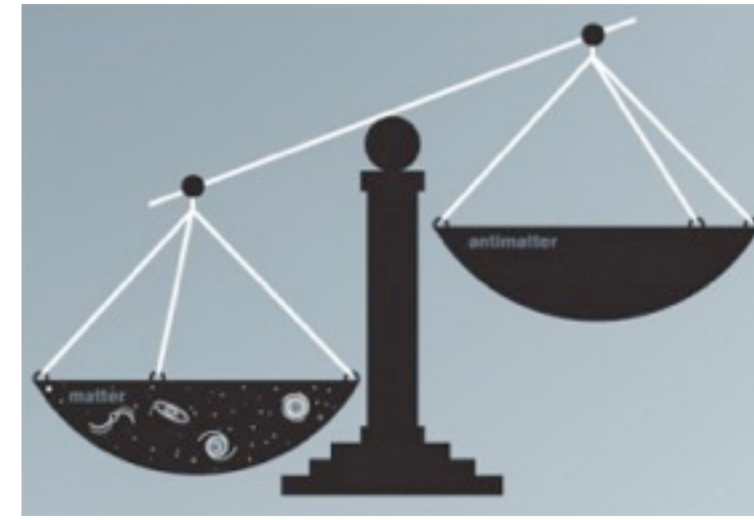




$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CP Violation and the BAU

- We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation
- Introduce parameterisation invariant measure of CP in quark sector, **J**.



$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

$$F_u\, F_d\, J \neq 0$$

where:

$$\begin{aligned} F_u &= (m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2) \\ F_d &= (m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2) \\ J &= \mathrm{Im}[V_{us} V_{cd} V_{cs}^* V_{ub}^*] \\ &= c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta \\ &= A^2 \lambda^6 \eta \end{aligned}$$

Mass scale **M** can be taken to be EW scale O(100 GeV)
This gives an asymmetry **O(10^{-17})** much below observed **O(10^{-10})**

The Six Unitarity Triangles

$$V^\dagger V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

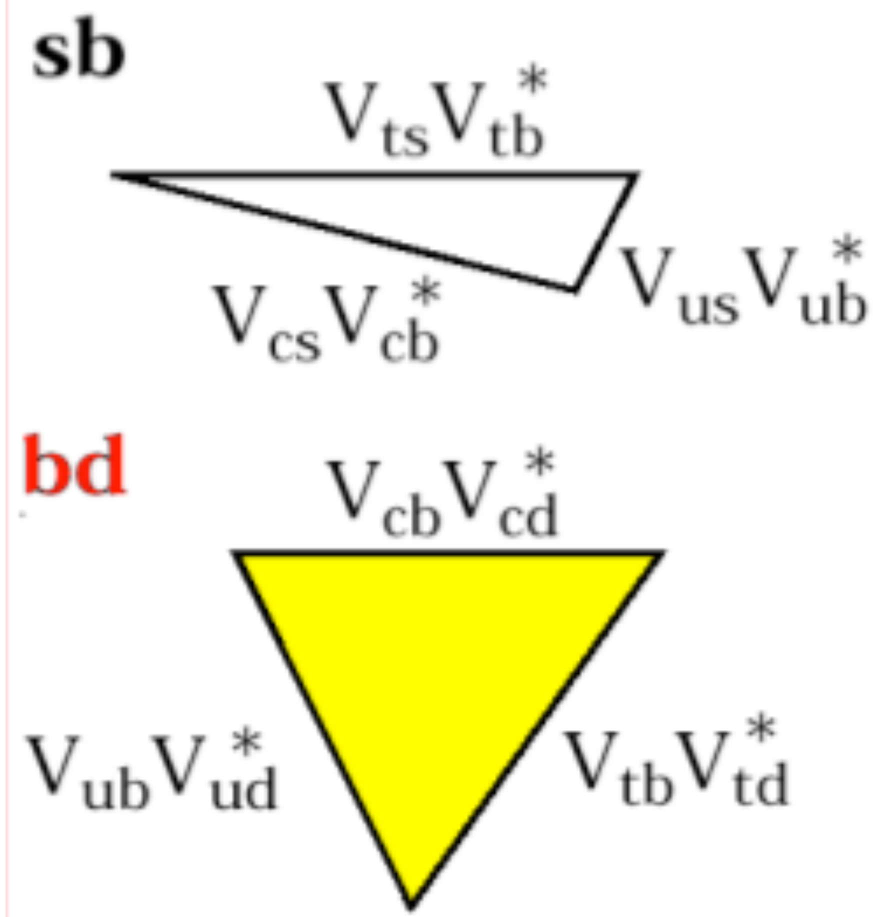
$$(d)\; V_{td}V_{cd}^* + V_{ts}V_{cs}^* + V_{tb}V_{cb}^* = 0$$

$$\propto\lambda^2 \qquad \propto\lambda^2 \qquad \propto\lambda^4$$

$$(e)\; V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

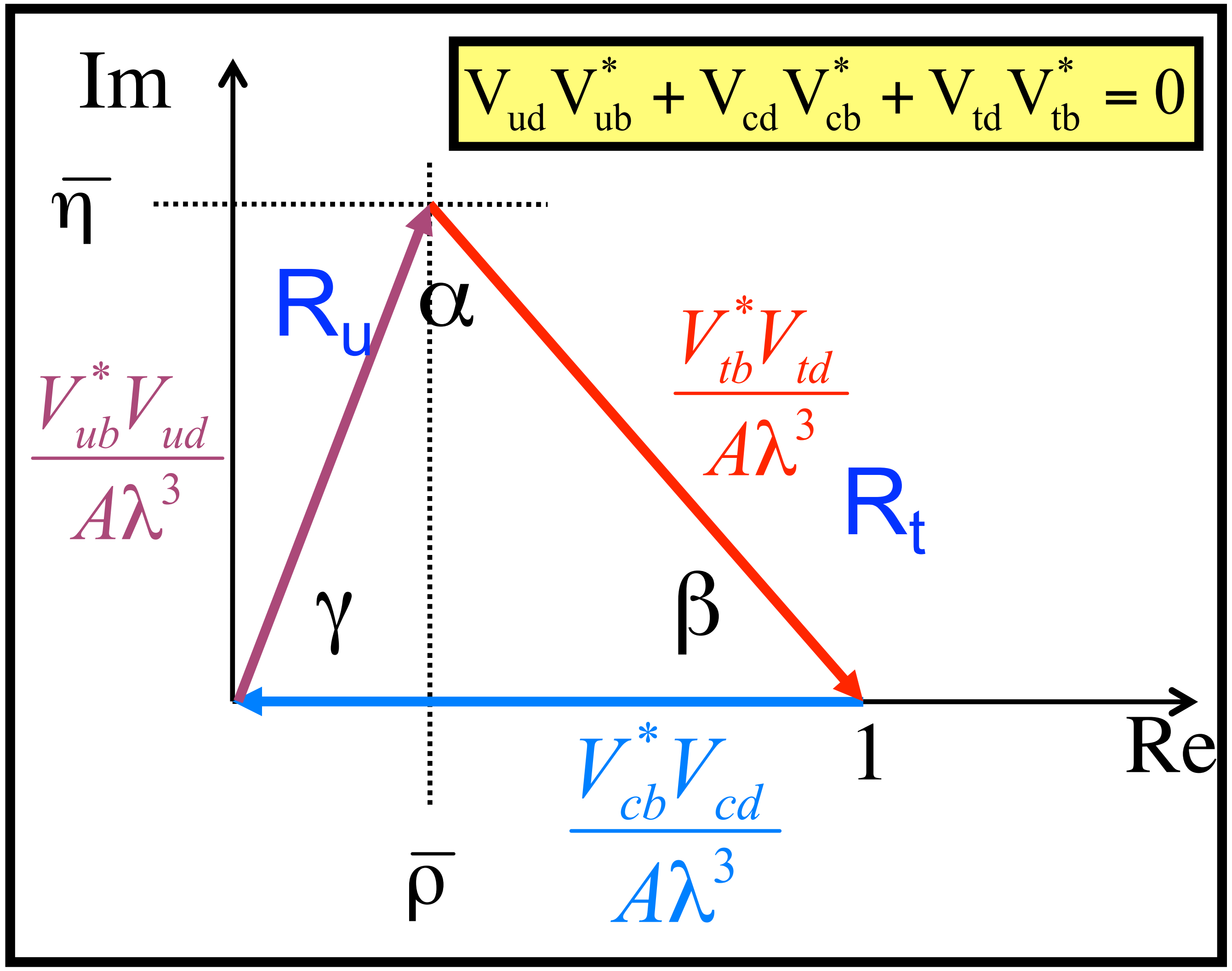
$$(f)\; V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0$$

$$\propto\lambda^3 \qquad \propto\lambda^3 \qquad \propto\lambda^3$$



Unitarity Triangles for B_d

The Unitarity Triangle
("B_d Triangle")



$V_{td} = |V_{td}|\, e^{-i\beta}$

$V_{ub} = |V_{ub}|\, e^{-i\gamma}$

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

Consistency check for new CP violation sources

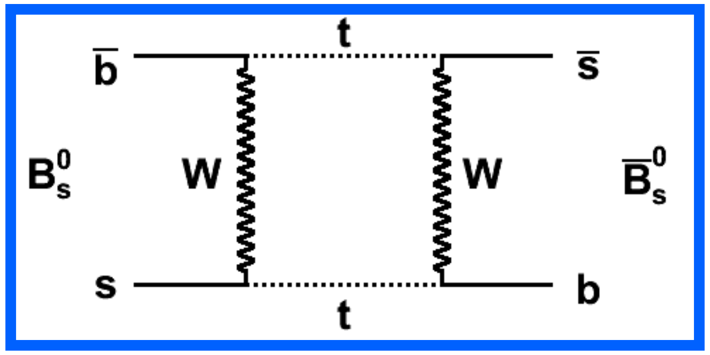
2. Meson Mixing

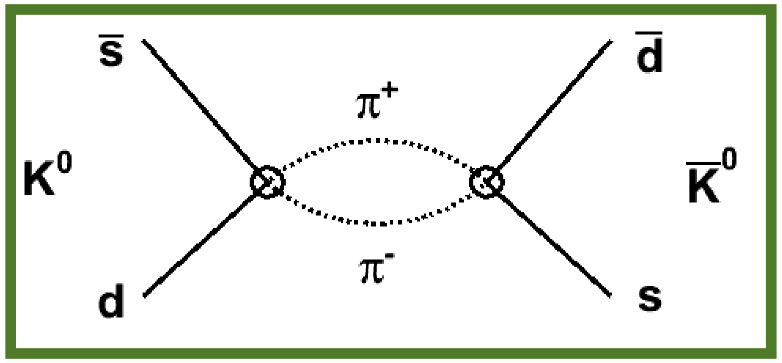
Neutral Meson Mixing

The eigenstates of flavour M^0 anti-M^0, degenerate in pure QCD, mix under weak interactions.

M^0 : K^0 (anti-s d), D^0(c anti-u), B^0(anti-b d), B_s^0(anti-b s)

Mixing can occur via short distance or long distance processes





Time dependent Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

H is Hamiltonian, **M** & **Γ** are 2x2 Hermitian matrices

Mixing formalism

Hamiltonian

$$\mathcal{H} = M - \frac{i}{2}\Gamma = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \mathcal{H}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

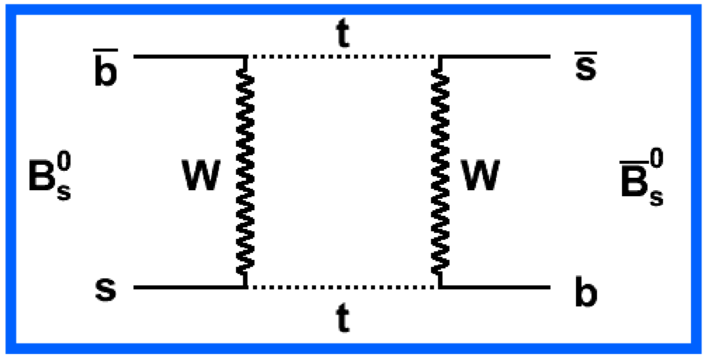
Diagonalising

$$\begin{aligned} \Delta m &= m_{B_H} - m_{B_L} = 2\,|M_{12}| \\ \Delta\Gamma &= \Gamma_L - \Gamma_H = 2\,|\Gamma_{12}|\cos\phi \end{aligned}$$

$$\phi = \arg\left(-M_{12}/\Gamma_{12}\right)$$

Neutral Meson Mixing: 2 Mechanisms

Δm: value depends on rate of mixing diagram

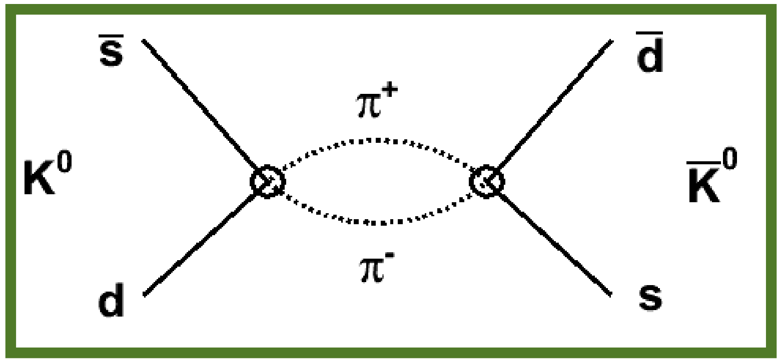


$$x = \frac{\Delta m}{\Gamma} \sim \mathcal{O}(1)$$

short distance, virtual

ΔΓ: value depends on widths of decays into common final states (CP - eigenstates)

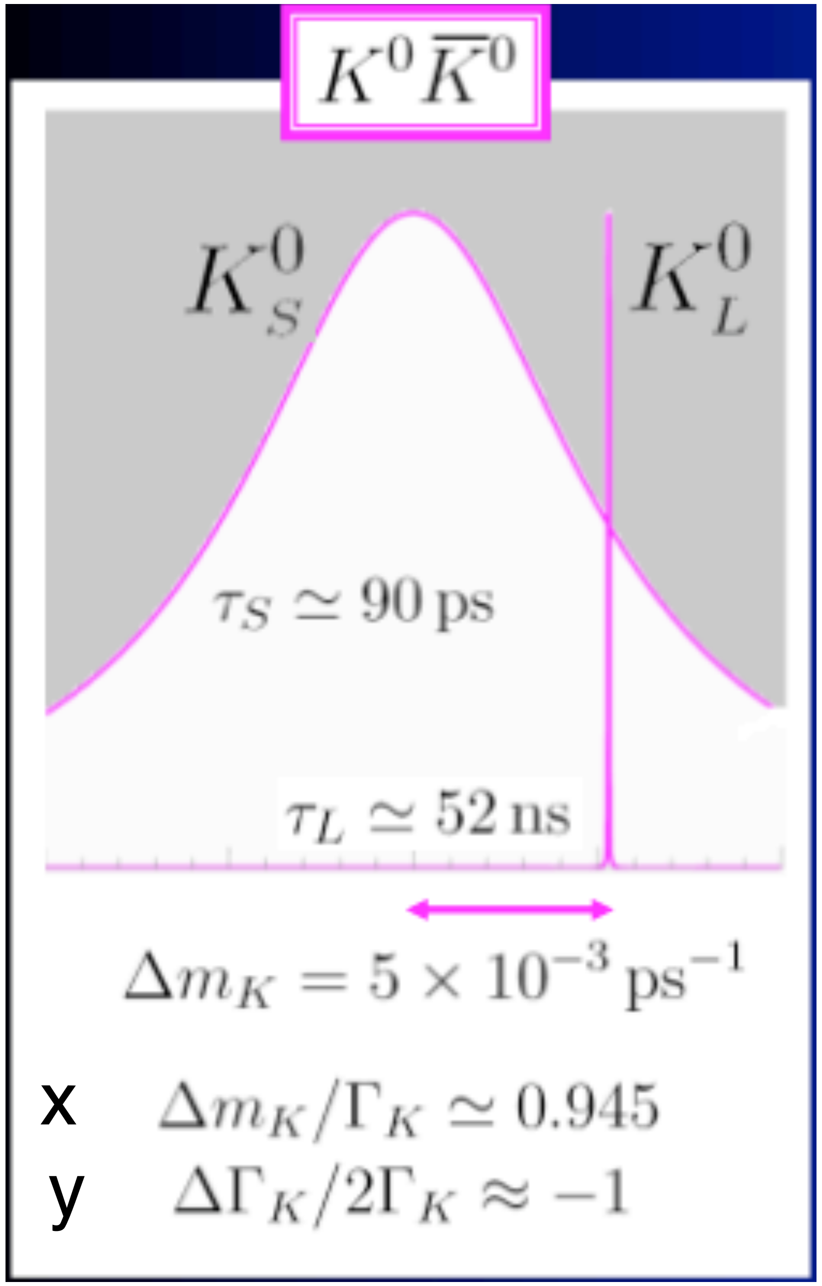
large for K, small for D and B

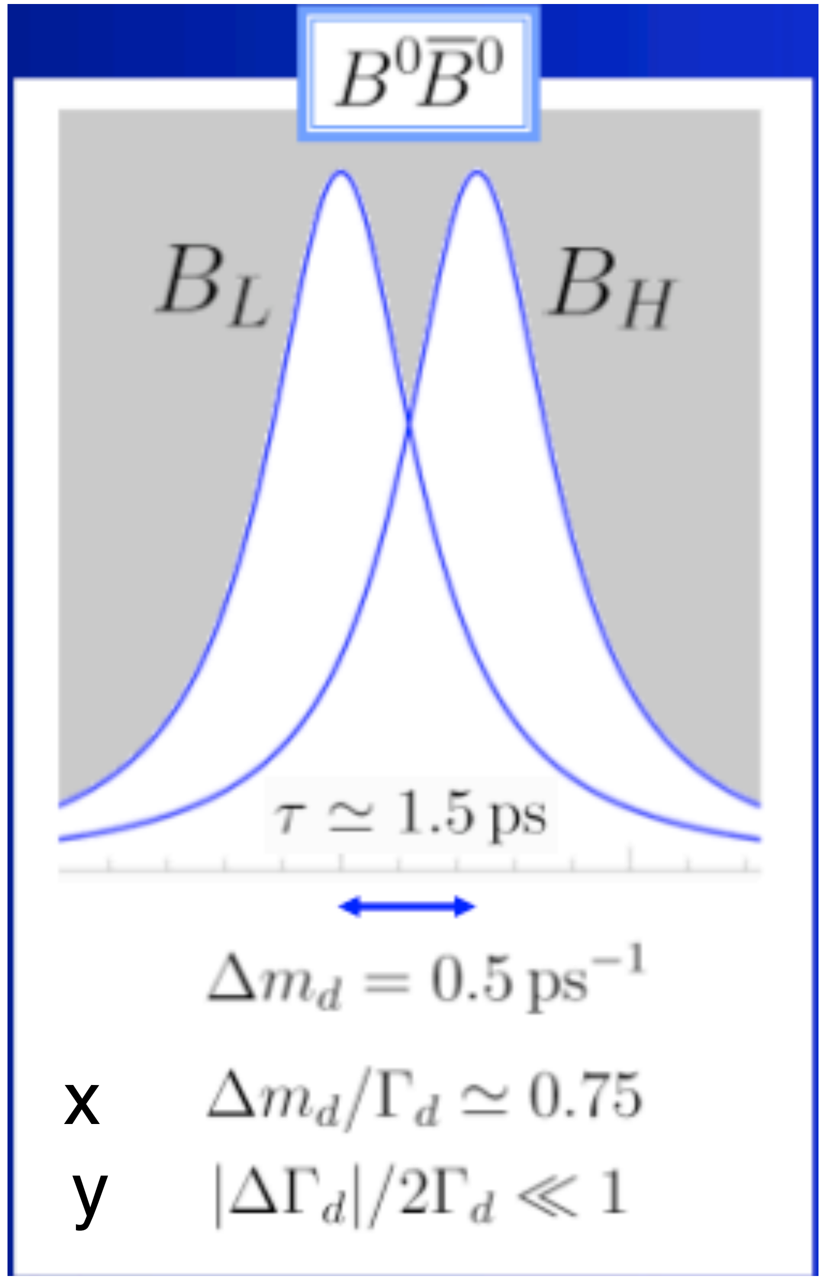


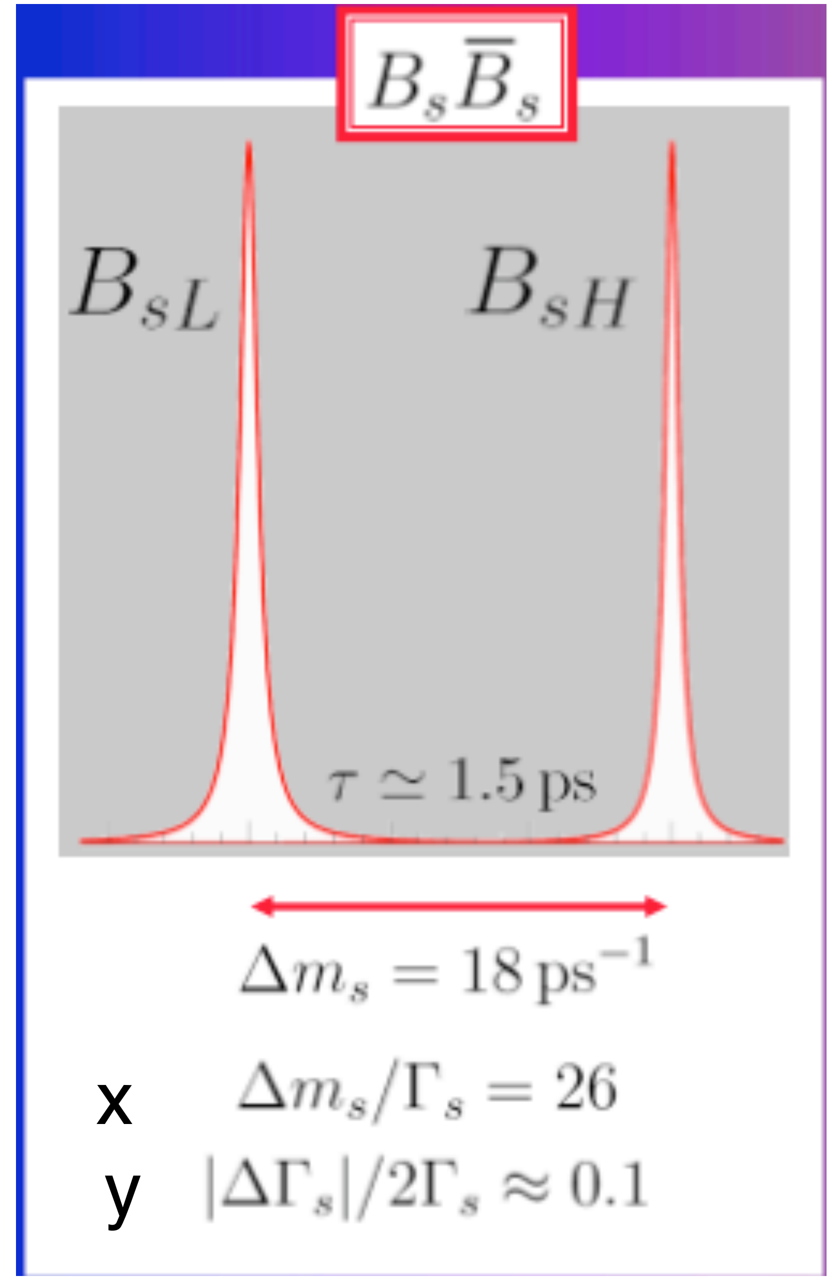
$$y = \frac{\Delta\Gamma}{\Gamma} \sim \mathcal{O}(1)$$

Long distance, on shell states
important for K, not B mesons

The Neutral Meson-Antimeson Systems





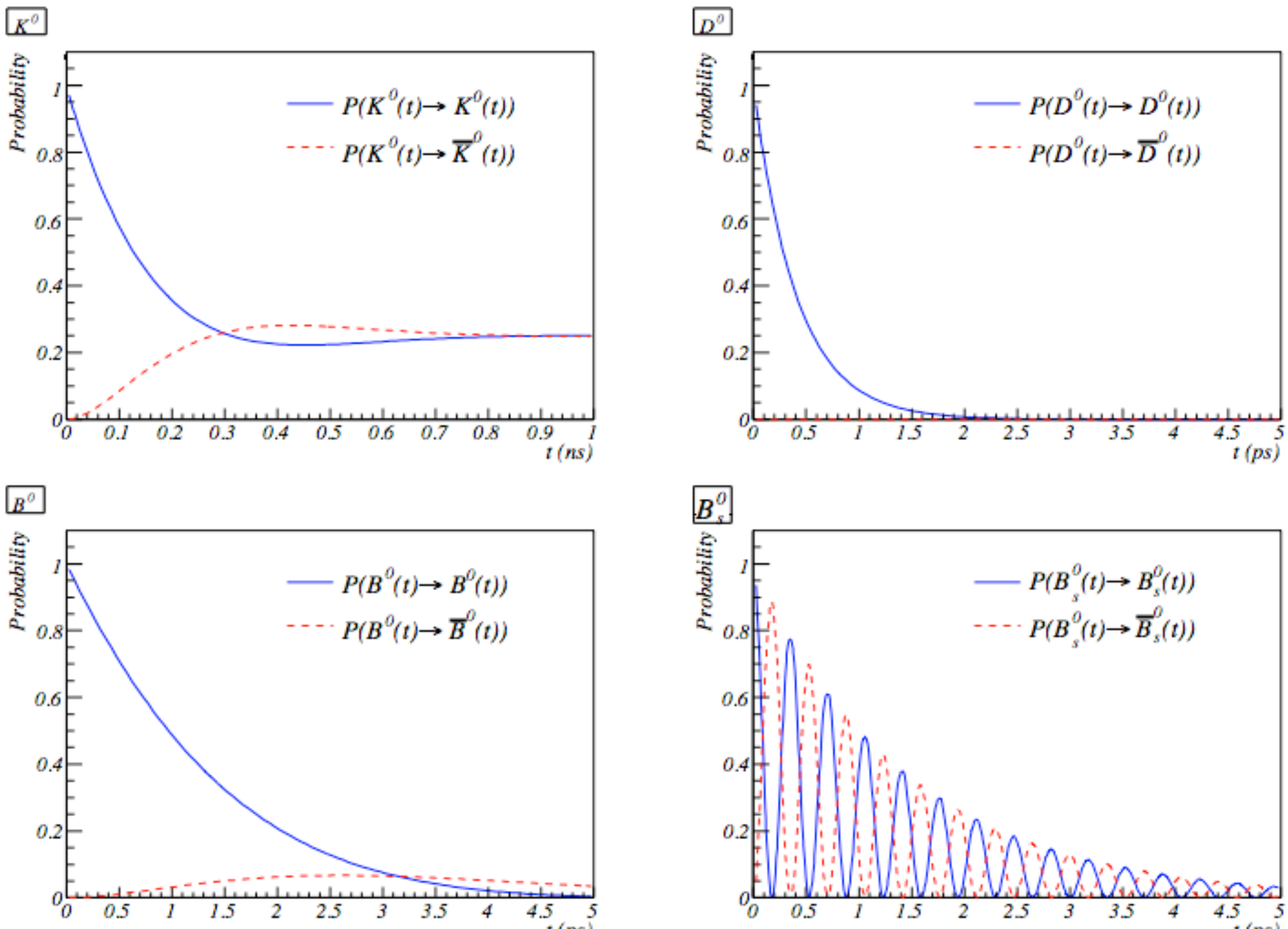


$D^0/\overline{D^0}$

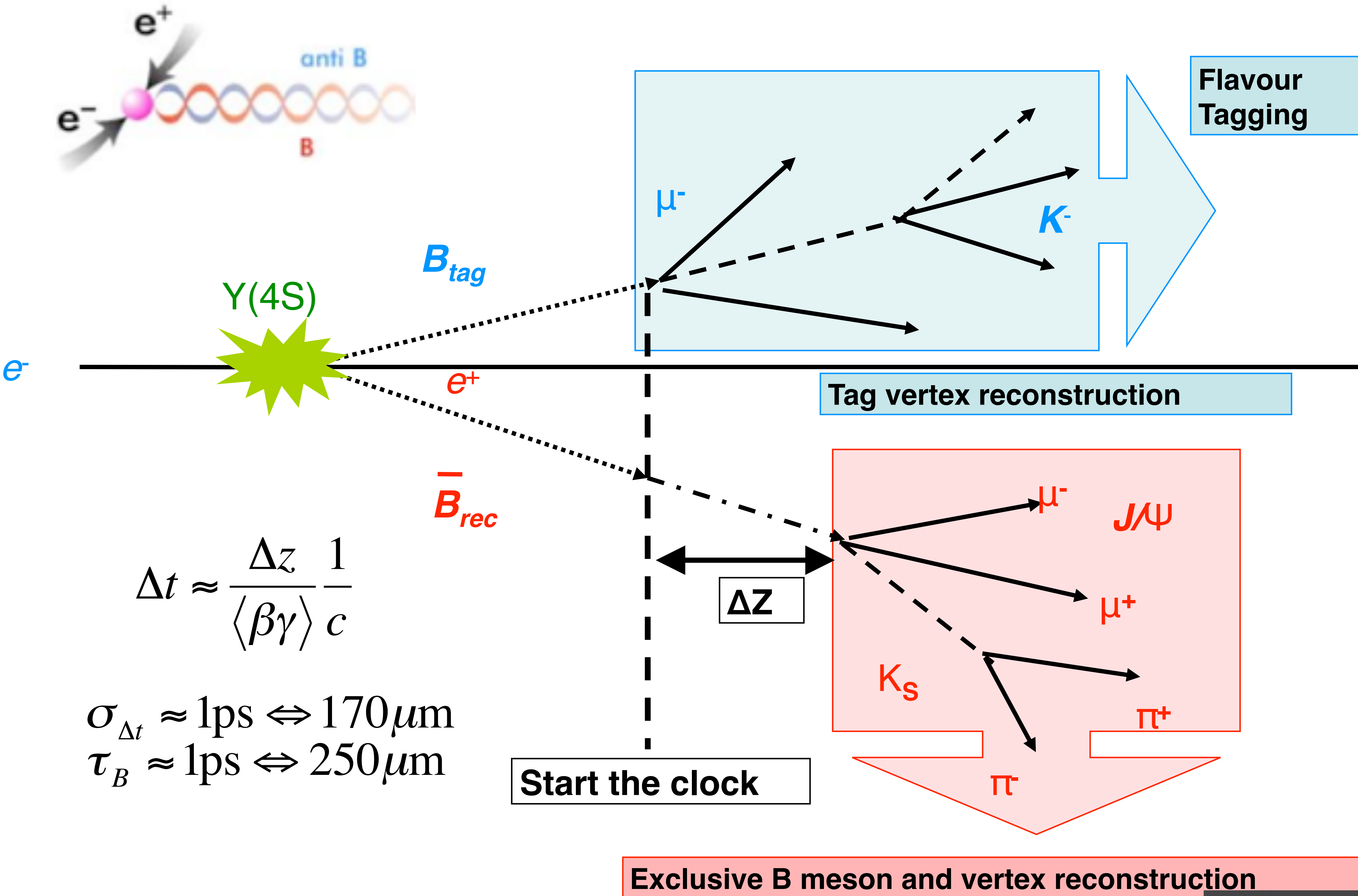
τ=0.4 ps^{-1}
mixes slowly
$\Delta m_D \sim 0.01$

Δm=2π ×frequency of flavour oscillation (1 ps^{-1} →160 GHz)

Mixing in the K, D, B, B_s Systems



CP Asymmetry at e+e- collider

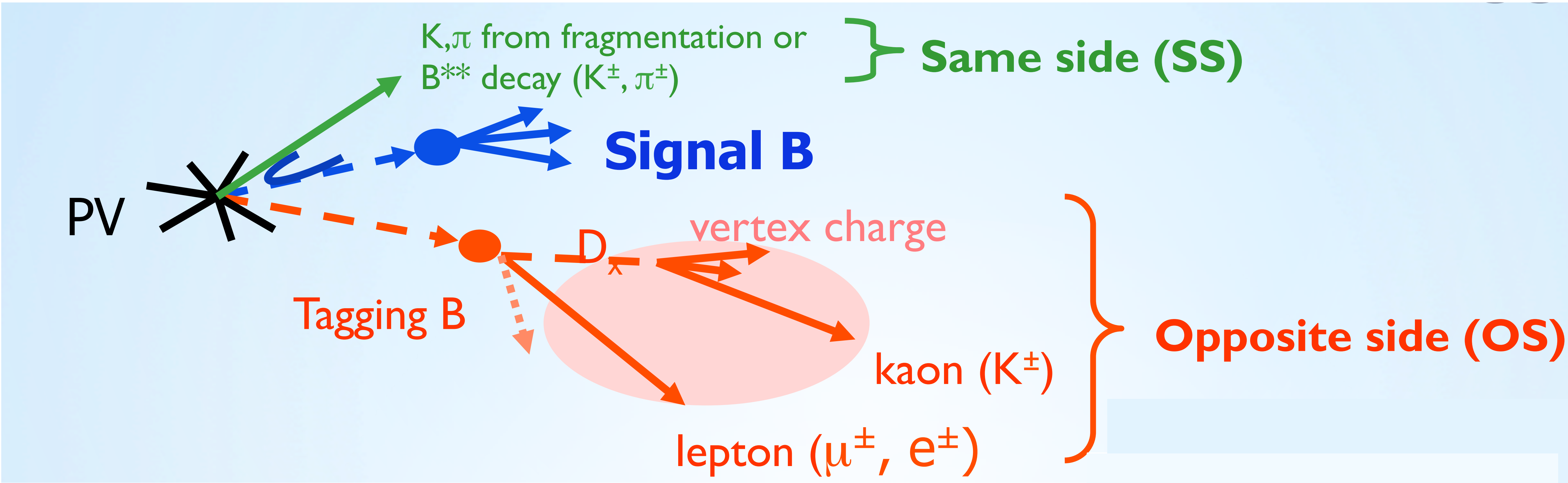


$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle}\frac{1}{c}$$

$$\sigma_{\Delta t} \approx 1\text{ps} \Leftrightarrow 170\mu\text{m}$$
$$\tau_B \approx 1\text{ps} \Leftrightarrow 250\mu\text{m}$$

CP asymmetry at hadron collider

b-hadrons of all species
Oscillation occurs incoherently



Flavour tagging Efficiency ~10x less than e+e-, time resolution much better.

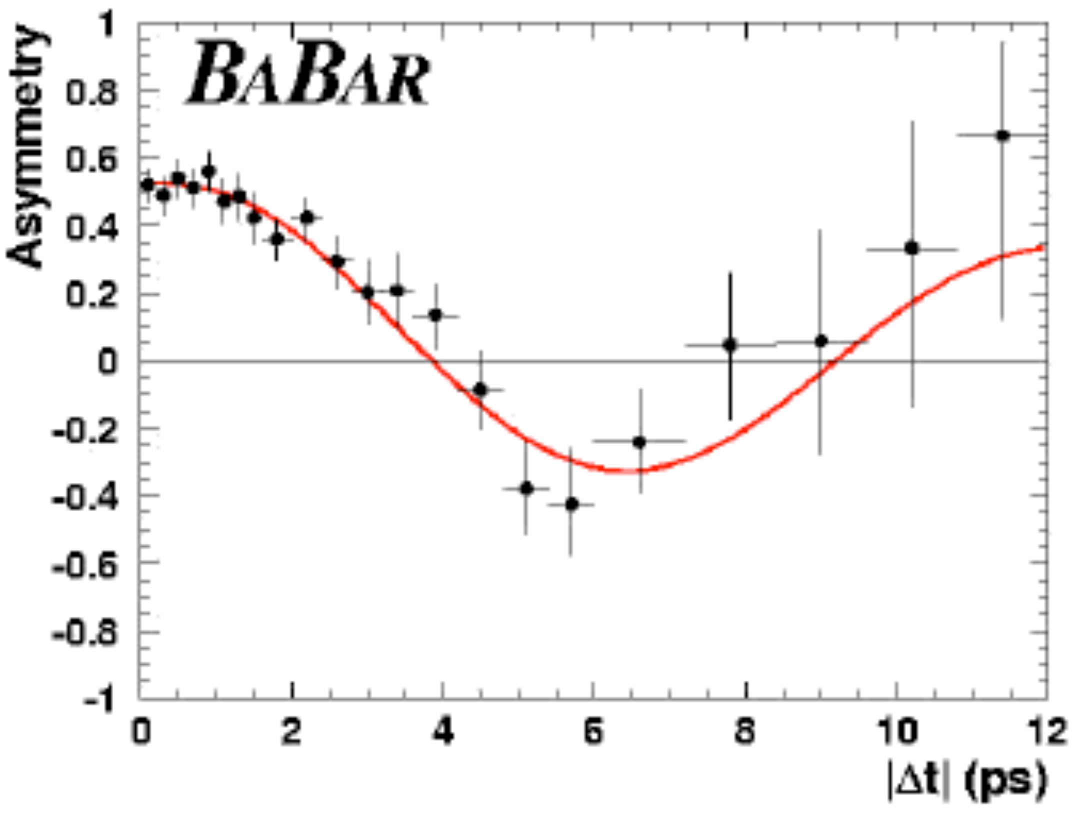
	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~100 fs	~70 fs	87 fs	**45 fs**

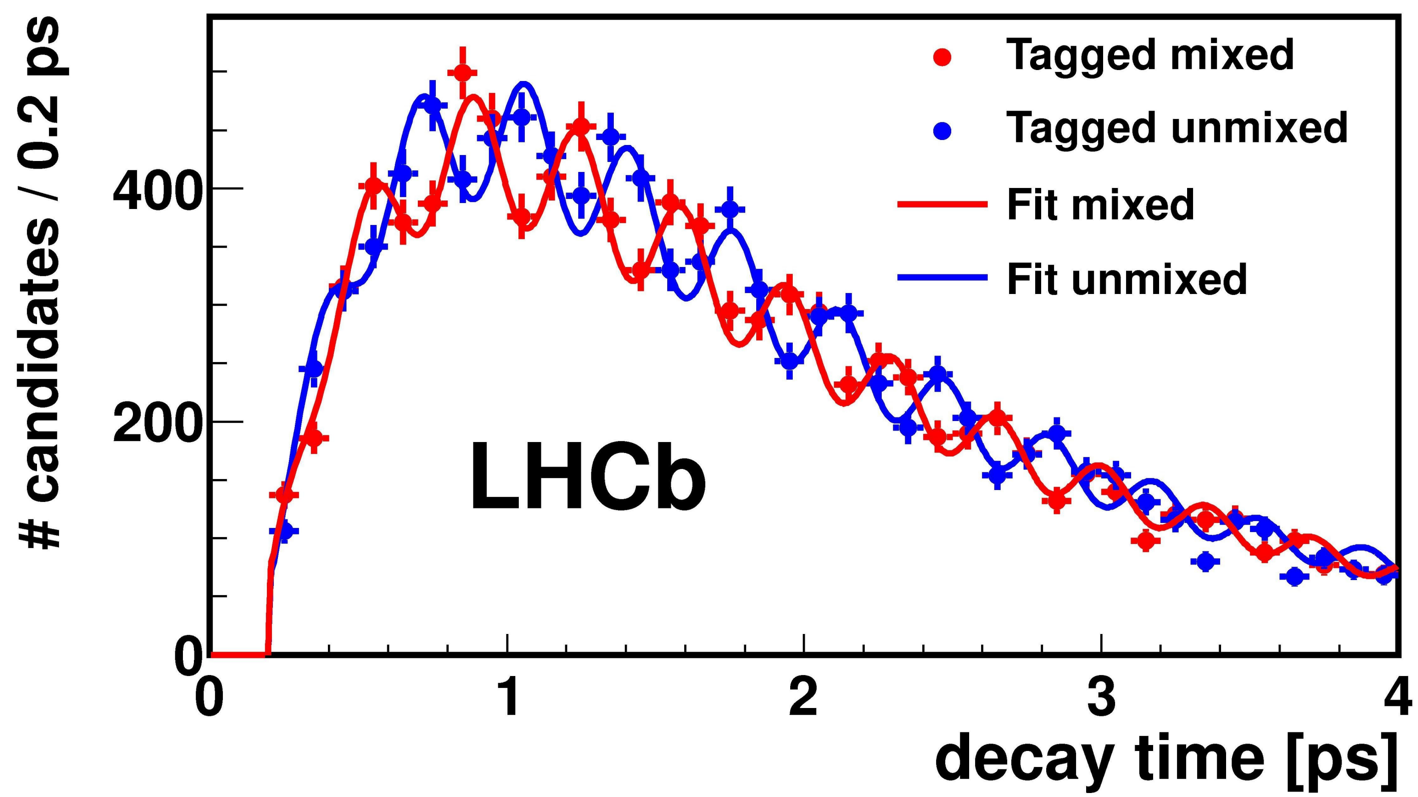
B mixing data

BABAR @ SLAC

LHCb @ CERN

$$A_{\text{mix}}(t) = \frac{N(B)_{\text{un-mixed}}(t) - N(B)_{\text{mixed}}(t)}{N(B)_{\text{un-mixed}}(t) + N(B)_{\text{mixed}}(t)} \sim \cos(\Delta m t)$$



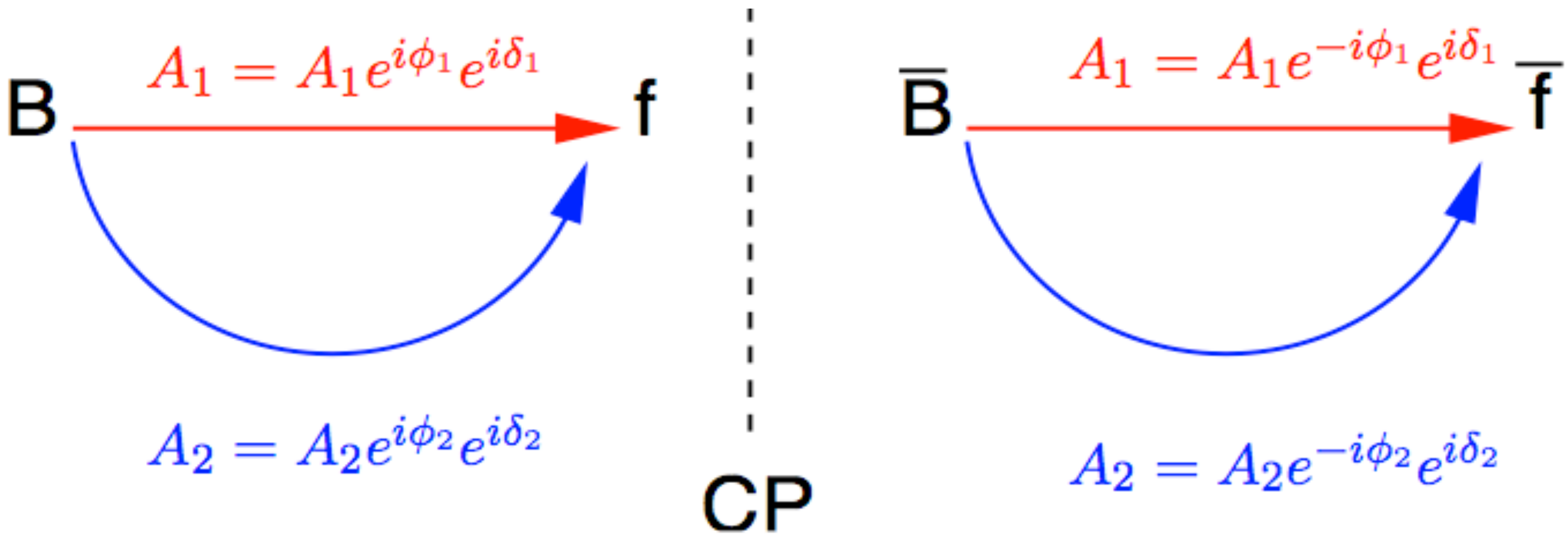


3. CP Violation with B mesons

CP Violation

CP violation caused by different interference effects in particle and anti-particle decays

- One of the two amplitudes could be from mixing
- Due to complex part of CKM matrix



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

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

For CPV A1 and A2 need to have **different weak phases Φ** and different **CP invariant (e.g. strong) phases δ**

Classification of CP-violating Effects

1. CP violation in the decay
   (direct CP violation)

$$\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f}) \Leftrightarrow \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

2. CP violation in mixing
   (indirect CP violation)

$$\Gamma(P^0 \to \bar{P}^0) \neq \Gamma(\bar{P}^0 \to P^0) \Leftrightarrow \left|\frac{q}{p}\right| \neq 1$$

3. CP violation in mixing/
   decay **interference**

$$\Gamma(P^0(\rightsquigarrow \bar{P}^0) \to f)(t) \neq \Gamma(\bar{P}^0(\rightsquigarrow P^0) \to f)(t)$$

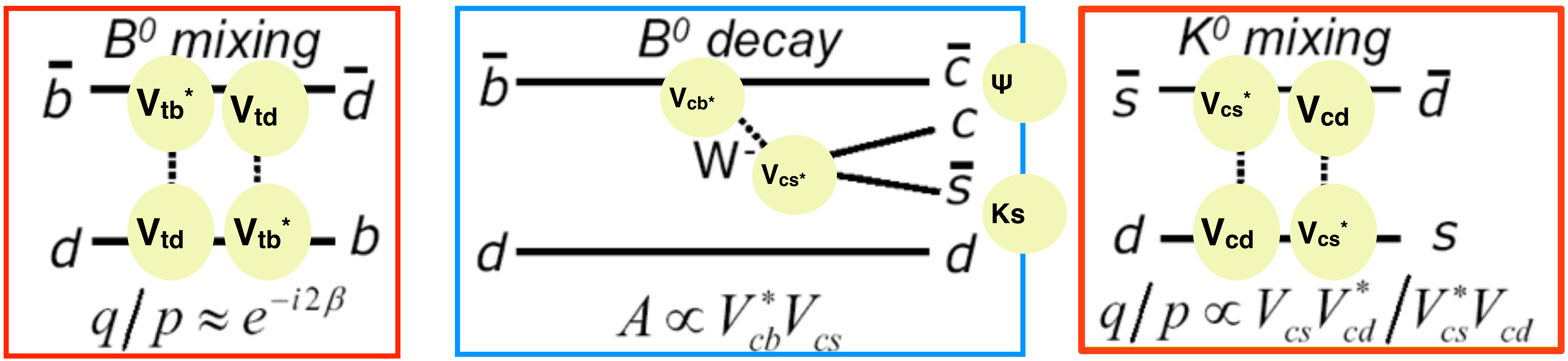
large strong phase effects in charm sector make it difficult to determine weak phases.

CPV in Interference

Measurement of β using CP eigenstates

CP violation in interference between **decay** w/ and w/o **mixing**

The "Golden Decay": **$B^0 \to J/\Psi\, K^0$**



decay

decay + mixing

$$\arg(V_{cs}V_{cb}^{*}) - \arg(V_{td}^{2}V_{tb}^{2}V_{cb}V_{cs}^{*}V_{cs}^{2}V_{cd}^{*2}) = -2\beta$$

Time dependent asymmetry

- Define the time-dependent CP asymmetry

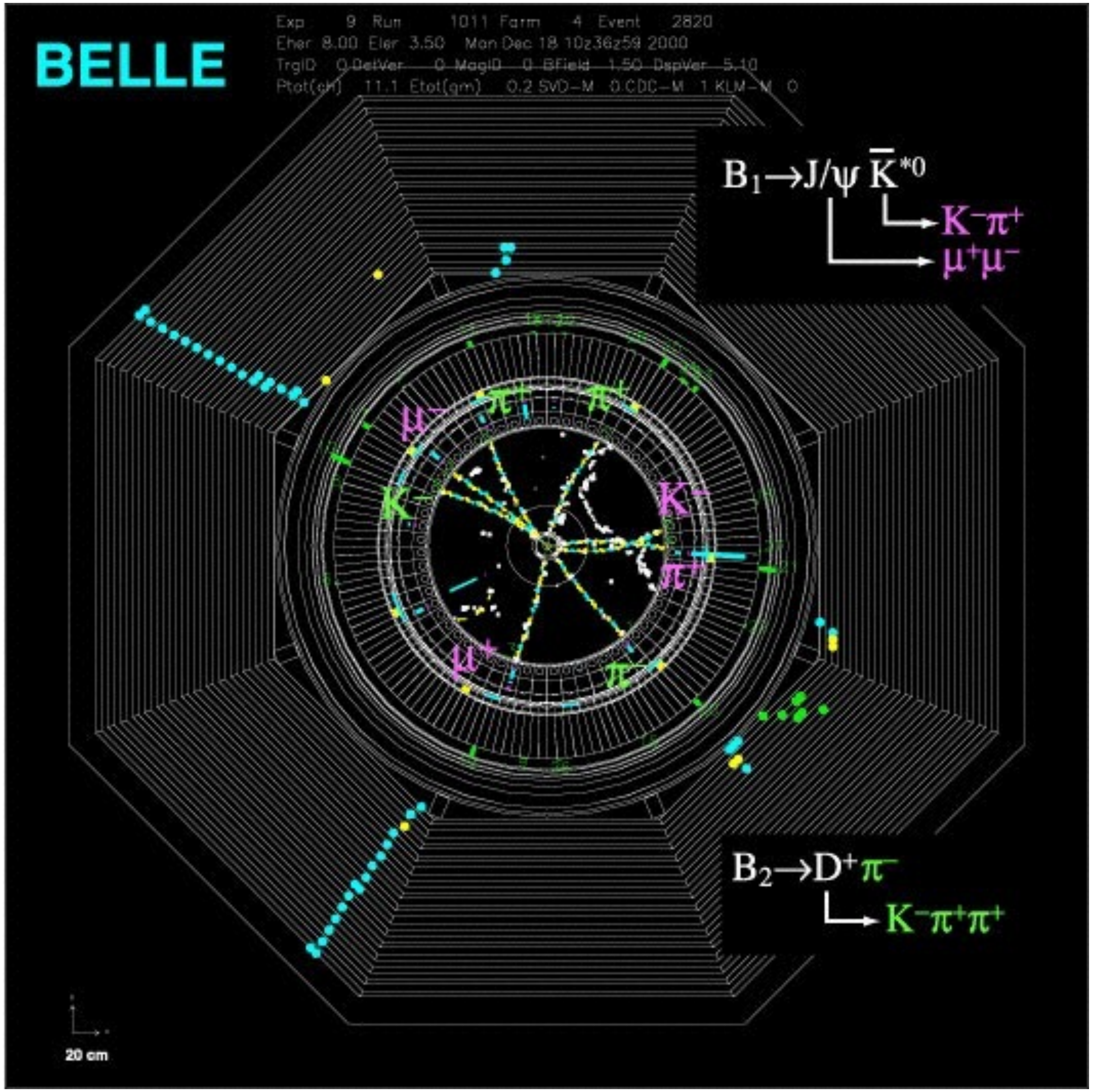
$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \to J/\psi K_S^0) - N(B^0(t) \to J/\psi K_S^0)}{N(\bar{B}^0(t) \to J/\psi K_S^0) + N(B^0(t) \to J/\psi K_S^0)} = \sin(2\beta)\sin(\Delta m t)$$

- We can measure the angle of the UT

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

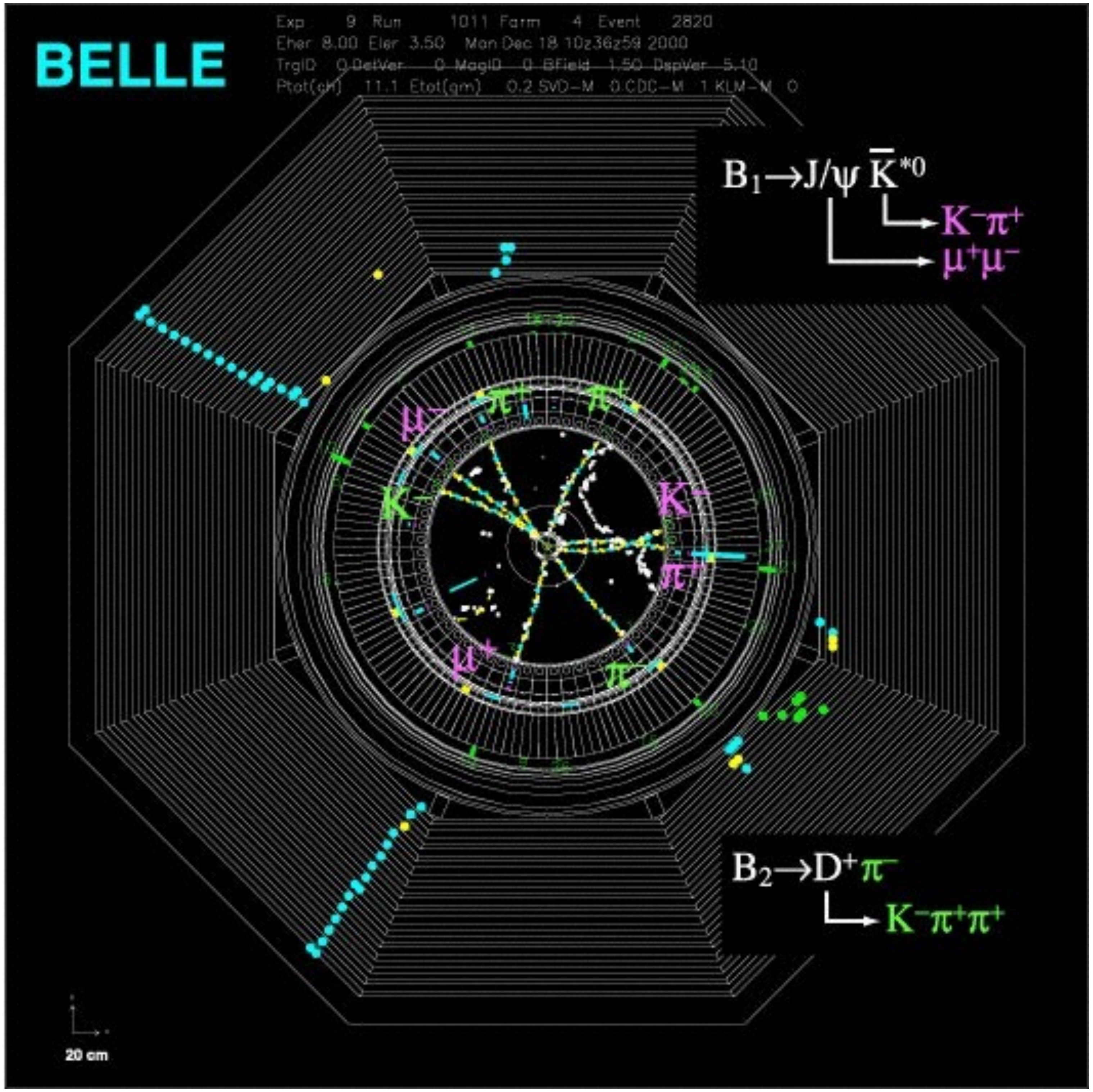
- Step 1: Produce and detect $B^0 \to f_{CP}$ events
- Step 2: Separate B^0 from $\bar{B}^0$
- Step 3: Measure the decay time t

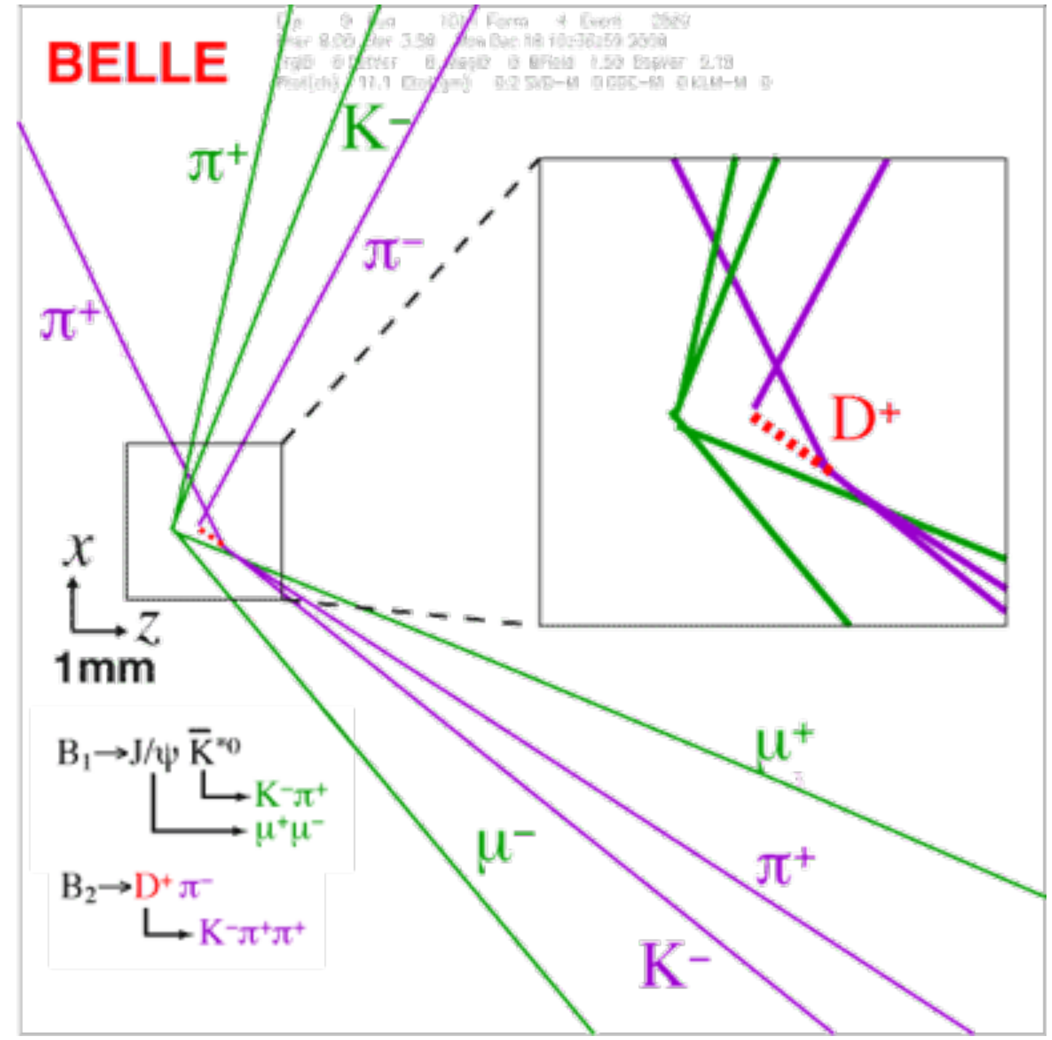
Discovery in Belle



Overpowering evidence for CP violation (matter-antimatter asymmetries)

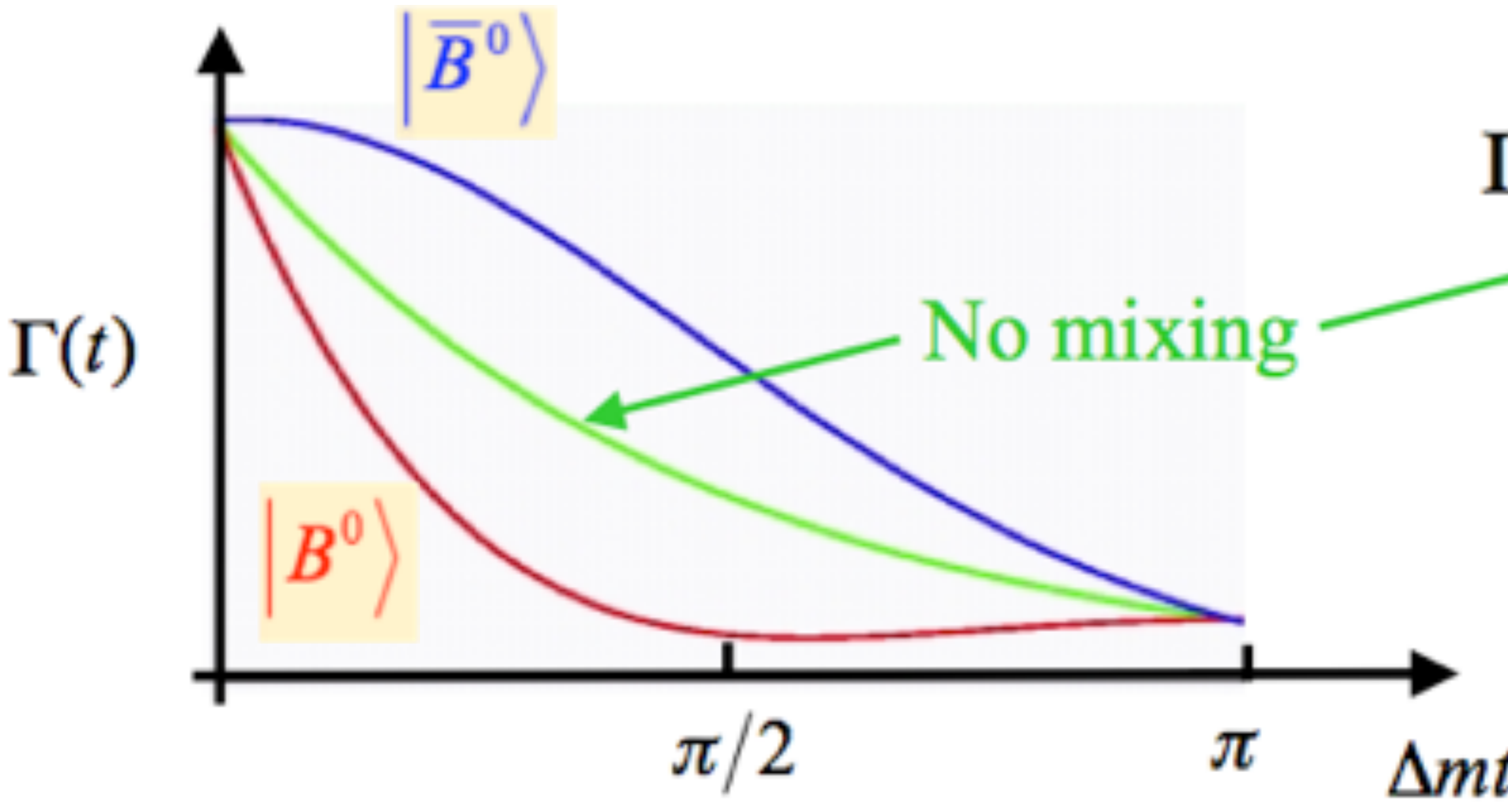
Discovery in Belle





Overpowering evidence for CP violation (matter-antimatter asymmetries)

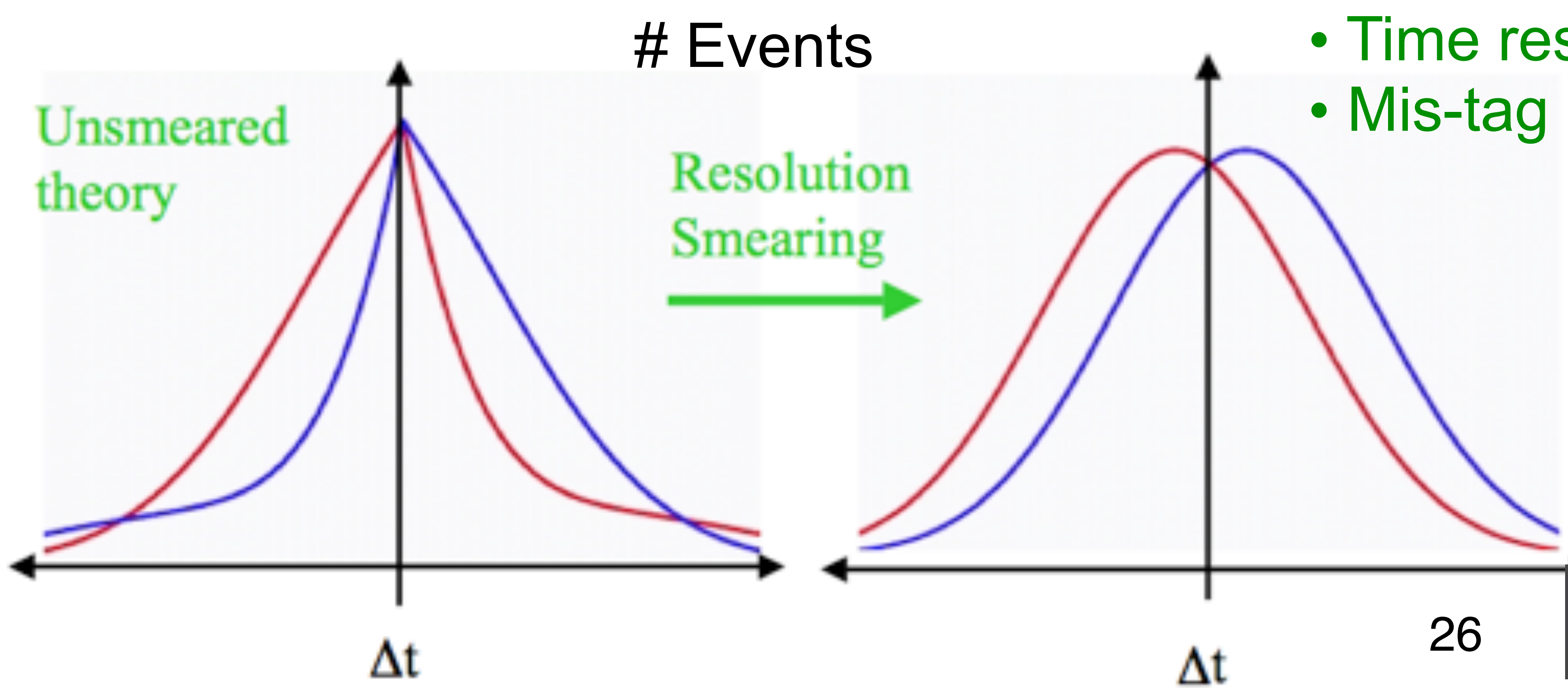
sin2β Measurement Principle



$$\Gamma(t) = \frac{e^{-t/\tau_B}}{\tau_B}$$

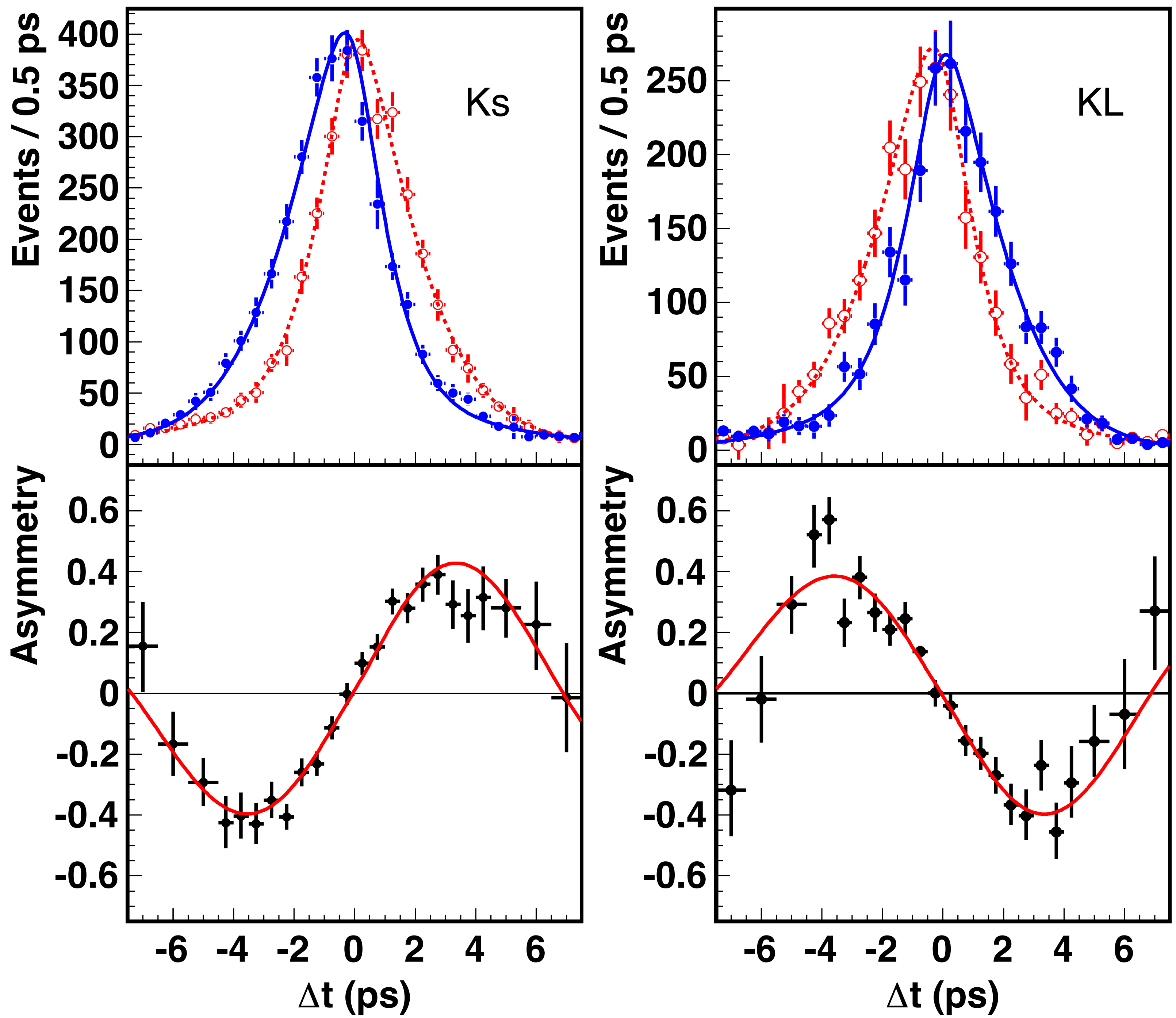
× [1 ± sin(2β) sin(Δmt)]

- Time resolution
- Mis-tag probability



sinβ Results

772M BB; PRL 108, 171802 (2012)

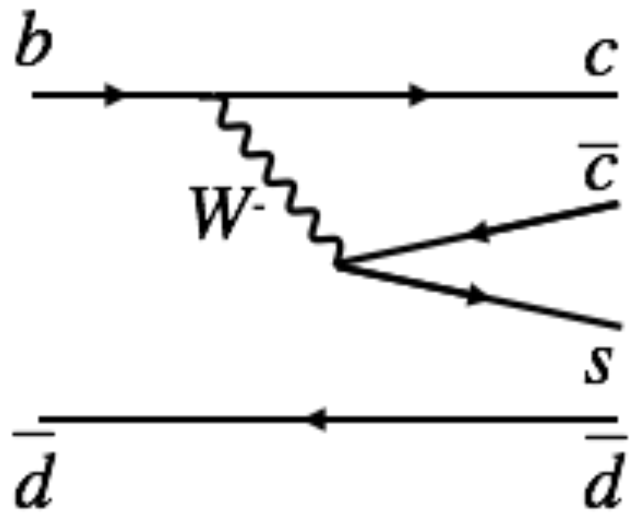


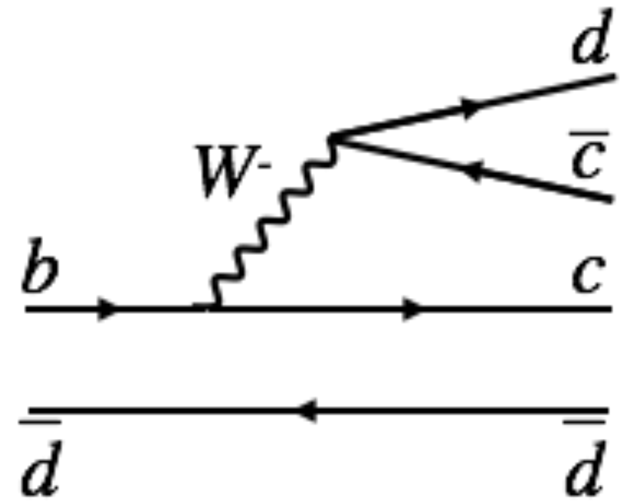
$$\sin 2\beta = 0.667 \pm 0.023 \pm 0.012$$

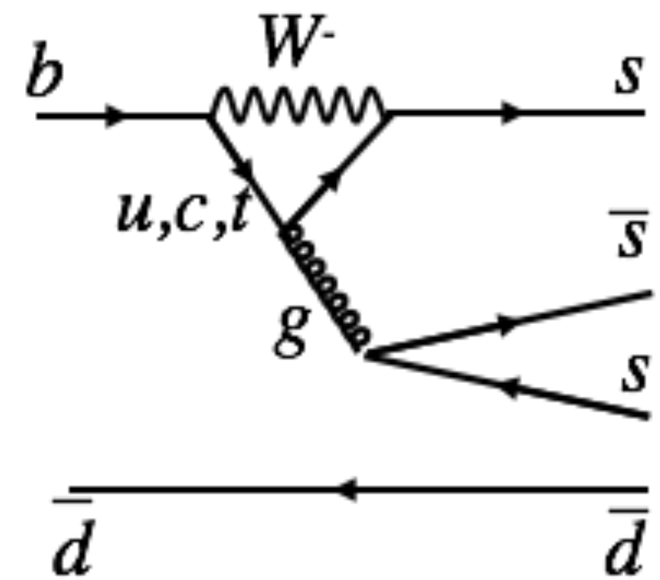
sin2β and the Nobel Prize

"... As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier."

Looking for new physics in Time Dep. CPV







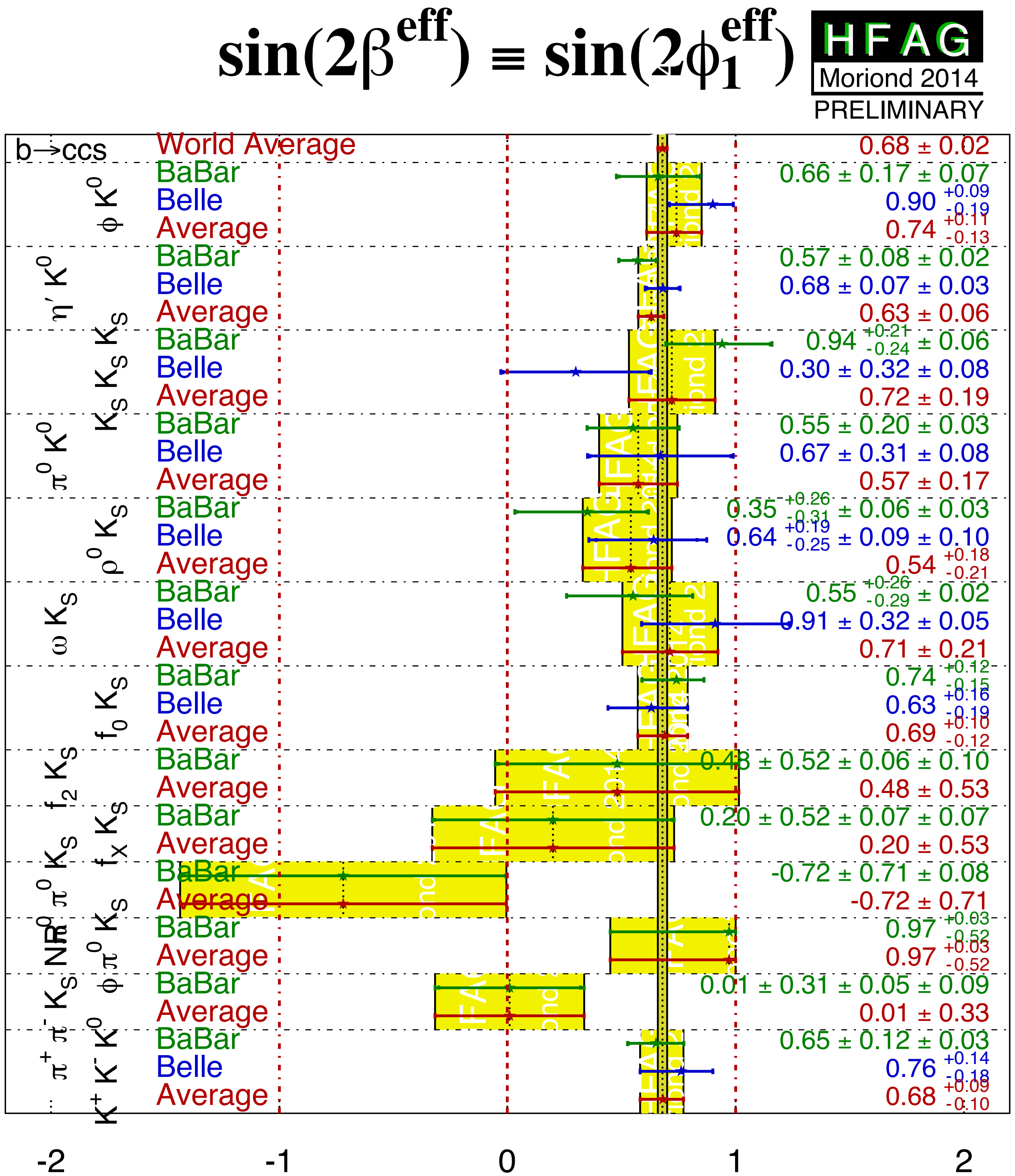
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \to K_S^0 \pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0,$ $K_S^0 K_S^0 K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$

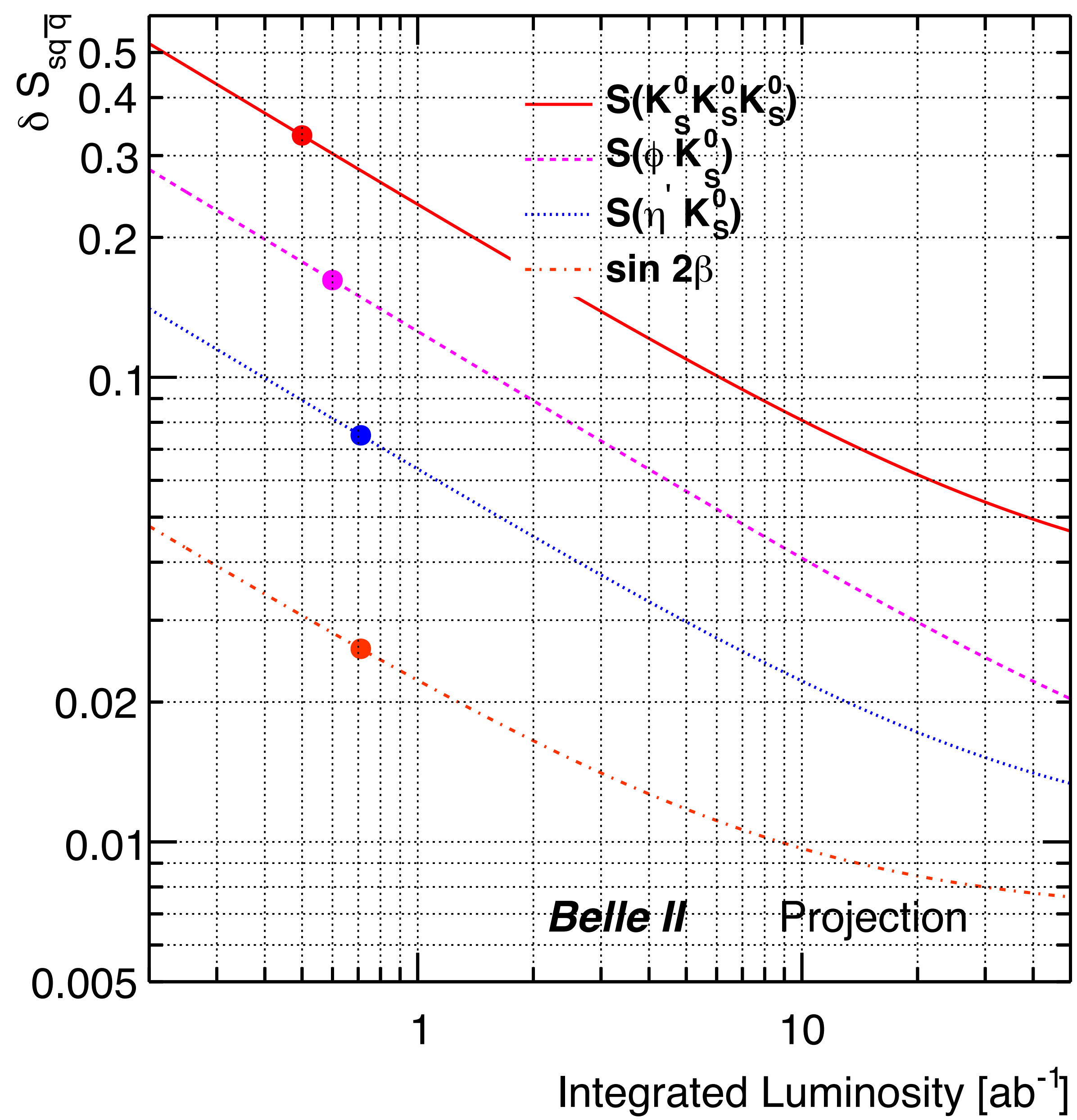
← Increasing Tree diagram amplitude

Increasing NP sensitivity →

Penguin sin 2Φ1

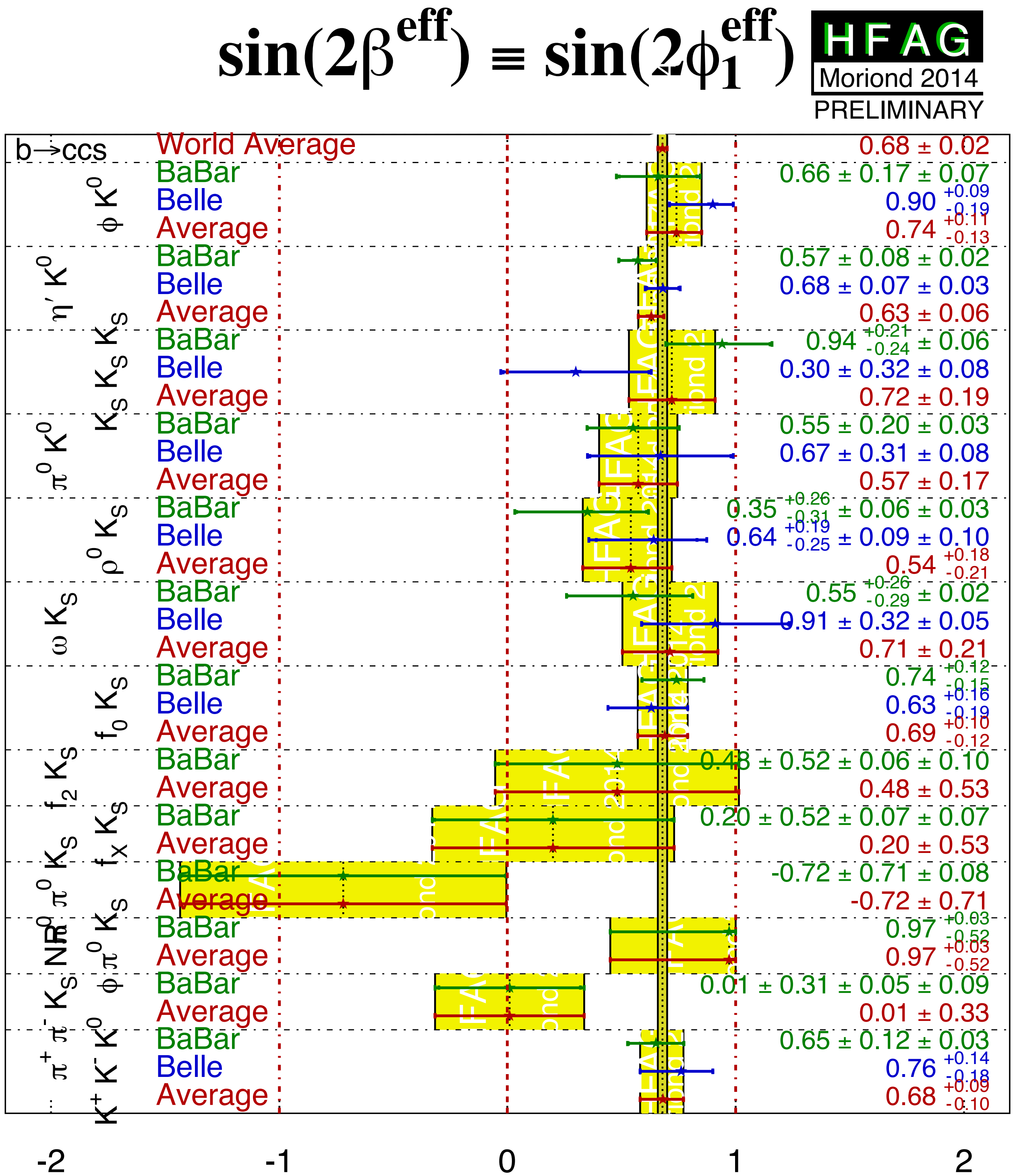
Belle, B → η' K0, JHEP 10 (2014) 165
Belle, B → ω Ks0, PRD 90 012002 (2014)

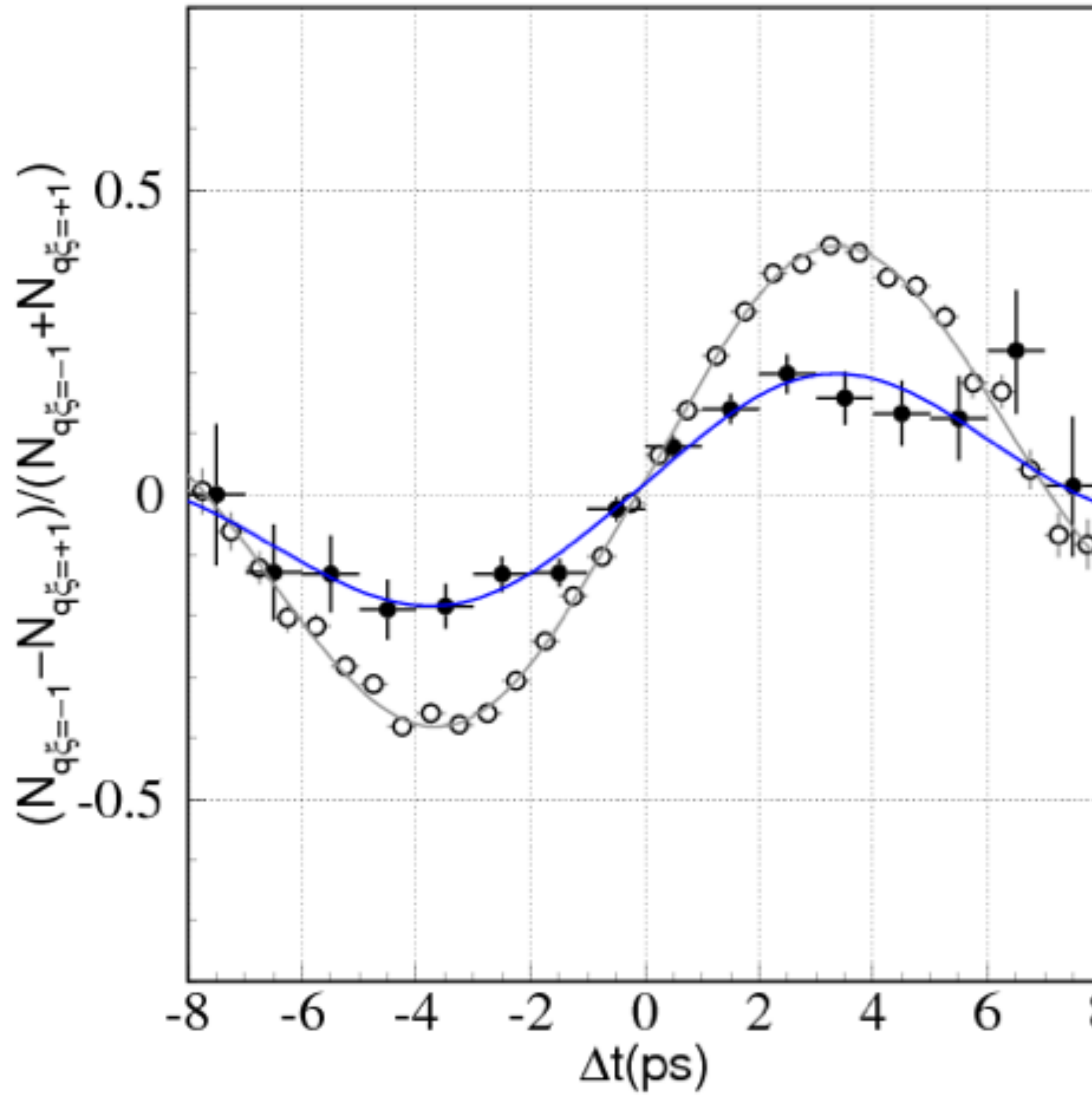




Penguin sin $2\Phi_1$

Belle, B → η‘ K0, JHEP 10 (2014) 165
Belle, B → ω Ks0, PRD 90 012002 (2014)

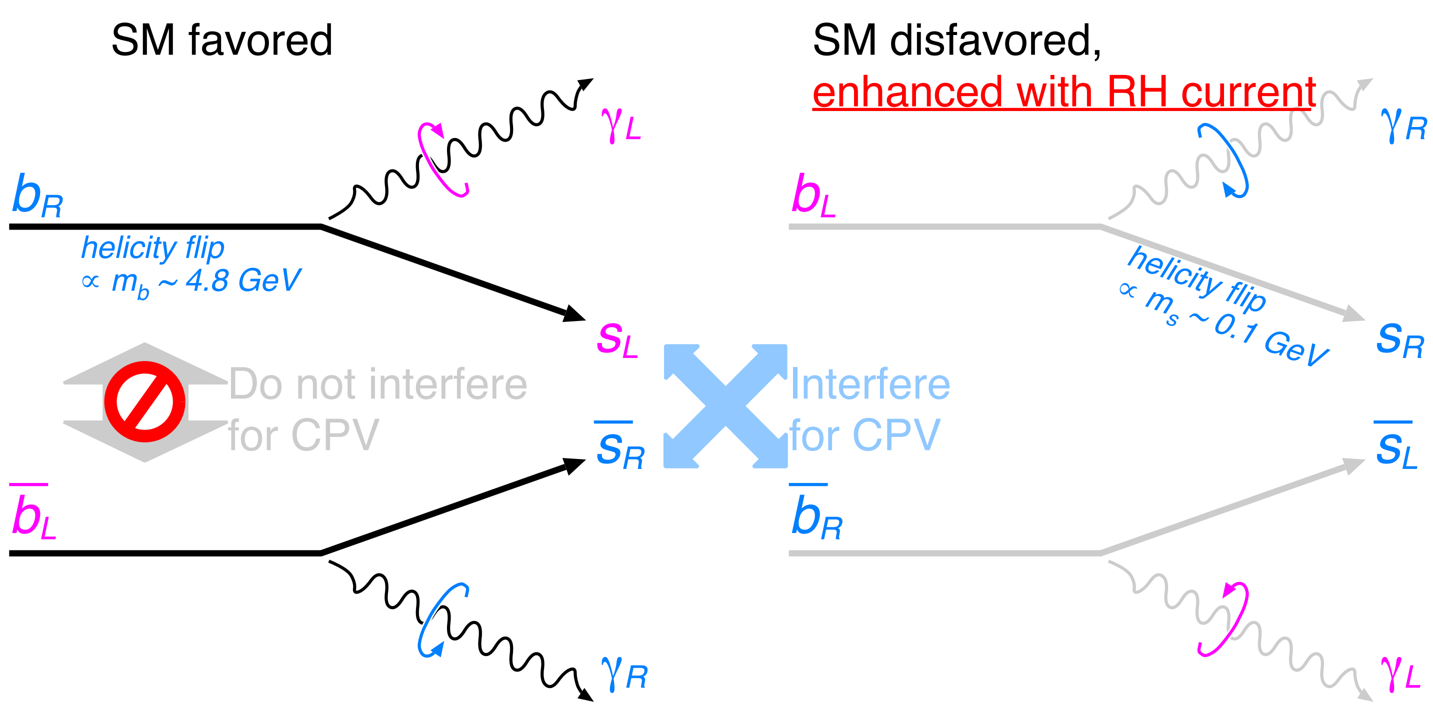




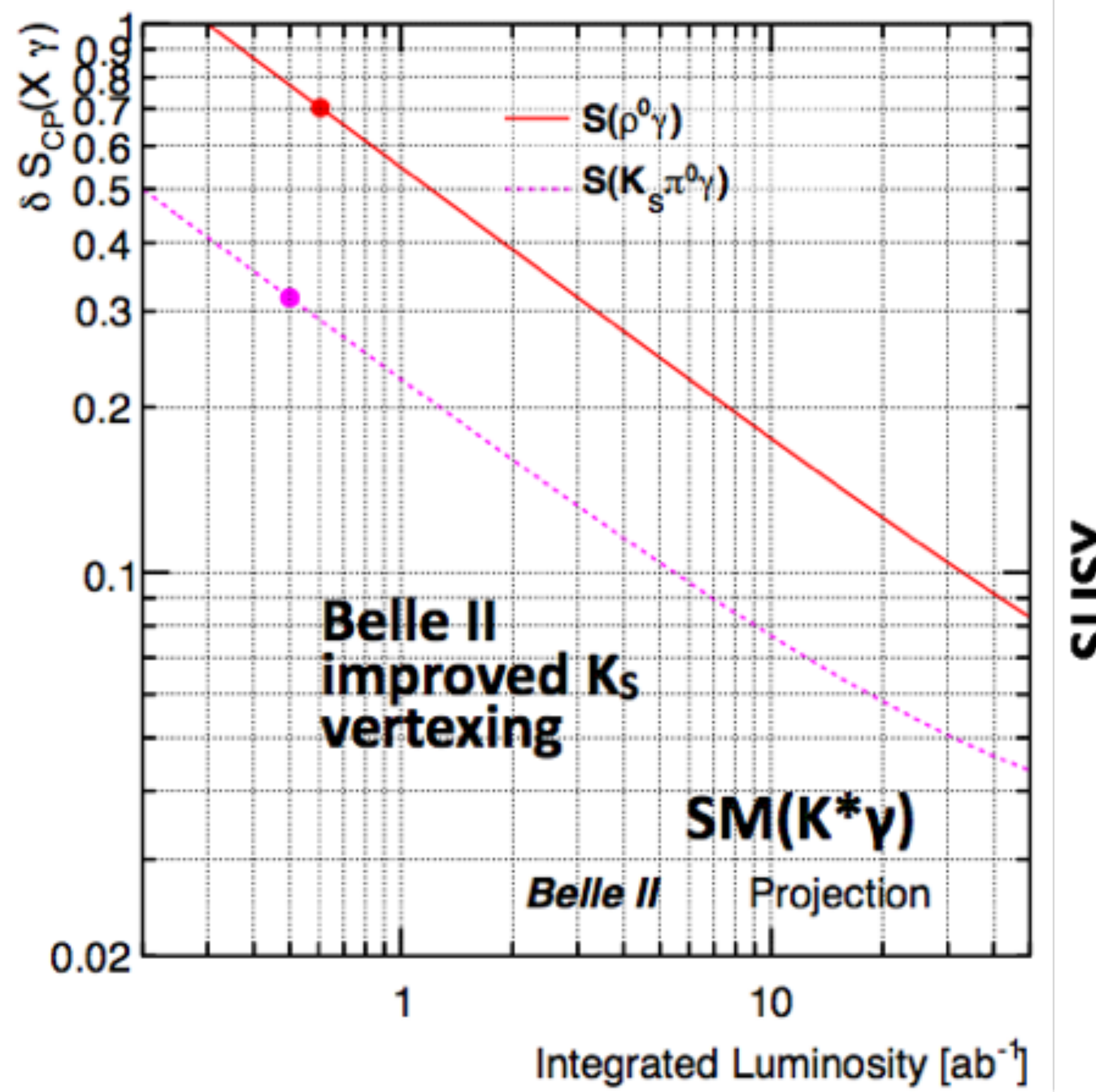
Φ_1 from Radiative Penguin Modes

- SM EW purely L-handed.
- Right-handed current is a signature of NP

$$S = -2(m_s/m_b)\sin(2\phi_1) \sim -0.03$$

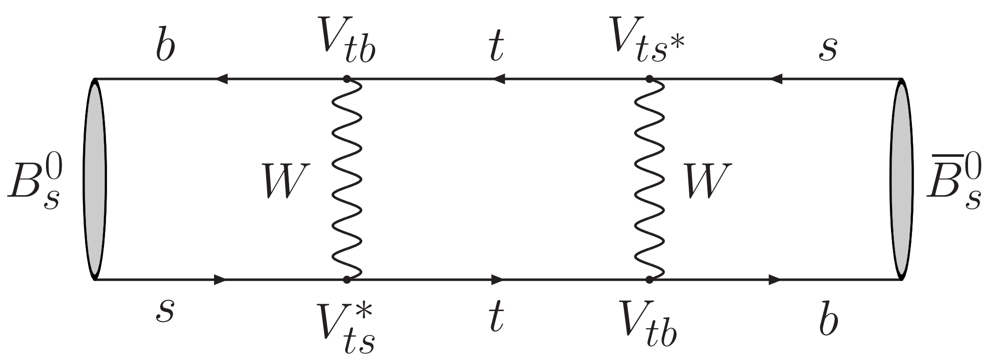


Precision tested at Belle II

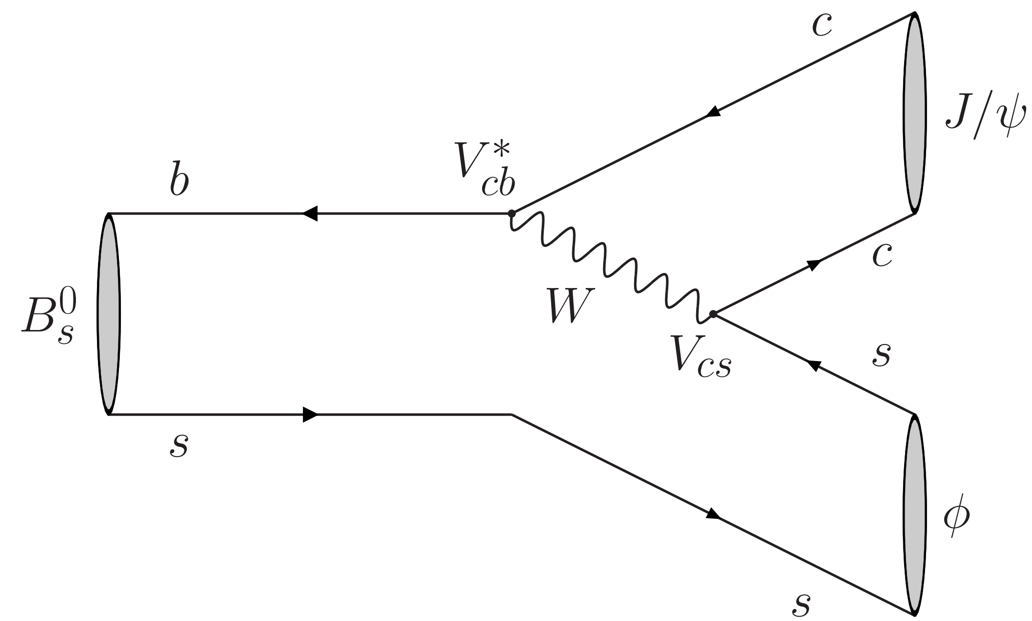


$\Phi_s = \Phi_M - 2\,\Phi_D$

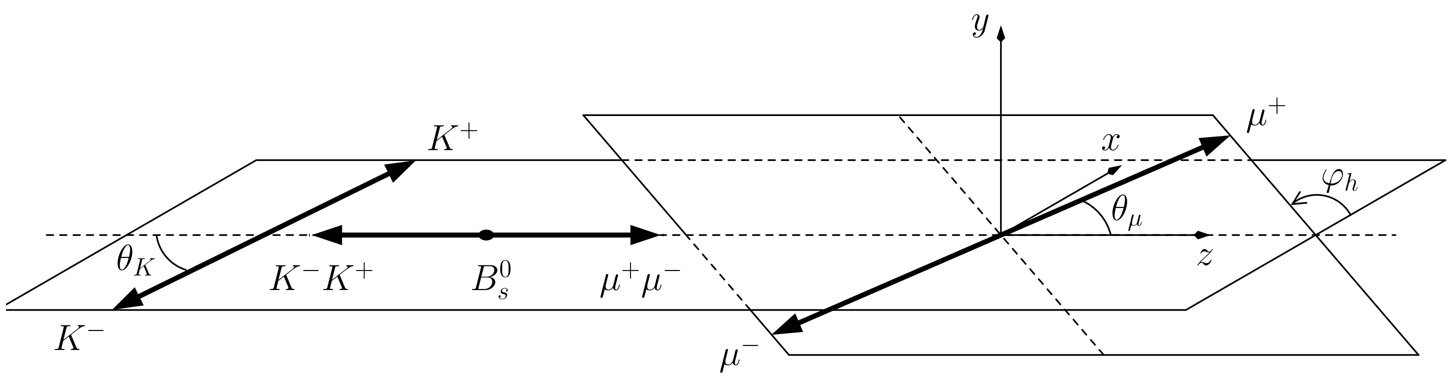
LHCb, PRL 114 (2015) 041801

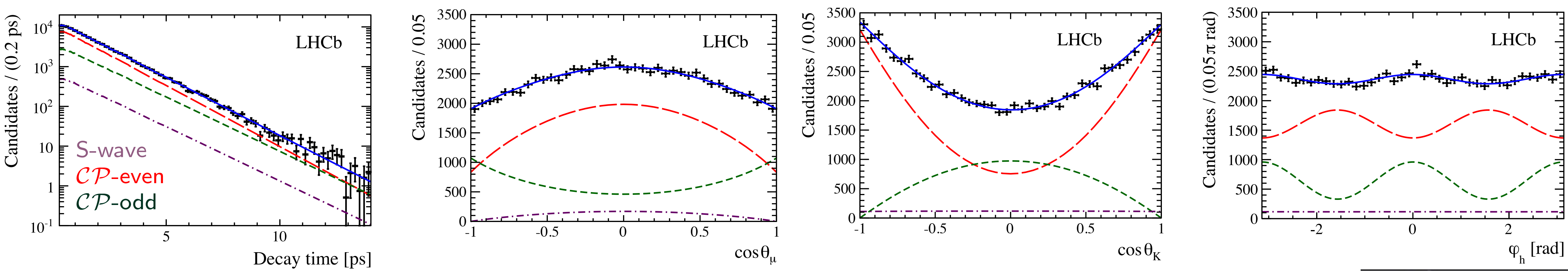


Mixing: $\phi_M = 2\arg(V_{tb}V_{ts}^*)$



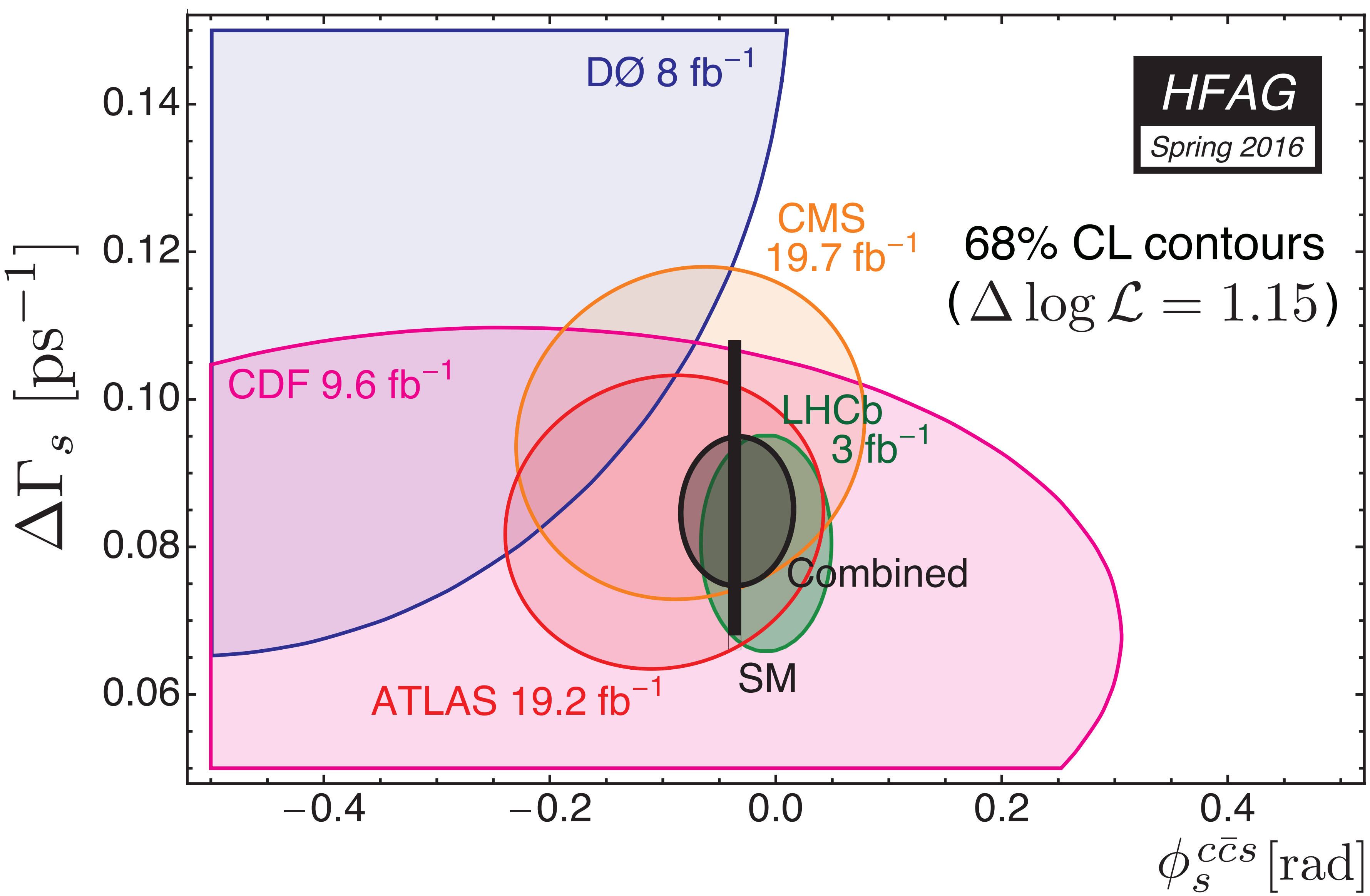
Decay: $\phi_D = \arg(V_{cb}V_{cs}^*)$





Φs Grand combination

HFAG 2016



$$\phi_s^{c\bar{c}s} = -0.033 \pm 0.033 \text{ rad}$$

$$\Delta\Gamma_s = 0.083 \pm 0.006 \text{ ps}^{-1}$$

Compatible with SM estimations:

[arXiv:1511.09466] [CKMfitter, PRD 84 (2011) 033005]

$$\phi_s^{c\bar{c}s} = -0.0376 \,^{+0.0008}_{-0.0007} \text{ rad}$$

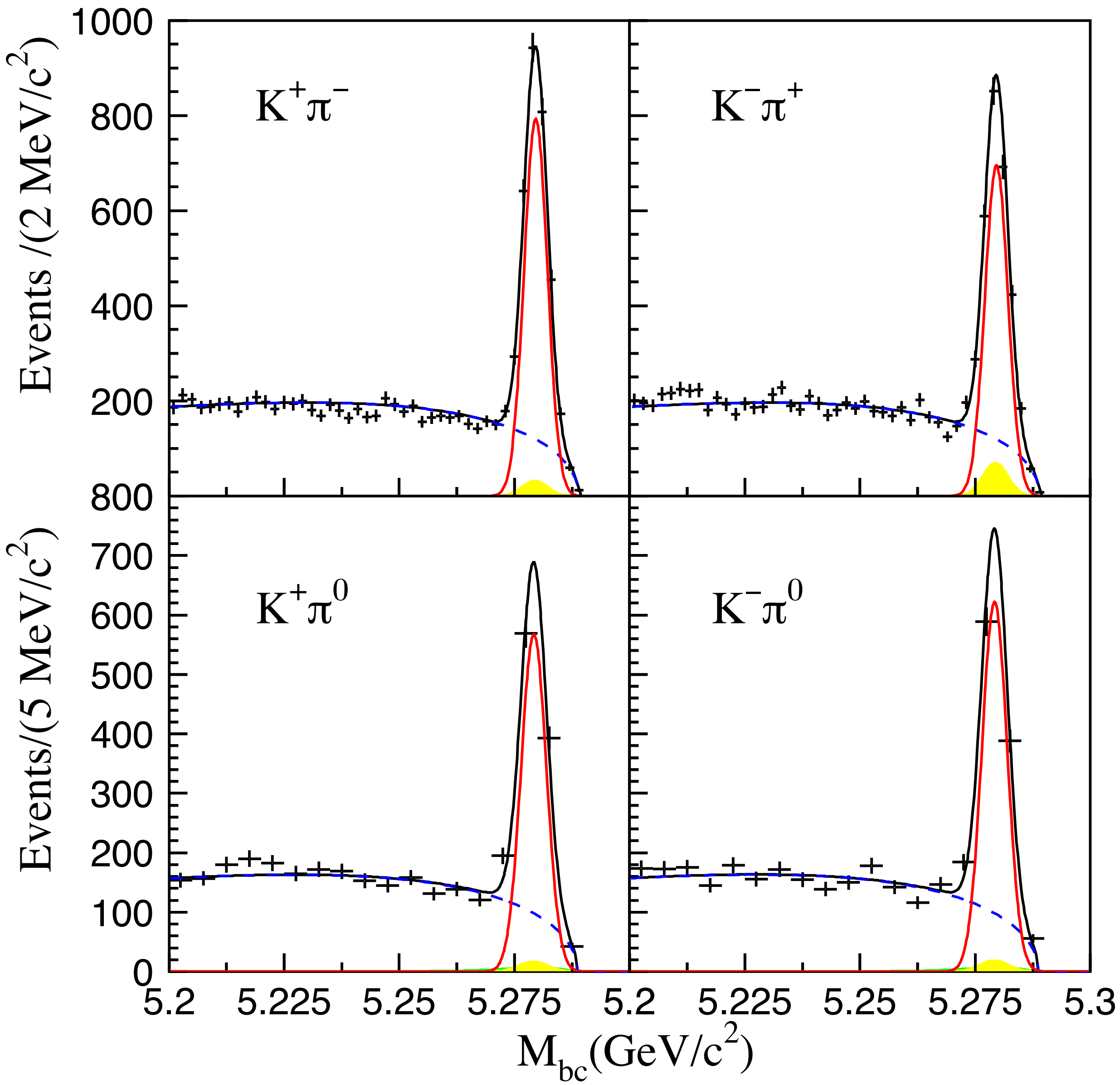
$$\Delta\Gamma_s = 0.088 \pm 0.020 \text{ ps}^{-1}$$

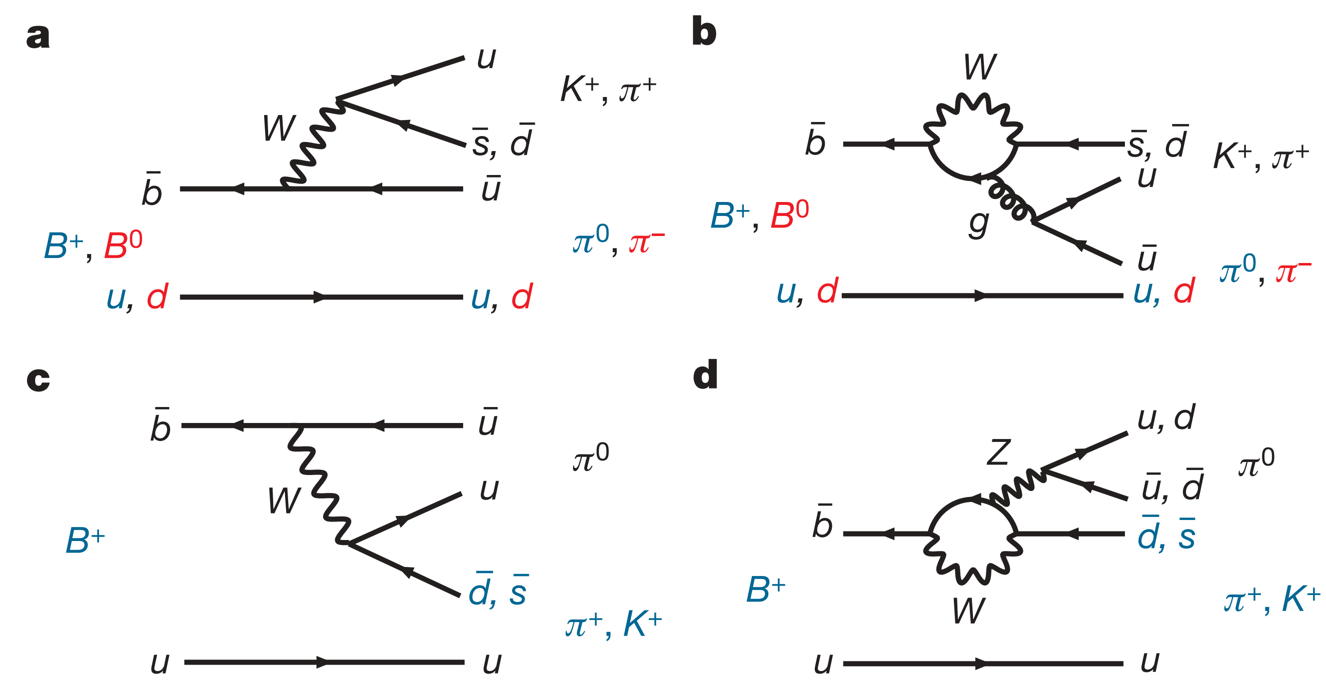
Direct CPV

Direct CP Violation in charmless hadronic decays

Belle, PRD87, 031103(R)(2013)
Belle, Nature 452, 332 (2008)

- First evidence 2008
- Unexpected difference in Acp between B^+ and $B^0 \rightarrow K\pi$



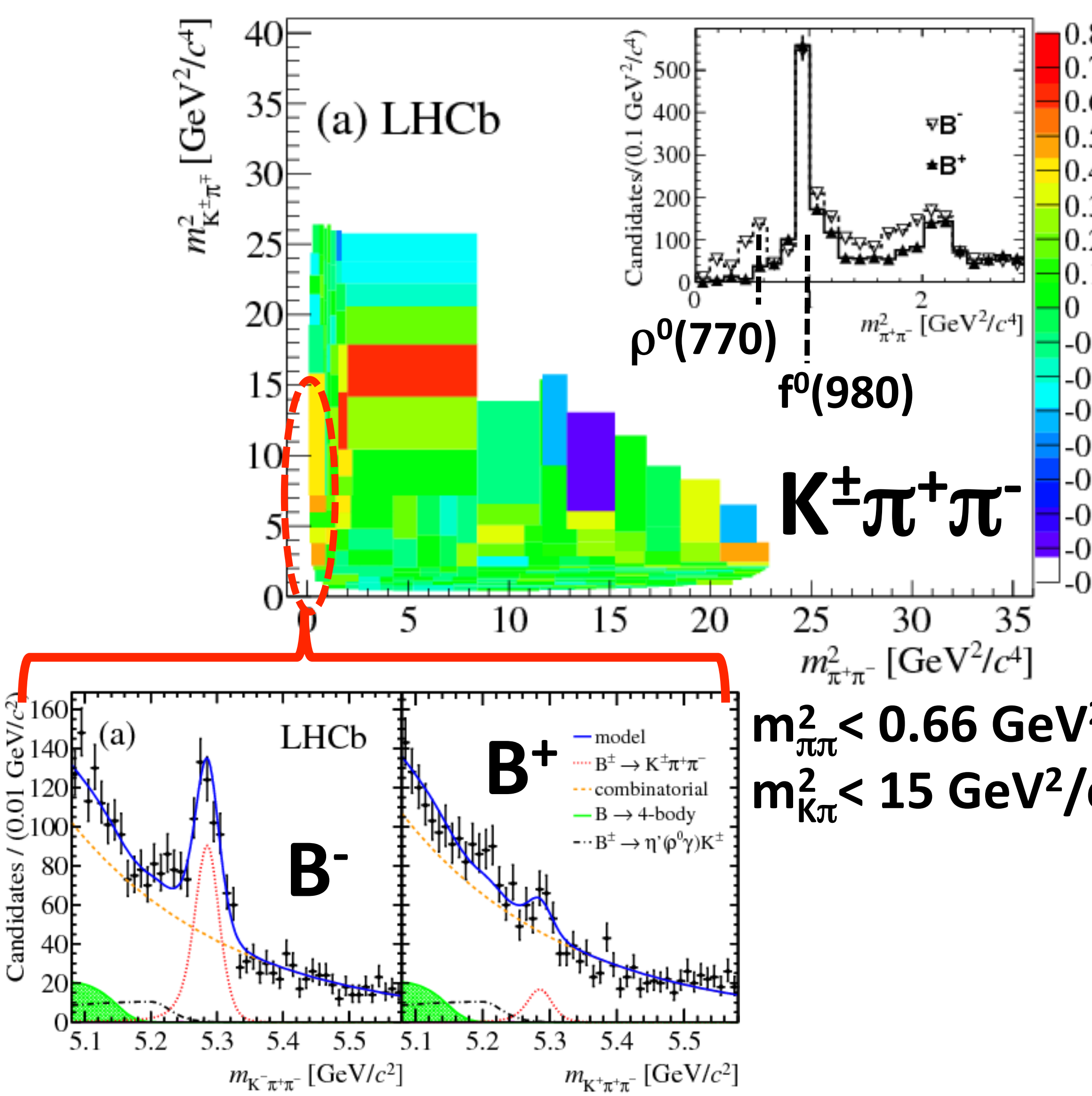


$A_{cp}(K^0\pi^0) = 0.006 \pm 0.06$
$A_{cp}(K^0\pi^+) = -0.015 \pm 0.019$
$A_{cp}(K^+\pi^0) = 0.040 \pm 0.021$
$A_{cp}(K^+\pi^-) = -0.082 \pm 0.006$

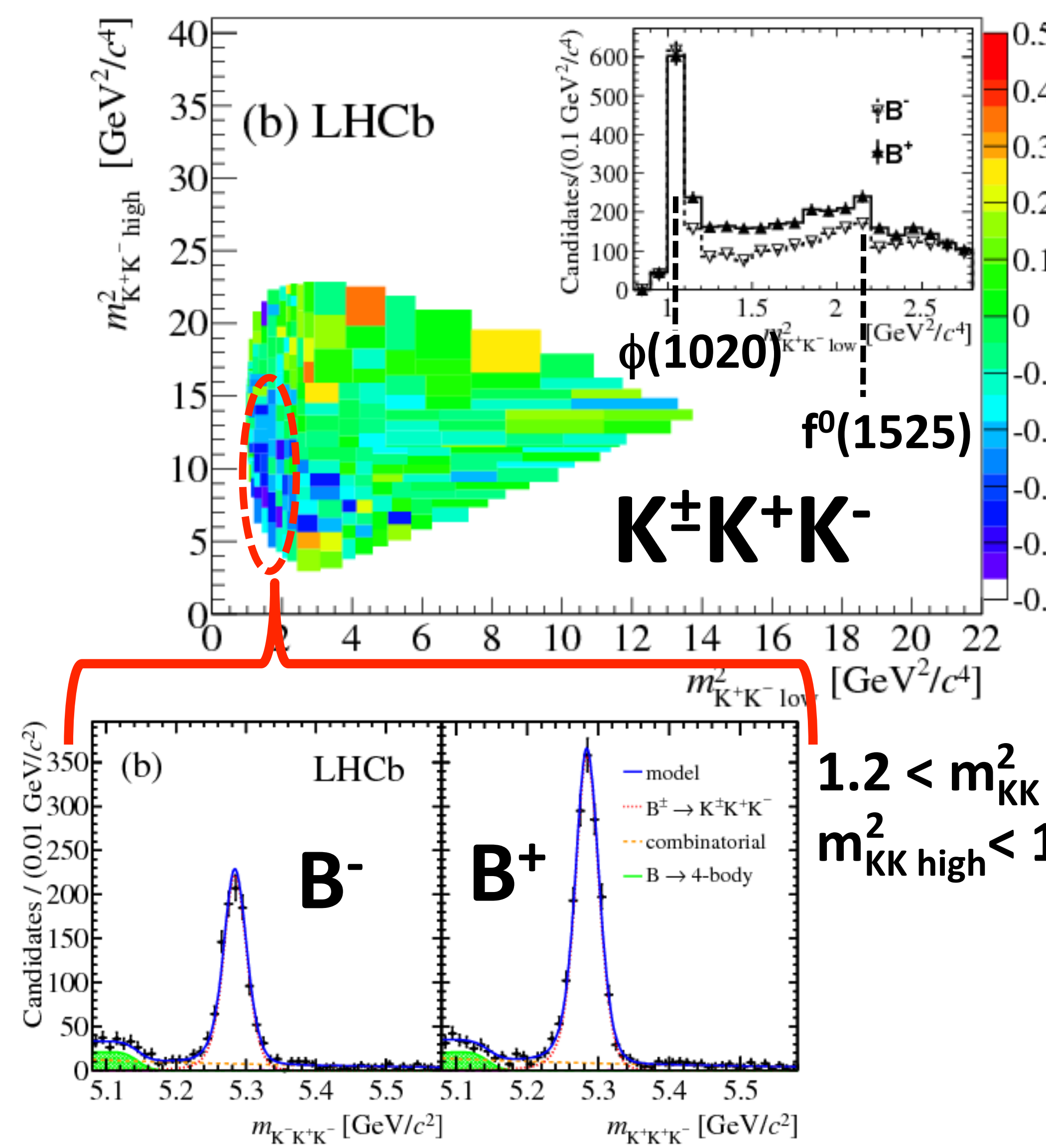
B→ K h h, B → π h h @ LHCb

PRL 111 (2013) 101801
PRL 112 (2014) 011801

- Puzzling patterns of CPV in $B^{\pm} \rightarrow K^{\pm}h^{+}h^{-}$ and $B^{\pm} \rightarrow \pi^{\pm}h^{+}h^{-}$
- Large local asymmetries in regions not associated to resonances
  - Possibly final state re-scattering generates strong phase difference



$m^2_{\pi\pi} < 0.66$ GeV^2/c^4
$m^2_{K\pi} < 15$ GeV^2/c^4



$1.2 < m^2_{KK\,low} < 2.0$
$m^2_{KK\,high} < 15$ GeV^2/c^4

$A_{CP}(K^{\pm}\pi^{+}\pi^{-}|\text{local}) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007$

$A_{CP}(K^{\pm}K^{+}K^{-}|\text{local}) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007$

What could it be?

B.Bhattacharya, M. Gronau, J. Rosner Phys.Lett. B726 (2013) 337-343

We have examined the CP asymmetries in three-body decays of $B^{\pm}$ mesons to charged pions and kaons. Predictions of ratios of asymmetries on the basis of U-spin are seen to be obeyed qualitatively, with violations ascribable to resonant substructure differing for $\pi^+\pi^-$ and K^+K^- substates. Larger CP asymmetries for regions of the Dalitz plot involving low effective mass of these substates can be undertood qualitatively in terms of large final-state strong phases; the weak phases are conducive to such large asymmetries, being nearly maximal. We conclude that further resolution of this problem must rely either on a deeper understanding of the resonant substructure in $B \to PPP$ decays, or further understanding of the hadronization process independently of resonances. We have argued that the approximately equal magnitudes and opposite signs measured for asymmetries in $B^+ \to \pi^+\pi^+\pi^-$ and $B^+ \to K^+\pi^+\pi^-$ may follow from the closure of low-mass $\pi^+\pi^-$ and K^+K^- channels involving only $\pi\pi \leftrightarrow K\bar{K}$ rescattering.

CPV in mixing

CP violation in mixing

LHCb-Paper-2016-013

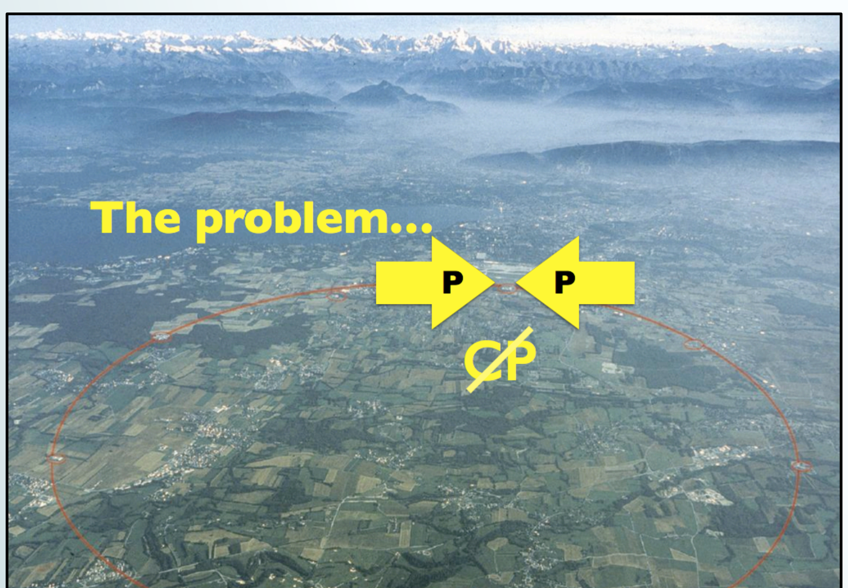
- a_s^{sl} and a_d^{sl} with full Run1 dataset (3/fb)

$$A_{\rm raw}(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} \approx \underbrace{A_D + \frac{a_{\rm sl}^d}{2}}_{\text{Offset}} + \underbrace{\left(A_P - \frac{a_{\rm sl}^d}{2}\right)}_{\text{Amplitude}} \underbrace{\cos(\Delta m_d t)}_{\text{Mixing}}$$

Offset | Amplitude | Mixing

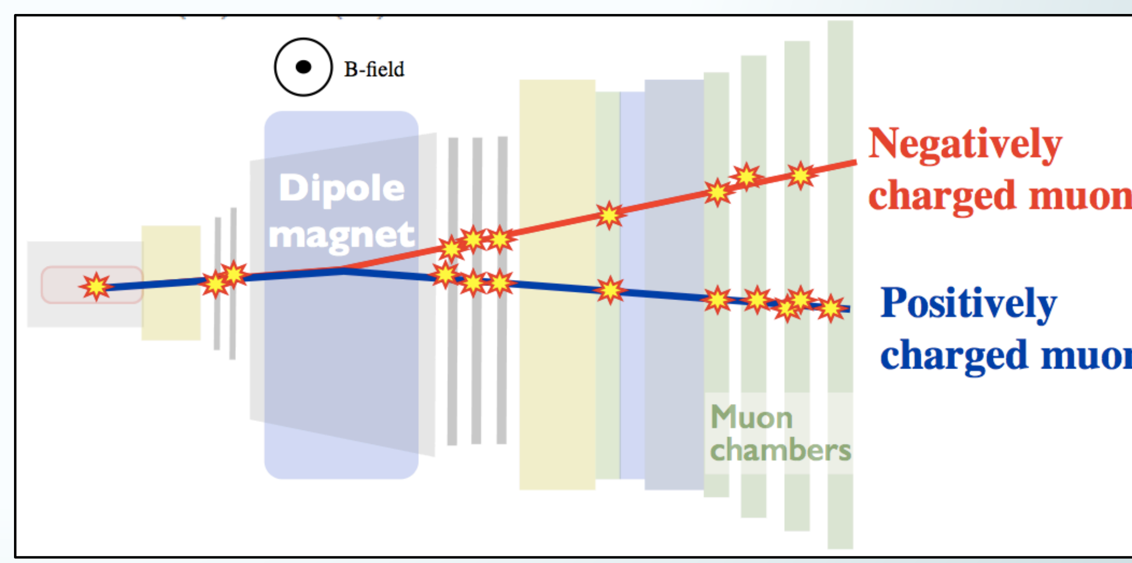
Production asymmetry:

$$A_P = \frac{N(B) - N(\bar{B})}{N(B) + N(\bar{B})}$$

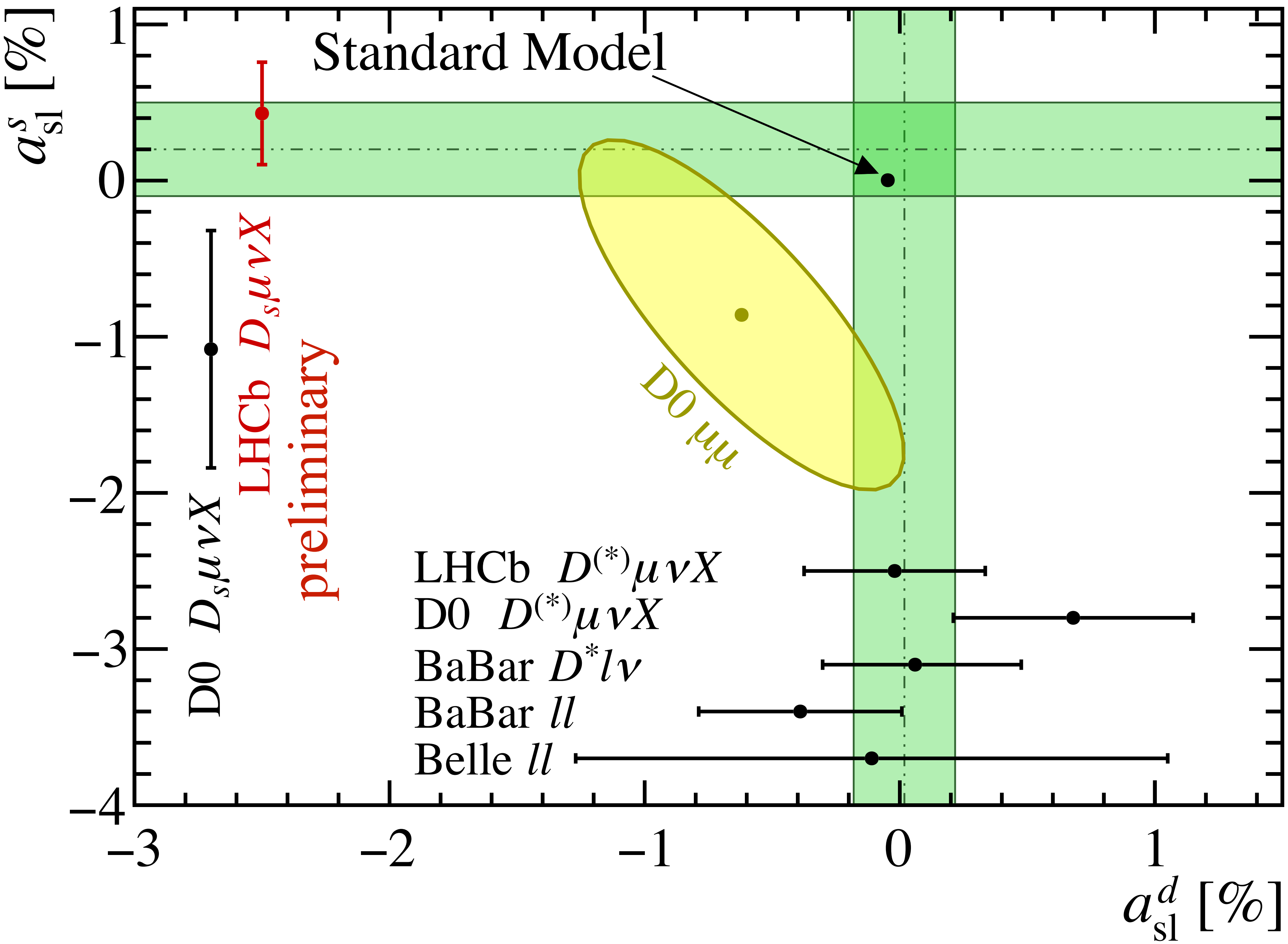


Detection asymmetry:

$$A_D = \frac{\epsilon(D^-\mu^+) - \epsilon(D^+\mu^-)}{\epsilon(D^-\mu^+) + \epsilon(D^+\mu^-)}$$



CP violation in mixing



2016 $a^s_{\rm sl} = (0.45 \pm 0.26({\rm stat}) \pm 0.20({\rm syst}))\%$

2015 $a^d_{sl} = (-4.7 \pm 0.6) \times 10^{-4}$

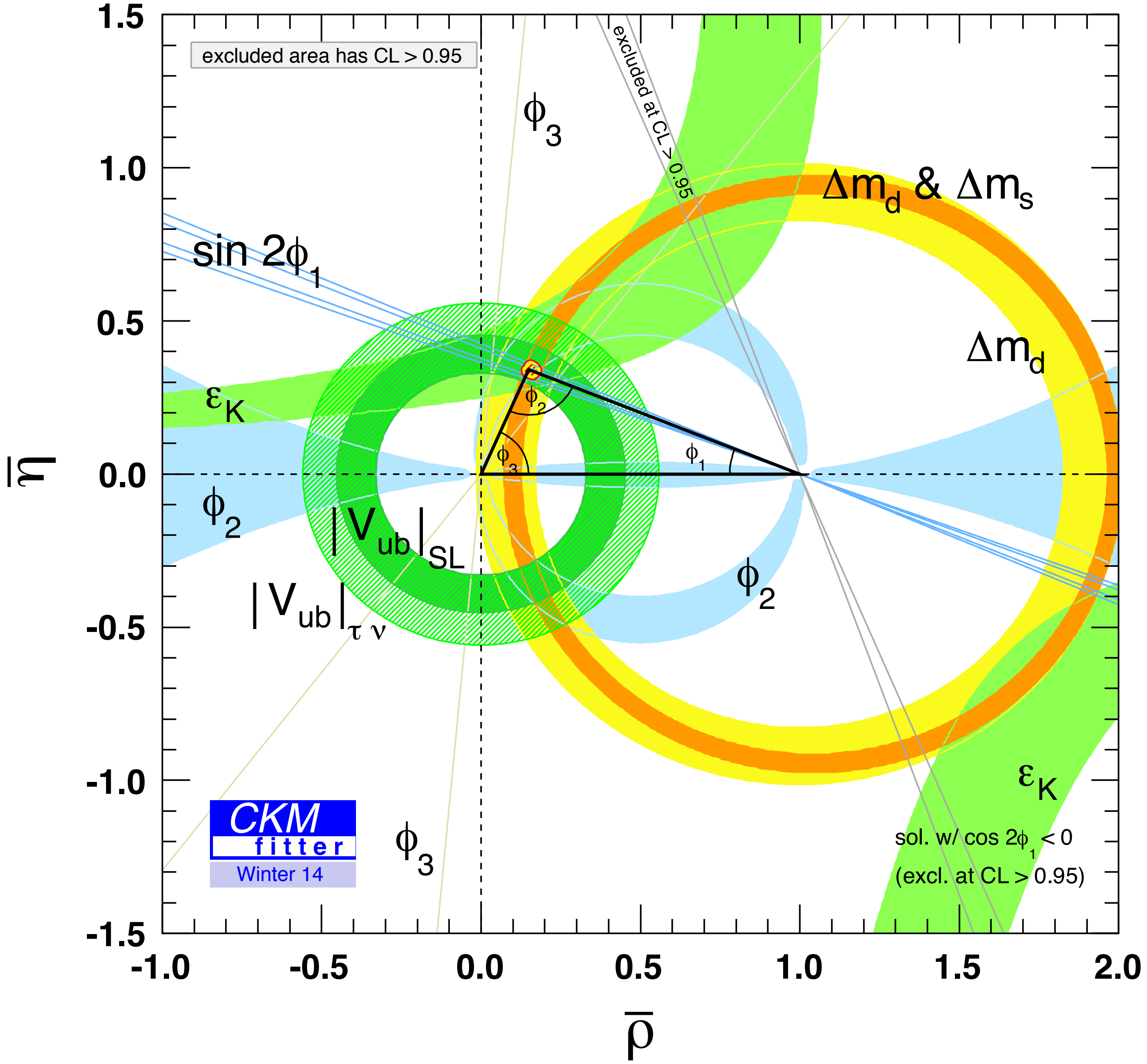
4. Global Fit & Future Facilities

Generic Analyses for New Physics

CKMfitter PRD 91, 073007 (2015),

- Consistency is only at the 5% level in global fit.

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



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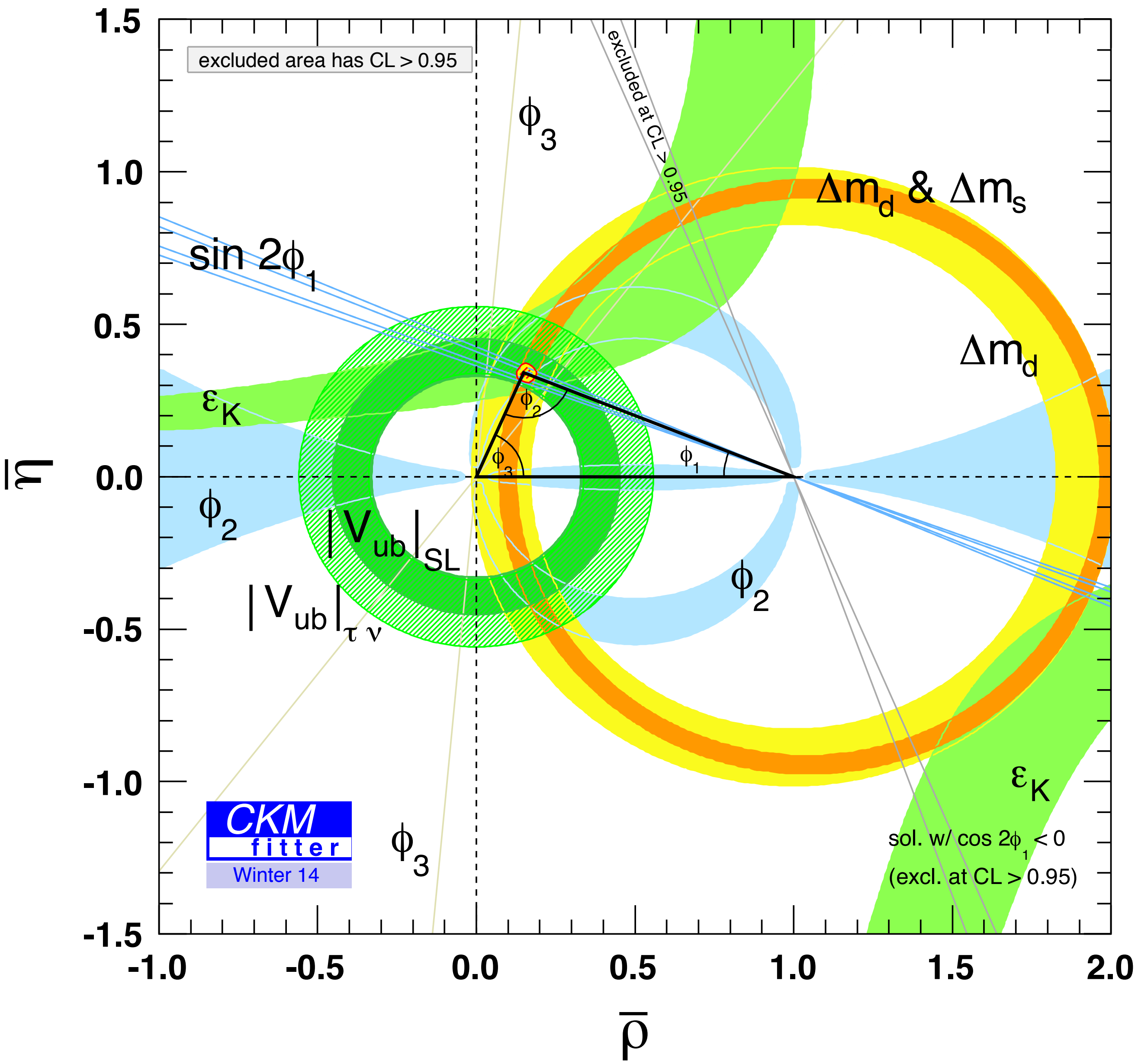

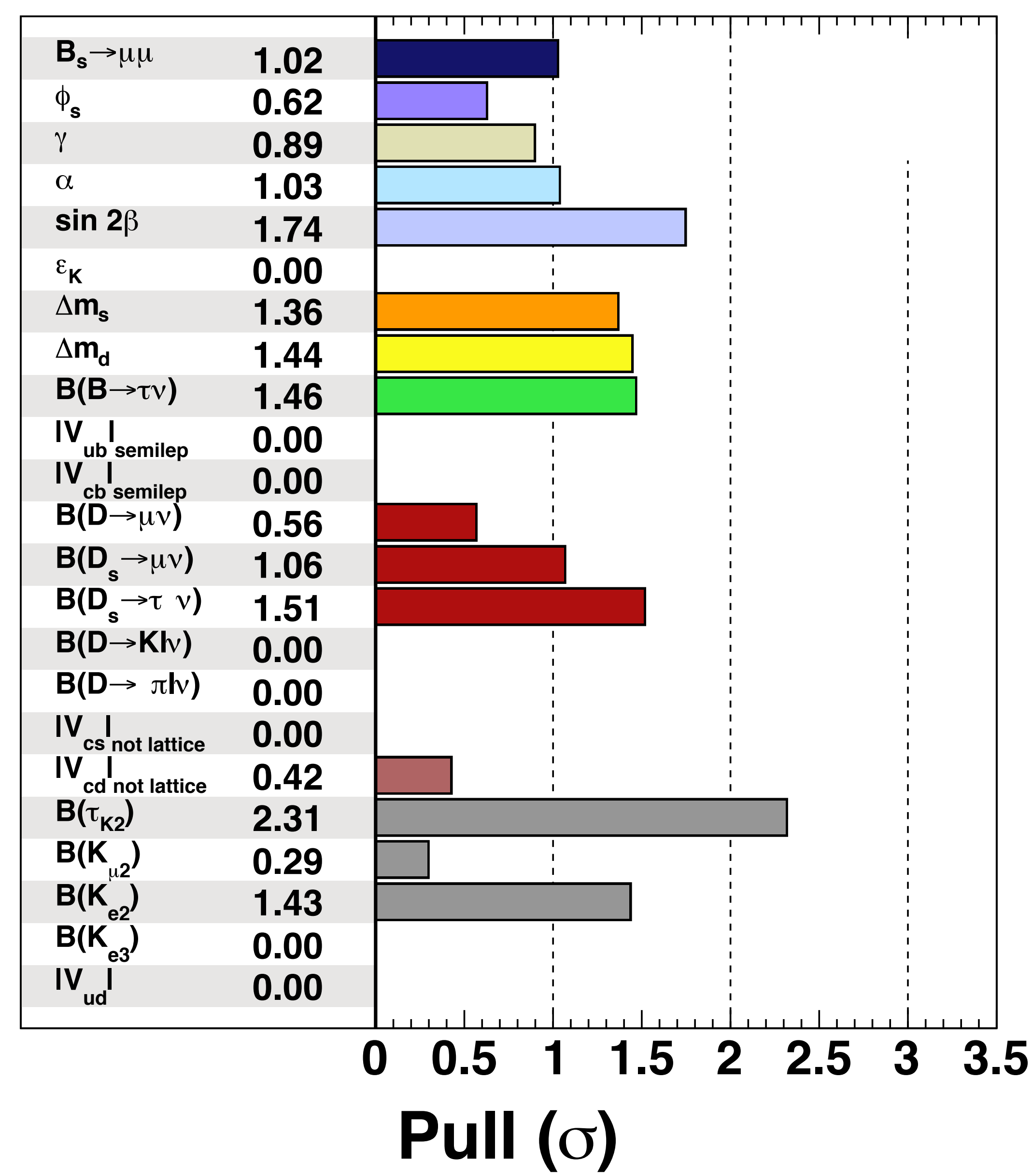

"Tsukuba, we have a Problem"

WMAP data

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

KM Theoretical prediction

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$$\left(\frac{n_b}{n_\gamma}\right)^{\mathrm{SM}} \propto \frac{J_{CP}}{T_c^{12}} \sim 10^{-20}$$

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→ What does this mean ?

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The CP Violation predicted by Kobayashi and Maskawa is too small by ~*10 orders of magnitude* in the Standard Model.

What does this mean ?

→ New Physics (Particles)

Lesson from Flavour

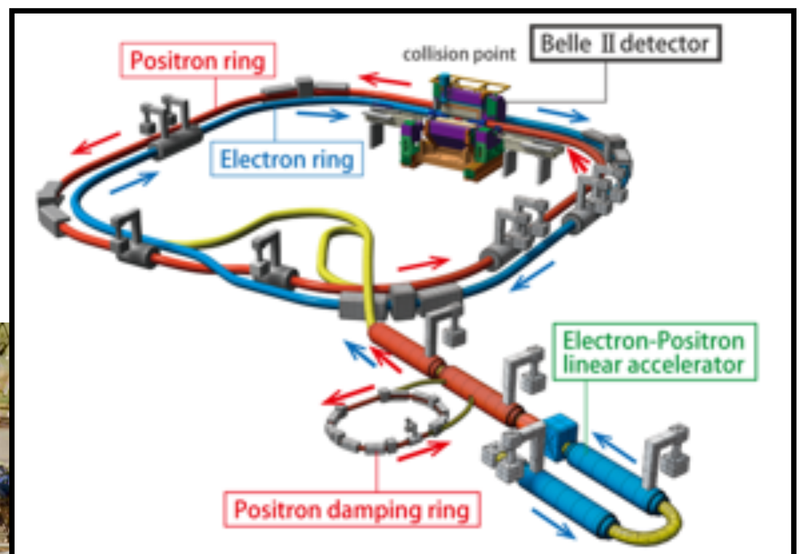
- Unwise to assume ~10% (or even 0.1%) is 'good enough' with flavour

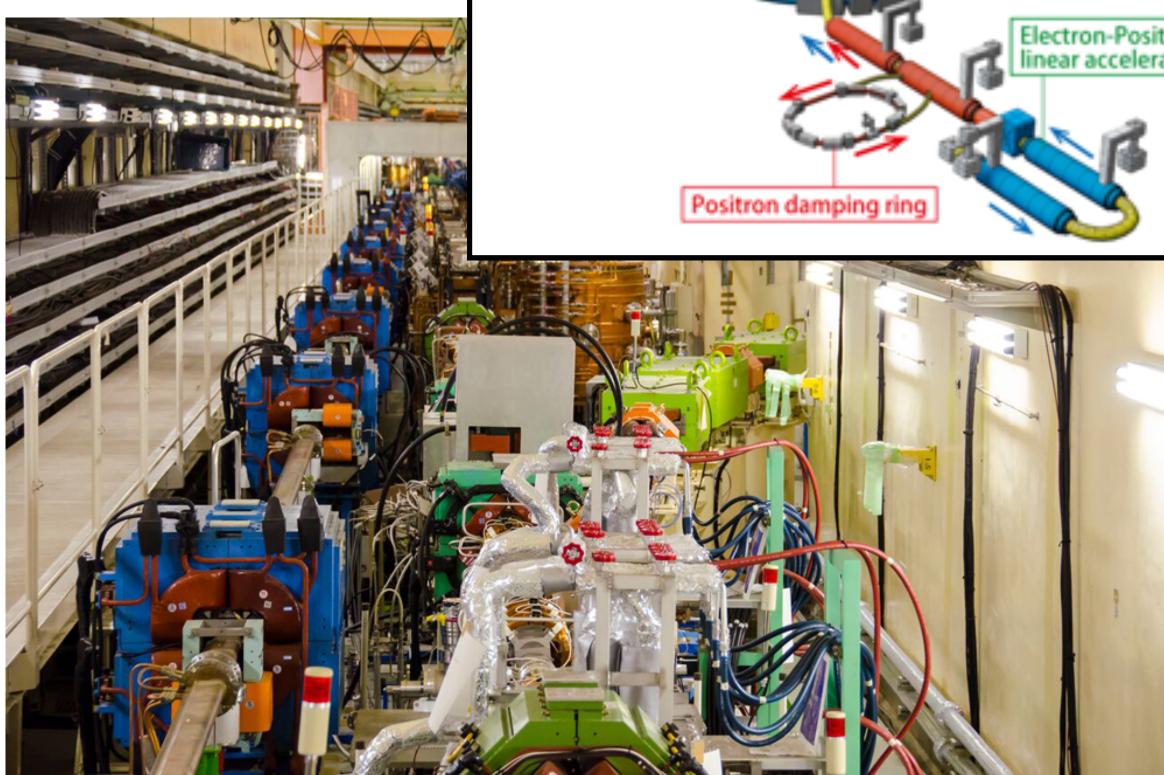
- **1962:** "A special search at Dubna was carried out by E. Okonov and his group. They did not find a single
K_L to $\pi^+ \pi^-$ event among 600 decays into charged particles (Anikira *et al*, JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."
-Lev Okun, "The Vacuum as Seen from Moscow"

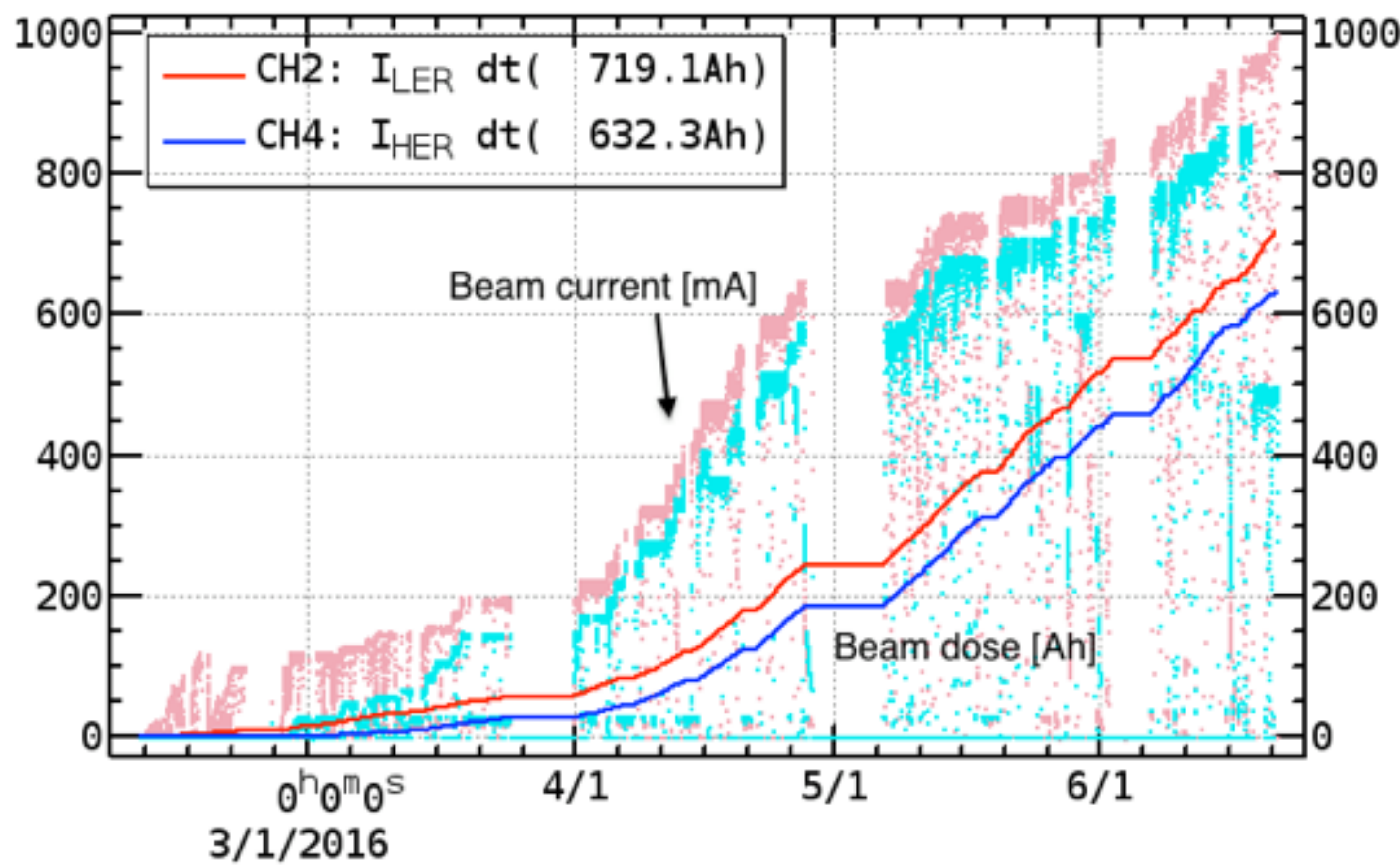
- **1964**: BF= 2×10^{-3}, Cronin, Fitch et al. 1964.

SuperKEKB now in operation!

- First new particle collider since the LHC (intensity frontier rather than energy frontier; e+ e- rather than p p)
- **1 Amp achieved in Low energy ring, 21 June 2016 - Milestone achieved.**
- Shutting down until 2017 to install superconducting final focusing magnets.







Belle II Detector: Starting up in 2017

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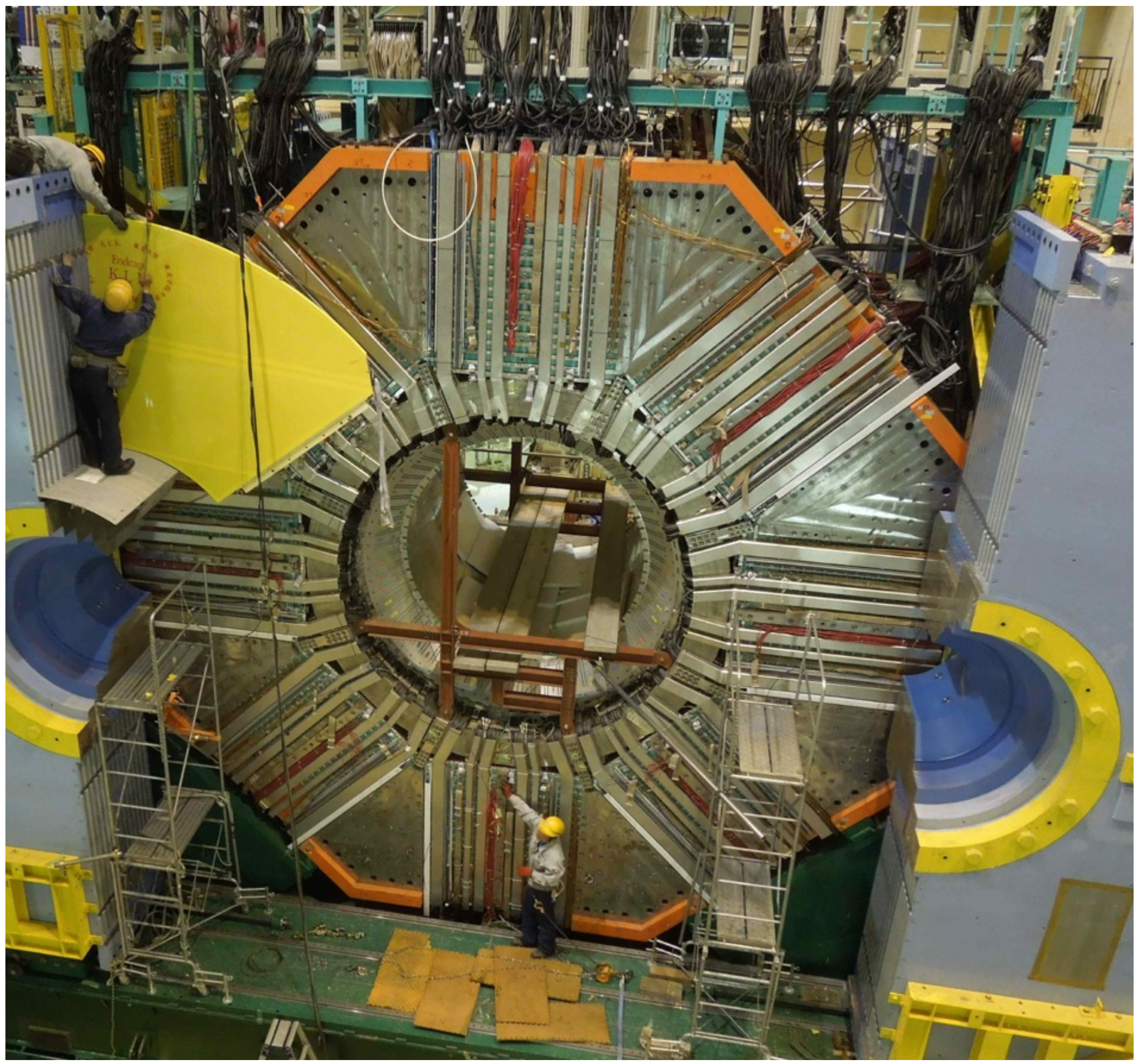
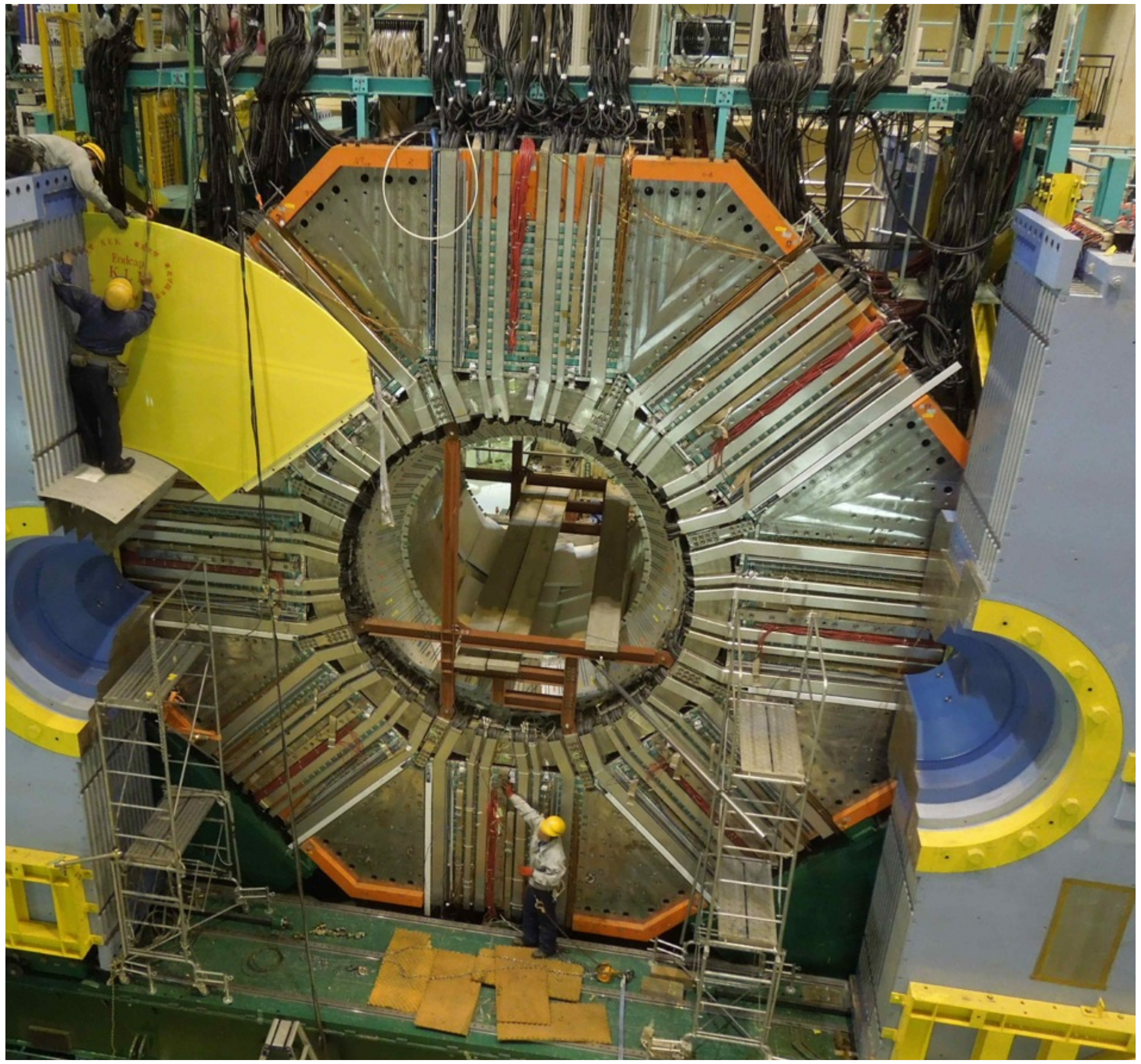
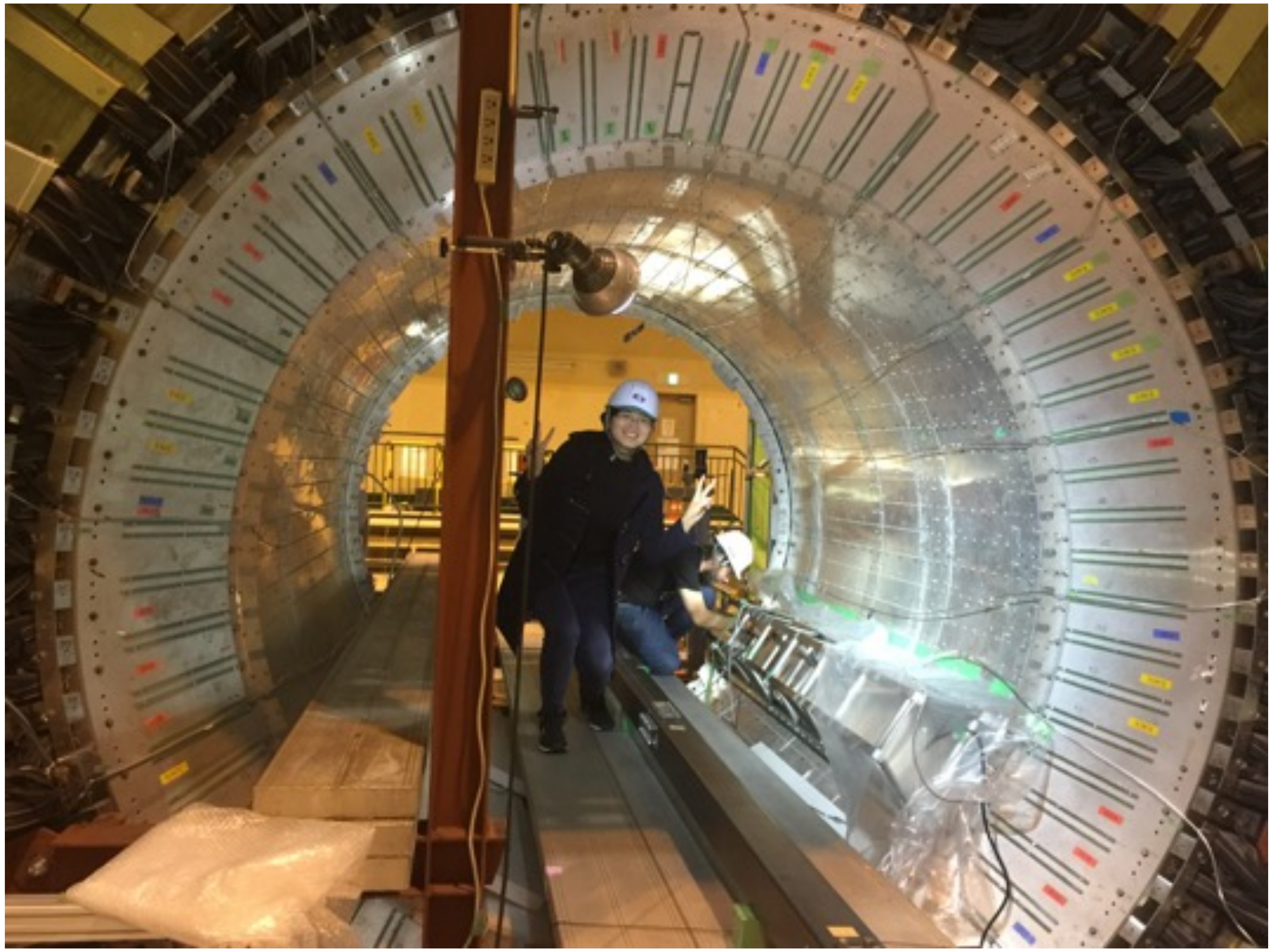
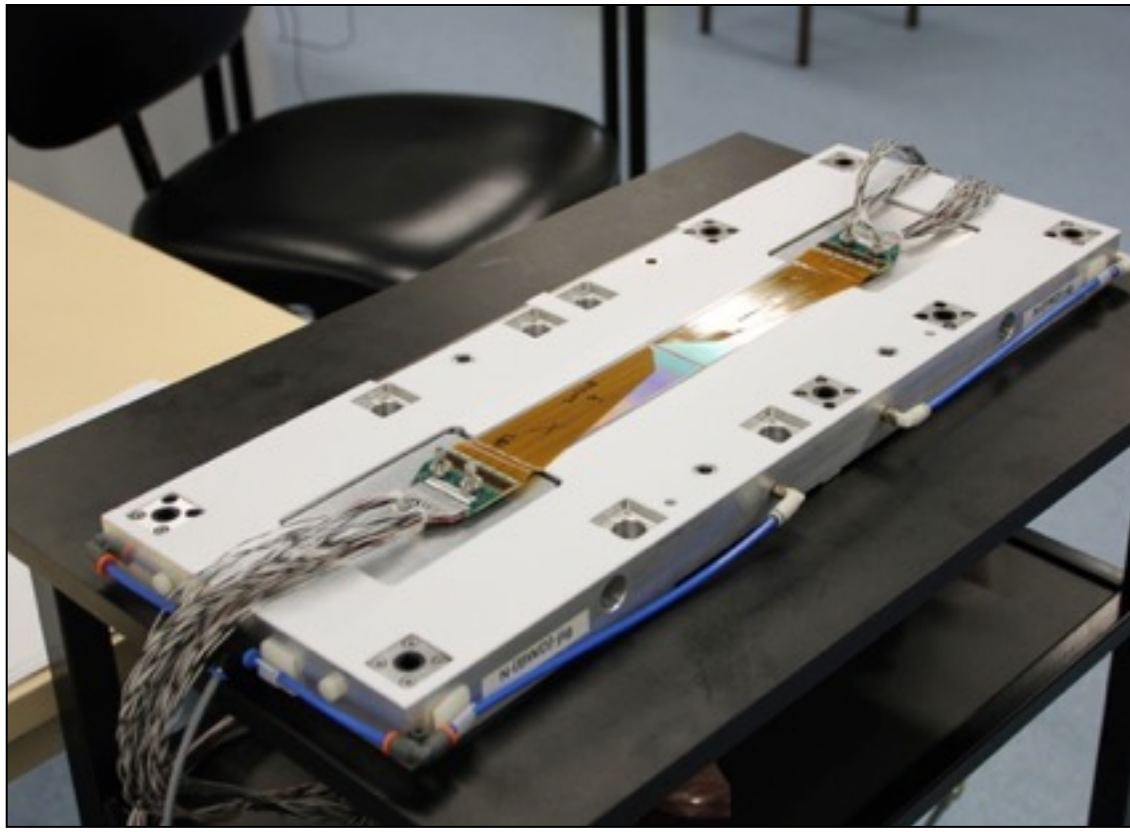
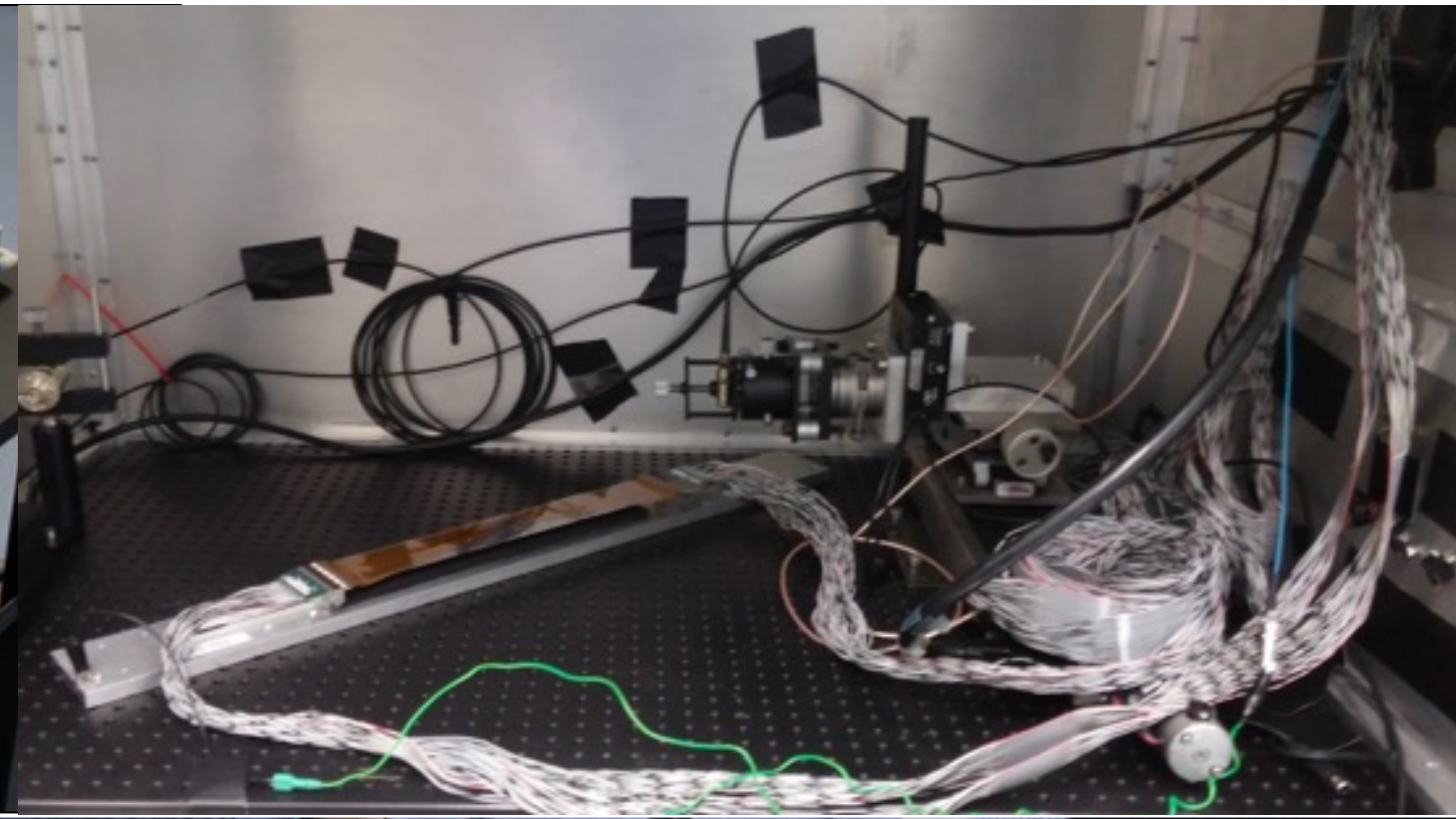
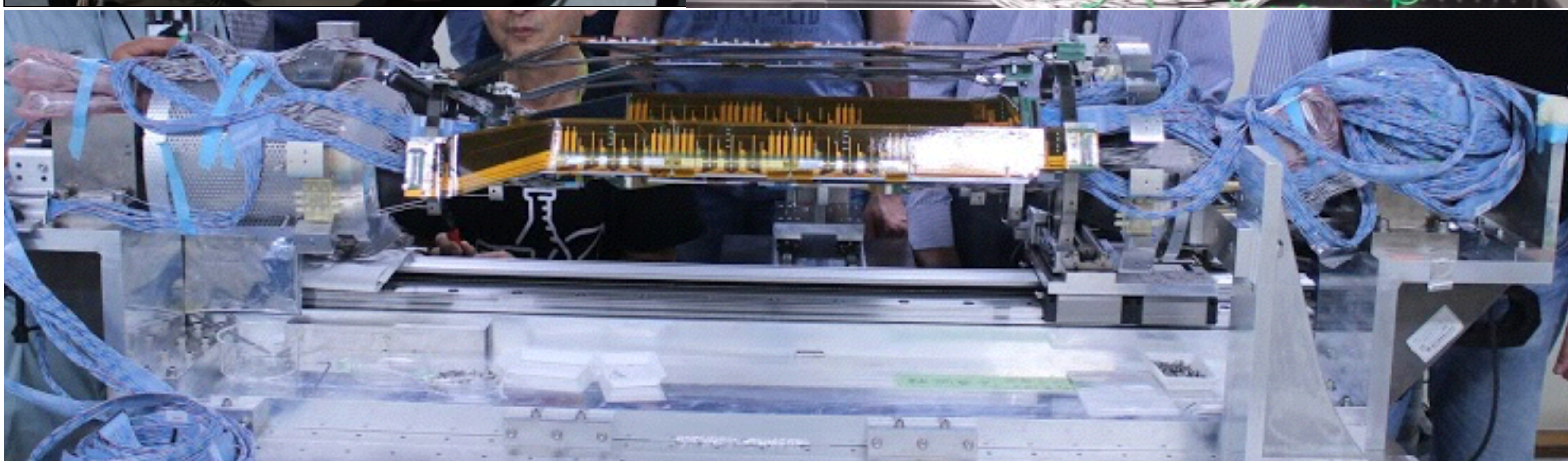


Belle II Detector: Starting up in 2017

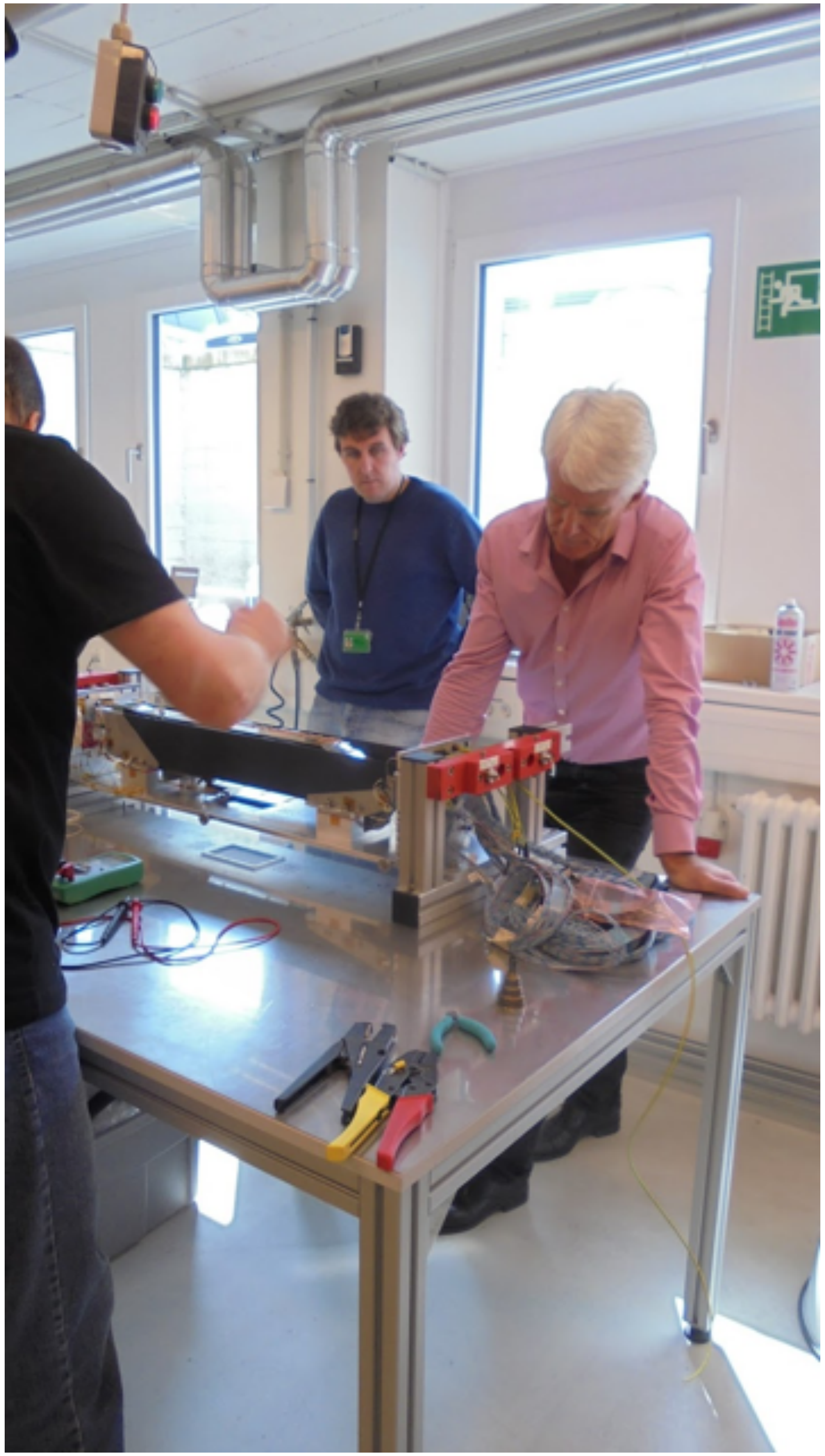




Silicon Vertex Detector Construction

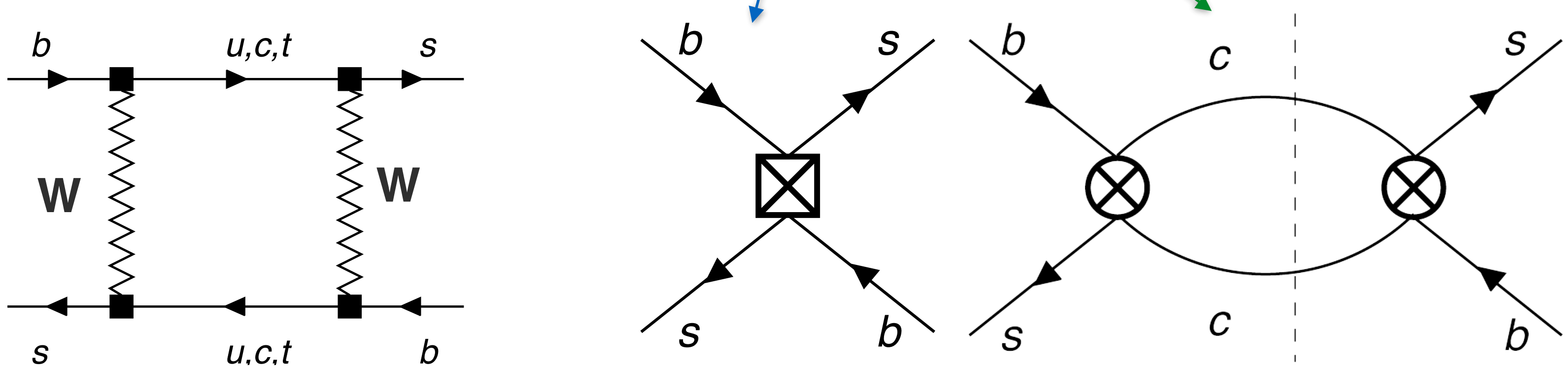
Melburnians @ DESY Test Beam



New Physics in mixing: past & future data

- Meson mixing,

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(M^q - \frac{i}{2}\Gamma^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$



- SM: C_{SM}/m_W^2
- NP: C_{NP}/Λ^2

- What is the scale Λ ? How different is C_{NP} from C_{SM} ?
- If deviation from SM seen → upper bound on Λ

- Assume NP from Trees in negligible, test for NP in loops only - i.e. New Physics only enters M_{12}, the real part of the mixing Hamiltonian.

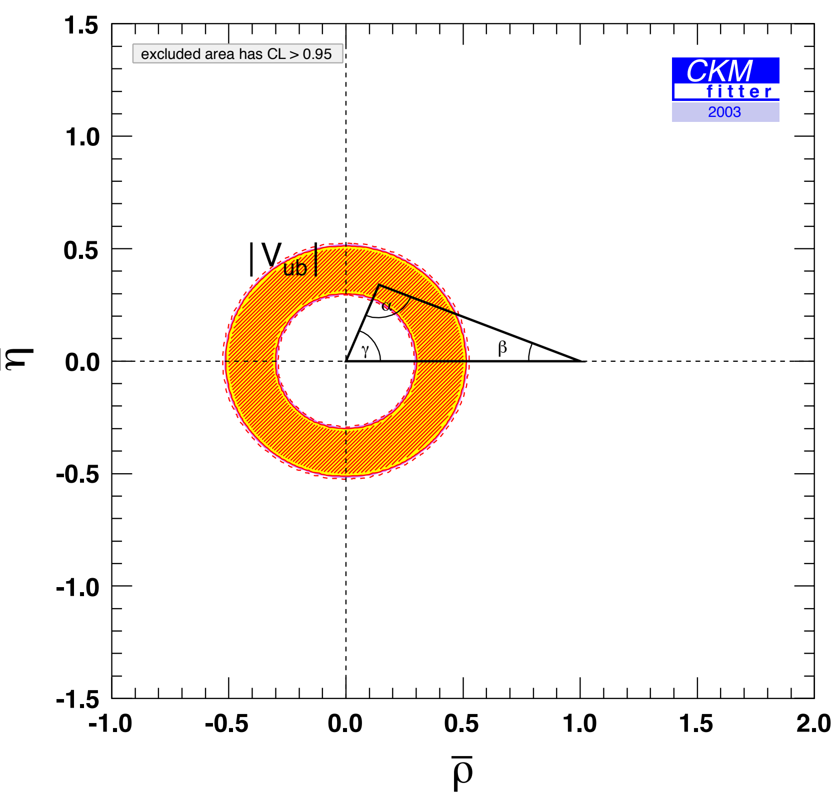
- 3 x 3 CKM matrix is unitary.

$$M_{12} = M_{12}^{SM} \times \left(1 + he^{2i\sigma}\right)$$

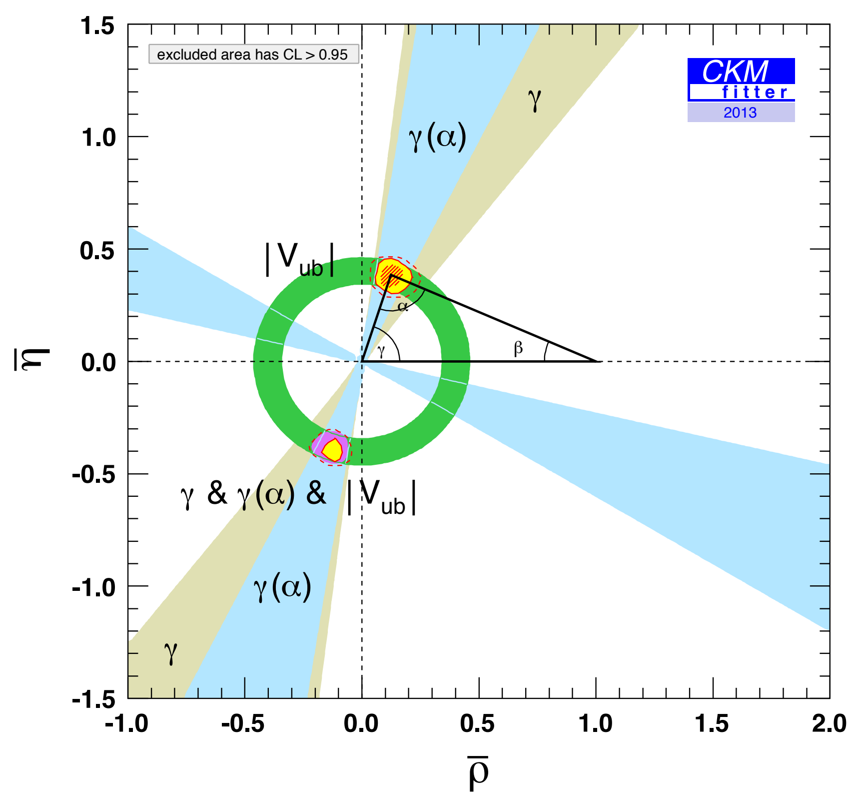
NP in $B_{\{d,s\}}$ & K mixing: Input

- Observables not affected by NP first used to constrain CKM:
  $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, Φ_3 and $\Phi_2 = \pi - \Phi_3 - \Phi_{1\mathrm{eff}}((c\ \text{anti-}c)K)$
- NP impact estimated from
  Meson mixing Δm_s, Δm_d, $|\varepsilon_K|$,
  Lifetime difference $\Delta\Gamma_s$, & semileptonic asymmetry A_{SL},
  Time dep. CP asymmetries β_s, Φ_1, and Φ_2 (decay-mixing interference)

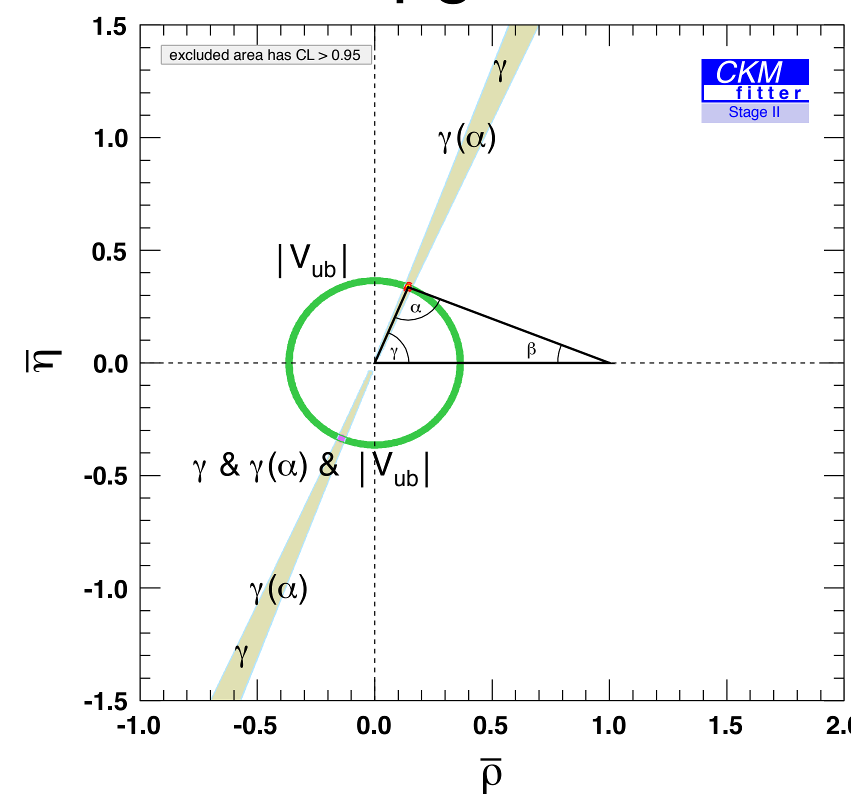
2003



2013



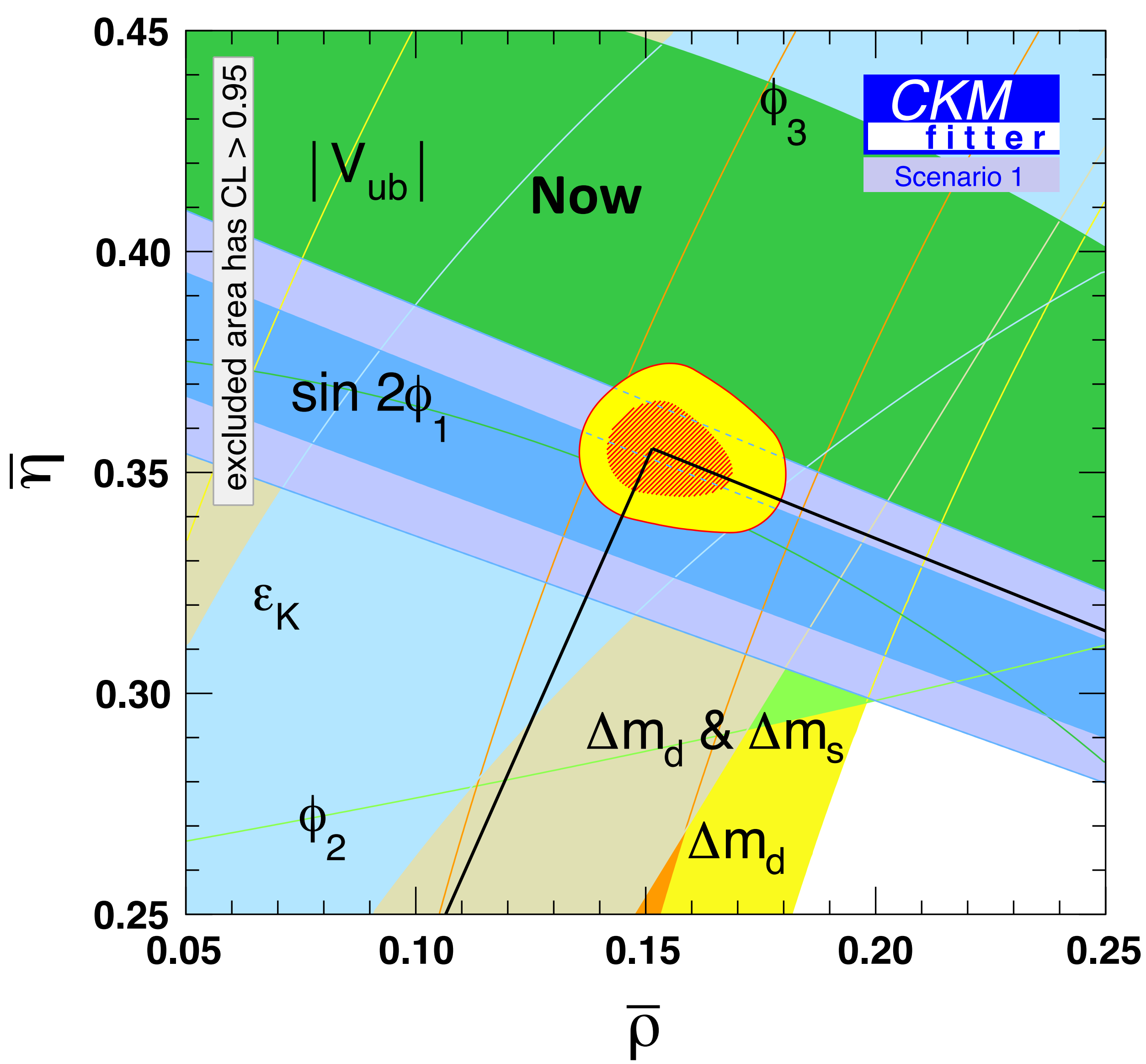
LHCb Upg.+ Belle II



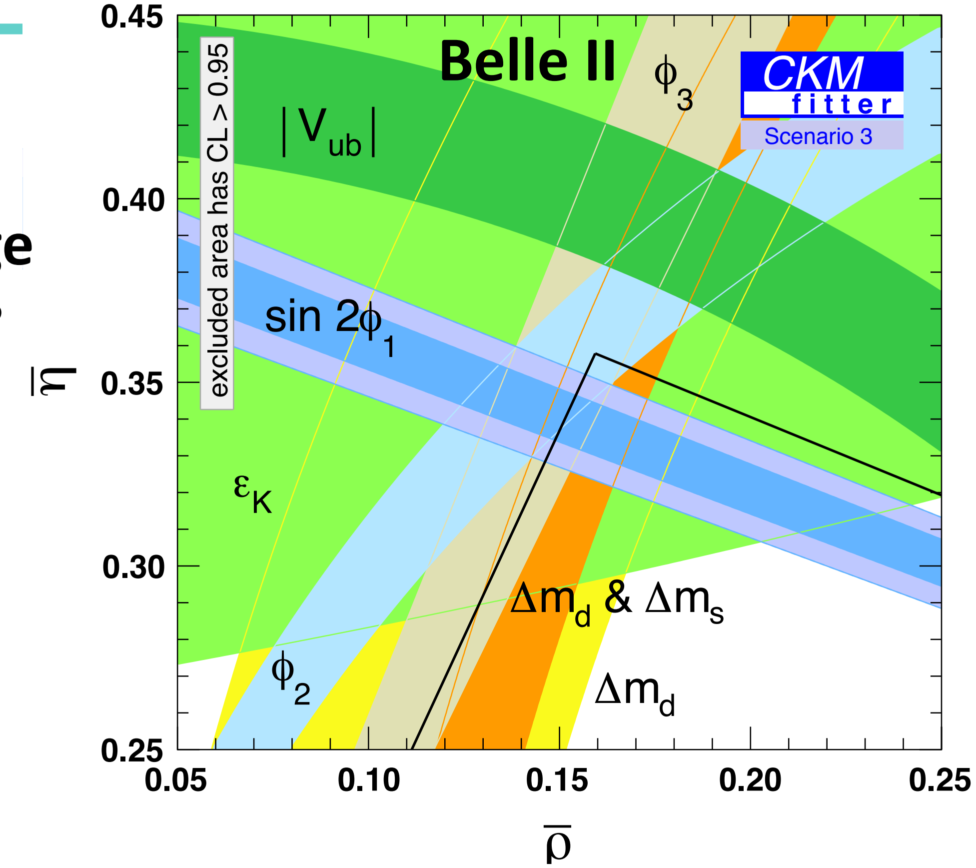
- Qualitative change after 2003: first Φ_3 and Φ_2 constraints

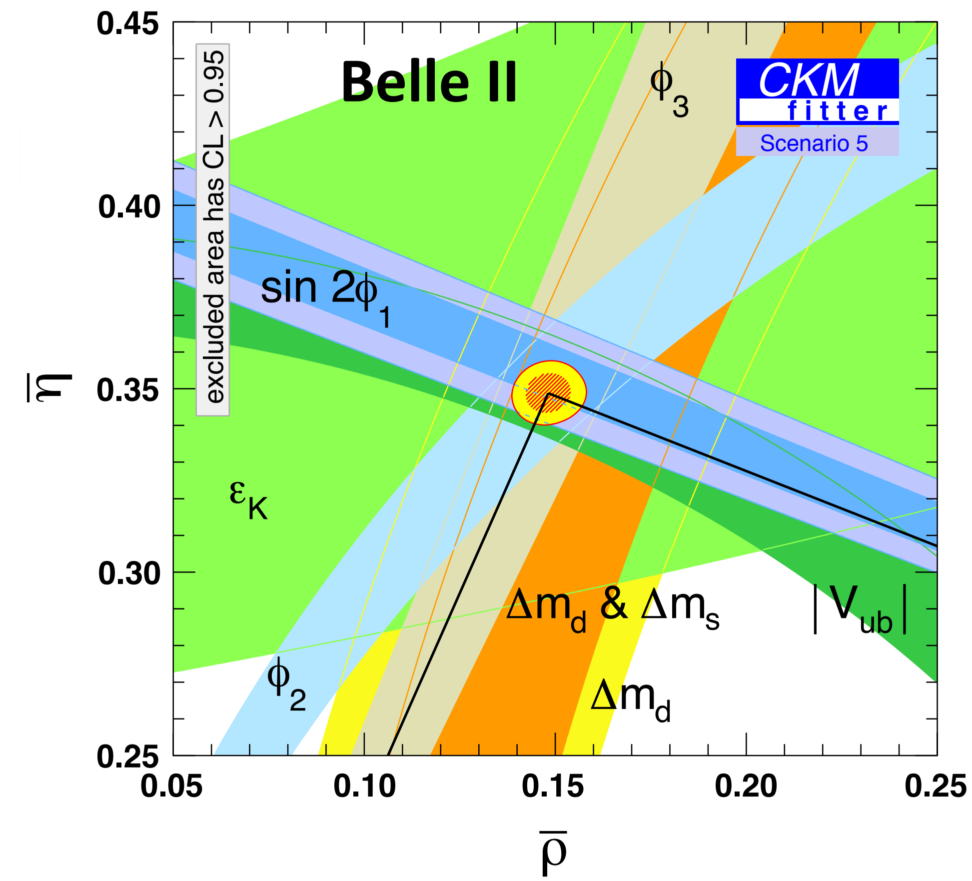
Belle II & LHCb projections

CKMfitter preliminary



World Average
p-value=10^{-5}



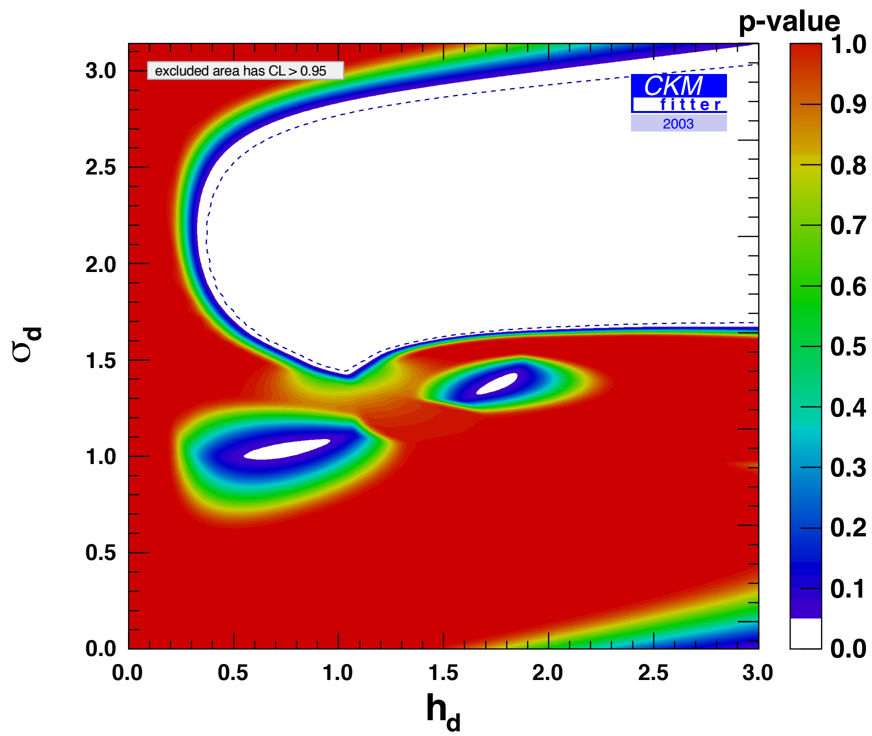


Phase	**J [10^{-5}]**	**SM-like Δ**
2016	3.140 [+0.069 -0.084]	2%
Belle II + LHCb upgrade - SM-like	3.125 ± 0.033	1%

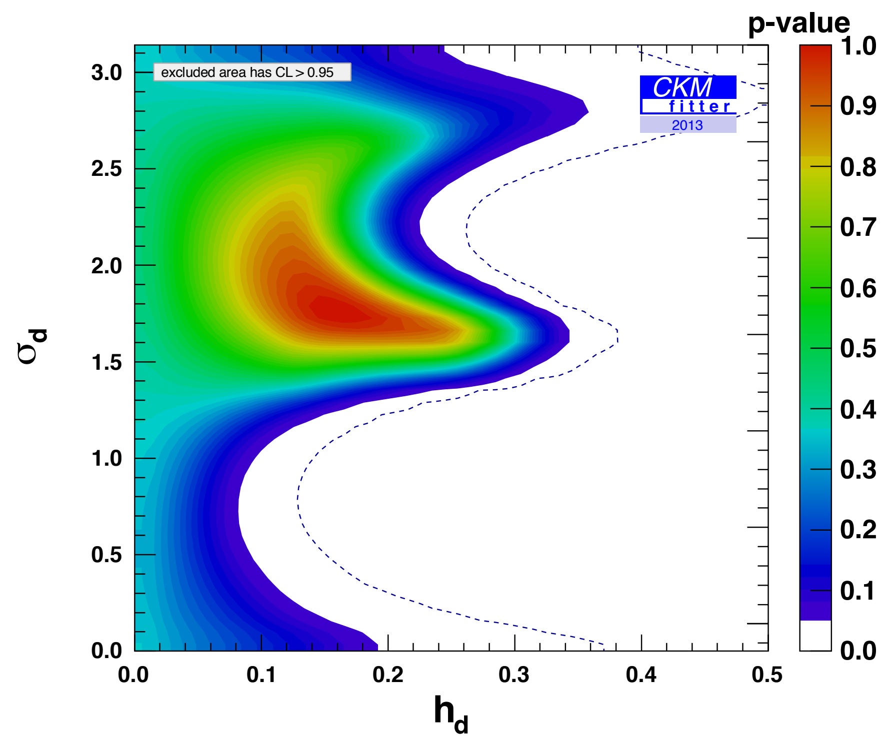
NP in B_d mixing: Fit results

CKMfitter PRD 91, 073007 (2015), PRD 89, 033016 (2014)

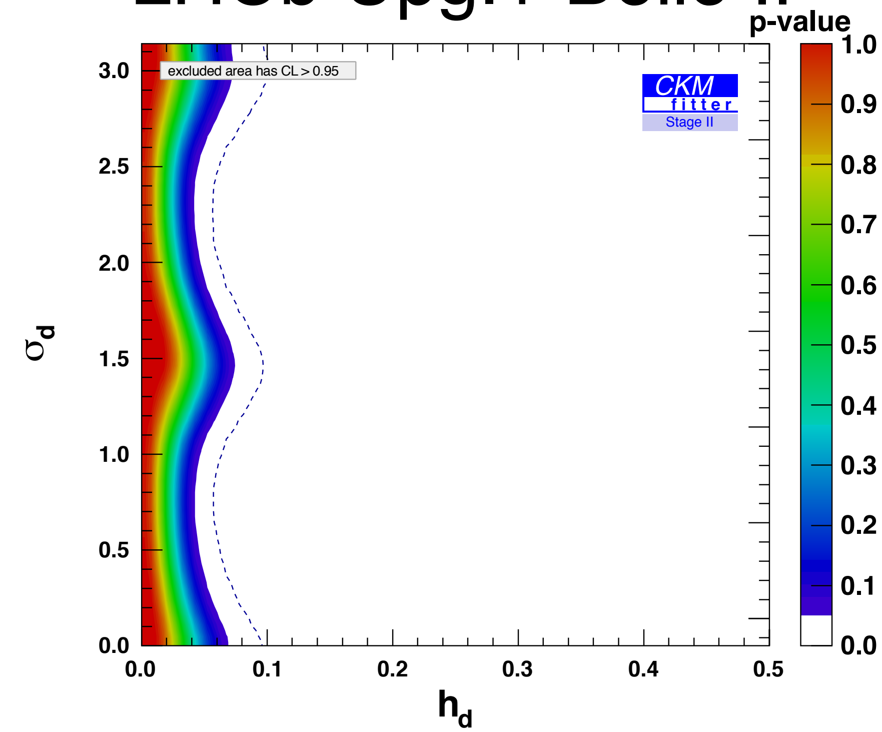
2003



2013



LHCb Upg.+ Belle II



- at 95% NP≲(many × SM) ⟹ NP≲(0.3 × SM) ⟹ NP≲(0.05 × SM)

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5 \text{ TeV}}{\Lambda} \right)^2$$

$$\sigma = \arg(C_{ij} \lambda_{ij}^{t*})$$

Couplings	NP loop order	Scales (TeV) probed by B_d mixing	Scales (TeV) probed by B_s mixing
$\lvert C_q\rvert = \lvert V_{tb}V_{tq}^*\rvert$	tree level	17	19
(CKM-like)	one loop	1.4	1.5
$\lvert C_q\rvert = 1$	tree level	2×10^3	5×10^2
(no hierarchy)	one loop	2×10^2	40

- Stage II: similar sensitivity to gluino masses explored at LHC 14TeV

Generic Bounds on New Phenomena

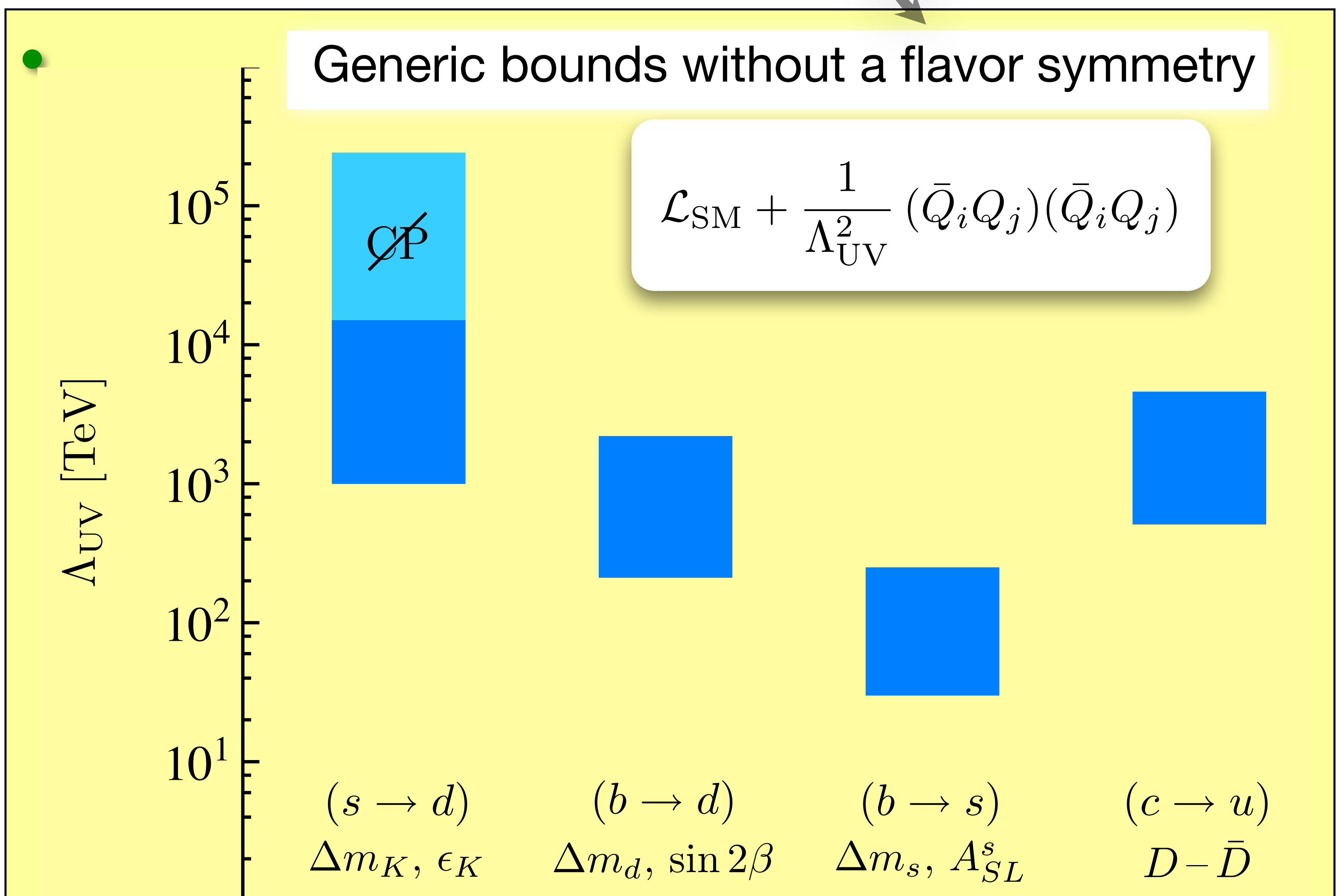
Meson Mixing

Rare Decays

Charged Lepton Flavor Violation

Electric Dipole Moments

meson mixing observables probe generic New Physics at very high scales



- Ways out

1. New particles have masses » 1 TeV
2. New particles have degenerate masses
3. Mixing angles in the new sector are small

Wrap up

- **Flavor physics is exciting and fundamental. Did we just find NP via new weak interaction couplings ?**
- **Flavor could be the path for the future of HEP but we need much more data.**

- **SuperKEKB commissioning started in February. Belle II rolls in at the end of the year. First collisions in late 2017. Belle II physics runs in 2018 and the LHCb upgrade in ~2021. These facilities will inaugurate a new era of flavor physics and the study of CP violation.**
- **Other new facilities in lepton sector not discussed here, e.g. COMET, MEG.**

https://www.facebook.com/belle2collab

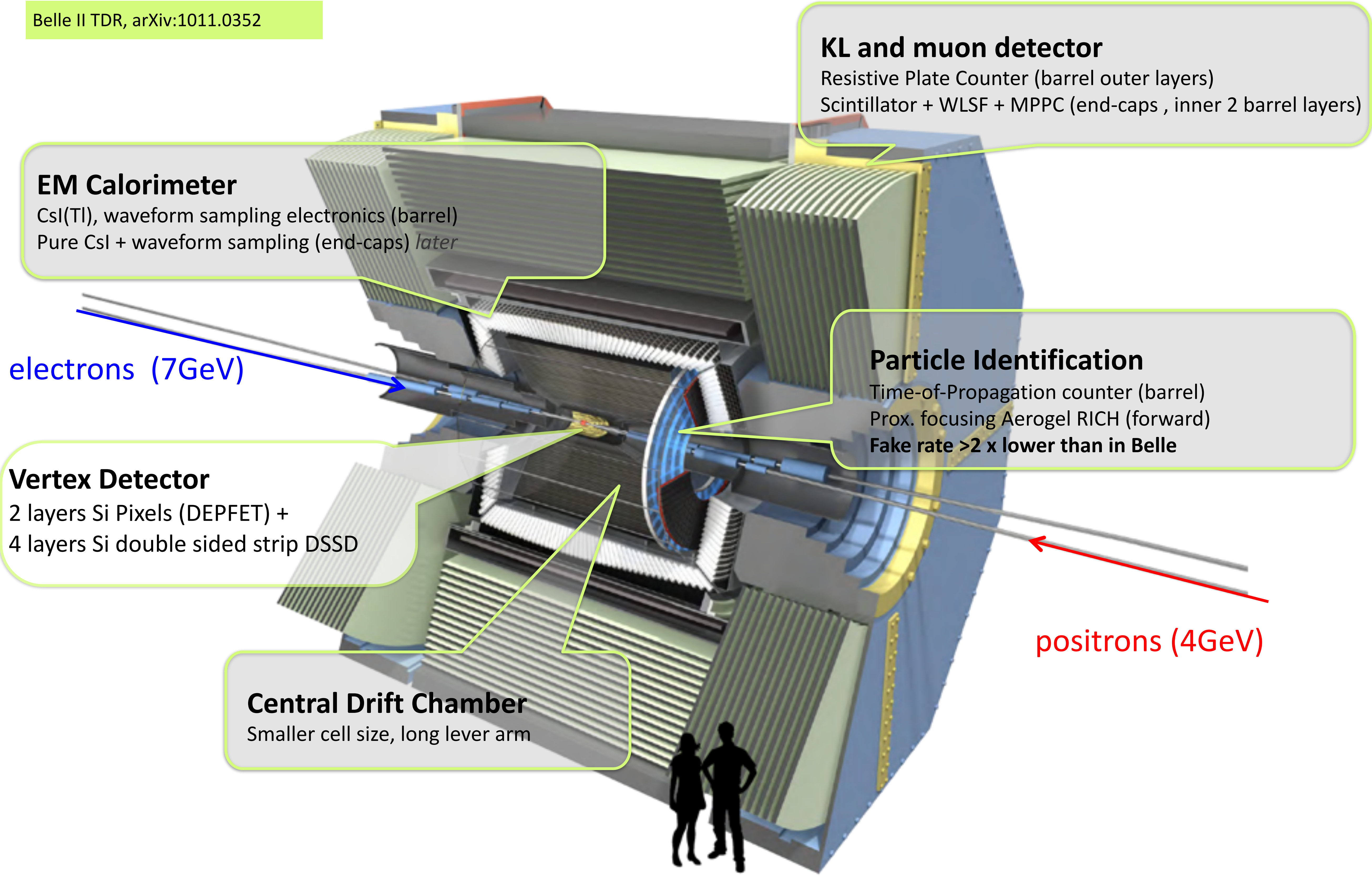
https://twitter.com/belle2collab

Backup

Belle II Detector

[600+ collaborators, 99 institutes, 23 nations]

Belle II TDR, arXiv:1011.0352



Golden modes: B physics

SuperKEKB TDR (2014)

	Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$ [10]	1.8%	1.4%
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ [5]	3.4%	3.0%
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	$96(1 \pm 27\%)$ [26]	10%	5%
	$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7 [67]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.6%	3.4%
	$R(B \to D^*\tau\nu)^\dagger$	$0.332(1 \pm 9.0\%)$ [29]†	3.2%	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ [10^{-6}]	< 40 [30]	< 15	30%
	$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ [10^{-6}]	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 $(B \to X_s\ell\ell)$	$\sim$20% [36]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ [10^{-3}]	–	< 2 [44]‡	–

Golden modes: D and Tau physics

SuperKEKB TDR (2014)

	Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$ [46]	2.9%	0.9%
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$ [46]	3.5%	2.3%
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5 [49]	30%	25%
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-2}]$	$-0.32 \pm 0.21 \pm 0.09$ [69]	0.11	0.06
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$ [70]	0.29	0.09
	$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$ [70]	0.08	0.03
Charm Mixing	$x(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$ [52]	0.14	0.11
	$y(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$ [52]	0.08	0.05
	$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$ [52]	0.10	0.07
	$\phi(D^0 \to K_S^0\pi^+\pi^-)$ $[^\circ]$	$-6 \pm 11 \pm {}^{4}_{5}$ [52]	6	4
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45 [71]	< 14.7	< 4.7
	$\tau \to e\gamma$ $[10^{-9}]$	< 120 [71]	< 39	< 12
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0 [72]	< 3.0	< 0.3

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5^o	Belle II
ϕ_3	***	3^o	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0 \pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^* \mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5^o	Belle II

- Belle II:
  - Decays with neutrinos, or multiple photons.
  - “Inclusive” decays.
  - Long-live particles: K-shorts & K-longs
- LHCb:
  - Decays to all charged particle final states.
  - Fast mixing.