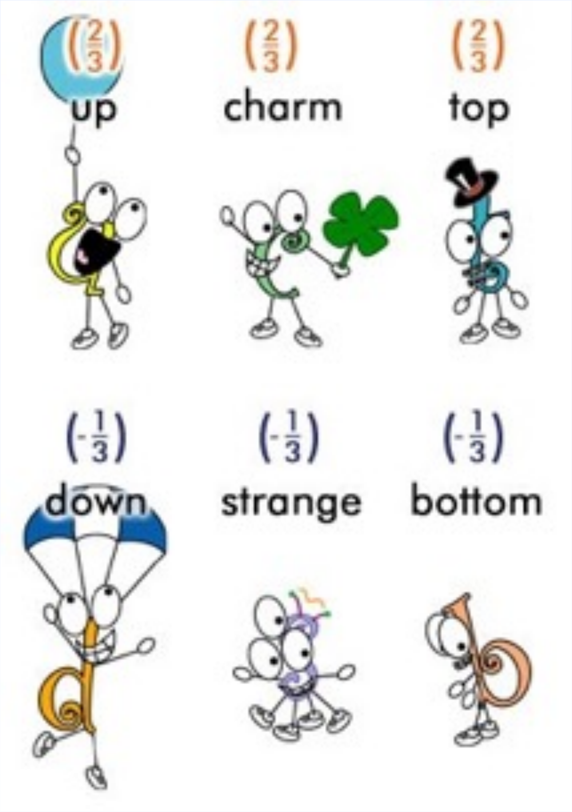
Introduction to flavour physics

Evelina Gersabeck



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

LHCb

Acknowledgements

- Many thanks to those who (un)knowingly helped me: Tim Gershon, Mika Vesterinen, Marco Gersabeck, Uli Uwer, Johannes Albrecht, Sevda Esen, Christoph Langenbruch, Vava Gligorov, Jeroen van Tilburg, Chris Parkes

I will be talking about quark flavour physics and mostly about heavy quarks

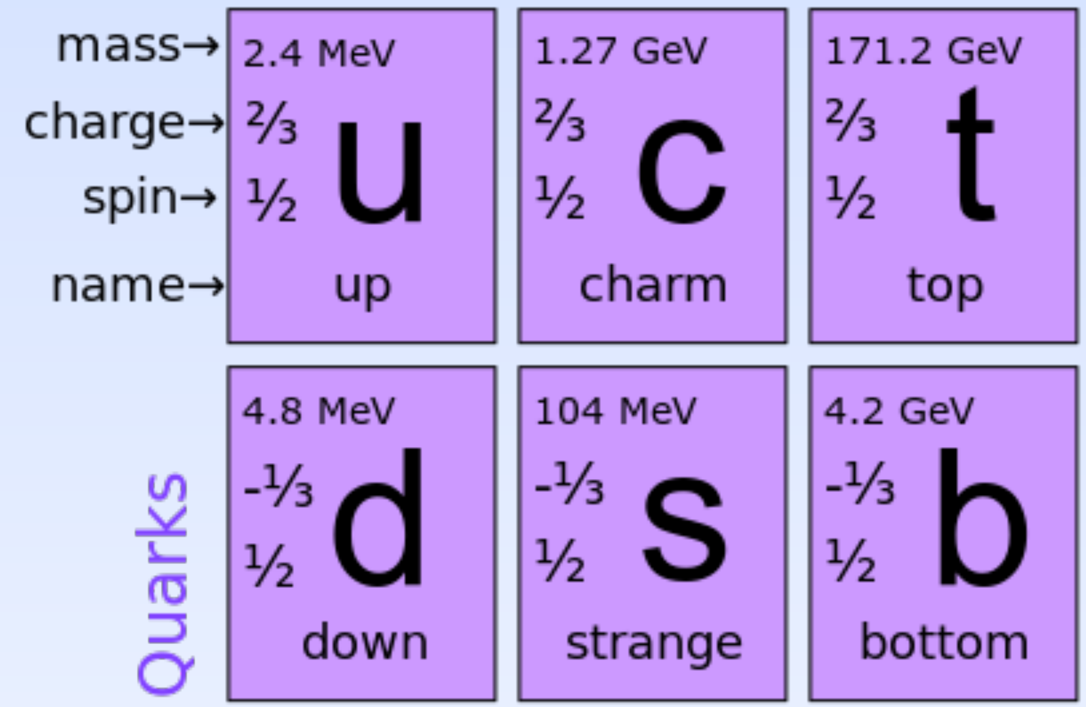
Just as ice cream has both color and flavor so do quarks.

Murray Gell-Mann

Outline

- Where do we produce heavy quarks?
- CKM matrix
- Neutral mesons mixing
- Types of CPV
- CPV in mixing
- CPV in interference
- CPV in decay
- Rare B decays

Heavy 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
  - B mesons have a long lifetime (~1.6ps)

The charm quark …

– Provides the only up-type quark decay from a bound system
– Quasi two generation system
– D mesons have a lifetime ~0.4ps

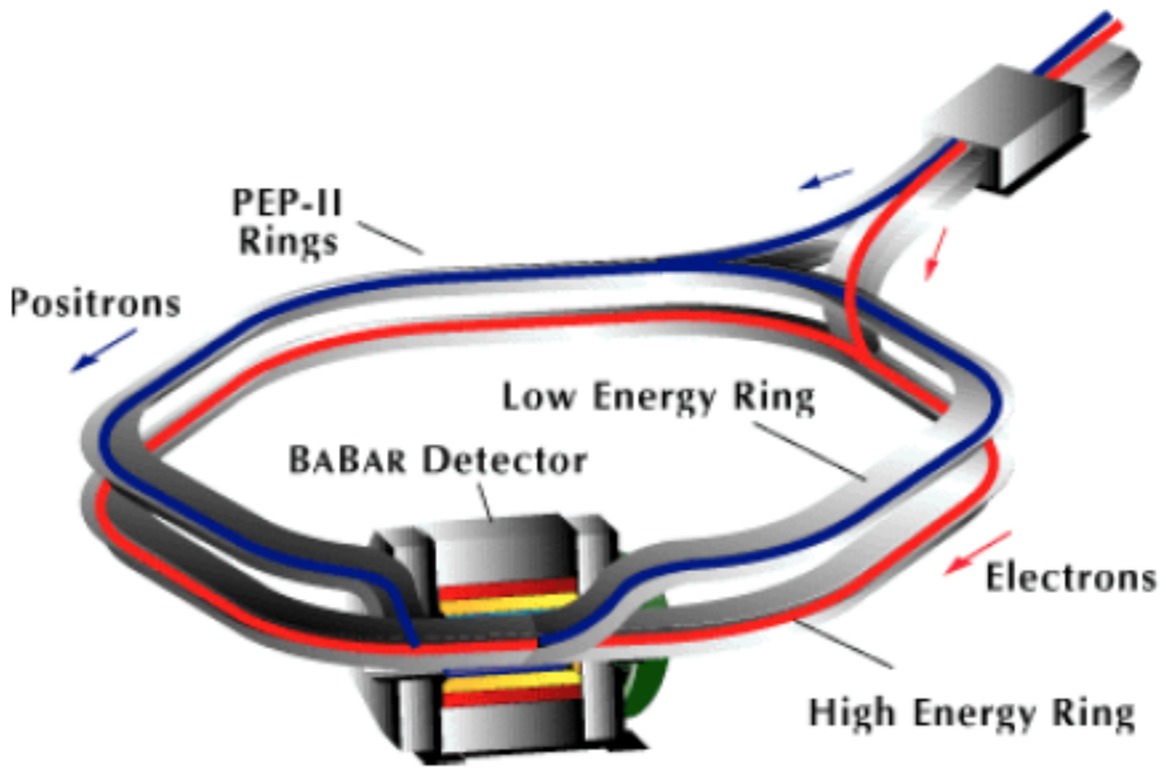
Interesting to compare the phenomena in the up- and down- sector

Where do we produce heavy quarks?

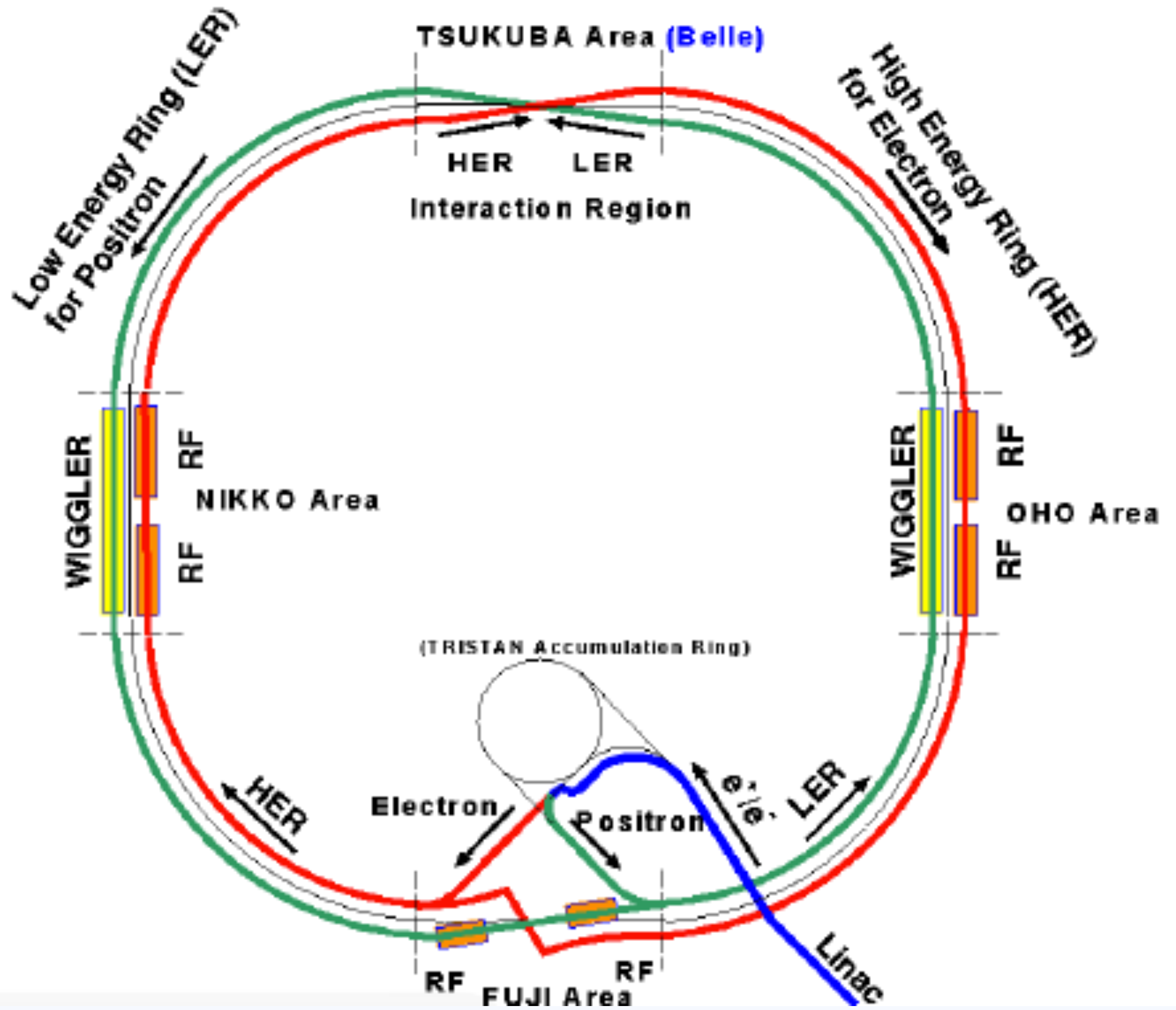
B-factories

Babar & Belle

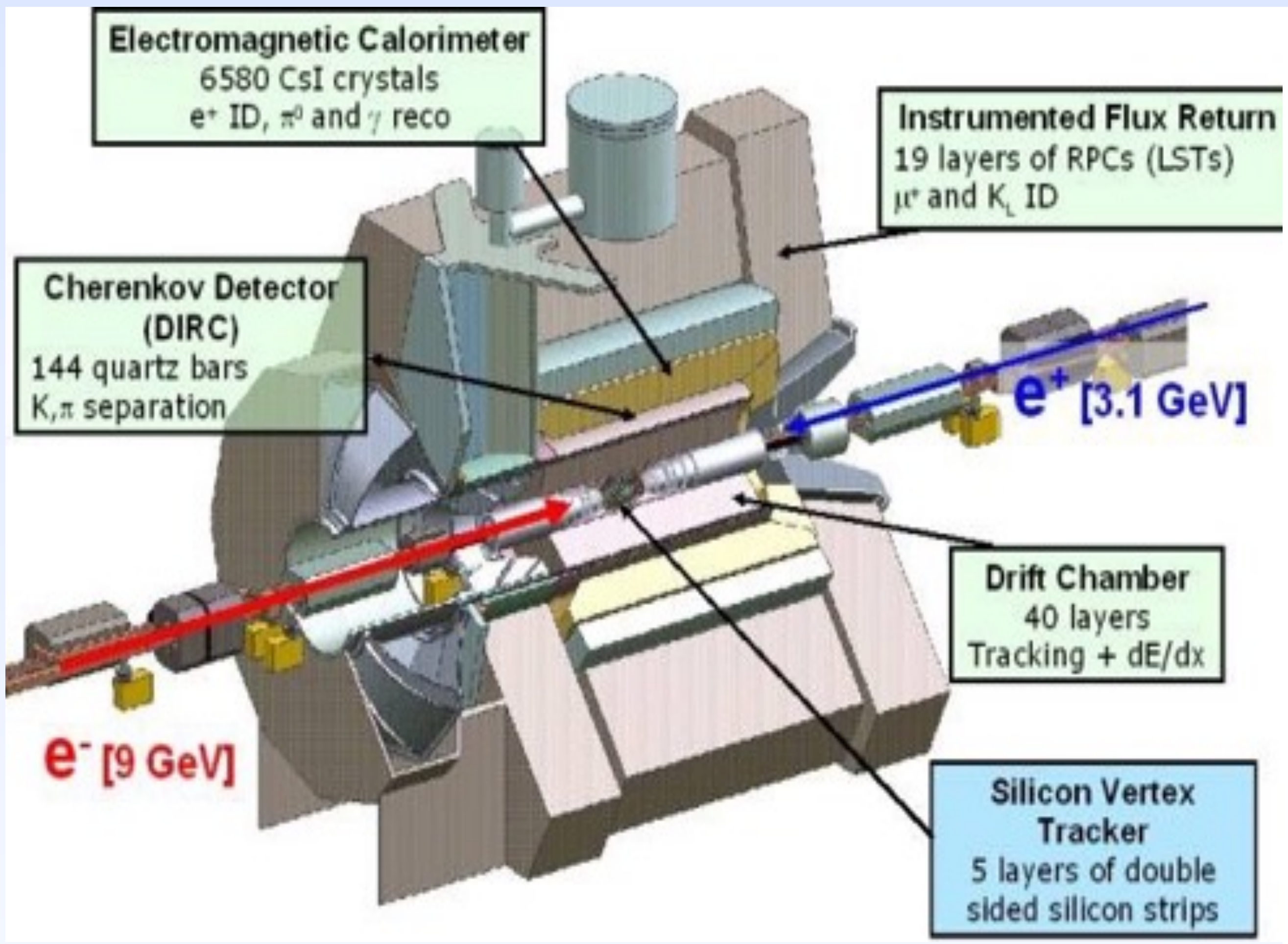
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

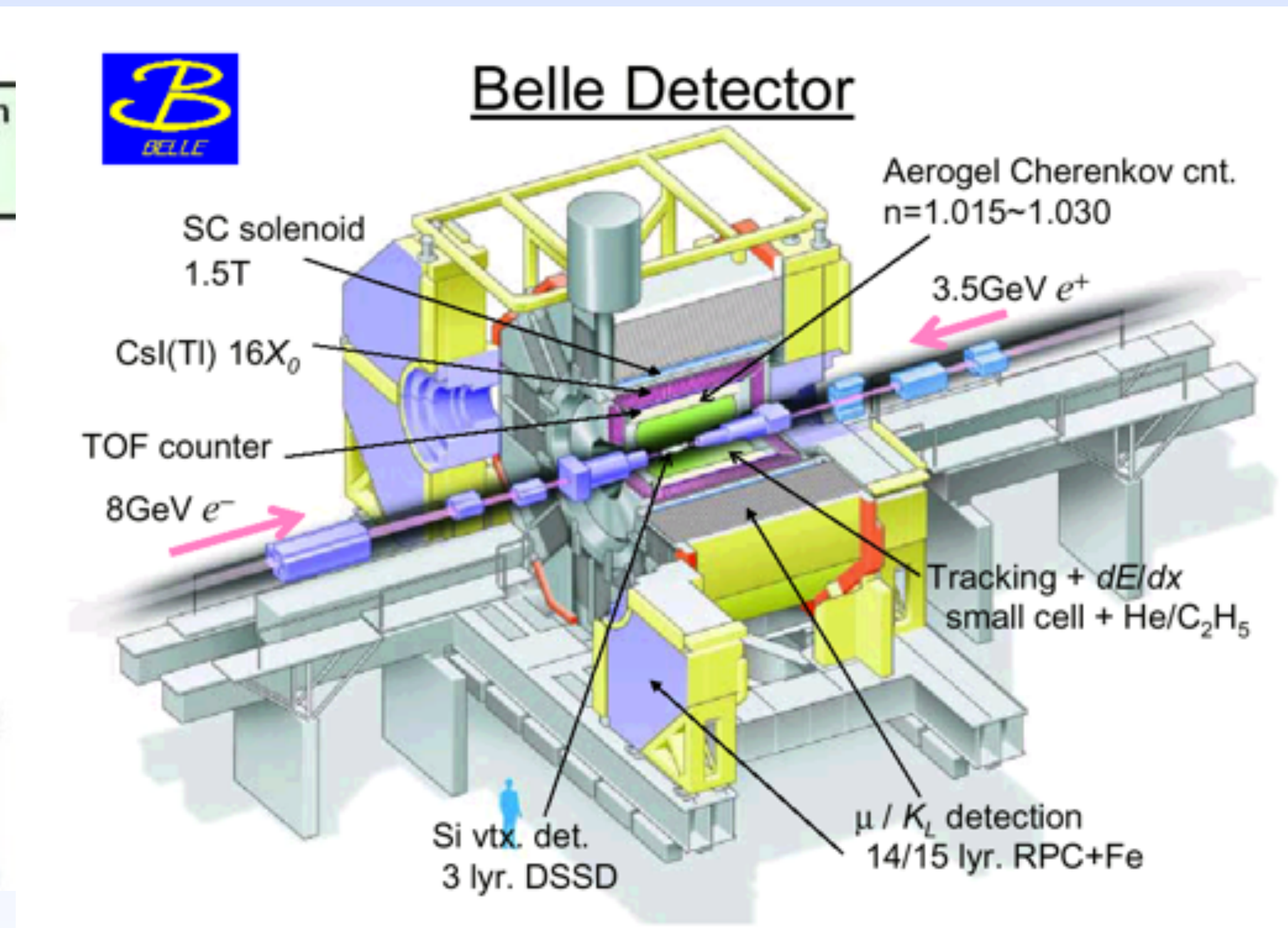


KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+



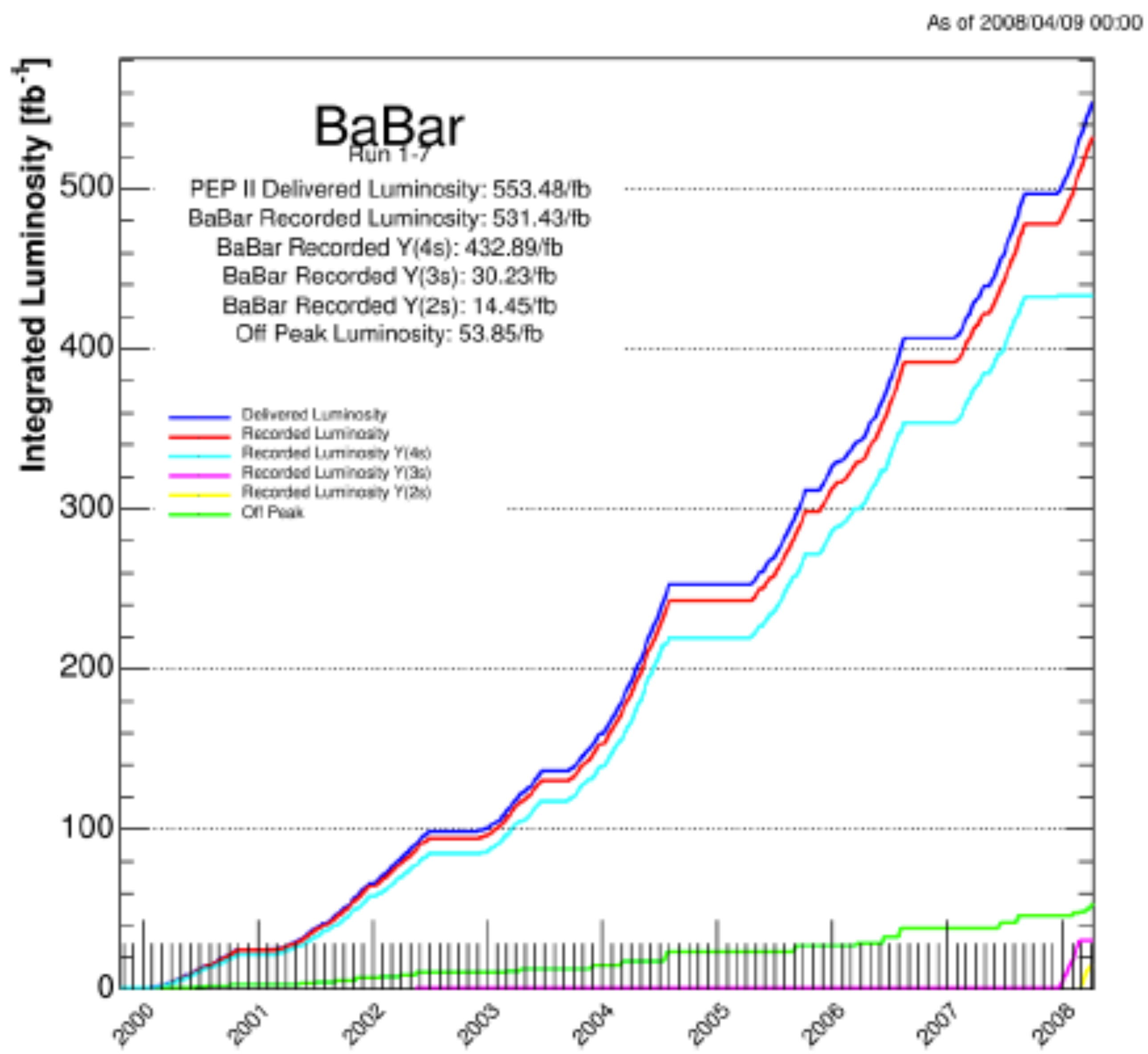
Babar & Belle

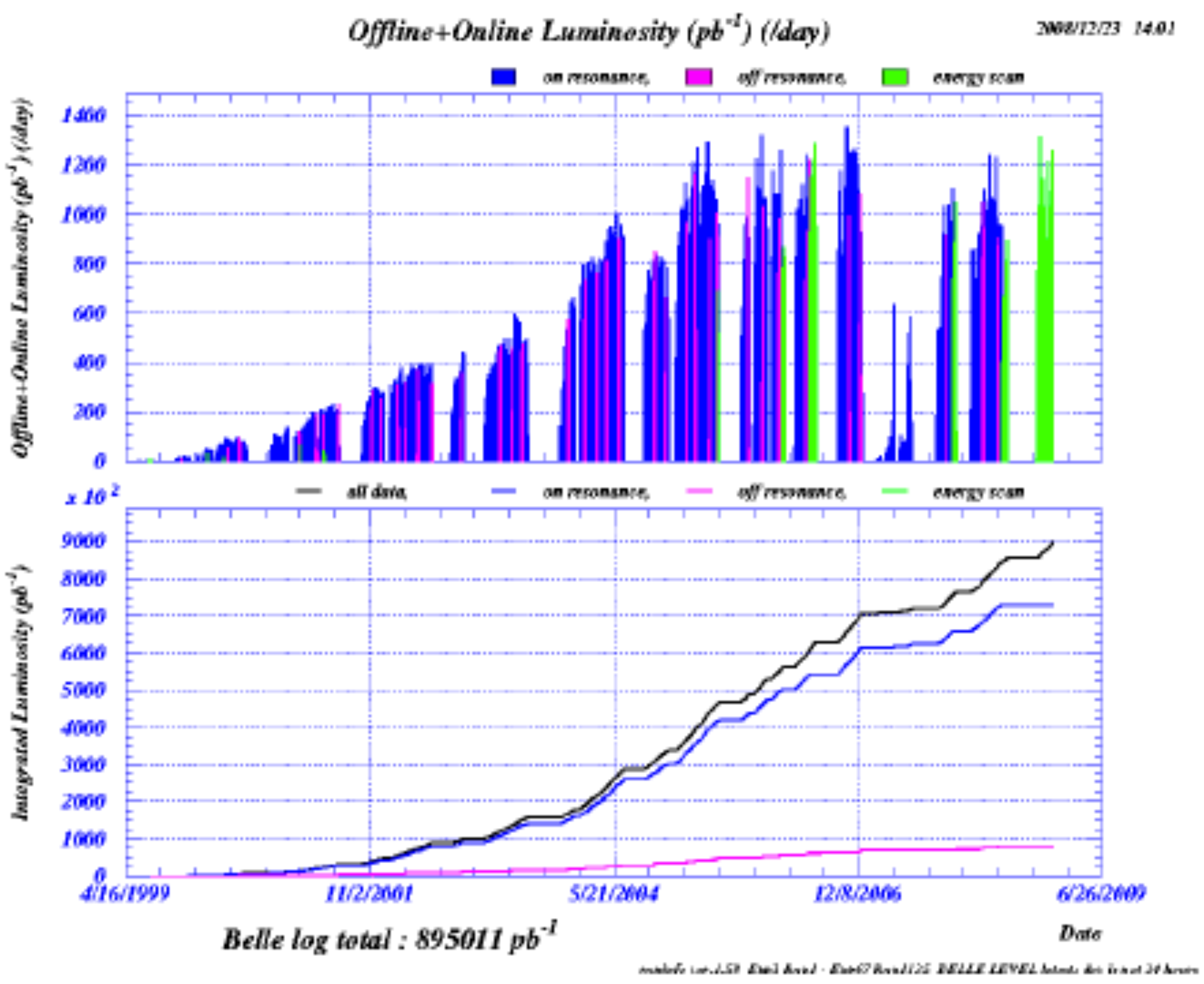




hermetic detectors (*blind spot around beampipe), low background, mainly access $B^{0,+}$ and charm Belle is being upgraded, Belle II aims to collect 50x the Belle dataset

Luminosities of the B-factories

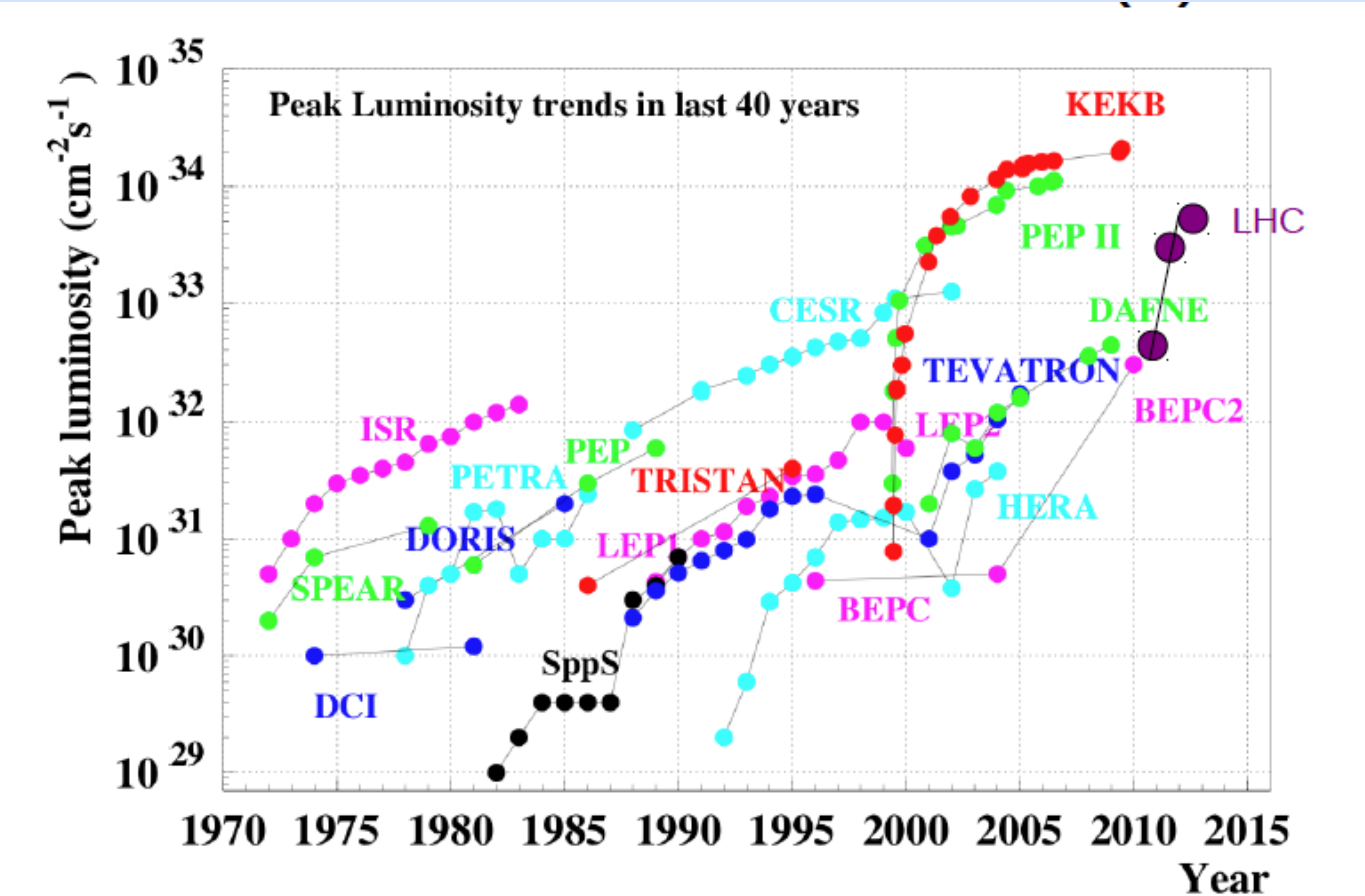




~ 433/fb on Y(4S)

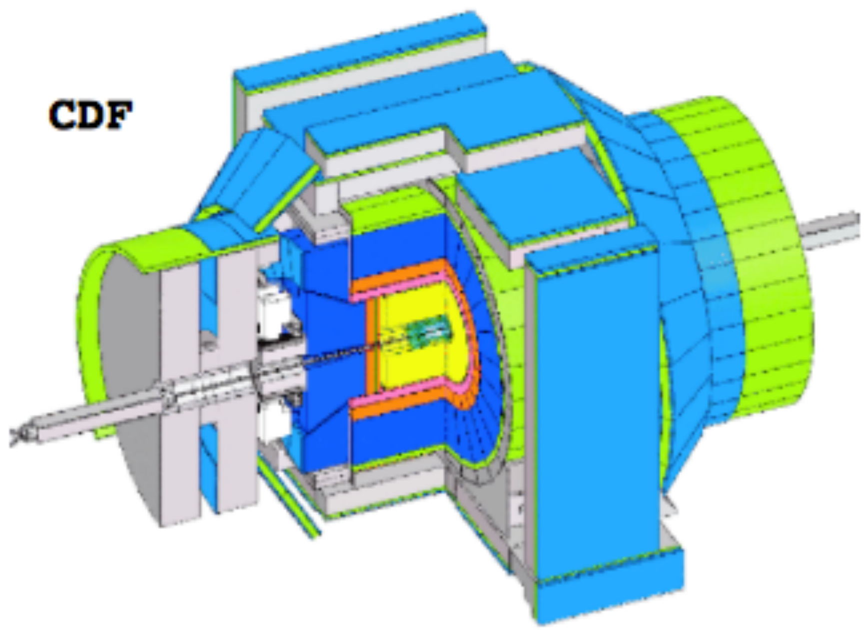
~ 711/fb on Y(4S)

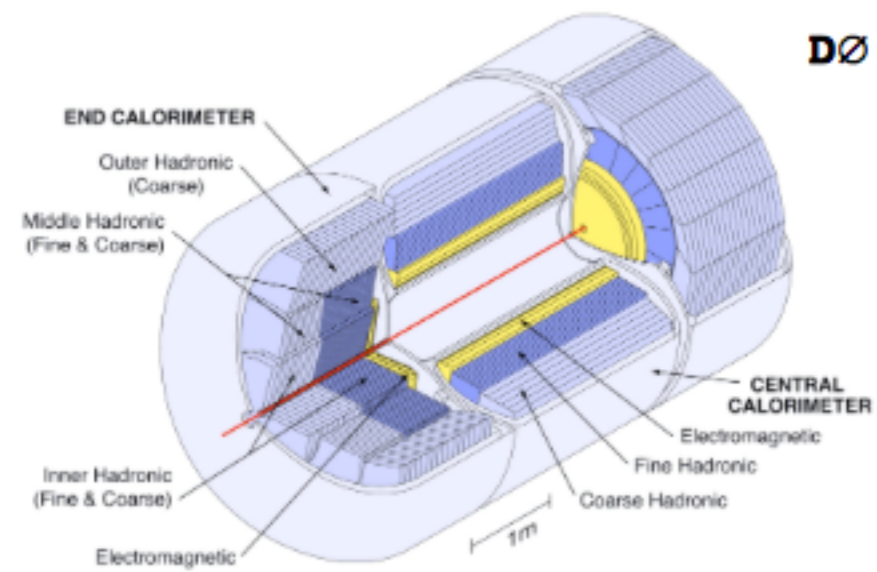
Luminosity

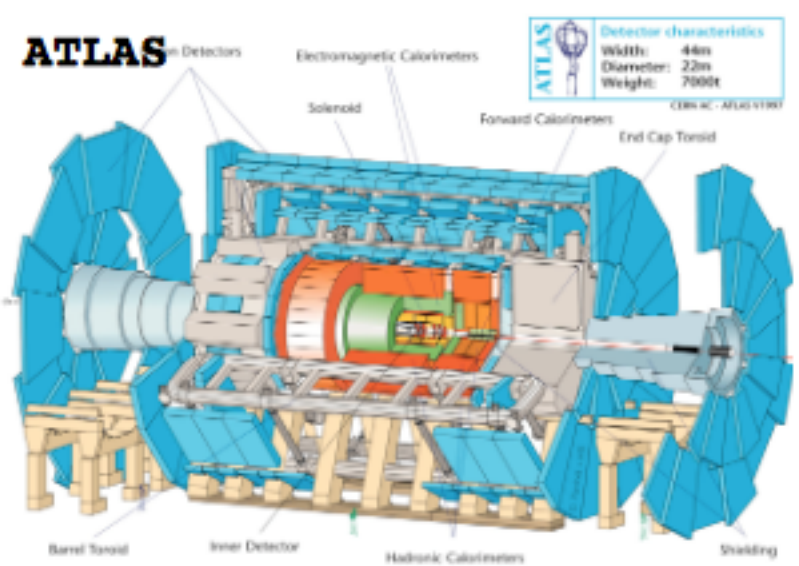


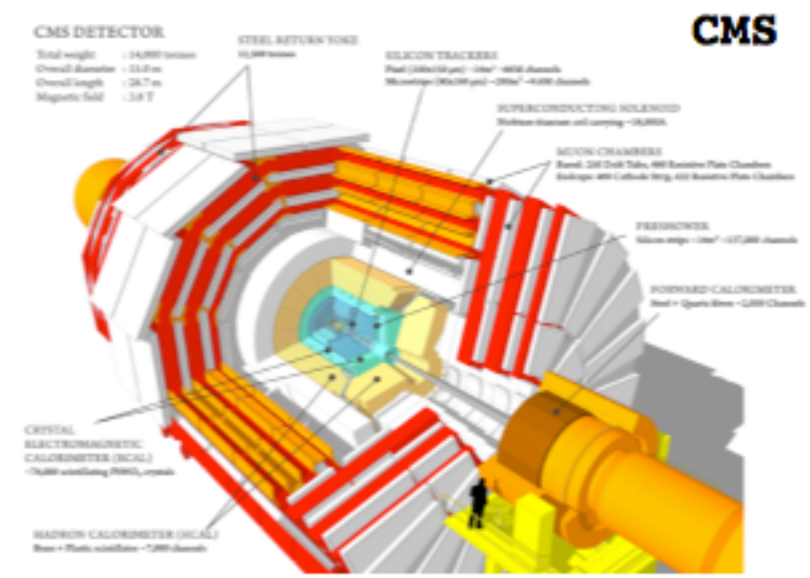
Peak Luminosity trends in last 40 years
Peak luminosity (cm^{-2}s^{-1})
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
10^{29}
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
KEKB
LHC
PEP II
DAFNE
CESR
TEVATRON
BEPC2
ISR
LEP2
PEP
PETRA
TRISTAN
HERA
DORIS
LEP1
SPEAR
BEPC
SppS
DCI

Experiments at hadron colliders





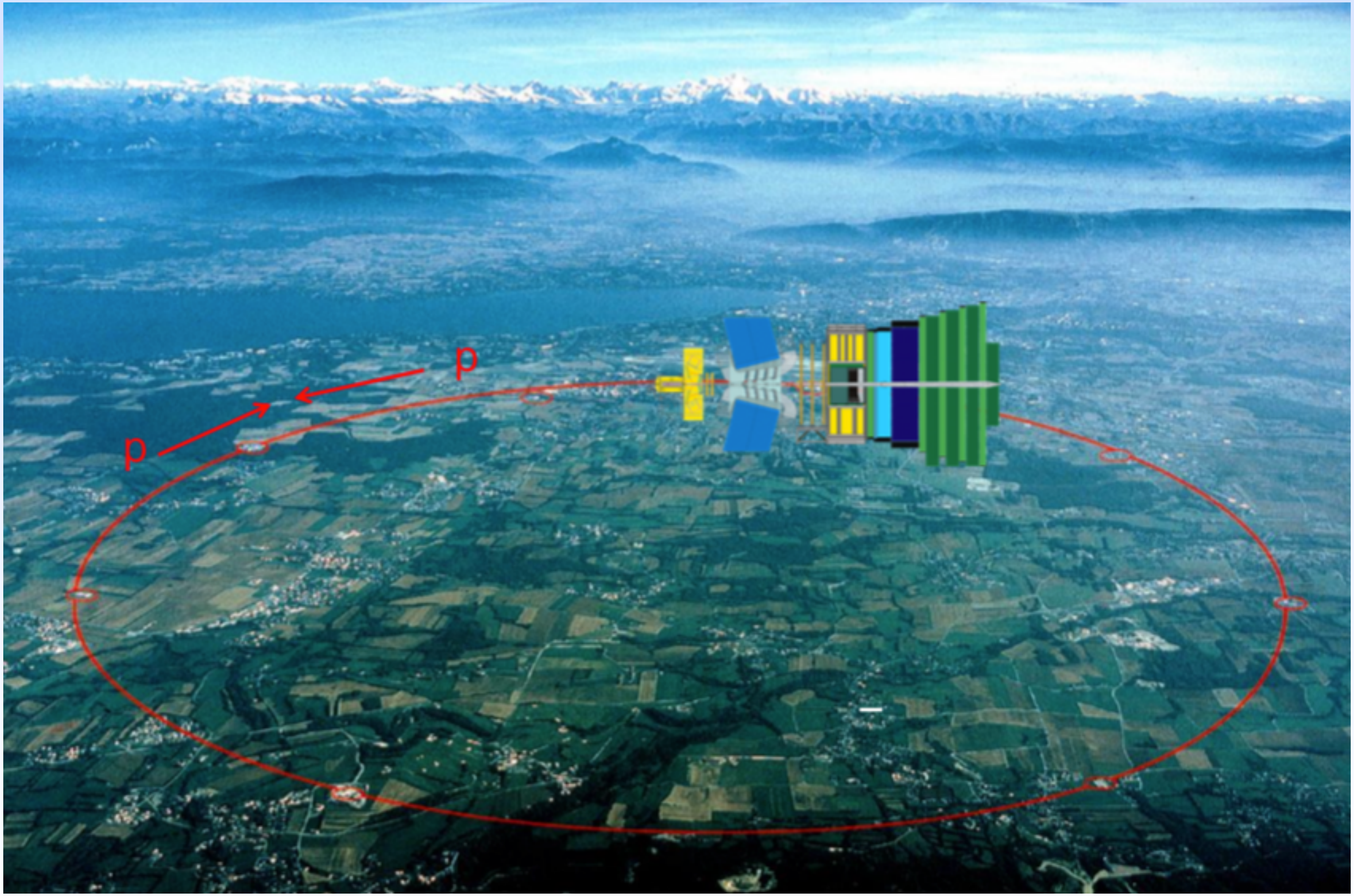




hermetic detectors, but hadronic environment: much harsher background conditions

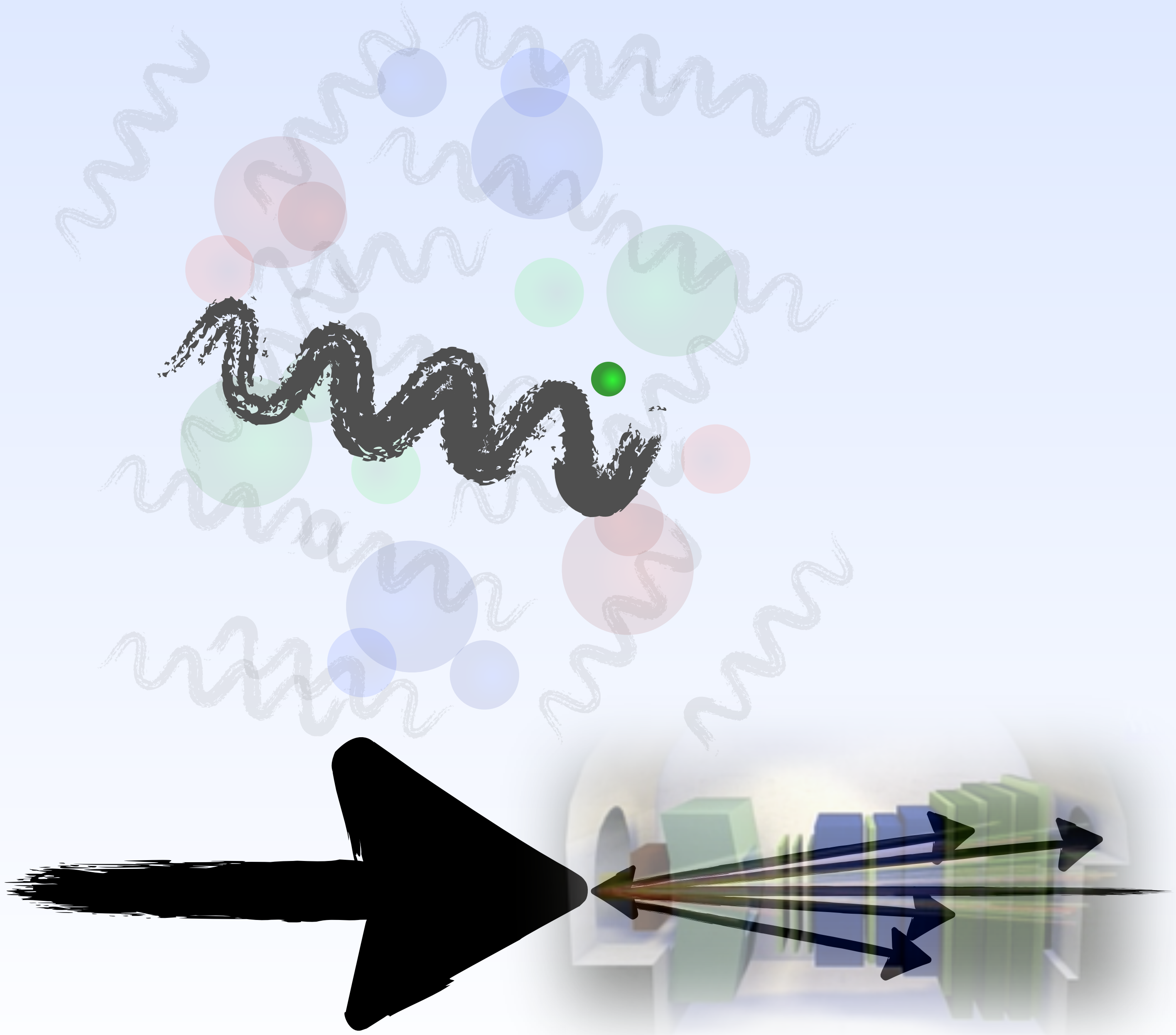
LHCb experiment

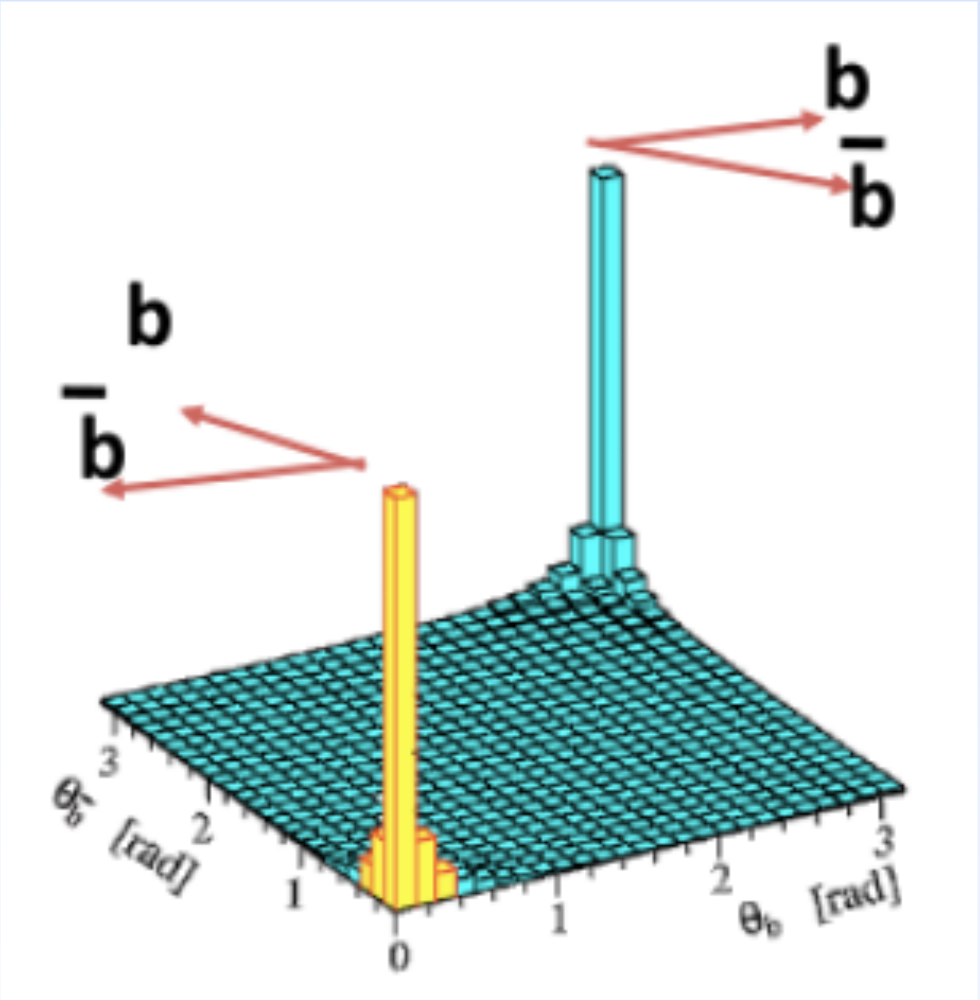
LHC & LHCb



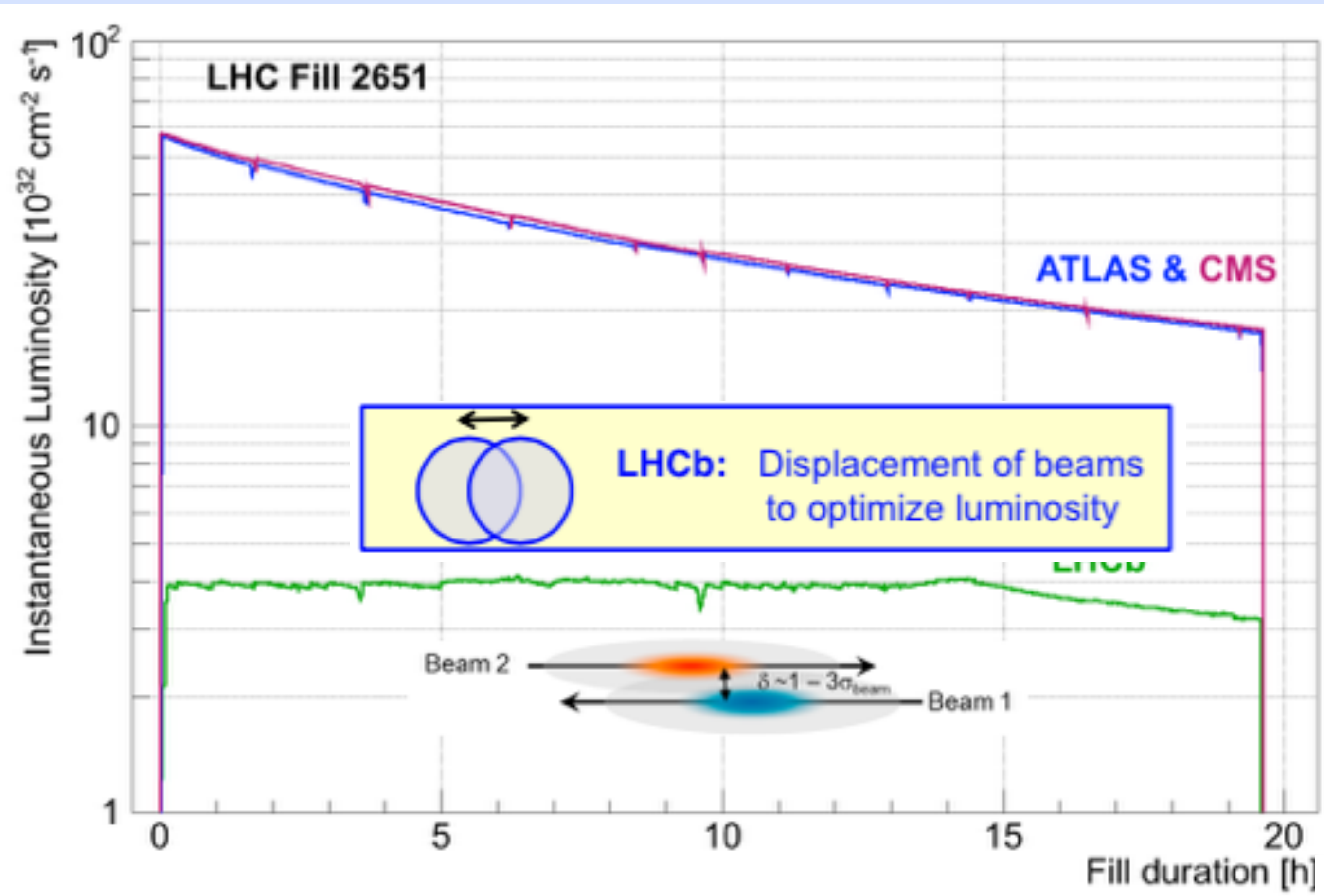
Asymmetric collisions

pp have the same energy but not a point-like objects collision



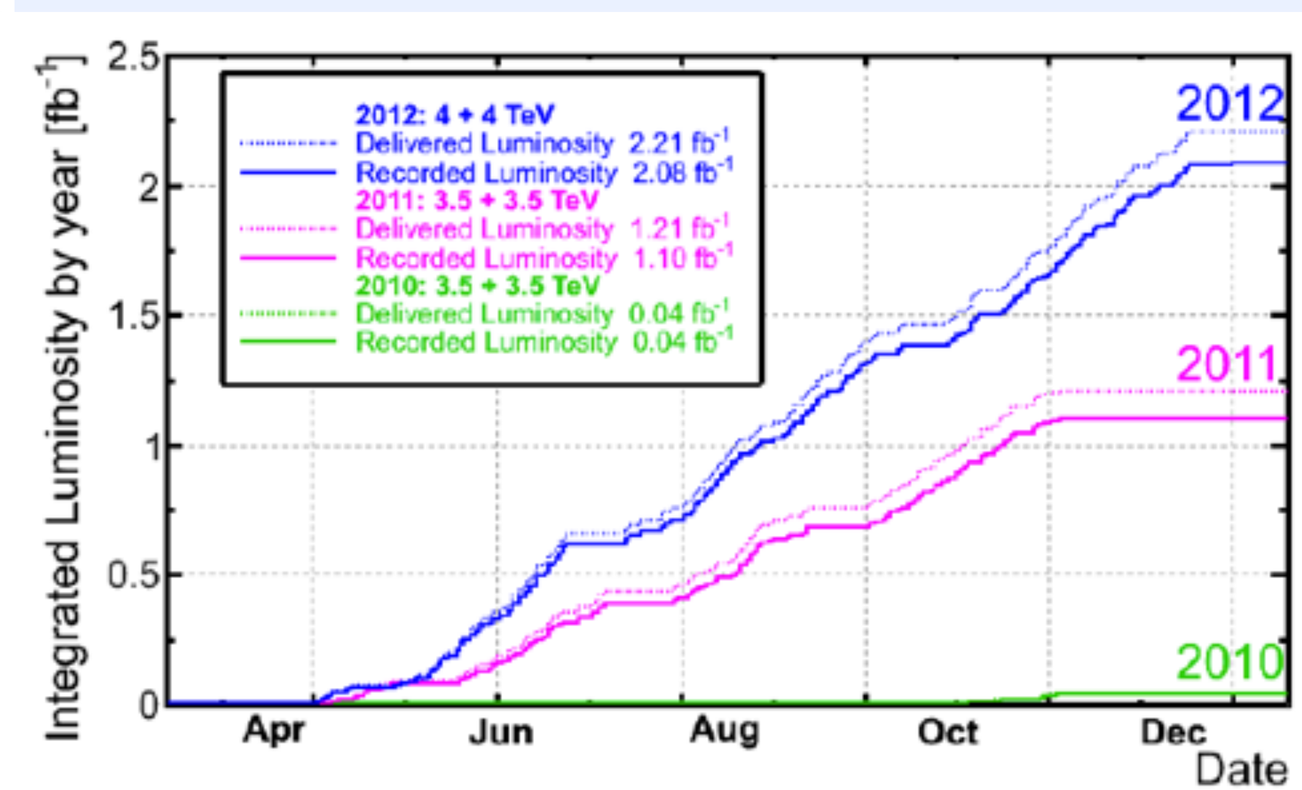


Constant luminosity

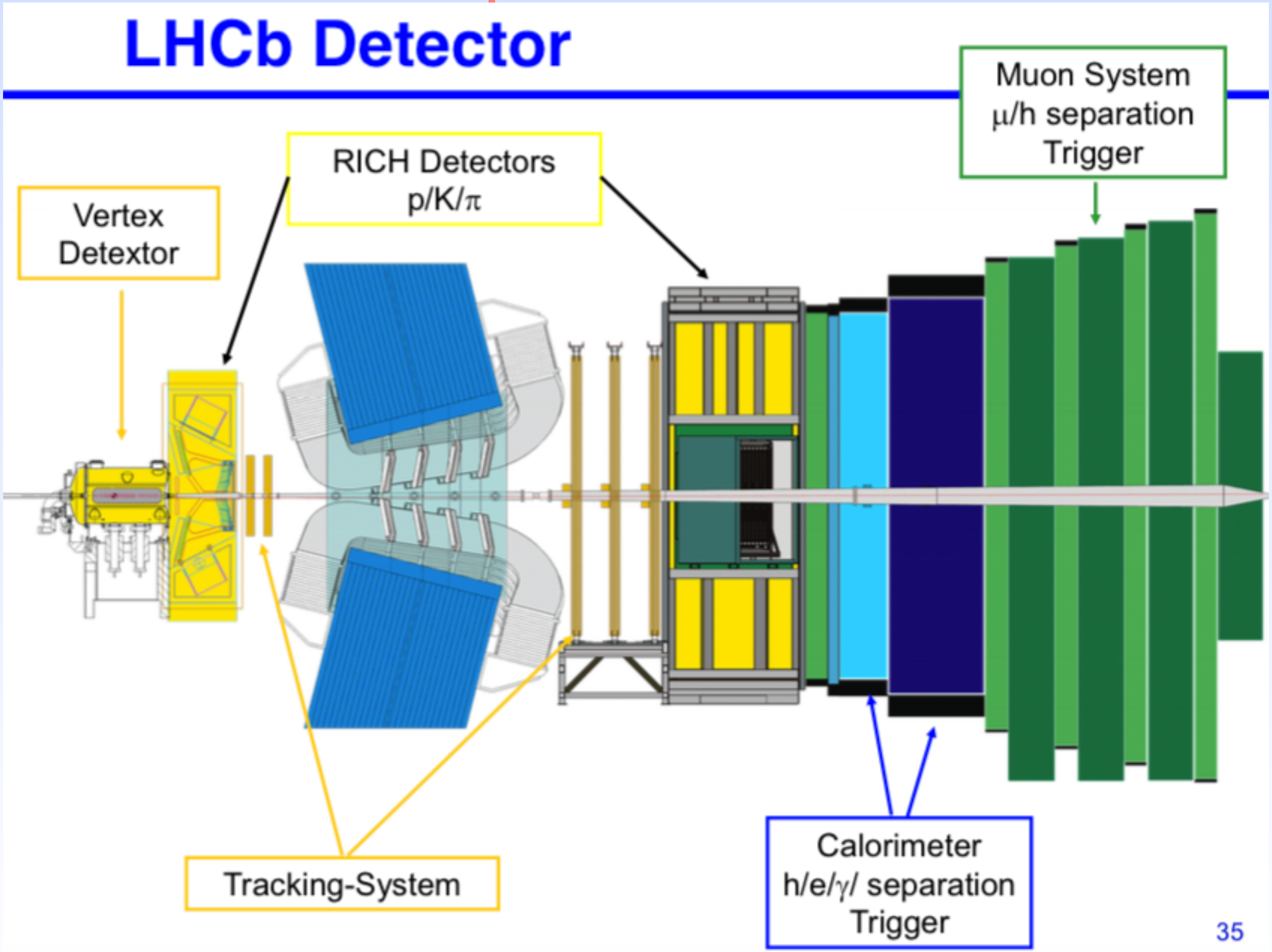


- In total so far:
  - ➡ 2010 peanuts
  - ➡ 2011 1 fb^{-1}
  - ➡ 2012 2 fb^{-1}

Instantaneous luminosity (2012) ~ 4 $10^{32}/cm^2/s$
LHCb design luminosity: 2 $10^{32}/cm^2/s$



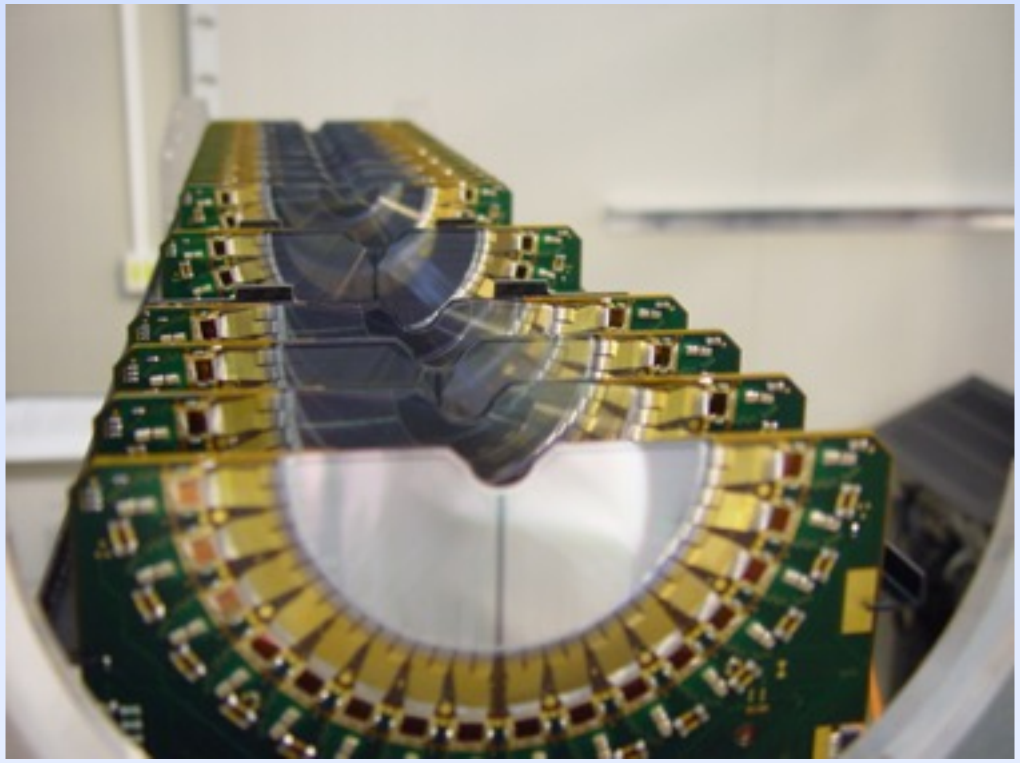
Forward spectrometer at LHC

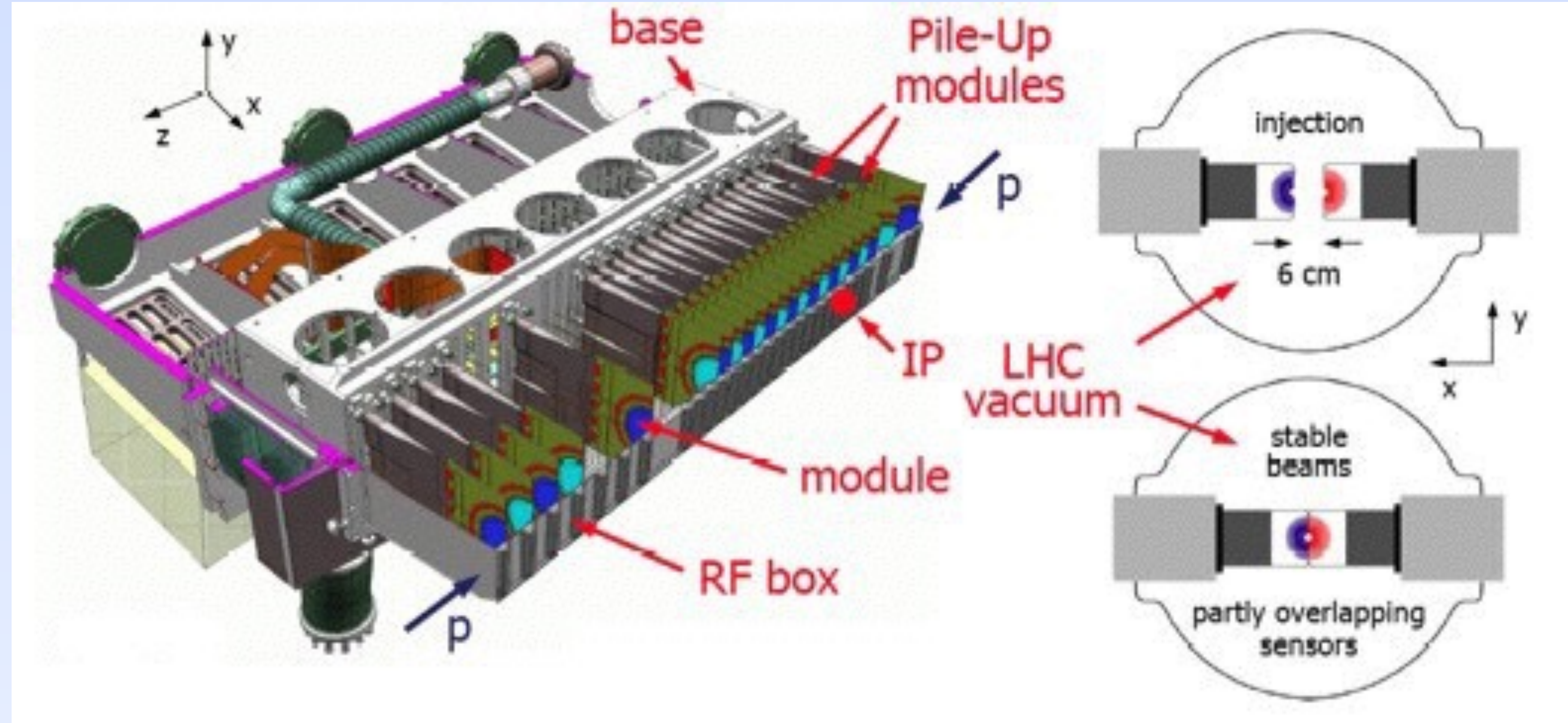


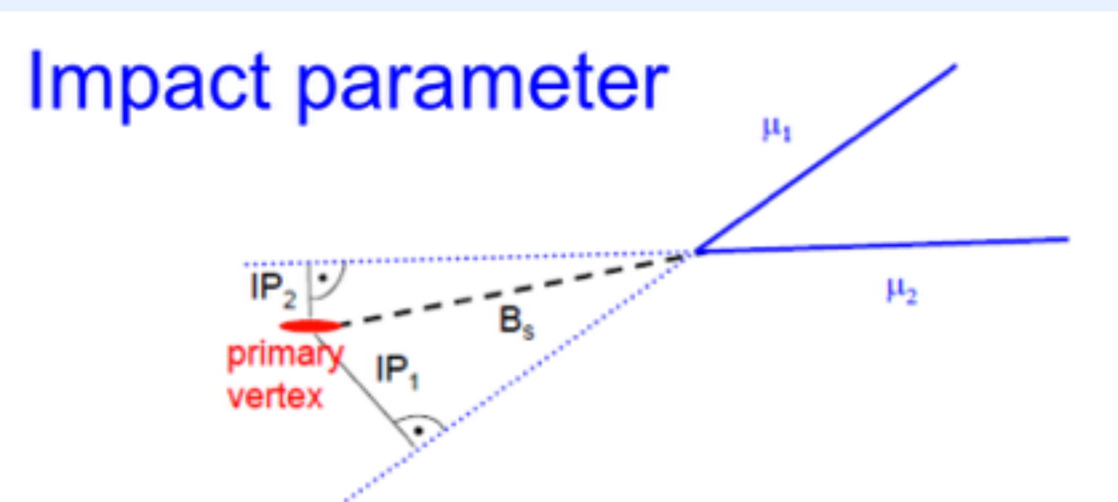
Keys for heavy flavour physics

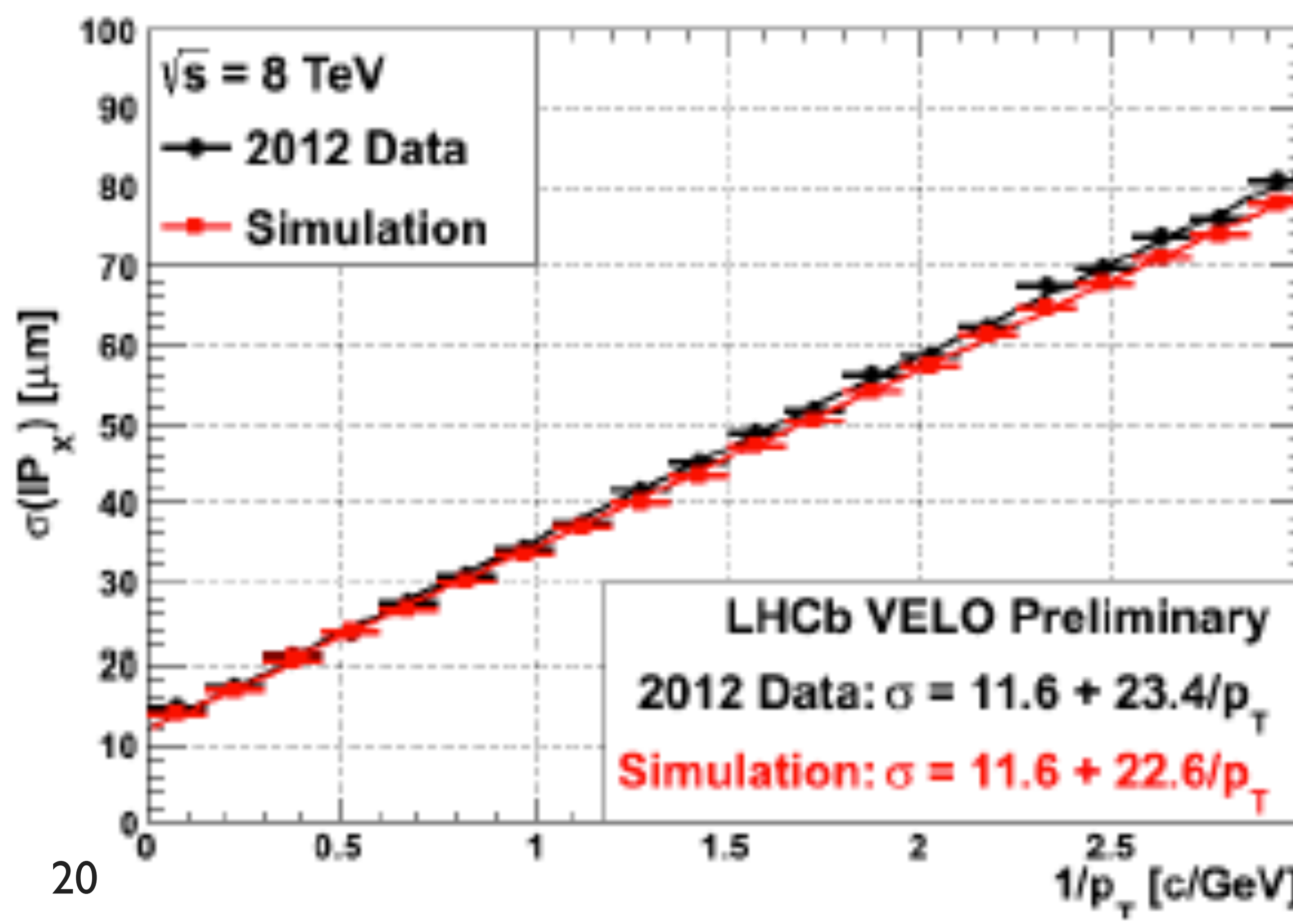
- Vertex resolution
- Particle identification
- Mass resolution
- Production rates

VELO



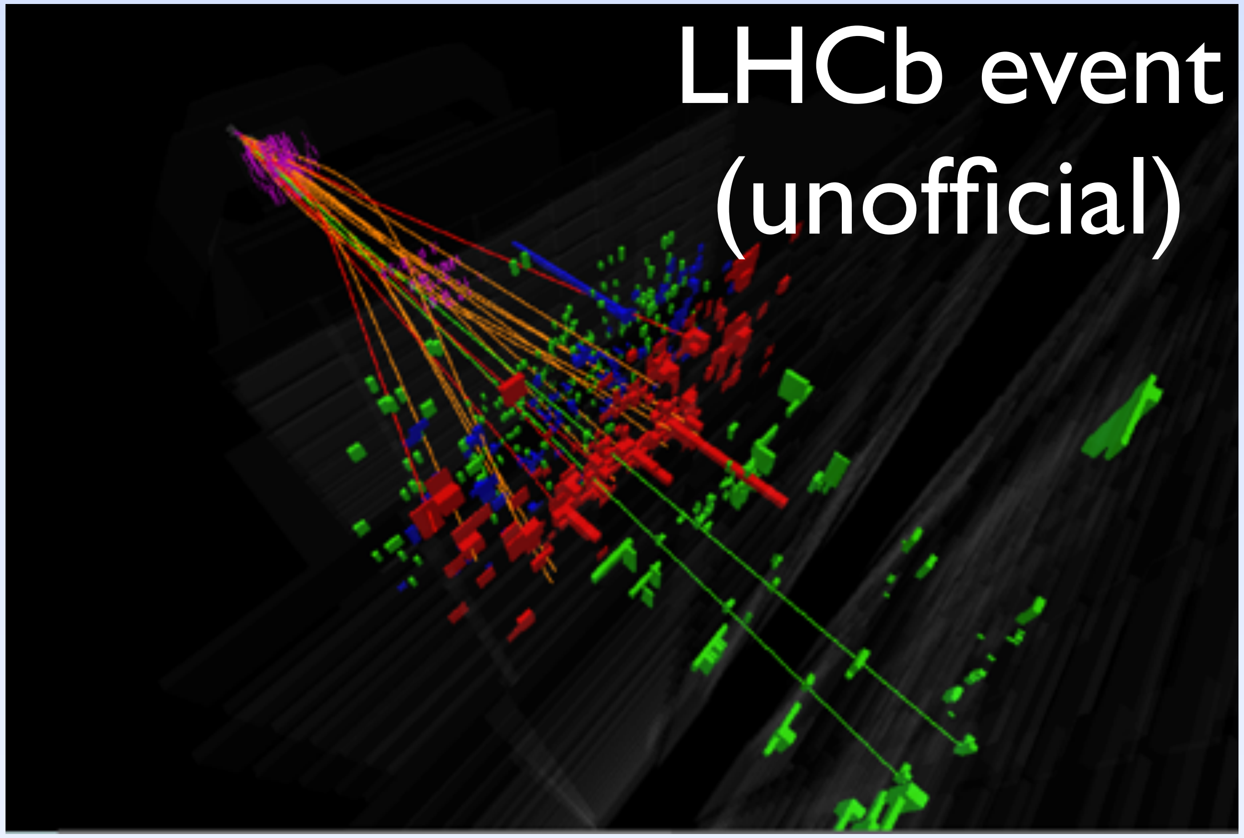


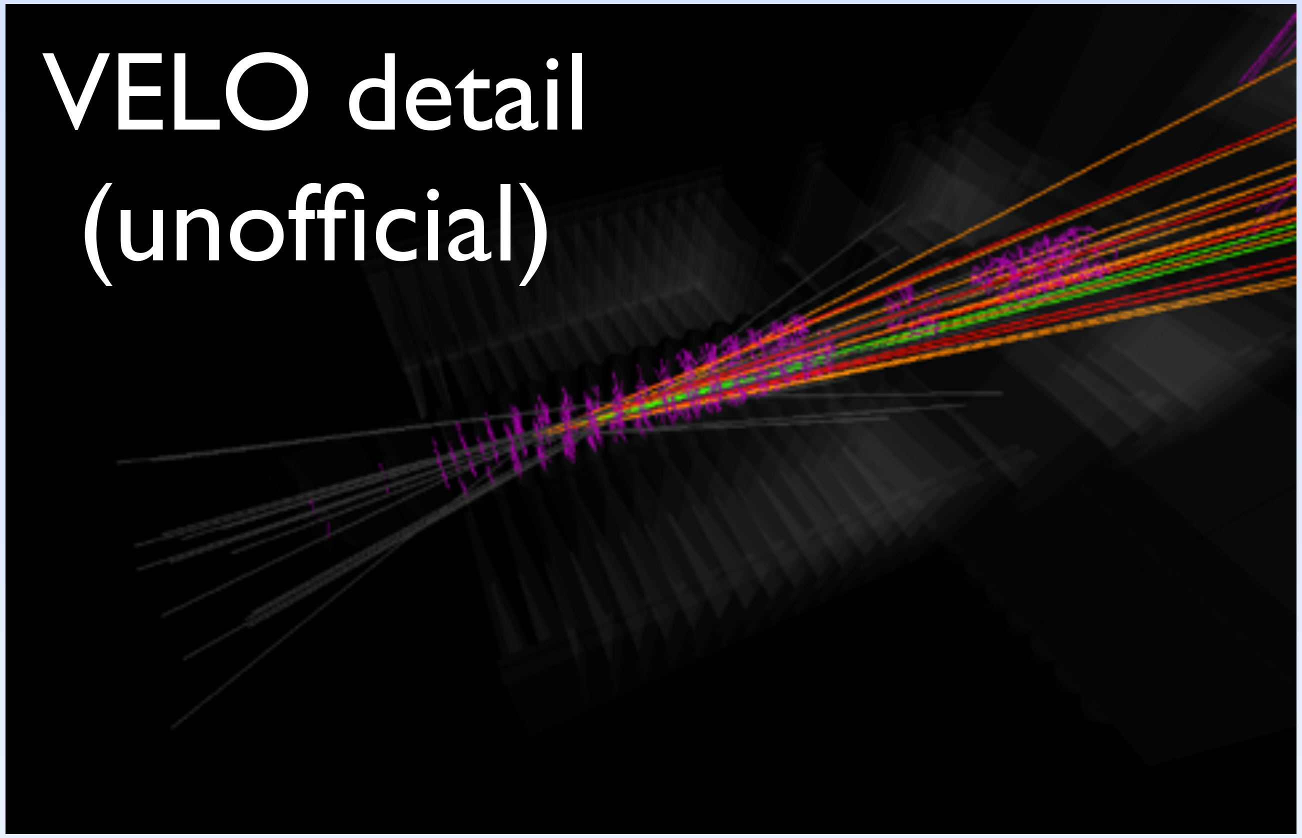




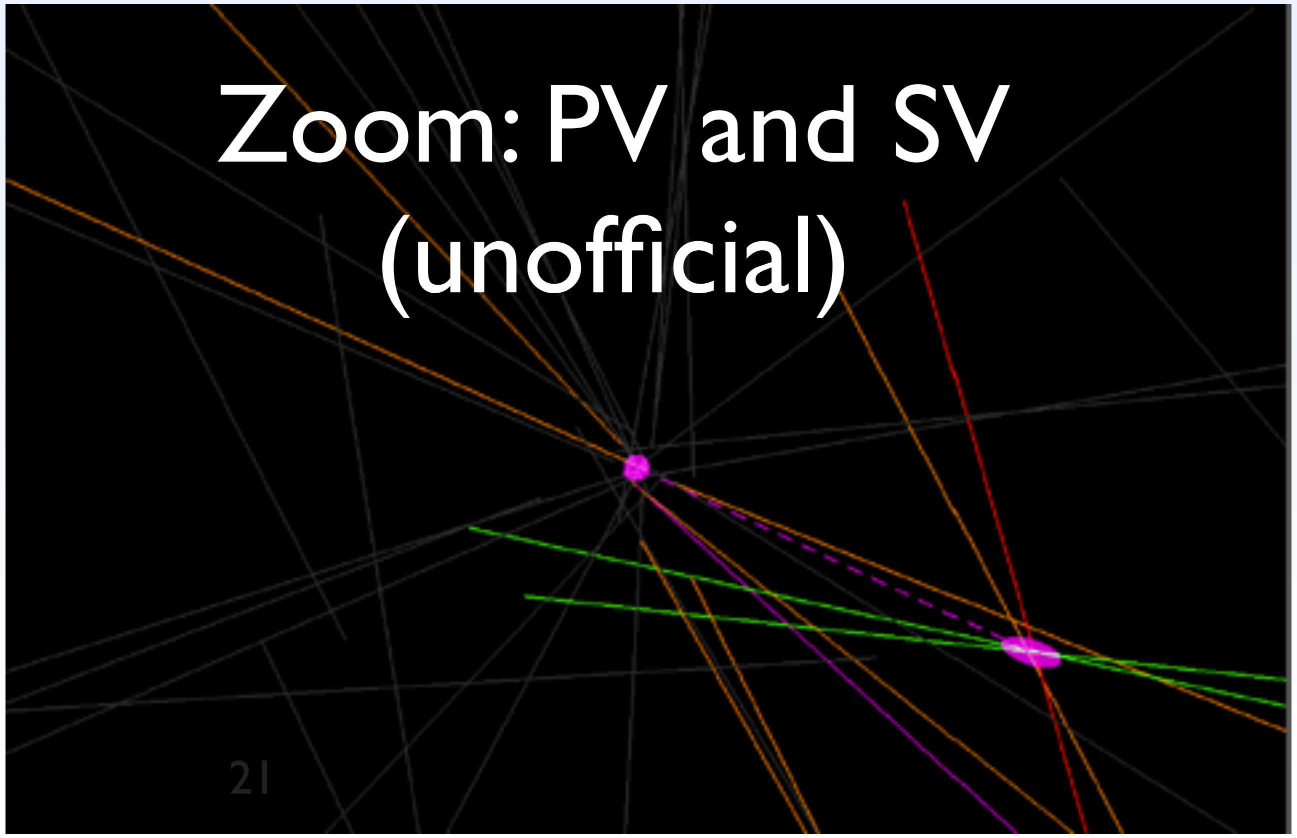
the minimum distance of a track to a primary vertex

Velo

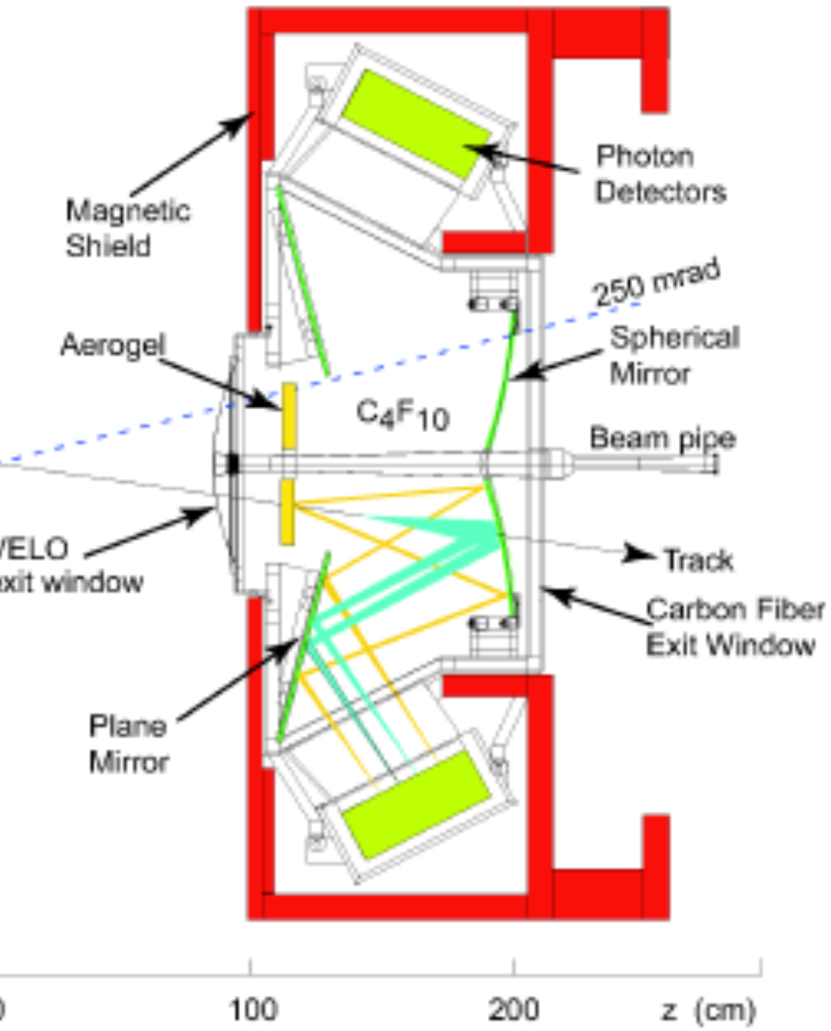


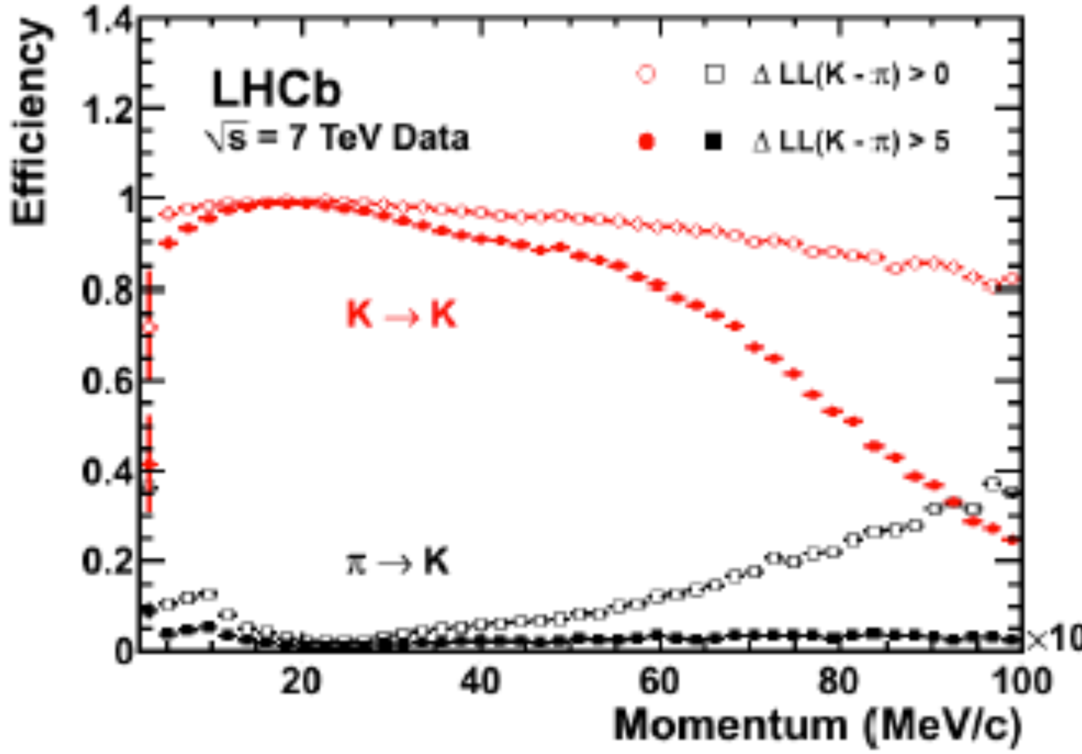


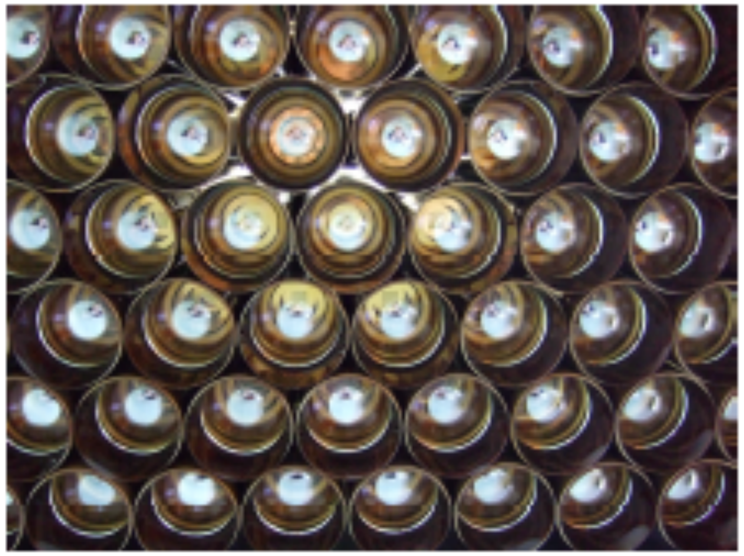
Heavy flavour particles fly a few mm

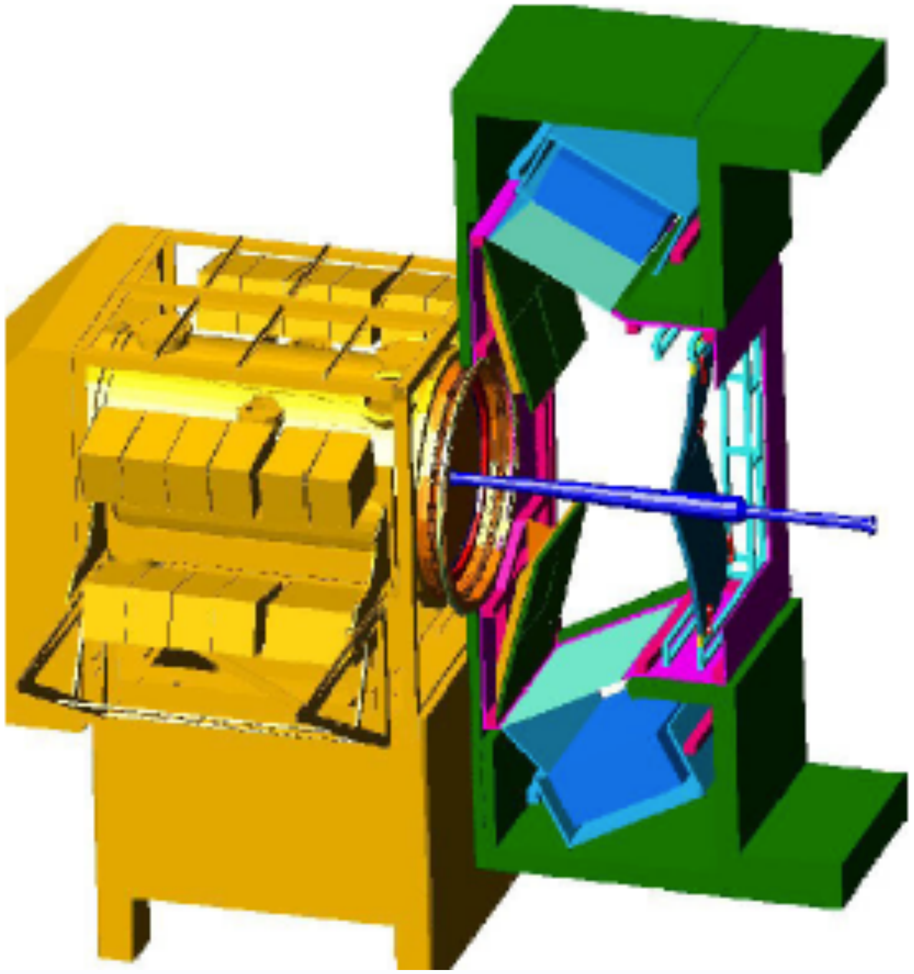


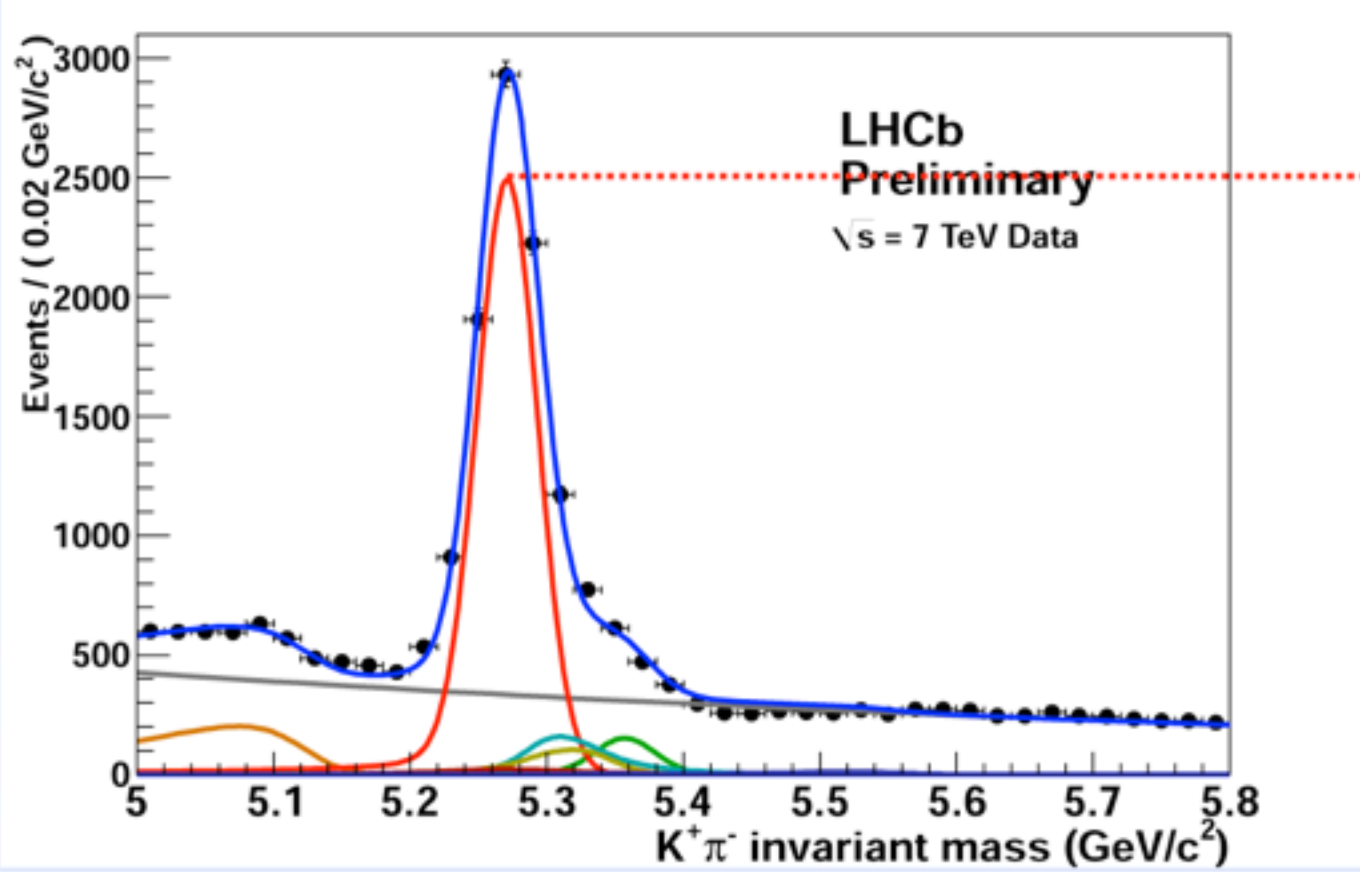
RICH

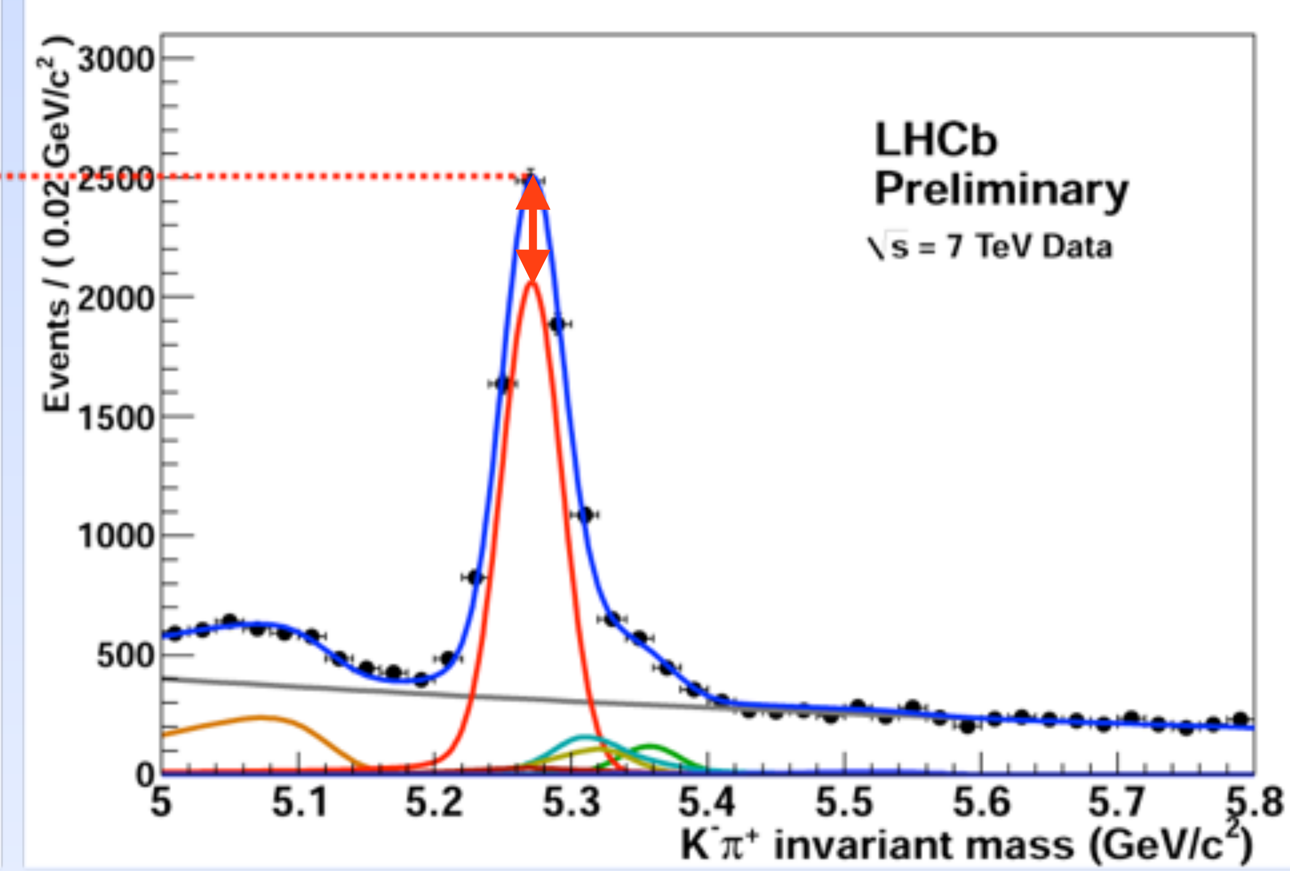

Magnetic
Shield
Photon
Detectors
250 mrad
Aerogel
Spherical
Mirror
C_4F_{10}
Beam pipe
VELO
exit window
Track
Carbon Fiber
Exit Window
Plane
Mirror
100
200
z (cm)


LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
Efficiency
Momentum (MeV/c)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
20
40
60
80
100

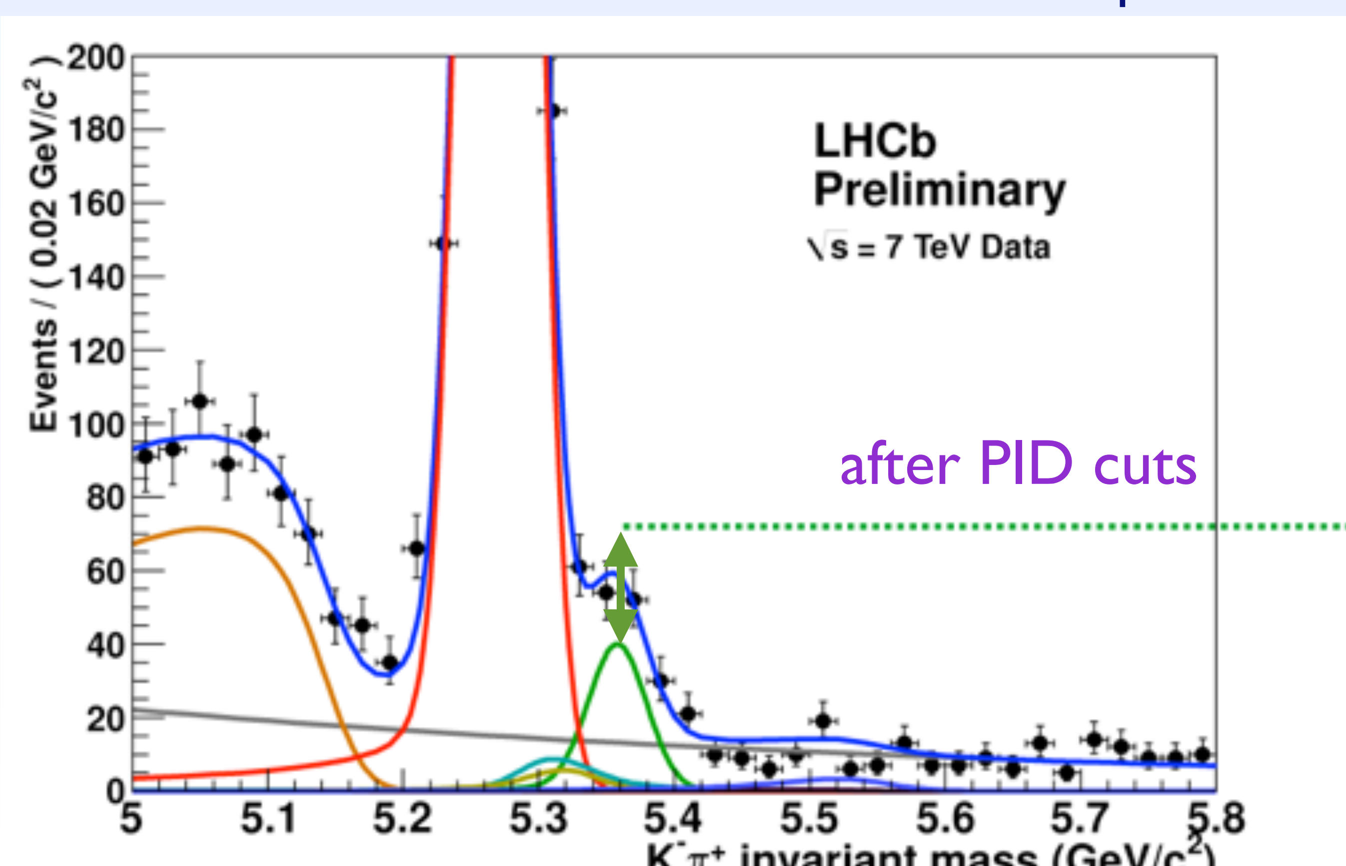


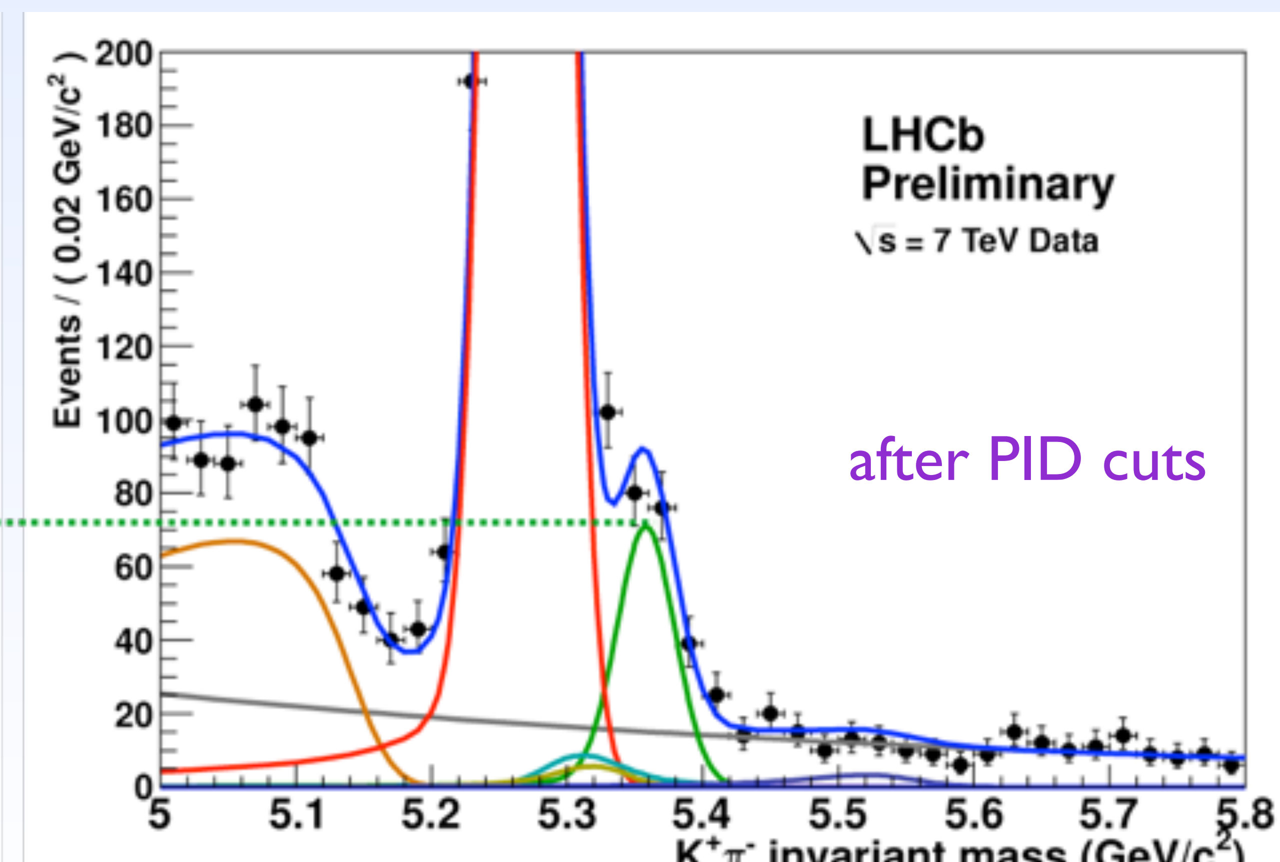






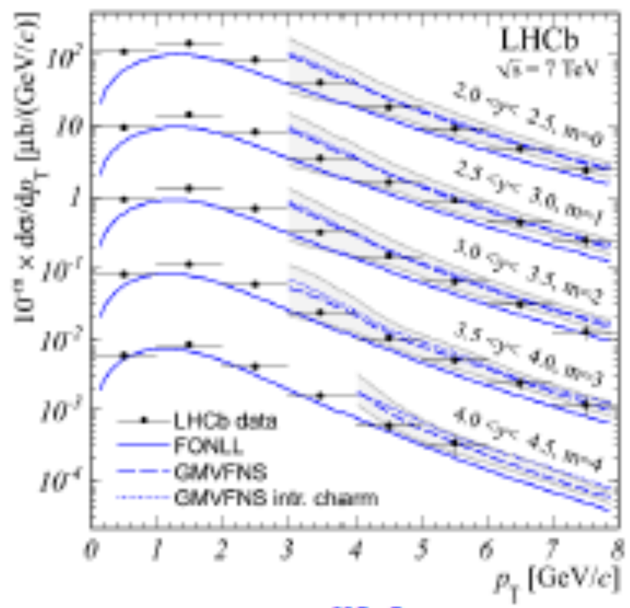
Excellent separation of Bd and Bs



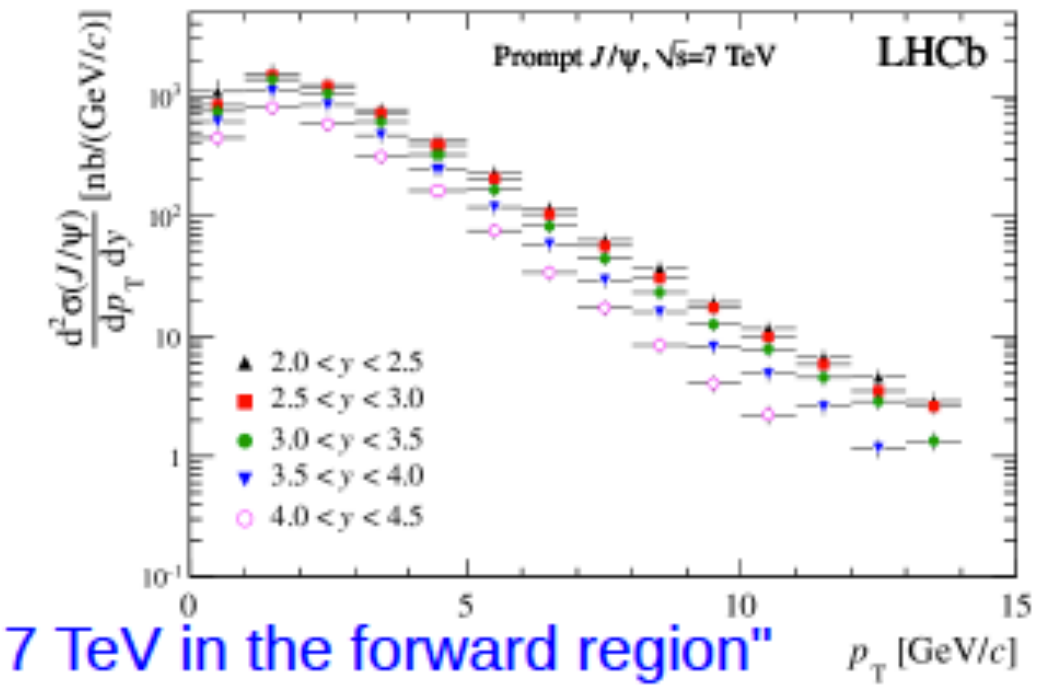


Production measurements at LHCb

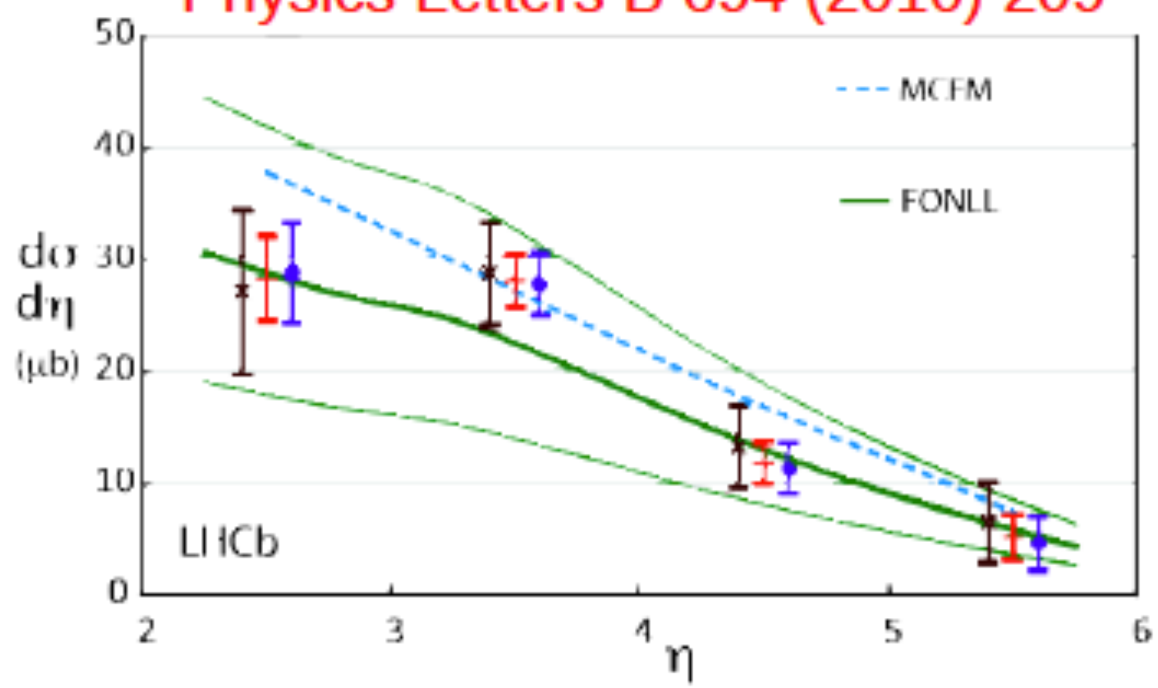
"Prompt charm production in pp collisions at $\sqrt{s}$ = 7 TeV"
Nucl. Phys. B 871 (2013) 1



"Measurement of J/ψ production in pp collisions at $\sqrt{s}$ = 7 TeV"
Eur. Phys. J. C 71 (2011) 1645



"Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s}$ = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



14

What does $\int L\,dt = 1/\text{fb}$ mean?

- Measured cross-section, in LHCb acceptance

$$\sigma(pp \rightarrow b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced in 1/fb (2011 sample)

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- "B factories" BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \rightarrow c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

e^+e^- vs pp colider

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\text{TeV}$) LHC
Production cross-section	1 nb	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\text{kHz}$	$\sim 500\,\text{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B^0_s (10%), Λ^0_b (10%), others (< 1%)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

Access to B^0, B^+,(B_s)

Access to $B^0_{(s)}$, B^+,B_c,Λ_b

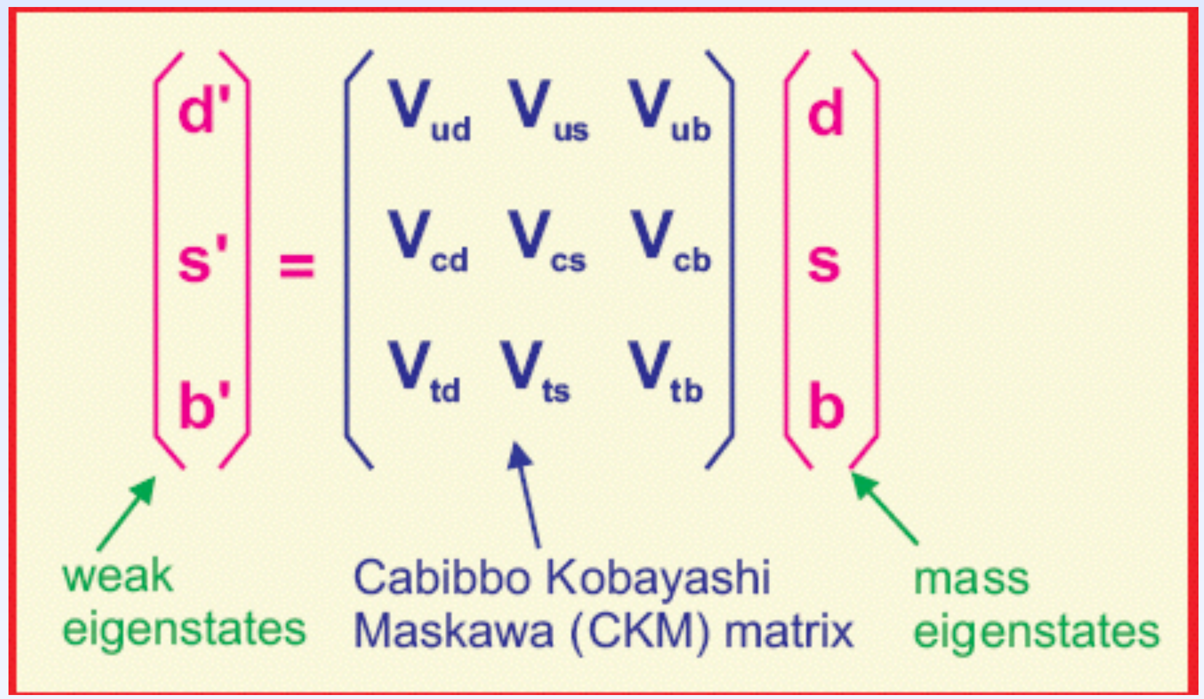
Message

- For successful flavour physics program:
- Large cross sections
- Excellent detectors (resolution, PID)

Flavour physics

quark mixing
CKM matrix

CKM matrix - very important role in the flavour physics



V_{CKM} describes the rotation between weak (d’, s’, b’) and mass eigenstates (d, s, b)

CKM parameterisations

Many different possible choices of 4 parameters

Standard parameterisation: 3 mixing angles and 1 phase

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parameterisation

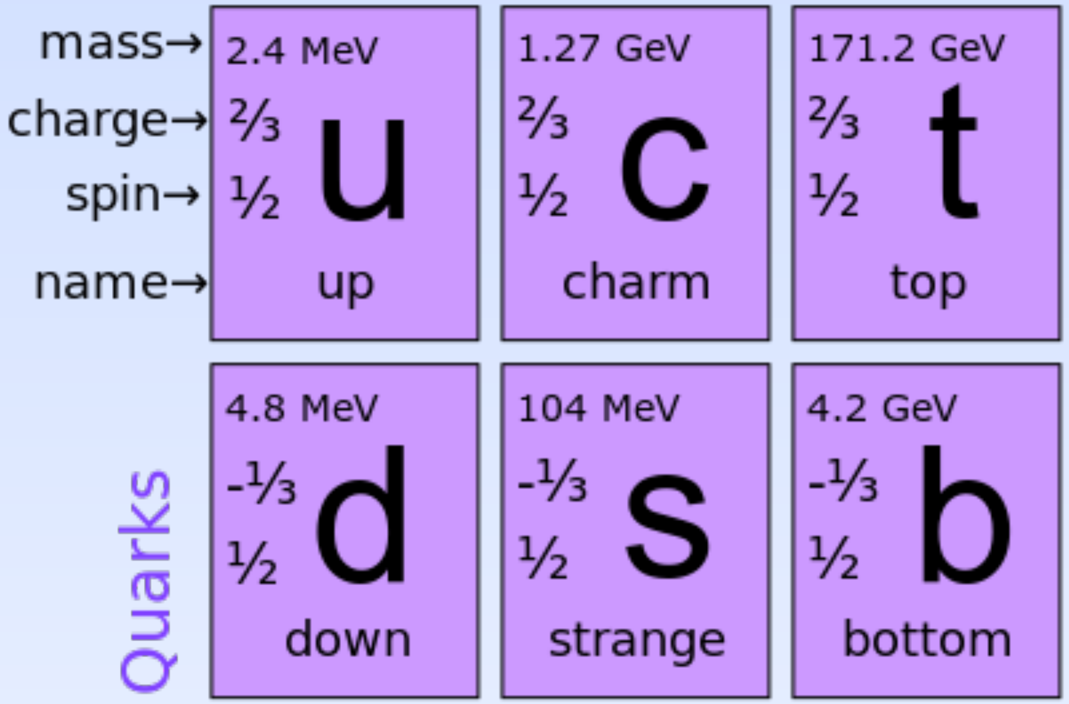
CPV in the imaginary part of the elements

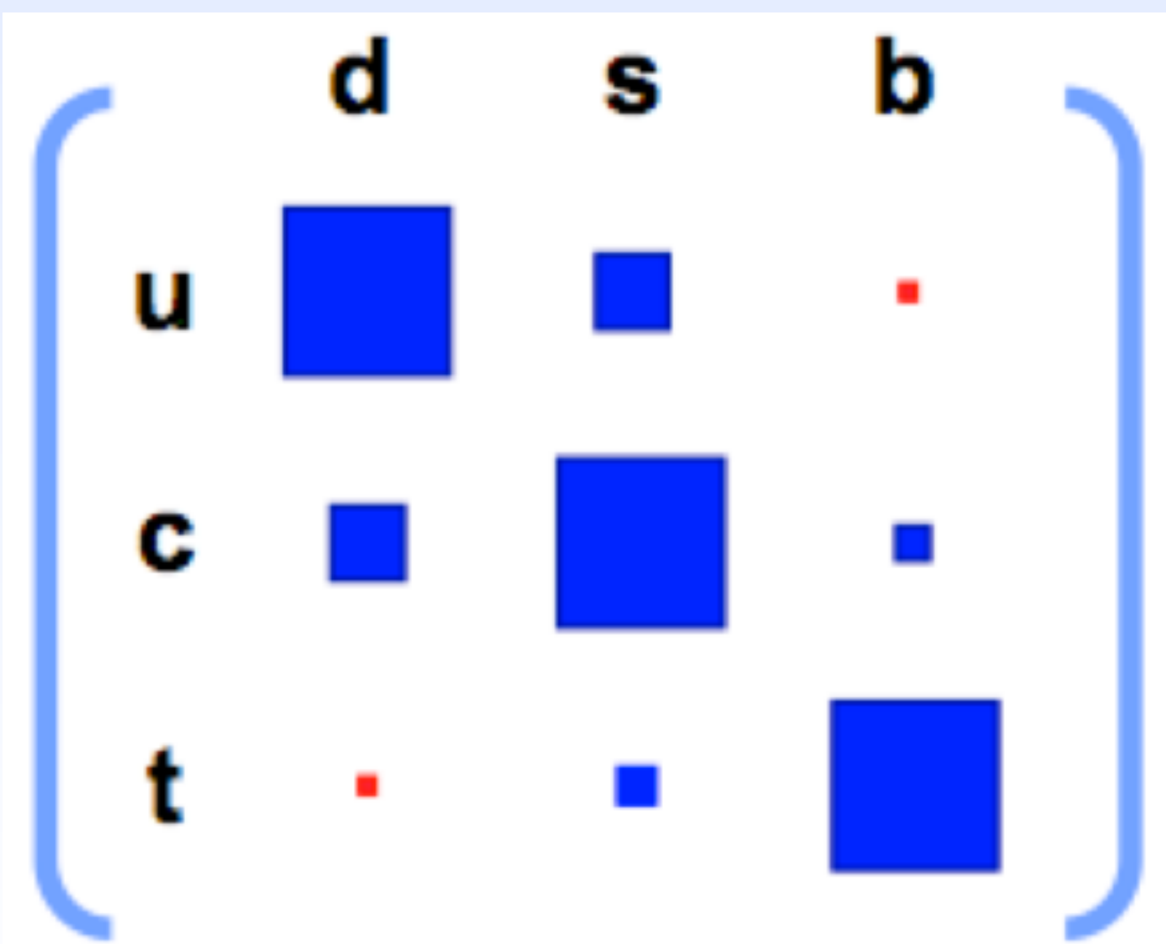
$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

small

Apparent hierarchy: $\lambda \approx \cos \Theta c = 0.22$ (Cabibbo angle)

Reflects hierarchy of quark transitions





Beauty-decays:

– Dominant decay process: "tree" b→c transition

– Very suppressed "tree" b→u transition

– FCNC "penguin" b→ s and b→d transitions

– Flavour oscillations (b→t "box" diagrams)

– CP violation – expect large CP asymmetries in some B decays

Charm-decays:

– Dominant decay process: "tree" c→s transition

– Flavour oscillations (c→d,s,b suppressed "box" diagrams)

– FCNC "penguin" c→ u transitions

– CP violation is suppressed

Situation for leptons(neutrinos) is completely different

The magnitude of the elements

PDG 2014

superallowed $0^+ \to 0^+$ β decays

semileptonic / leptonic kaon decays
hadronic tau decays

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97425 \pm 0.00022 & 0.2253 \pm 0.0008 & (4.13 \pm 0.49) \times 10^{-3} \\ 0.225 \pm 0.008 & 0.986 \pm 0.016 & (41.1 \pm 1.3) \times 10^{-3} \\ (8.4 \pm 0.6) \times 10^{-3} & (40.0 \pm 2.7) \times 10^{-3} & 1.021 \pm 0.032 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

B_d oscillations

semileptonic / leptonic charm decays

single top production

B_s oscillations

Testing the unitarity

Unitary matrix -highly predictive

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad V^*_{CKM} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix}$$

$$V_{CKM} V^{\dagger}_{CKM} = V^{\dagger}_{CKM} V_{CKM} = 1$$

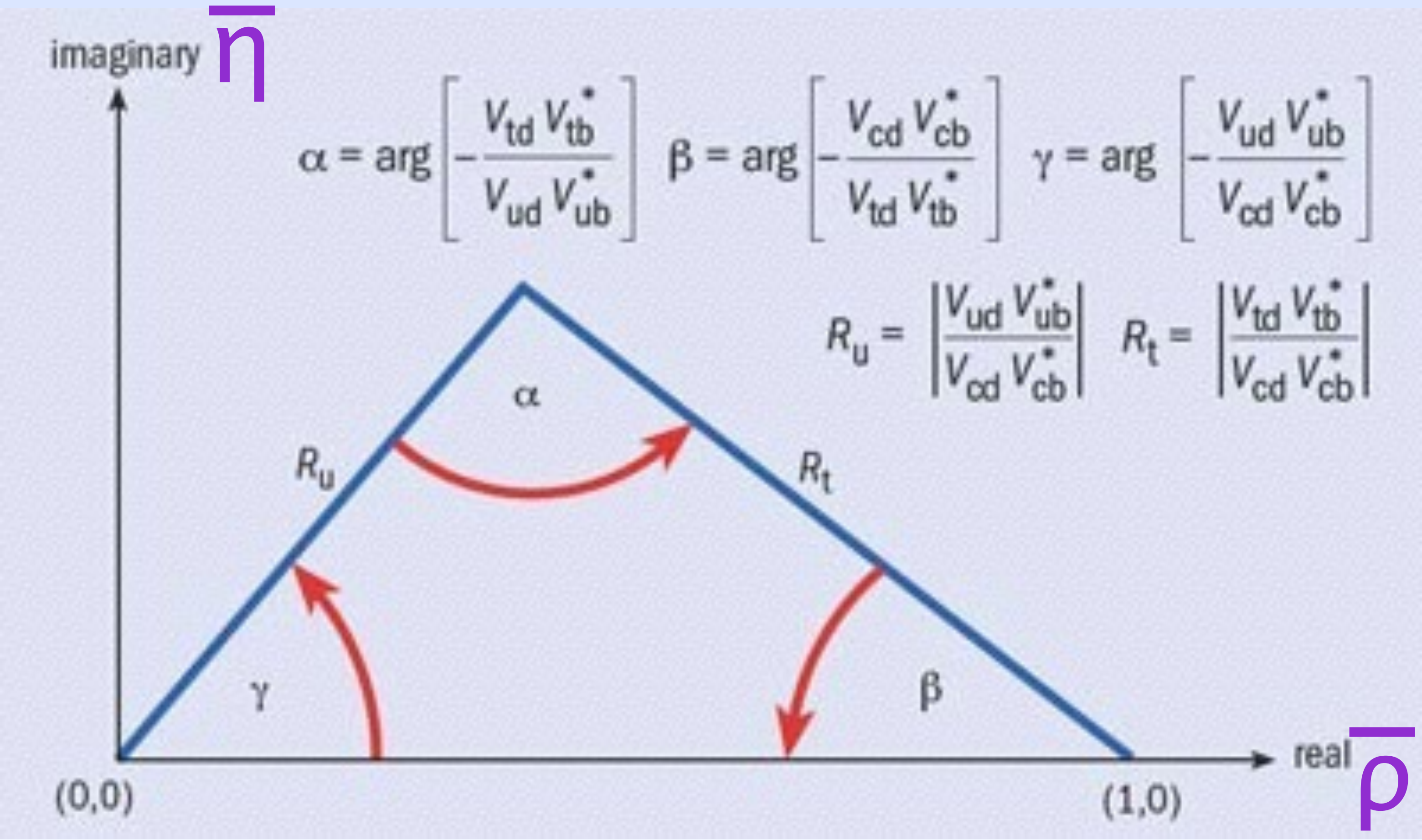
Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$$

The unitarity triangle

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$



Axes

$$\bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}$$

$$\rho + i\eta = \frac{\sqrt{1 - A^2\lambda^4}(\bar{\rho} + i\bar{\eta})}{\sqrt{1-\lambda^2}\,[1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})]}$$

Many triangles

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

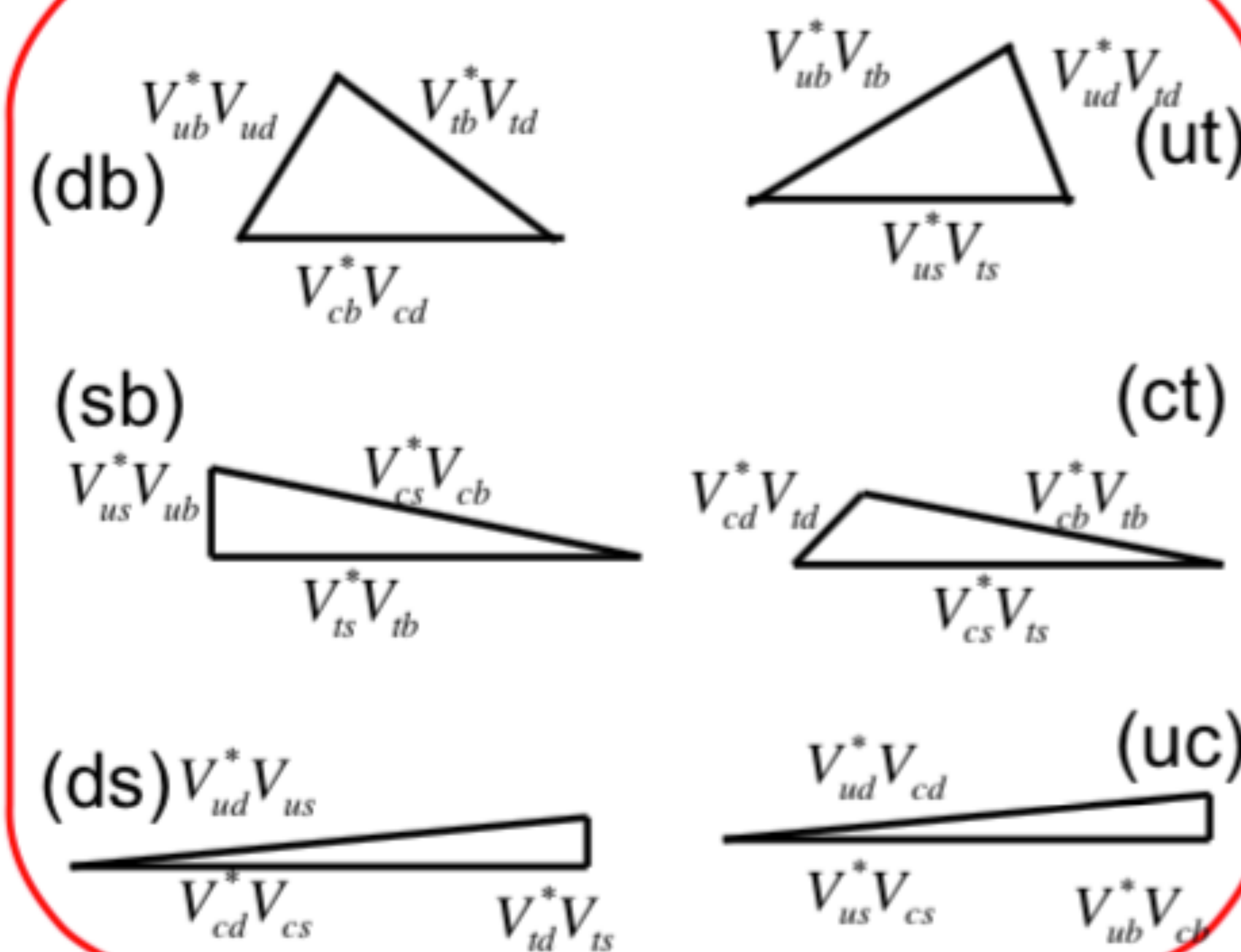
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \text{ (sb)}$$

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \text{ (ds)}$$

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

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

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \text{ (uc)}$$



All 6 triangles have the same area: $J_{CP}/2$

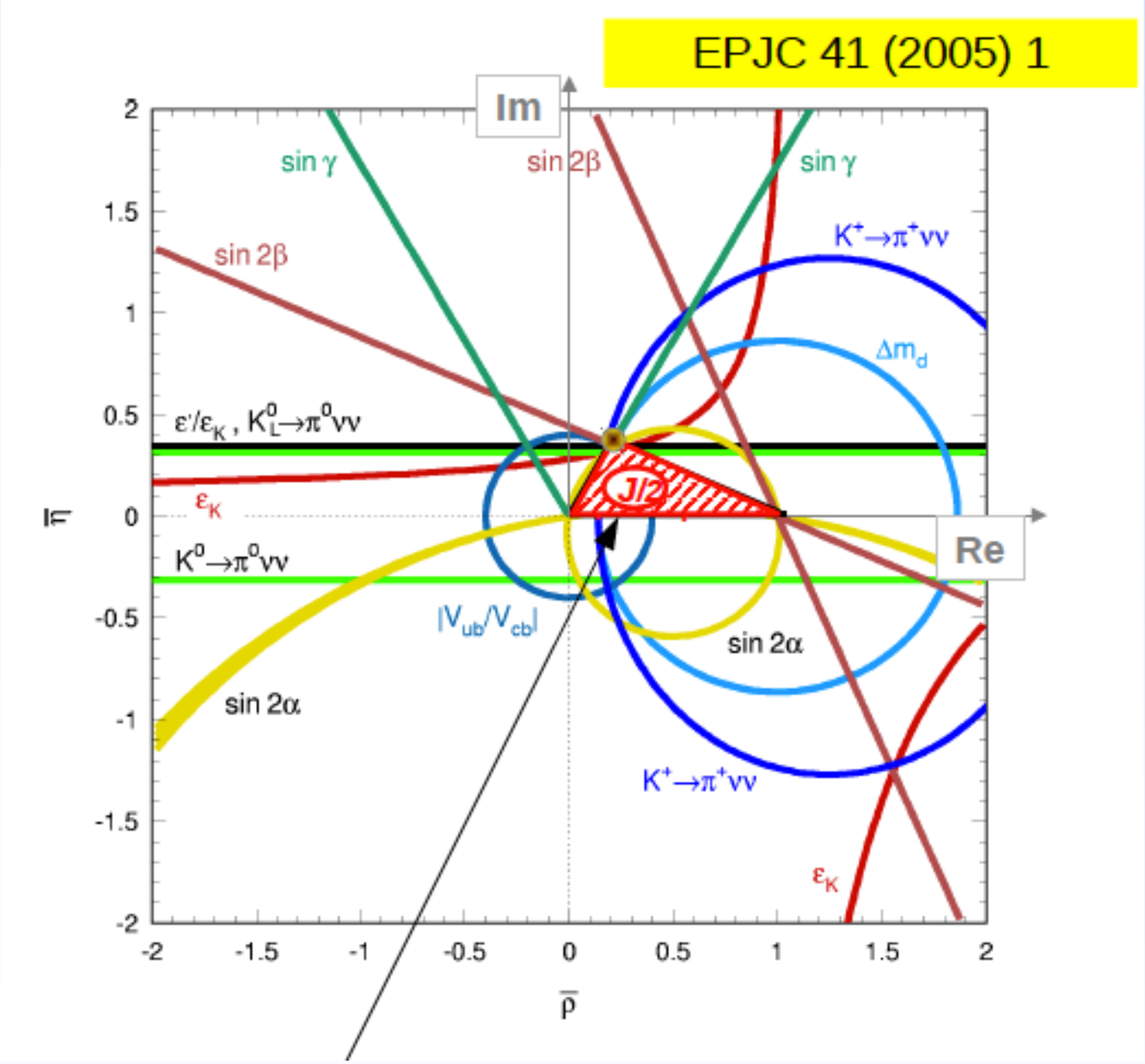
J_{CP} is called Jarlskog invariant, it is a measure of CPV in Standard Model.

Constraints for the UT triangle

Simplified picture

In the SM, the CKM is the only source of CPV

Hence, all measurements should agree on the position of the apex of the UT



area of UT given by the Jarlskog invariant

Message

- CKM is very predictive
- 4 parameters
- Describes phenomena over a huge range
- CPV in one imaginary phase

CP symmetry

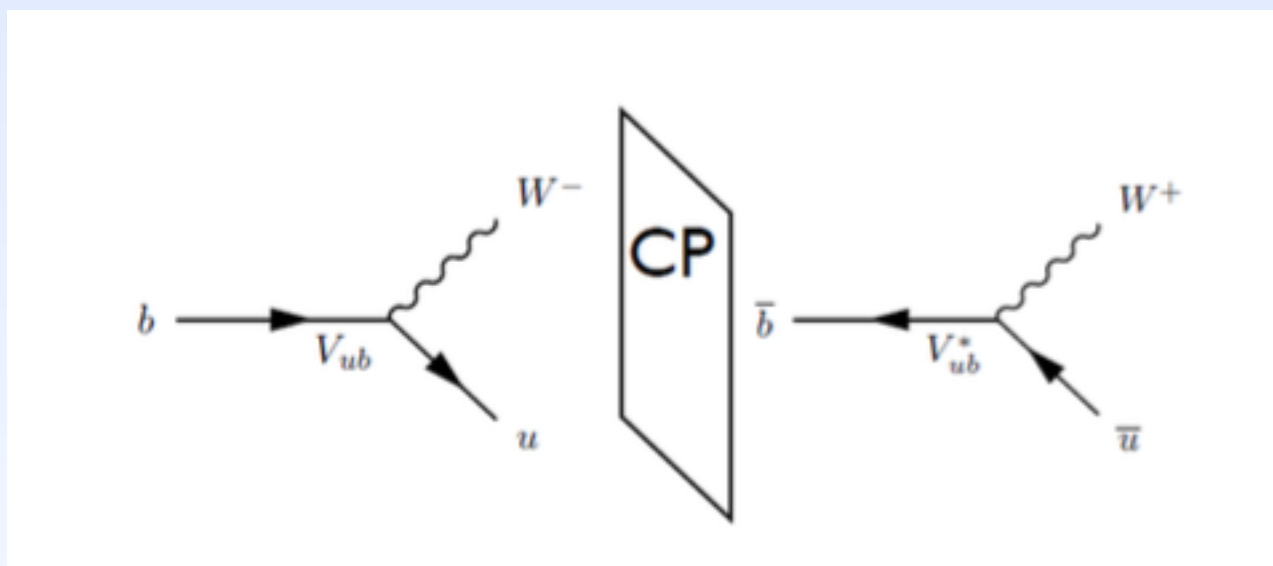
What is CP violation

Experiments [show]

V•T•E

CP-symmetry [edit]

CP-symmetry, often called just *CP*, is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which creates the mirror image of a physical system. The strong interaction and electromagnetic interaction seem to be invariant under the combined CP transformation operation, but this symmetry is slightly violated during certain types of weak decay. Historically, CP-symmetry was proposed to restore order after the discovery of parity violation in the 1950s.



The symmetry under *CP* transformation, *i.e.* the exchange of particles and anti-particles can be violated in different ways.

Types of CPV

CPV in mixing (involves neutral mesons)

The transition probability of mesons to anti- mesons compared to the reverse process. This type of *CP* violation is independent of the decay mode.

$$P(M^0(t) \to \overline{M}^0) \neq P(\overline{M}^0(t) \to M^0)$$

$$|q/p| \neq 1$$

CPV in decay

The decay rate of a meson to a final state f, A_f, is different than the rate of the anti-meson decay to the *CP* conjugate final state $\bar{f}$, $\bar{A}_{\bar{f}}$. This type of CPV depends on decay mode.

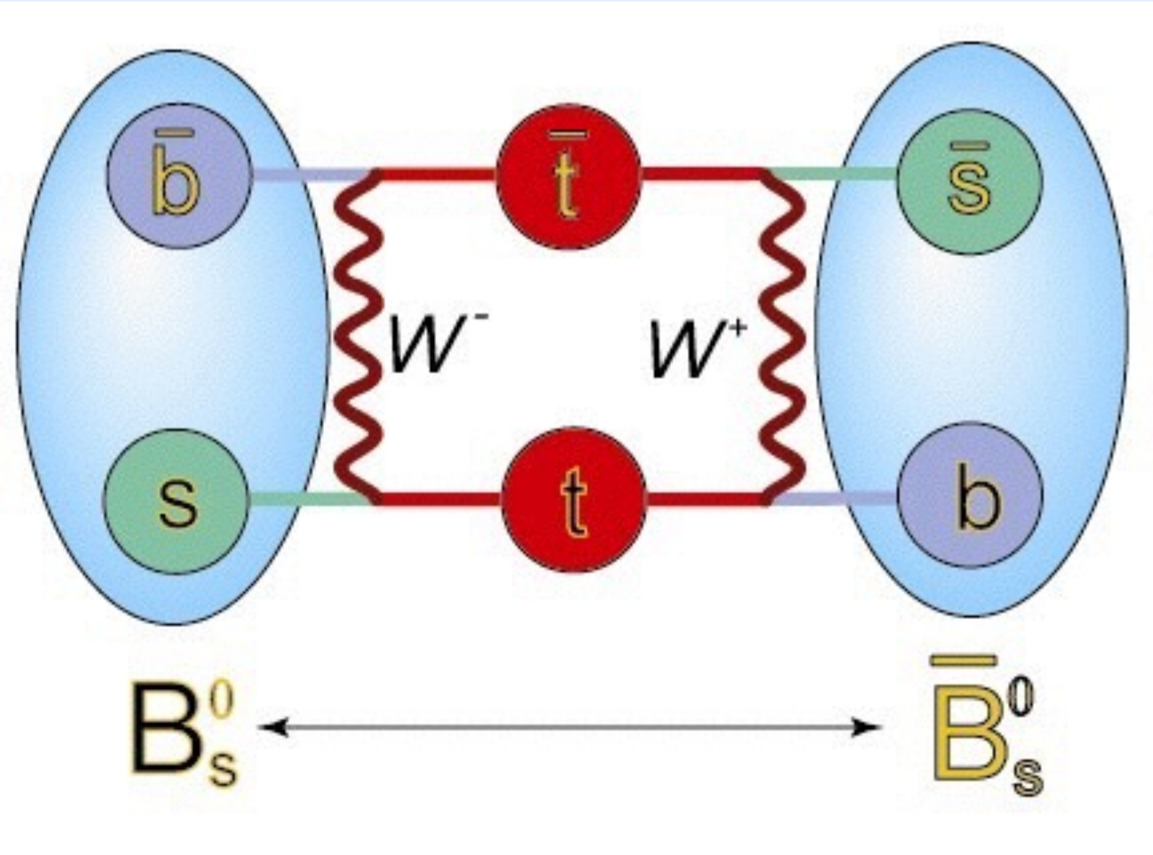
$$|\bar{A}_{\bar{f}}/A_f| \neq 1$$

CPV in interference (mixing and decay amplitudes can interfere) a.k.a. indirect CPV

It involves neutral meson decaying to a *CP* eigenstate f with eigenvalue η_{CP} and φ is the *CP* violating relative phase between q/p and $\bar{A}_f/A_f$.

CPV if $\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right|e^{i\phi} \neq 1$ (has a non-0 imaginary part)

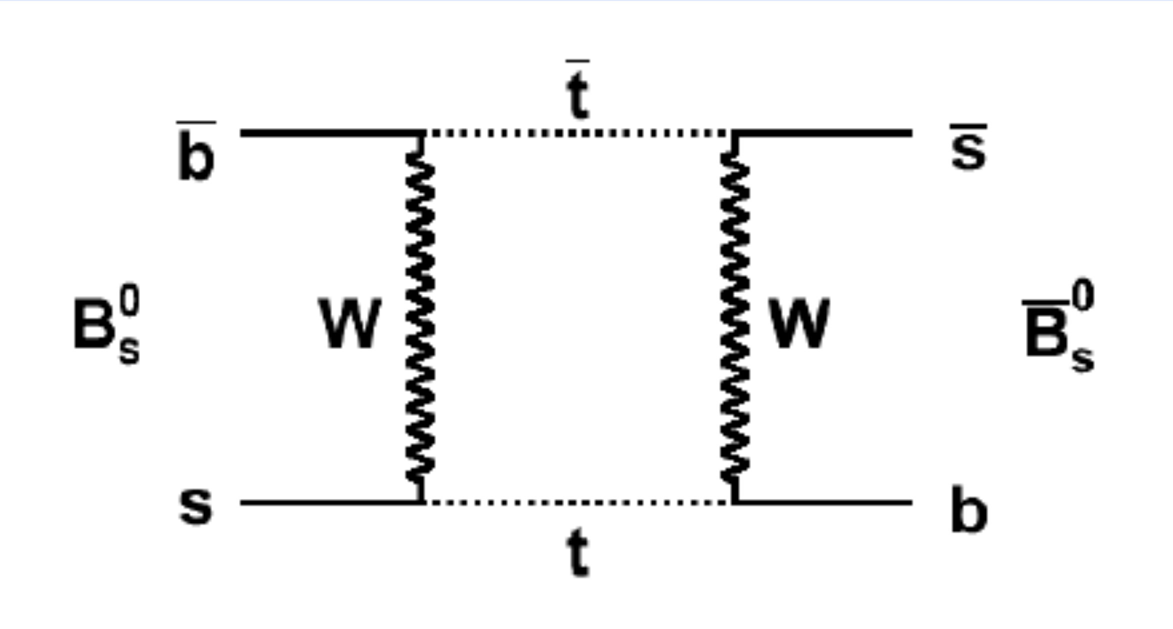
Neutral mesons mixing

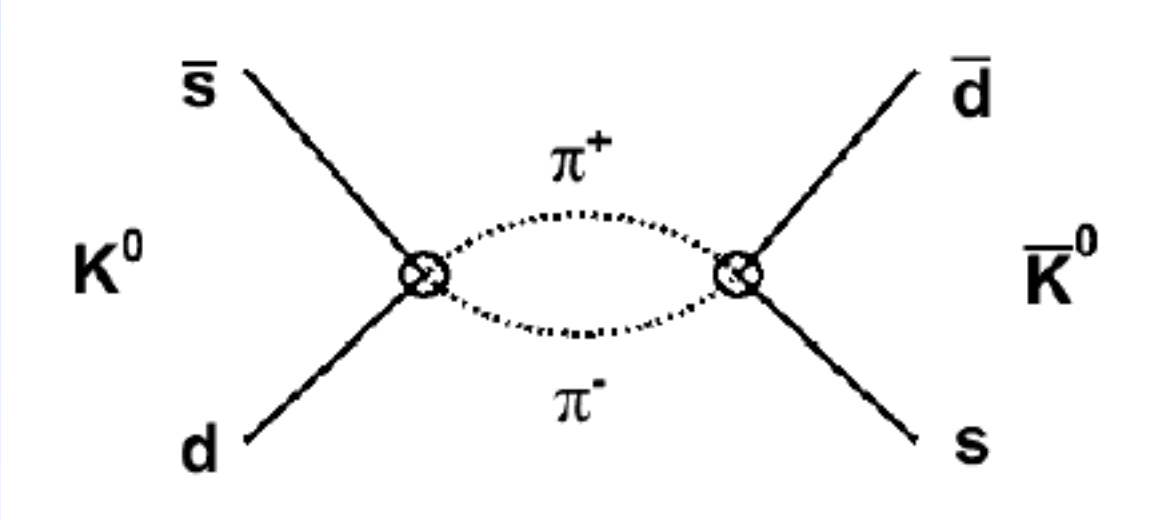


Neutral mesons

Flavour eigenstates M^0 can be K^0 ($\bar{s}d$), D^0 ($c\bar{u}$), B_d^0 ($\bar{b}d$) or B_s^0 ($\bar{b}s$)

The neutral mesons can mix into each other via:





Short distance process

Long distance process

For neutral mesons, the mass eigenstates, *i.e.* the physical particles, do not *a priori* coincide with the flavour eigenstates

Neutral meson mixing formalism

In general the physical state can be presented as:

$$|\psi\rangle = a(t)|M^0\rangle + b(t)|\bar{M}^0\rangle$$

the mixing can be represented in by the time dependent Schrödinger equation

$$\imath\hbar\frac{\partial}{\partial t}\psi = \mathscr{H}\psi$$

$$\mathscr{H} = M - \frac{\imath}{2}\Gamma = \begin{pmatrix} M_{11} - \frac{\imath}{2}\Gamma_{11} & M_{12} - \frac{\imath}{2}\Gamma_{12} \\ M_{21} - \frac{\imath}{2}\Gamma_{21} & M_{22} - \frac{\imath}{2}\Gamma_{22} \end{pmatrix}$$

M, Γ- hermitian matrices

CPT theorem: $M_{11}=M_{22}$: particles have equal masses and lifetimes

The time evolution of the physical states is therefore given as

$$|M_{1,2}(t)\rangle = e^{-\imath m_{1,2}t}e^{-\Gamma_{1,2}t/2}|M_{1,2}(0)\rangle$$

Assuming *CPT* symmetry, the physical eigenstates can be expressed as

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle$$

with complex coefficients p,q satisfying

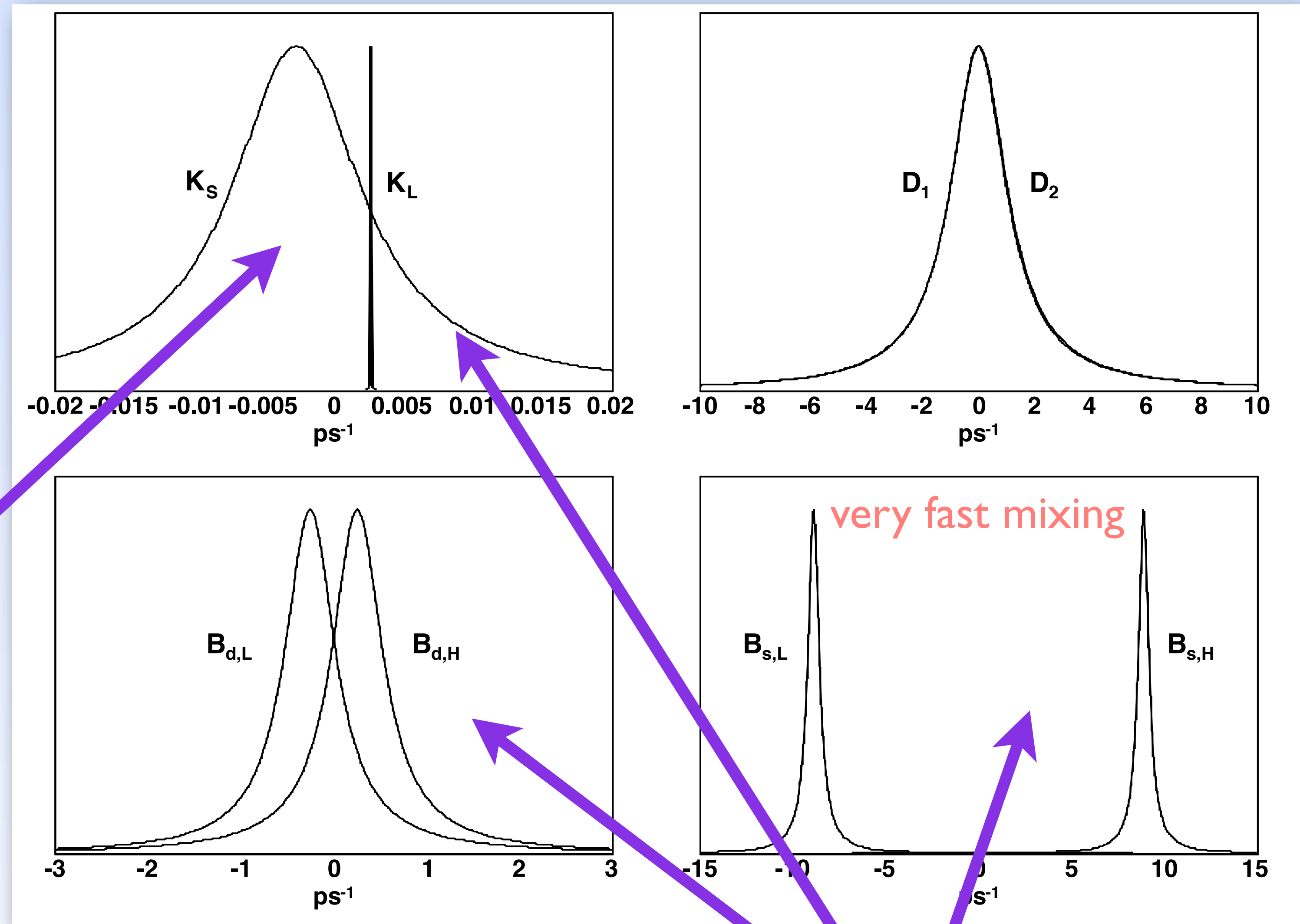
$$|p|^2 + |q|^2 = 1$$

Mixing parameters

very slow mixing

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Mass eigenstates   Flavour eigenstates



Width difference

→ Lifetime difference

$$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$$

$$y \equiv \Delta\Gamma/(2\Gamma)$$

Mass difference

→ Oscillation

$$\Delta m \equiv m_2 - m_1$$

$$x \equiv \Delta m/\Gamma$$

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

Magnitude of the mixing parameters

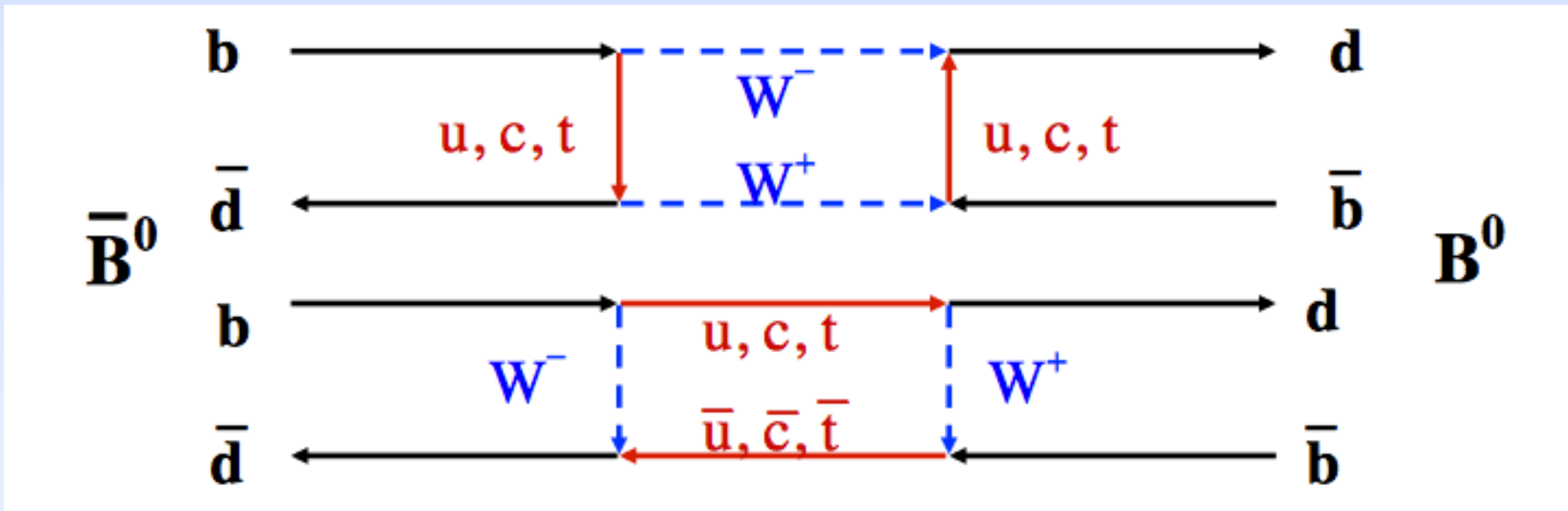
	Δm ($x = \Delta m/\Gamma$)	$\Delta\Gamma$ ($y = \Delta\Gamma/(2\Gamma)$)	$\lvert q/p \rvert$ ($a_{sl} \approx 1 - \lvert q/p \rvert^2$)
K^0	large	$\sim$ maximal	small
	~ 500	~ 1	$(3.32 \pm 0.06) \times 10^{-3}$
D^0	small	small	small
	$(0.63 \pm 0.19)\%$	$(0.75 \pm 0.12)\%$	$0.52^{+0.19}_{-0.24}$
B^0	medium	small	small
	0.770 ± 0.008	0.008 ± 0.009	-0.0003 ± 0.0021
B_s^0	large	medium	small
	26.49 ± 0.29	0.075 ± 0.010	-0.0109 ± 0.0040

well-measured only recently

More precise measurements needed (SM prediction well known)

Neutral B mixing

dominated by top quark contributions



similar for Bs

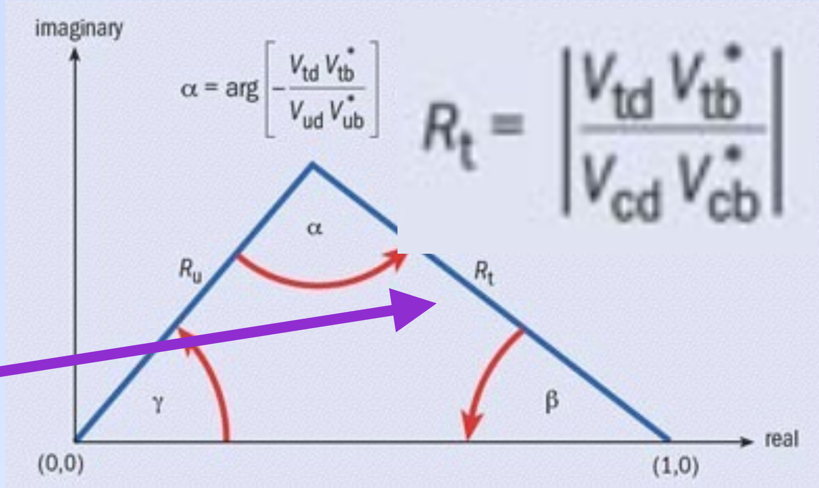
For B^0 $\quad \dfrac{q}{p} \approx \dfrac{V_{tb}^{*} V_{td}}{V_{tb} V_{td}^{*}}$ → Sensitivity to a CKM triangle side and angle β

For B_s^0 $\quad \dfrac{q}{p} \approx \dfrac{V_{tb}^{*} V_{ts}}{V_{tb} V_{ts}^{*}}$ → Sensitivity to side and equivalent angle β_s

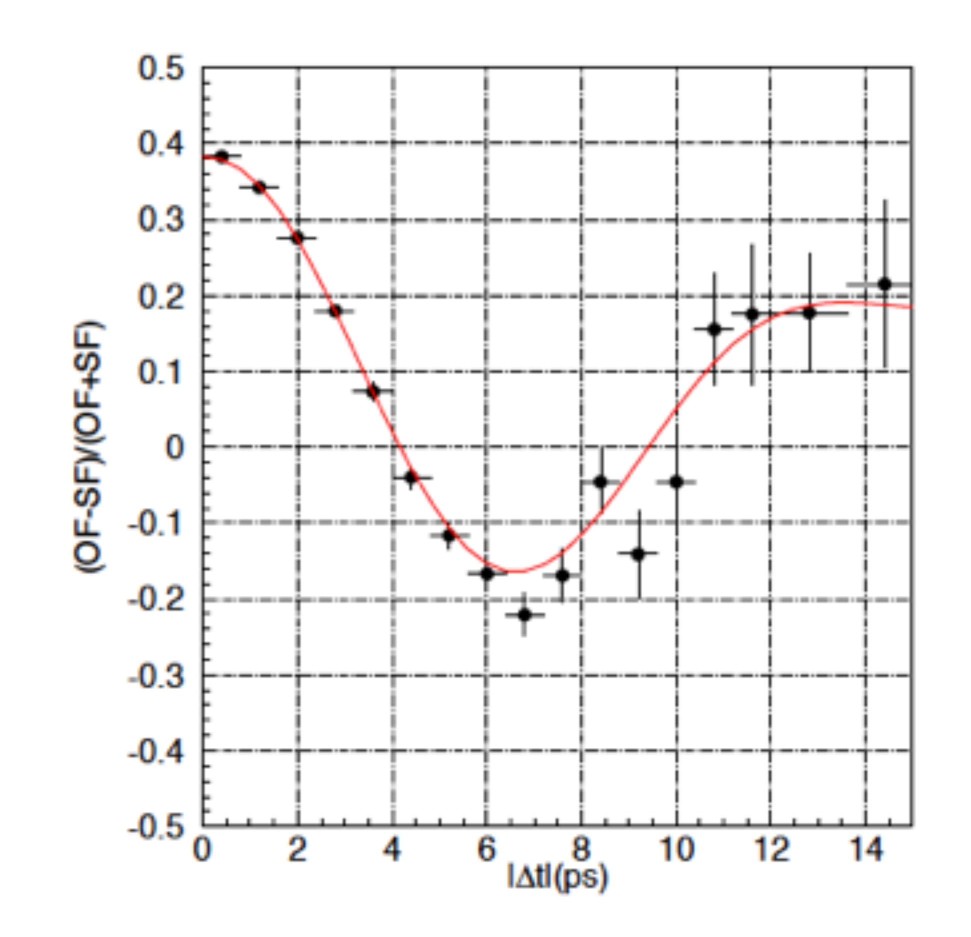
The most important difference of B_d and B_s is the V_{td}/V_{ts}

Rt from B^0-$\bar{B}^0$ mixing

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$



Asymmetry



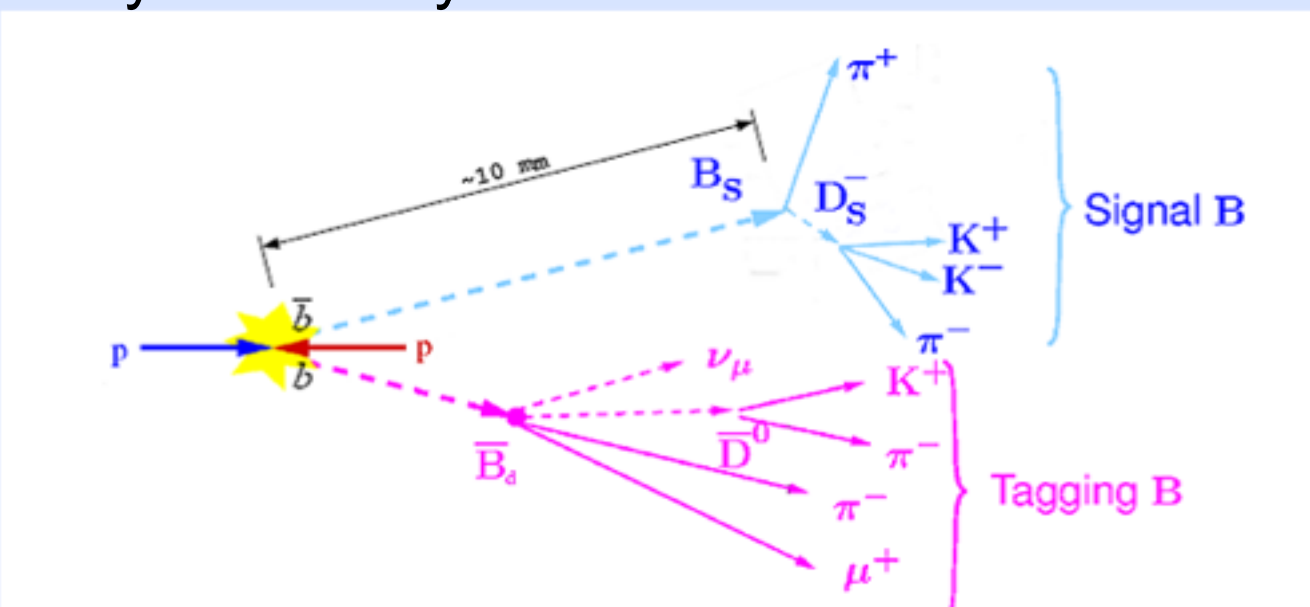
Belle

$$\Delta m_d = [0.511 \pm 0.005(\mathrm{stat}) \pm 0.006(\mathrm{syst})]\ \mathrm{ps}^{-1}.$$

$B^0 \rightarrow D^{*-}l^+\nu$, $J/\Psi K^{*0}(K^+\pi^-)$, $D^{*-}\pi^+$, $D^{*-}\pi^+$, $D^{*-}\rho^+$

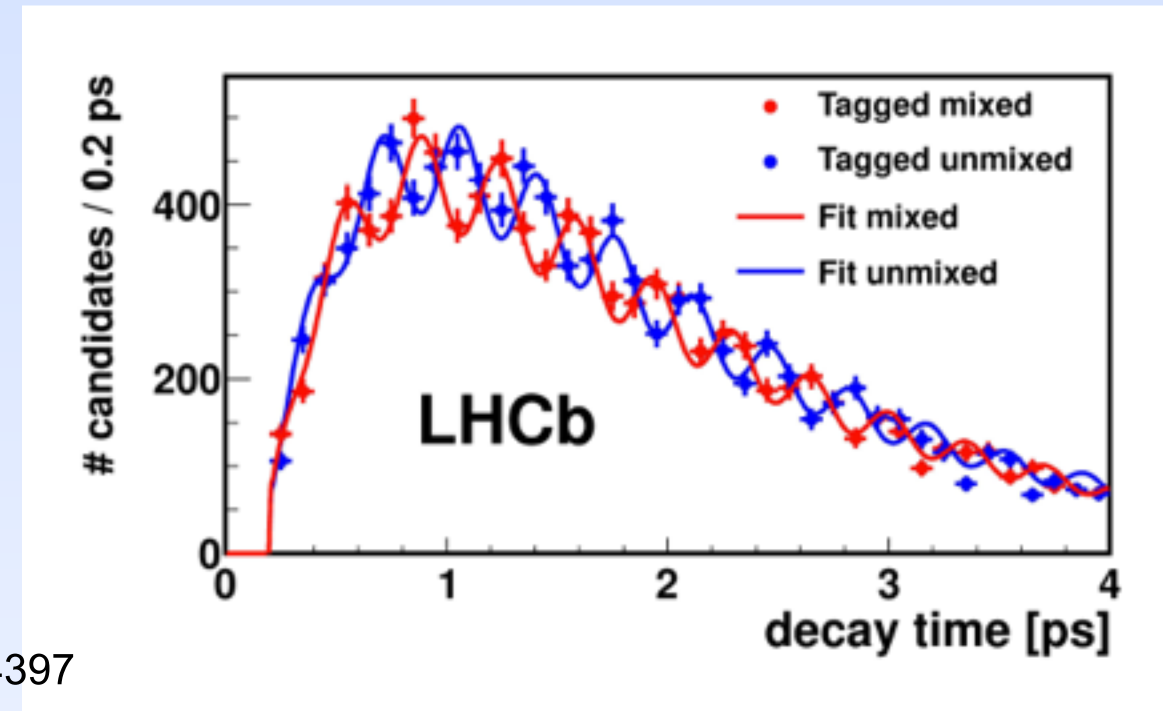
Bs mixing

Important to reconstruct the positions of the decays vertices very accurately : VELO



tagging: leptons or kaons at the OS

Oscillations



arXiv:1212.4397

Need to determine:

- Flavour at production ⇔ tagging
- Flavour at decay, from final state
- B decay length

Δm_s = (17.768 ± 0.023 ± 0.006) ps^{-1}

NJP 15 (2013) 053021

Measure as a function of the decay time

$$\mathcal{A}_{\rm mix}(t) = \frac{N_{\rm unmixed}(t) - N_{\rm mixed}(t)}{N_{\rm unmixed}(t) + N_{\rm mixed}(t)} = \cos\left(\Delta m_q t\right)$$

Most precise measurement of $\left|V_{td}/V_{ts}\right| = 0.216 \pm 0.001 \pm 0.011$

Mixing in charm

$$D^0 \to \bar{D}^0 \to D^0 \to \bar{D}^0$$

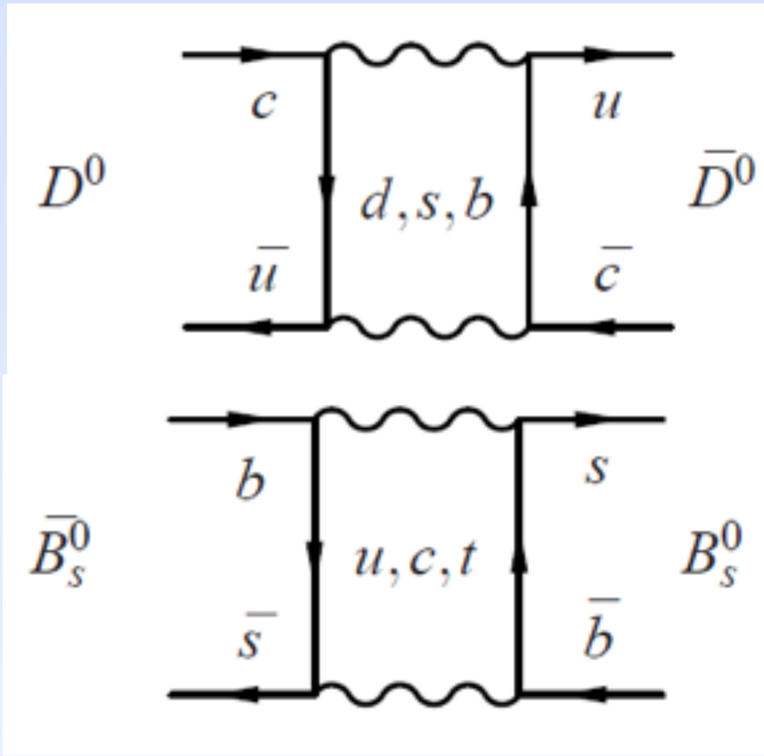
$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Mass eigenstates

Flavour eigenstates

$$y \equiv \Delta\Gamma/(2\Gamma) \qquad x \equiv \Delta m/\Gamma$$

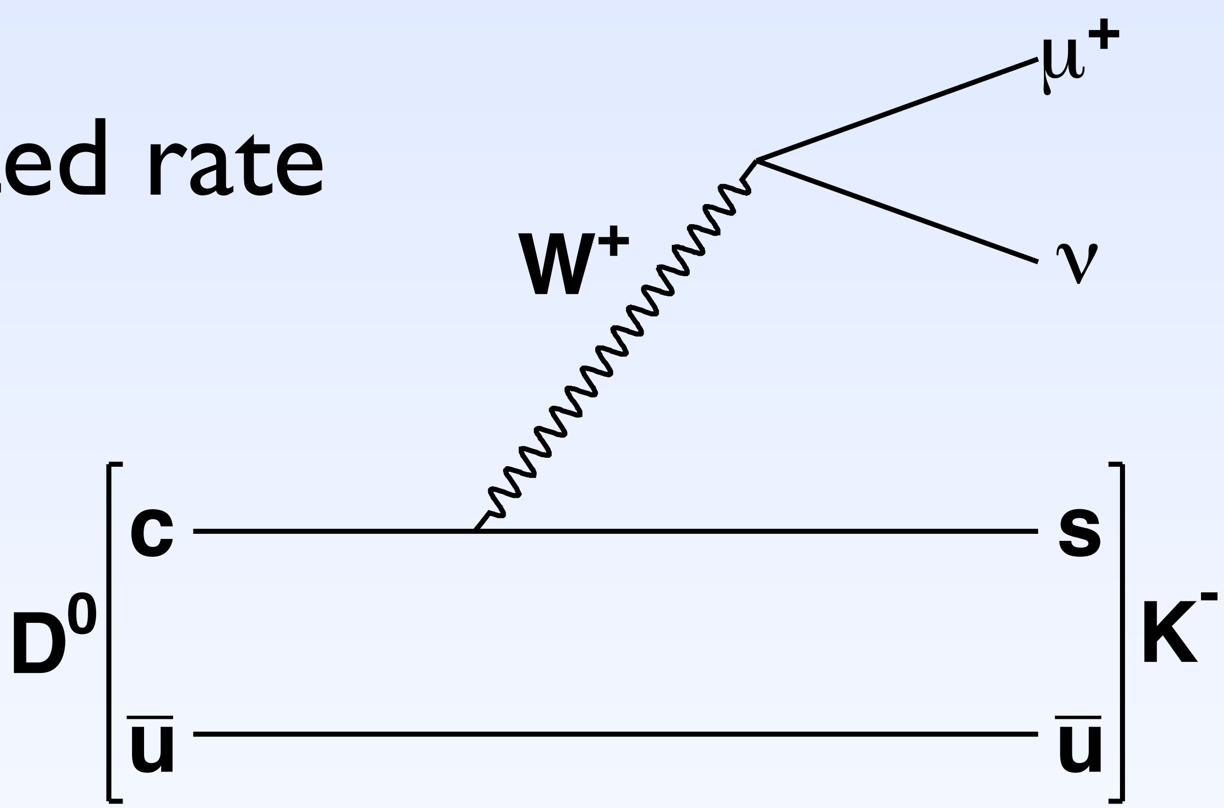
D^0 mixing theory



- Mixing box contains down-type quarks
- No dominance of top mass as in B sector
- CKM-suppression balances GIM cancellation
- Huge cancellations
  - ➡ Long-distance effects become important
- Over 1000 lifetimes for 1 full oscillation
- Difficult to measure
  - ➡ CP violation even more tricky to discover

$D^0 \rightarrow K^+ \mu^- \nu$

- Semileptonic decay is flavour tagging
- Charge-conjugate final state only accessible through mixing
- Measure time-integrated rate
  - ➡ Proportional to mixing probability



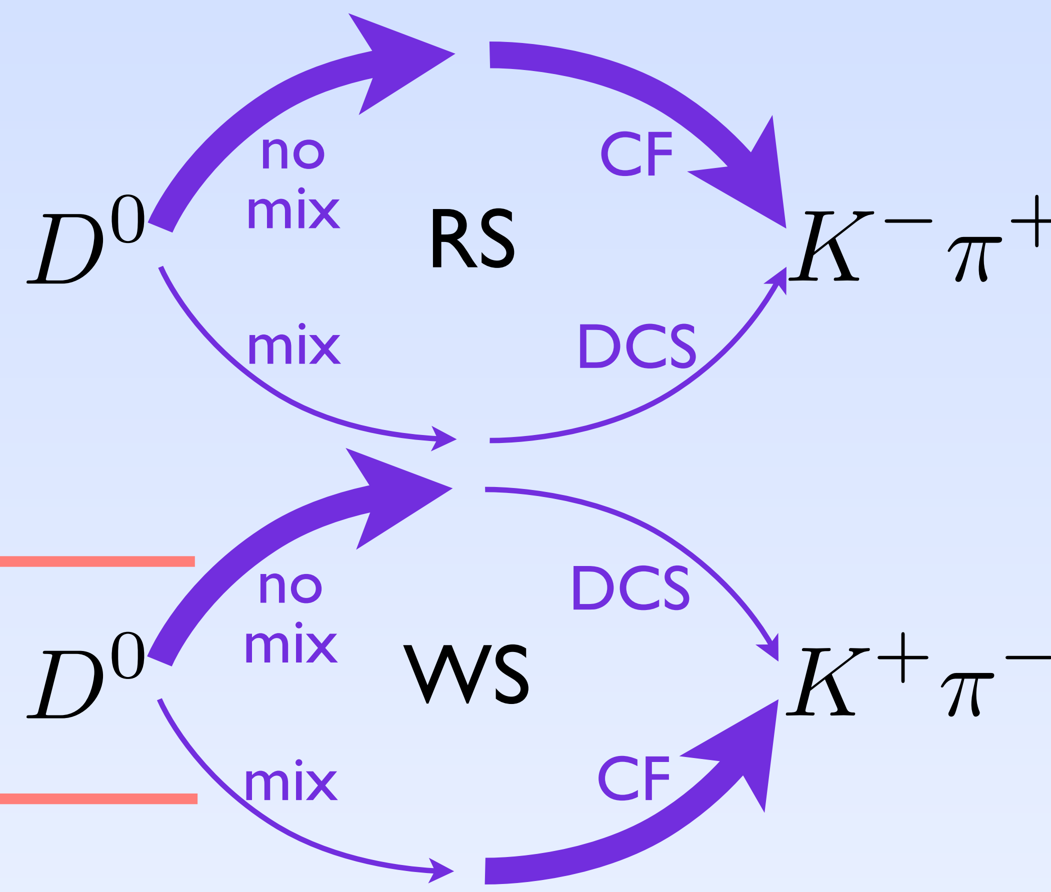
Main challenge: Finding it
Low rate and high backgrounds due to partial reconstruction

mixing in charm

- Measure the ratio of WS to RS events

interference

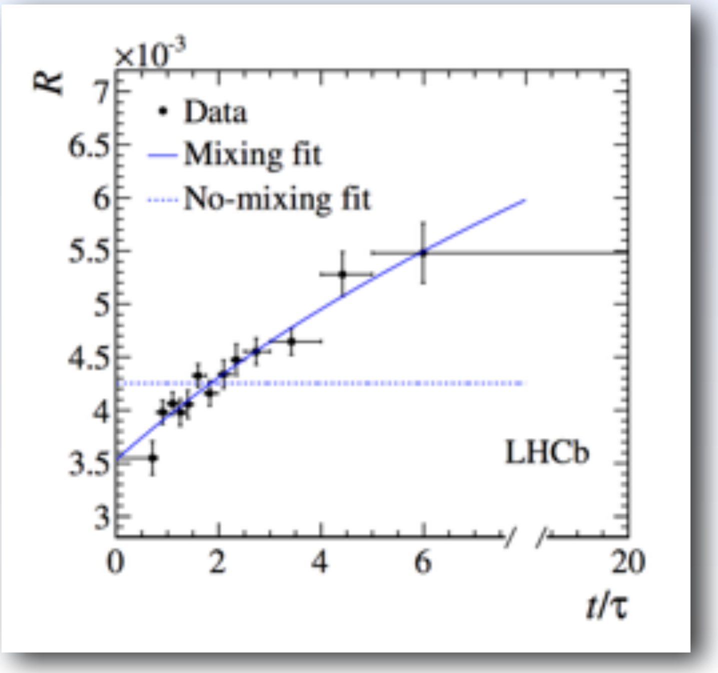
$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2+y'^2}{4}(\frac{t}{\tau})^2$$

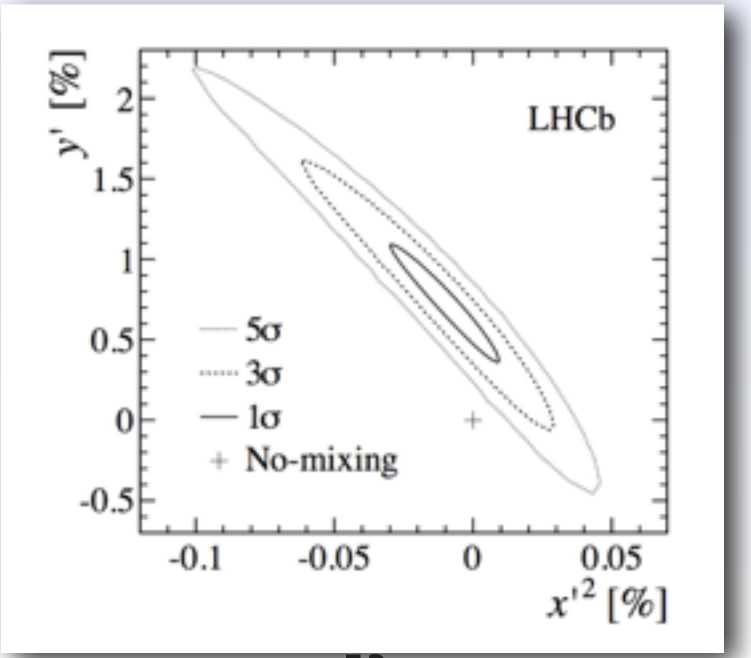


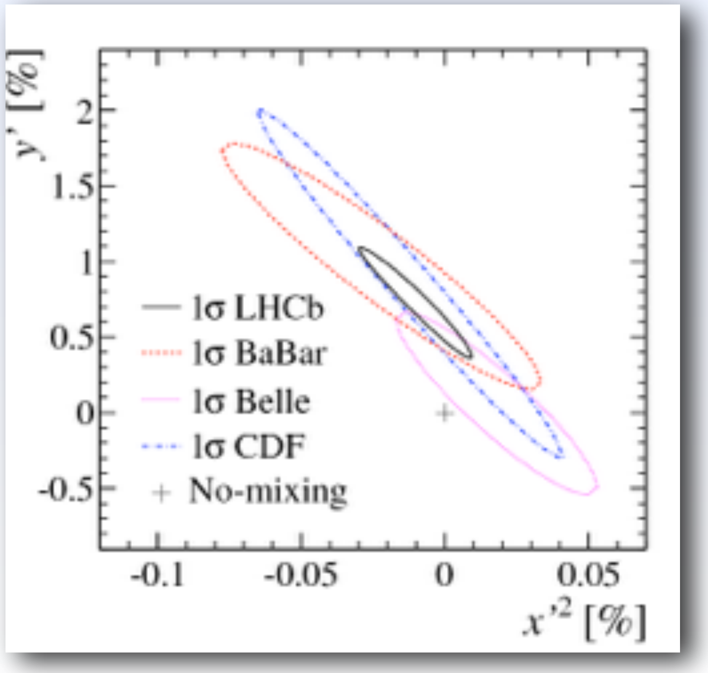
Mixing parameters

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$$







CPV and mixing in charm

- Measure the ratio of WS to RS events

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}(\frac{t}{\tau})^2$$

- Measurements use prompt $D^0 \to K\pi$ decays (3 fb^{-1}): split by flavour to search for CPV: $q/p \neq 1$ or

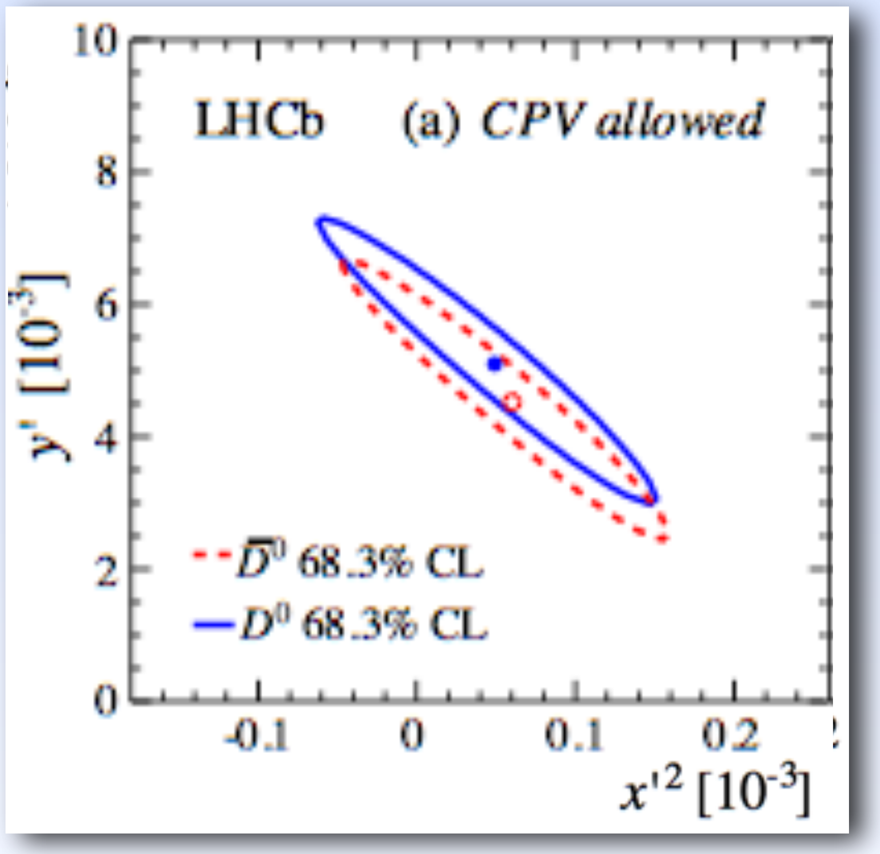
$$\phi \equiv \arg\left[q\mathcal{A}(\overline{D}^0 \to K^+\pi^-)/p\mathcal{A}(D^0 \to K^+\pi^-)\right] - \delta \neq 0$$

- $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$
- $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$

R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$

Most stringent constraint on the magnitude of q/p

PRL 111 (2013) 251801



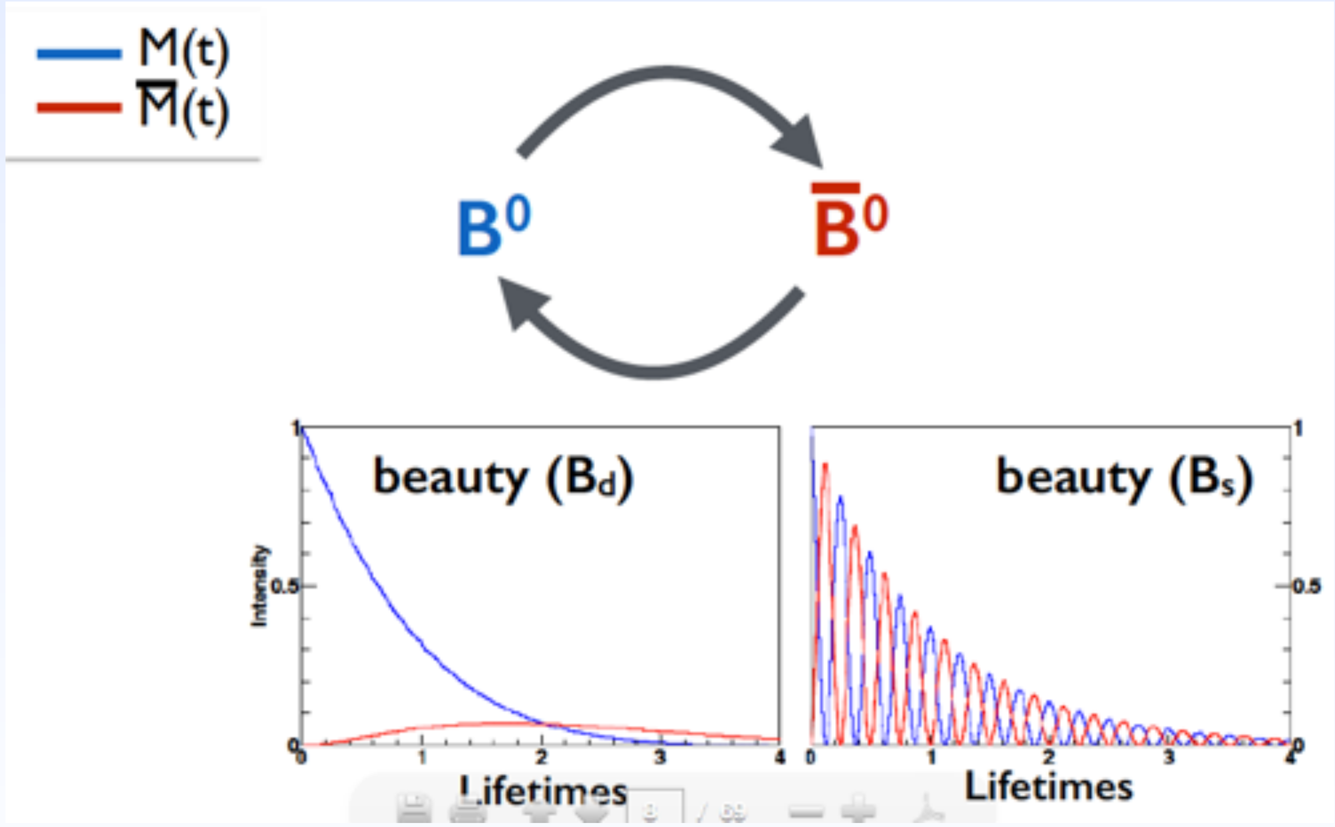
No direct or indirect CPV

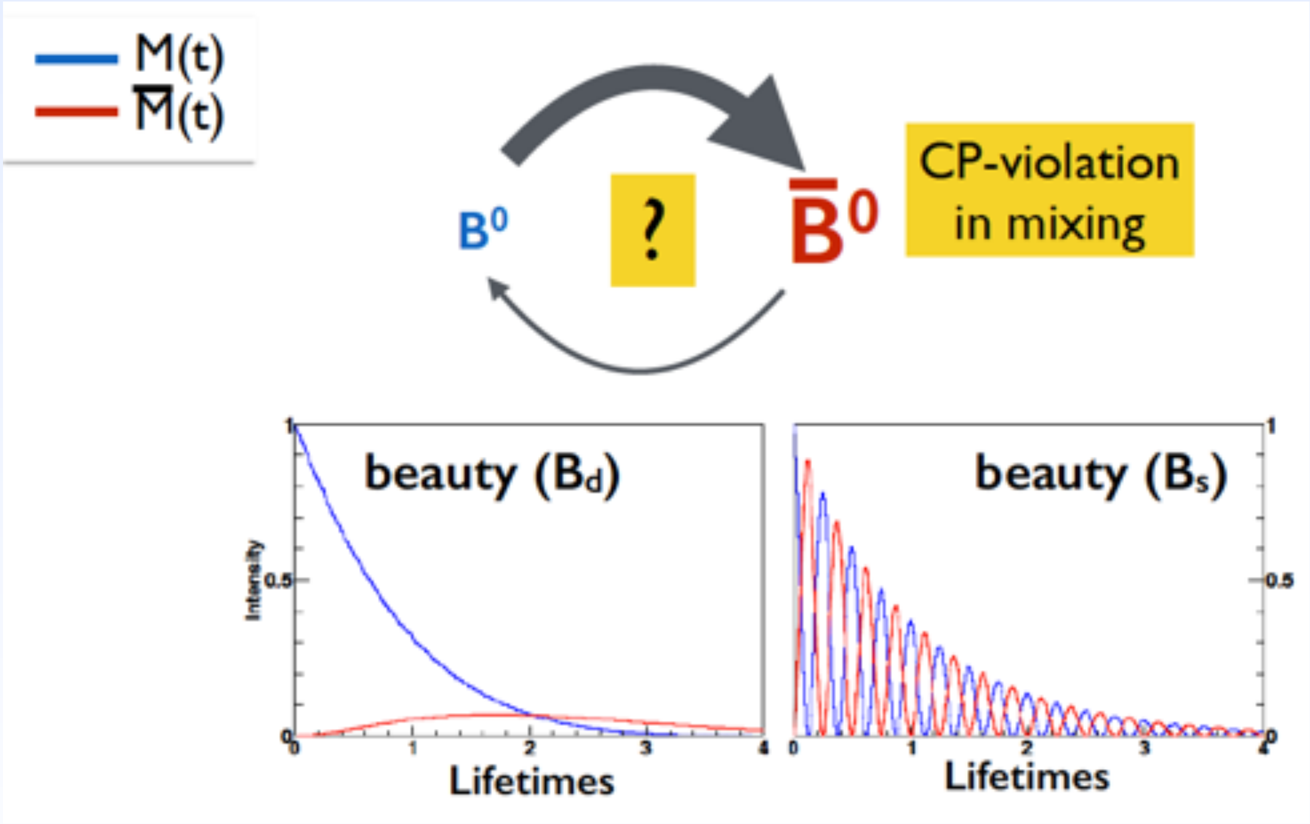
Message

- Neutral mesons are different but they all mix
- Some parameters are not well measured

CPV in mixing

$$|q/p| \neq 1$$





a_{sl}

If $|q/p| \neq 1$ then $a_{sl} = 0$

- The CP-violating "semileptonic" asymmetry:

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})}$$

Measure asymmetry after mixing

In the Standard Model*:

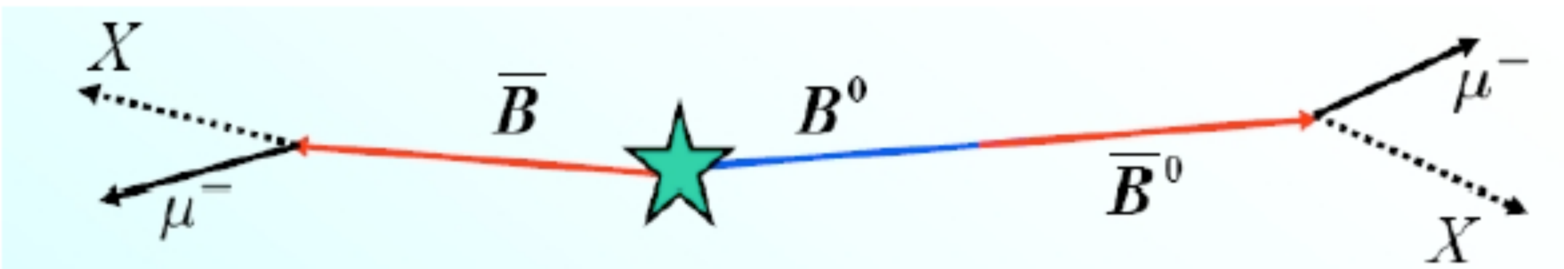
$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$

$a_{sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$

≈ ZERO

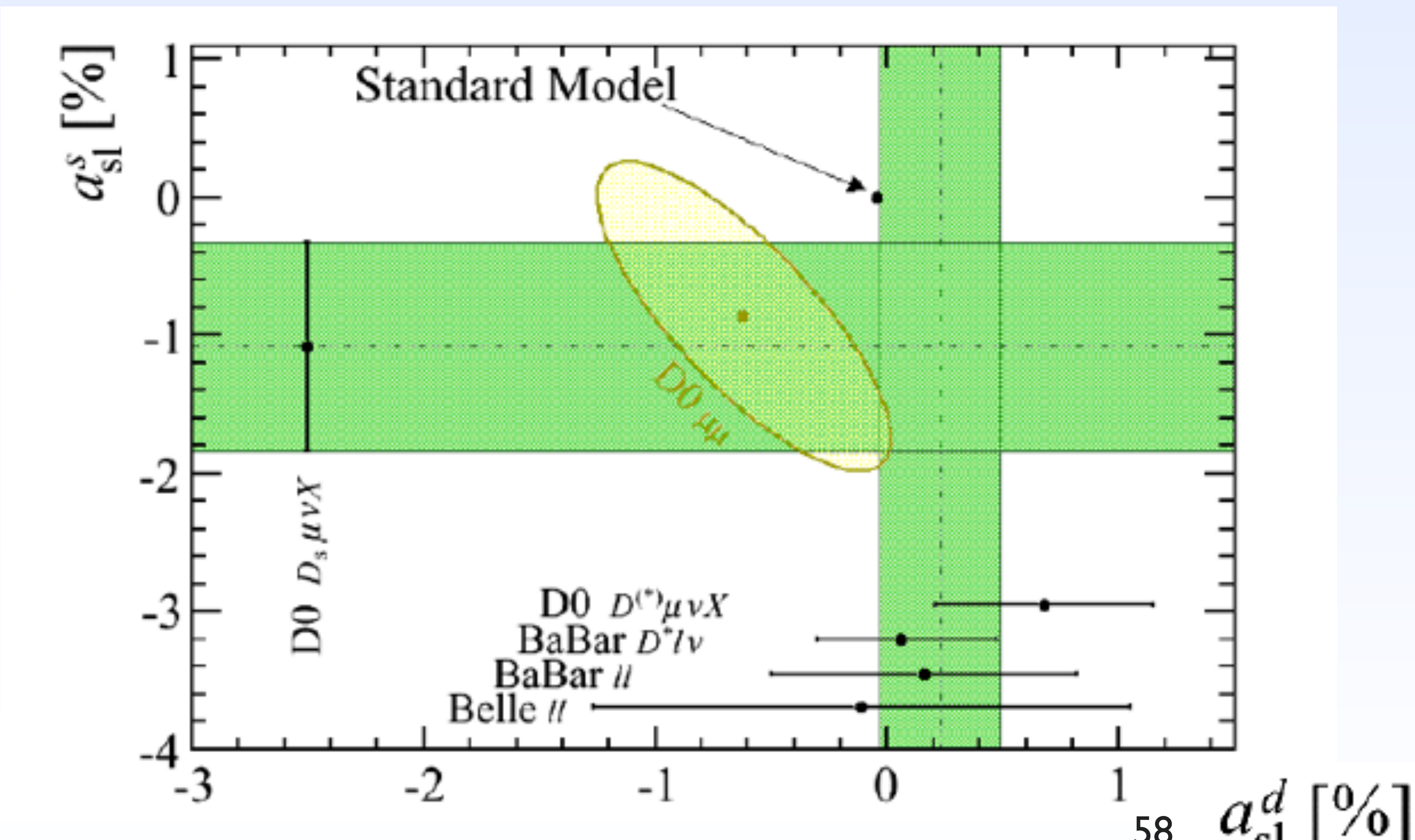
(Experimental precision: few x 10^{-3})

Method A



$$A_{\ell\ell} \equiv \frac{\Gamma(\ell^+\ell^+) - \Gamma(\ell^-\ell^-)}{\Gamma(\ell^+\ell^+) + \Gamma(\ell^-\ell^-)} = a_{\rm sl}$$

If one of the B-mesons decays after mixing we get leptons with the same sign



For these measurement, B_d and B_s taken together: inclusive measurement of a_{sl}^s and a_{sl}^d

Dimuon asymmetry from D^0 is 3.6σ from the SM

Method B - measure untagged asymmetry

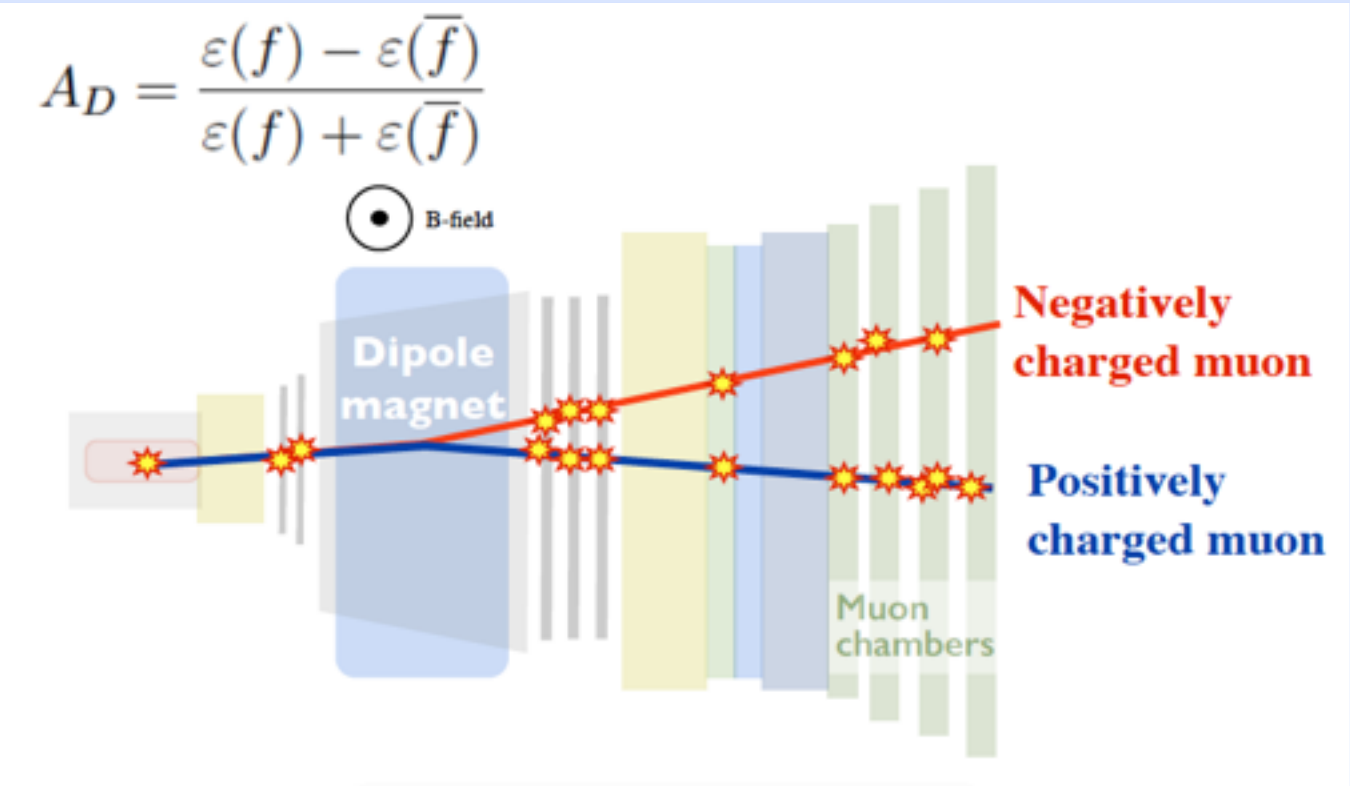
Direct measurements: more consistent with the SM

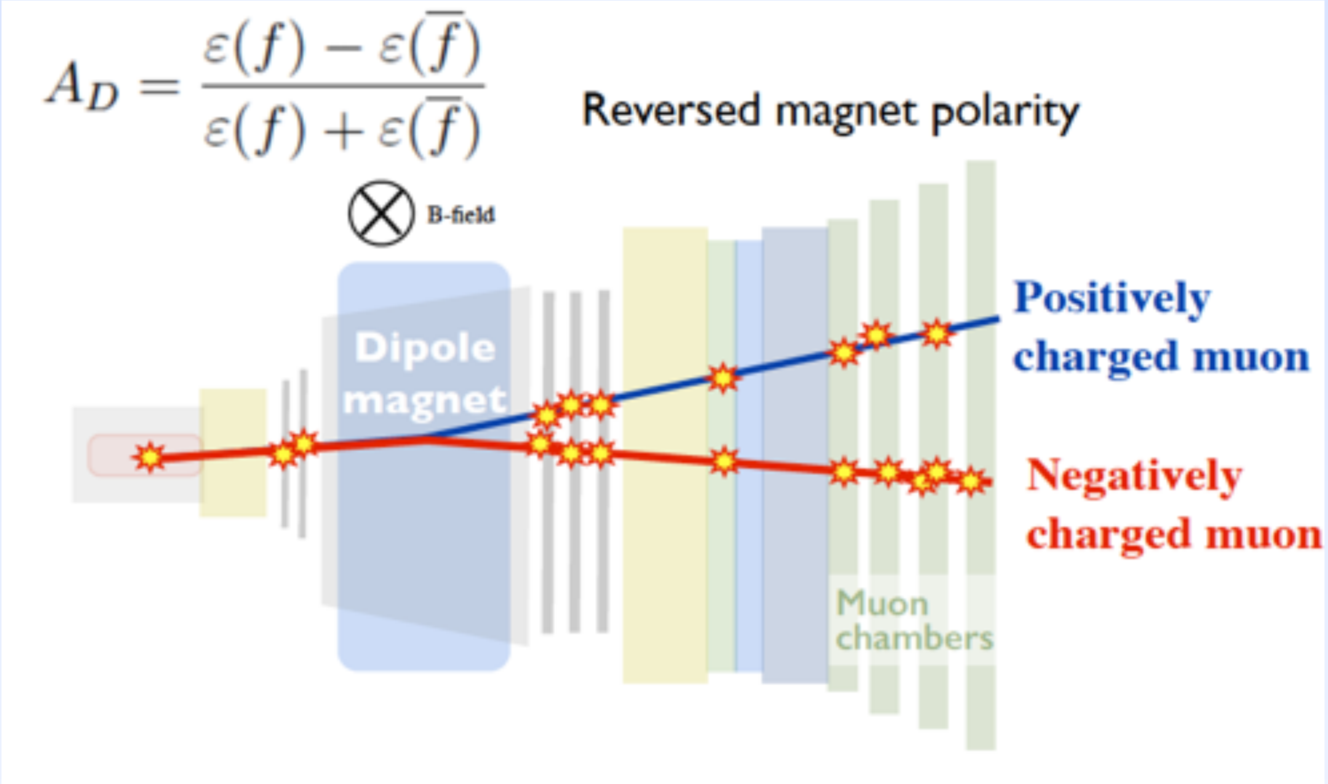
$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} \cdot \left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta\Gamma t}{2}}\right]$$

Look for an oscillating asymmetry as a function of decay time

at LHCb

Detection asymmetries



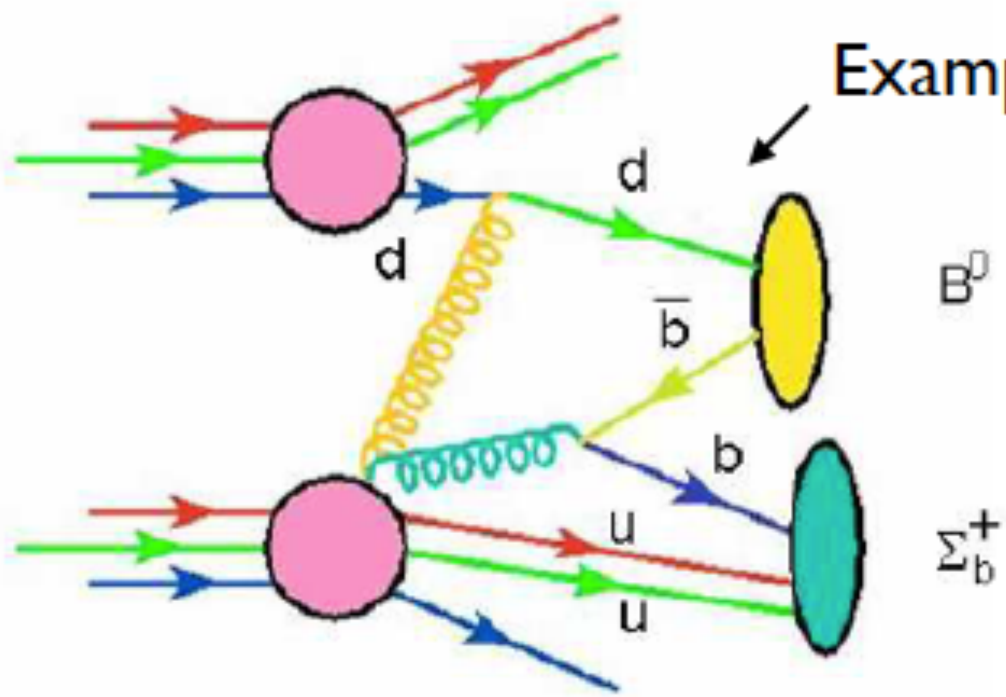


- Cancel left-right asymmetries by swapping dipole field

Production asymmetries

Production rates of B and $\overline{B}$ are not the same

gluon fusion, quarks combine with valence quark from the beam protons, valence quark scattering, etc.



Expected to be around 1%

$$a_P = \frac{\sigma(pp \to \bar{B}) - \sigma(pp \to B)}{\sigma(pp \to \bar{B}) + \sigma(pp \to B)}$$

➡ Not present at Tevatron or B-factories

a_{SL}^s

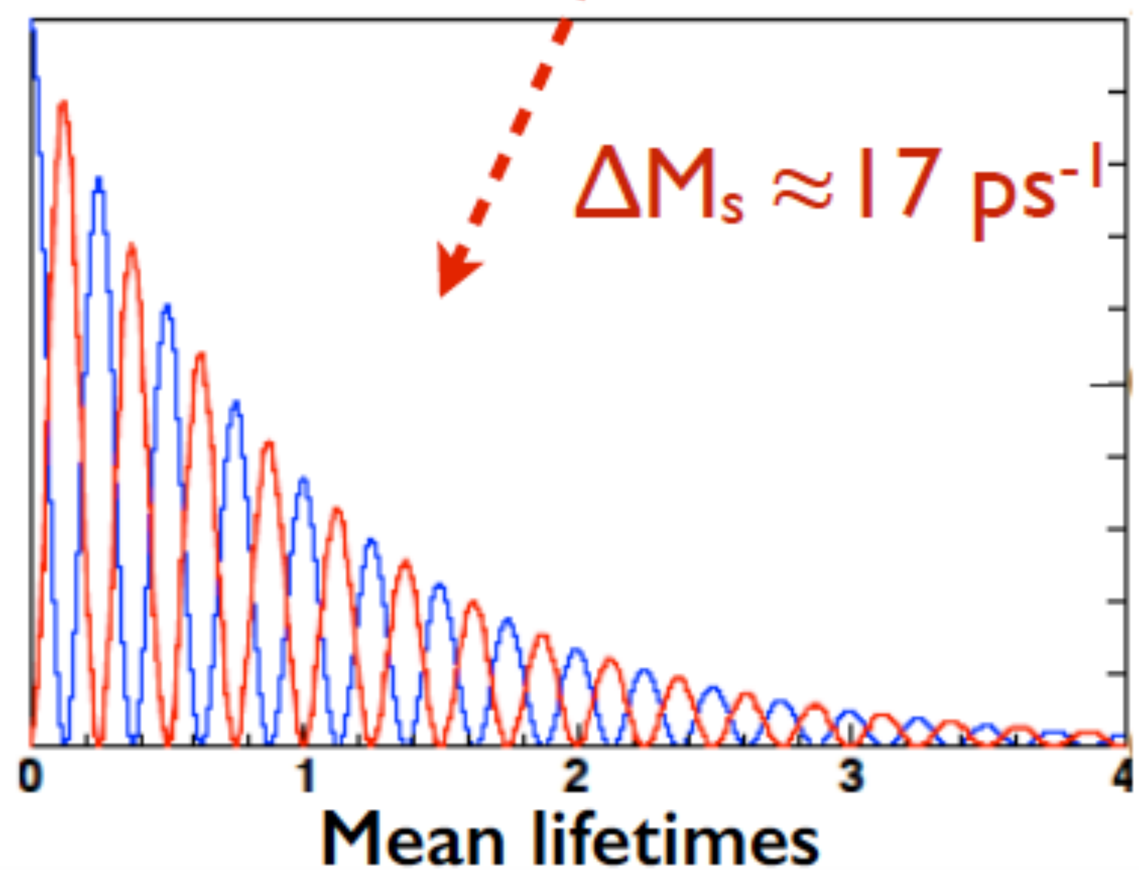
Simpler for a_{sl}^s

Decay time integrated asymmetry

< 10^{-4}

$$\frac{N(B_s^0)-N(\overline{B}_s^0)}{N(B_s^0)+N(\overline{B}_s^0)}=\frac{a_{\rm sl}^s}{2}+\left[a_{\rm P}-\frac{a_{\rm sl}^s}{2}\right]\frac{\int_{t=0}^{\infty}e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty}e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)dt}$$

Effect of a_P is washed out by the fast oscillations!

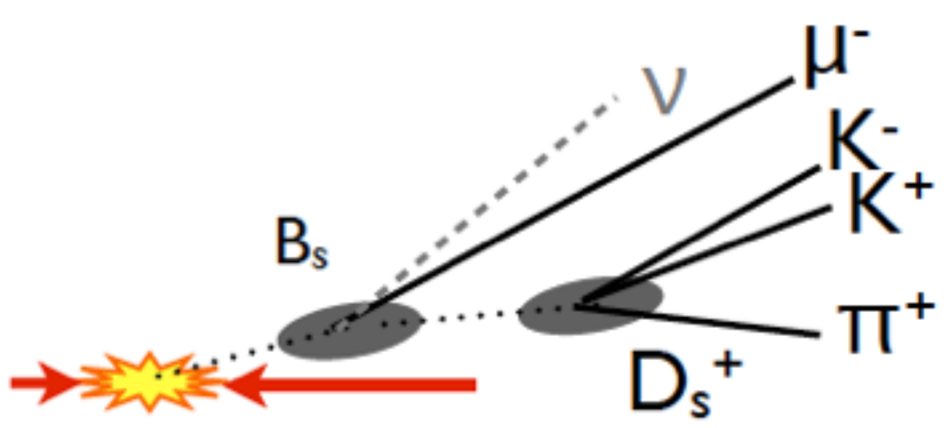


a_{SL}^{s}

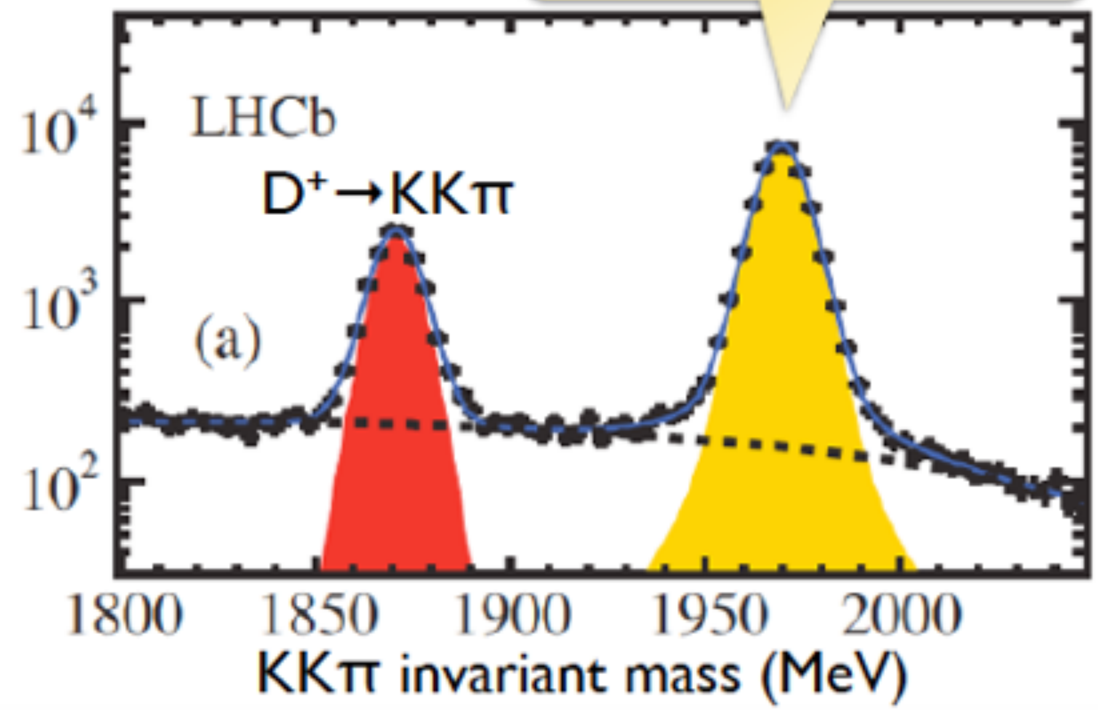
- The main problem is the detection asymmetry.
- Restricting to the $\phi \rightarrow KK$ resonance so only have a $\mu^{\pm}\pi^{\mp}$ asymmetry.

"Simply" need to measure:

$$\frac{N(B_s^0) - N(\overline{B}_s^0)}{N(B_s^0) + N(\overline{B}_s^0)} = \frac{a_{sl}^s}{2}$$



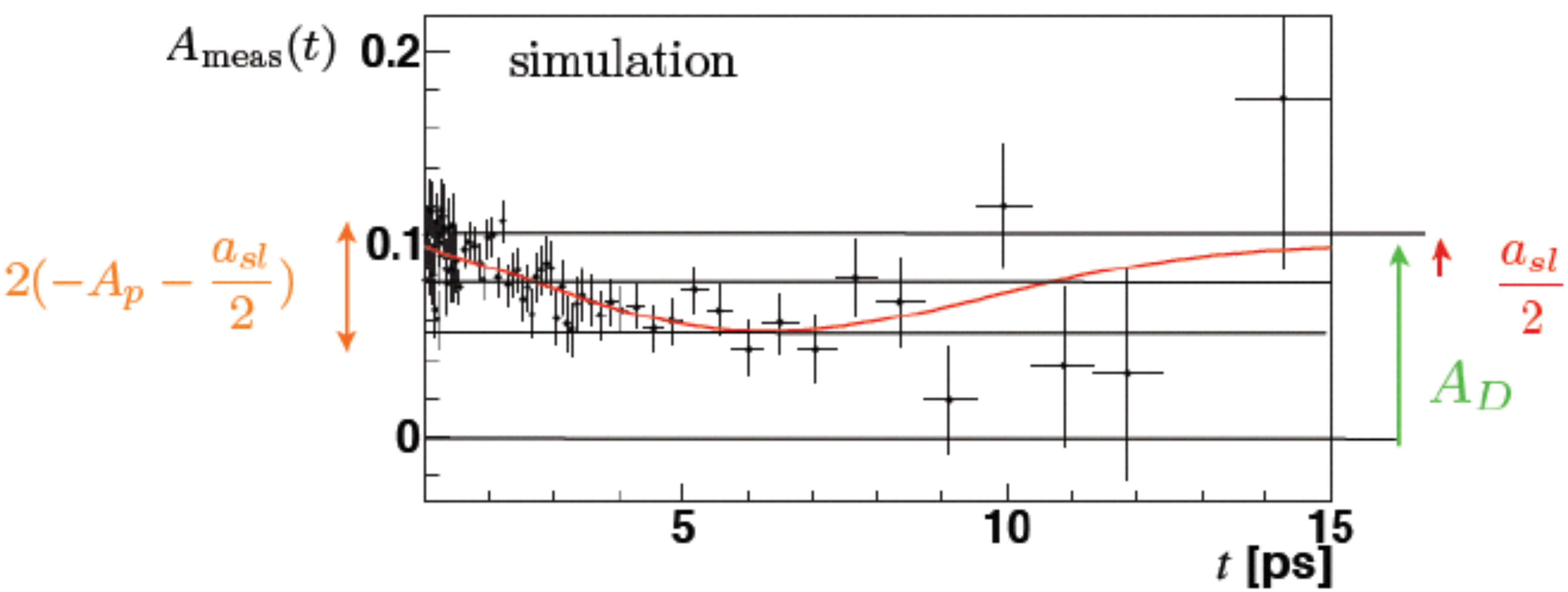
200k $B_s \rightarrow D_s\mu$ signal events in 2011



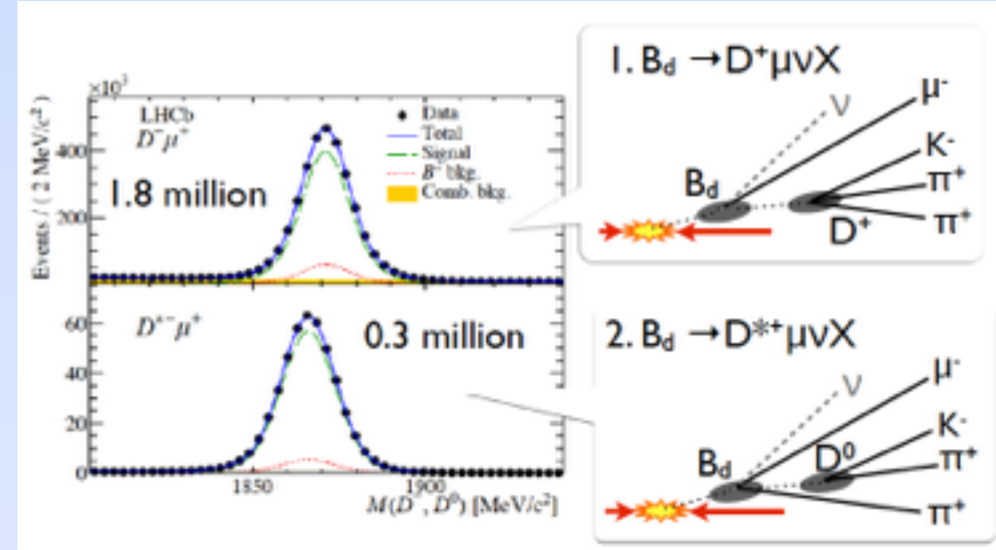
$a_{SL}{}^{d}$

- B_d mesons oscillate too slowly
- Fit the asymmetry as a function of decay time, to disentangle a_p and a_{sl}.

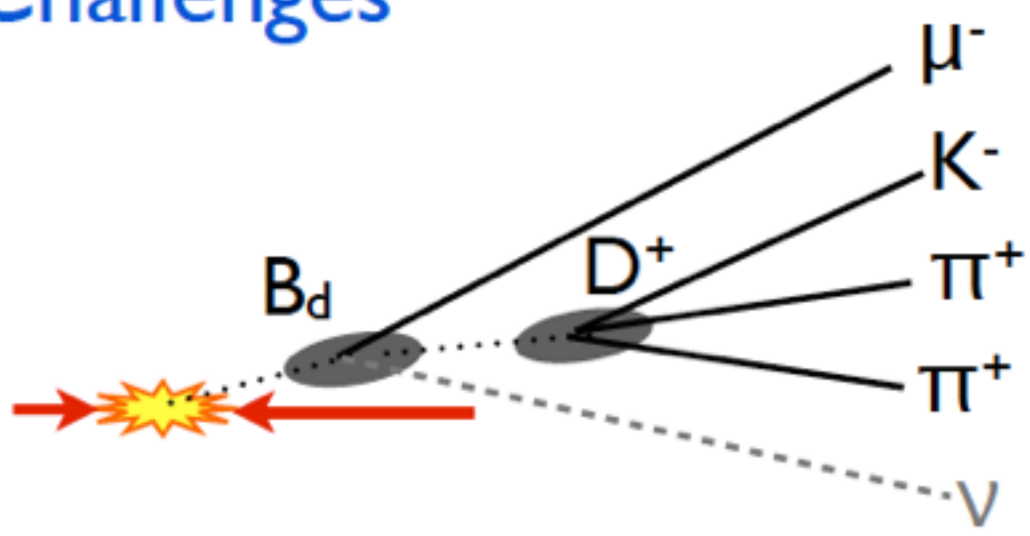
$$\frac{N(B,t)-N(\bar{B},t)}{N(B,t)+N(\bar{B},t)} = \frac{a_{\rm sl}}{2} - \left[a_P + \frac{a_{\rm sl}}{2}\right]\cdot\frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma t}{2}}$$



a_{SL}^d



Challenges

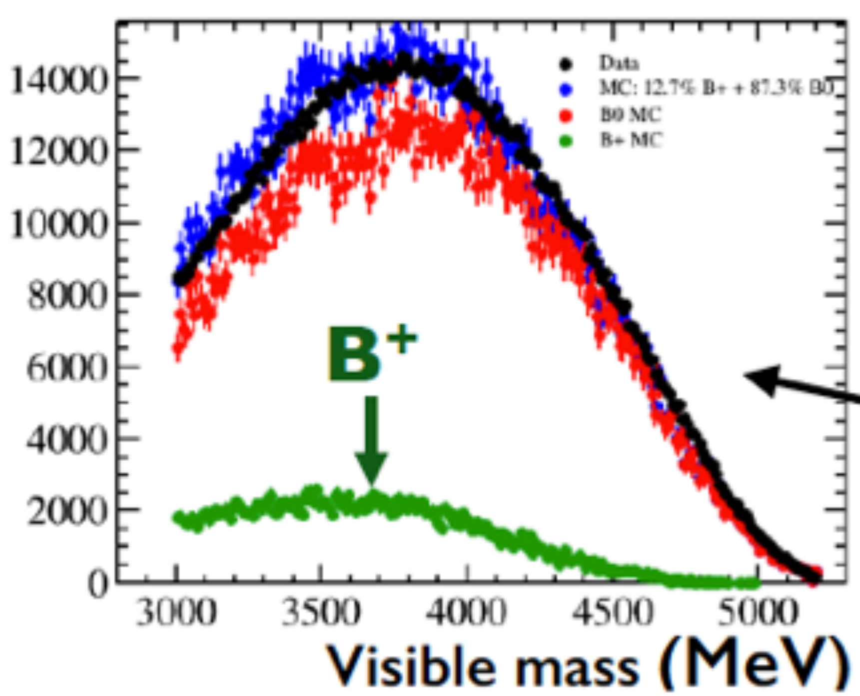


1. The detection asymmetry for the $\mu^{\pm}\pi^{\mp}K^{\pm}\pi^{\mp}$ final state

2. Don't know the B momentum

$$t = L \cdot \frac{M}{|p|}$$

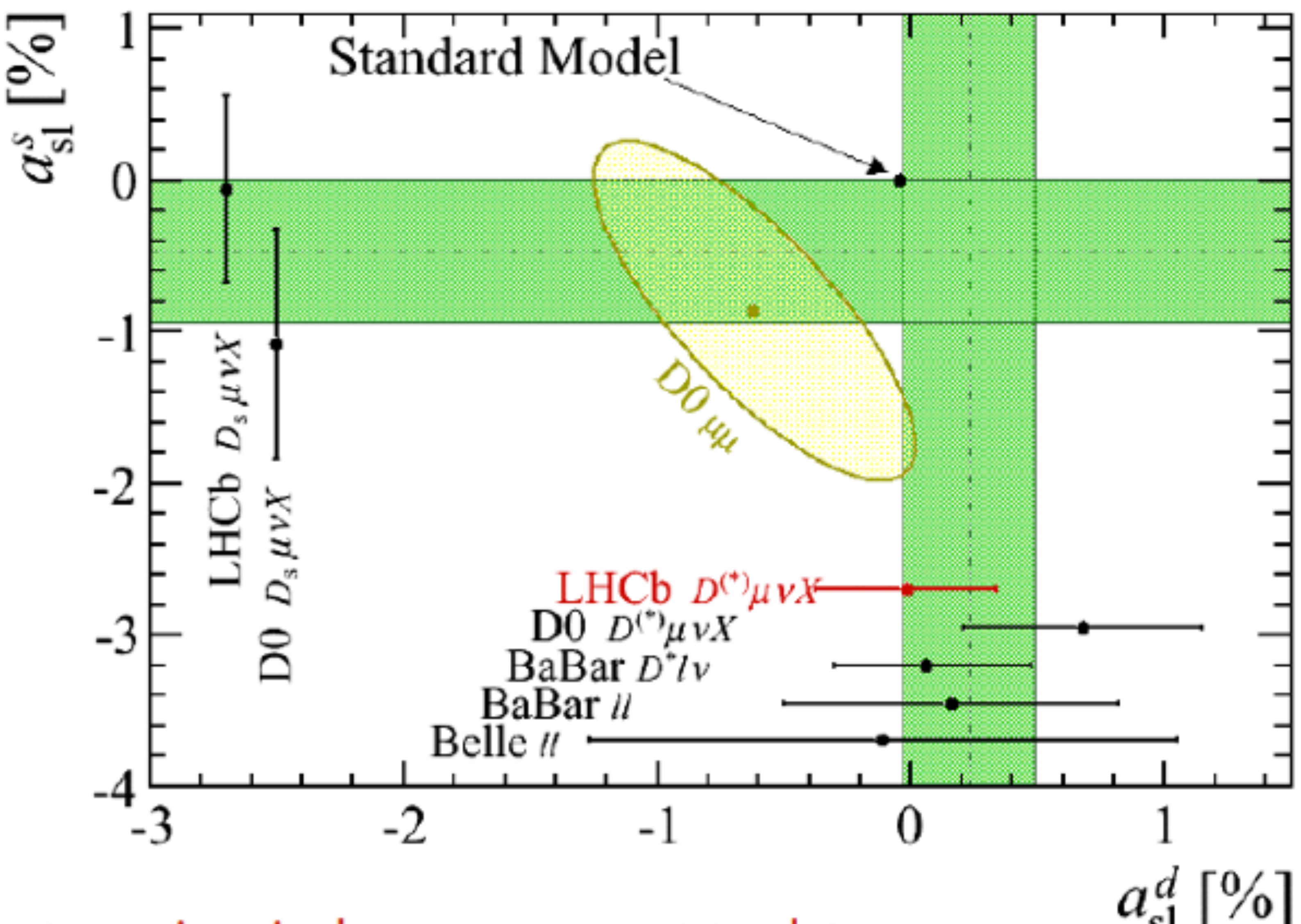
correction factor from simulation



3. No mass peak. Backgrounds!

background not oscillating, shape from simulation

World average post LHCb



- Most precise single measurement to date.
- Do not see an anomalous asymmetry.

- First LHCb measurements of CP-violation in B_s and B_d mixing.

$a_{sl}^d = (-0.02 \pm 0.19_{stat} \pm 0.30_{syst})\%$ PLB 728C 607-615 (2014)

$a_{sl}^s = (-0.06 \pm 0.50_{stat} \pm 0.36_{syst})\%$ LHCb-PAPER-2014-053 Update soon

Message

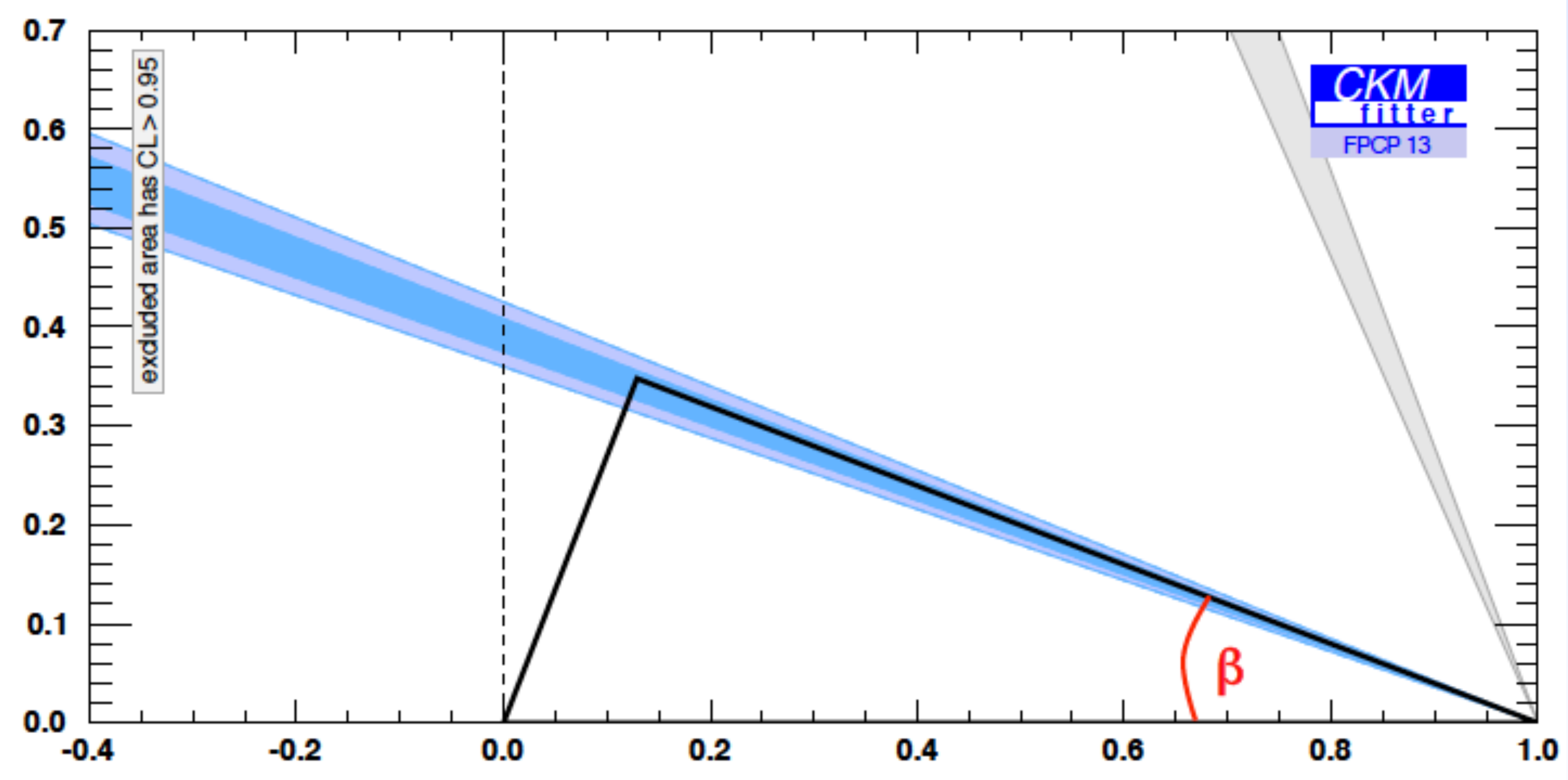
- More statistics needed
- SM predicts negligible CPV in mixing for B mesons (not the case for kaons)

CPV in interference

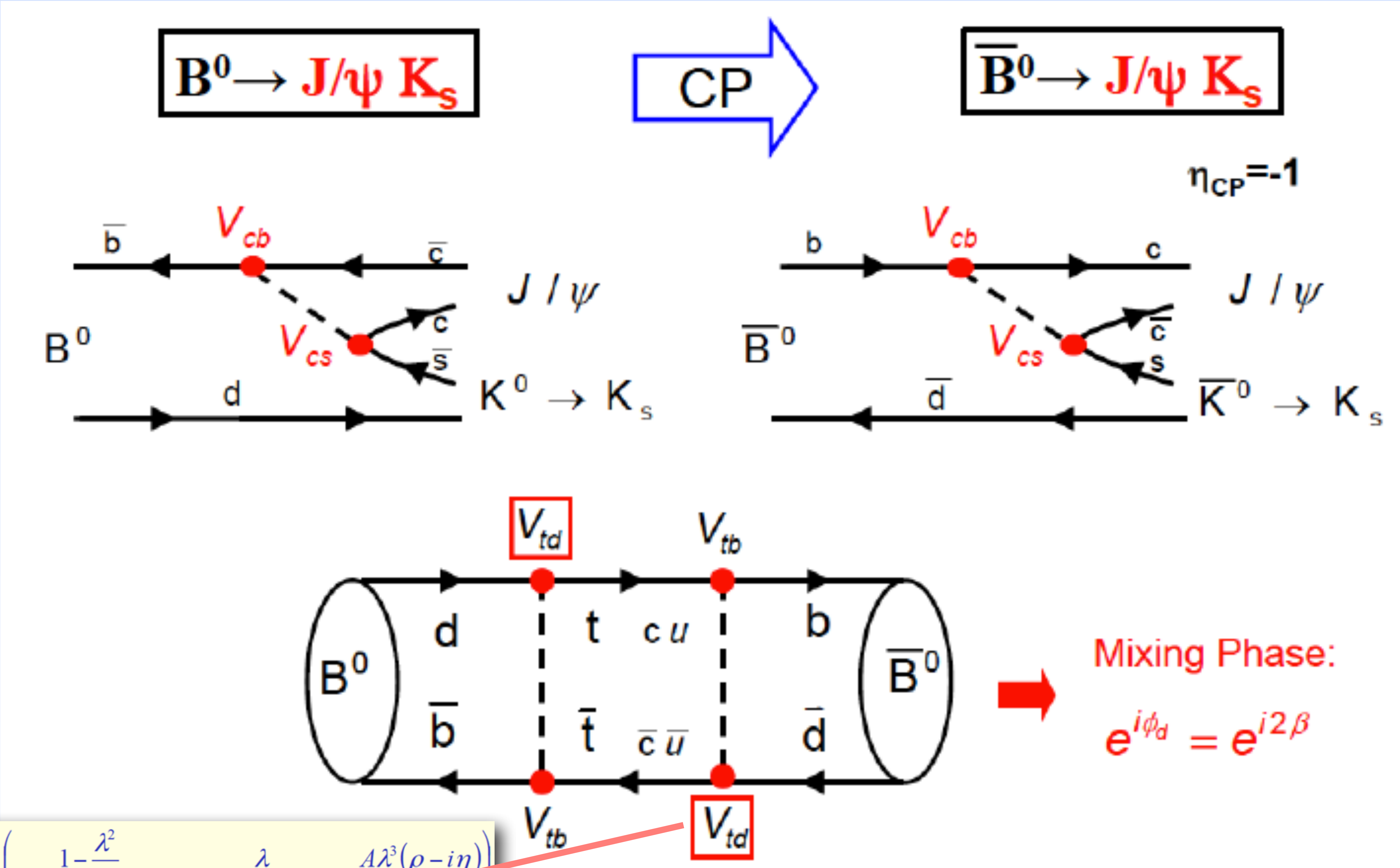
$$\Im(q/p) \neq 0$$

→ $\phi \equiv \arg(q/p) \neq 0, \pi$

β measurements



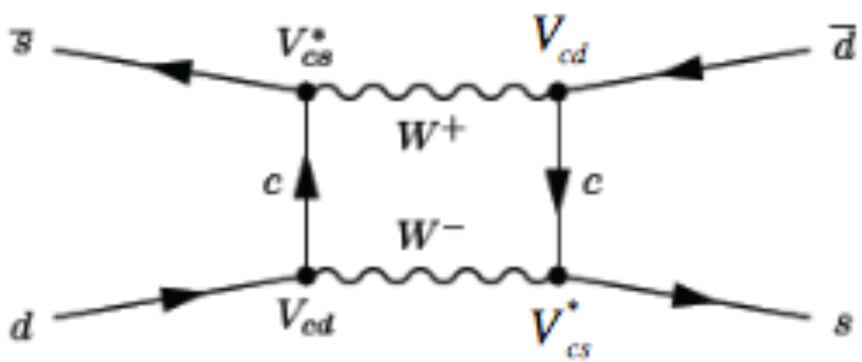
Time dependent CPV in the B^0-B^0 system

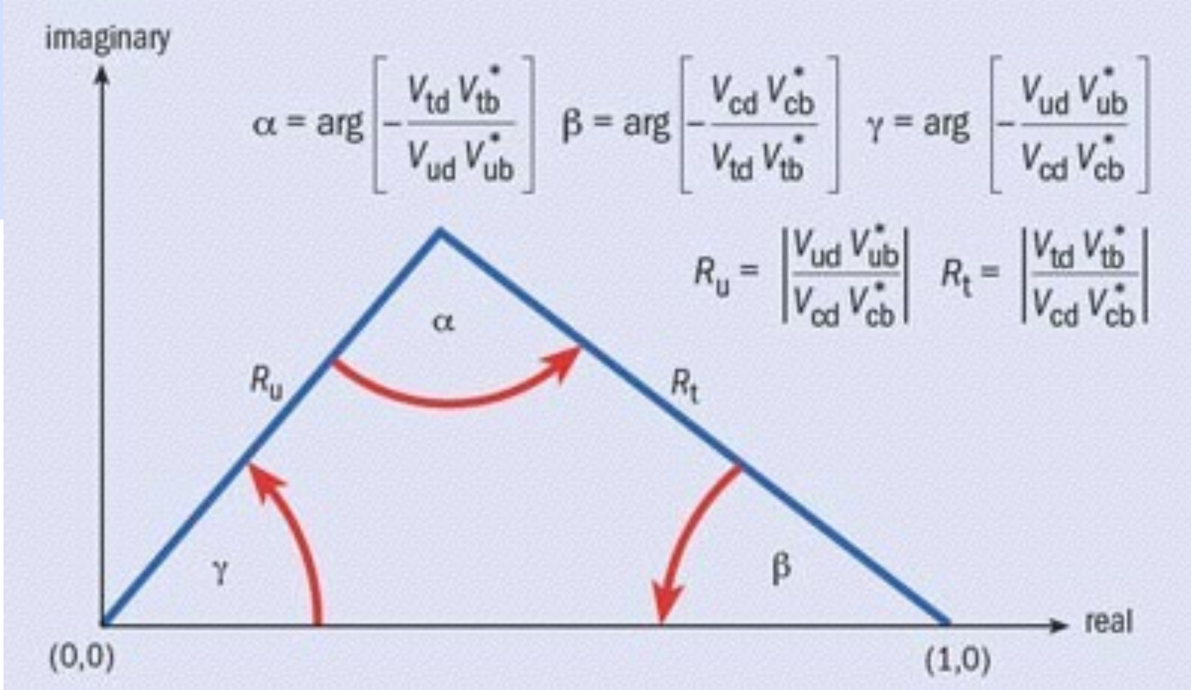


$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

Why is this β

$$\frac{q_K}{p_K} \approx \frac{V_{cs}^* V_{cd}}{V_{cs} V_{cd}^*}$$





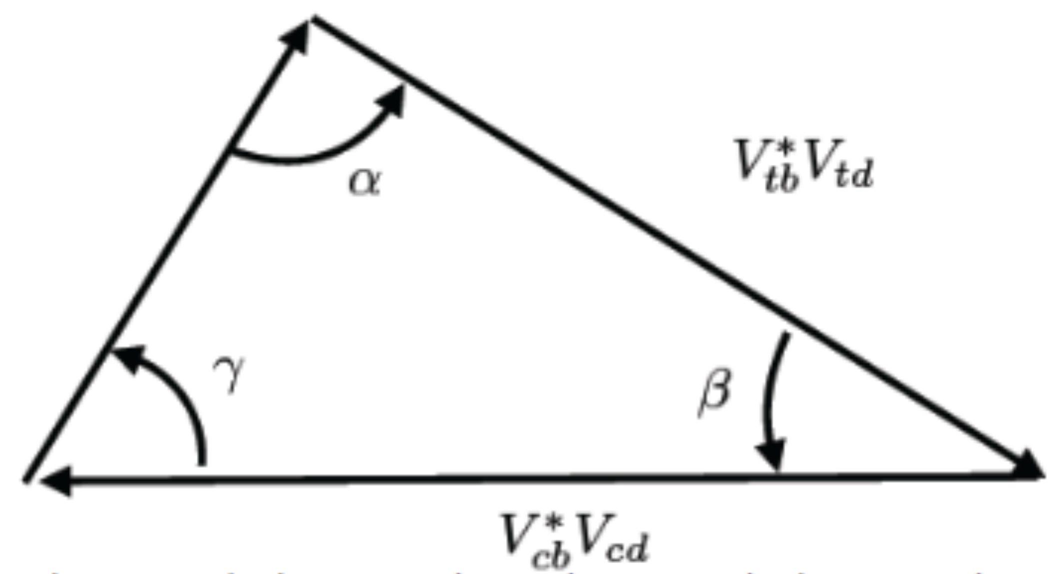
$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$= -\frac{q}{p}\frac{\bar{A}_{J/\psi \overline{K^0}, \overline{K^0} \to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$

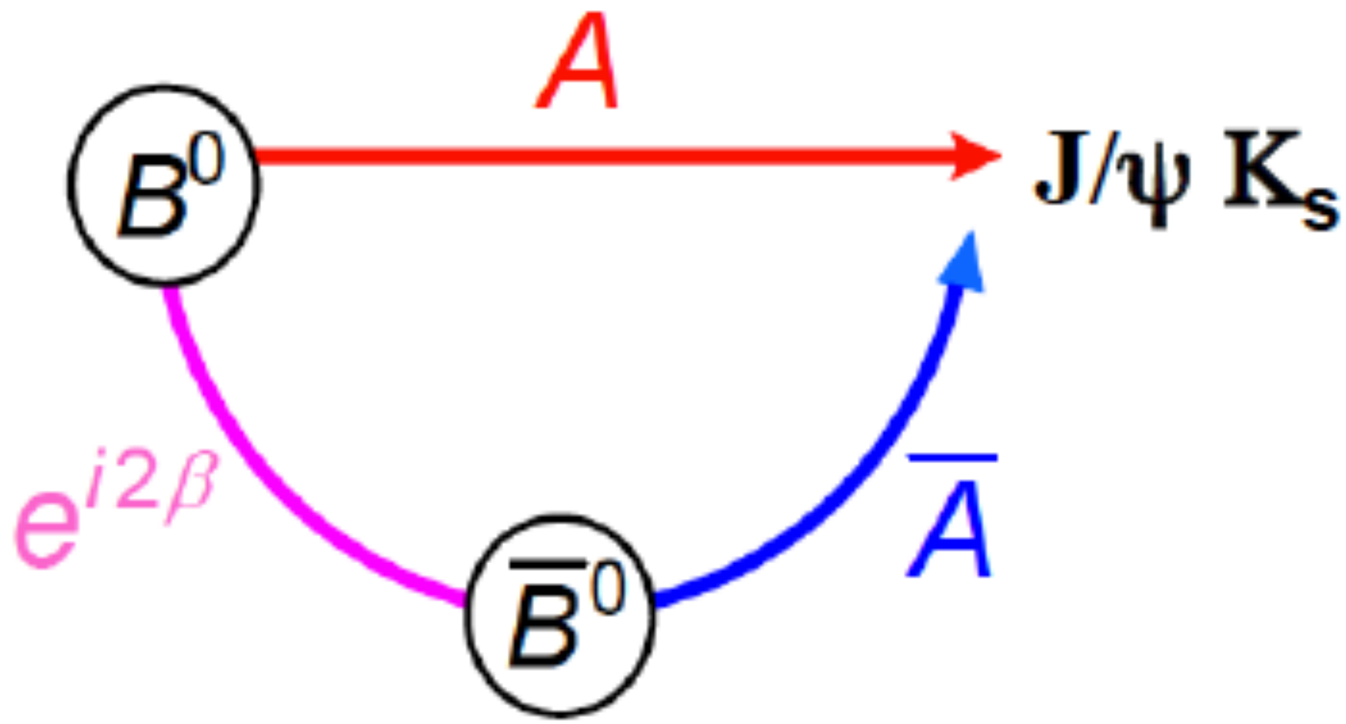
$$= -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)\left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right) = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right) = \left(\frac{V_{tb}^* V_{td}}{V_{cb}^*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

$$\frac{q}{p} \qquad \frac{\bar{A}_{J/\Psi \bar{K}^0}}{A_{J/\Psi K^0}} \qquad \frac{p_k}{q_k}$$

$$= -e^{-2i\beta}$$



The time-dependent CP asymmetry

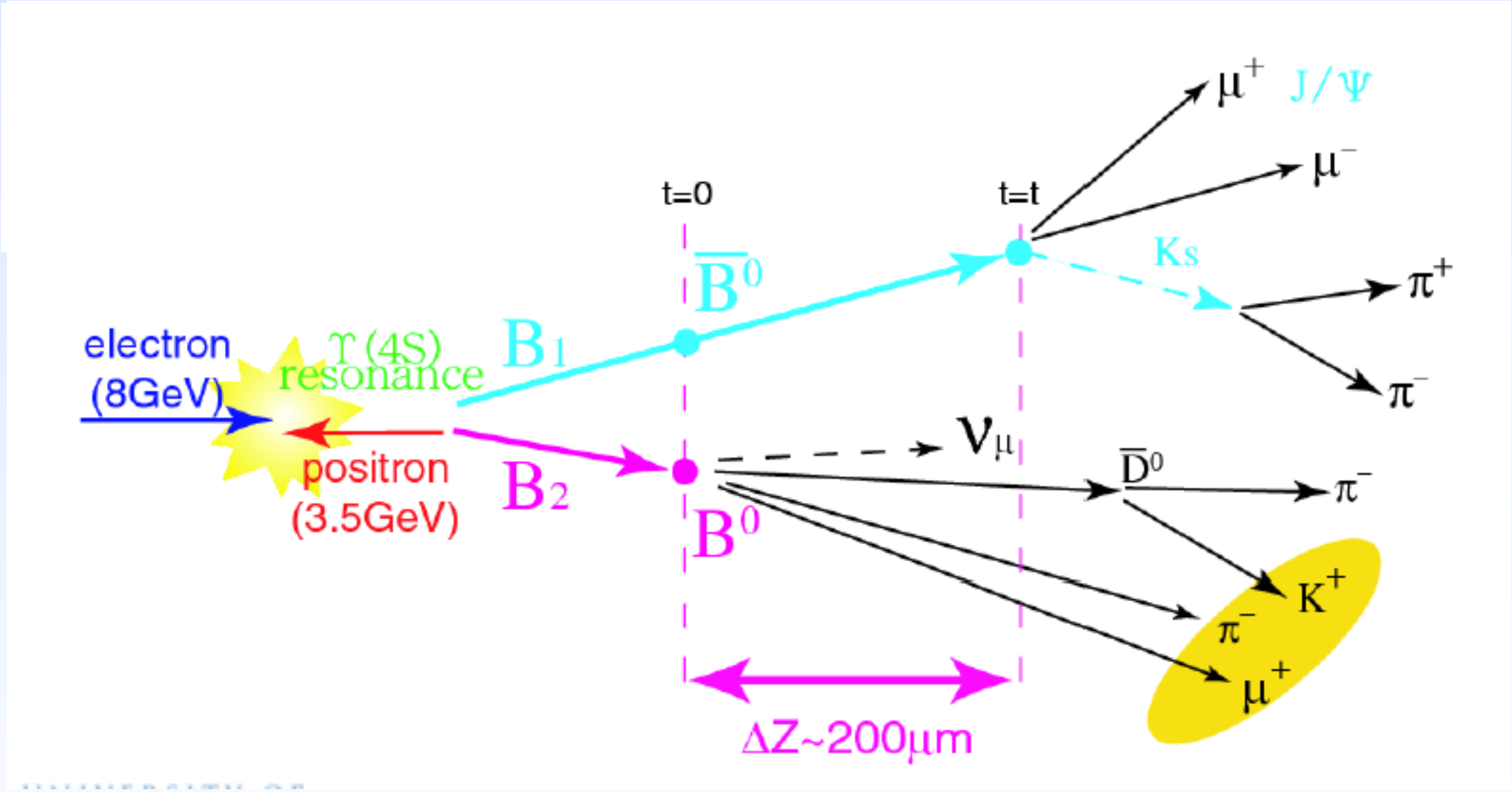


$$\Gamma(B^0 \to J/\psi K_s)(t) \neq \Gamma(\overline{B}^0 \to J/\psi K_s)(t)$$

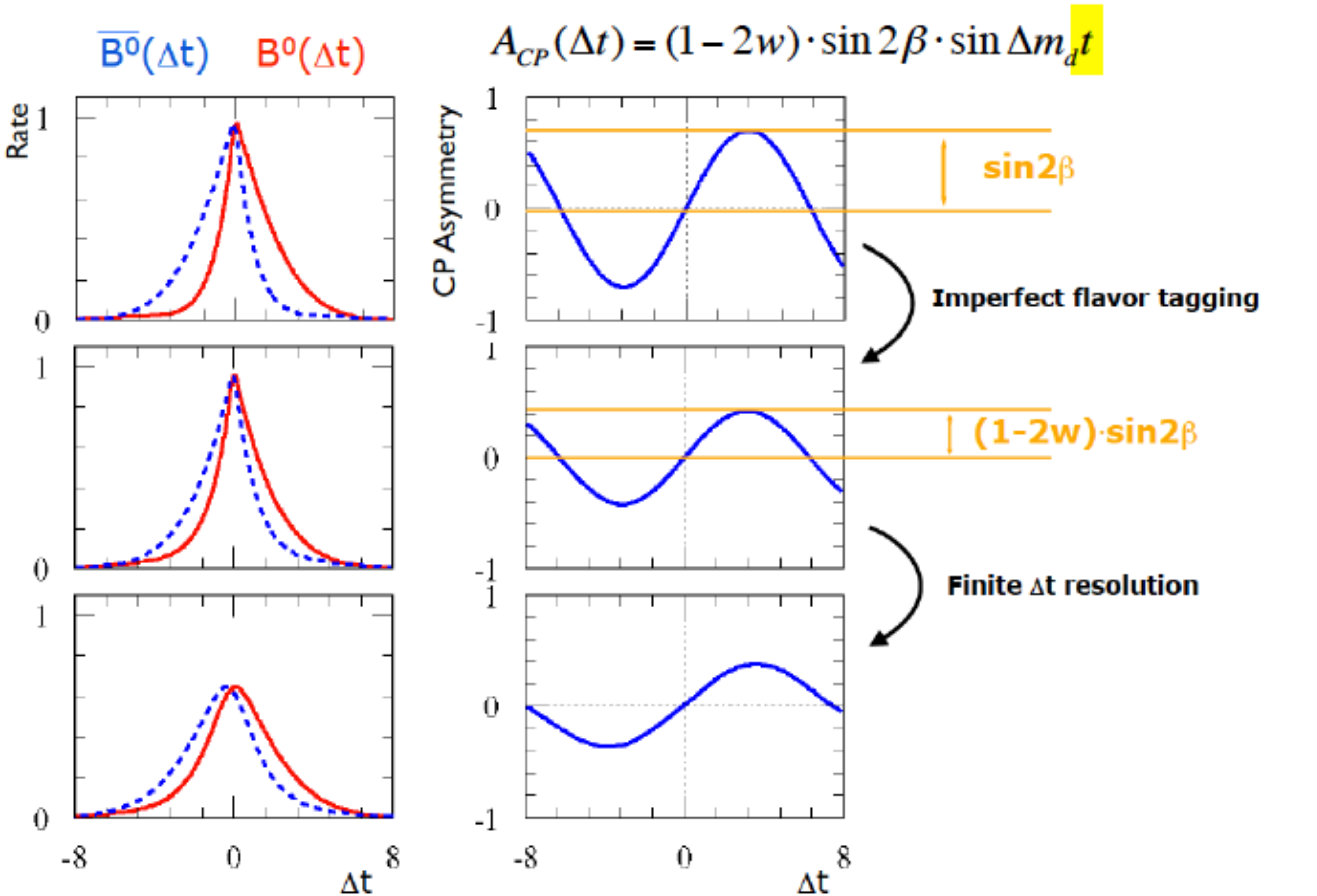
$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B^0} \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$

requires knowledge of the flavour of the B^0

Asymmetric B-factory principle



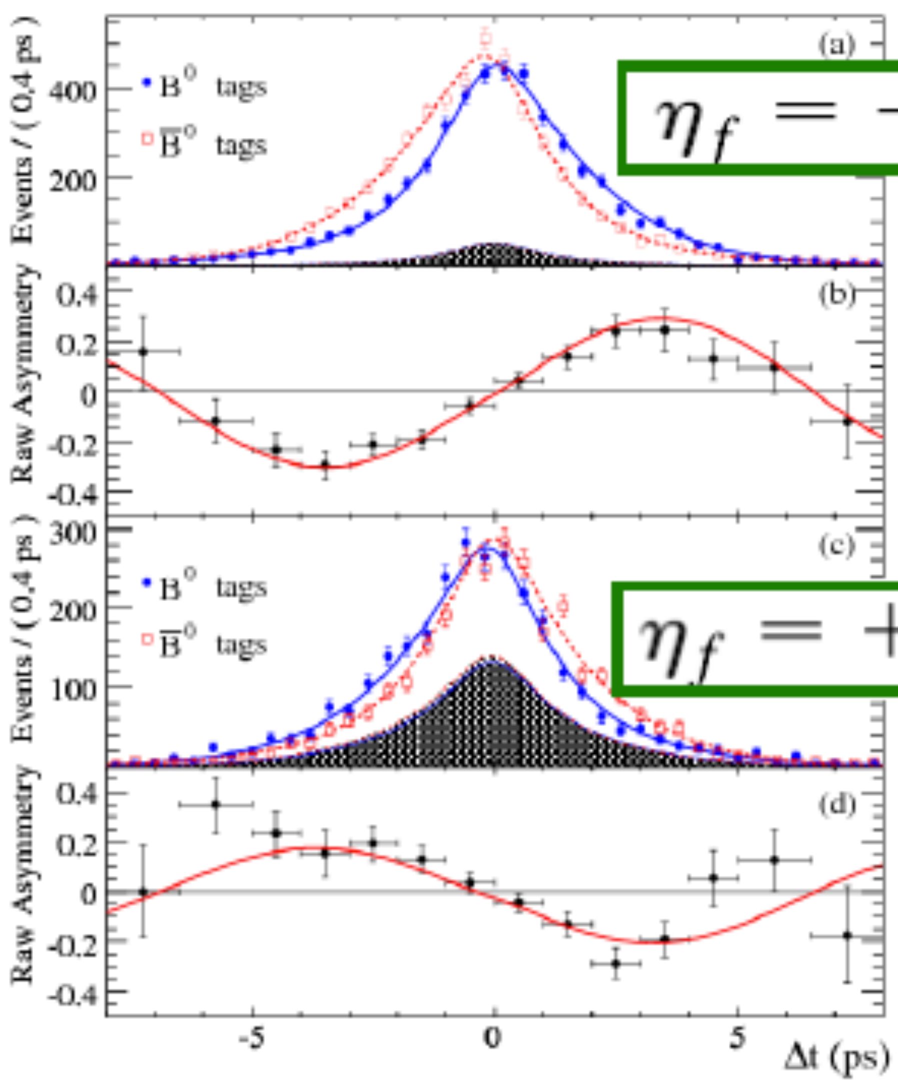
Experimental effects



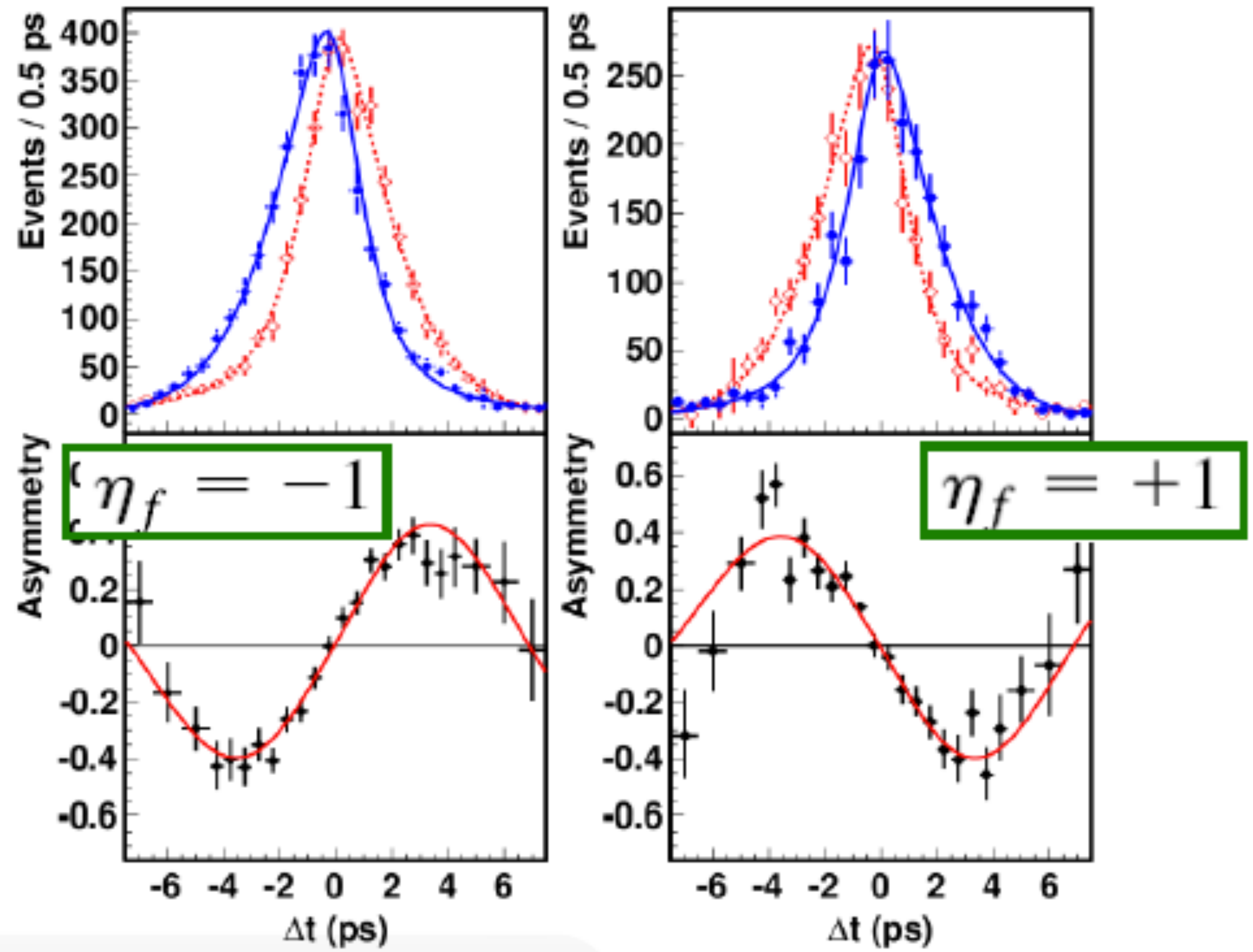
Results for the golden mode

$$B^0 \rightarrow J/\psi K^0$$

BABAR



BELLE

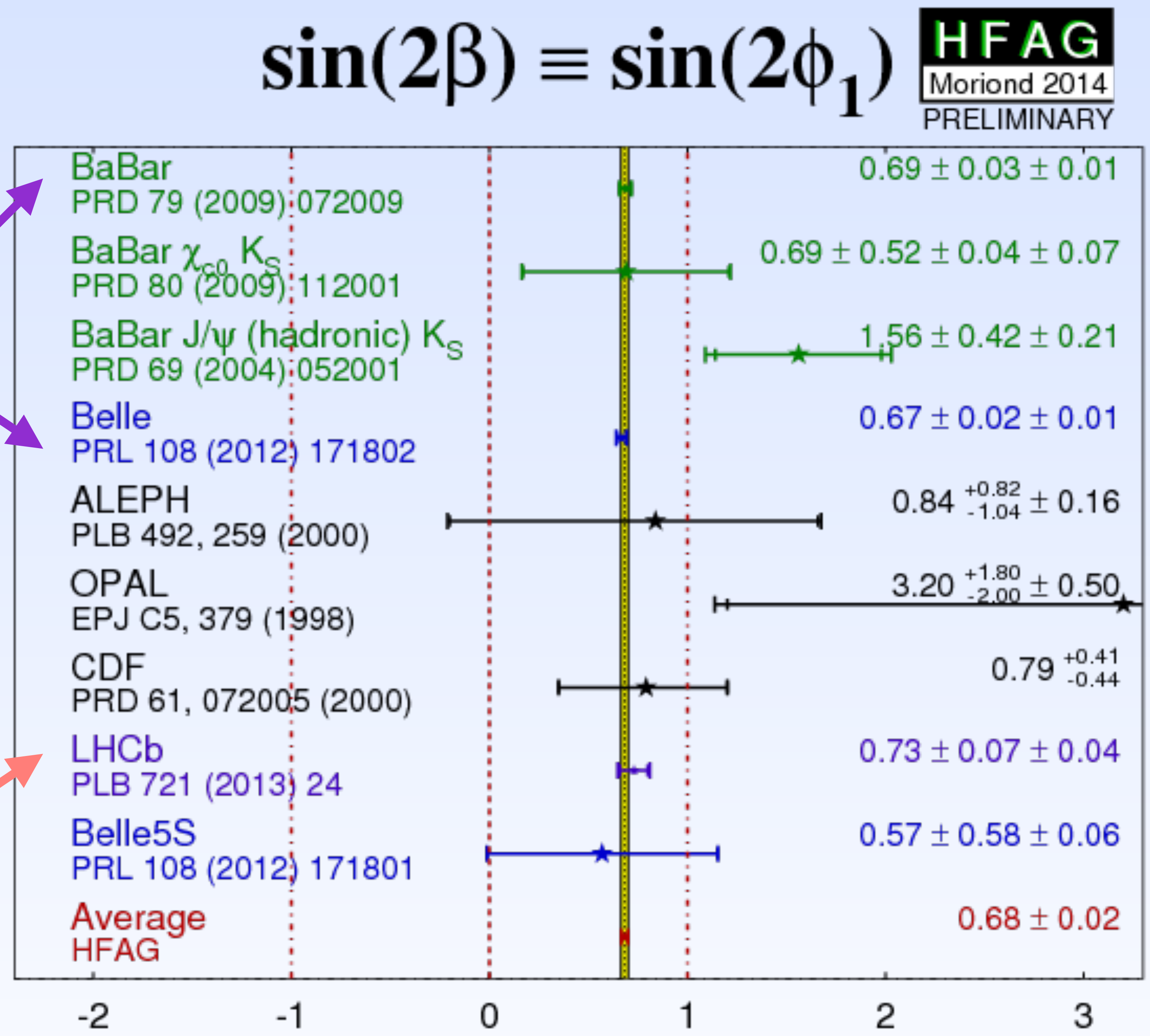


PRD 79 (2009) 072009

PRL 108 (2012) 171802

WA

Most precise



LHCb will improve soon

General formalism of time dependent CPV and βs (the other UT)

$$\lambda = \frac{q}{p}\frac{\bar{A}(\bar{\mathrm{B}}^0_s \to f_{CP})}{A(\mathrm{B}^0_s \to f_{CP})}, \text{ with } \phi_s = -arg(\lambda)$$

Time dependent CPV formalism

Generic decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right].$$

Time dependent CPV formalism

Generic decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \Big[\; 1 \; + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) \; 0 \; + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \Big]$$

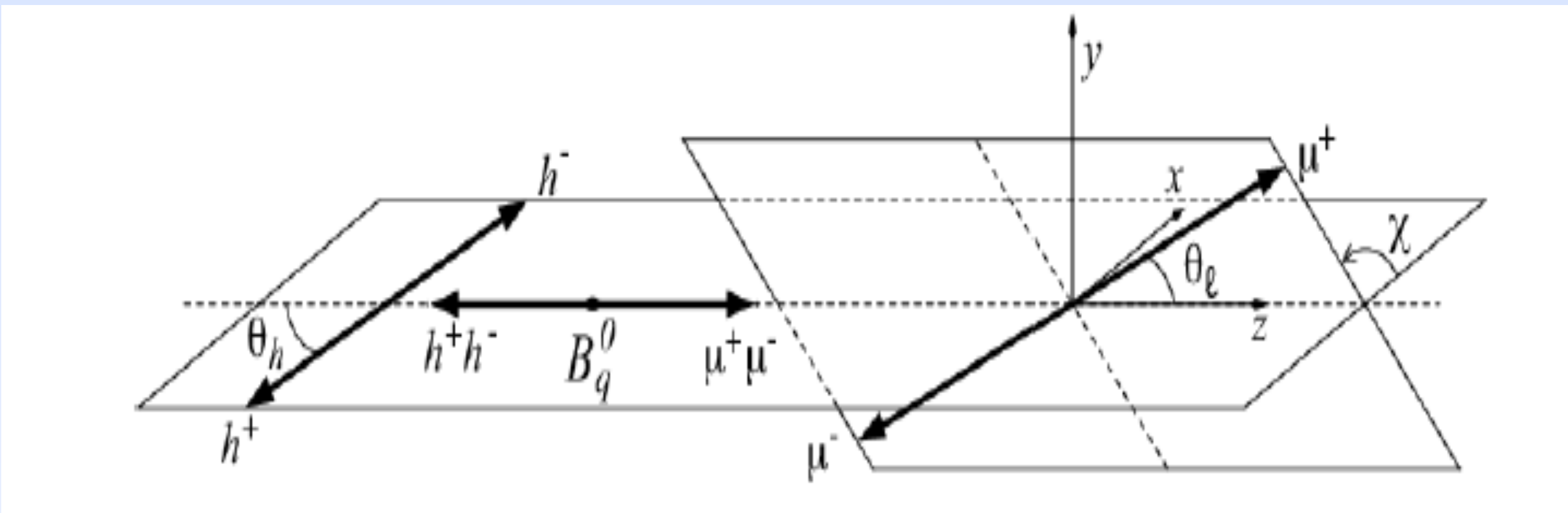
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \Big[\; 1 \; - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) \; 0 \; - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \Big] \, .$$

B_d case: $\Delta\Gamma$ - negligible

ϕ_s = -2ß$_s$

ϕ_s: relative phase between interfering
$A(B_s^0 \rightarrow J/\psi h^+ h^-)$ and $A(B_s^0 \rightarrow \bar{B}_s^0 \rightarrow J/\psi h^+ h^-)$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = |\lambda_f| e^{-i\phi_s^f}$$



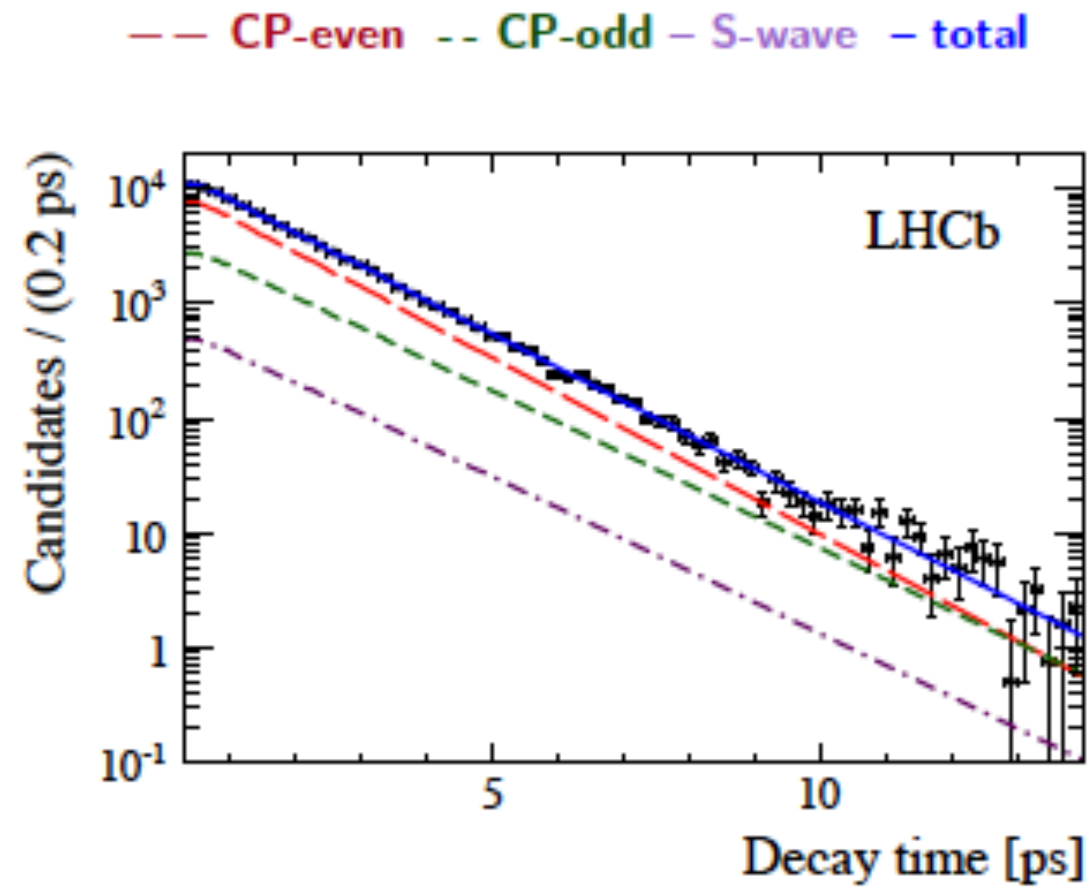
Precise SM prediction:
$\phi_s = (-0.036 \pm 0.002) rad$

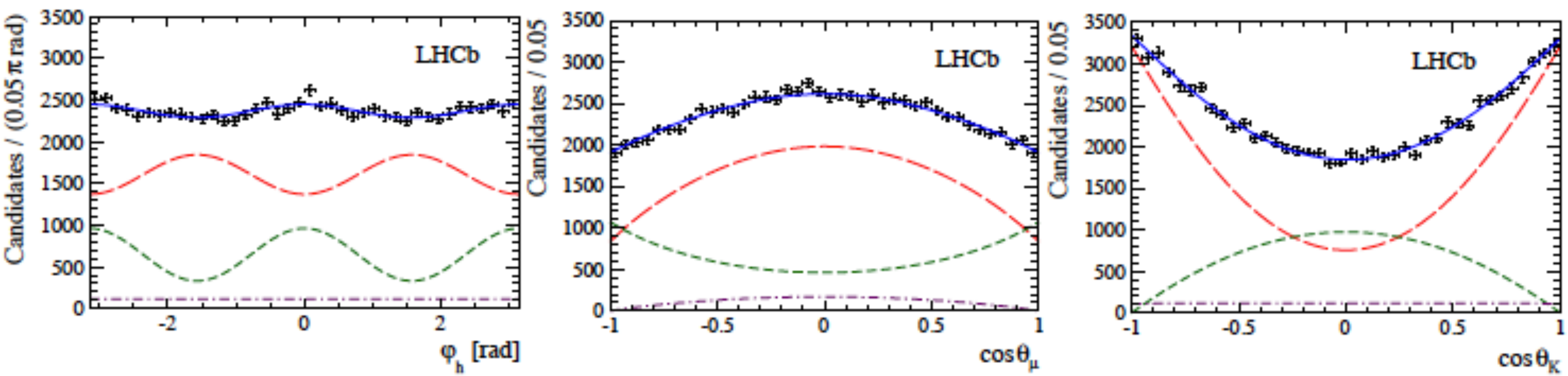
- Most attractive channel: B^0_s
  - VV final state: 3 helicity amplitudes
  - mixture of CP-even and CP-odd
  - angular analysis needed to disentangle them
  - many correlated variables: complicated analysis

ϕ_s is sensitive to new physics in B_s^0 mixing
$\phi_s = \phi_s^{SM} + \Delta\phi_s \Rightarrow \Delta\phi_s = arg(M_{12}/M_{12}^{SM})$

$B_s^0 \to J/\psi K^+ K^-$ results arXiv:1411.3104

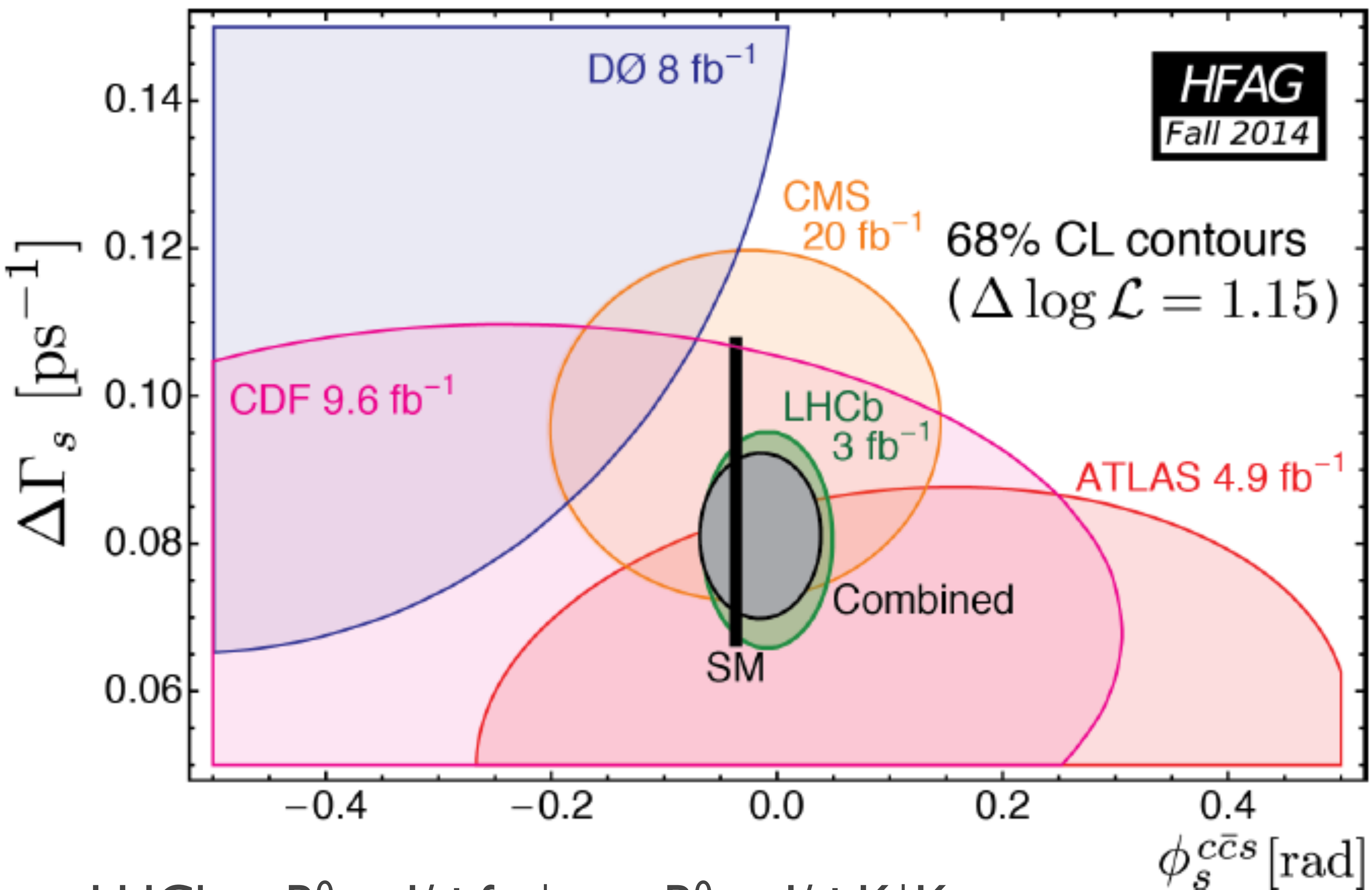
Parameter	Value
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\|\lambda\|$	$0.964 \pm 0.019 \pm 0.007$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0033$
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
Δm_s [ps^{-1}]	$17.711 \ ^{+0.055}_{-0.057} \pm 0.011$





Current WA

ϕ_s-$\Delta\Gamma_s$ world average



- LHCb = $B^0_s \to J/\psi f \pi^+\pi^-$ + $B^0_s \to J/\psi K^+K^-$

Indirect CPV in charm

CPV in mixing and/or the interference of direct CPV and mixing; time dependent

Indirect CP violation in $D^0 \to h^+h^-$

- Measure asymmetries of effective lifetimes

of decays to CP eigenstates:

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}}$$

$A_\Gamma \approx A_M\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$

(Neglecting A_d y cos ϕ)

$\phi = \beta_c \approx 0.35°$ (theory) : tiny

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

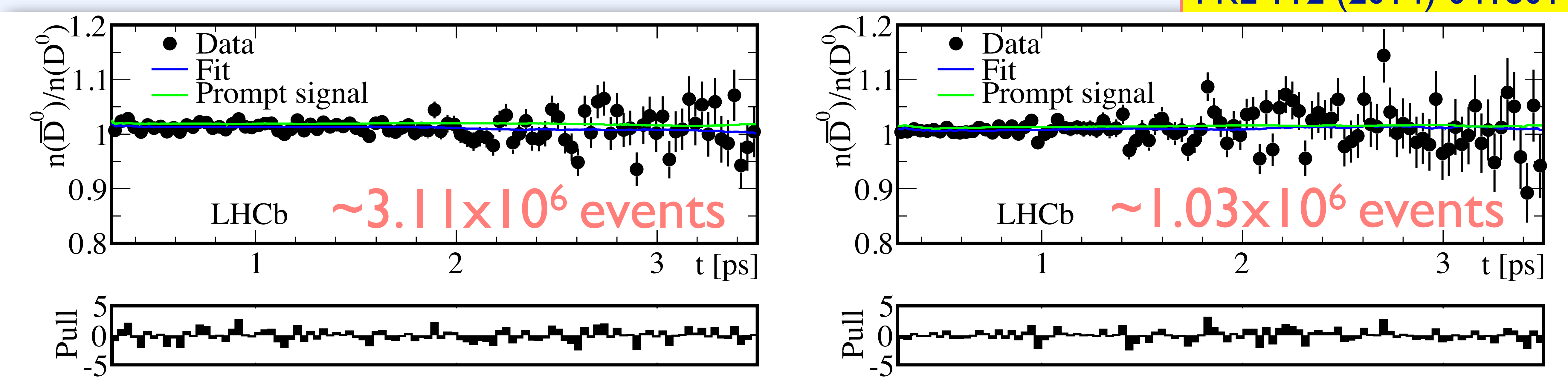
- Measurements use prompt $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays (1 fb^{-1})

$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

Most precise measurement of CP asymmetries

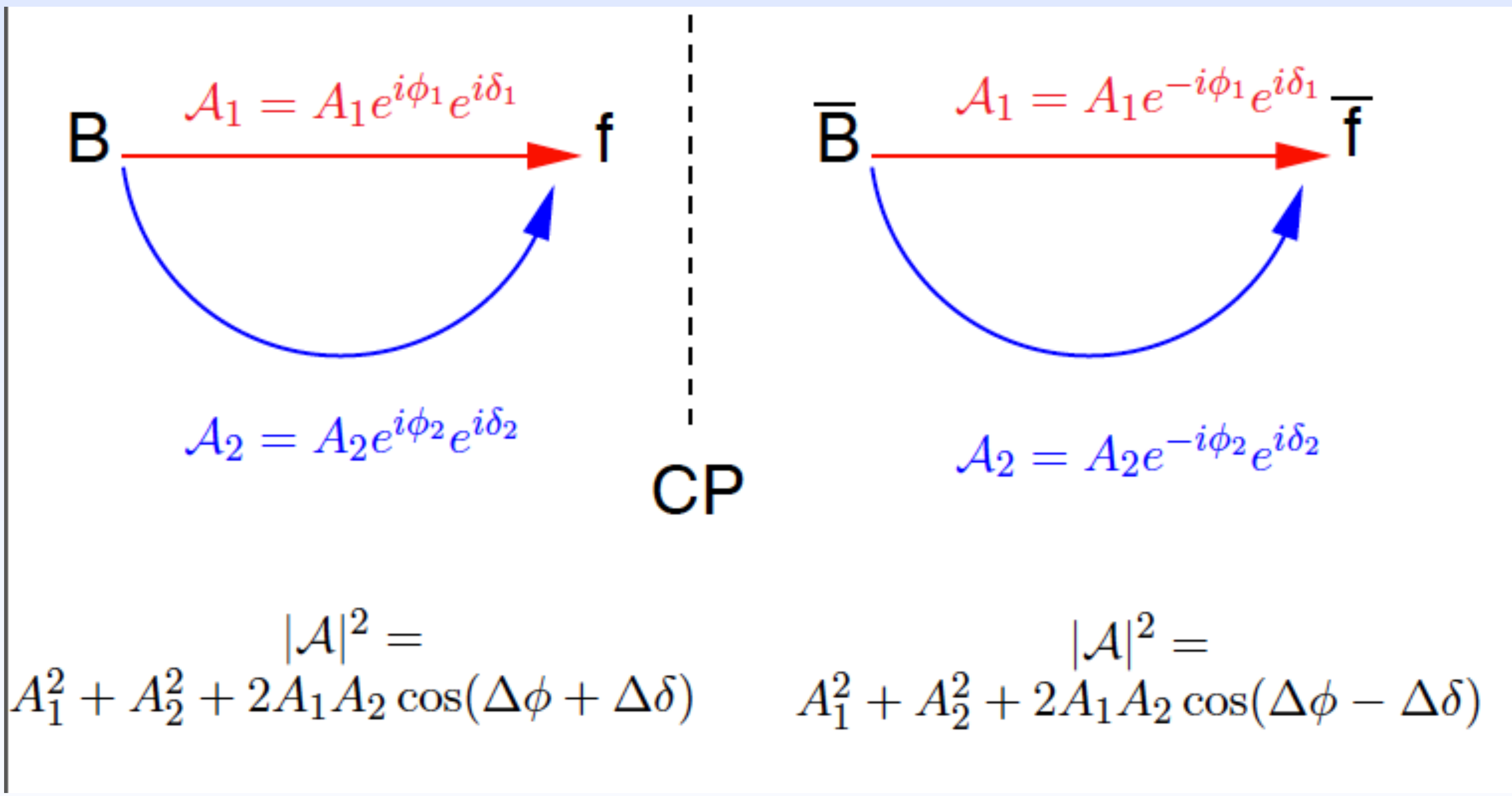
PRL 112 (2014) 041801



Message

- One phase in CKM governing CPV

CPV in decay



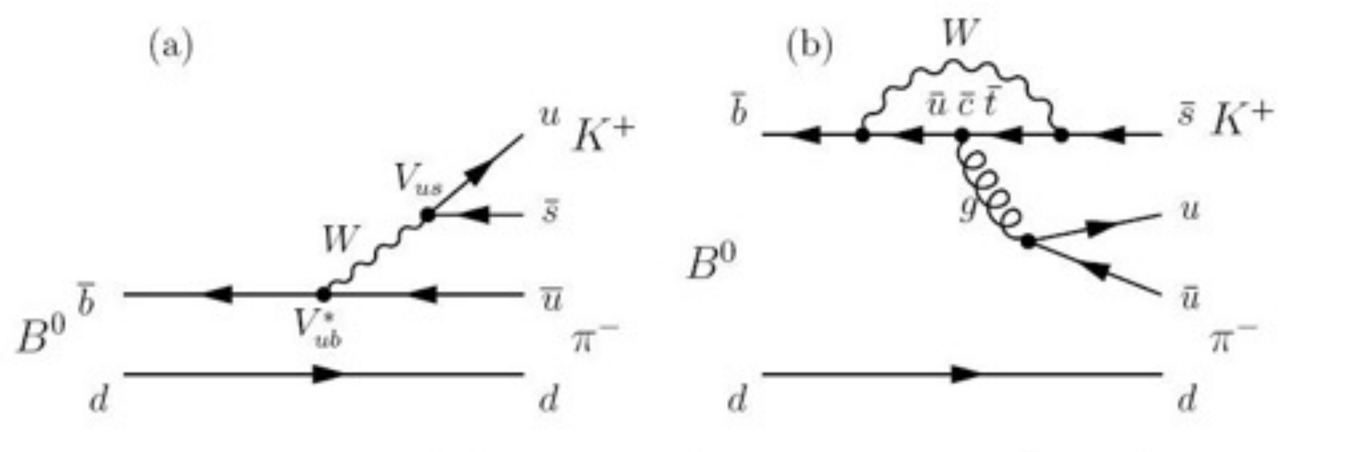
B
$\mathcal{A}_1 = A_1 e^{i\phi_1} e^{i\delta_1}$
f
$\mathcal{A}_2 = A_2 e^{i\phi_2} e^{i\delta_2}$
CP
$\overline{\text{B}}$
$\mathcal{A}_1 = A_1 e^{-i\phi_1} e^{i\delta_1}$
$\overline{\text{f}}$
$\mathcal{A}_2 = A_2 e^{-i\phi_2} e^{i\delta_2}$
$|\mathcal{A}|^2 =$
$A_1^2 + A_2^2 + 2A_1 A_2 \cos(\Delta\phi + \Delta\delta)$
$|\mathcal{A}|^2 =$
$A_1^2 + A_2^2 + 2A_1 A_2 \cos(\Delta\phi - \Delta\delta)$

CPV in decay

Condition for CPV in decay:
$|\bar{A}/A| \neq 1$

- Need $\bar{A}$ and A to consist of (at least) two parts with different weak (φ) and strong (δ) phases

Often realised by "tree" and "penguin" diagrams



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

- Divide amplitudes into leading and sub-leading parts:

$$A(M \to f) = C(1+re^{i(\delta+\phi)})$$
$$A(\bar{M} \to f) = C(1+re^{i(\delta-\phi)})$$

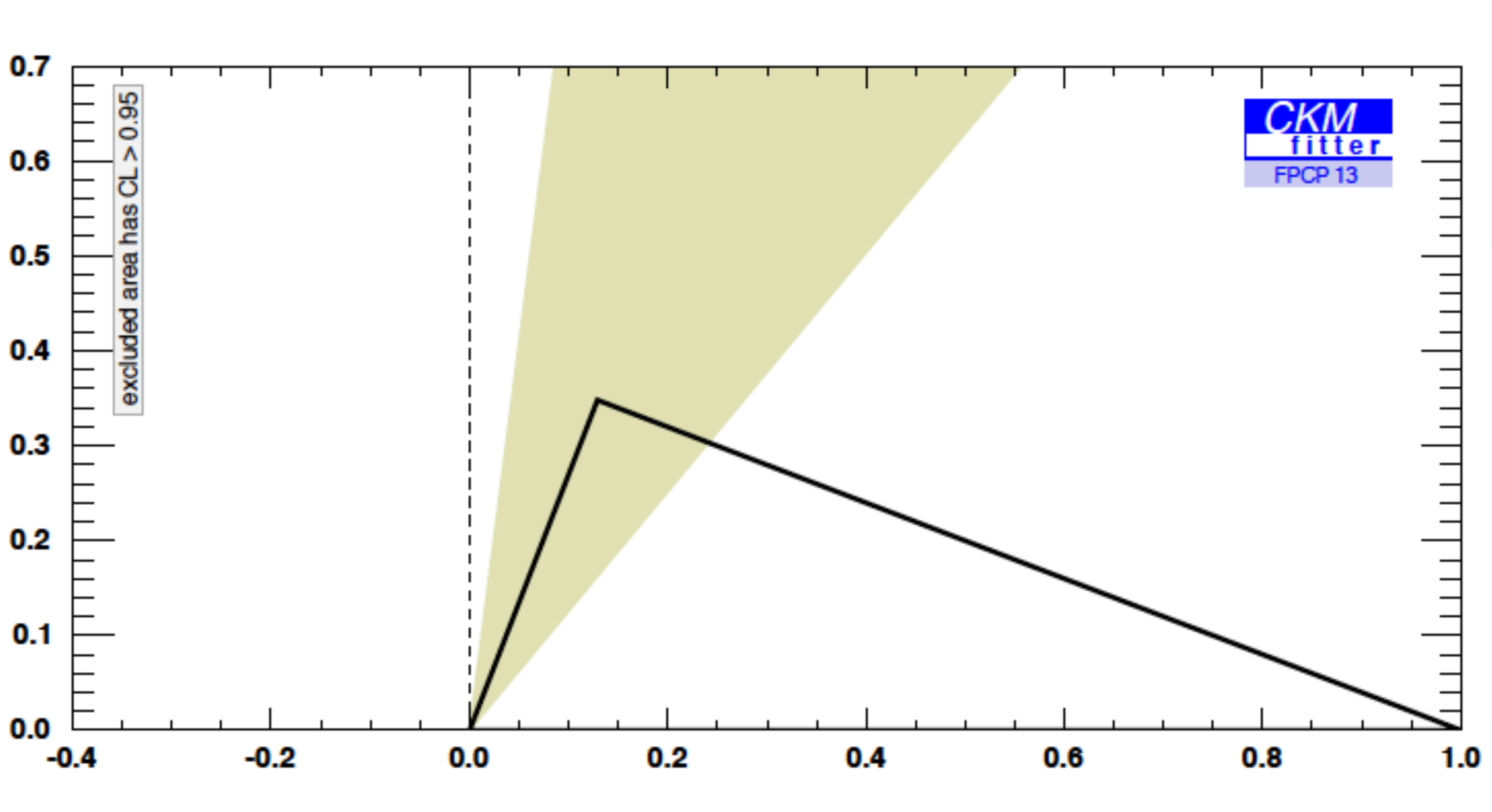
here M can be D or B meson

- r is the ratio of sub-leading over leading amplitude
- CP violation requires difference in strong (δ) and weak phase (ϕ):

$$a_{CP} \equiv [\Gamma(M\to f)-\Gamma(\bar{M}\to f)] / [\Gamma(M\to f)+\Gamma(\bar{M}\to f)]$$
$$= 2\, r \sin(\delta) \sin(\phi)$$

with $\Gamma(M\to f) = {}_0\!\int^\infty \Gamma(M(t)\to f)\, dt \propto |A|^2$

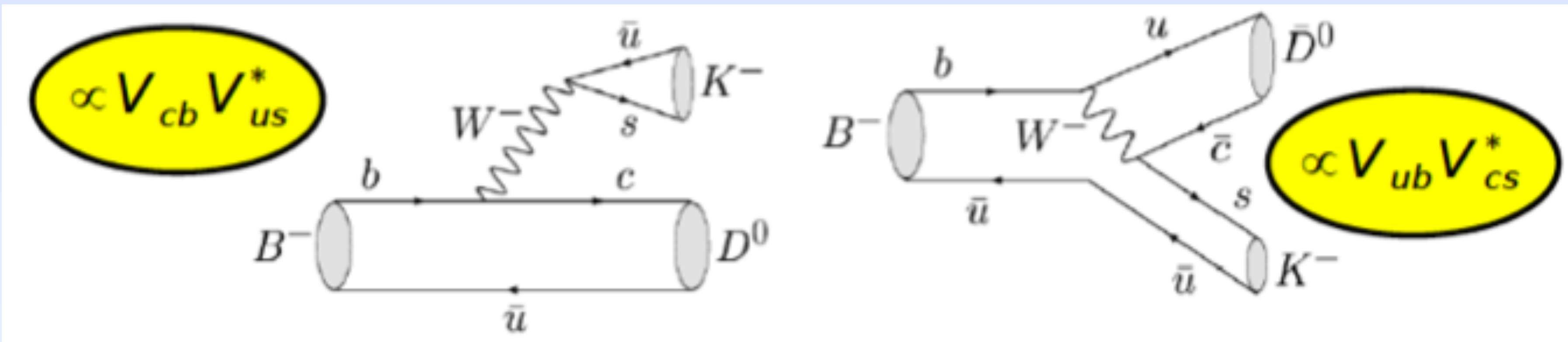
γ from trees



excluded area has CL > 0.95
CKM
fitter
FPCP 13
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

The importance of γ from $B \to DK$

γ has unique role: it is the only CPV parameter that can be measured through tree decays : a benchmark for SM



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

Theoretical side:

– Dominant, single tree diagram, no penguins

Experimental side:

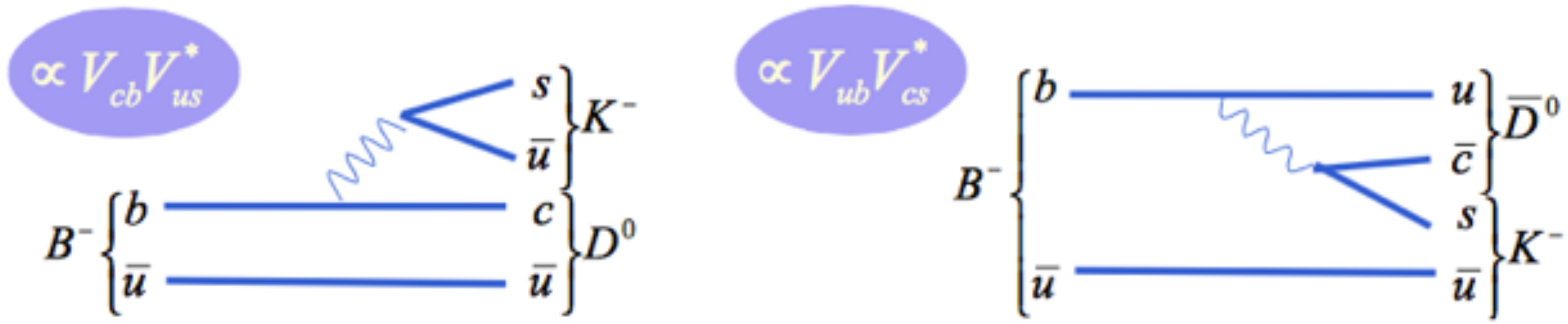
– Many different final states: different observables

All parameters can be determined from data :

γ, δ_b (weak and strong phase differences),

r_b -ratio of amplitudes

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}$$



- final state contains D

- final state contains D-bar

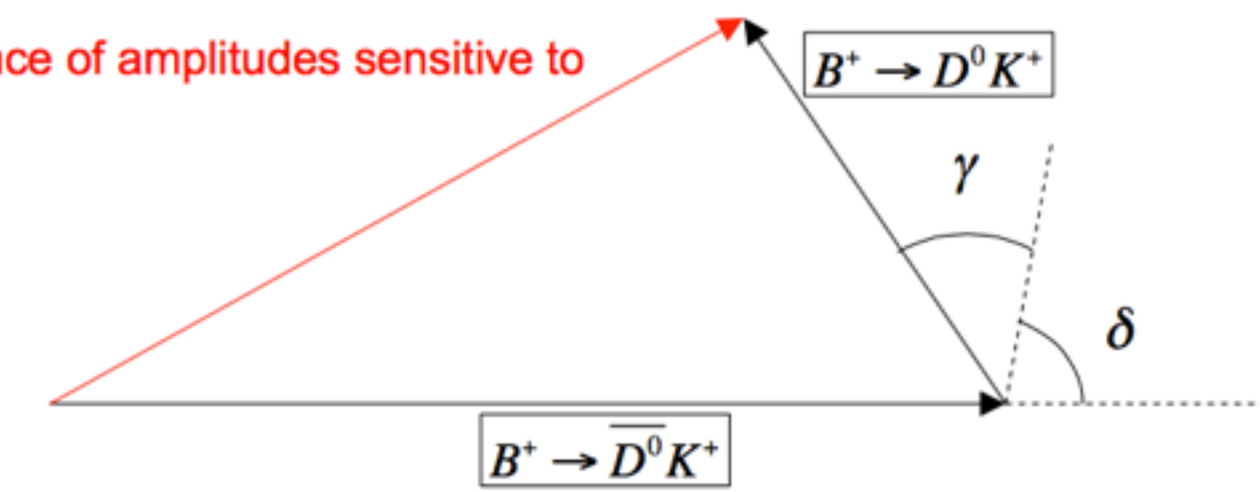
1. Why is this γ ?

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

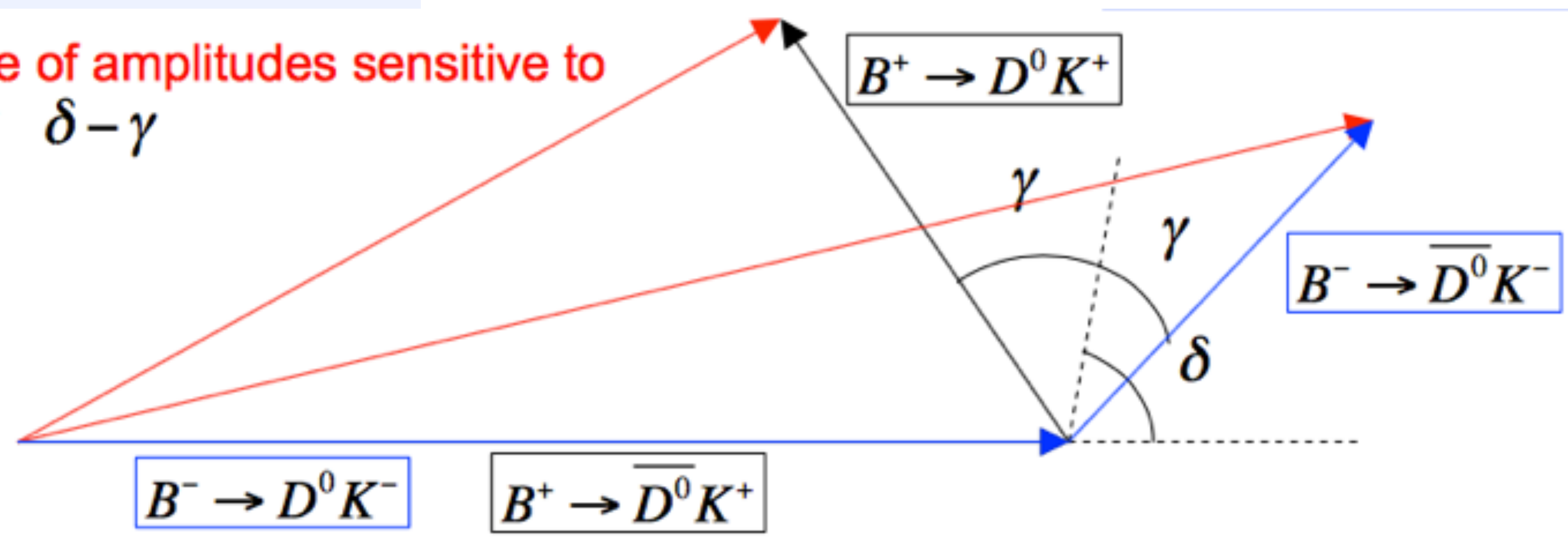
In both cases only complex phase is in V_{ub} element, so this measures γ

2. How to get round strong phase

Interference of amplitudes sensitive to $\gamma+\delta$



Interference of amplitudes sensitive to $\delta+\gamma$ or $\delta-\gamma$



Hence using all four processes can get γ

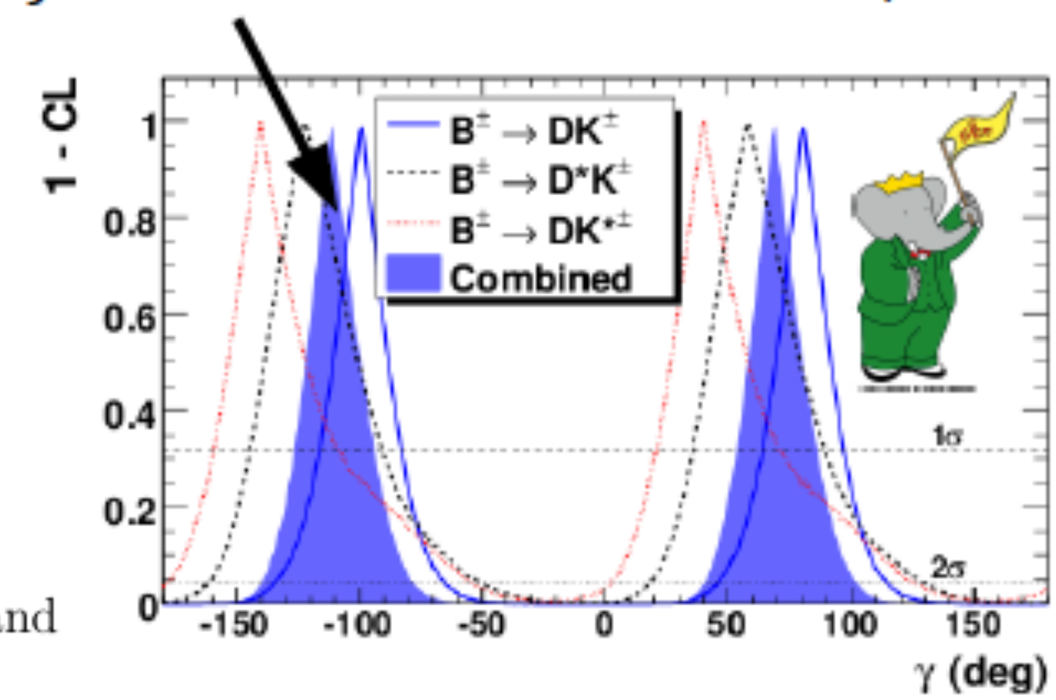
γ from combination of $B^+ \to DK^+$ modes

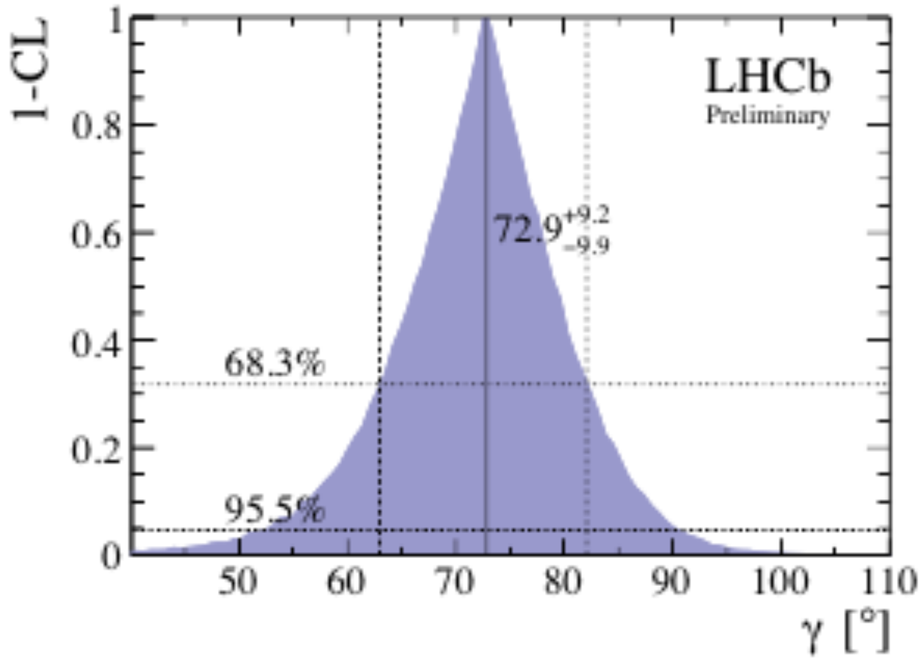
Type of D decay	Method name	D final states studied
CP-eigenstates	GLW	CP-even: K^+K^-, $\pi^+\pi^-$; CP-odd $K^0_S\pi^0$, $K^0_S\eta$
CF and DCS	ADS	$K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^0$, $K^\pm\pi^\mp\pi^+\pi^-$
Self-conjugate	GGSZ	$K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$, $\pi^+\pi^-\pi^0$
SCS	GLS	$K^0_S K^\pm\pi^\mp$

- All direct CP violation effects caused by γ in the Standard Model
- Only those in $B \to DK$ type processes involve only tree-level diagrams
  - enable determination of γ with negligible theoretical uncertainty
- Several different B and D decays can be used
- Combination includes results from GLW/ADS ($D \to hh$) & GGSZ ($D \to K_s hh$)
- Sensitivity: BaBar & Belle each ~16°; latest LHCb ~10 °

WA

$$\gamma = (73.2^{+6.3}_{-7.0})^\circ \,,$$
$$r_B = 0.0970^{+0.0062}_{-0.0063} \text{ and}$$
$$\delta_B = (125.4^{+7.0}_{-7.8})^\circ \,.$$





Direct CPV in charm decays

➡ No CP violation in decay at first order

- Imaginary part of V_{cd} very small

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

The ΔA_{CP}

- Measure time-integrated CP asymmetries in $D \to hh'$ decays

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})}$$

- Decays to CP eigenstates: $f = K^-K^+, \pi^-\pi^+$
- A_{CP} is a sum of direct and indirect CP violation, leading to

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(KK) - A_{CP}(\pi\pi) \\ &\approx \Delta a_{CP}^{dir}\,(1 + y_{CP}\,\overline{\langle t\rangle}/\tau) + a_{CP}^{ind}\,\Delta\langle t\rangle/\tau\end{aligned}$$

- Need to measure asymmetries and time distributions §
- In the difference detection and production asymmetries chancel to first order
- Expected $a_{CP}^{dir} < 10^{-3}$ in SM and $a_{CP}^{dir} < 10^{-2}$ with NP

§MG et al., JPhysG 39 (2012) 045005

What to expect?

Expect indirect CP violation to cancel in difference as caused by common mixing process (* but small contribution can be present due to different decay time acceptance)

Direct CP violation expected to differ for different final states

Individual asymmetries are expected to have opposite sign due to CKM structure

$$A(D^0 \to \pi^+\pi^-, K^+K^-) = \mp\tfrac{1}{2}(V_{cs}V_{us}^* - V_{cd}V_{ud}^*)\,(T \pm \delta S) - V_{cb}V_{ub}^*\,(P \mp \tfrac{1}{2}\delta P)\,,$$

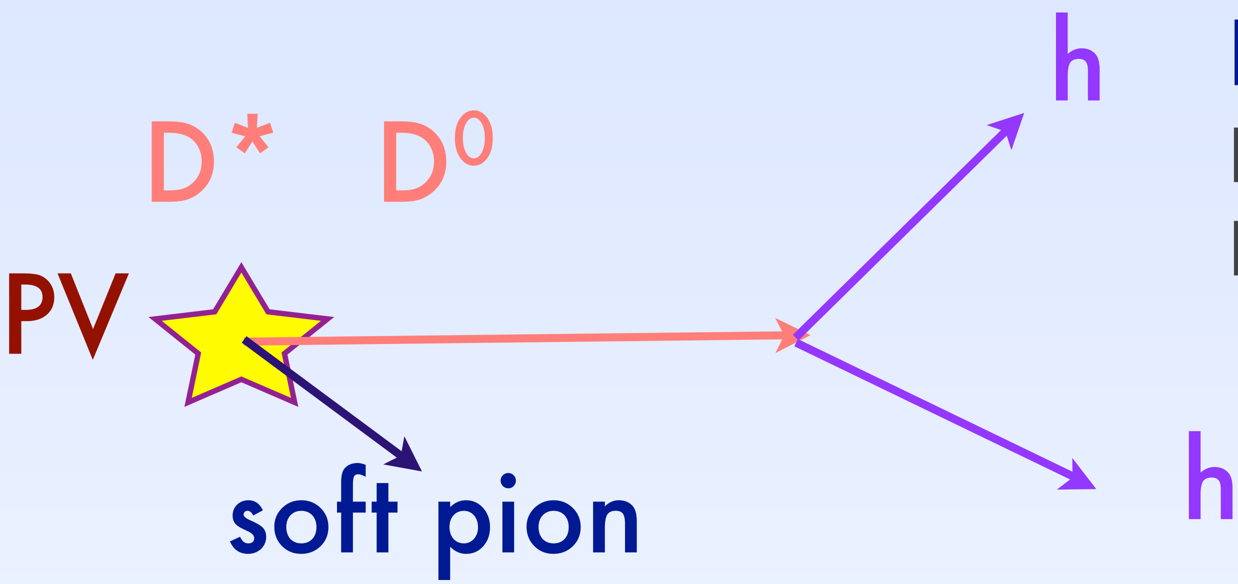
Expect non-zero ΔA_{CP} result in presence of direct CP violation

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$

PRL 108 (2012) 111602

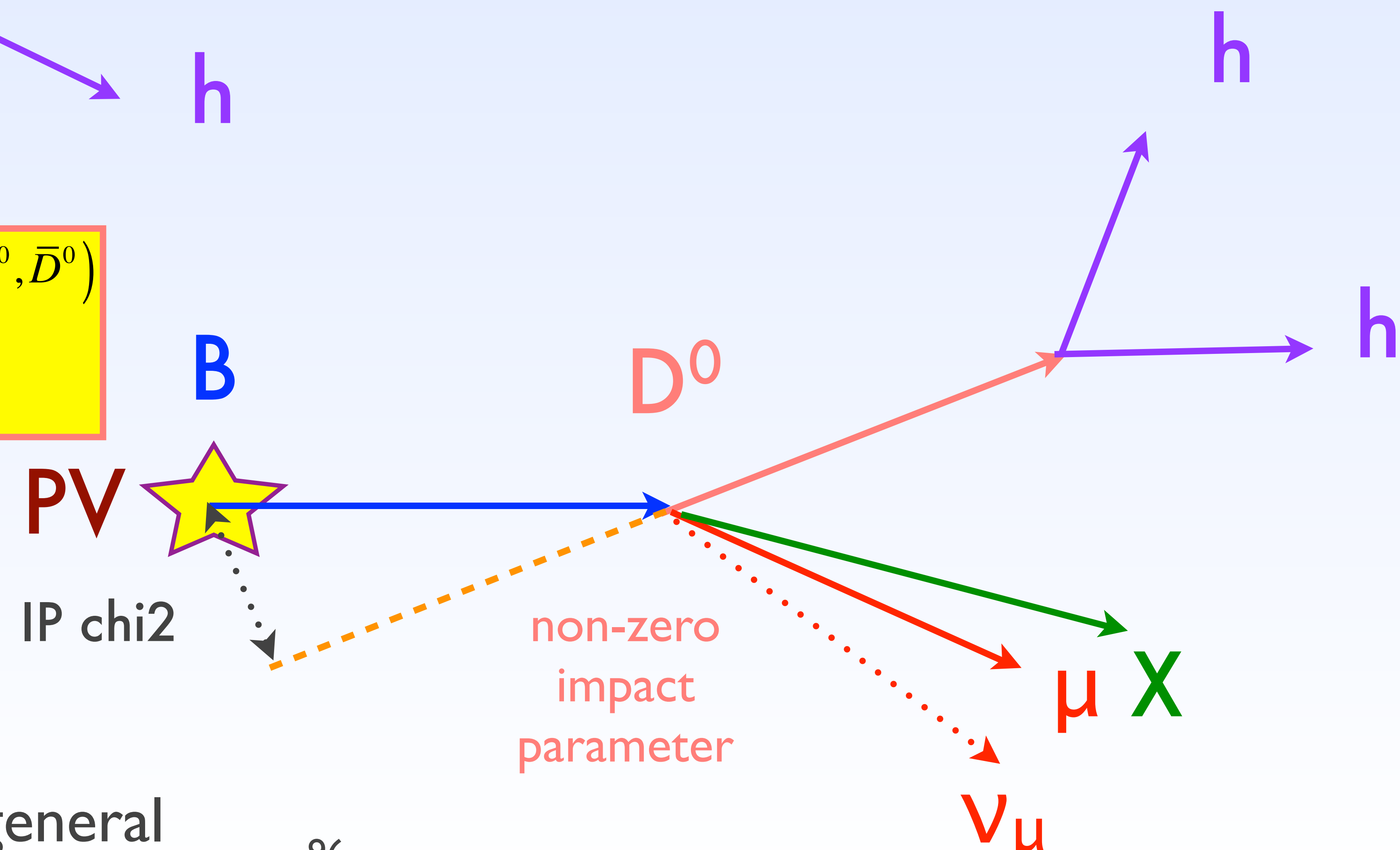
How to tag the D^0 flavour: prompt and secondary charm

- Huge amount of prompt and secondary charm decays collected and reconstructed at LHCb
- Sensitivity to measure small CP violating effects



Prompt charm:
D points to primary vertex
Daughters of D don't in general

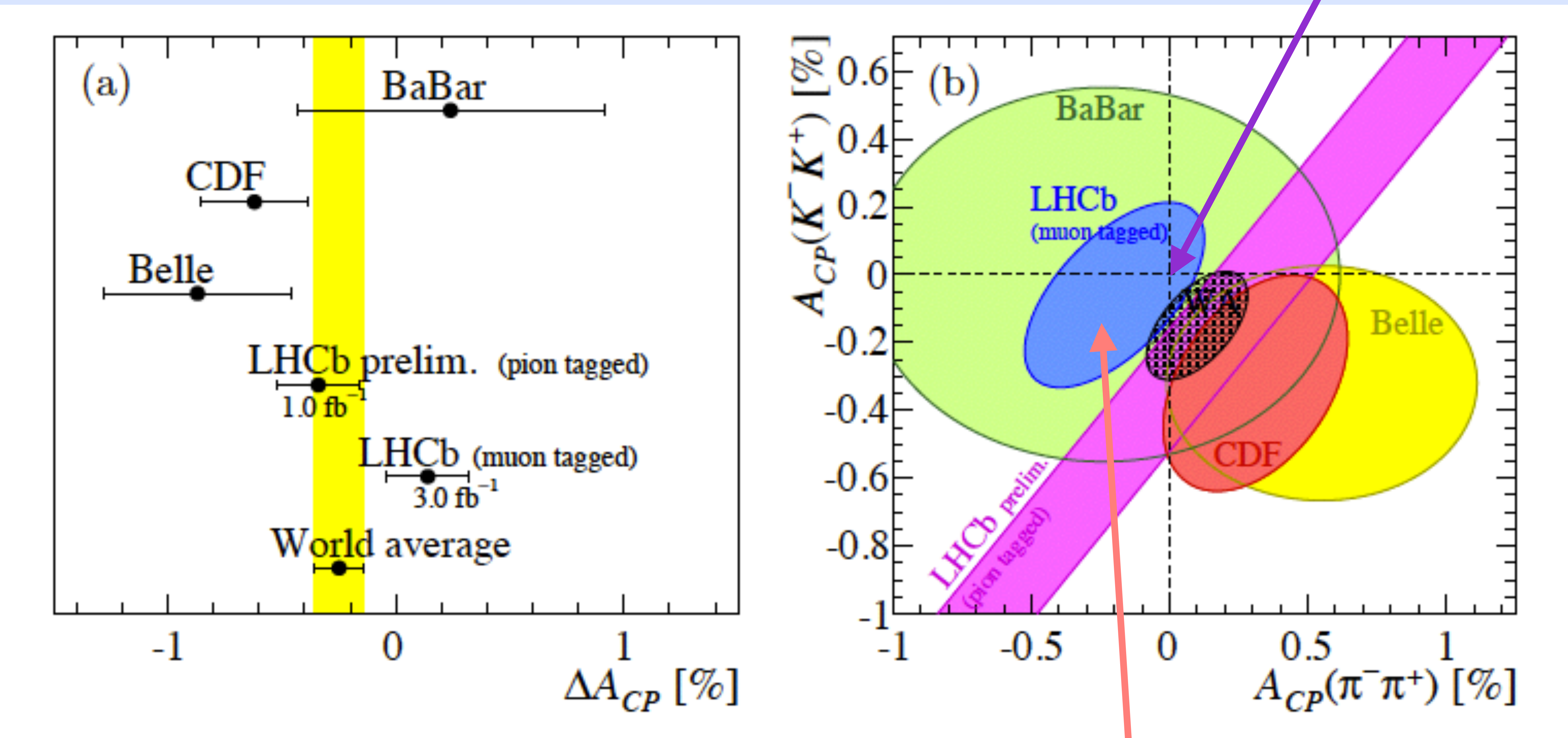
The flavour of the initial state $\left(D^0, \bar{D}^0\right)$ is tagged by the charge of the **soft pion** or the **muon**



Secondary charm:
D doesn't point to PV in general

World averages

No CPV point



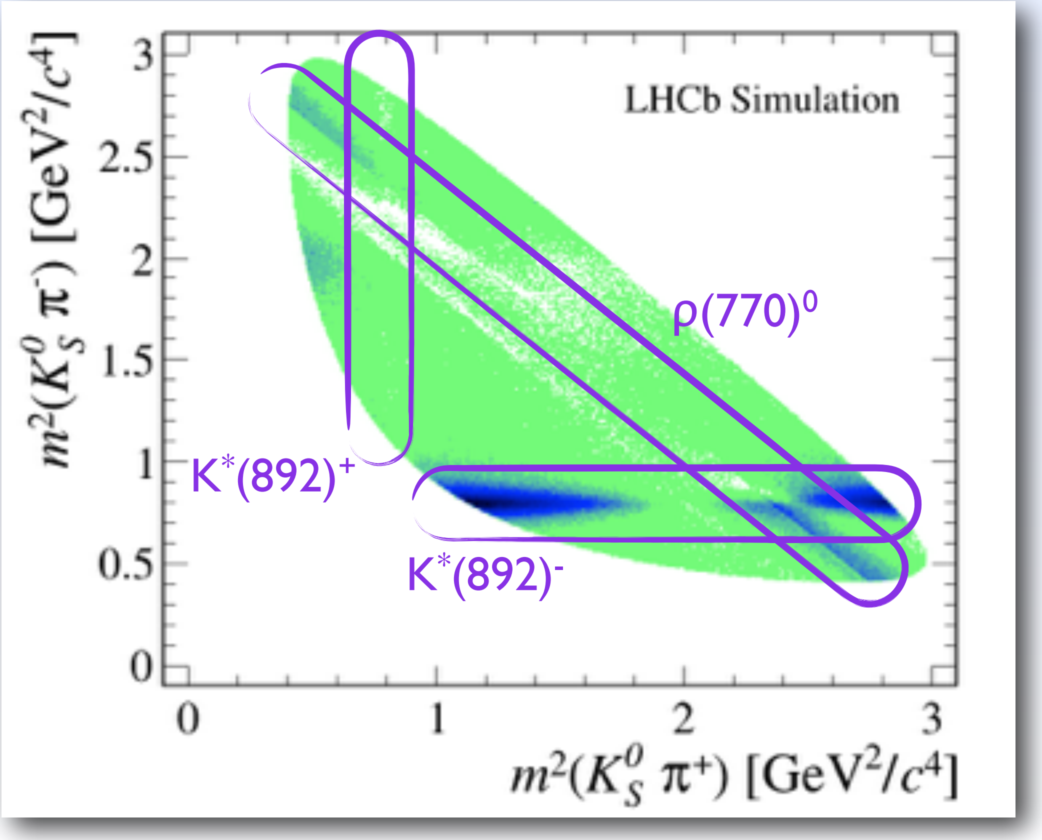
Most precise measurement of these individual asymmetries

Direct CPV in multi body charm decays

On Dalitz plots

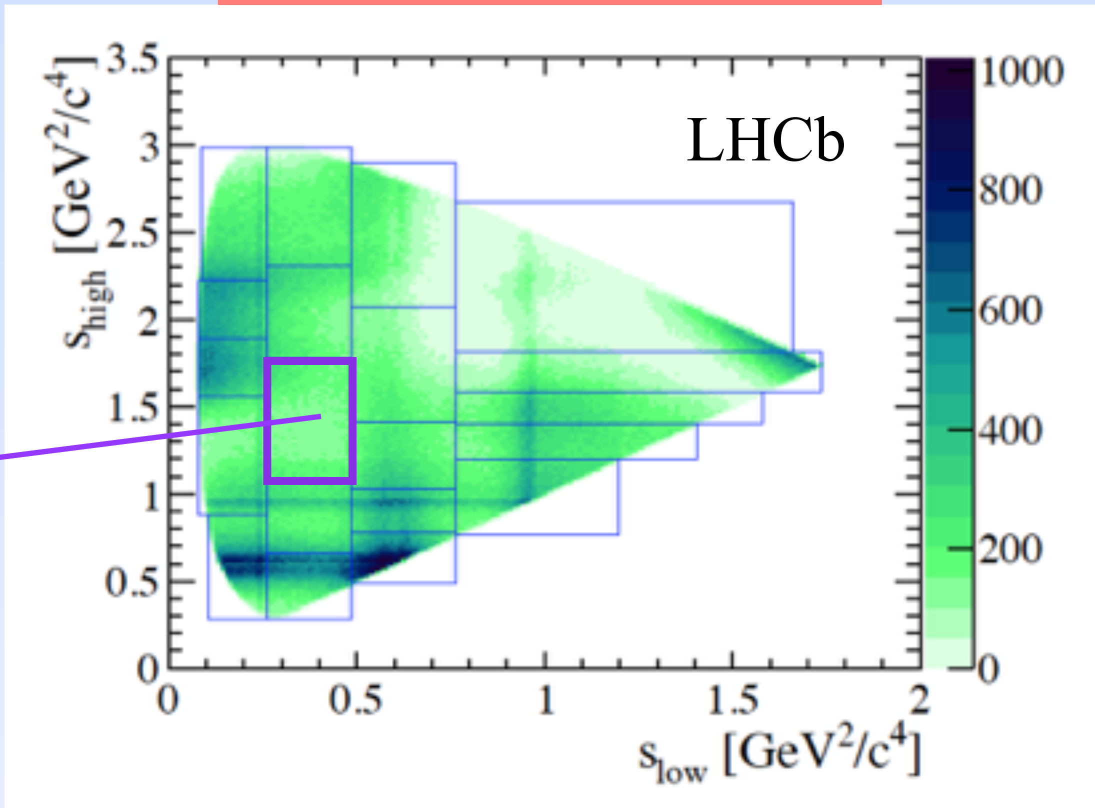
- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases
  - ➡ Superb playground for CP violation
- Look for local asymmetries
  - ➡ Model-dependent:
    Fit all contributions to phase-space and look for differences in fit parameters
  - ➡ Model-independent:
    Look for asymmetries in regions of phase space by "counting"
  - ➡ Binned, unbinned
  - ➡ Everything on Dalitz analysis in the next lecture of Jonas

- larger than the phase space integrated ones
- may change sign across the Dalitz plot
- additional information about the dynamics



Courtesy of S. Reichert

PLB 728 (2014) 585-595



Binned method

asymmetry significance

$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

$$\alpha = \frac{N_{\text{tot}}(D^+)}{N_{\text{tot}}(D^-)}$$

removes sensitivity to global asymmetries

$$\chi^2 = \sum (\mathcal{S}^i_{CP})^2$$

p-values for no-CPV hypothesis > 50% for different binnings

No CPV

With 2011 data sensitive to 1°-10° differences in phase and 1-10% in magnitude

Message

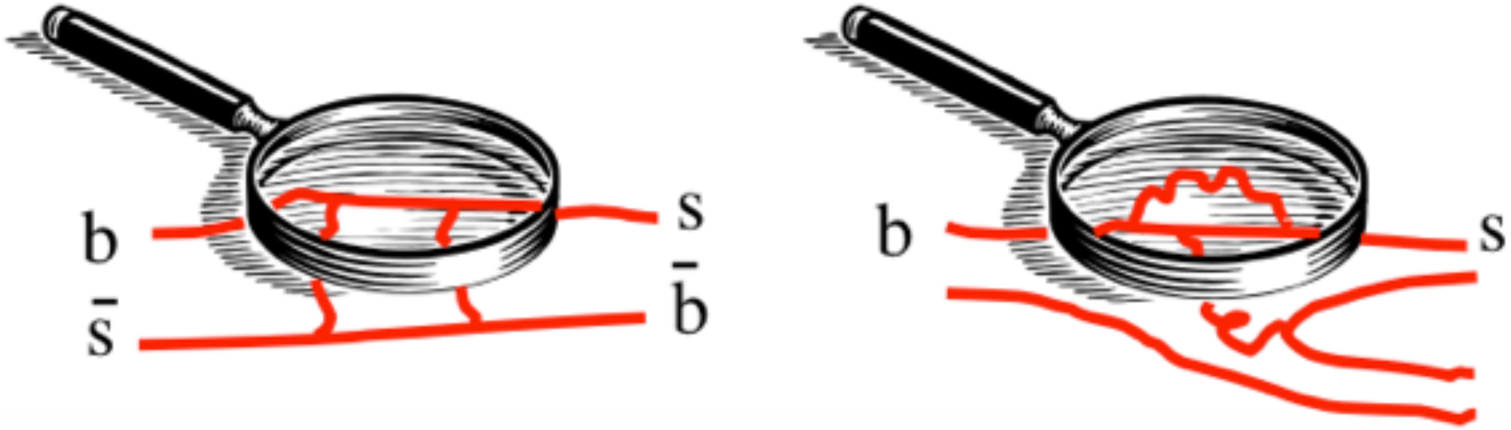
- 2 interfering amplitudes are needed to realise CPV in decay
- This type of CPV is decay dependent
- Large in B, small in C: as predicted by CKM
- Many ways to measure: 2 body, multi body decays; charged and neutral mesons

Rare B decays

Introduction to rare decays

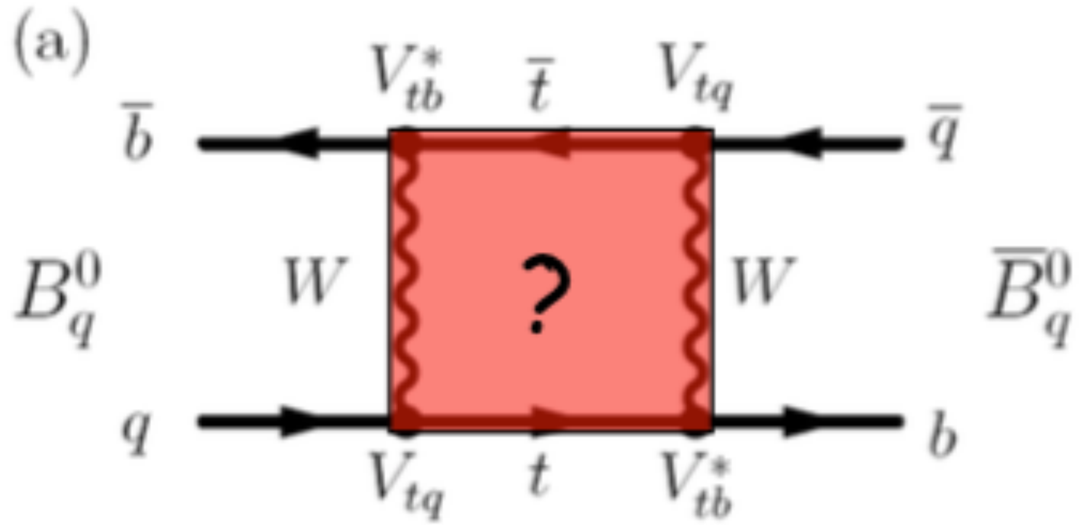
- Flavour changing neutral currents (FCNC) forbidden in SM at tree level.
  - Suppressed at higher-order due to GIM mechanism
- FCNC decays good testing ground for SM.
  - Corresponding decays are always rare (B-mesons < 10^{-5})
- New particles can appear as virtual particles in box and penguin diagrams.
  - Indirect searches have a high sensitivity to effects from new particles.
- Good testing ground: b $\rightarrow$ s transitions.
  - B_s oscillations $\rightarrow$ box diagram
  - $B_s \rightarrow \phi \gamma$
  - $B_{d,s} \rightarrow \mu^+ \mu^-$
  - $B_d \rightarrow K^* \mu^+ \mu^-$

  } $\rightarrow$ Penguin diagrams



Recap

New particles could enter in the B_s box diagram



Could affect both amplitude and phase:

$\Delta m_s = \Delta m_s^{SM} + \Delta m_s^{NP}$

$\beta_s = \beta_s^{SM} + 2\beta_s^{NP}$

LHCb's measurements:

Preliminary

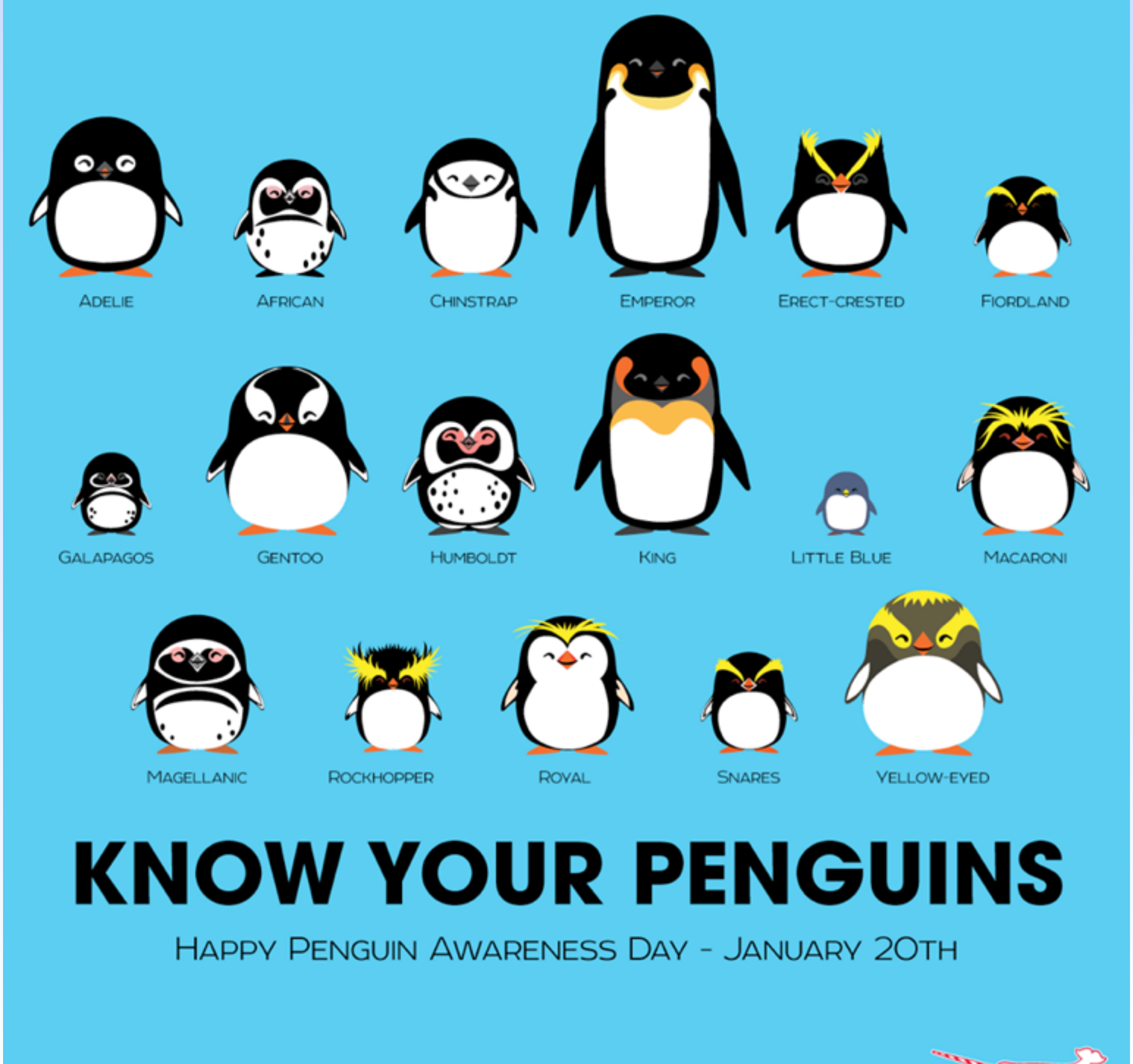
$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ ps^{-1}$

SM: $\Delta m_s = 17.3 \pm 2.6\ ps^{-1}$

ϕ_s [rad] $\quad -0.058 \pm 0.049 \pm 0.006$

SM: $2\beta_s = 0.036 \pm 0.002$

No hints (yet) for new physics in box diagrams, but still some room left.


ADELIE
AFRICAN
CHINSTRAP
EMPEROR
ERECT-CRESTED
FIORDLAND
GALAPAGOS
GENTOO
HUMBOLDT
KING
LITTLE BLUE
MACARONI
MAGELLANIC
ROCKHOPPER
ROYAL
SNARES
YELLOW-EYED
KNOW YOUR PENGUINS
HAPPY PENGUIN AWARENESS DAY - JANUARY 20TH

Construct effective field theory for ΔB=ΔS =1transitions

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^{*}\sum C_i(\mu)O_i(\mu)$$

Ci - Wilson coefficients corresponding to local operators
Oi - with different Lorenz structure

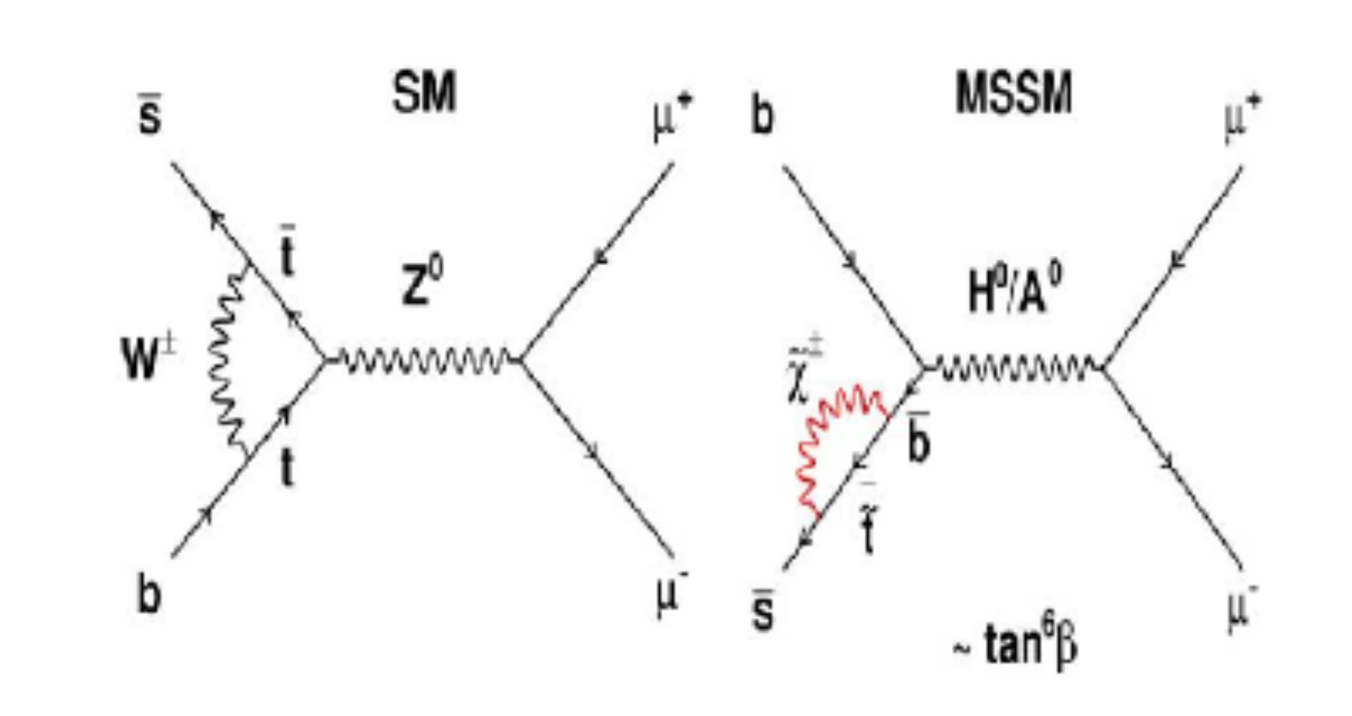
New physics could show up as:

- Modified Wilson coefficients
  → new particles in the penguin loop
- New operators
  → e.g. right-handed currents

Three interesting channels:

	SM operators	@ LHCb
$B_s \to \phi\gamma$	$Q_{7\gamma}$	γ polarisation
$B_d \to K^* \mu^+\mu^-$	$Q_7^{\gamma}, Q_9, Q_{10}$	Angular distributions
$B_s \to \mu^+\mu^-$	Q_S, Q_P	BR

B→μμ



- In SM its rate is very small
  - no tree level FCNC
  - suppression due to the off-diagonal elements of the CKM matrix
  - helicity suppressed

none of them this needs to be in extensions of SM

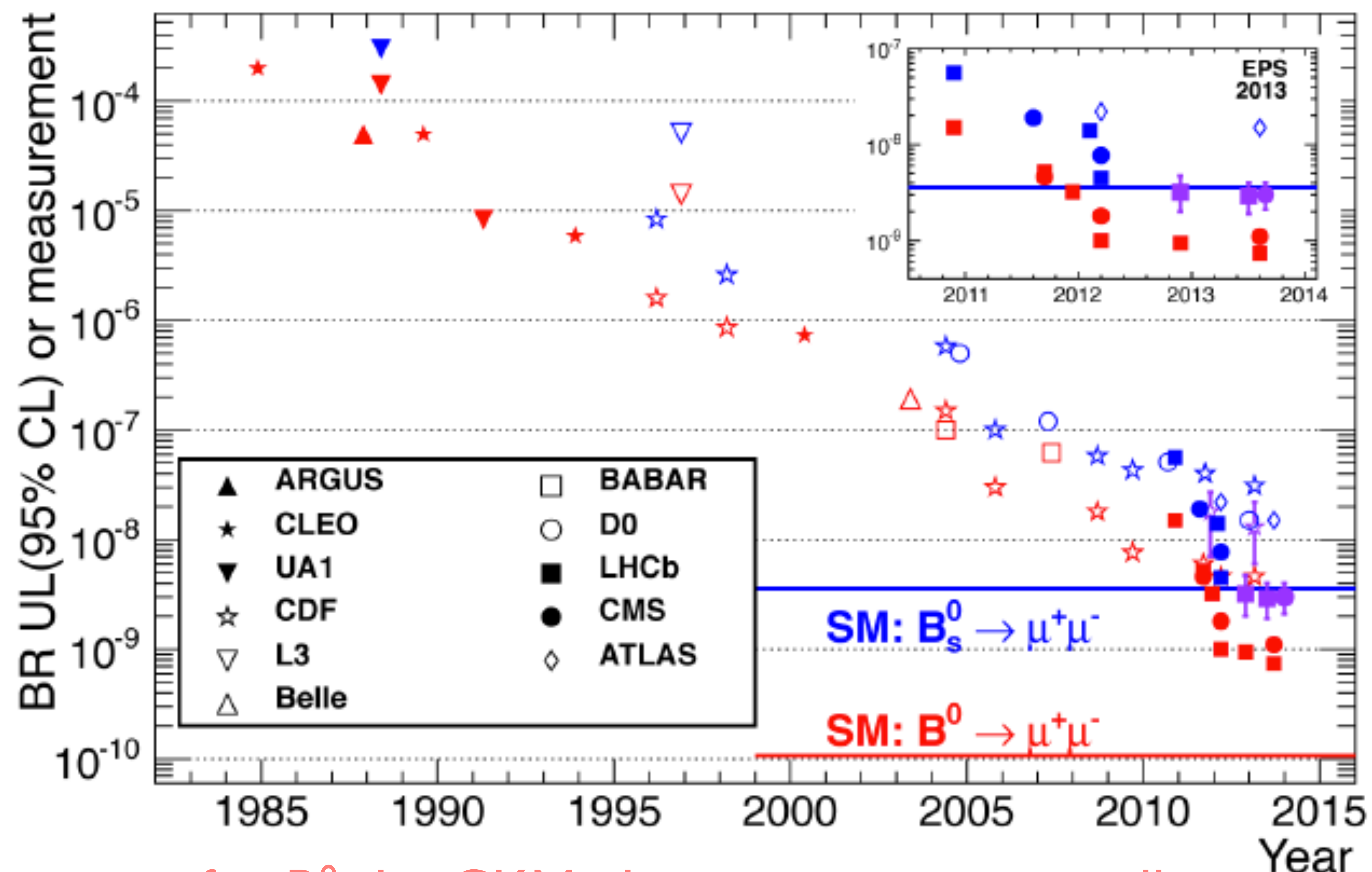
Huge NP enhancement possible (tan β = ratio of Higgs vevs)

$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \quad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$

Clean experimental signature

β - ratio of the Higgs vacuum expectations

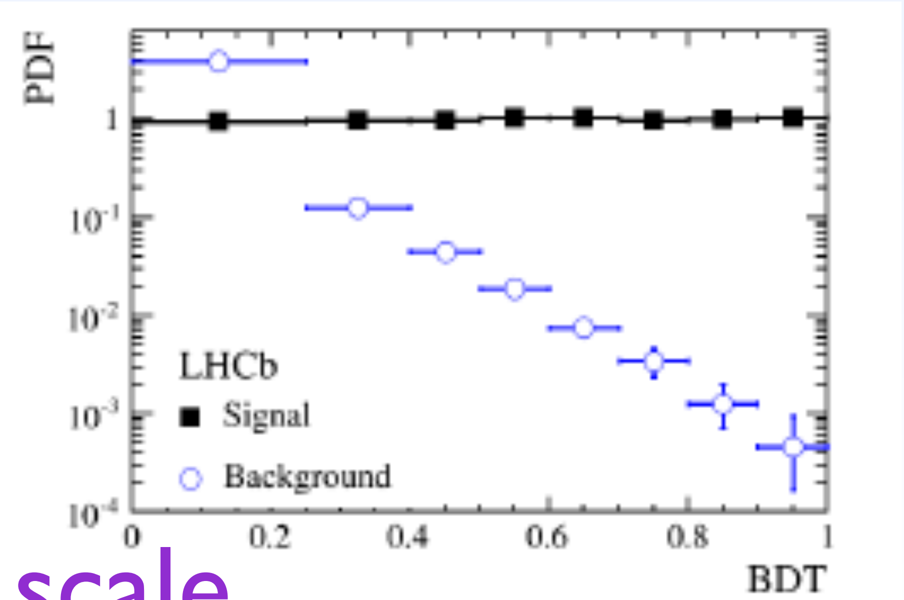
Search over 30 years



for B^0 the CKM elements are even smaller

Keys for the successful analysis

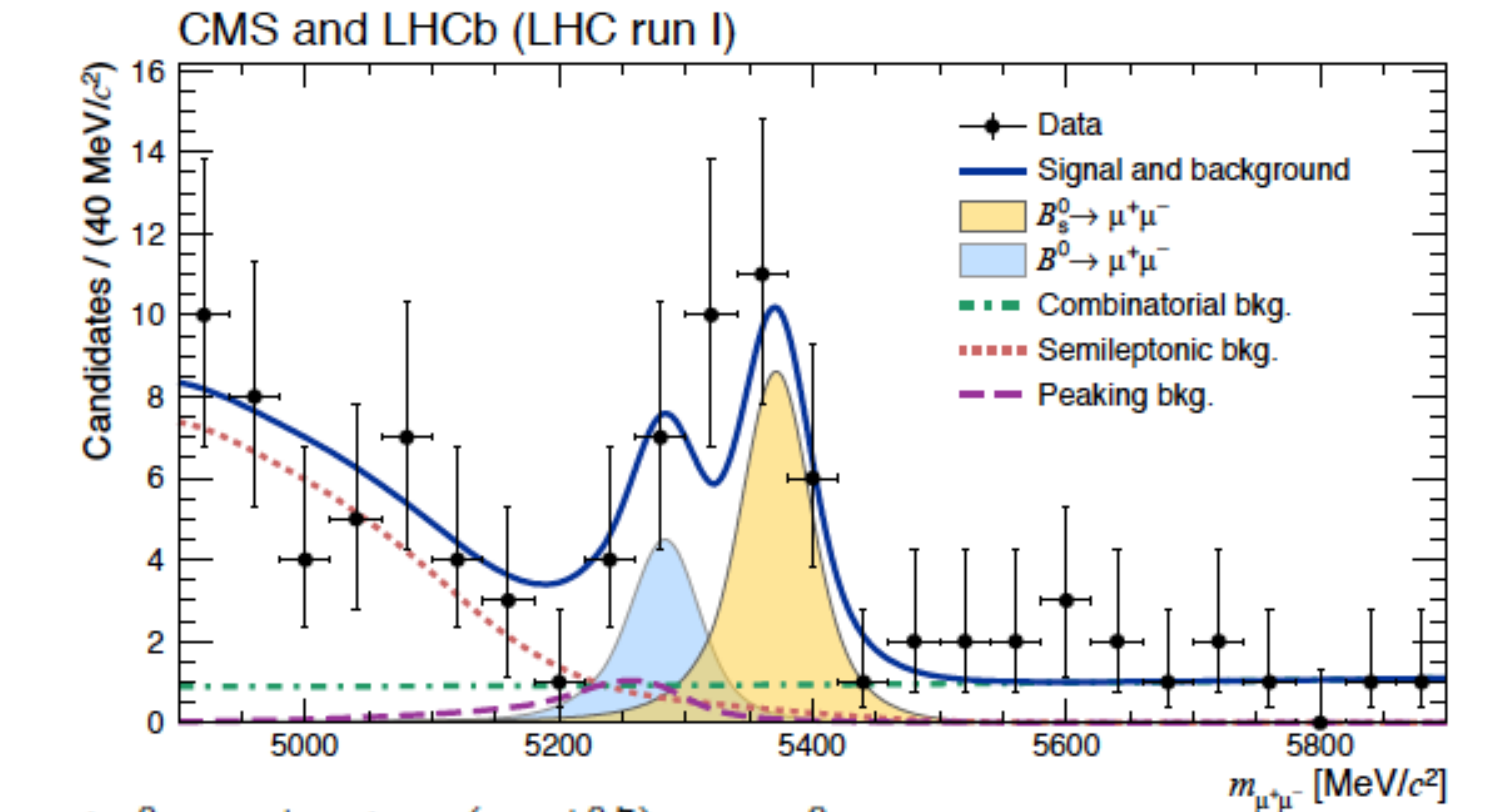
- Large sample of B mesons
- Triggers efficiencies: dimuon signature
- Excellent separation of the PV and the B-vertex
- Mass resolution: separate B^0 and Bs^0
- Powerful separation of muons and pions
- Combination of everything (without the mass) in a multivariate classifier



log scale

2014 results combined CMS + LHCb

3.2 σ for the B^0 peak **6.2 σ for the Bs peak**



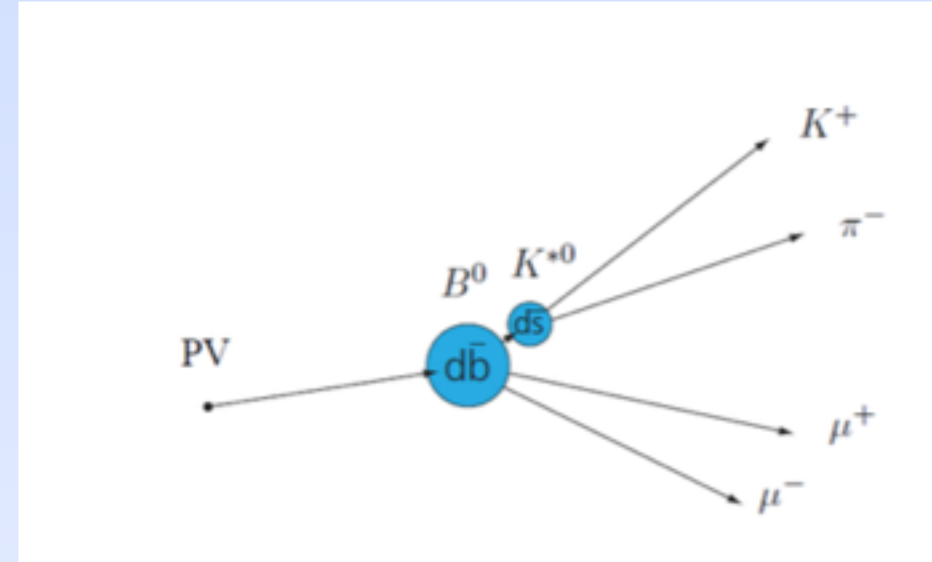
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}\,,$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}\,,$$

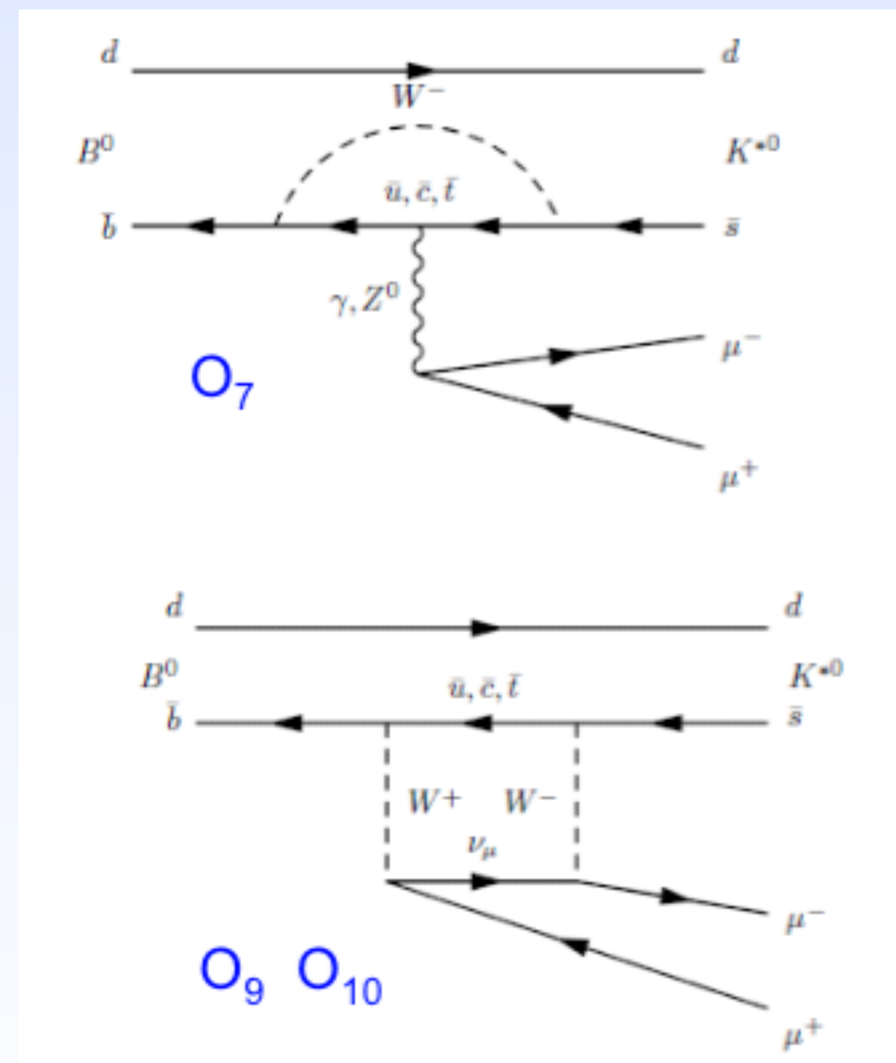
LHCb smaller sample but optimised for B-physics

Very strong constraints on extensions of SM

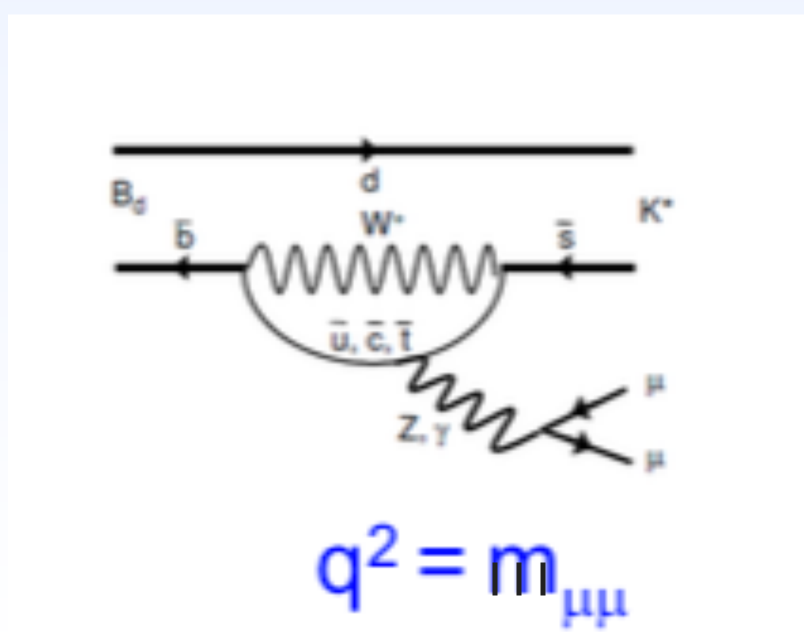
$B_d \to K^*\mu\mu$

- Similar transition to $B_s \to \mu\mu$ but more observables in the final state
- Not so rare: no helicity suppression
- Larger samples: we can study angular distributions: rather sensitive to SM extensions

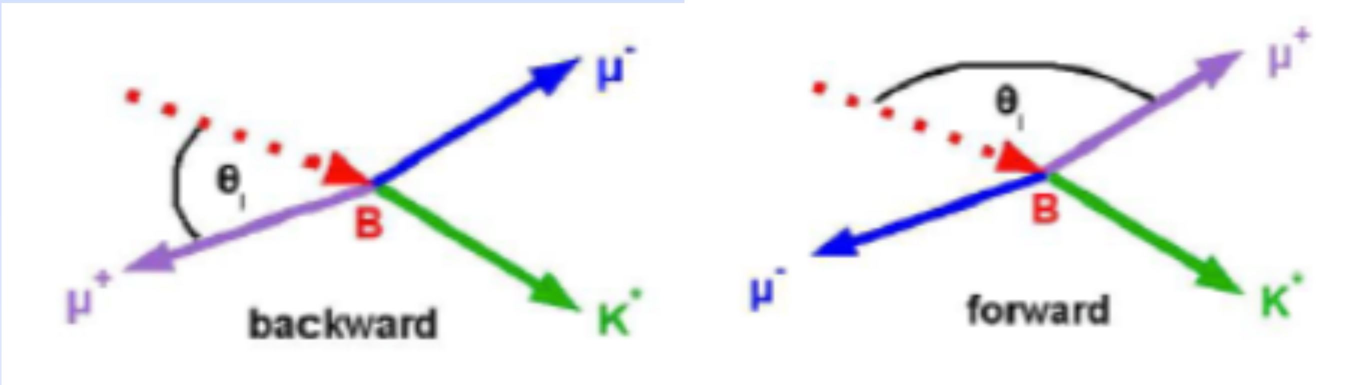




other particles in the loops in the SM extensions

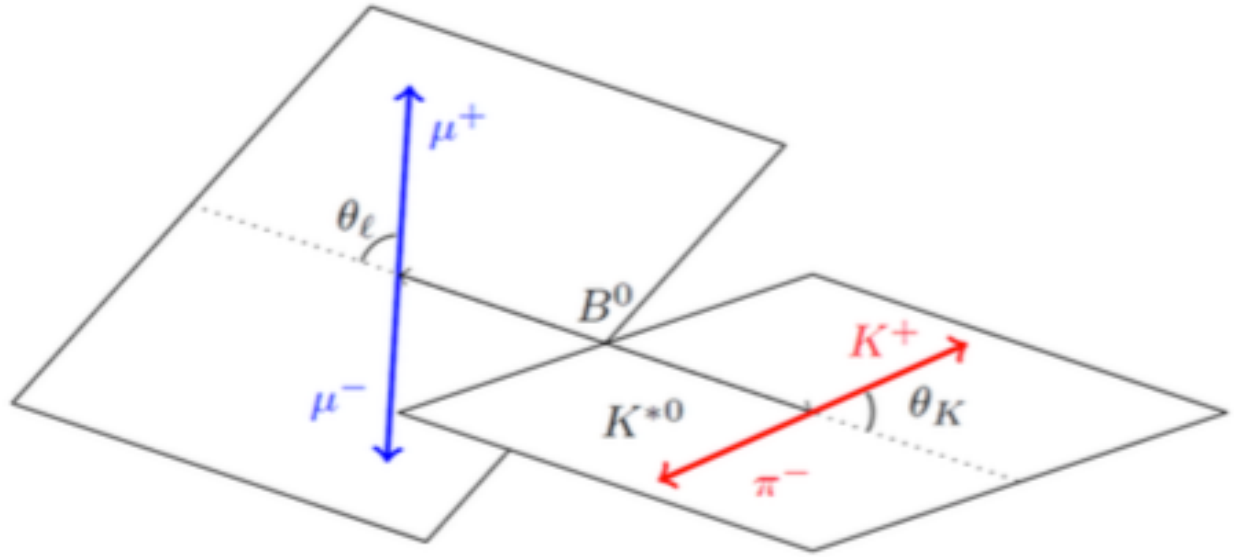


Angular analysis: simple or full



$$A_{FB}(q^2) = \frac{N_F - N_B}{N_F + N_B}$$

$B^0 \rightarrow K^* (K\pi)\, \mu\mu$

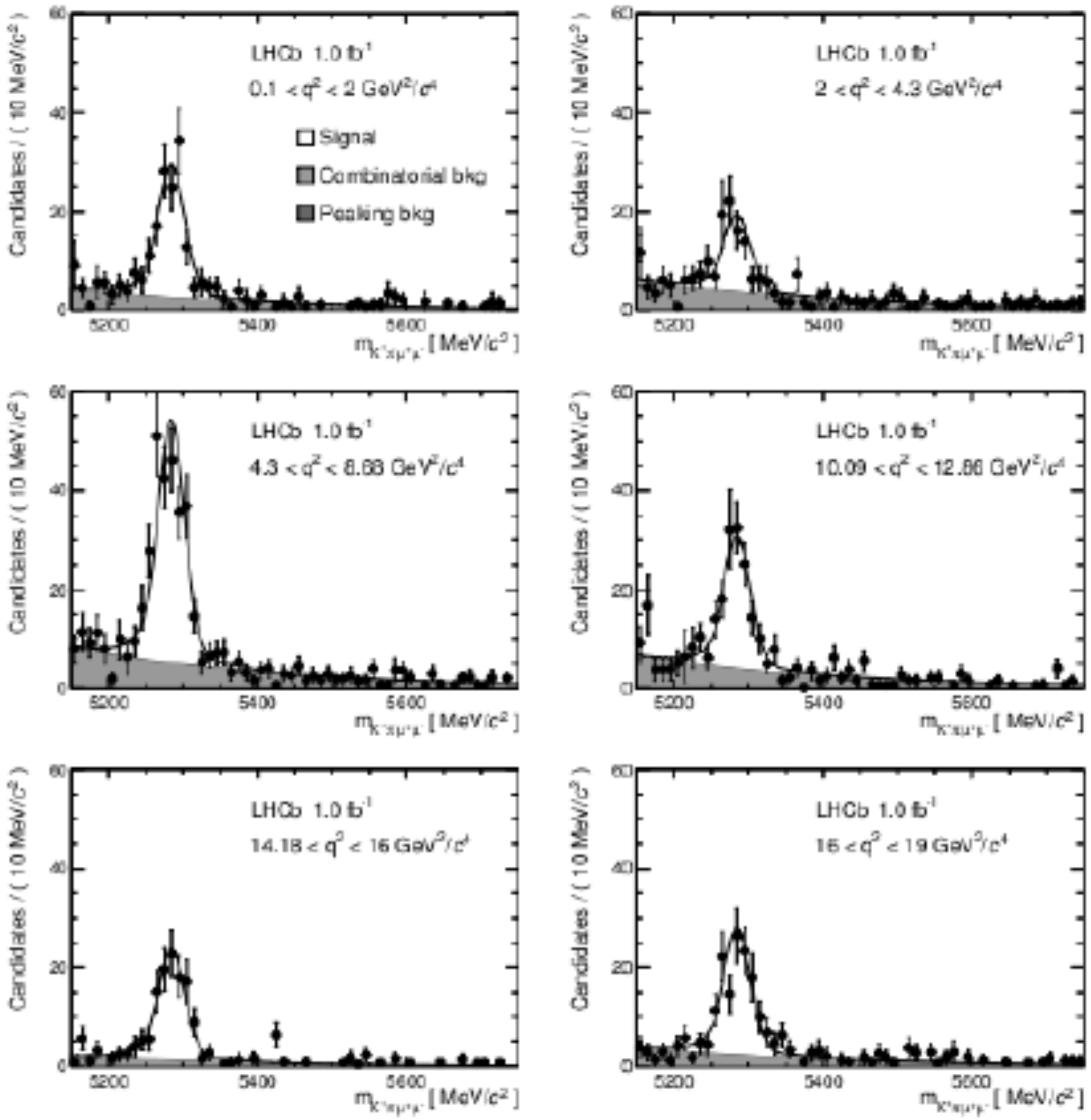


$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

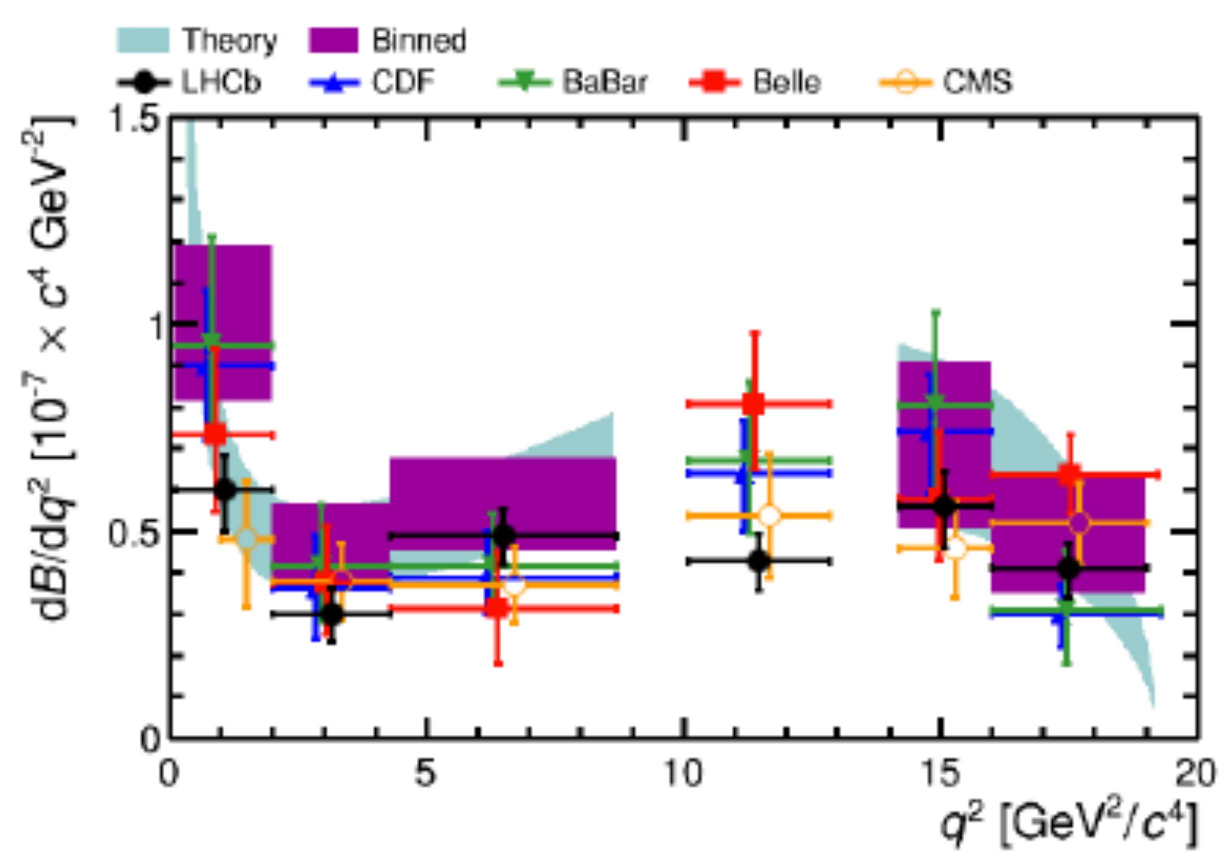
$$S_6^s = \frac{3}{4}A_{FB}$$

Differential branching fractions in bins of q^2

LHCb invariant mass in bins of q^2



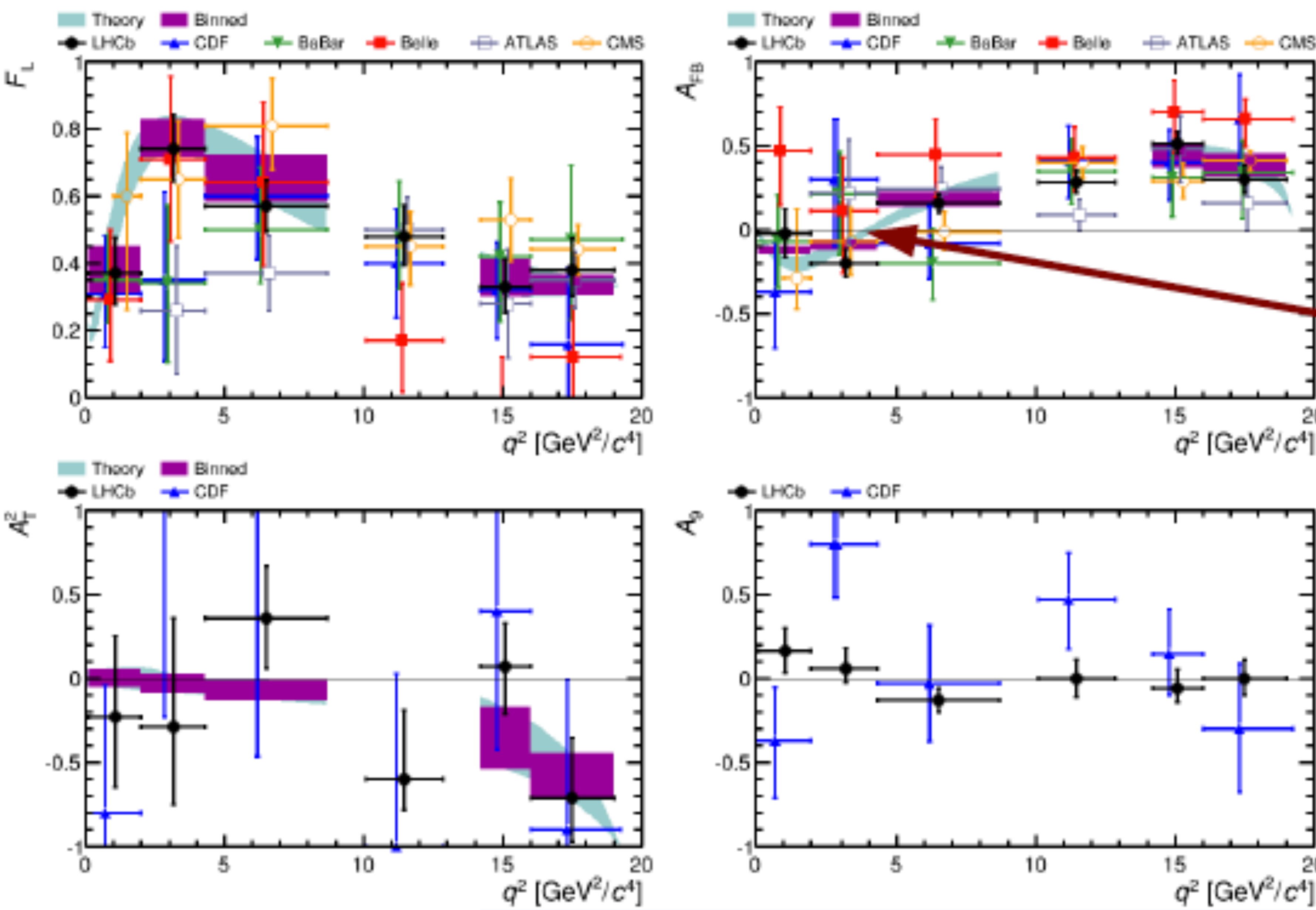
LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807,
BaBar PRD 86 (2012) 032012,
Belle PRL 103 (2009) 171801,
ATLAS-CONF-2013-038 &
CMS PLB 727 (2013) 77



Theory consistent
with measurements

If deviations from SM are small, the angular analysis is more sensitive

LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807, BaBar PRD 86 (2012) 032012,
Belle PRL 103 (2009) 171801, ATLAS-CONF-2013-038 & CMS PLB 727 (2013) 77



Theory can predict very precisely the zero crossing point

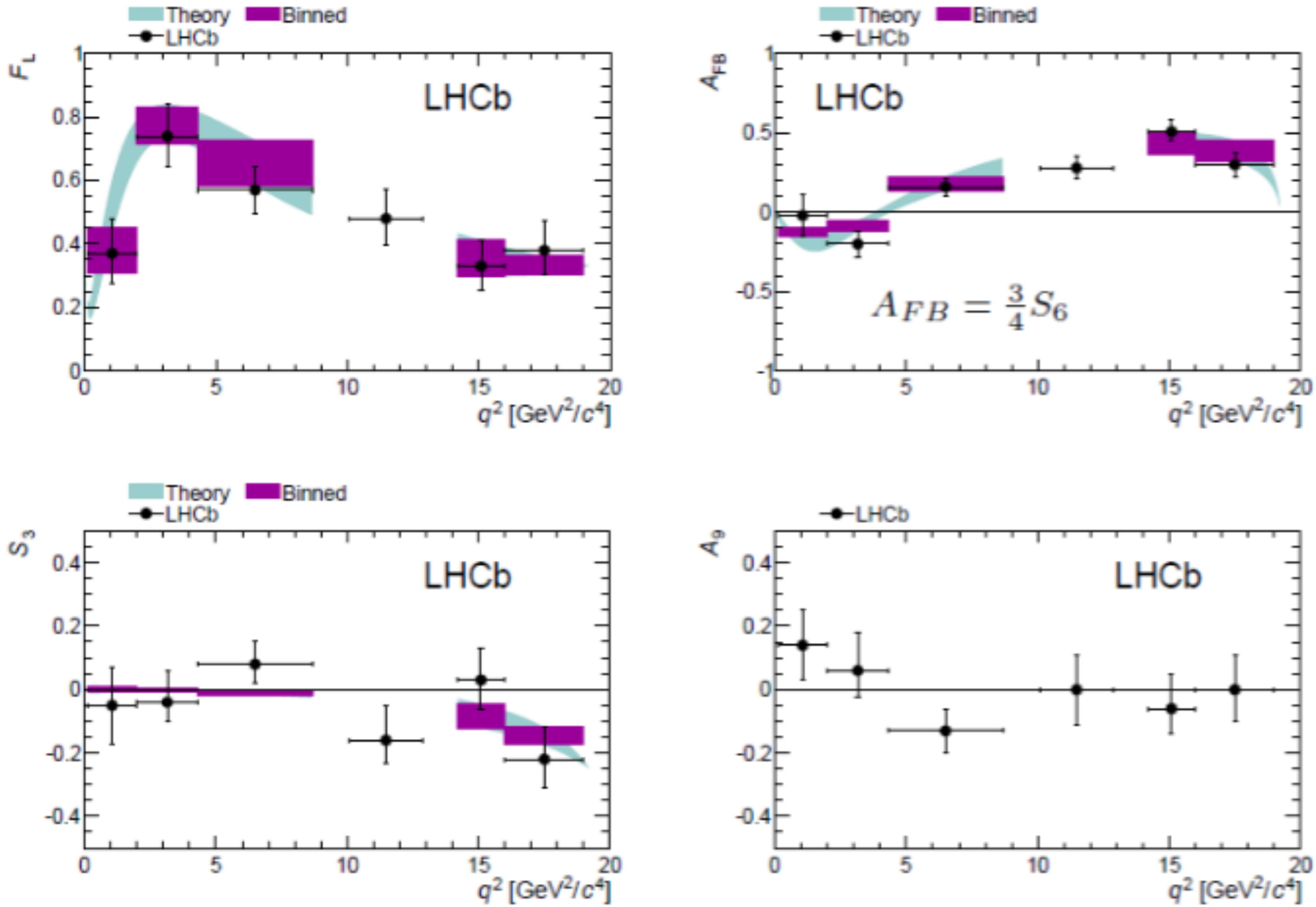
First measurement of zero-crossing point of A_{FB}

$q^2_0 = (4.9 \pm 0.9)$ GeV^2/c^4

Consistent with SM expectation

First measurement made with LHCb data

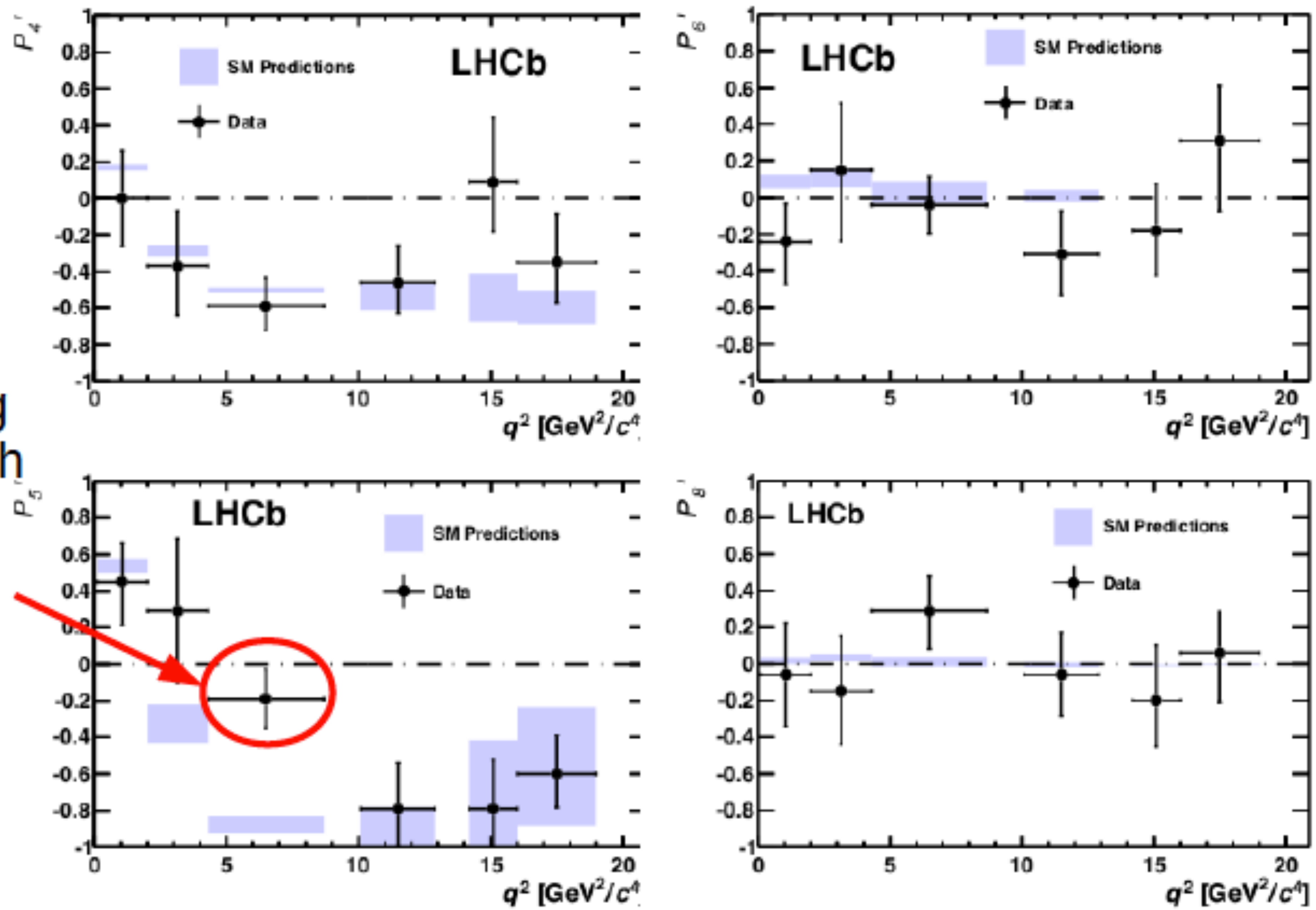
A bit cleaner



More angular observables

LHCb PRL 111 (2013) 191801

Interesting tension with the SM prediction



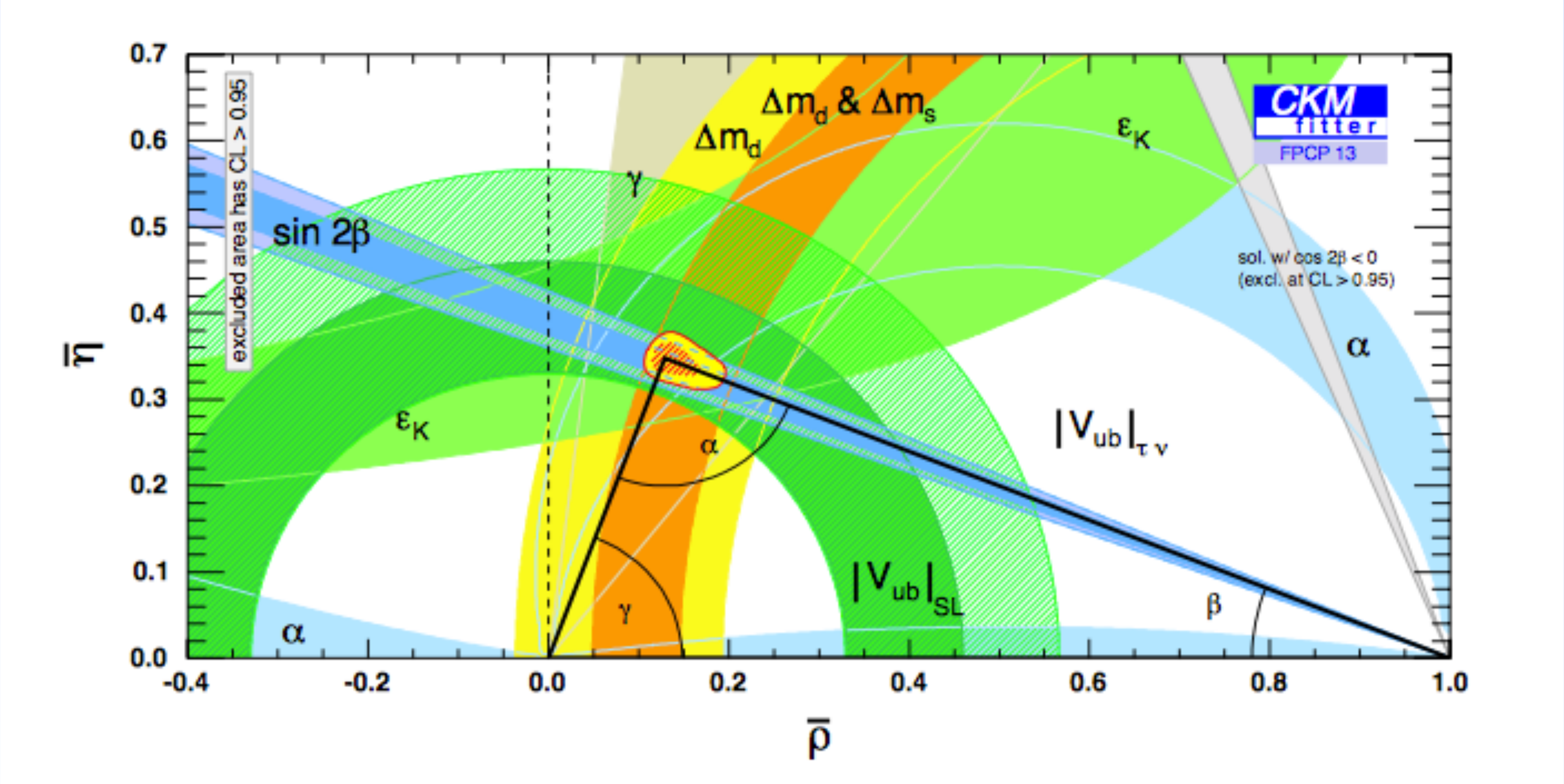
Update with full LHCb is eagerly awaited

Message

- FCNC processes provide sensitive tests of SM
- Many observables, many ways to look for new physics

Conclusions

- Things seem consistent but
- Continue to improve precision!



BACK UP

CPV in charmless decays

Direct CPV in B→Kπ

- Direct CPV in B→Kπ

too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naive expectation

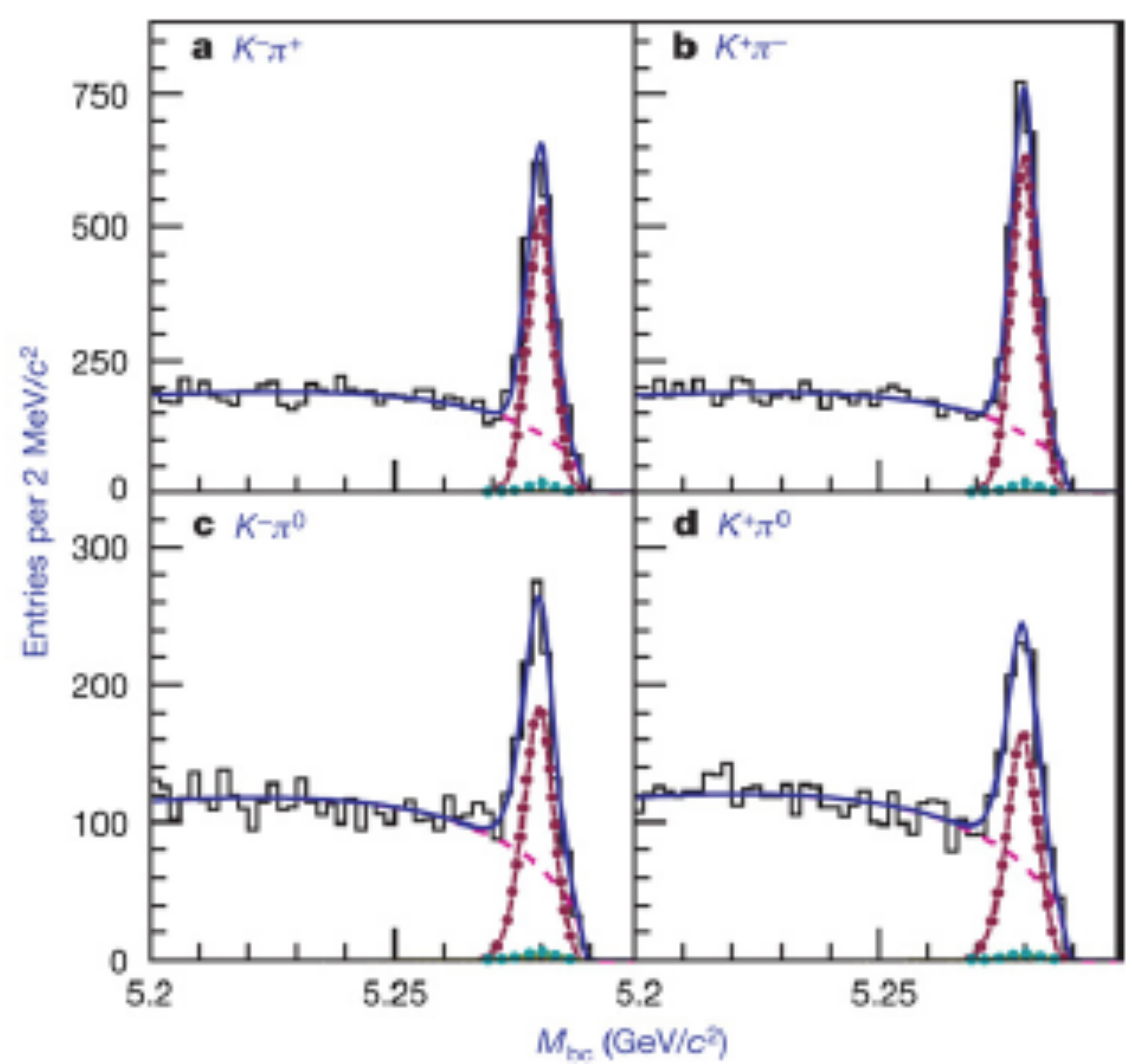
$A_{CP}(K^-\pi^+) = -0.082 \pm 0.006$

$A_{CP}(K^-\pi^0) = +0.040 \pm 0.021$

referred to as Kπ puzzle

Could be a sign of new physics …
… but first need to rule out possibility of larger than expected QCD corrections

Belle Nature 452 (2008) 332



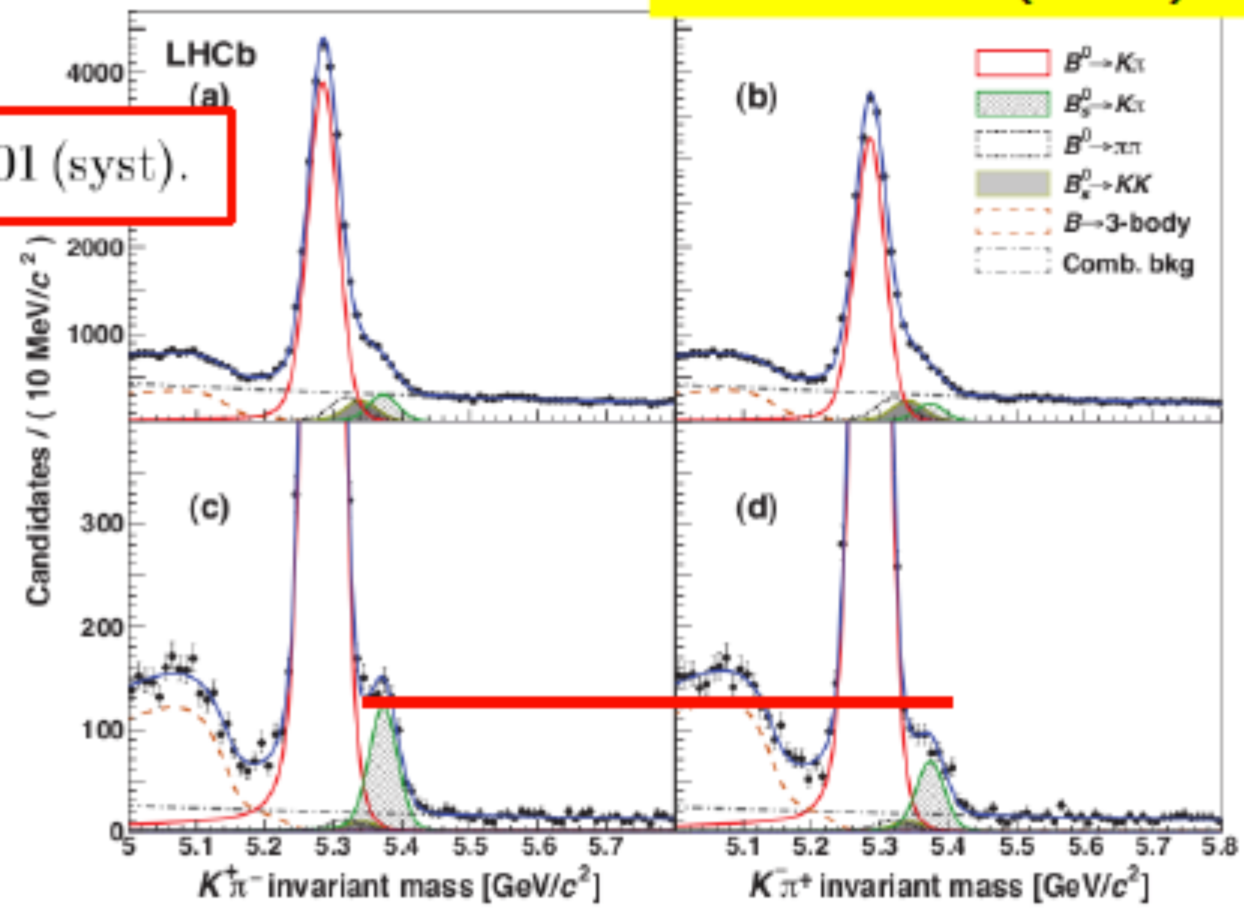
How to solve it? Measure more!

- Measure more $B_{u,d} \rightarrow K\pi$ decays & relate by isospin
- Perform similar analysis on $B \rightarrow K^*\pi$ &/or $B \rightarrow K\rho$

PRL 110 (2013) 221601

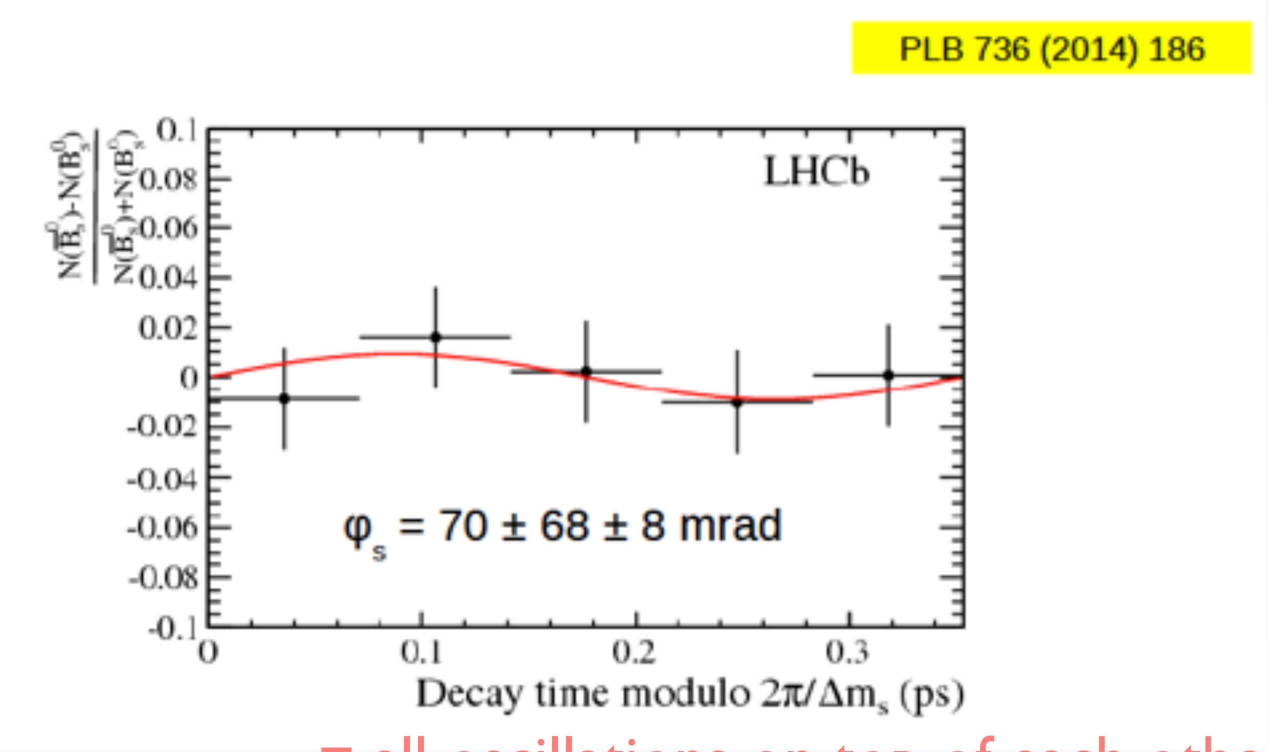
$$A_{CP}(B_s^0 \rightarrow K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

consistent with SM expectation



Simpler

- $B^0_S \rightarrow J/\psi f \pi^+ \pi^-$
  - final state: CP eigenstate-simpler analysis
  - but fewer events, and requires input from $B^0_S \rightarrow J/\psi \phi$ analysis (Γ_s, $\Delta\Gamma_s$)

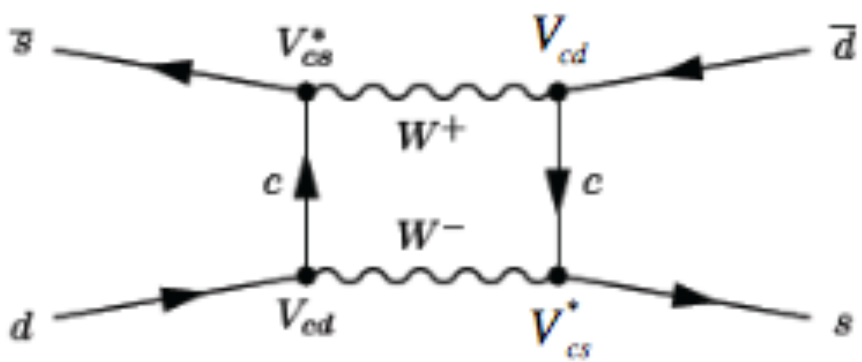


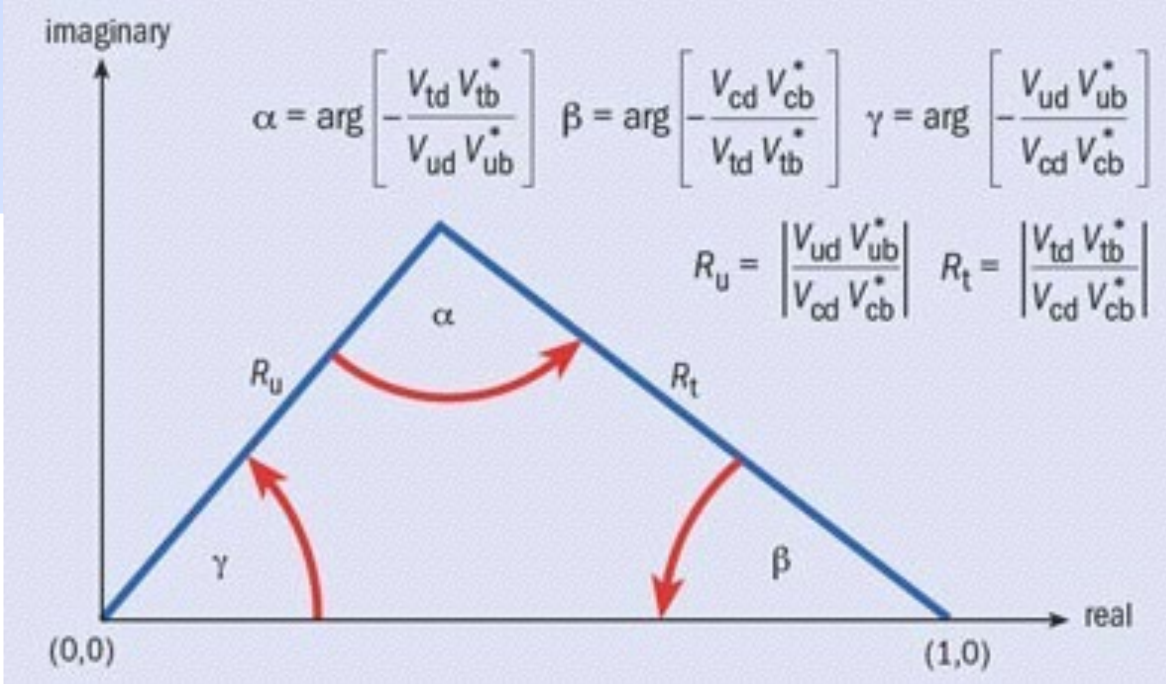
= all oscillations on top of each other

Asymmetry expected to be very small in the SM

Why is this β

$$\frac{q_K}{p_K} \approx \frac{V_{cs}^* V_{cd}}{V_{cs} V_{cd}^*}$$



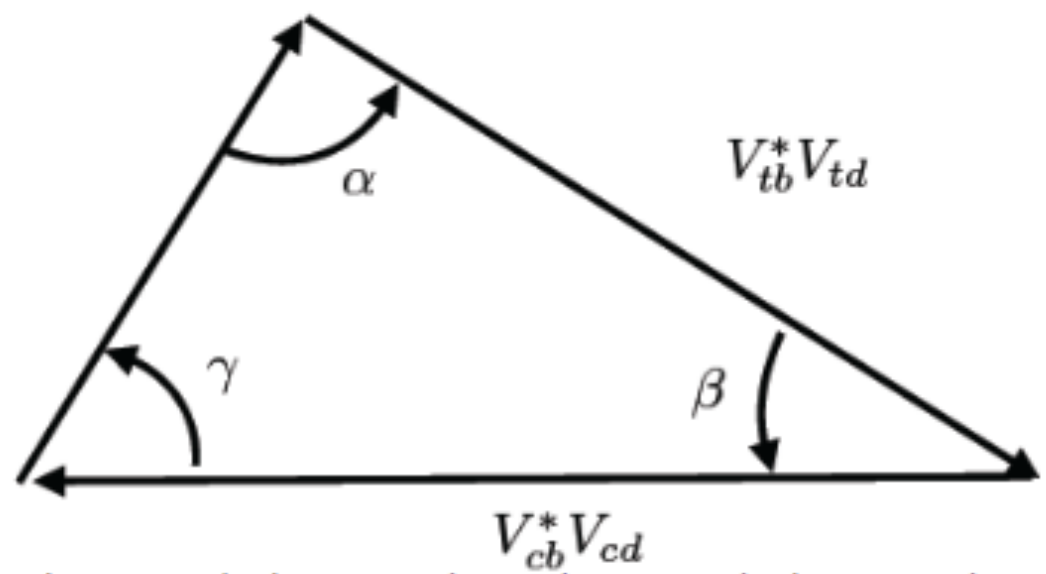


$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

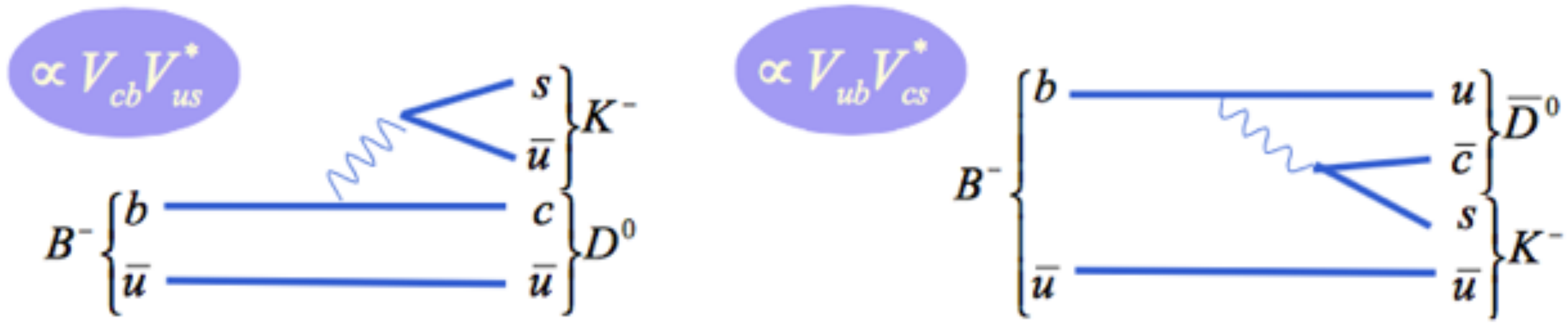
$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0\to K_S}}$$

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

$$\frac{q}{p} \qquad \frac{\overline{A}_{J/\Psi \overline{K}^0}}{A_{J/\Psi K^0}} \qquad \frac{p_k}{q_k}$$



$$= -e^{-2i\beta}$$



- final state contains D

- final state contains D-bar

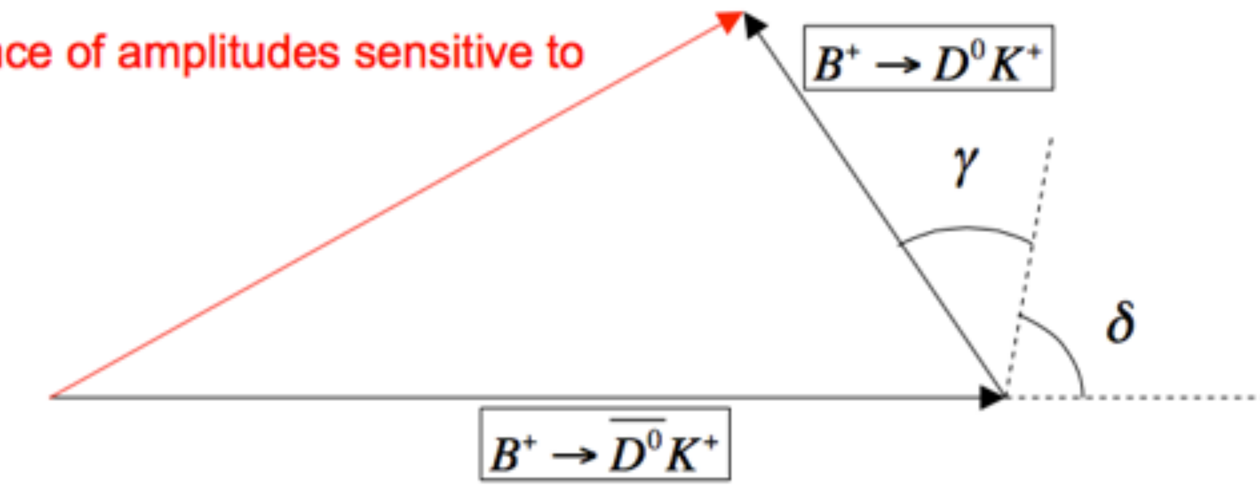
1. Why is this γ ?

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

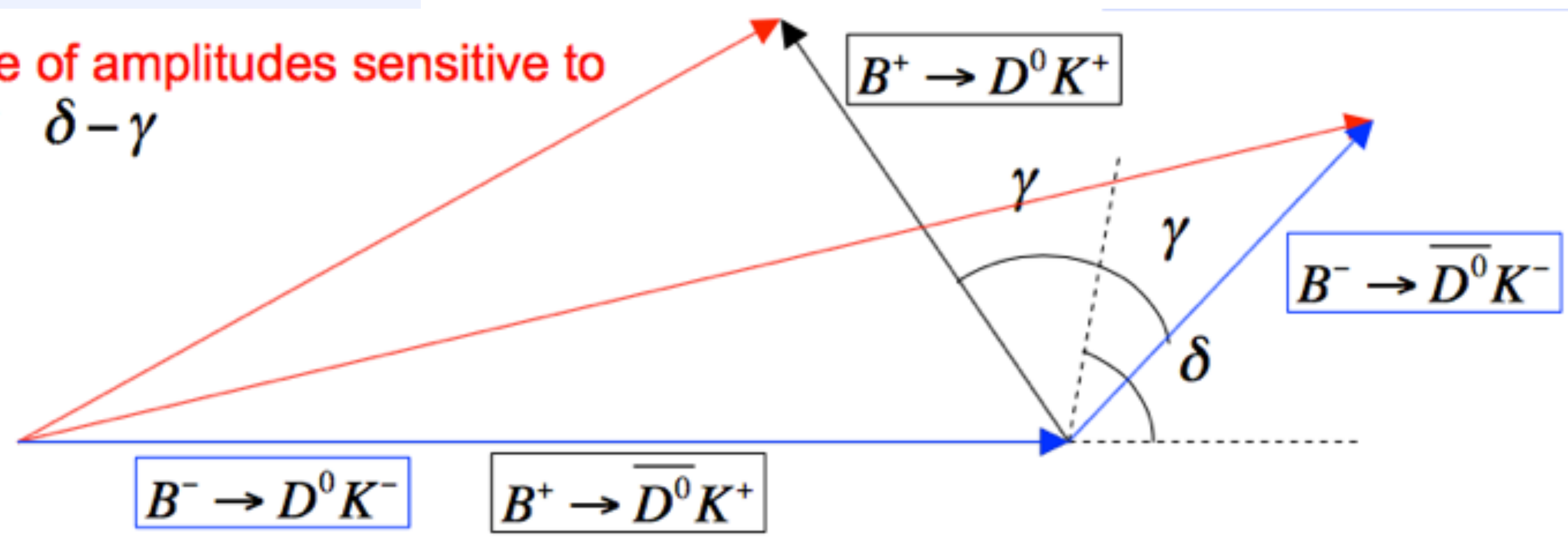
In both cases only complex phase is in V_{ub} element, so this measures γ

2. How to get round strong phase

Interference of amplitudes sensitive to $\gamma+\delta$



Interference of amplitudes sensitive to $\delta+\gamma$ or $\delta-\gamma$



Hence using all four processes can get γ

Challenge: Individual CP asymmetries

$$A_{CP}(KK) = A_{raw}(KK) - \underbrace{A_D(\mu) - A_P(B)}$$

want   measure

Measure the nuisance asymmetries by using control modes with CF final states (= no CPV)

Additional asymmetries arising

$$A_D(K\pi) \leftarrow B \rightarrow D^0(\rightarrow K\pi)\mu^- \nu_\mu X$$

$$A_D(\pi^+), A_P(D^+) \leftarrow \begin{cases} D^+ \rightarrow K^- \pi^+ \pi^+ \\ D^+ \rightarrow K_S^0 \pi^+ \end{cases}$$

$D^+ \rightarrow K_S^0 \pi^+ \rightarrow$ $A_{CP/int}(K^0)$

Careful treatment of kaon interactions with matter

$$A_{CP}(\pi\pi) = A_{CP}(KK) - \Delta A_{CP}$$

First measurement by LHCb of the two individual CP asymmetry

Physical states and CP eigenstates

The eigenstates of the Hamiltonian, have eigenvalues

$$\lambda_{1,2} \equiv m_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

The time evolution of the physical states is therefore given as

$$|M_{1,2}(t)\rangle = e^{-im_{1,2}t} e^{-\Gamma_{1,2}t/2} |M_{1,2}(0)\rangle$$

Assuming *CPT* symmetry, the physical eigenstates can be expressed as

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

with complex coefficients p,q satisfying

$$|p|^2 + |q|^2 = 1$$

the phase can be chosen such that in the limit of the no CPV i.e. M_1 is CP-even, and M_2-CP-odd

$$CP|M^0\rangle = -|\overline{M}^0\rangle$$

The mixing parameters

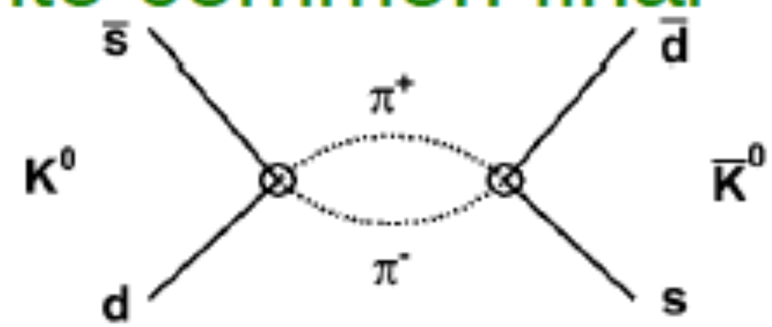
- Δm: value depends on rate of mixing diagram
  - together with various other constants ...

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

  - that can be made to cancel in ratios

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

- $\Delta\Gamma$: value depends on widths of decays into common final states (CP-eigenstates)
  - large for K^0, small for D^0 & B_d^0



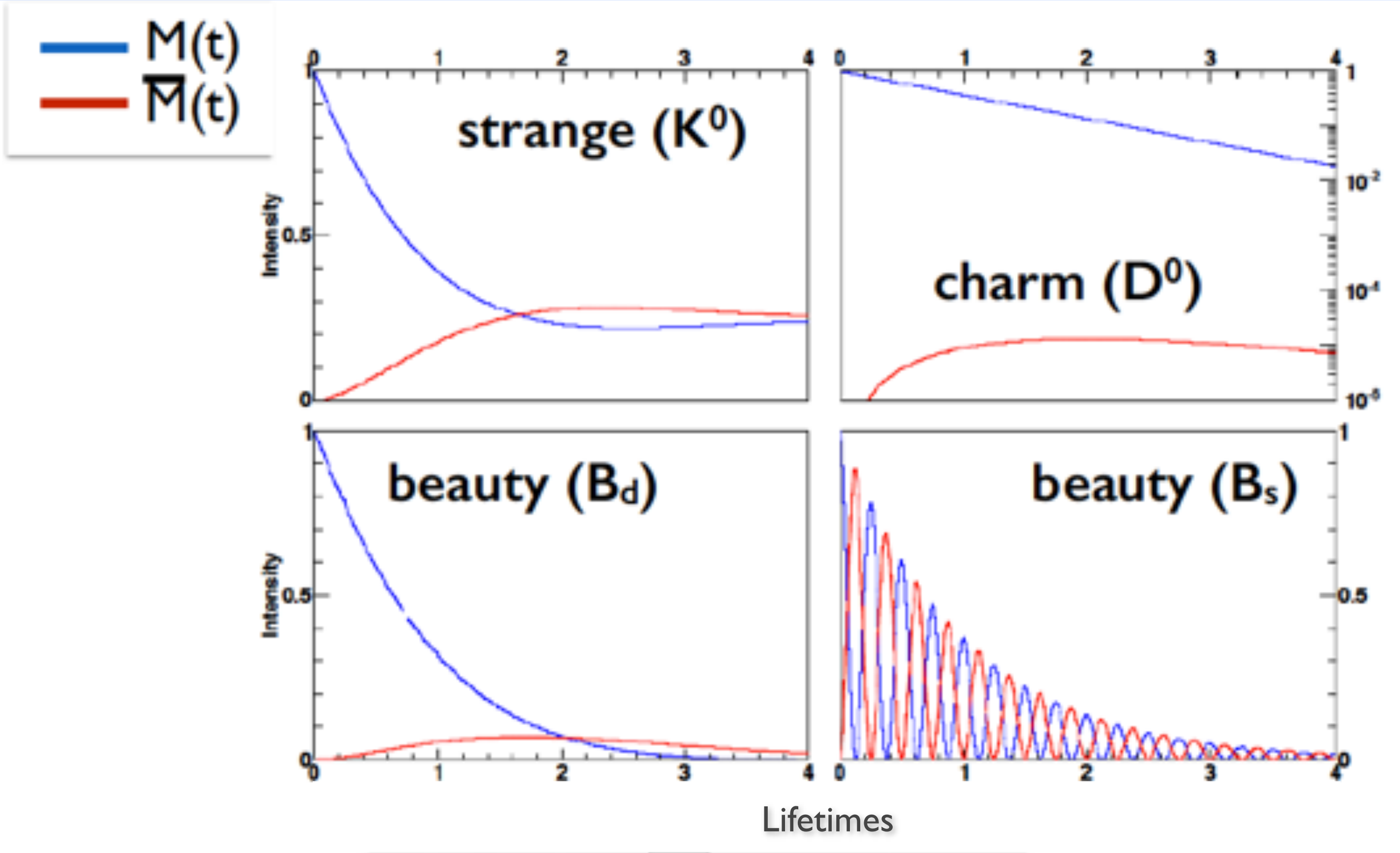
Time dependent probabilities

The time dependence can be expressed as

$$|M^0(t)\rangle = f_+(t)|M^0\rangle + \frac{q}{p} f_-(t)|\overline{M}^0\rangle$$
$$|\overline{M}^0(t)\rangle = f_+(t)|\overline{M}^0\rangle + \frac{p}{q} f_-(t)|M^0\rangle.$$

with

$$f_\pm(t) = \frac{1}{2} e^{-\imath m_1} e^{-\Gamma_1 t/2} \left(1 \pm e^{-\imath \Delta m t} e^{\Delta\Gamma t/2}\right)$$



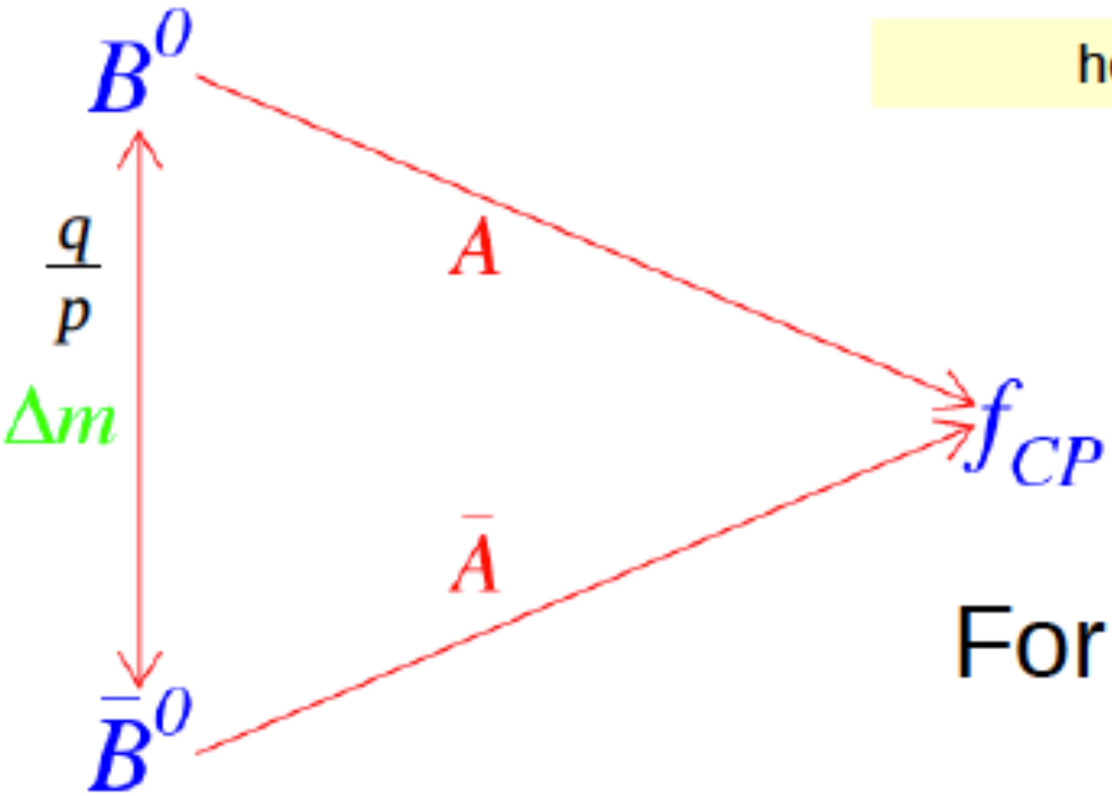
Probabilities

$$P(M^0(t) \to M^0) = P(\overline{M}^0(t) \to \overline{M}^0) = |f_+(t)|^2 = \tfrac{1}{2} e^{-\Gamma t}(\cosh(y\Gamma t) + \cos(x\Gamma t)),$$
$$P(M^0(t) \to \overline{M}^0) = \left|\frac{q}{p}\right|^2 |f_-(t)|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t)).$$
$$P(\overline{M}^0(t) \to M^0) = \left|\frac{p}{q}\right|^2 |f_-(t)|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t)).$$

Time dependent CPV in the B^0-$\overline{B}^0$ system

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, then at later time t:

$$\Gamma(B^0_{phys} \to f_{CP}(t)) \propto e^{-\Gamma t}\left(1-(S\sin(\Delta m t)-C\cos(\Delta m t))\right)$$
$$\Gamma(\overline{B}^0_{phys} \to f_{CP}(t)) \propto e^{-\Gamma t}\left(1+(S\sin(\Delta m t)-C\cos(\Delta m t))\right)$$



here assume ΔΓ negligible – will see full expressions later

$$S = \frac{2\Im(\lambda_{CP})}{1+|\lambda_{CP}^2|} \qquad C = \frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

For $B^0 \to J/\psi\, K_S$, $S = \sin(2\beta)$, $C=0$

NPB 193 (1981) 85

Time dependent CPV formalism

Generic decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}$$
$$\times\left[\cosh\frac{\Delta\Gamma\,t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\,\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\,\sinh\frac{\Delta\Gamma\,t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\,\sin(\Delta m\,t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,(1+a)\,e^{-\Gamma t}$$
$$\times\left[\cosh\frac{\Delta\Gamma\,t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\sinh\frac{\Delta\Gamma\,t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta m\,t)\right].$$

CPV asymmetries

CP conserving asymmetries

$$A_{CP}^{dir} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$$

$$A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

Time dependent CPV formalism

Generic decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma\, t}{2} \quad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma\, t}{2} \quad \right]$$
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, (1 + a) \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma\, t}{2} \quad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma\, t}{2} \quad \right] .$$

Untagged analyses have sensitivity to some interesting physics

Time dependent CPV formalism

Generic decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1 + 0) \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right] .$$

In some channels we expect no direct CPV

and/ or no CPV in mixing

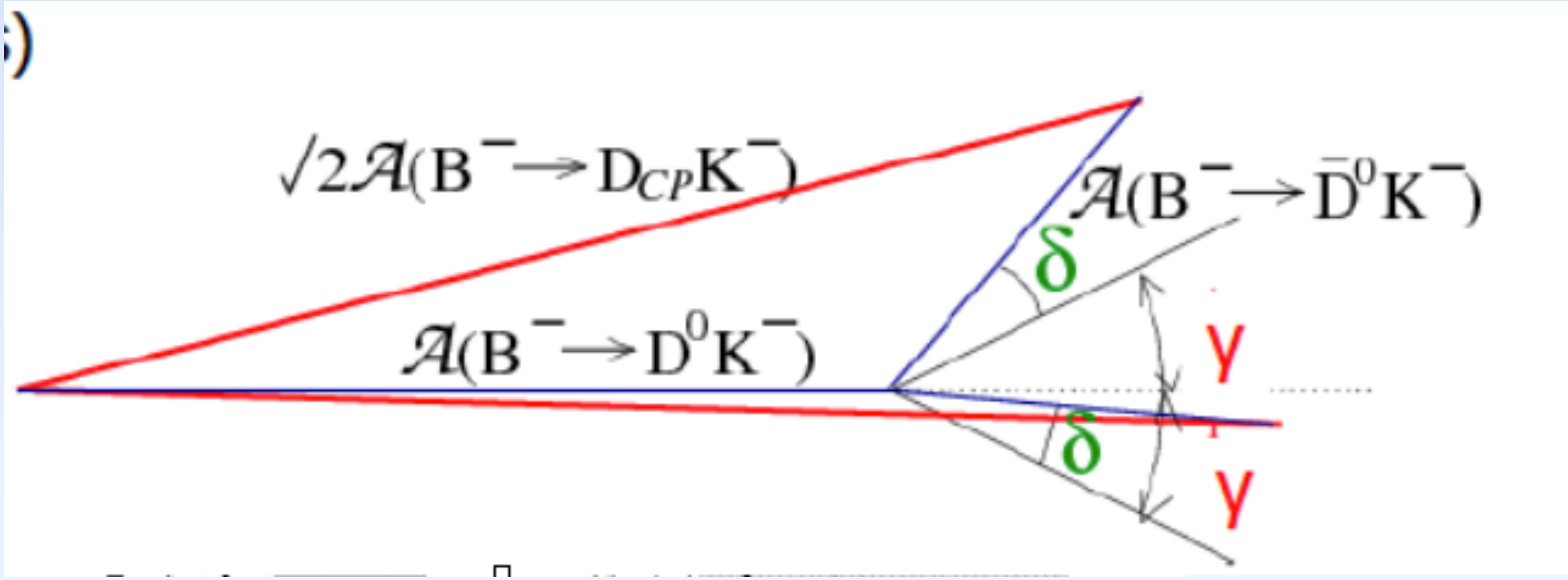
Time dependent CPV formalism

Generic decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[1 + \mathcal{A}_{\rm CP}^{\rm dir} \, 1 + \mathcal{A}_{\Delta\Gamma} \, y\Gamma t + \mathcal{A}_{\rm CP}^{\rm mix} \, x\Gamma t \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t} \times \left[1 - \mathcal{A}_{\rm CP}^{\rm dir} \, 1 + \mathcal{A}_{\Delta\Gamma} \, y\Gamma t - \mathcal{A}_{\rm CP}^{\rm mix} \, x\Gamma t \right].$$

D^0 case: both x and y are small



$\sqrt{2}\mathcal{A}(B^- \to D_{CP}K^-)$
$\mathcal{A}(B^- \to \bar{D}^0K^-)$
$\mathcal{A}(B^- \to D^0K^-)$
δ
γ
δ
γ

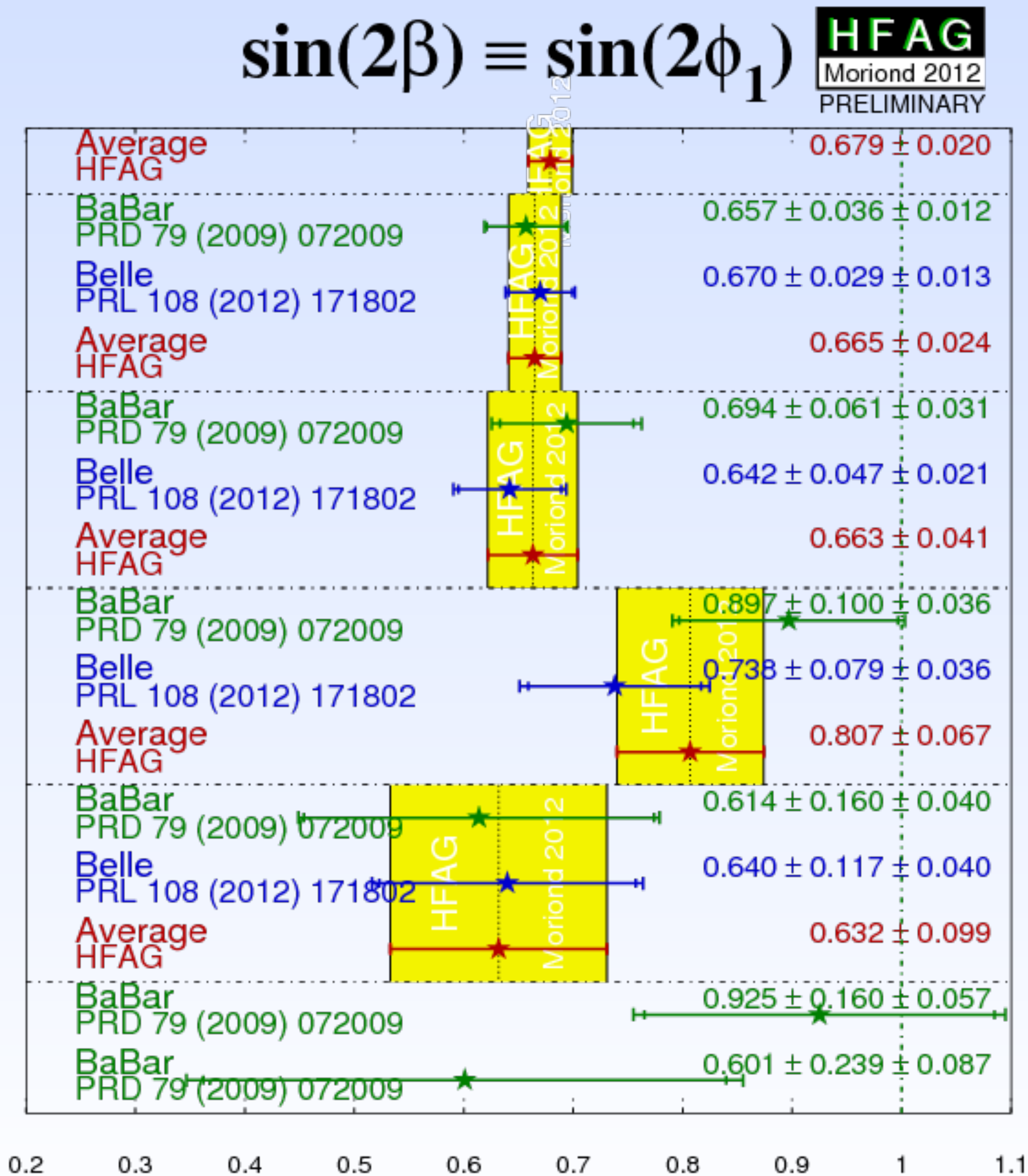
How to search for new physics?

High energy:
"real" new particles can be produced and discovered via their decays

High precision:
"virtual" new particles can be discovered in loop processes

Direct and indirect searches are both needed,
both equally important,
and complementary to each other

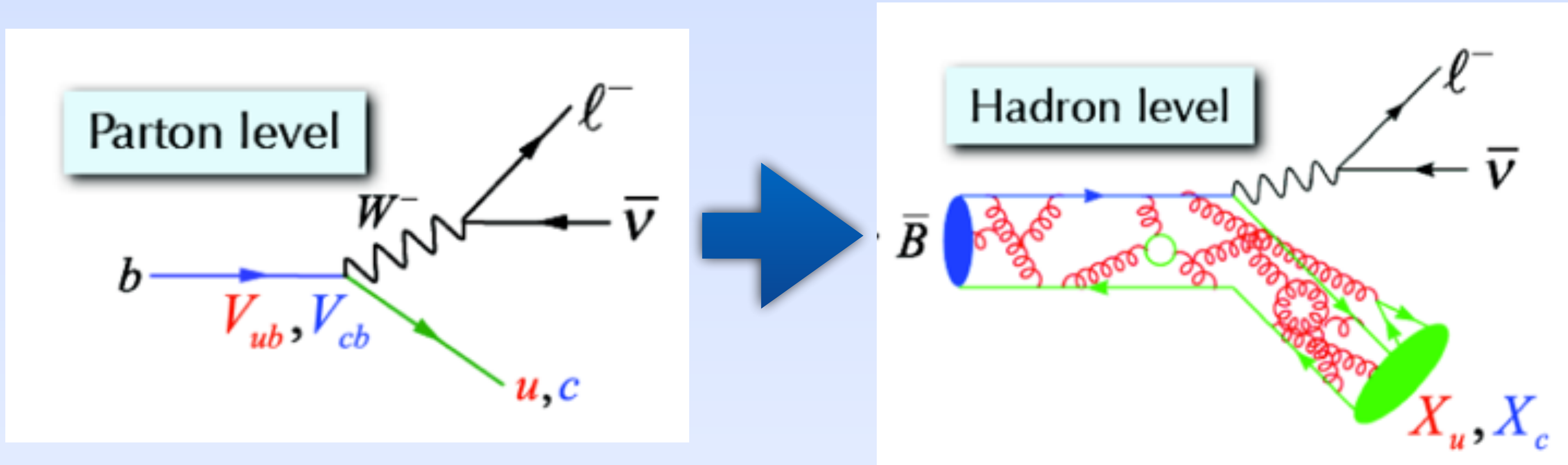
Compilation of results



UT sides

Ru side from semileptonic decays

$$R_u = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right|$$

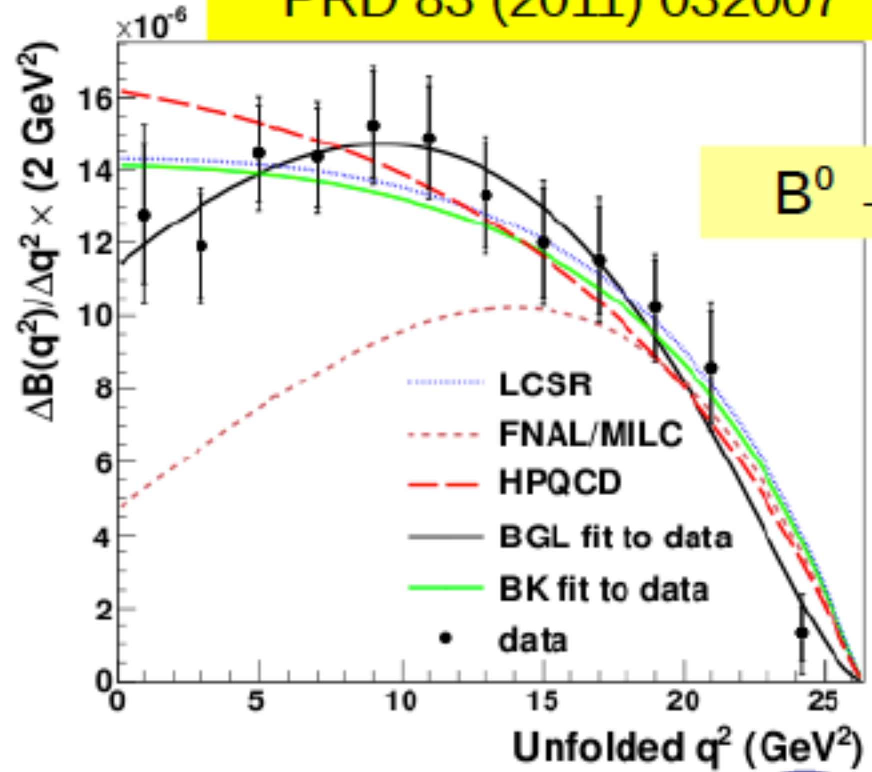


- Exclusive measurements e.g. $B^0 \to e^+ \pi^- \nu$
  - need to know form factors, can be calculated in lattice QCD
- Inclusive measurements e.g. $B^0 \to e^+ X_u^- \nu$
  - clean theory based on Operator Product Expansion
  - experimentally challenging: need to reject b c background; cuts reintroduce theoretical uncertainties

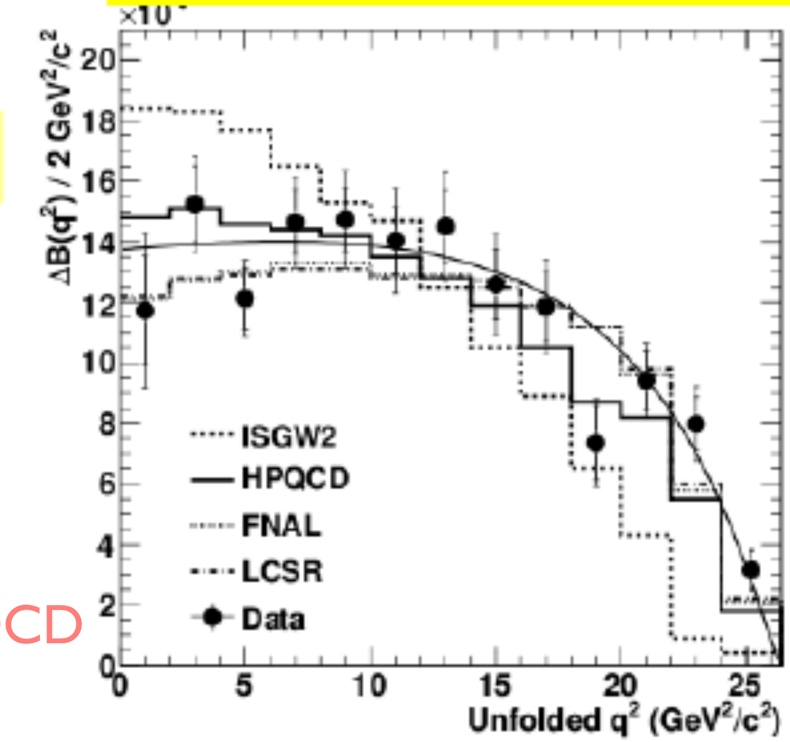
|Vub|

BaBar experiment
PRD 83 (2011) 052011
PRD 83 (2011) 032007

Belle experiment
PRD 83 (2011) 071101(R)



$B^0 \to \pi^- l\nu$



lattice QCD

$$|V_{ub}| = (3.09 \pm 0.08 \pm 0.12 {}^{+0.35}_{-0.29}) \times 10^{-3}$$

$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$

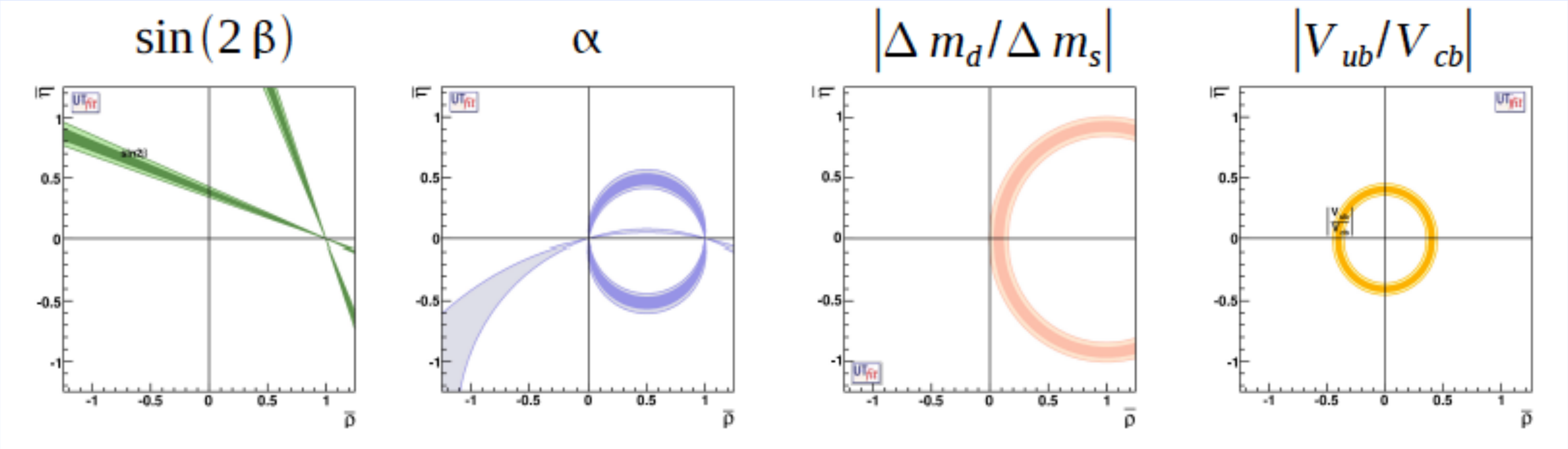
Current best measurements come from exclusive measurements

Visible tension

Exclusive $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$

Inclusive $|V_{ub}| = (4.41 \pm 0.22) \times 10^{-3}$

Partial summary

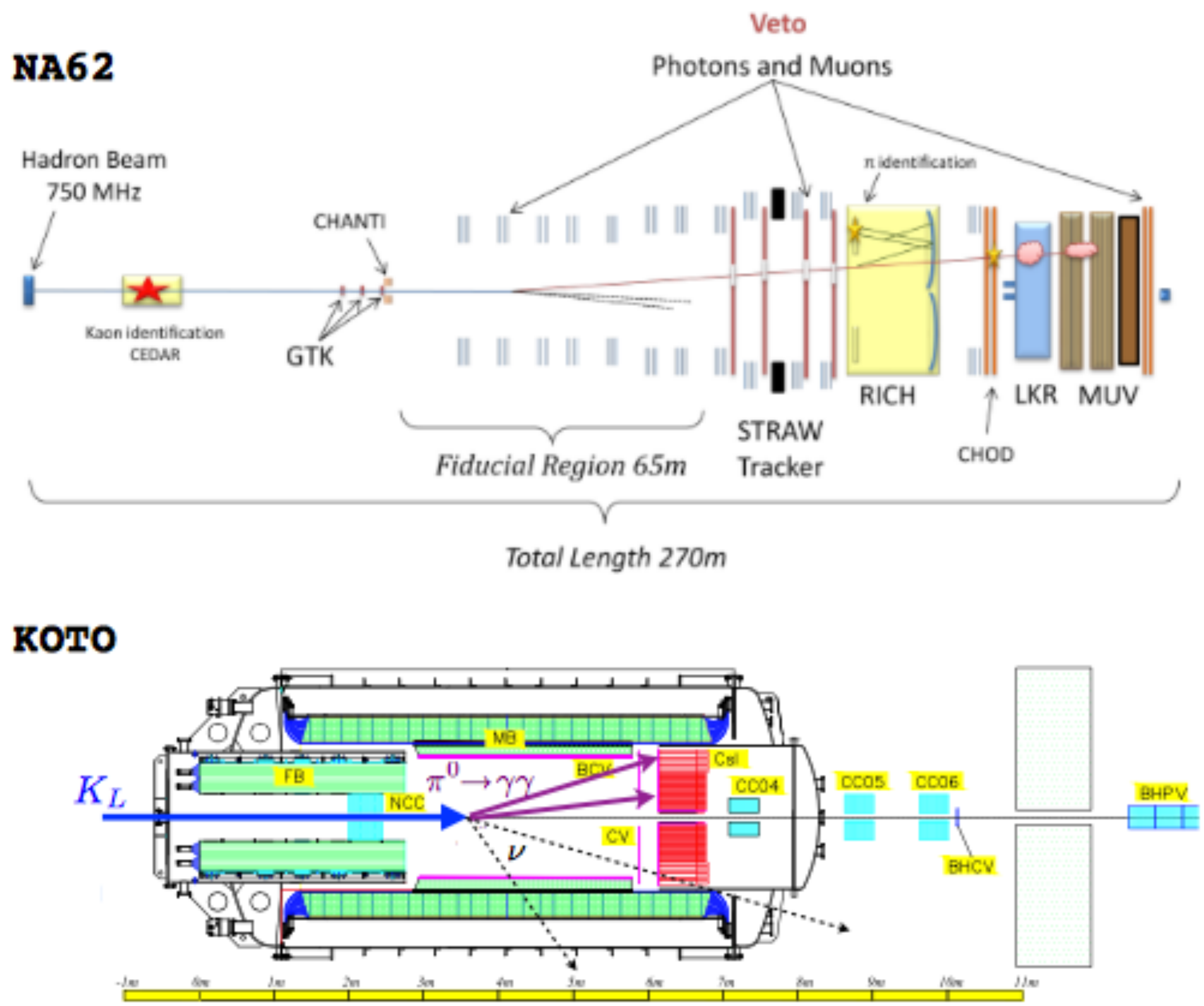


Observed CPV effects

- Kaon sector
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$
  - $\mathrm{Re}(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- B sector
  - $S_{\psi K0} = +0.679 \pm 0.020$
  - $S_{\eta' K0} = +0.59 \pm 0.07$, $S_{\varphi K0} = +0.74^{+0.11}_{-0.13}$, $S_{f0K0} = +0.69^{+0.10}_{-0.12}$, $S_{K+K-K0} = +0.68^{+0.09}_{-0.10}$
  - $S_{\pi+\pi-} = -0.65 \pm 0.07$, $C_{\pi+\pi-} = -0.36 \pm 0.06$, $A_{Bs \to K\mp\pi\pm} = 0.26 \pm 0.04$
  - $S_{\psi\pi0} = -0.93 \pm 0.15$, $S_{D+D-} = -0.98 \pm 0.17$, $S_{D*+D*-} = -0.77 \pm 0.10$
  - $A_{K\mp\pi\pm} = -0.082 \pm 0.006$
  - $A_{D(CP+)K\pm} = +0.19 \pm 0.03$
  - Phase-space distributions in $B^{+} \to$ KKK, KKπ, Kππ, πππ decays

α measurements

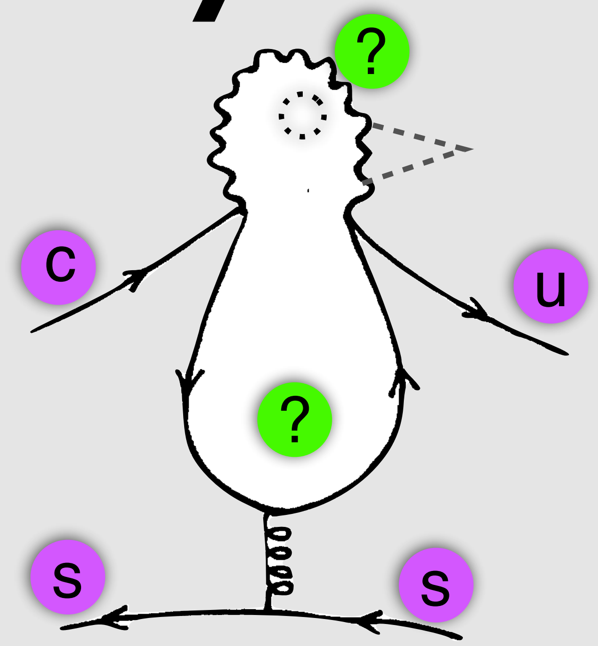
Kaon physics



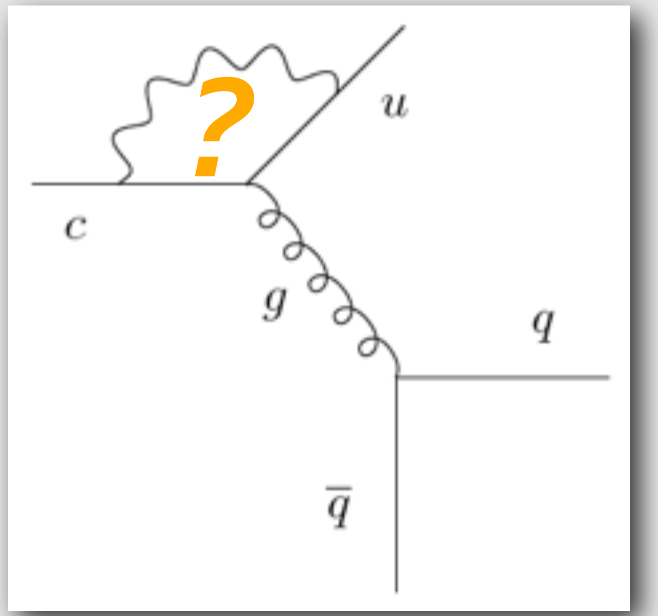
NA62/KOTO: forward spectrometers for rare kaon decays

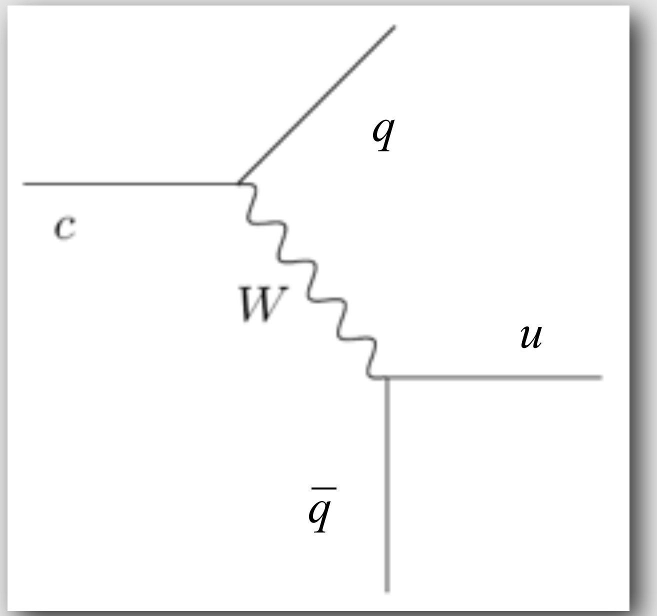
CP violation in decay

- CP violation in decays requires interference of several amplitudes
- Example:
  - ➡ singly Cabibbo-suppressed (SCS) decays $c \to d\bar{d}u$ ($D^0 \to \pi^-\pi^+$) or $c \to s\bar{s}u$ ($D^0 \to K^-K^+$)



- Only SCS decays have gluonic penguin contributions (need $\mathbf{q\bar{q}}$)
- Penguins can carry strong and weak phase w.r.t. trees





Direct CPV searches in multibody decays

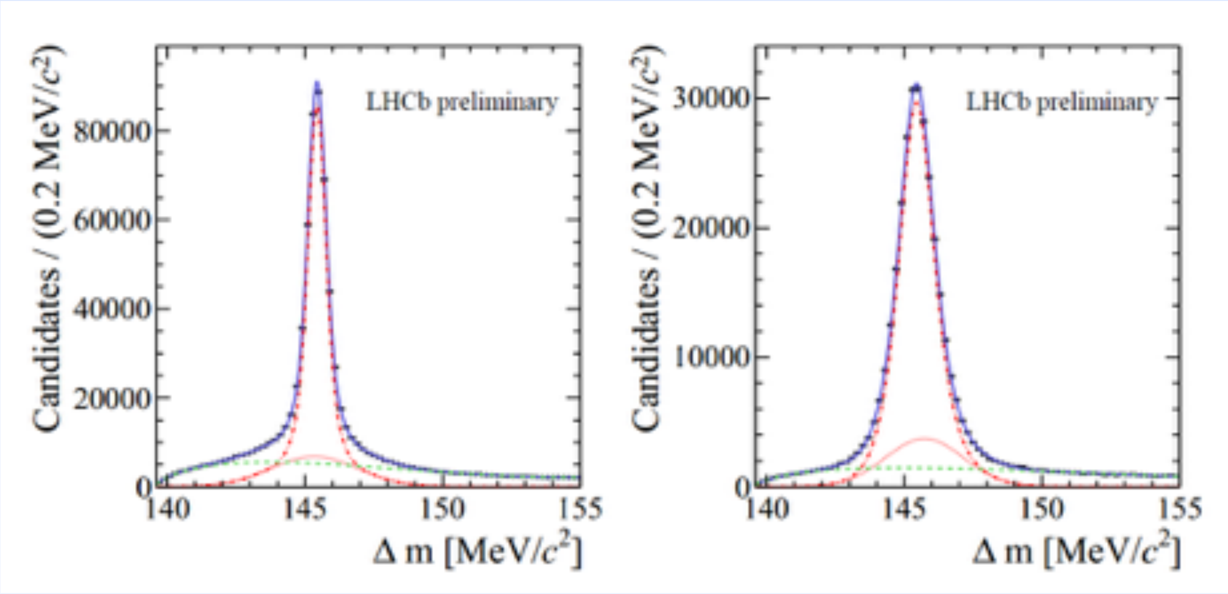
Sensitive to local asymmetries

Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays

- Decay proceeds via a SCS transition
- Decay dominated by $\rho(770)$ resonances: $\rho^0\pi^0, \rho^+\pi^-, \rho^-\pi^+$
- Using 2012 data, prompt charm
- Model independent
- Previous measurement : Belle (PRD 78 (2008) 051102)

Resolved π^0 : both γ were detected separately

Merged π^0 : both γ form 1 cluster



~413 x 10^3 events

~247 x 10^3 events

Energy test: unbinned sample comparison used to assign p-value for hypothesis of identical distributions (= no CPV)

Analysis method: Energy test

Distance metric for the discrete distributions:

test statistic

$$T \approx \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(\Delta\vec{x}_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(\Delta\vec{x}_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\Delta\vec{x}_{ij}).$$

average ψ of D^0 events w.r.t. each other

average ψ of $\bar{D}^0$ events w.r.t. each other

average ψ of D^0 to $\bar{D}^0$ events

Method sensitive to local CP asymmetries but not to global asymmetries

$$\vec{x} \equiv (M_{ab}^2, M_{bc}^2, M_{ca}^2)$$

Point in phase space, all 3 invariant masses used

$$\psi(\Delta\vec{x}) = e^{-\Delta\vec{x}^2/2\sigma^2}.$$

Gaussian metric function

- no CP violation
  - ➡ all average distances equal → T≈0
- CP asymmetry
  - ➡ average distance btw. D^0 and $\bar{D}^0$ events larger
  - ➡ average ψ btw. D^0 and $\bar{D}^0$ events smaller
  - ➡ T > 0

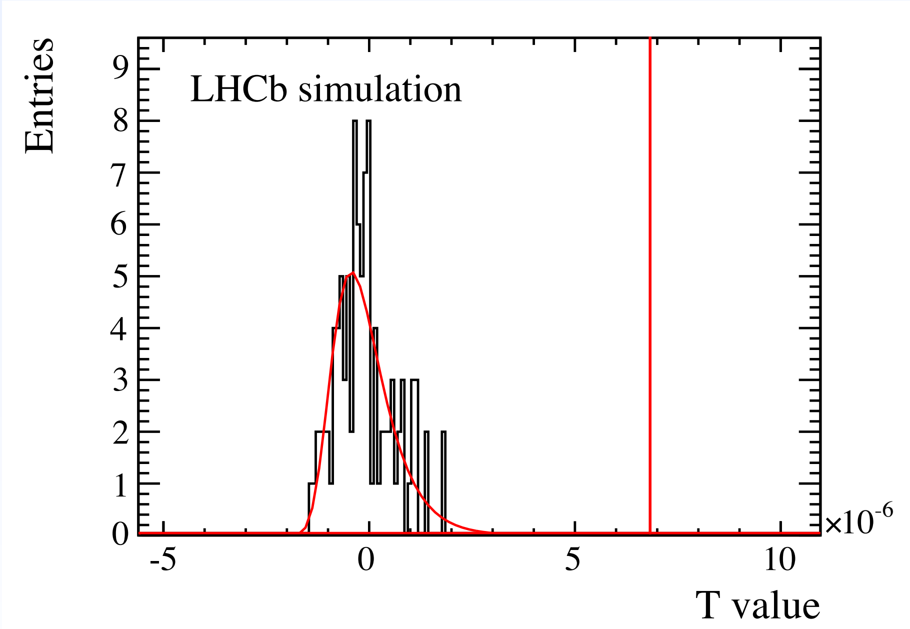
σ -tunable parameter: effectively, radius in the phase space in which a local asymmetry is measured

P-values

- Calculate p-value for no CPV hypothesis
- Can obtain p-value from counting permutation T values (used for final result)
- Or for small p-values from fitting distribution and calculating fractional integral (used for sensitivity studies)

Compare nominal T-value to T-values for no CPV

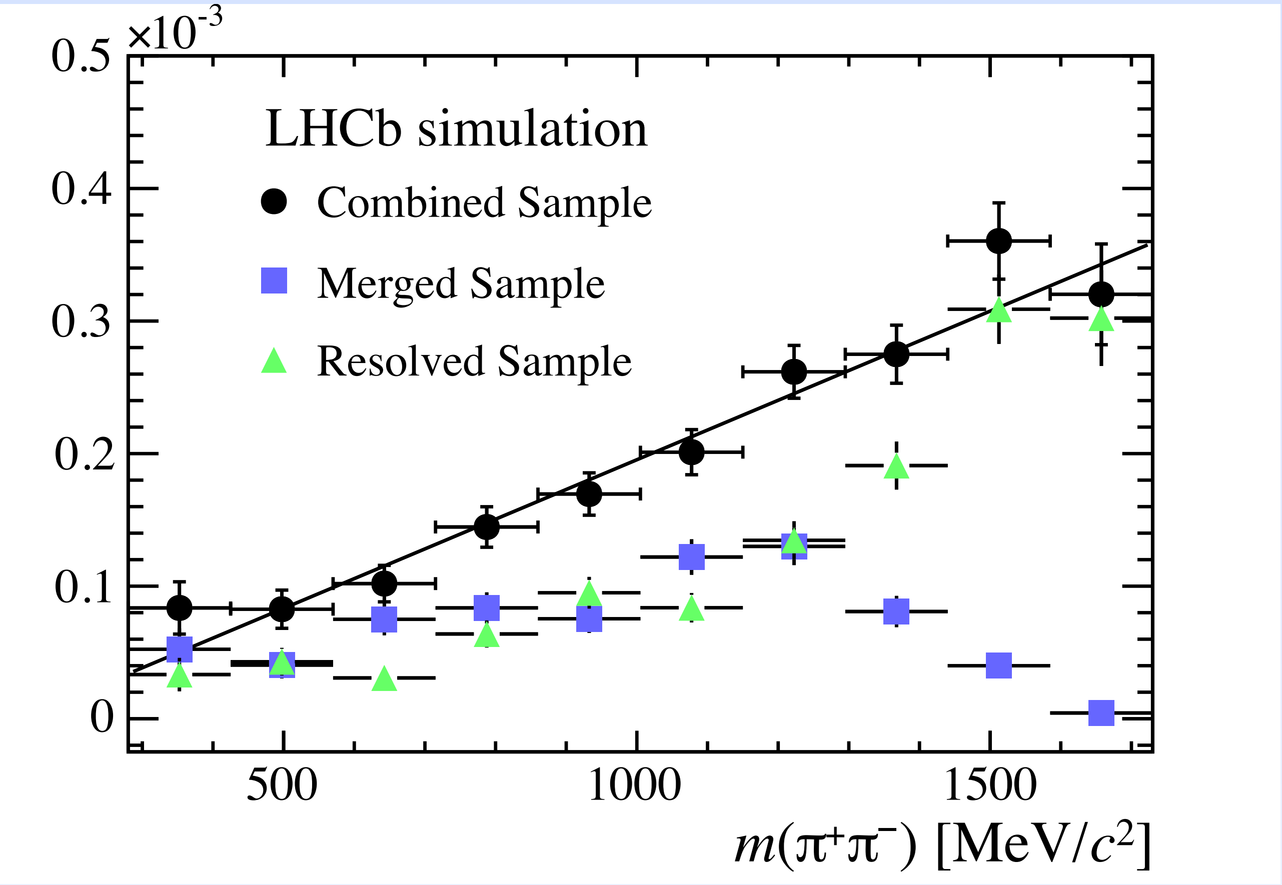
Distribution obtained by randomly assigning flavour tags to events thus creating no CPV permutations



Sensitivity

- The selection efficiency obtained using full LHCb MC
- The sensitivity studies use toy MC: Laura++ to model signal decays
- Background events modelled according to sideband distributions

Similar sensitivity to BABAR for ρ^0 amplitude CPV, otherwise better



Resonance (A, ϕ)	p-value (fit)	upper limit
ρ^0 $(+3\%, +0°)$	$1.1^{+2.4}_{-1.1} \times 10^{-2}$	4.0×10^{-2}
ρ^0 $(+0\%, +3°)$	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ $(+2\%, +0°)$	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ $(+0\%, +1°)$	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- $(+2\%, +0°)$	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- $(+0\%, +1.5°)$	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

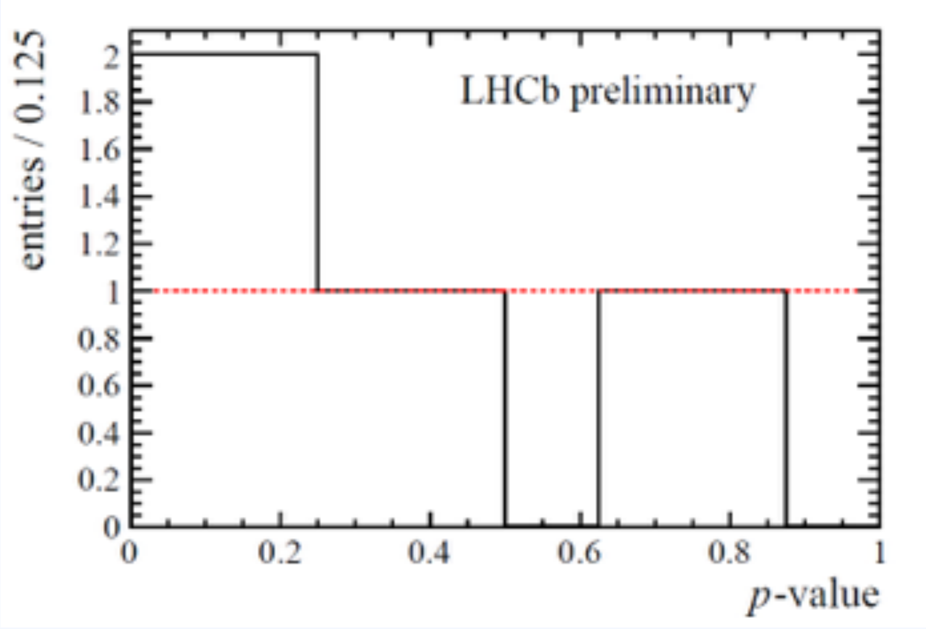
LHCb-PAPER-2014-054

Cross checks

Two major sources of asymmetries that may bias the result:

- Asymmetries from background events
  - Apply energy test to the upper sideband of Δm
  - Generating toys for D^0 and $\overline{D}^0$ sidebands
- Detection asymmetries
  - Use the Cabibbo-favoured $D^0 \to K^- \pi^+ \pi^0$ mode (conservative test because of the larger kaon detection asymmetry)
  - Split the sample in 8 subsamples
  - Split the sample by polarity

LHCb-PAPER-2014-054



No indication of background or detector related asymmetries

Crosscheck with a binned method yields consistent results

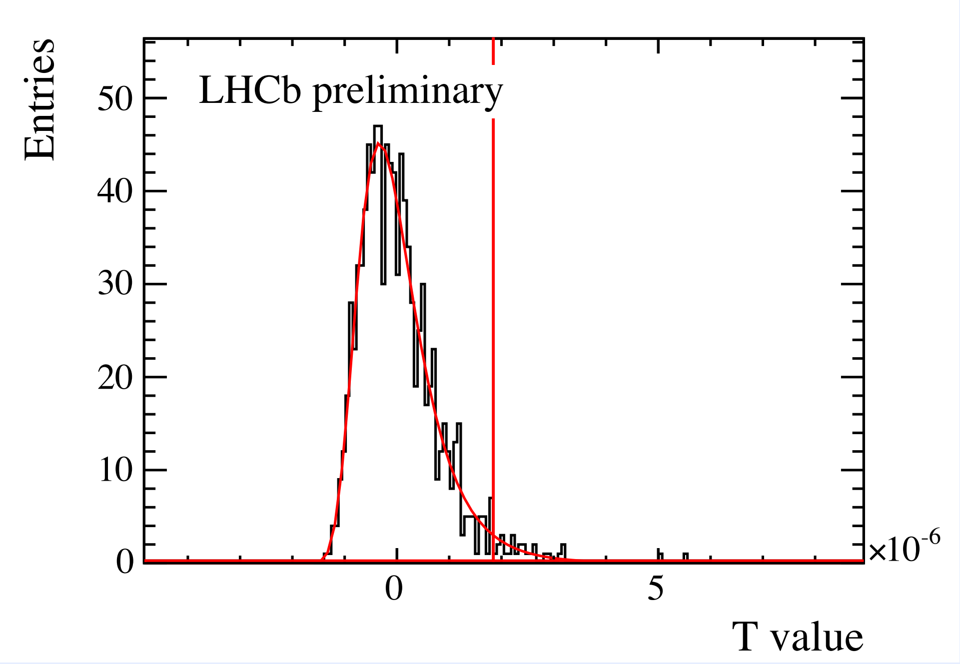
Results

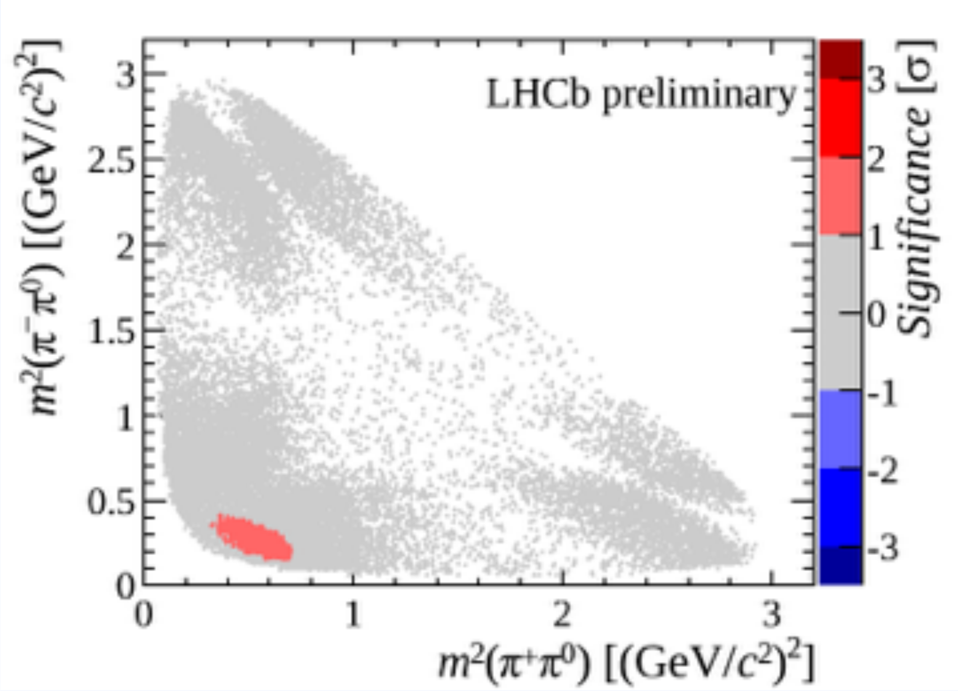
- With1000 permutations
- For no-CPV hypothesis:
  - p-value = (2.6±0.5)%
- Other metric parameters
  - σ = 0.2: p = (4.6±0.6)%
  - σ = 0.4: p = (1.7±0.4)%
  - σ = 0.5: p = (2.1±0.5)%

Method allows visualisation of local asymmetry significances

World's best sensitivity for CPV in $D^0 \to \pi^- \pi^+ \pi^0$

LHCb-PAPER-2014-054





Result consistent with no CP violation

P-values

- Calculate p-value for no CPV hypothesis
- For small p-values from fitting distribution and calculating fractional integral (used for sensitivity studies)
  - Fit using generalised extreme value function

$$f(x;\mu,\sigma,\xi) = N\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{(-1/\xi)-1} \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\},$$

Visualisation

- Split T value in 2 parts

$$T = \sum_i T_i + \sum_i \bar{T}_i.$$

- Obtain "contribution" of each event

$$T_i = \frac{1}{2n(n-1)} \sum_{j \neq i}^{n} \psi(\Delta \vec{x}_{ij}) - \frac{1}{2n\bar{n}} \sum_{j}^{\bar{n}} \psi(\Delta \vec{x}_{ij}).$$

$$\bar{T}_i = \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{j \neq i}^{\bar{n}} \psi(\Delta \vec{\bar{x}}_{ij}) - \frac{1}{2n\bar{n}} \sum_{j}^{n} \psi(\Delta \vec{\bar{x}}_{ij}).$$

- Calculate permutation T_i values
- Take smallest and largest T_i of each permutation

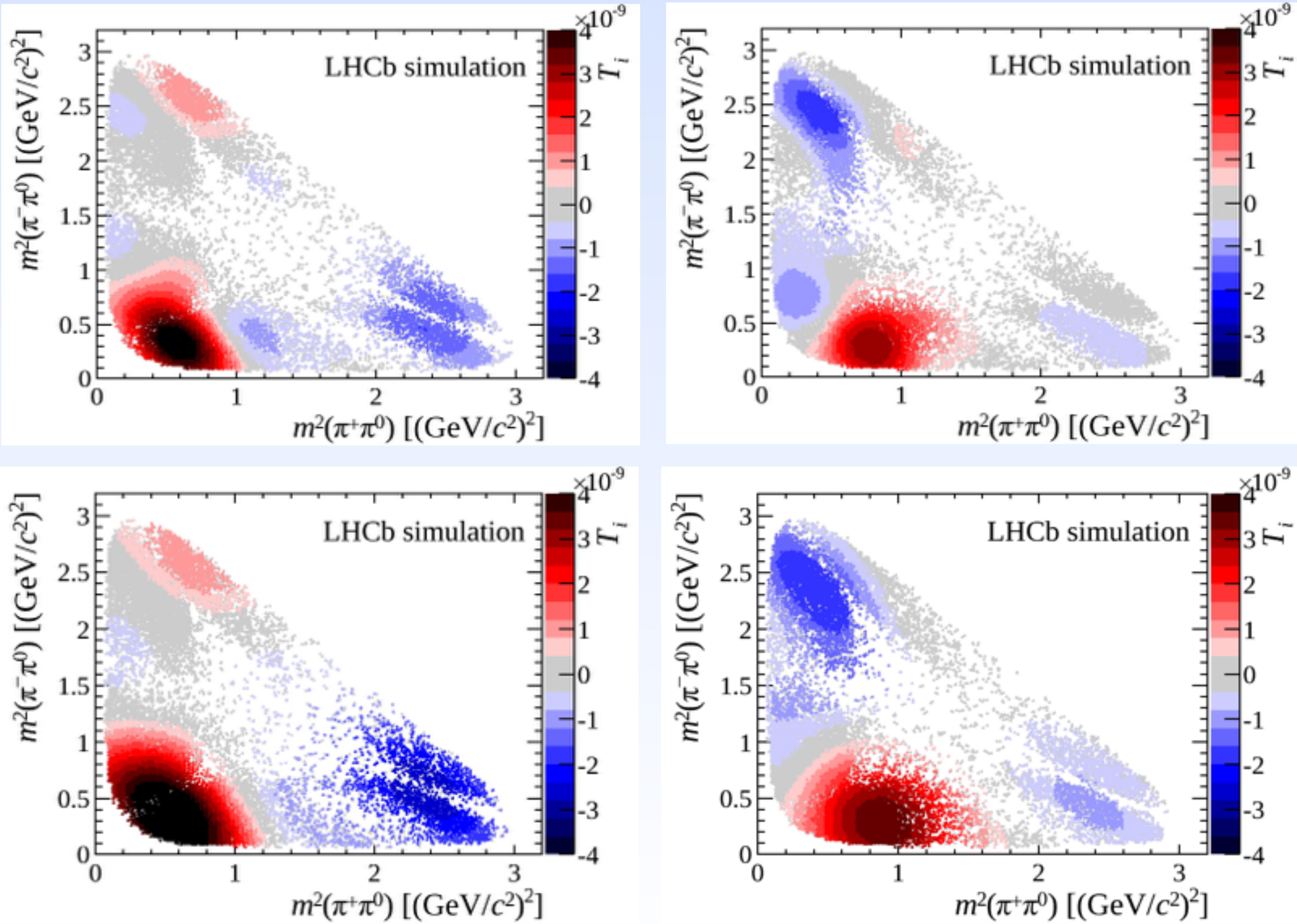
➡ Calculate T_i significance for being larger than T_i^{max} or smaller than T_i^{min} distribution

➡ Can plot significance of positive or negative asymmetry for each event

Metric parameter σ

LHCb-PAPER-2014-054

$$\psi(\Delta\vec{x}) = e^{-\Delta\vec{x}^2/2\sigma^2}.$$



σ = 0.3

GeV^2/c^4

σ = 0.5

ρ^+ amplitude CPV

ρ^+ phase CPV