Experimental Prospect on the Favour Physics in the LHC Era

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LPHE

Quark Flavour Physics

- Theory
  - Introduction of "strangeness" quantum number

    Gelmann, Nishijima, and others (1955)
  - Flavour mixing

    Cabibbo (1963)
  - GIM mechanism

    Glashow, Iliopoulos, and Maiani (1970)

- Experiment
  - Discovery of strange particles, **their decay properties**

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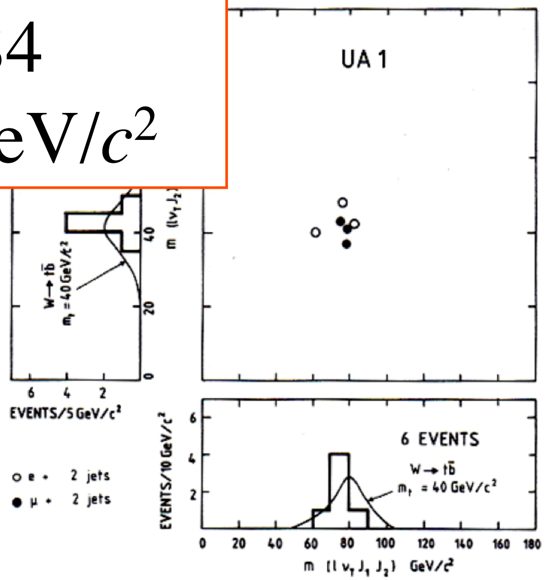
  - ???
- Experiment
  - Discovery of strange particles, **their decay properties**
    ⇒ discovery of c, b and t and studies of their decays
  - Discovery of CP violation in the kaon system (1964)
    ⇒ further investigations in the K, D and B systems

Quark Flavour Physics

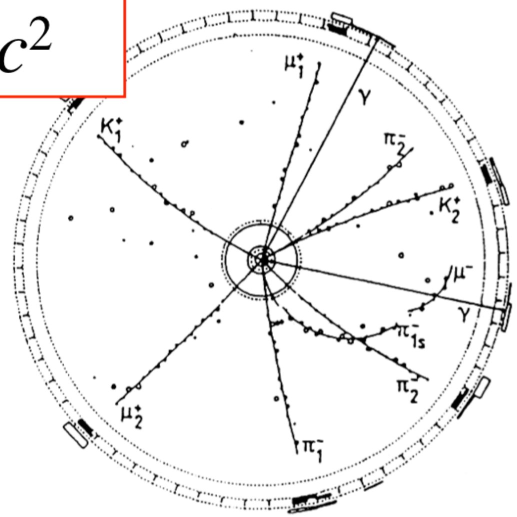
- Also some less spectacular surprises
  - long b-quark lifetime → $|V_{cb}| < |V_{us}|$
    by MAC and Mark-II experiments (1983)

  - large B-$\overline{\text{B}}$ oscillations → first indication of large m_t

UA1 1984
30~50 GeV/c^2



ARGUS 1987
> 50 GeV/c^2



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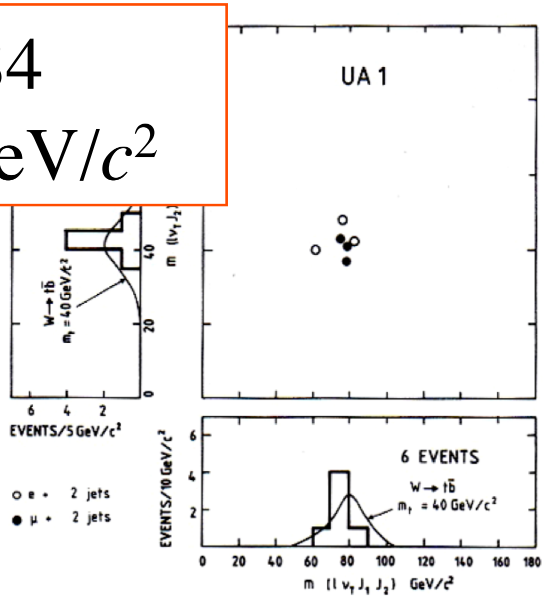

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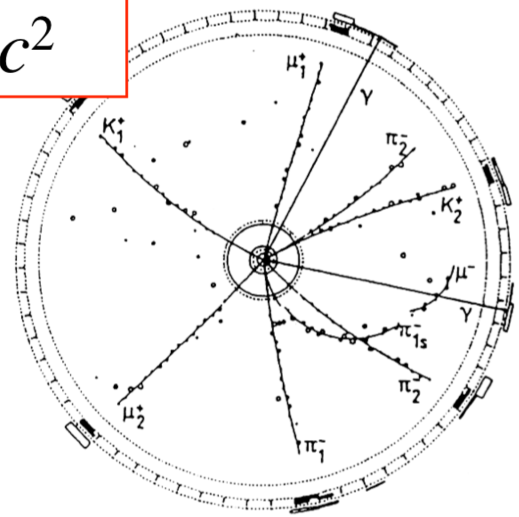
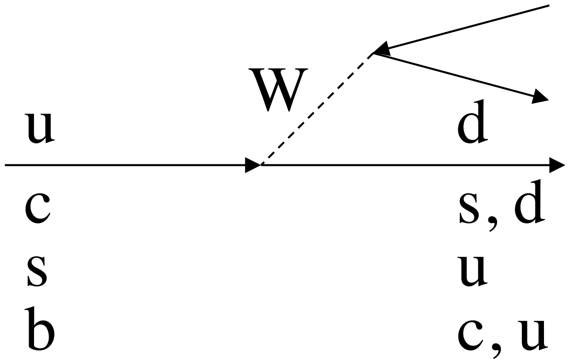


- Unfortunately, no surprise from CPV in B so far…

Recent Progress

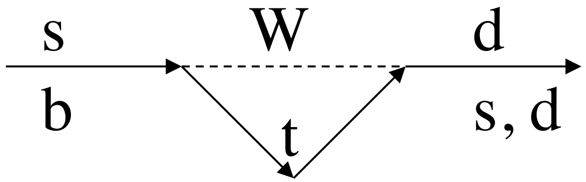
- Many precise experimental tests on the decays of u, c, s, and b hadrons and K-$\overline{\text{K}}$ and B-$\overline{\text{B}}$ oscillations

Tree level decays



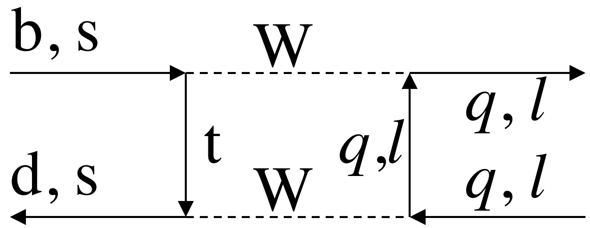
$|V_{ud}|, |V_{cs}|, |V_{cd}|$
$|V_{us}|, |V_{cb}|, |V_{ub}|$

Penguin level decays



$|V_{ts}|, |V_{td}|, |V_{tb}|$

Box level decays



$|V_{ts}|, |V_{td}|, |V_{tb}|$

dominant contributions

Plus some other diagrams but less relevant for "flavour" physics

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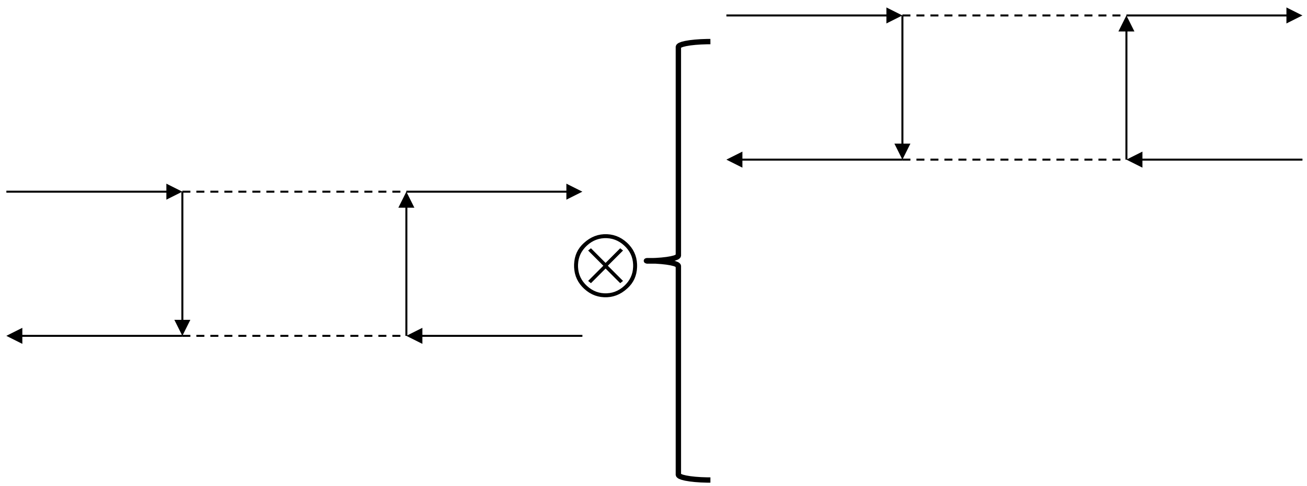

CP violation in the oscillations
arg $V_{\text{td(s)}}$ (arg V_{cs})

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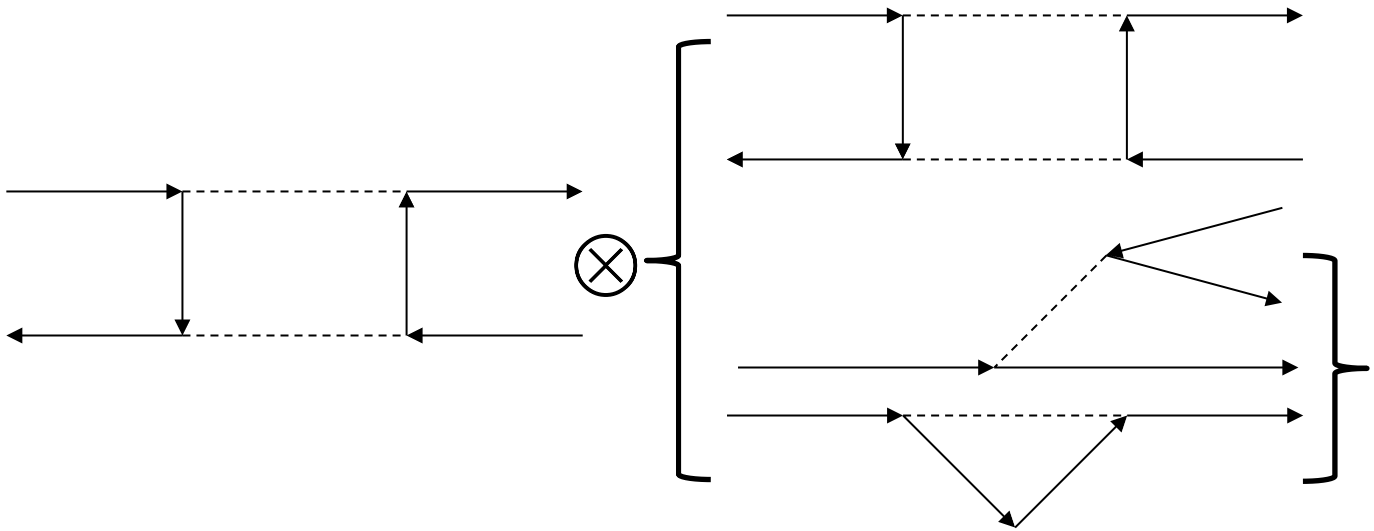

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CP violation in interplay between the oscillations and decays.
arg $V_{td(s)}V_{c(u)b}^*$,
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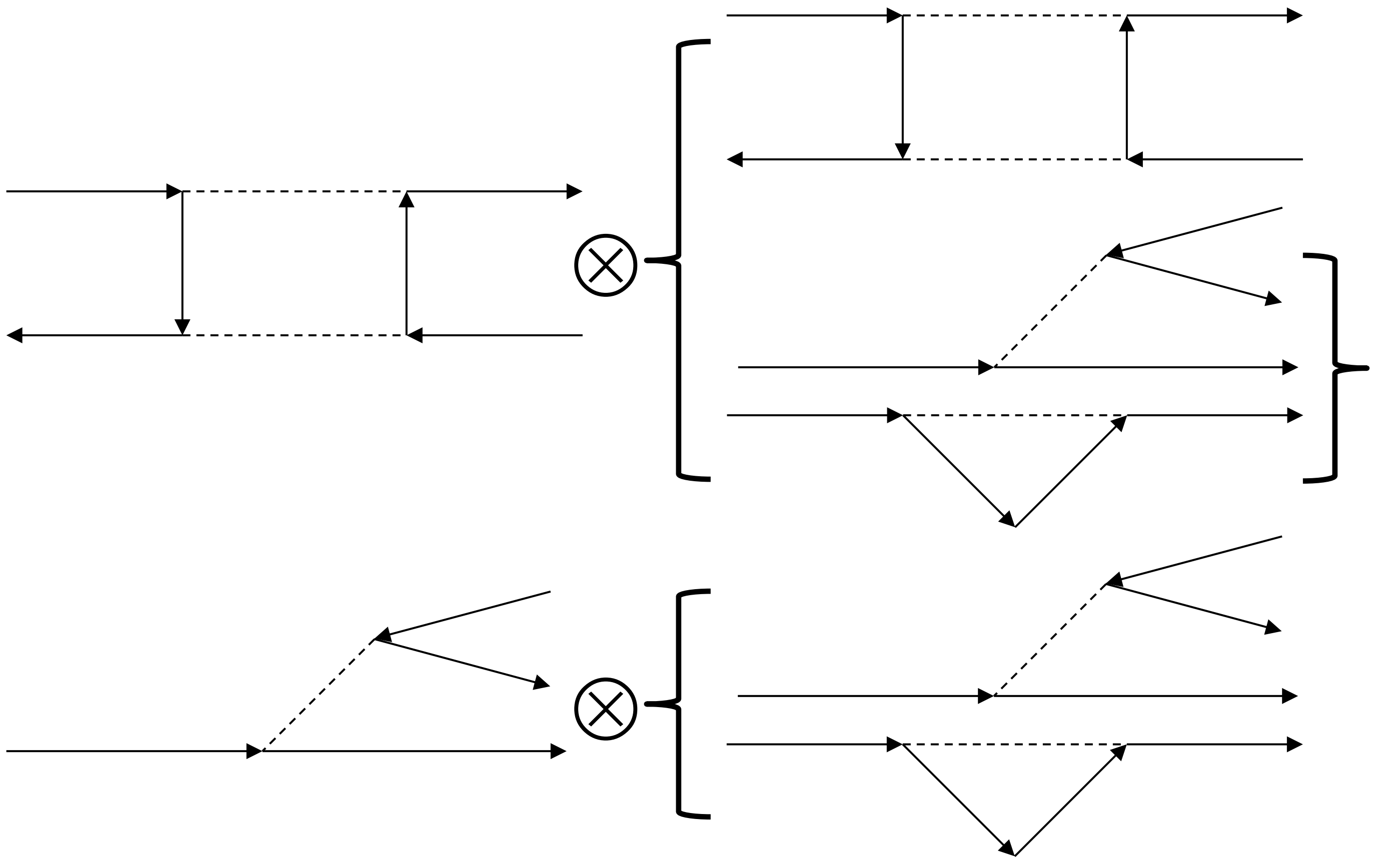

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CP violation in the decays.
arg V_{ub}, arg V_{td}, arg V_{ts}

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- CP violation in K and B systems

  For the kaon system

  i) Oscillations: Reη_{+-}, Reη_{00} (Reε) $\neq 0$

  ii) Interplay decay-oscillations: Imη_{+-}, Im$\eta_{00} \neq 0$

  iii) Decay amplitudes: $|\eta_{+-}| - |\eta_{00}| \neq 0$

  have been well experimentally established

  measured with ~5‰ accuracy for i) and ii)

  ~16% for iii)

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  Results not fully exploited ← hadronic uncertainties

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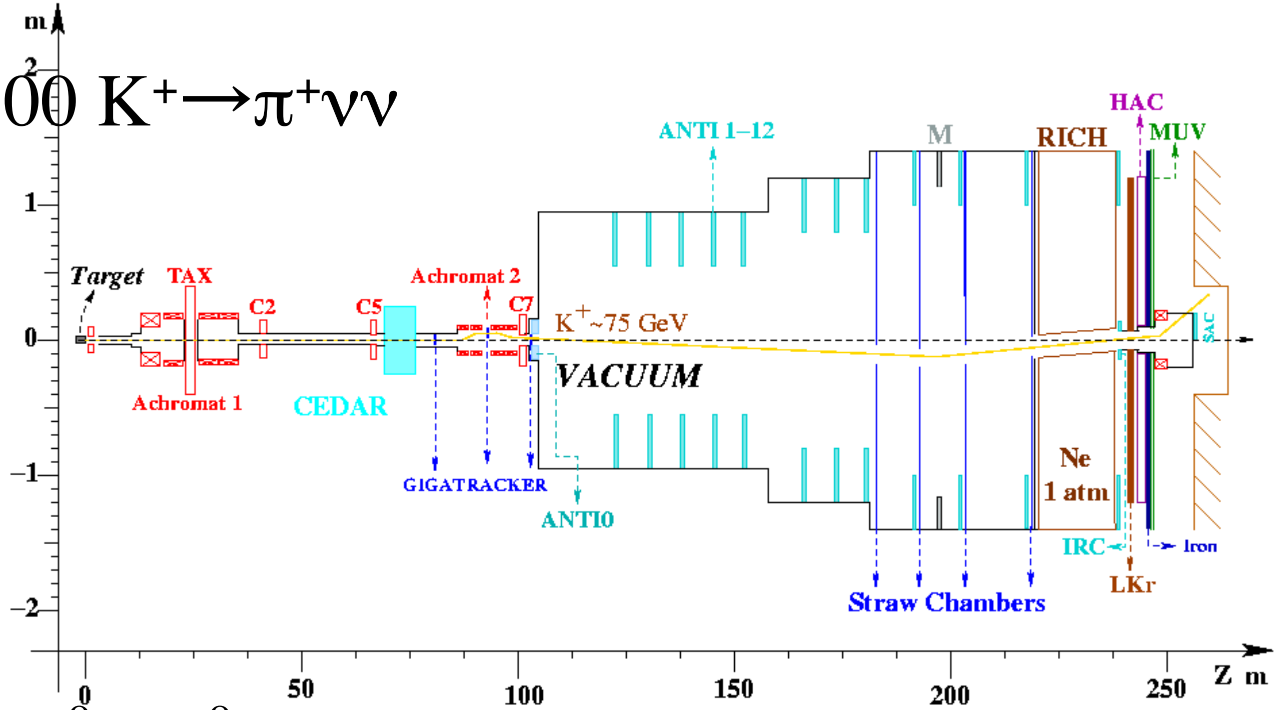
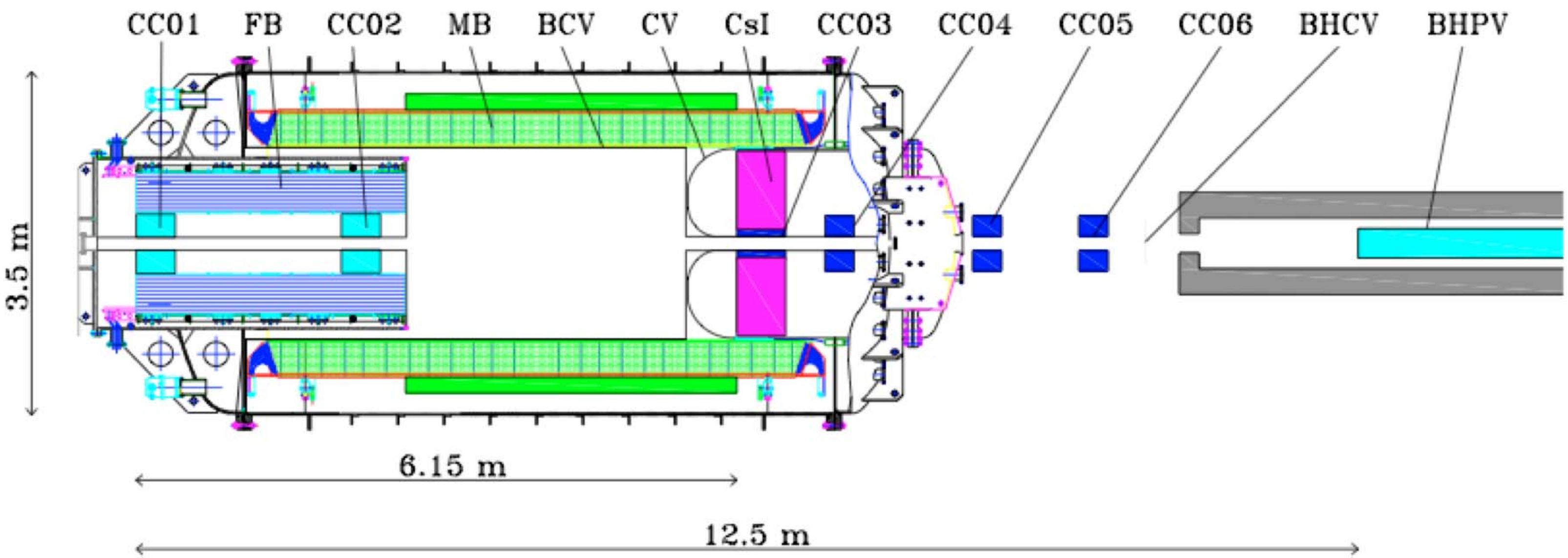
  Future: $K \rightarrow \pi\nu\bar{\nu}$ at CERN(K^+) and JPARC(K_L)

CERN NA62: ~100 $K^+ \to \pi^+ \nu\nu$



JPARC E14: few $K^0 \to \pi^0 \nu\nu$



Recent Progress

- B-factories
  - PEP-II closed down
  - KEKB completed the $\Upsilon(4S)$ run

    BBABR   433 fb^{-1} $\Upsilon(4S)$ = ~500 M BB

    Belle: 720 fb^{-1} $\Upsilon(4S)$ = ~800 M BB

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    BBABR 433 fb^{-1} $\Upsilon(4S)$ = ~500 M BB

    Belle: 720 fb^{-1} $\Upsilon(4S)$ = ~800 M BB
- Tevatron

  CDF and D0 taking data

  ~7 fb^{-1}/experiment collected

  ~10 fb^{-1}/experiment by the end of data taking

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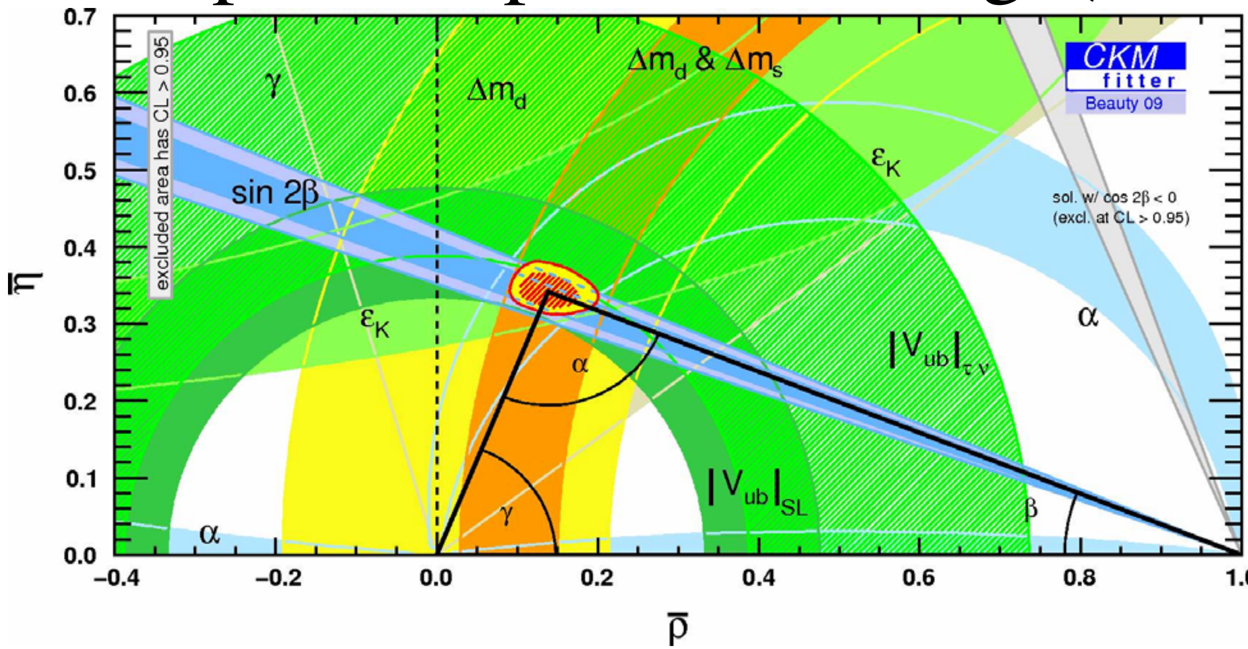
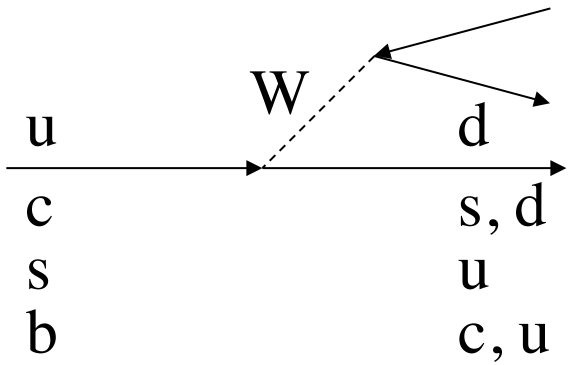


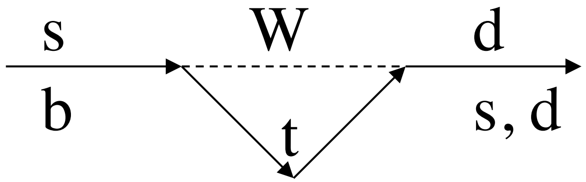
A closer look…

- If there were Physics beyond the Standard model,

Tree level decays



Penguin level decays



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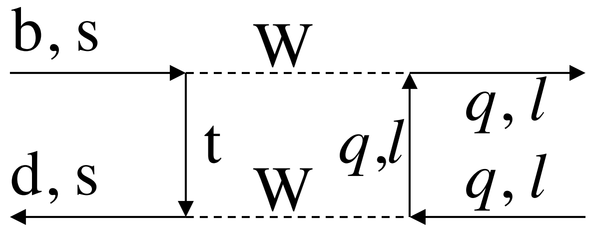

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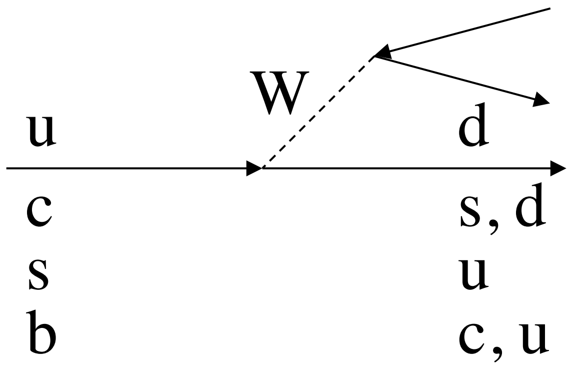

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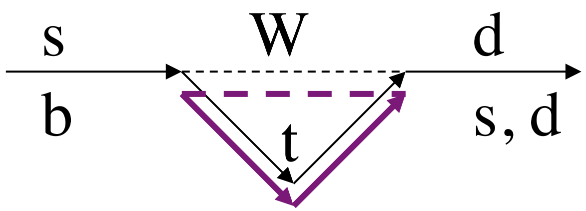

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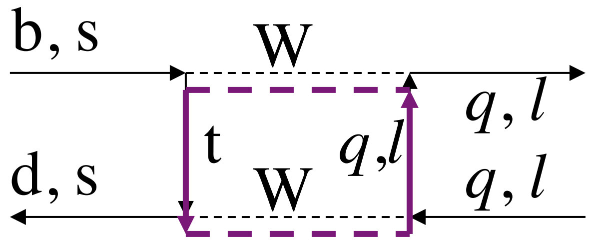


unchanged

+ new particles

Phases
Lorentz structure
Absolute values

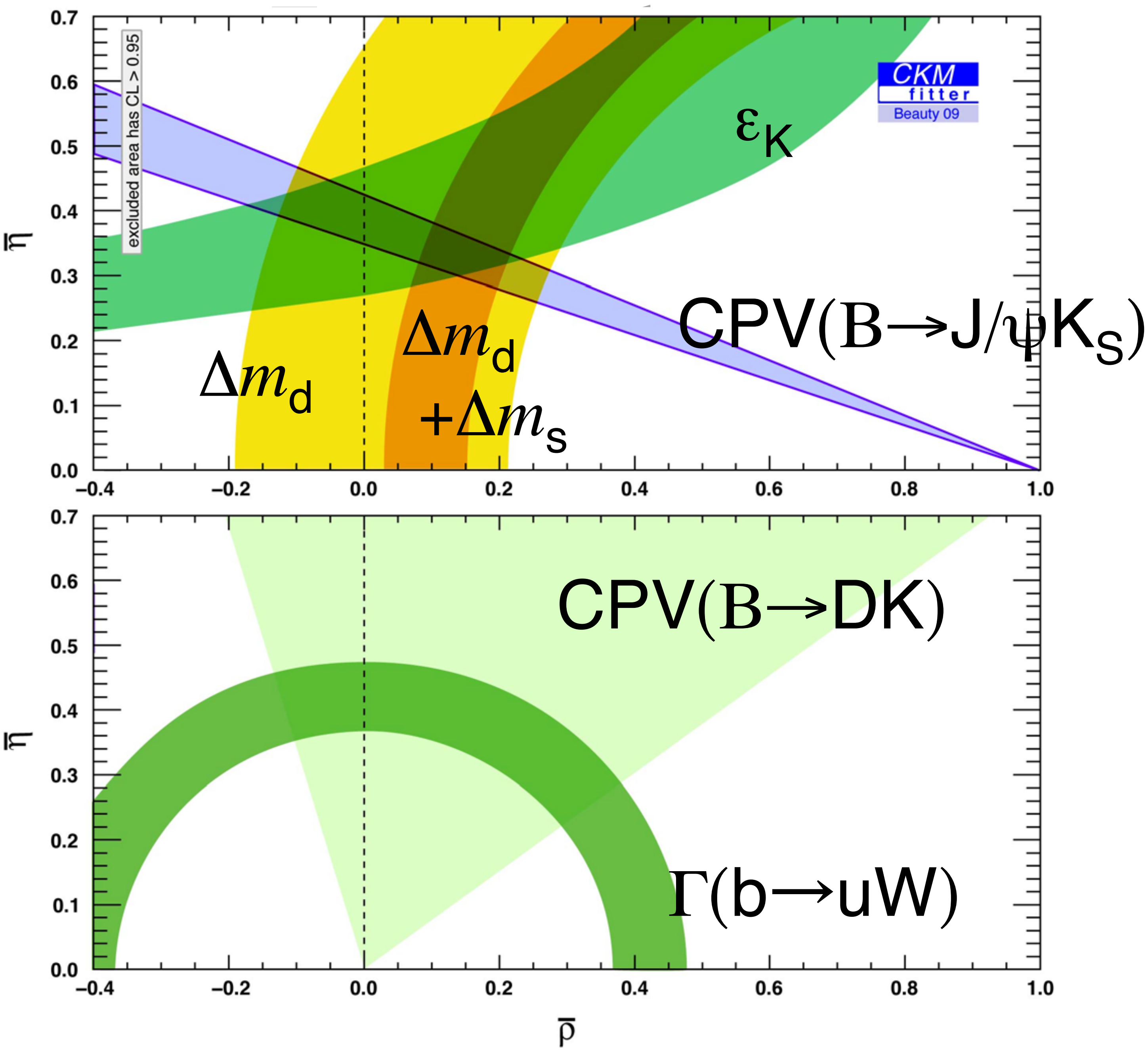
of the amplitude modified

For example…

- (ρ, η) determination with loop diagrams
  B-$\overline{\text{B}}$ oscillation frequency
  and CPV($B \to J/\psi K_S$, ε_K)
  versus
  (ρ, η) determination with tree diagrams
  CPV($B \to DK$) and $\Gamma(b \to u l \nu)$

• (ρ, η)
B-

(ρ, η)
CI


excluded area has CL > 0.95
CKM fitter
Beauty 09
ε_K
Δm_d
Δm_d
$+\Delta m_s$
CPV(B→J/ψK_S)
CPV(B→DK)
Γ(b→uW)
$\bar{\eta}$
$\bar{\rho}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

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  versus

  (ρ, η) determination with tree diagrams

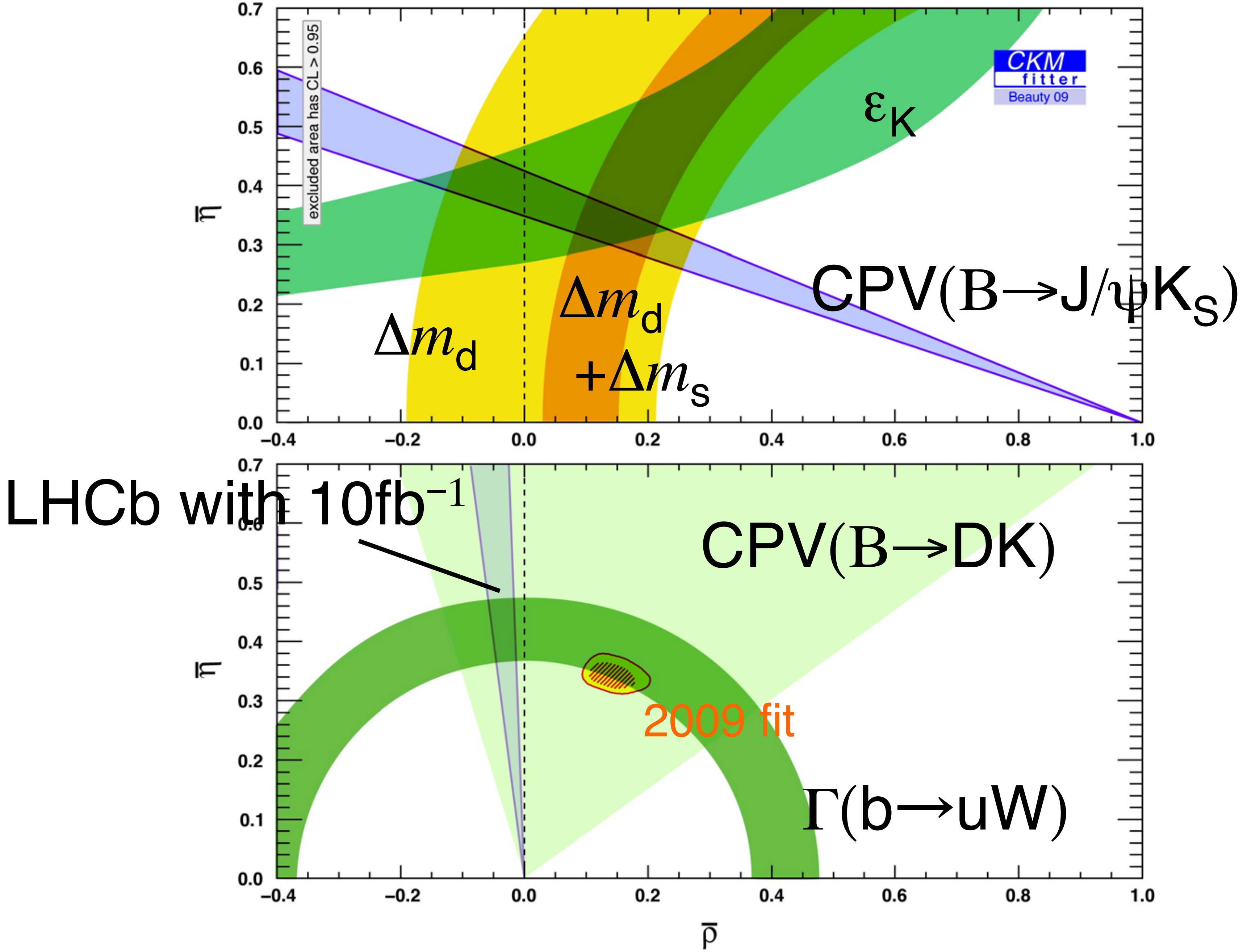
  CPV($B \rightarrow DK$) and $\Gamma(b \rightarrow u l \nu)$

  Better low energy QCD theory for $B_B f_B^{\,2}$, B_K, …

  and

  More statistics for CPV($B \rightarrow DK$) γ determination

  $\Rightarrow$LHCb experiments



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CKM fitter
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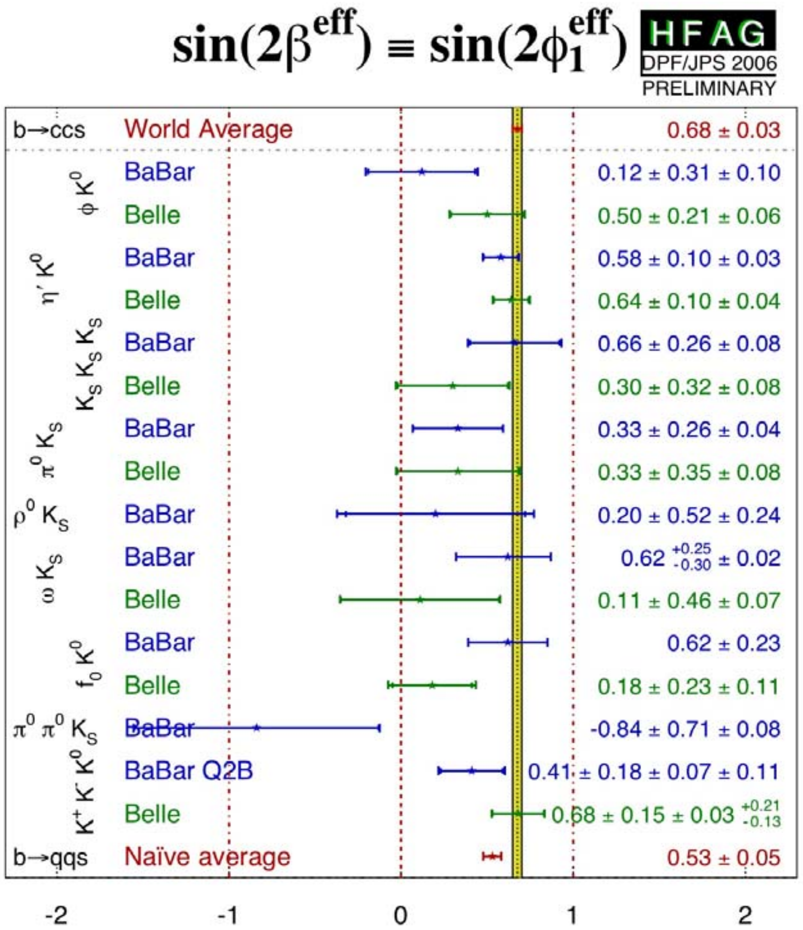
ε_K
Δm_d
$\Delta m_d + \Delta m_s$
CPV($B \rightarrow J/\psi K_S$)
$\bar{\eta}$
LHCb with $10 fb^{-1}$
CPV($B \rightarrow DK$)
2009 fit
$\Gamma(b \rightarrow uW)$
$\bar{\rho}$

Any hint of new physics?

- CPV in $B \rightarrow J/\psi K_S$ (tree) vs $\rightarrow \phi K_S$ (penguin)

in 2006



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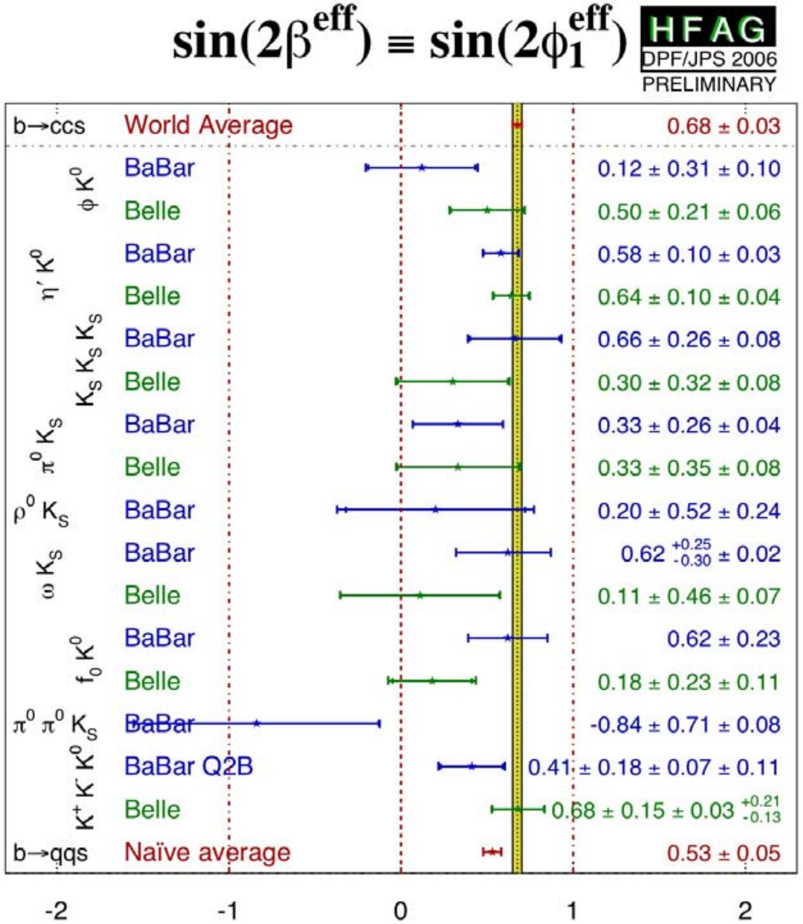
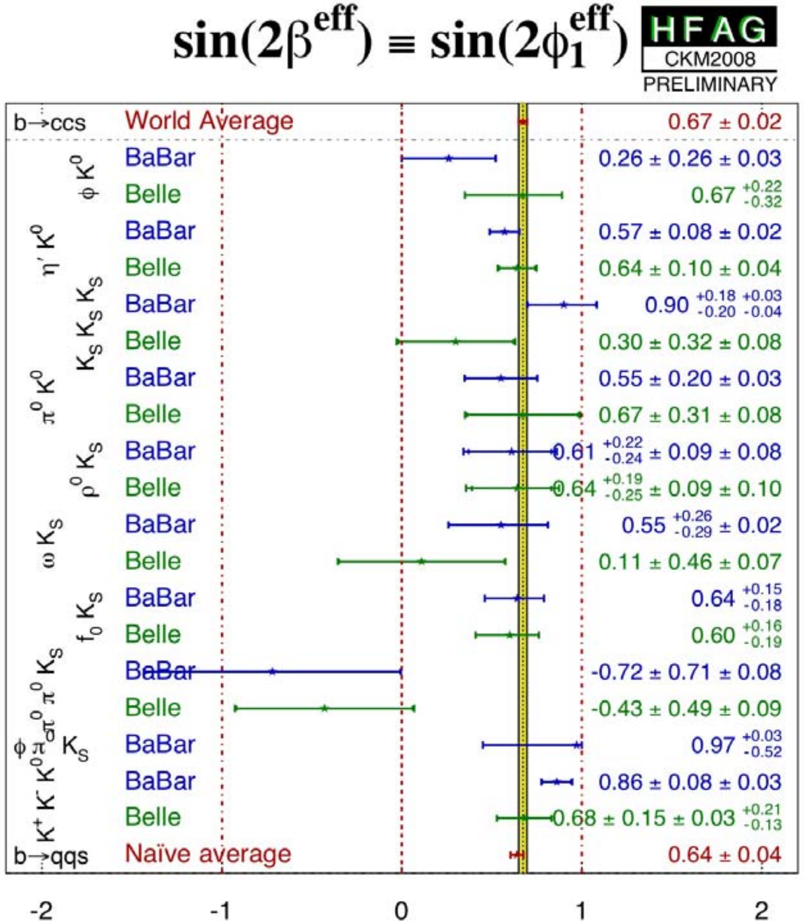


In 2009 BABAR: full statistics
Belle: ~70% statistics



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Statistically, no difference…

$\phi K_S = 0.44^{+0.17}_{-0.18}$

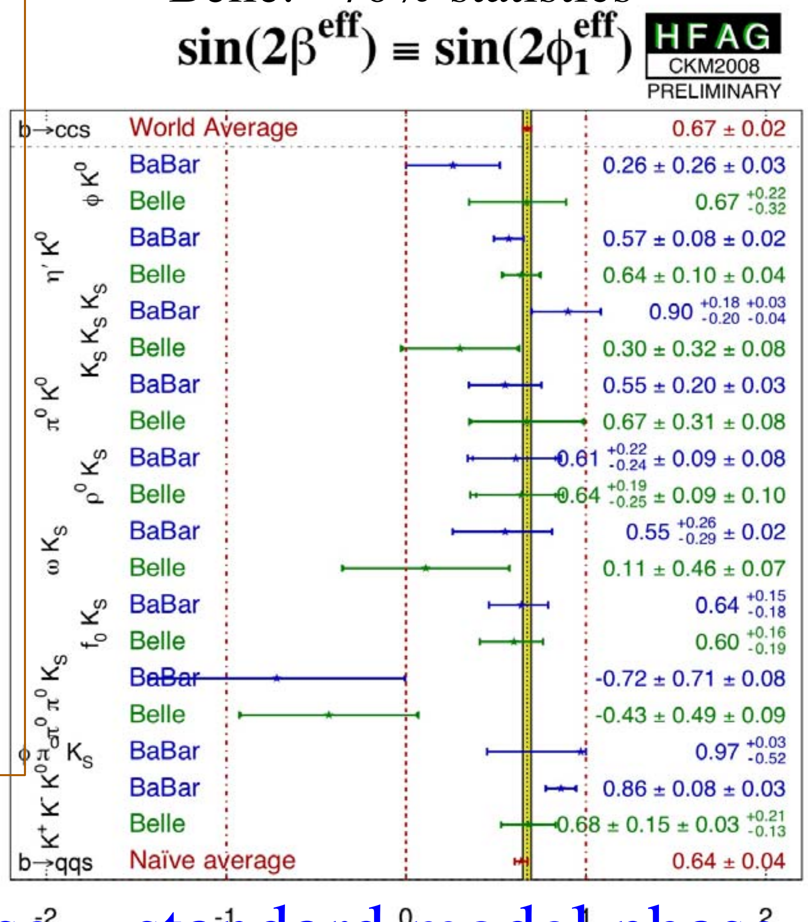
$\eta' K_S = 0.59 \pm 0.07$

Average: 0.57 ± 0.07

$J/\psi K_S = 0.67 \pm 0.02$

This is only 1.37σ effect…

Even with B factories full statistics we need 0.3 difference for 5σ discovery



b→s penguin phase = standard model phase

Any hint of new physics?

- An alternative channel for LHCb

  $B_s \to \phi\phi$

  (LHCb is not too good at $B_d \to \phi K_S$)

Yield (2 fb^{-1}): 4600 events, B/S <2.4

With 10 fb^{-1} data: $\sigma(S_{B_s \to \phi\phi}) = 0.06$

cf.

$\sigma(S_{B_d \to \phi K_S}) = 0.17$

$\sigma(S_{B_d \to \eta' K_S}) = 0.06$

with B factory full statistics

Any hint of new physics?

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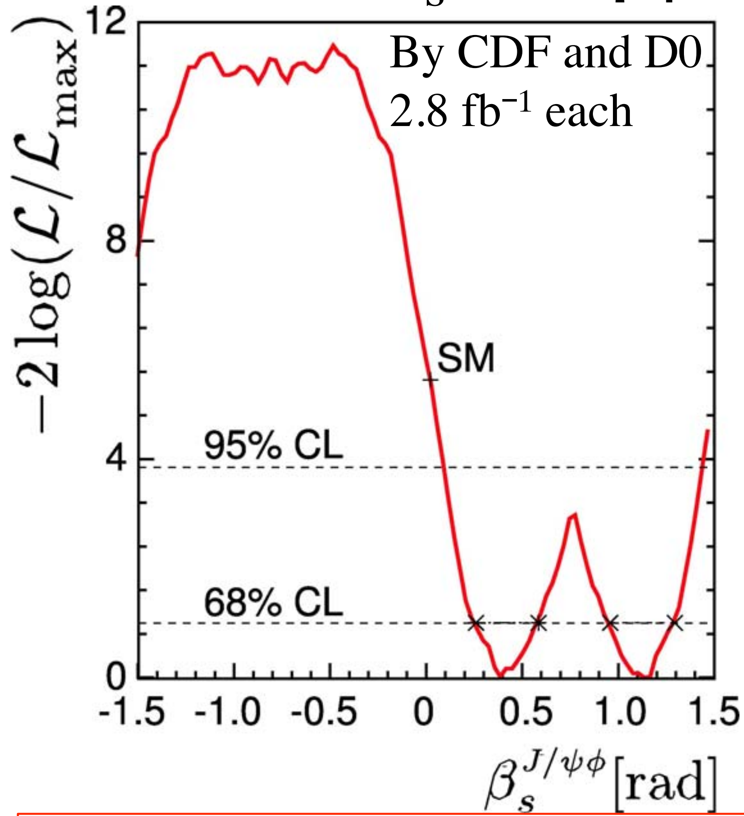
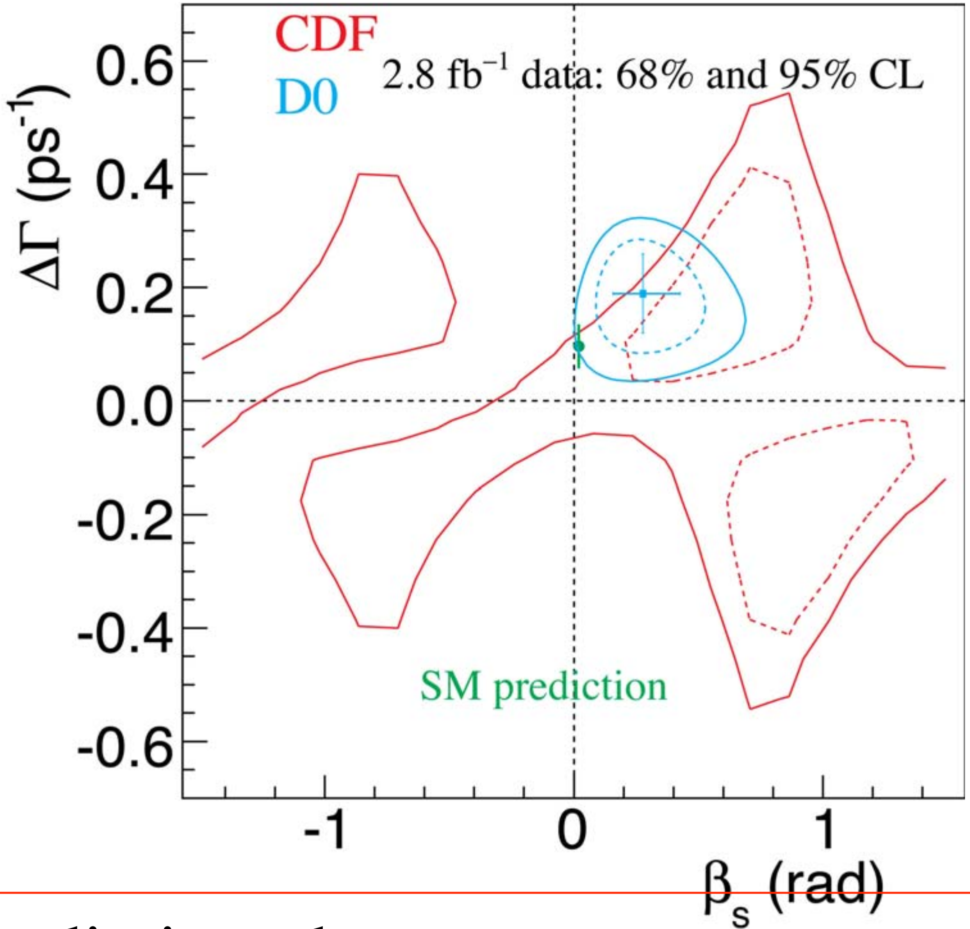


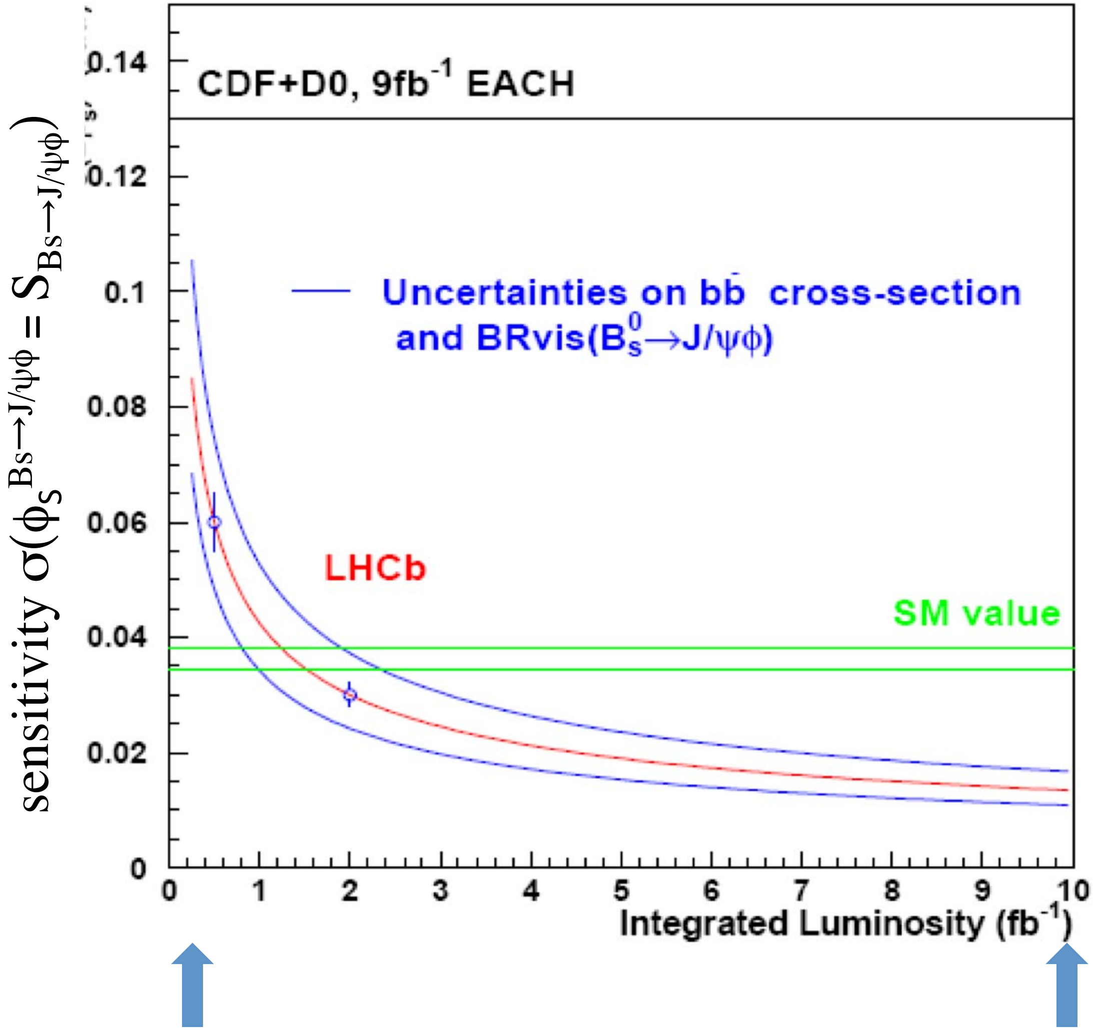


Comparing with the SM prediction, the current errors are too large to conclude anytting. CDF&D0 experimental errors will be reduced to a half.

Any hint of new physics?

- CPV in $B_s \to J/\psi\phi$

LHCb should be able to exclude or discover still possible large CPV due to new phys. during the first years of data taking



anticipated 2010 LHCb statistics

anticipated final LHCb statistics

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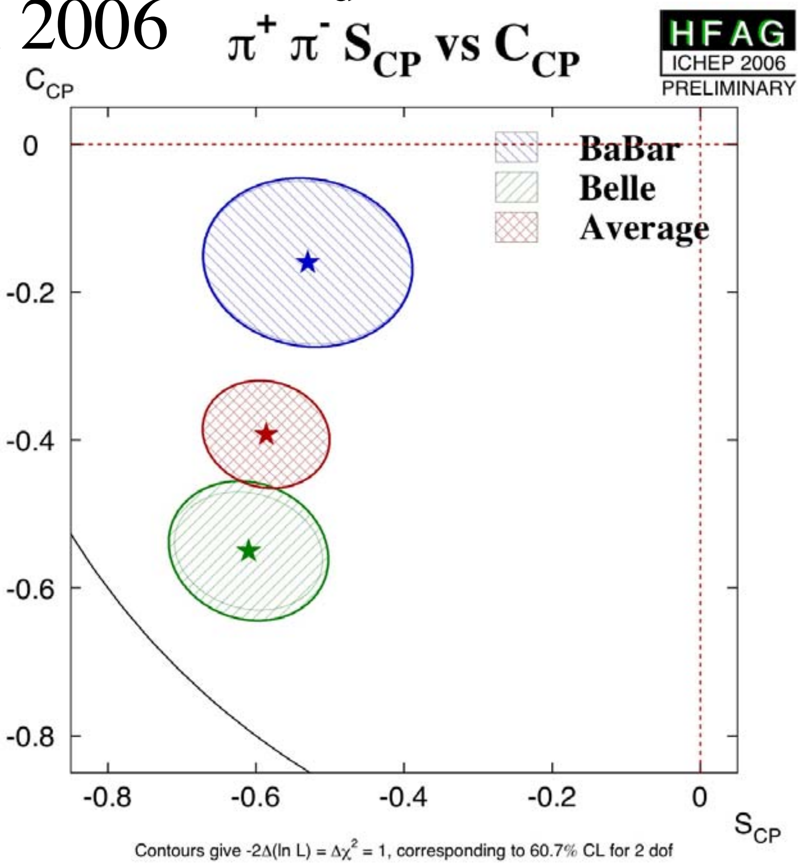

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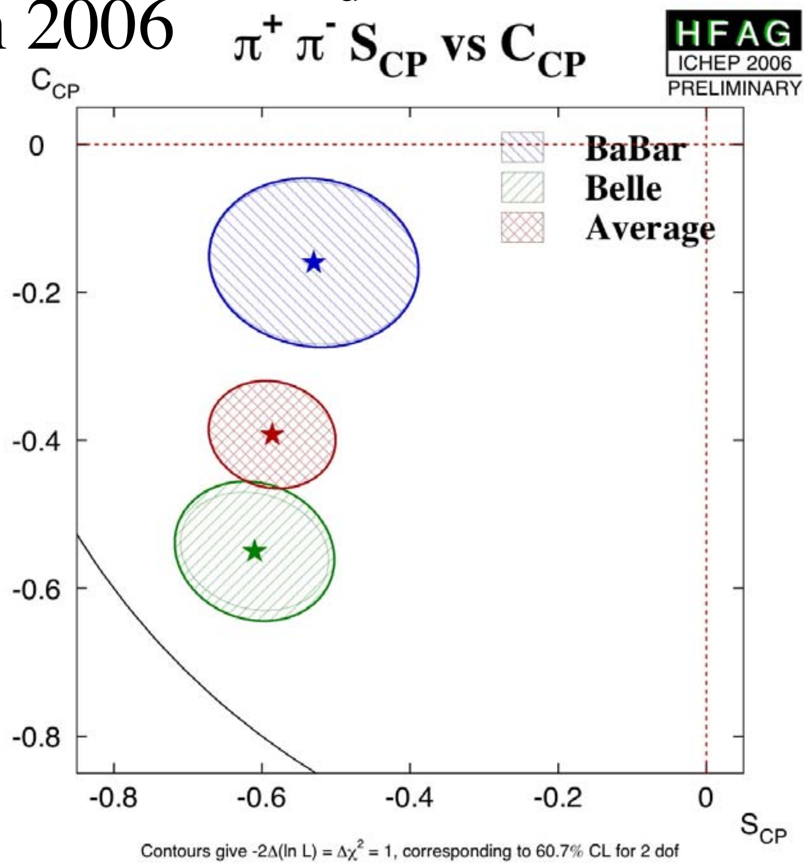

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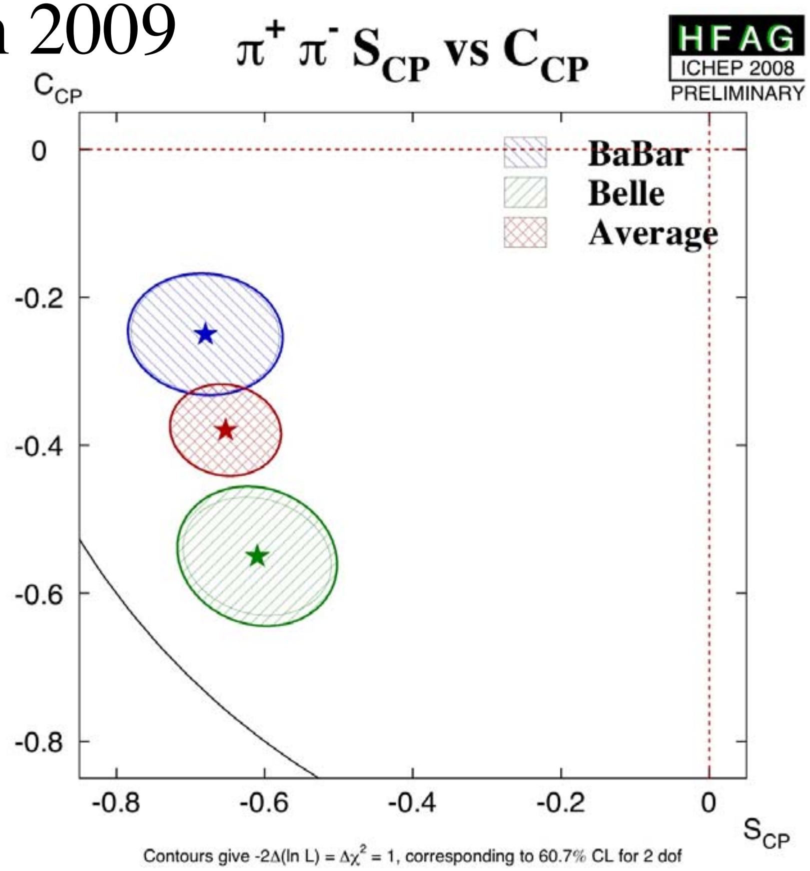

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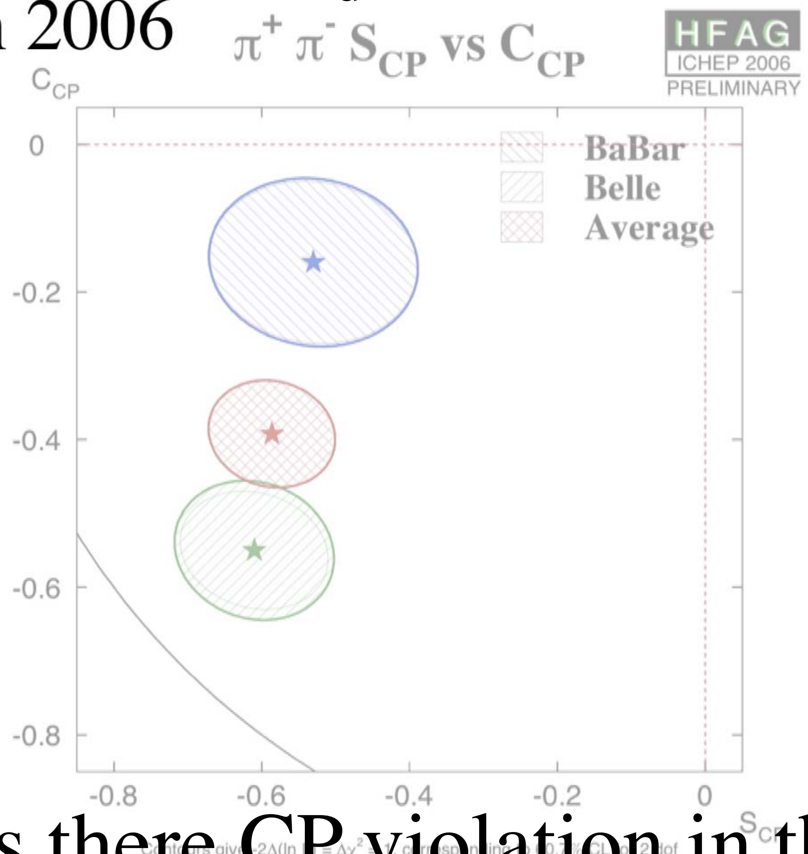

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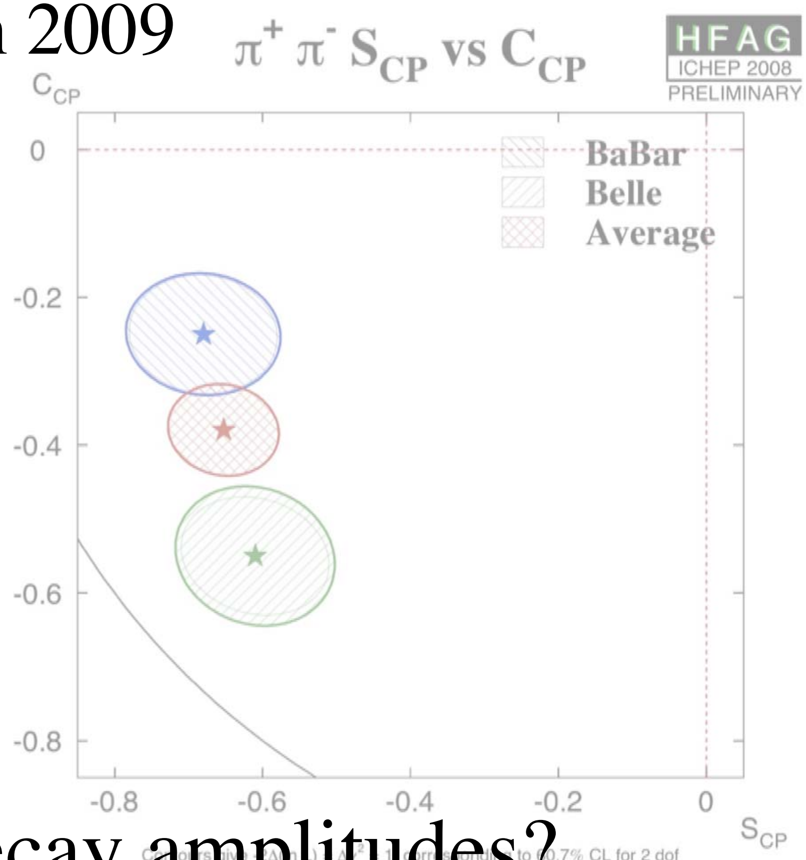


Is there CP violation in the decay amplitudes?

BABAR full statistics, Belle ~70%: →no clear answer

Belle: ~1500 $B \rightarrow \pi^+\pi^-$ LHCb: 36k/2 fb^{-1} $\varepsilon D^2 \approx 6\%$

Combine with $Bs \rightarrow K^+K^-$ a la R. Fleischer

Any hint of new physics?

- Experimentally established effects, i.e. >5σ effect, which is not well understood:
  A_{CP} difference between B^+ and $B^0 \rightarrow K\pi$

- LHCb will have high statistics samples for Kρ or B_s equivalent.
  ⇒ Will theory be able to digest, i.e. hadronic effect?

Any hint of new physics?

- What remarkable is that ε_K agrees with the measurements from the B system

ε_K: $s \to t \to d$,
$\beta_{(cc)(sd)CP}$: $b \to t \to d$
$\beta_{(ss)(sd)CP}$: $b \to t \to s$
and
γ: $b \to u$

$\Downarrow$

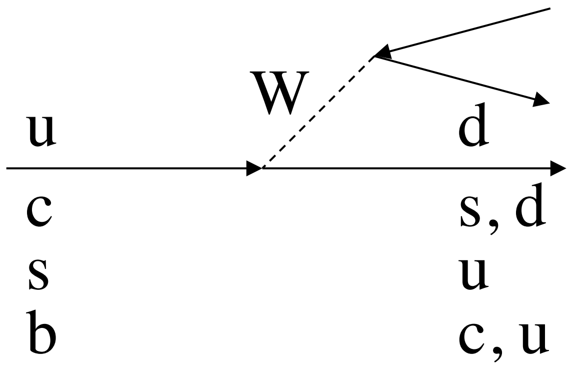
No real hit of new physics in the phases so far

$\Rightarrow$ May be new physics phases are very close to the Standard Model phase…

Back to a closer look…

- If there were Physics beyond the Standard model,

Tree level decays



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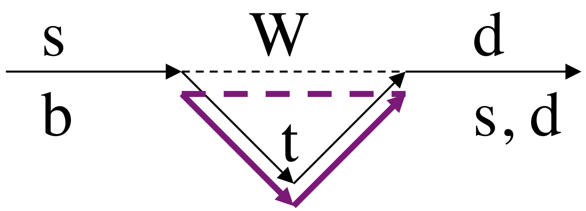

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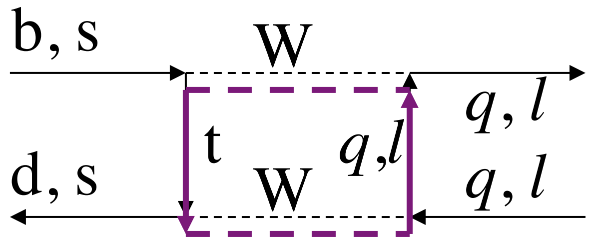


unchanged

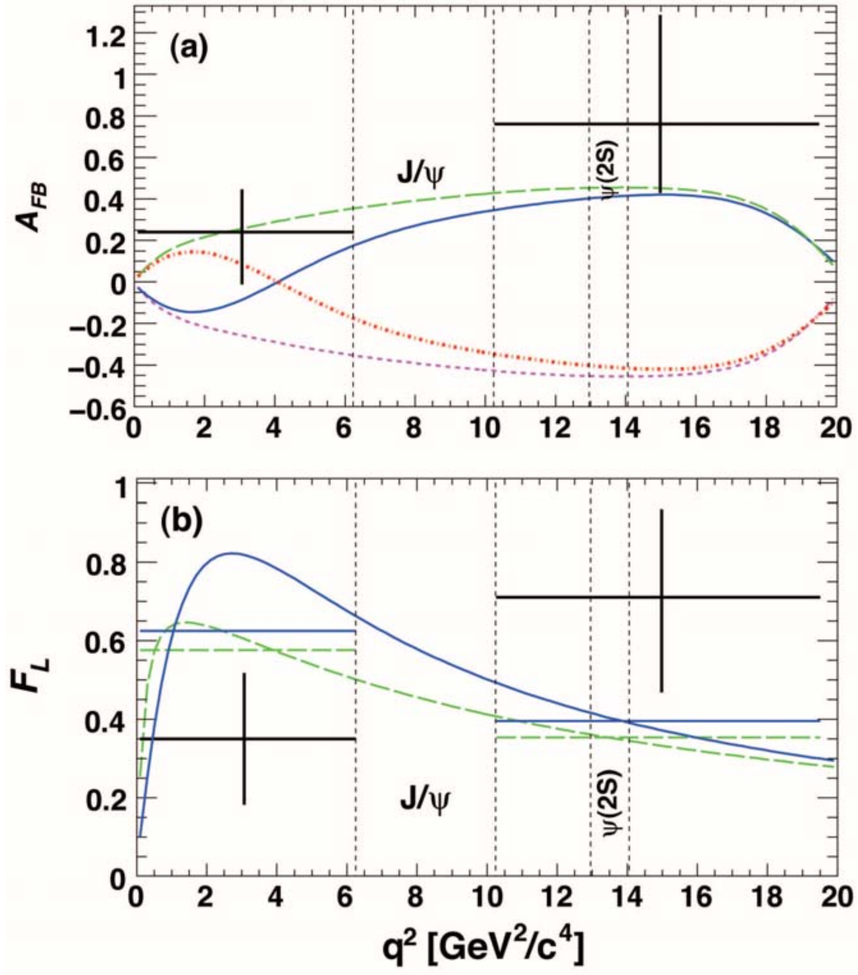
+ new particles

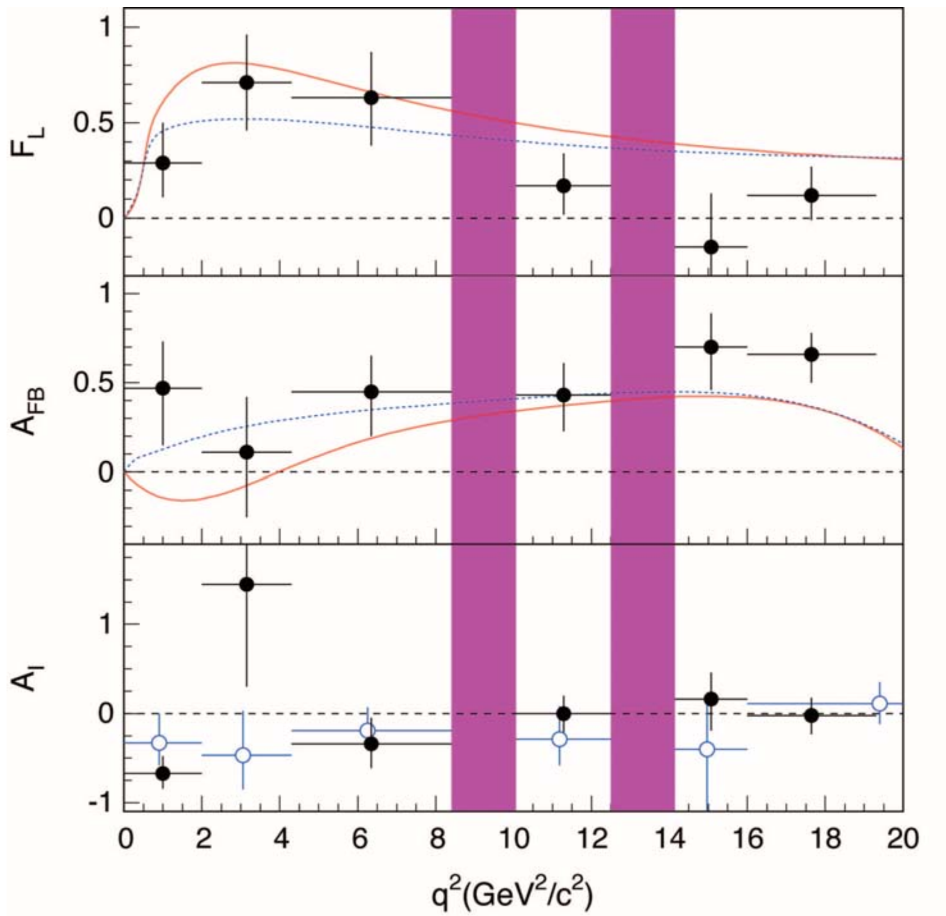
Phases
Lorentz structure
Absolute values

of the amplitude modified

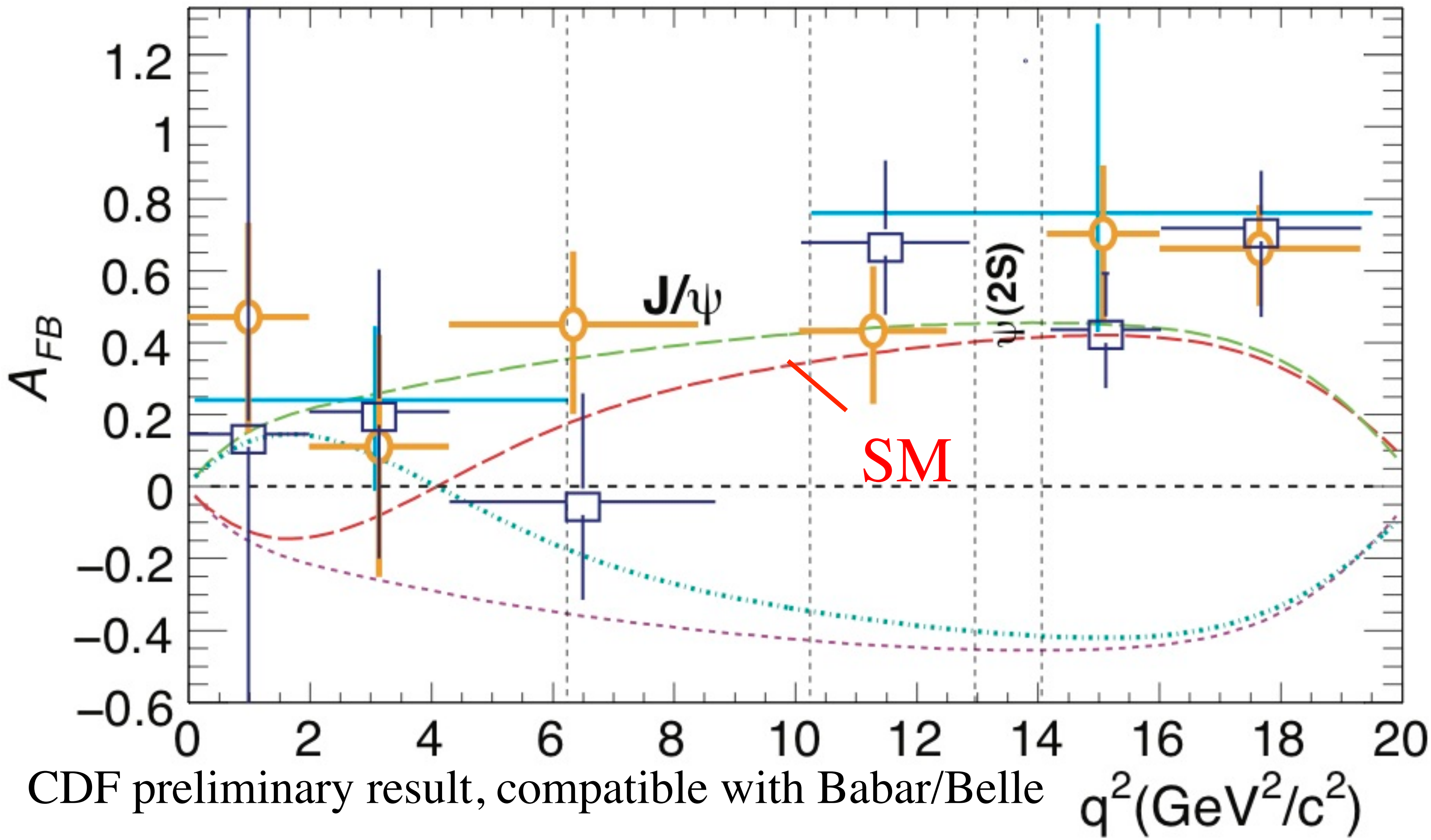
Any hint of new physics?

- $B \to K^* \mu^+ \mu^-$ angular distribution of the decay products: proving the Lorentz structure in $b \to s$



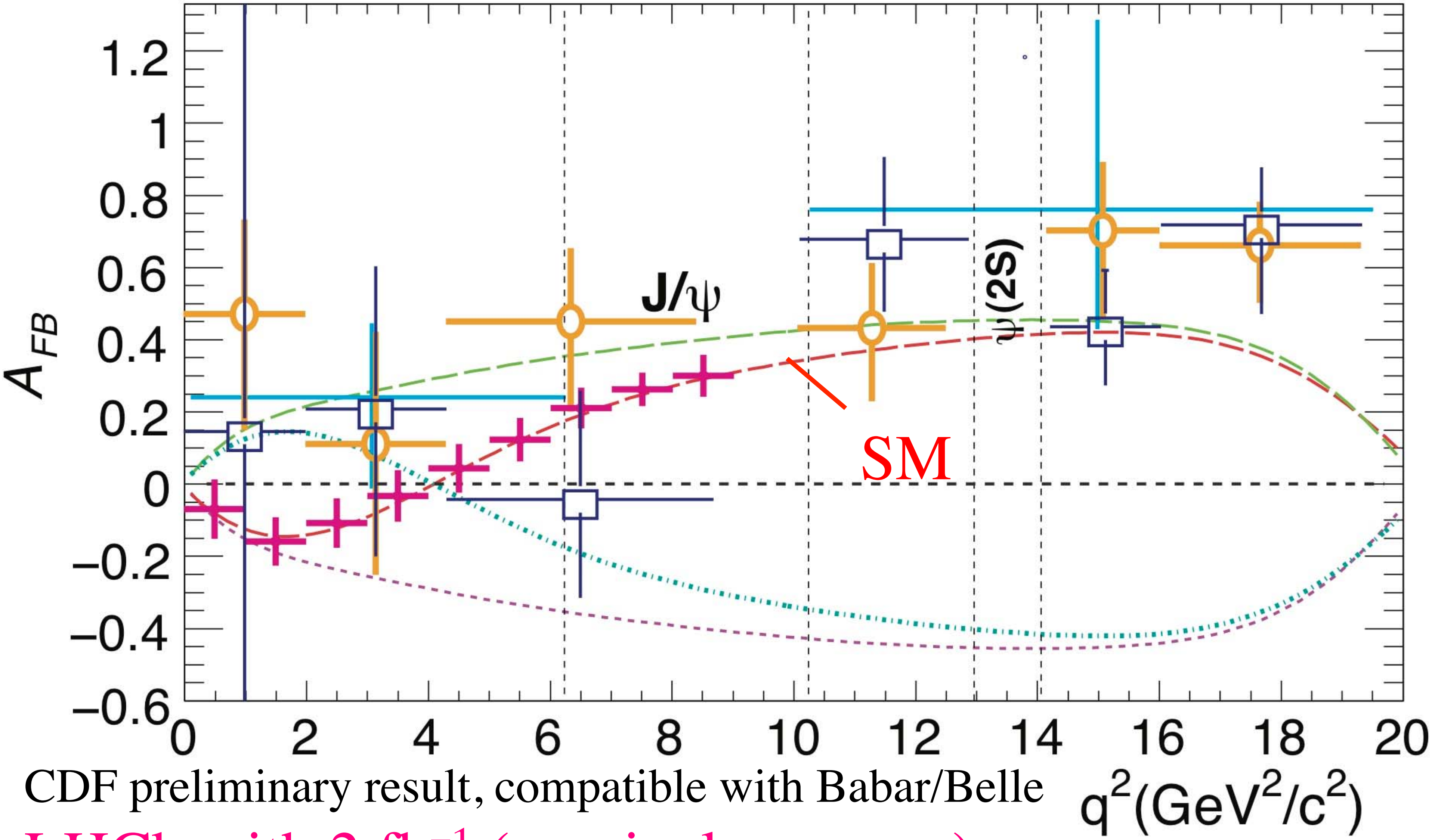


Babar(75% of data) and Belle(80% of data)



CDF preliminary result, compatible with Babar/Belle

Babar(75% of data) and Belle(80% of data)



CDF preliminary result, compatible with Babar/Belle

LHCb with 2 fb^{-1} (nominal one year)

Along the same line…

- Time dependent CP violation in $B \to f_{CP}\gamma$ only through "wrongly" polarised photon: probing the Lorentz structure in $b \to s$
  $B_d \to K^{*0}(K_S\pi^0)\gamma$ at B factories, $B_s \to \phi\gamma$ for LHCb

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

$$S = \sin 2\psi \sin\phi \qquad \psi = \tan^{-1} \frac{|A(b \to s\gamma_R)|}{|A(b \to s\gamma_L)|}$$

$$A^{\Delta} = \sin 2\psi \cos\phi$$

For B_d $\Delta\Gamma = 0$, $\sin\phi = S_{J/\psi K_S} = 0.67$ with absence of new phase

For B_s $\Delta\Gamma \neq 0$, $\sin\phi = S_{J/\psi\phi} = 0.04$ with absence of new phase

Photon polarisation from CP violation

- Belle

  $\sigma(S)={}^{+0.63}_{-0.50}$ with 253 fb^{-1} $\rightarrow \pm 0.3$ with full statistics

- BABAR

  $\sigma(S)=\pm 0.3$ with almost full statistics

$$\sigma\ (\sin 2\psi) = 0.3$$

Photon polarisation from CP violation

- Belle

  $\sigma(S)={}^{+0.63}_{-0.50}$ with 253 fb^{-1} $\rightarrow$ ±0.3 with full statistics
- BABAR

  $\sigma(S)=\pm0.3$ with almost full statistics

$$\sigma\,(\sin 2\psi) = 0.3$$

- LHCb

  $\sigma(A^{\Delta})=0.22$ and $\sigma(S) = 0.11$ with 2 fb^{-1}

  $\sigma\,(\sin 2\psi) = 0.1$ with 10 fb^{-1}

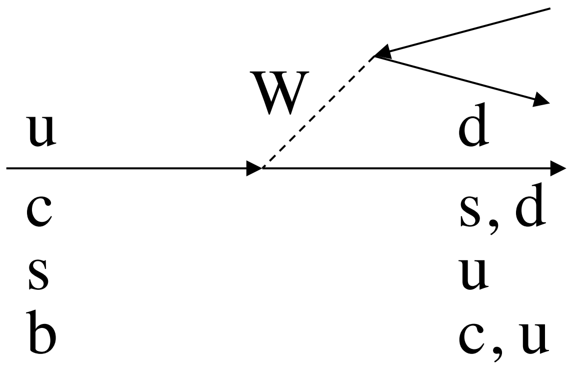
  i.e. fraction of wrongly polarised photon with ~5% error

  Also $B_d \rightarrow K^{*0}e^+e^-$ ($m_e \approx 0$)

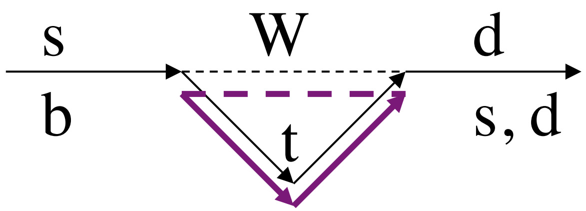
Another possibility…

- If there were Physics beyond the Standard model,

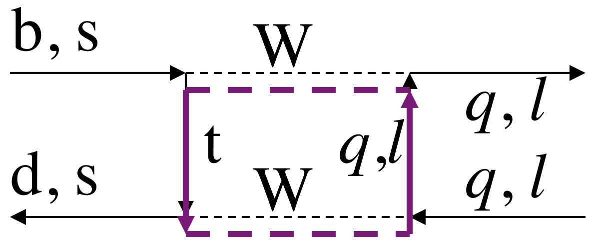
Tree level decays



Penguin level decays



Box level decays



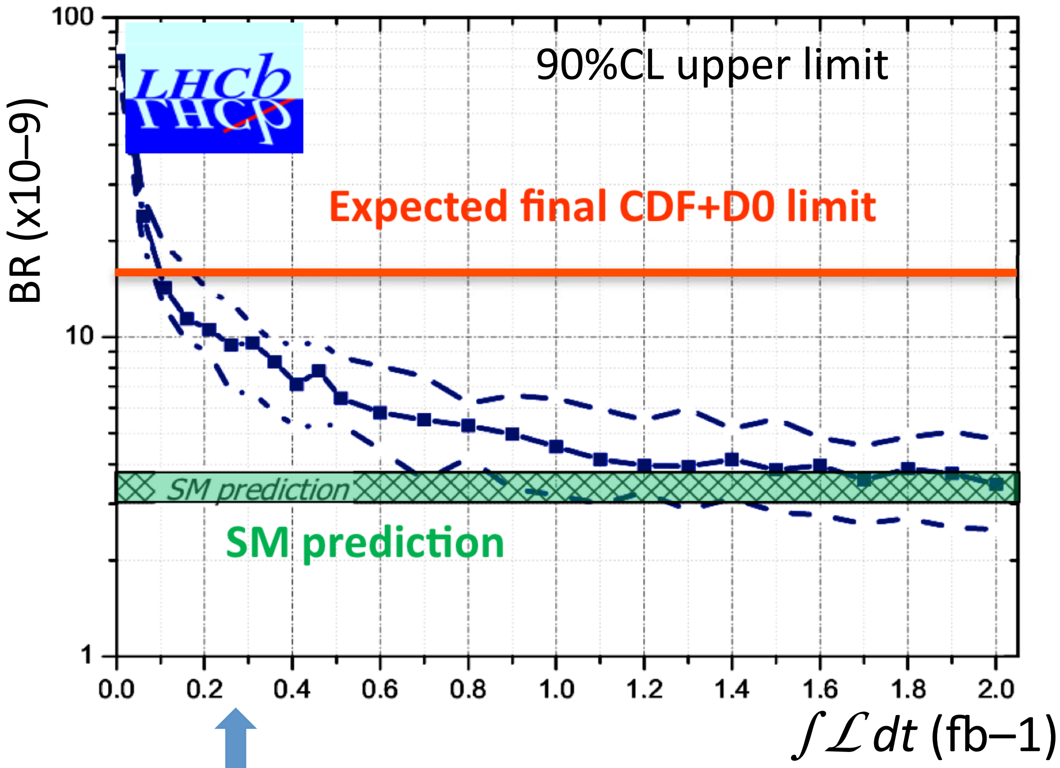
unchanged

+ new particles

Phases
Lorentz structure
Absolute values

of the amplitude modified

$B_s \to \mu^+\mu^-$



LHCb expected
2010 statistics

Exclusion @ 90% CL

- reach SM prediction: $2 fb^{-1}$

Observation if SM:

- Evidence (3σ): $3 fb^{-1}$
- Discovery (5σ): $10 fb^{-1}$

ATLAS	< 10-8	(2 fb^{-1})
CMS	< 1.4 × 10-8	(10 fb^{-1})

Charm physics

- Evidence of D-$\overline{\text{D}}$ oscillations have been seen by BABAR, Belle and CDF

  Compatible with the SM expectation but large hadronic uncertainties

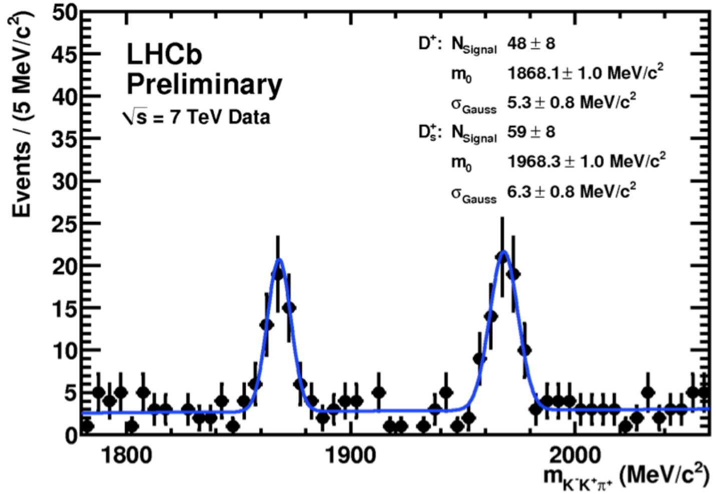
- The next step is toward CP violation

  LHCb D physics statistical error with 10 fb^{-1} data
  $\sigma(x'^2)=6.4\times10^{-5}$
  $\sigma(y')=8.7\times10^{-4}$
  $\sigma(y_{CP})=5\times10^{-3}$
  CP asymmetries for K^+K^- and $\pi^+\pi^-$ $<O(10^{-3})$

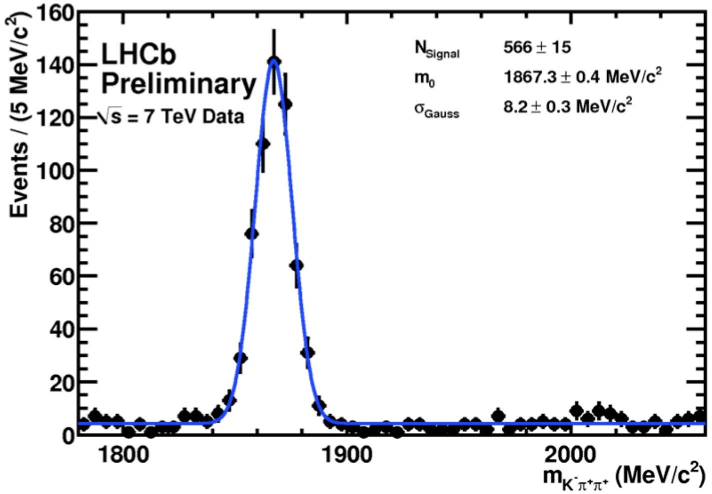
LHCb already sees charm decays

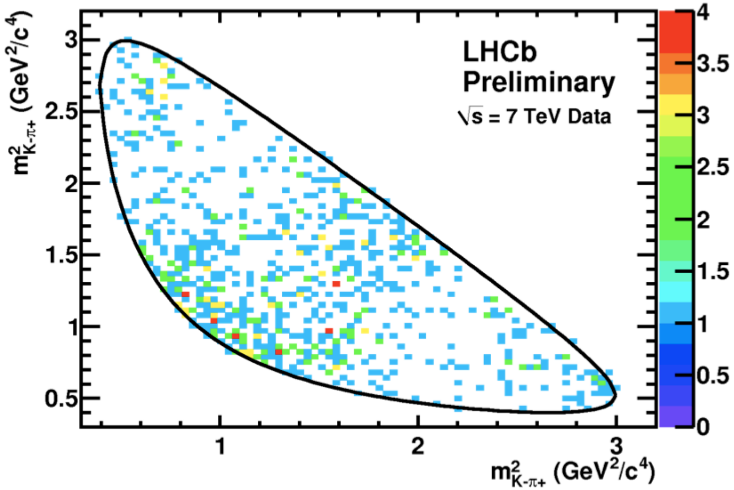
with less than
1 nb^{-1} of data
for example…

$D \rightarrow KK\pi$



$D^+ \rightarrow K^+\pi^+\pi^-$





Coming several years

- 2010 data; hopefully ~100 pb^{-1}
  overtake Tevatron for $B_s \rightarrow J/\psi\phi$ and $\mu^+\mu^-$ studies
  overtake B factories for $B_d \rightarrow K^{*0}\mu^+\mu^-$
- 2011 ~1 fb^{-1} data
  $S_{J/\psi\phi}$ and $Br(B_s \rightarrow \mu^+\mu^-)$ to the level of the SM, excluding the large New Physics effects which are still possible now
- 2014 >2 fb^{-1} data
  Start of comprehensive studies, γ, D, $\phi\gamma$, $K^{*0}\mu^+\mu^-$ full angular analysis, etc.
- ~2016 ~10 fb^{-1} data
  Phase I of LHCb competed, move to SLHCb, SB-factory, or something else?

A quick history of flavour physics

Leptons

1897 Discovery of e
1930 Postulation of ν
1936 Discovery of μ
1956 Discovery of ν
1957 Postulation of
  ν-$\bar{\nu}$ oscillations (P)
1962 Discovery of ν_μ
1962 Postulation of
  ν_e-ν_μ mixing (NMS)
1975 Discovery of τ
2000 Discovery of ν_τ
Now ν mixing well
  established

Hadrons

1932 Discovery of n
1947 Discovery of K
1956 Discovery of
  K^0-$\overline{K}^0$ oscillations
~1960 "quark" model
1963 Cabibbo mixing
1964 Discovery of CP violation
1970 GIM mechanism (c)
1973 Postulation of 3rd family (KM)
1974 Discovery of c
1977 Discovery of b
1995 Discovery of t
Now CKM picture well established

How are they related? Where do we find the next surprise?

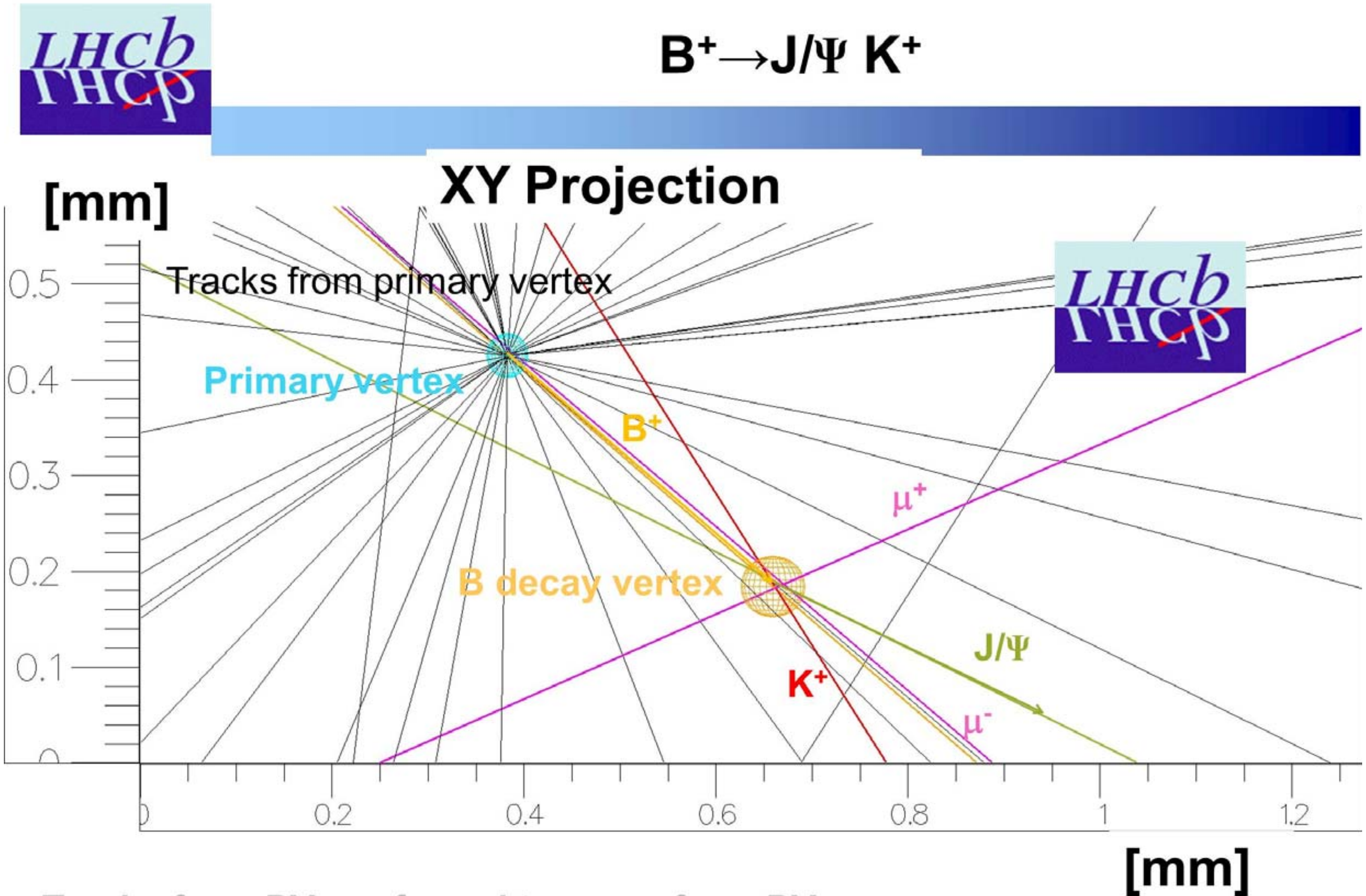
Conclusions

- Flavour physics was instrumental for establishing the Standard Model. Many clear indirect indications before the direct discovery by the energy frontier experiments.

Conclusions

- Flavour physics was instrumental for establishing the Standard Model. Many clear indirect indications before the direct discovery by the energy frontier experiments.
- We all hope that within the coming five years to see clear signs for Physics Beyond the Standard Model, both directly and indirectly…

We see B's at LHC



Tracks from PV are forced to come from PV