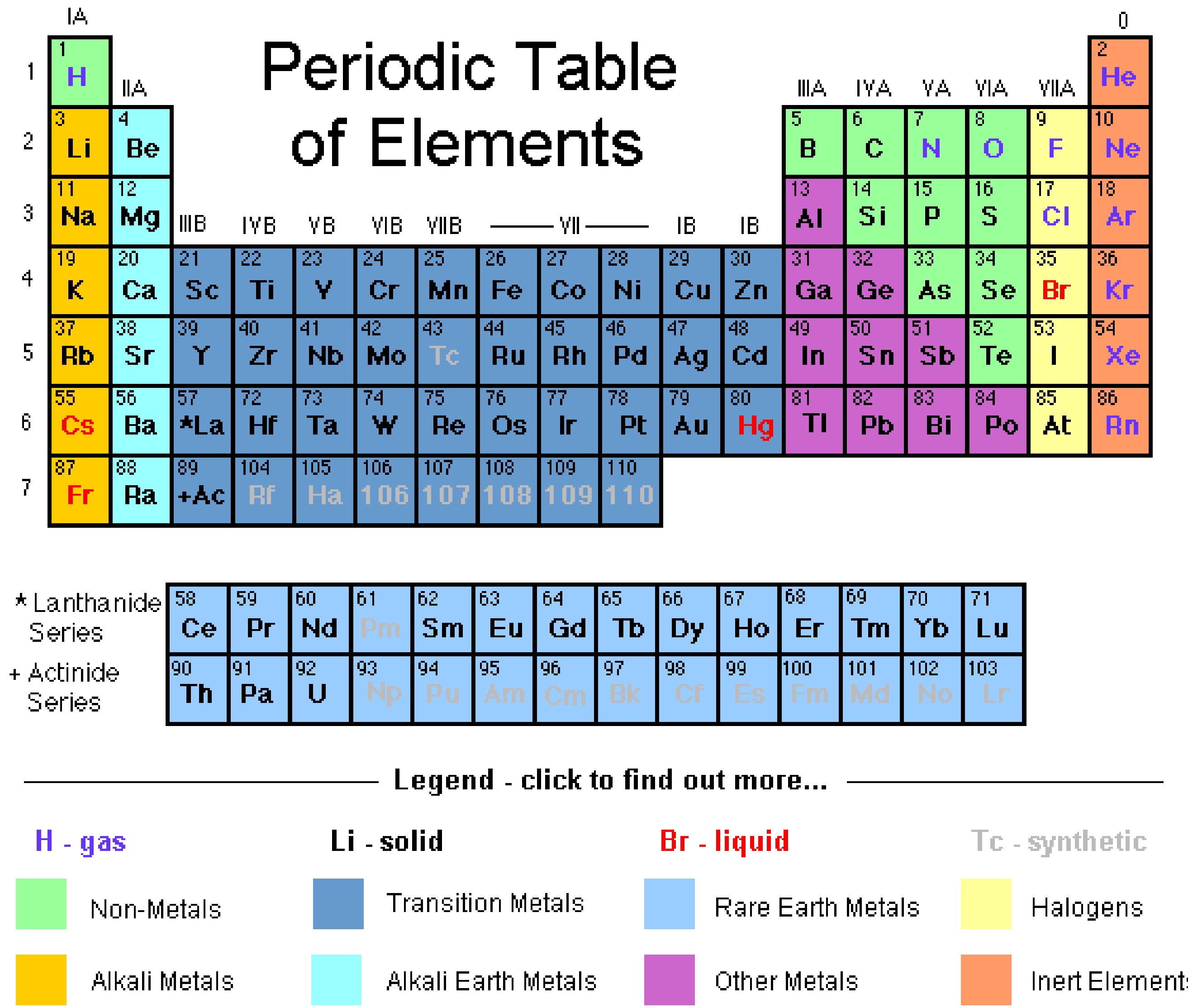
B physics experiments:
Current status and future prospects

Tim Gershon
University of Warwick

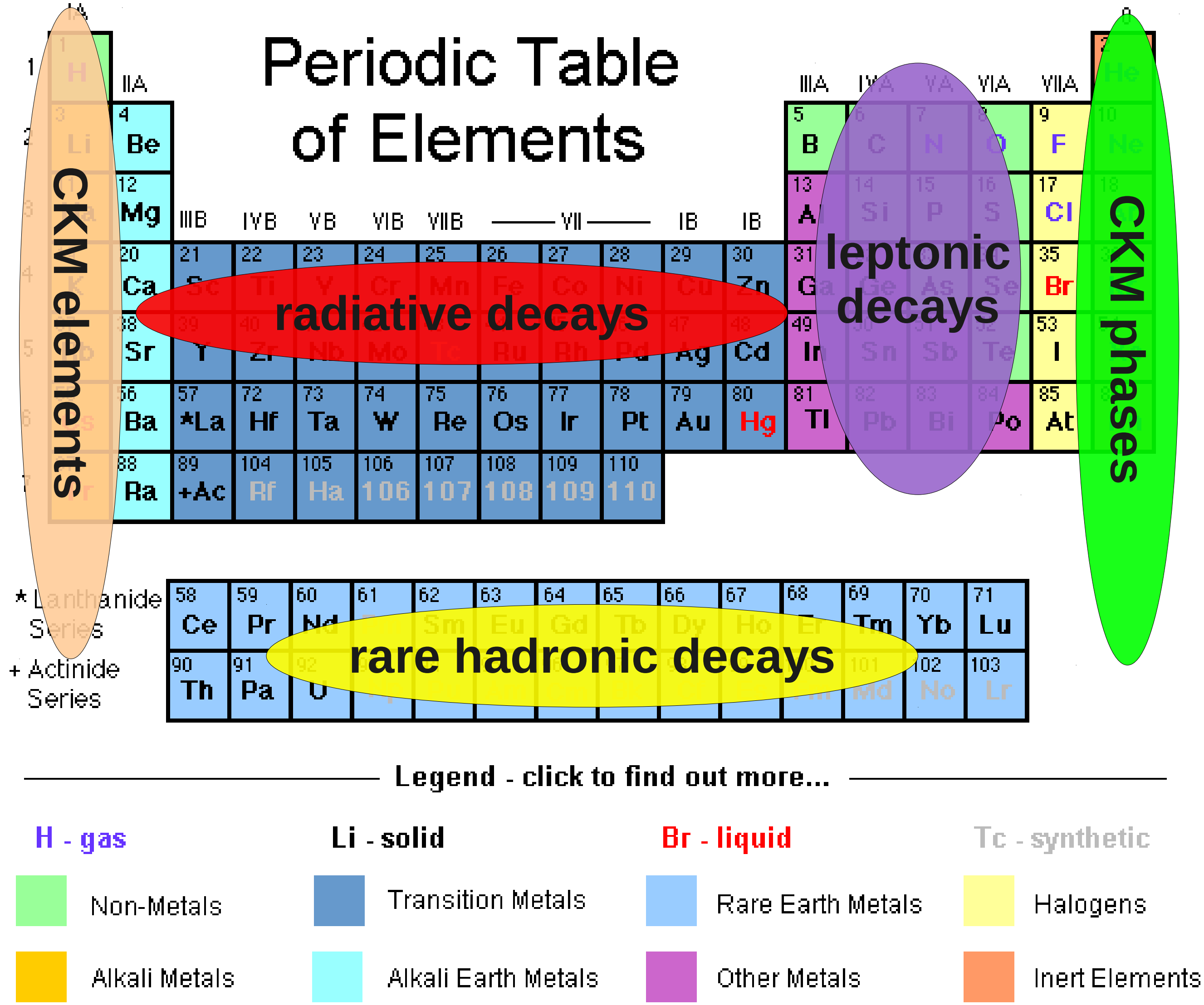
WHEPPXI
Workshop on High Energy Physics Phenomenology

January 2010

“B Chemistry”


Periodic Table
of Elements
IA IIA IIIB IVB VB VIB VIIB —— VII —— IB IB IIIA IVA VA VIA VIIA 0
1 H 2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 57 *La 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 89 +Ac 104 Rf 105 Ha 106 106 107 107 108 108 109 109 110 110
* Lanthanide Series 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
+ Actinide Series 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr
Legend - click to find out more...
H - gas
Li - solid
Br - liquid
Tc - synthetic
Non-Metals
Transition Metals
Rare Earth Metals
Halogens
Alkali Metals
Alkali Earth Metals
Other Metals
Inert Elements

"B Chemistry"



Periodic Table of Elements
CKM elements
radiative decays
leptonic decays
CKM phases
rare hadronic decays
* Lanthanide Series
+ Actinide Series
Legend - click to find out more...
H - gas
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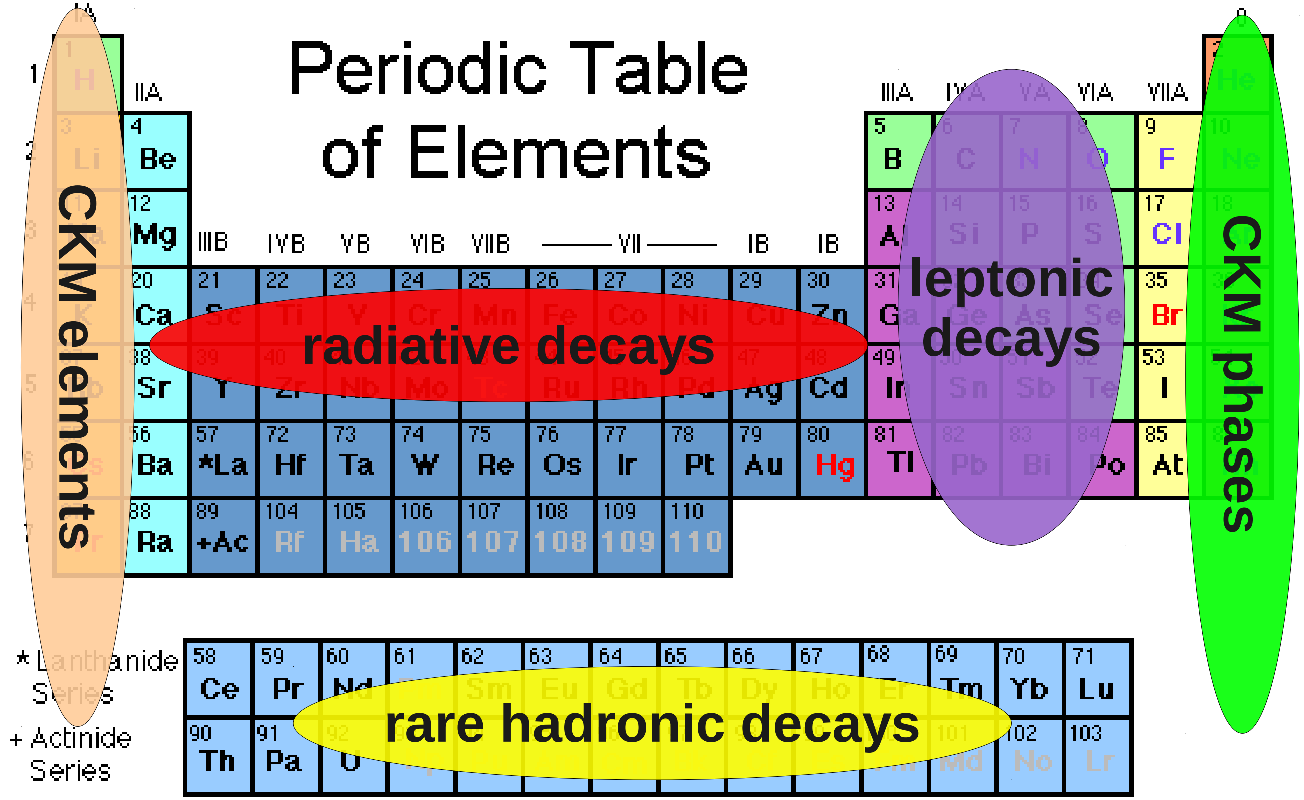
“B Chemistry”



Looks complicated but...

- governed by simple rules
- not fully explored
- uncovering the underlying physics

→ deep insights

B physics experiments

- BaBar:
  - data taking concluded 2008
- Belle:
  - still running; planned 3 year shutdown starting 2010
  - to be followed by Belle2; government decision imminent
- CDF & D0:
  - still running, still taking B physics triggers
- LHCb:
  - just started; upgrade planned after ~5 years data taking
- ATLAS & CMS:
  - just started; good opportunities for B physics at low luminosity
- SuperB:
  - new planned e^+e^- facility in Italy; government decision imminent
  - could be taking data in ~5 years

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asymmetric e^+e^- colliders

hadron colliders

Outline of the talk

B hadrons & spectroscopy

The CKM matrix & the Unitarity Triangle

- Angles of the Unitarity Triangle
- Sides of the Unitarity Triangle

Rare decays

- Leptonic decays
- Radiative decays

Outline of the talk

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Rare decays

- Leptonic decays
- Radiative decays

Necessarily selective

- Apologies for omissions

Focus on

- New physics sensitive channels
- New results
- Future prospects

ALL RESULTS ARE PRELIMINARY
UNLESS PUBLISHED REFERENCE GIVEN

Start of B physics – 1977

VOLUME 39, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1977

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

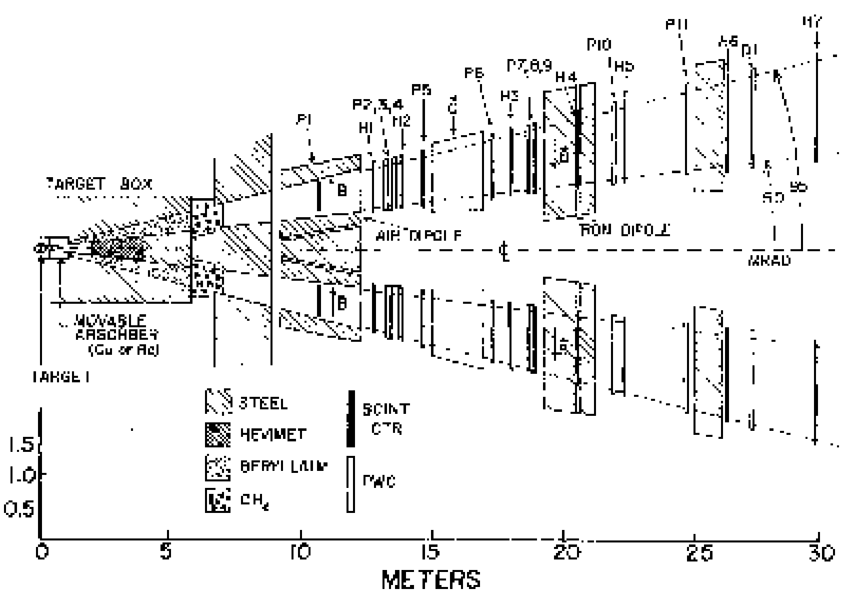


FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter $\check{C}$. Each arm is up/down symmetric and hence accepts both positive and negative muons.

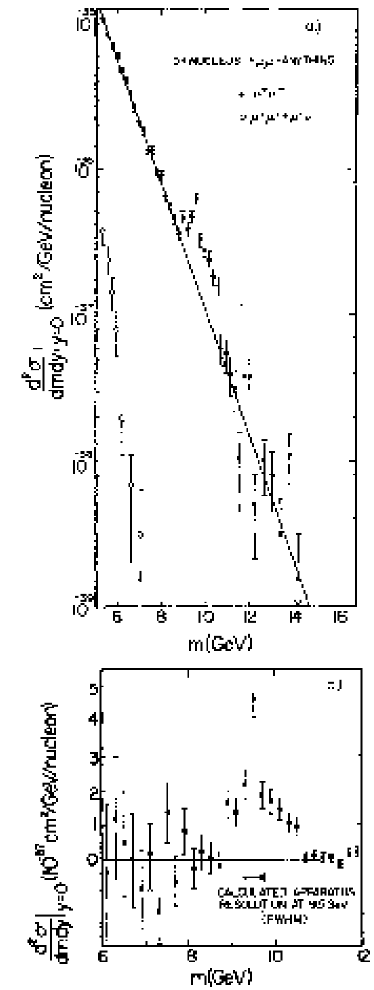
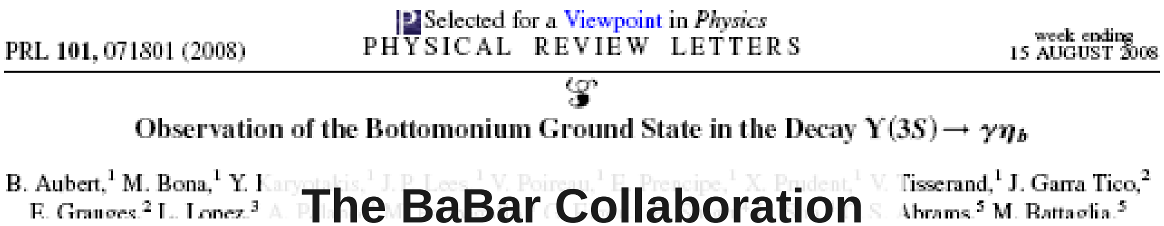


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign-dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

Discovery of the lightest $b\bar{b}$ state – 2008


Selected for a Viewpoint in *Physics*

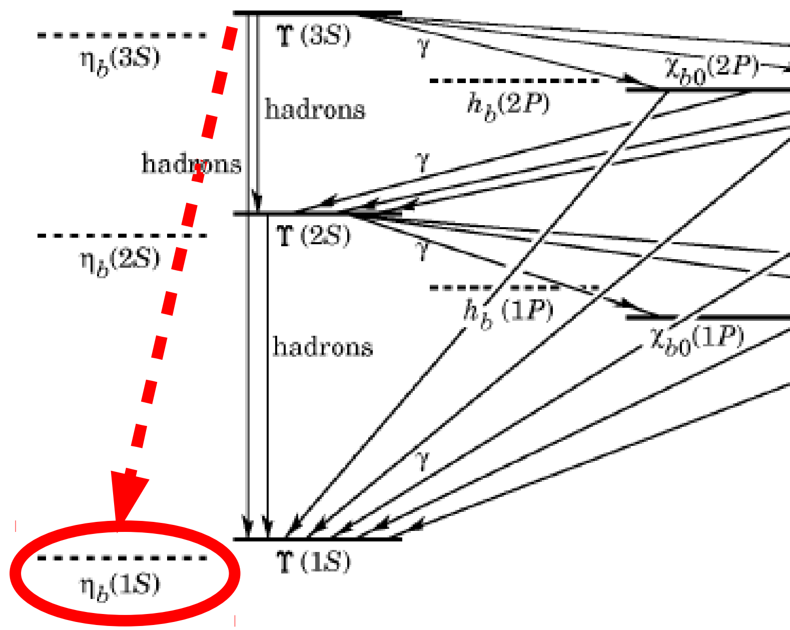
PRL 101, 071801 (2008) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2008

Observation of the Bottomonium Ground State in the Decay $\Upsilon(3S) \to \gamma\eta_b$

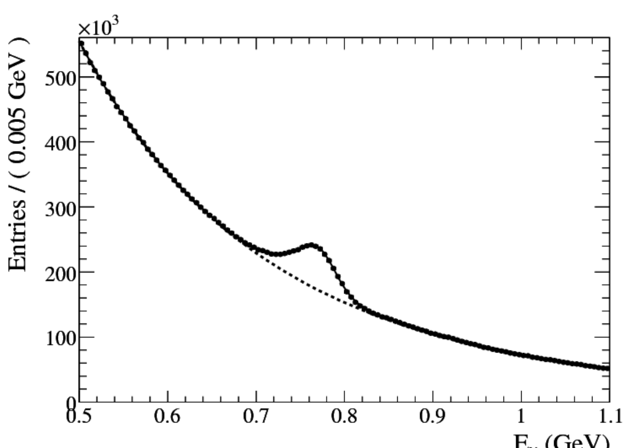
B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez,[3] A. Palano,[3] M. ... S. Abrams,[5] M. Battaglia,[5]

The BaBar Collaboration

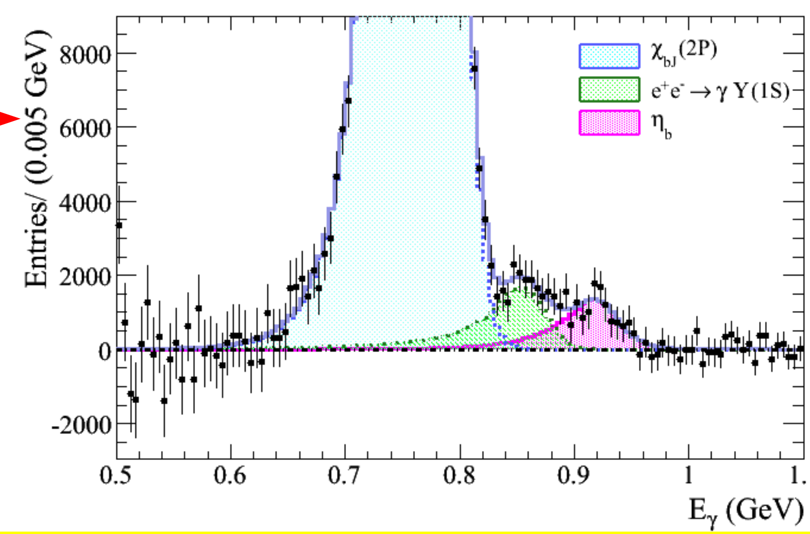
Only recoil γ is reconstructed



$$m(\eta_b(1S)) = (9388.9\,^{+3.1}_{-2.3} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$m(\Upsilon(1S)) - m(\eta_b(1S)) = (71.4\,^{+2.3}_{-3.1} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$B(\Upsilon(3S) \to \gamma\,\eta_b(1S)) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$



subtract smoothly varying background

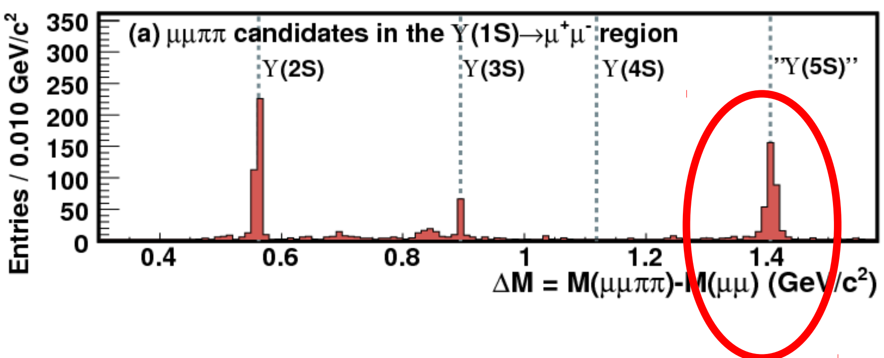


Signal confirmed in Υ(2S) transitions by BaBar, and by CLEO

$b\bar{b}$ spectroscopy

Excess of "Υ(5S)"→Υππ

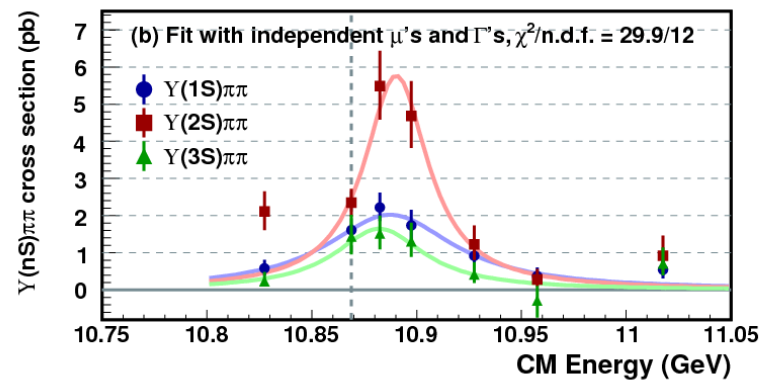
Belle PRL 100 (2008) 112001



Huge excess over expected rate

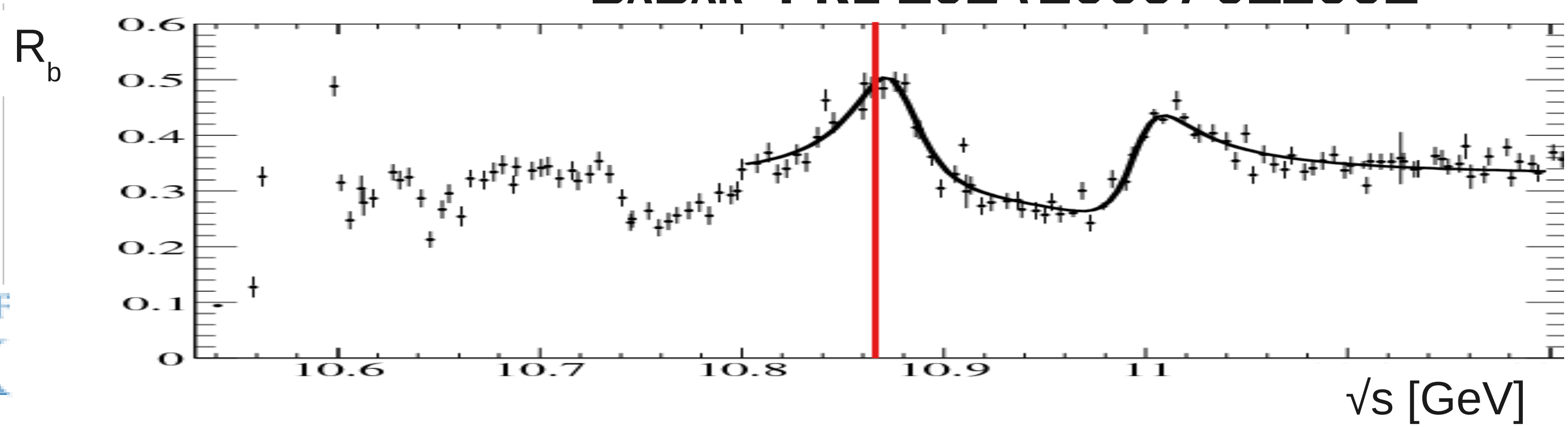
Compare lineshape to nominal Υ(5S)

Belle arXiv:0808.2445



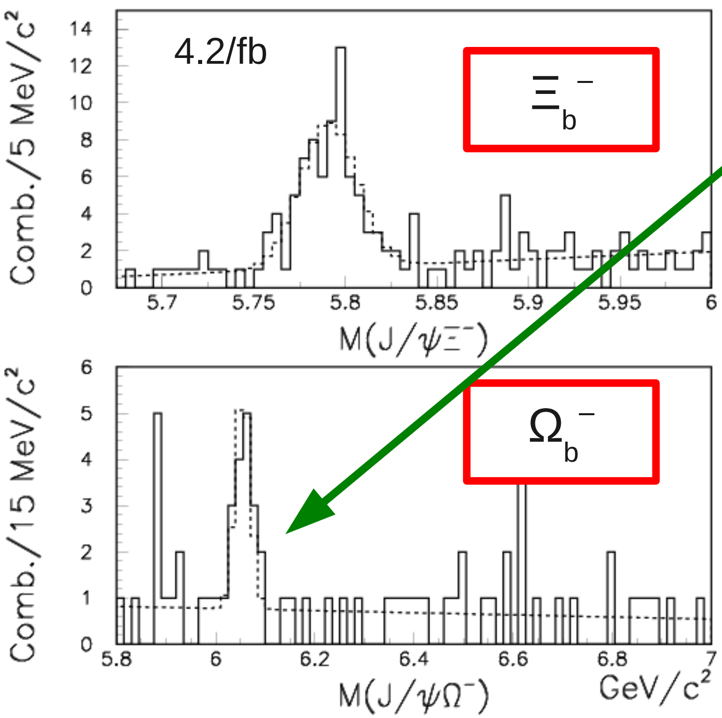
Compare R scan

BaBar PRL 102 (2009) 012001

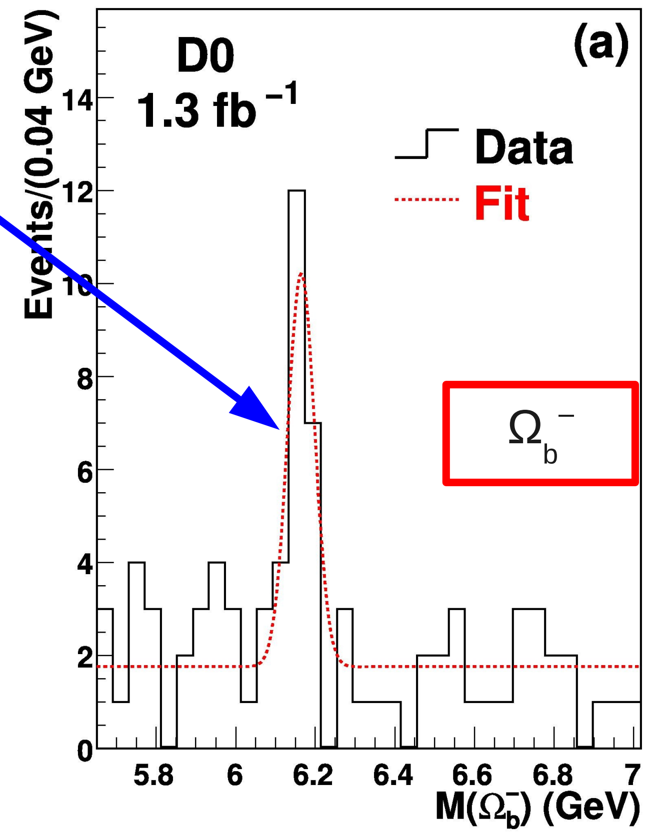


b hadron spectroscopy – Observation of the Ω_b

CDF PRD 80 (2009) 72003



D0 PRL 101 (2008) 232002

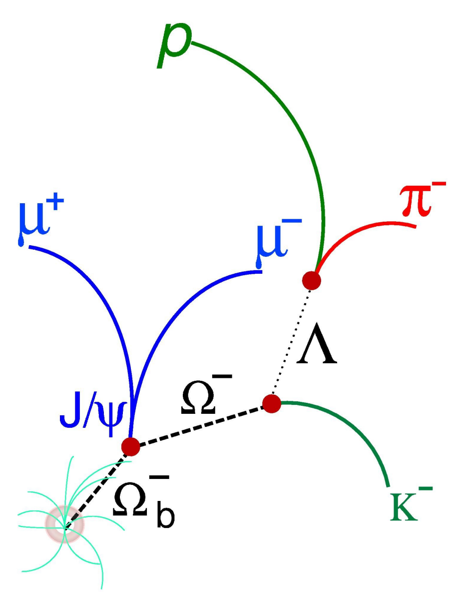


$m(\Omega_b)$ =

6054.4 ± 6.8 (stat.) ± 0.9 (syst.) MeV

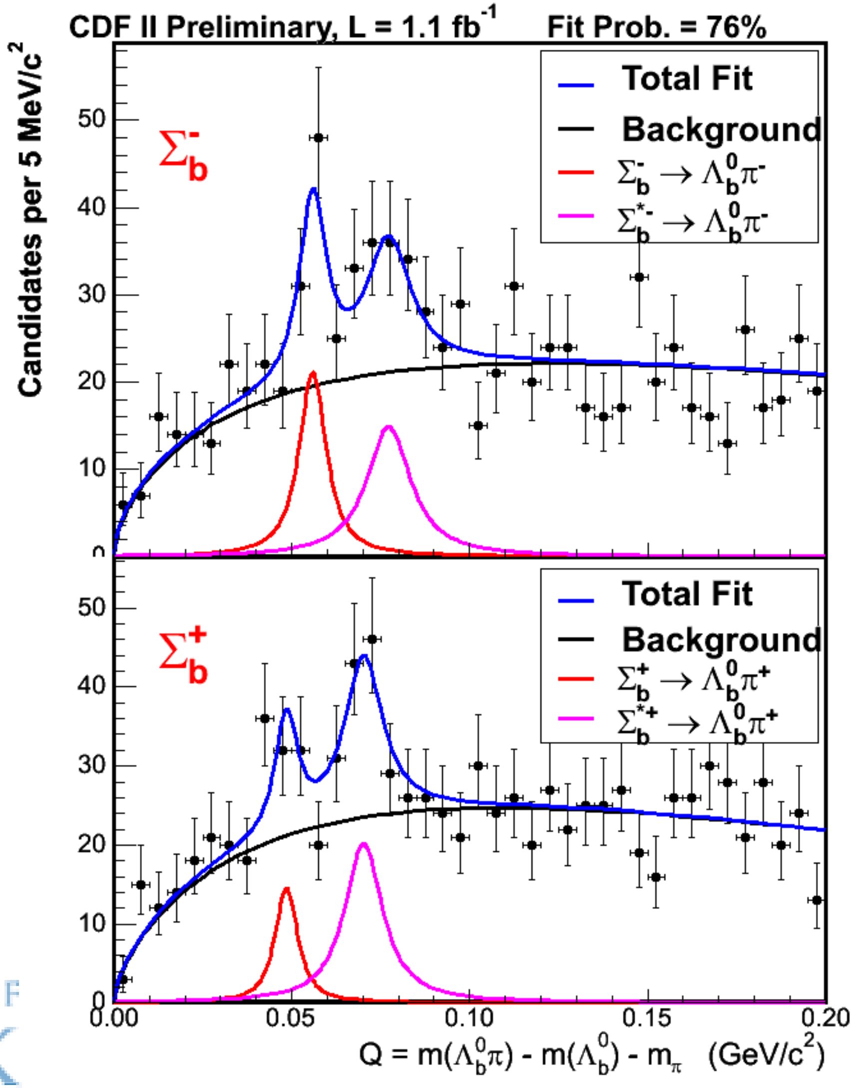
6165 ± 10 (stat) ± 13(syst.) MeV

significant discrepancy to be understood



b hadron spectroscopy – Observation of the Σ_b

CDF PRL 99 (2007) 202001



Fully hadronic decay chain:

$\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm$

$\Lambda_b^0 \to \Lambda_c^+ \pi^-$

$\Lambda_c^+ \to pK^-\pi^+$

Impressive demonstration of B physics potential with hadronic triggers

CKM physics

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

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

A 3x3 unitary matrix

Described by 4 real parameters – allows CP violation

PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ

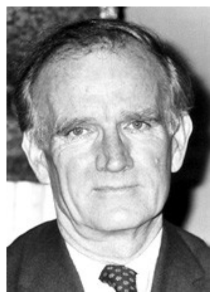
Wolfenstein parametrisation: λ, A, ρ, η

Highly predictive

Flavour oscillations, CP violation and Nobel Prizes

1964 – Discovery of CP violation in K^0 system

1980 – Nobel Prize to Cronin and Fitch

PRL 13 (1964) 138

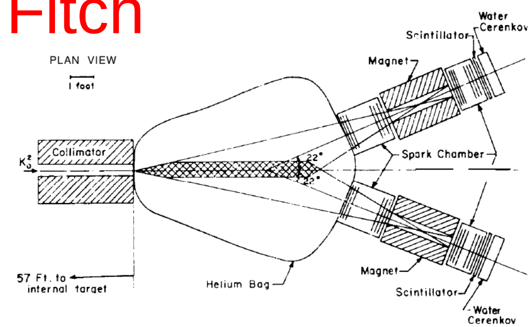


Fig. 1. Plan view of the apparatus as located at the A. G. S.

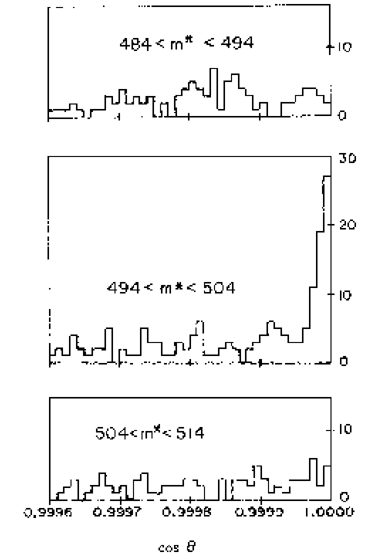
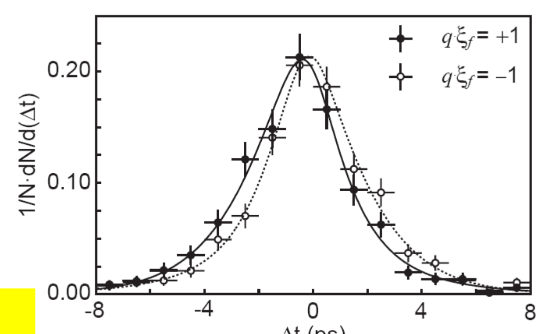


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

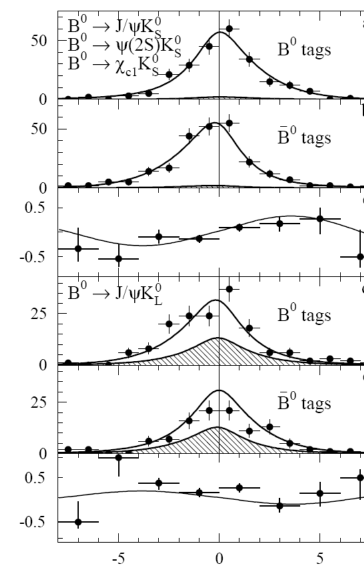
2001 – Discovery of CP violation in B_d system

2008 – Nobel Prize to Kobayashi and Maskawa


Prog.Theor.Phys. 49 (1973) 652



Belle PRL 87 (2001) 091802



BABAR PRL 87 (2001) 091801

CKM Matrix – Phases

P.Harrison *et al.*,
PLB 680 (2009) 328

Can form a matrix of angles between pairs of CKM matrix elements

Φ_{ij} = phase between remaining elements when row i and column j removed

unitarity implies sum of phases in any row or column = 180°

$$\Phi = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} \Phi_{ud} & \Phi_{us} & \Phi_{ub} \\ \Phi_{cd} & \Phi_{cs} & \Phi_{cb} \\ \Phi_{td} & \Phi_{ts} & \Phi_{tb} \end{pmatrix} \end{array} \simeq \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1^o & 22^o & 157^o \\ 67^o & 90^o & 23^o \\ 112^o & 68^o & 0^o \end{pmatrix} \end{array}$$

$\beta \equiv \varphi_1$

$\alpha \equiv \varphi_2$

$\gamma \equiv \varphi_3$

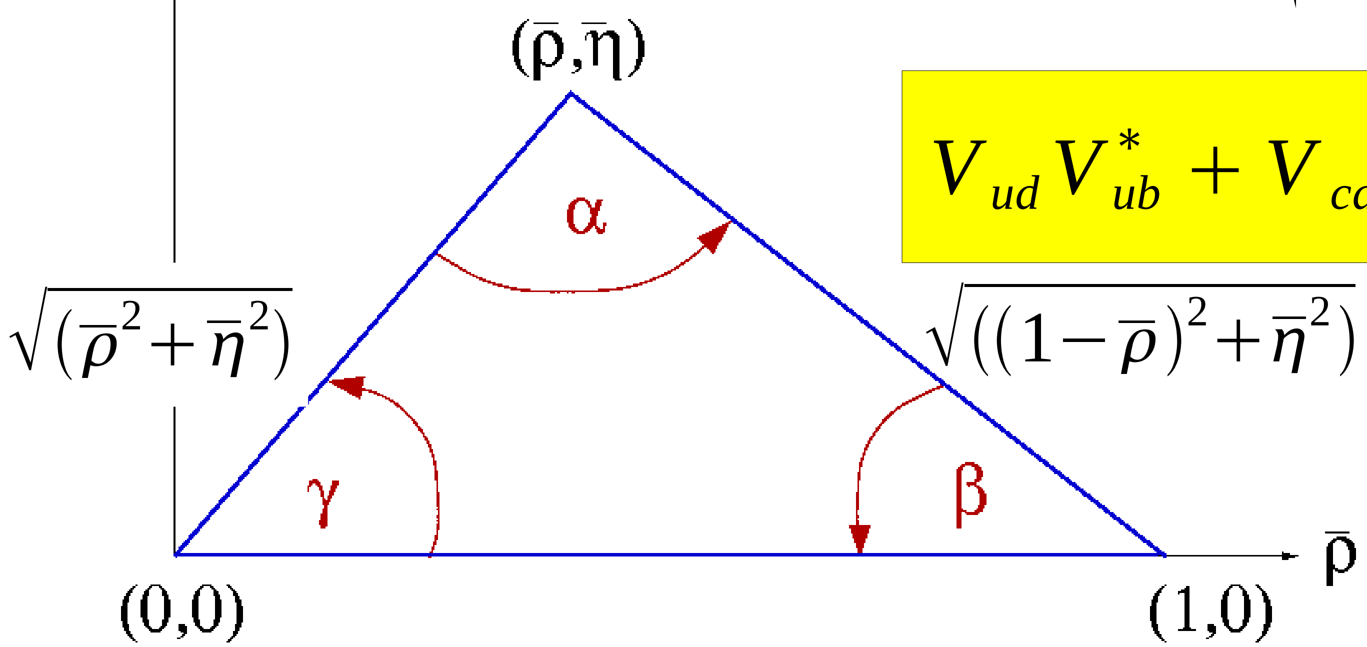
"The Unitarity Triangle"

The Cabibbo-Kobayashi-Maskawa Matrix & The Unitarity Triangle

Quark couplings to W boson described by 3x3 unitary matrix (4 free parameters, inc. 1 phase)

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

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

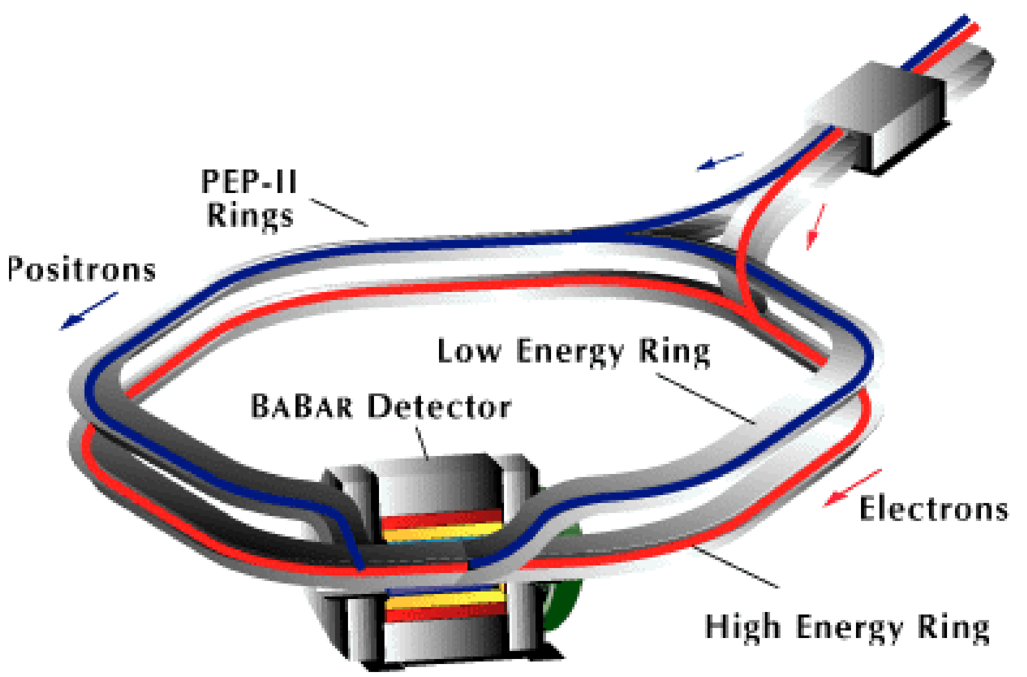


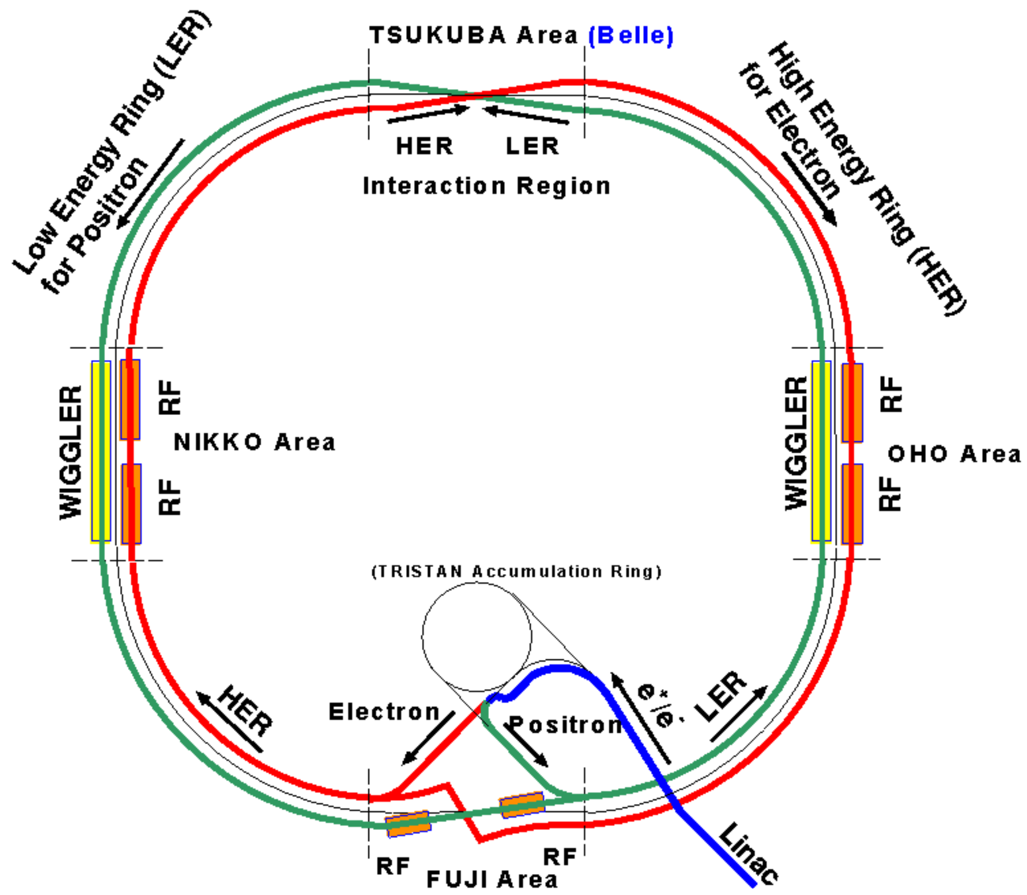
$$\alpha \equiv \phi_2 = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \phi_1 = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma \equiv \phi_3 = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

The Asymmetric B Factories

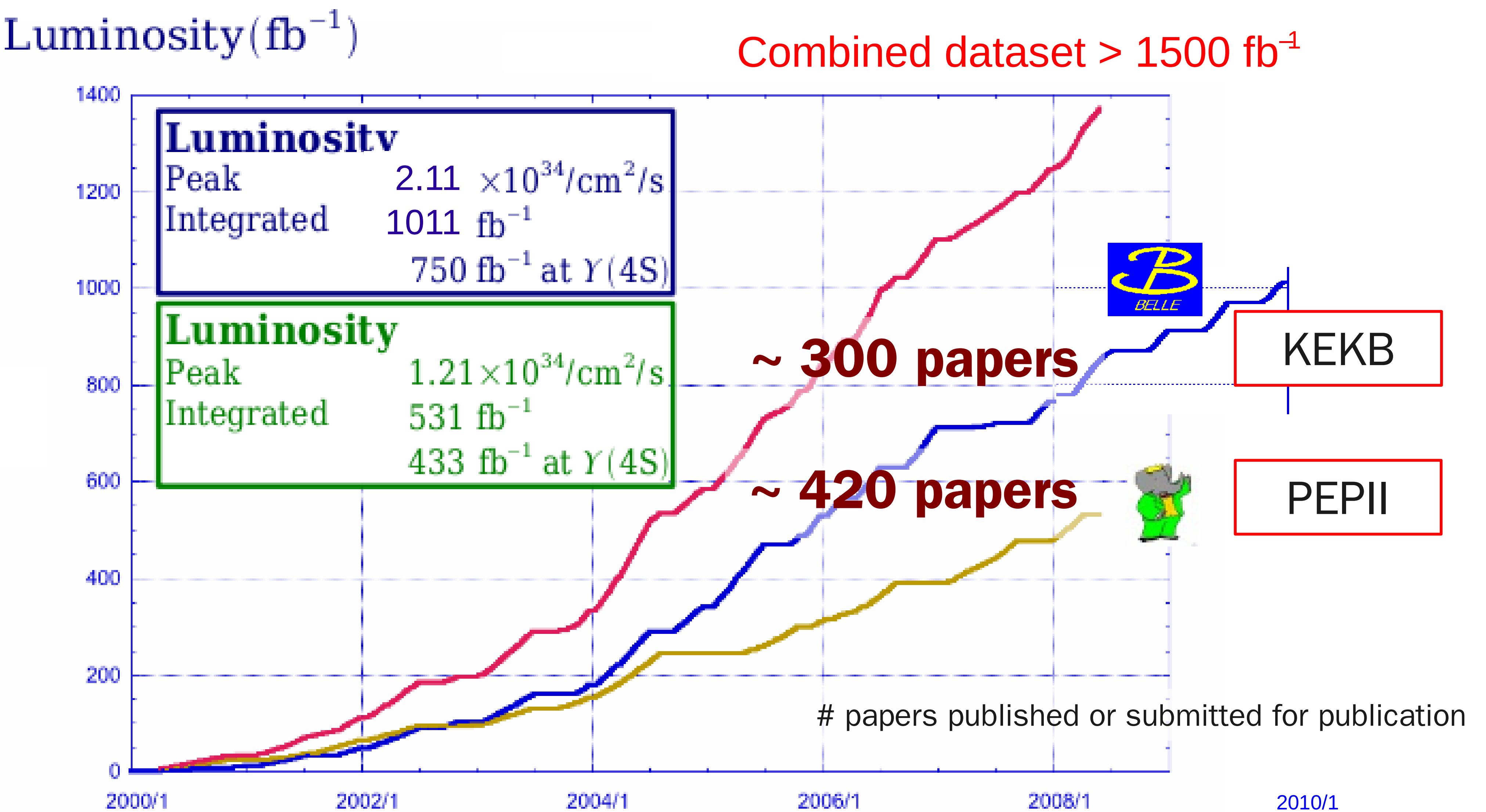
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

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





B factories – World Record Luminosities



Measurement of sin(2β)

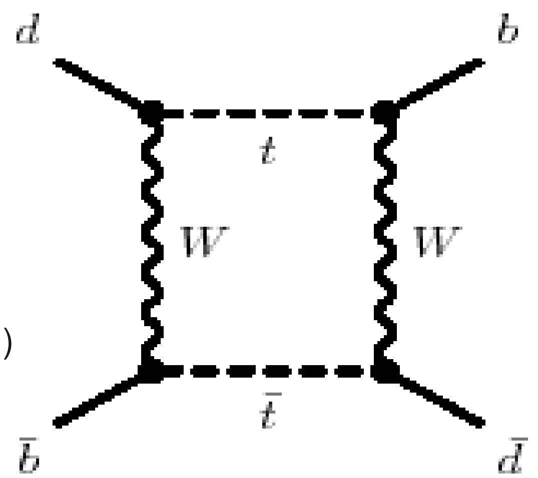
Carter & Sanda, PRD23 (1981) 1567; Bigi & Sanda, NP193 (1981) 85

Sensitivity to CP violation between B^0 decays to J/ψ K^0 with and without mixing

B^0–$\overline{B}^0$ mixing phase:

$$arg\left(\frac{V_{td}^* V_{tb}}{V_{td} V_{tb}^*}\right) = -2\beta$$

(usual phase convention)



Exploit quantum correlations in Υ(4S)→$B^0\overline{B}^0$

Energy asymmetry + vertexing ⇒ precise Δt measurement

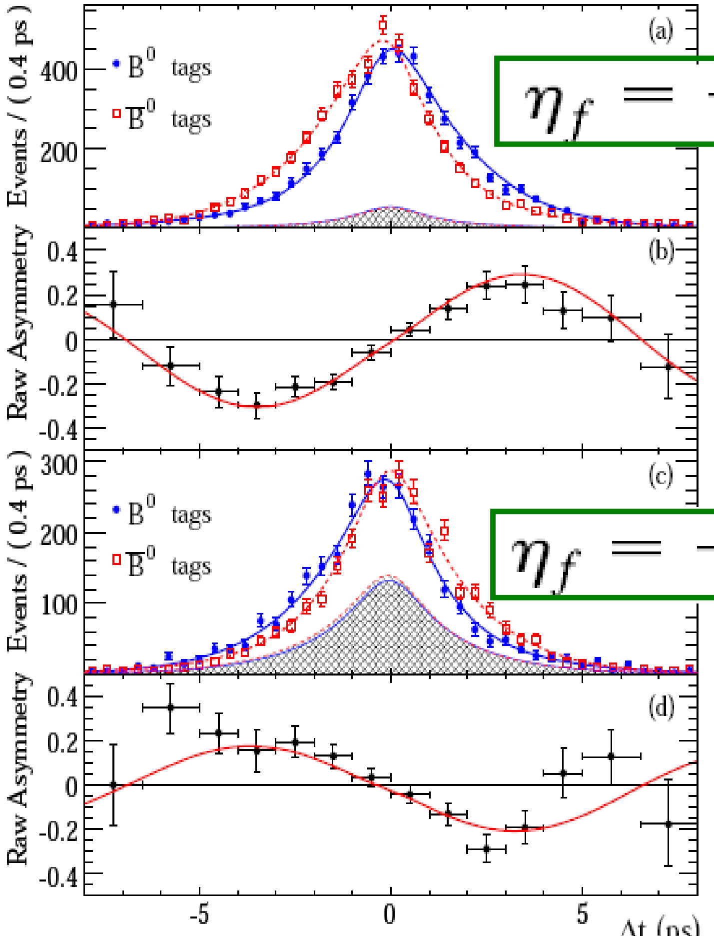
Lepton & hadron identification ⇒ performant flavour tagging

$$\Gamma_{B\to J/\psi K^0}(\Delta t) \propto e^{-|\Delta t|/\tau_B}\left(1\pm(S\sin(\Delta m\Delta t)-C\cos(\Delta m\Delta t))\right) \quad \begin{array}{l} + : \text{tag } B=B^0 \\ - : \text{tag } B=\overline{B}^0 \end{array}$$

$$\text{Standard Model} : S=-\eta\sin(2\beta) \qquad C=0$$

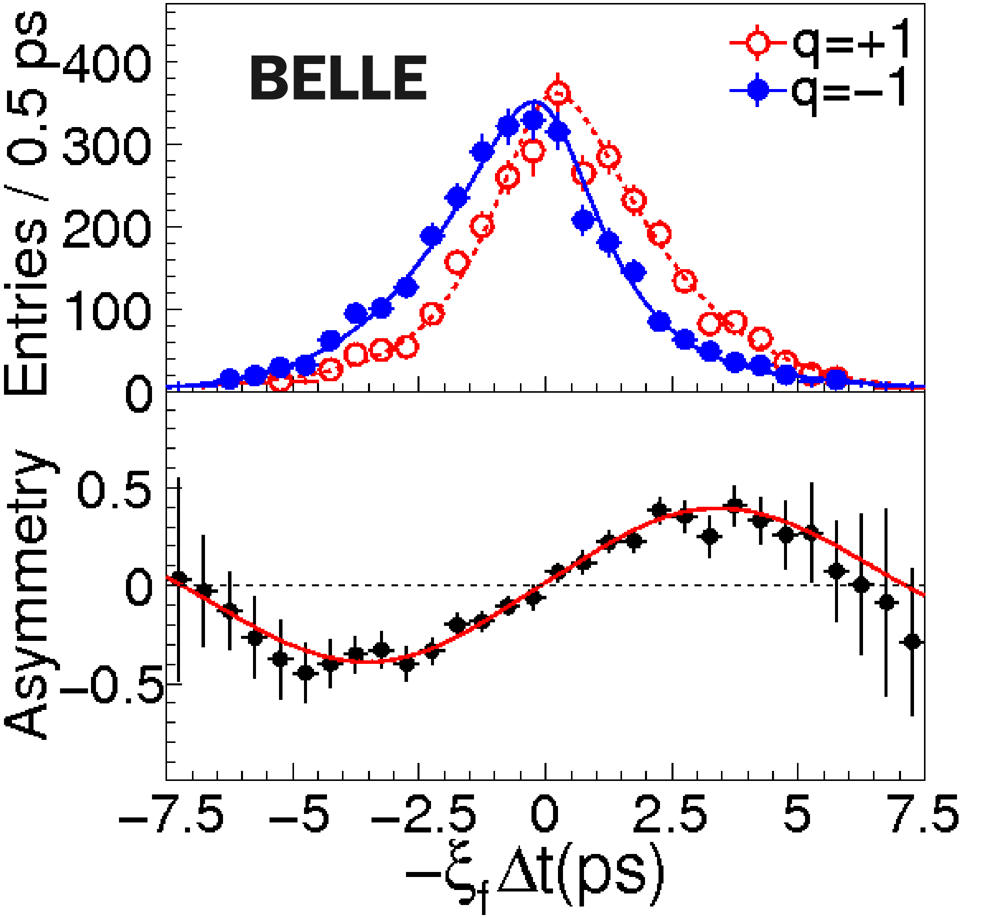
Results for the Golden Mode

$\sin(2\beta) = 0.687 \pm 0.028 \pm 0.012$



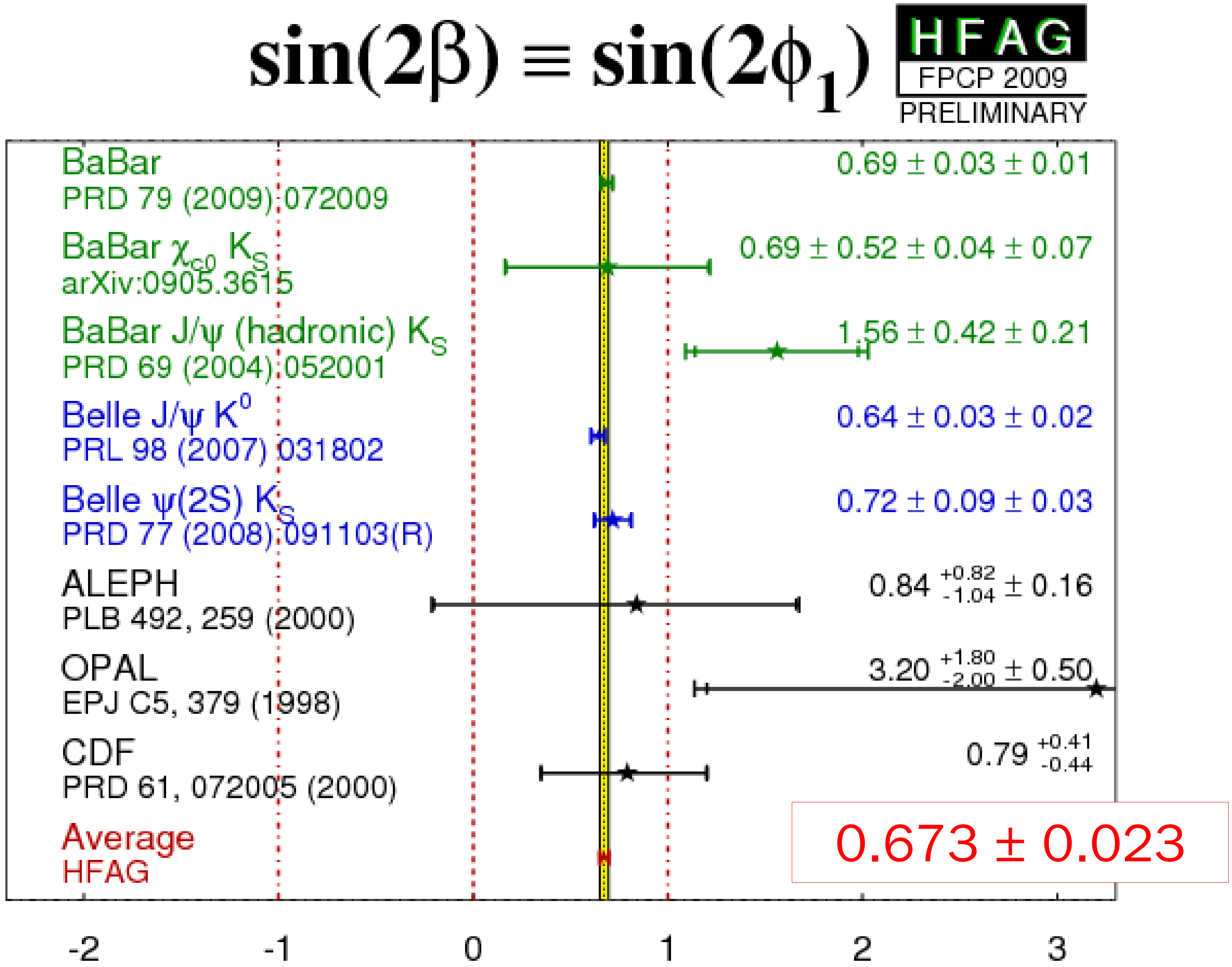
PRD 79 (2009) 072009

$\sin(2\phi_1) = 0.642 \pm 0.031 \pm 0.017$



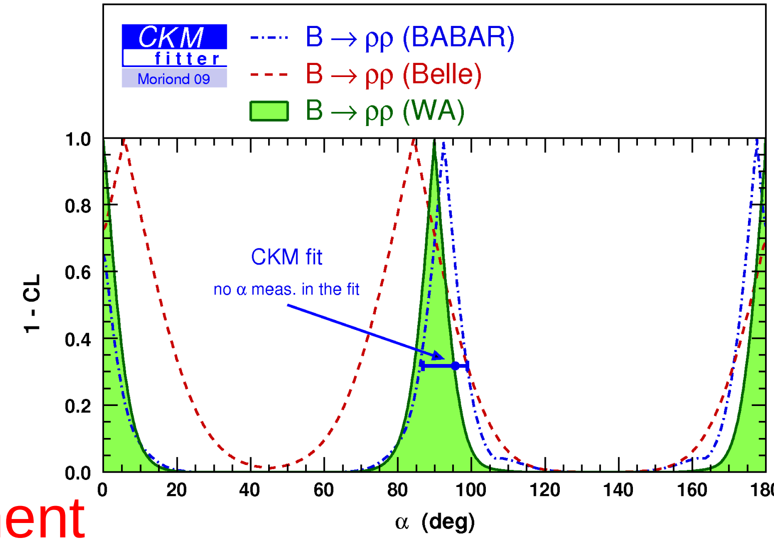
PRL 98 (2007) 031802

Compilation of Results



Measurement of α

http://ckmfitter.in2p3.fr/

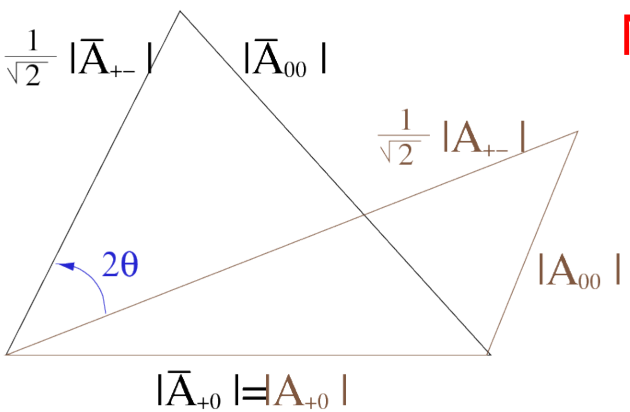


Now a precise measurement

$$\alpha = \left(89.0^{+4.4}_{-4.2}\right)^{\circ}$$

Dominated by B→ρρ system

Analysis uses isospin triangle



M.Gronau & D.London,
PRL 65 (1990) 3381

New $B^+ \to \rho^+\rho^0$ measurement

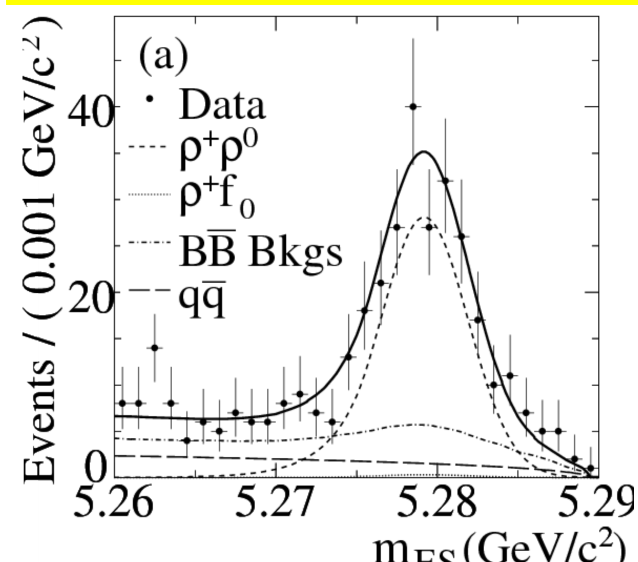
large amplitude

stretches triangles base

reduction in θ ≈ Δα

Further improvement in measurement of $B^+ \to \rho^+\rho^0$ could lead to larger uncertainty on α

BABAR PRL 102 (2009) 141802



Tim Gershon
B physics experiments

Importance of γ from B→DK

γ plays a unique role in flavour physics

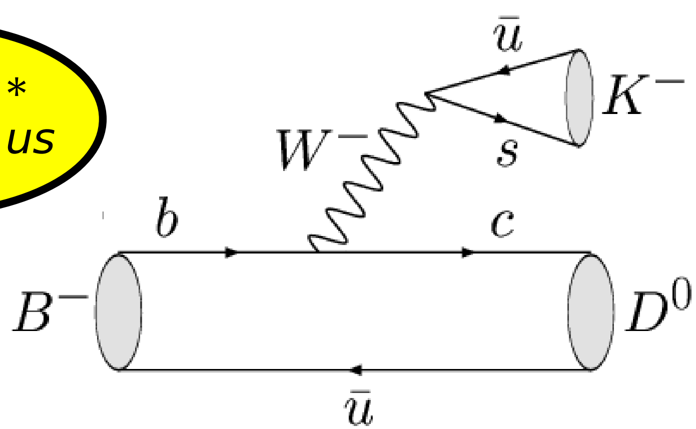
the only CP violating parameter that can be measured through tree decays (*)

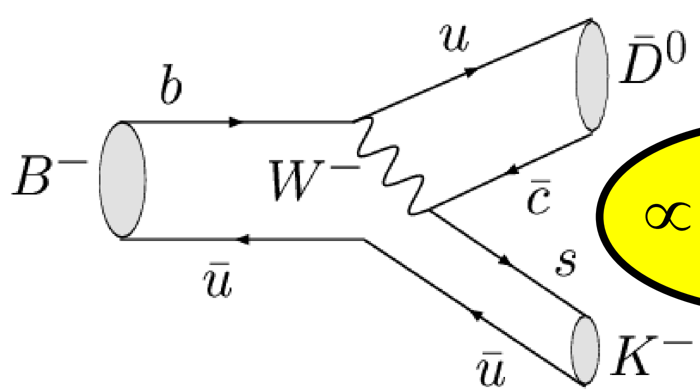
(*) more-or-less

A benchmark Standard Model reference point

doubly important after New Physics is observed

$\propto V_{cb} V^*_{us}$





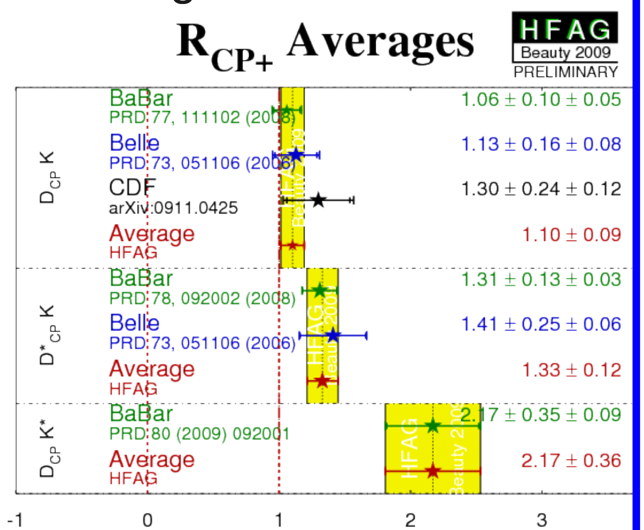
$\propto V_{ub} V^*_{cs}$

Variants use different B or D decays

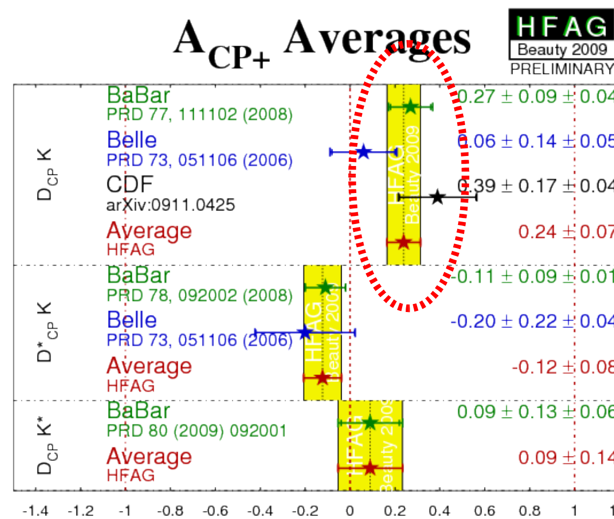
require a final state common to both D^0 and $\bar{D}^0$

Latest results on B→DK : GLW & ADS

GLW : D decays to CP eigenstate



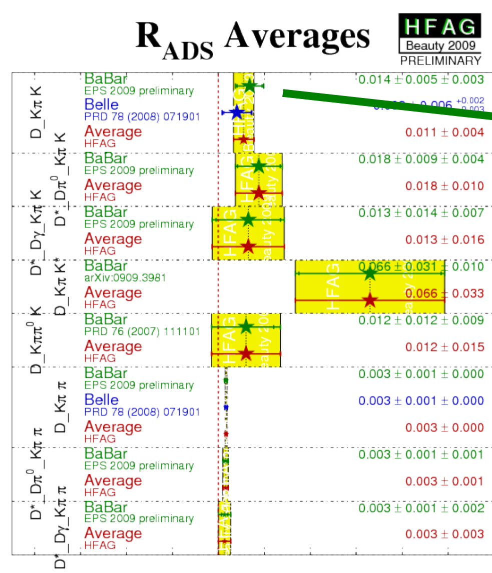
R ≠ 1 ↔ effect of suppressed amplitude

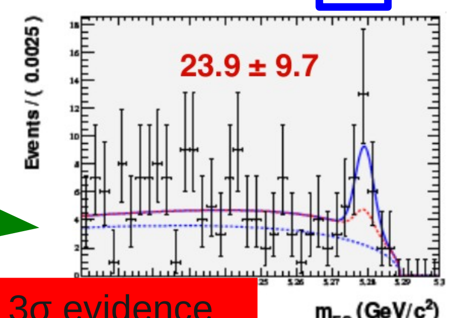


A ≠ 0 ↔ direct CP violation

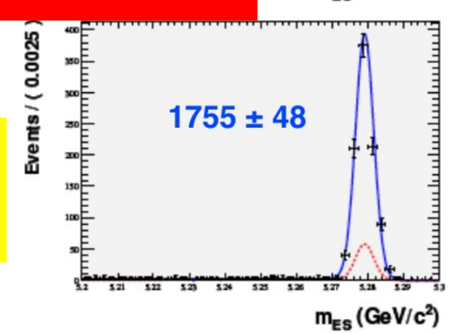
3σ evidence for DCPV also in $D \to K_S \pi^+ \pi^-$ Dalitz plot analysis (GGSZ)

ADS : D decays to suppressed final state





3σ evidence



BABAR D→Kπ
N.Lopez March at EPS'09

Tim Gershon
B physics experiments

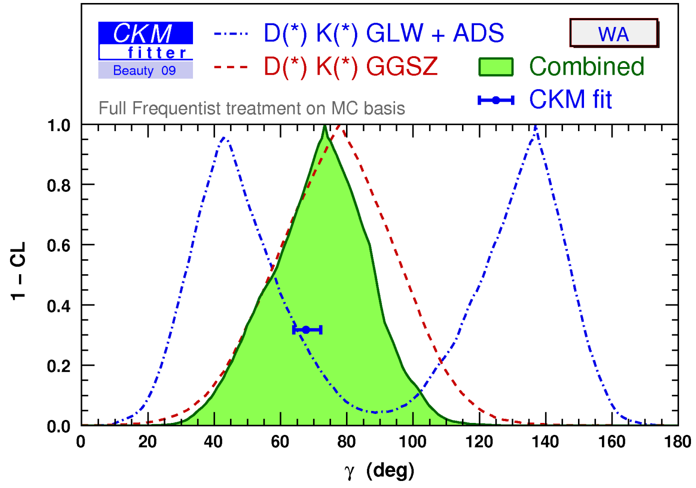
Combination of results on γ

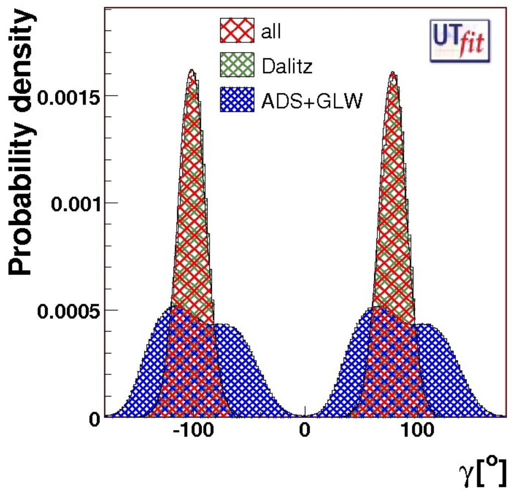
Combination is notoriously controversial

different results depending on statistical approach

CKMfitter: $\gamma = (73\ ^{+19}_{-24})°$

UTFit: γ = (78 ± 12)° ([54,102]° @ 95% Prob.)





- Starting to move out of the low statistics regime?
- Further updates (BaBar/Belle/CDF) could be very interesting
- LHCb has excellent capabilities for γ measurement
  - Precision of ≈ 5° with one nominal year's data (2/fb)

Charmless hadronic B decays

Direct CP violation in B → Kπ sensitive to γ

too many hadronic parameters ⇒ need theory input

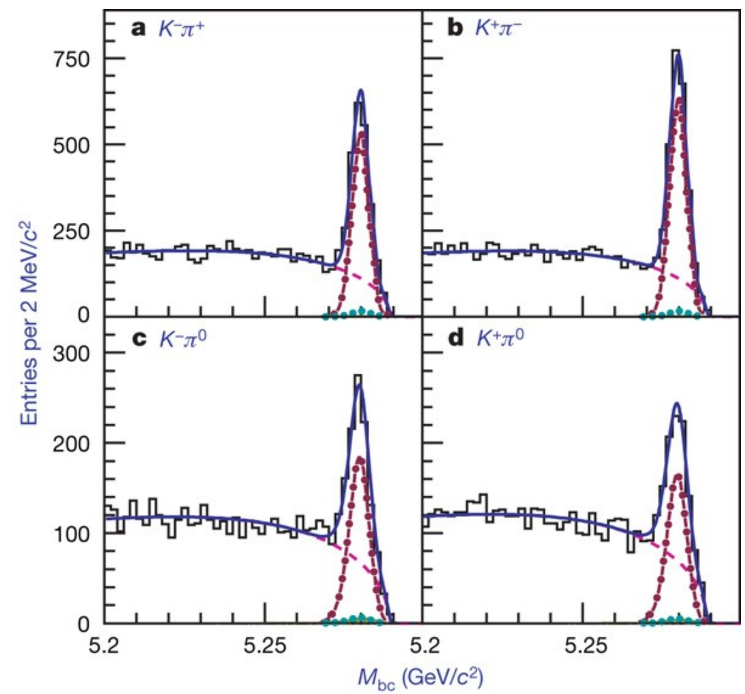
NB. interesting deviation from naïve expectation

"Kπ puzzle"

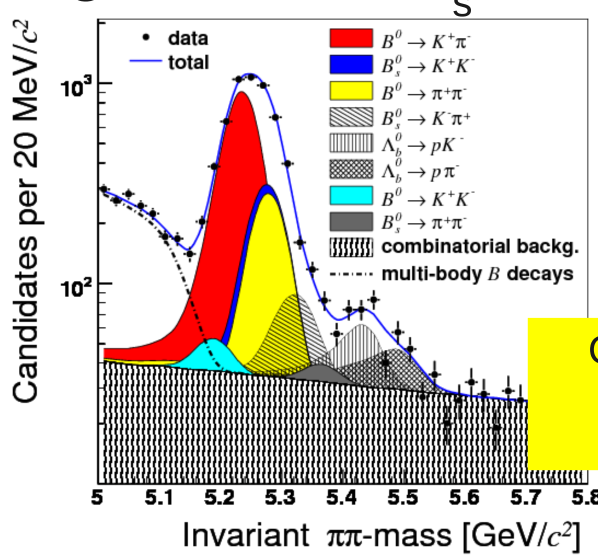
$$A_{CP}(K^-\pi^+) = (-9.8^{+1.2}_{-1.1})\% \quad A_{CP}(K^-\pi^0) = (5.0 \pm 2.5)\%$$
$$\Delta(A_{CP}) = (-14.8 \pm 2.8)\%$$

HFAG averages
BABAR PRD 76 (2007) 091102 & arXiv:0807.4226; also CDF

Belle Nature 452 (2008) 332



Gaining knowledge also on B_s → hh



CDF PRL 103 (2009) 031801. See also D.Tonelli at Beauty 2009 and Belle: R.Louvot at EPS 2009

Charmless hadronic B decays Dalitz plot analyses

Dalitz analyses measure both magnitude and phases, ie. probe dynamics at the amplitude level

Time-dependent analyses

$B \rightarrow K_S \pi^+ \pi^-$, $B \rightarrow K_S K^+ K^-$

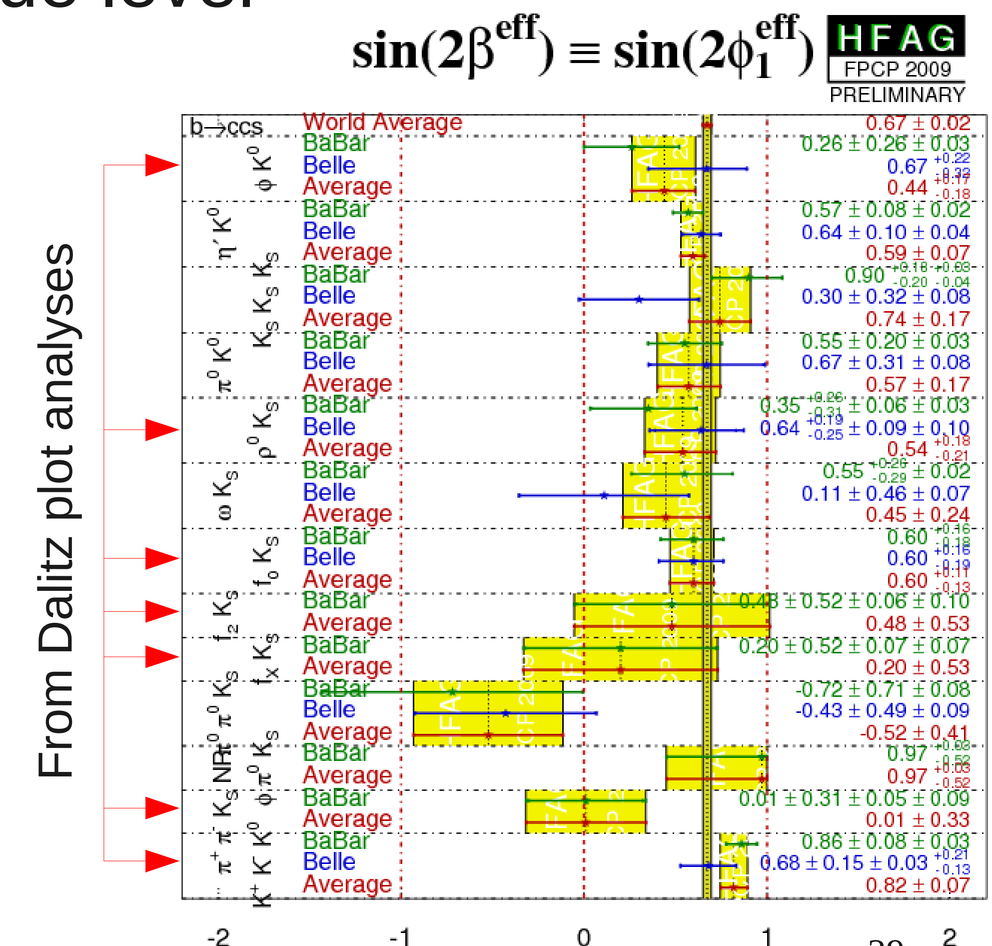
additional sensitivity to β

Interference of $K^* \pi$ bands

Various $B \rightarrow K\pi\pi$ channels

additional sensitivity to γ

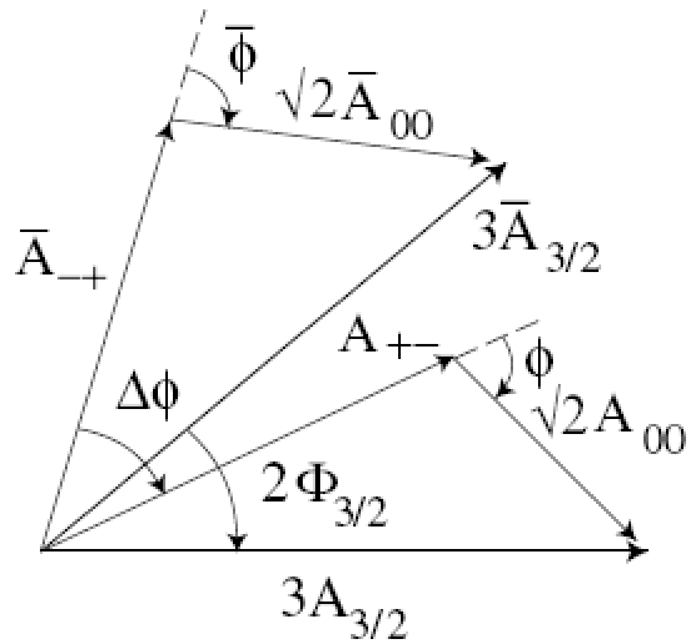
BABAR PRD 80 (2009) 112001
Belle PRD 79 (2009) 072004



No smoking gun for difference between $b \rightarrow c\bar{c}s$ and $b \rightarrow q\bar{q}s$

γ from $B^0 \rightarrow K\pi\pi$

Ciuchini et al., PRD 74 (2006) 051301, Gronau et al., PRD 75 (2007) 014002, PRD 77 (2008) 057504



Use $B_d \rightarrow K^{*+}\pi^-$ and $B_d \rightarrow K^{*0}\pi^0$

- form isospin triangles
  - $A_{ij} = A(B^0 \rightarrow K^{*i}\pi^j)$

Both contribute to $B_d \rightarrow K^+\pi^-\pi^0$

- determine $\varphi = \arg(A_{00}/A_{+-})$

Need relative phase between B_d and $\bar{B}_d$

- determine $\Delta\varphi = \arg(A_{+-}/\bar{A}_{+-})$ from time-dependent analysis of $B_d \rightarrow K_S\pi^+\pi^-$

Can now extract $\Phi_{3/2} \approx \gamma$ (with corrections due to EW penguins)

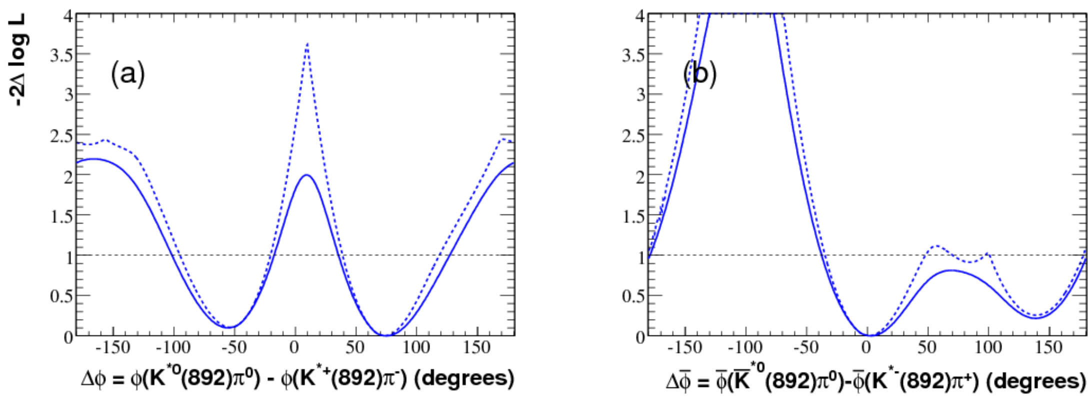
γ from $B^0 \to K\pi\pi$ – B factory results

$B_d \to K^+\pi^-\pi^0$ results

BaBar PRD 78 (2008) 052005

multiple solutions reduce precision

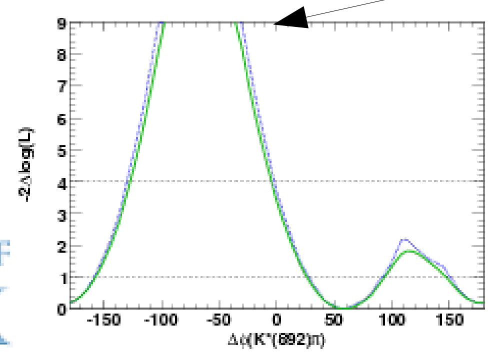
improvement expected with updated analysis (arXiv:0807.4567)

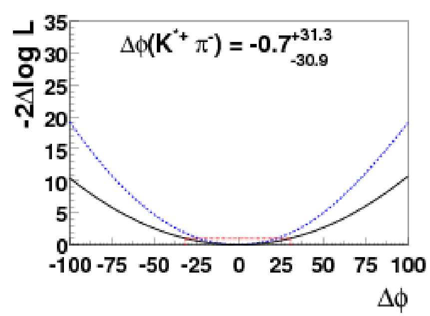


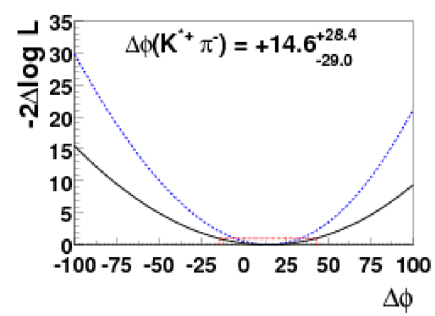
$B_d \to K_S\pi^+\pi^-$ results

BaBar PRD 80 (2009) 112001, Belle PRD 79 (2009) 072004

(two solutions)



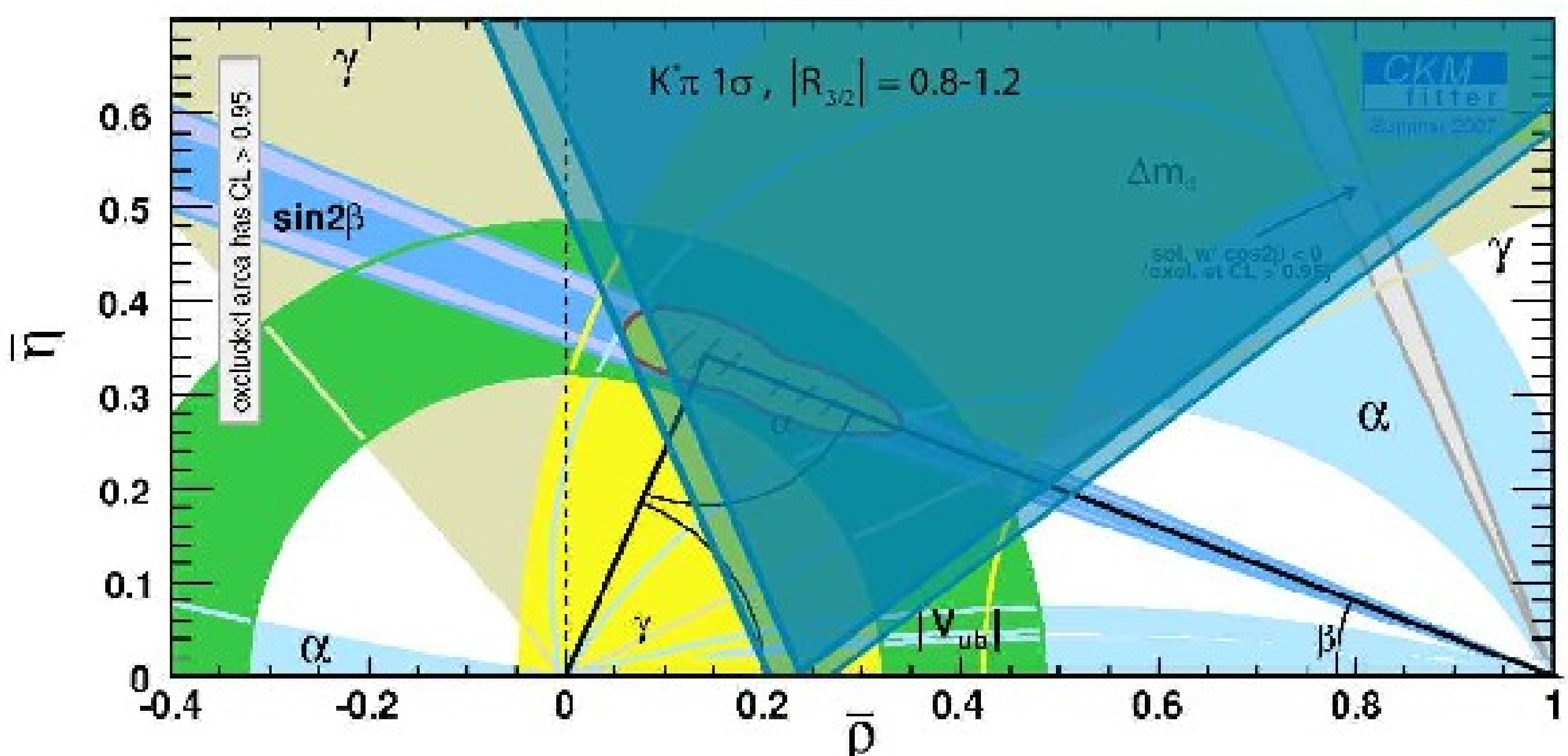




Tim Gershon
B physics experiments

γ from $B^0 \to K\pi\pi$ – B factory results

$$\bar{\eta} = \tan\Phi_{3/2}\left[\bar{\eta} - 0.24 \pm 0.03\right]$$



Does not include all latest data
Improvements expected with further updates

G.Lanfranchi at Firenze
LHCb Collaboration meeting

LHCb

B→ hh physics reach with 200 pb^{-1}

With ~200 pb^{-1} the B→hh sample will be the larger ever collected:

=> competitive statistical sensitivity on relative BR and charge asymmetries

=> first evidence of B→KK mode [for BR~10^{-7}: ~110 events in 200 pb^{-1}]

=> calibrate tagging & proper time resolution for time-dependent CPV

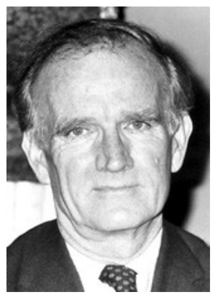
assuming σ(b$\bar{b}$) = 500 μb

	Current knowledge	LHCb stat. sensitivity
$\mathcal{A}^{CP}_{K^+\pi^-}$	$-0.098^{+0.012}_{-0.011}$	0.008
$\mathcal{A}^{CP}_{\pi^+K^-}$	$0.39 \pm 0.15 \pm 0.08$	0.05
$\mathcal{A}^{CP}_{p\pi^-}$	$0.03 \pm 0.17 \pm 0.05$	0.05
$\mathcal{A}^{CP}_{pK^-}$	$0.37 \pm 0.17 \pm 0.03$	0.03
$\mathcal{A}^{dir}_{\pi^+\pi^-}$	0.38 ± 0.06	0.13
$\mathcal{A}^{mix}_{\pi^+\pi^-}$	-0.65 ± 0.07	0.13
$\mathrm{Corr}(\mathcal{A}^{dir}_{\pi^+\pi^-}, \mathcal{A}^{mix}_{\pi^+\pi^-})$	0.08	-0.03
$\mathcal{A}^{dir}_{K^+K^-}$	Still unmeasured	0.15
$\mathcal{A}^{mix}_{K^+K^-}$		0.11
$\mathrm{Corr}(\mathcal{A}^{dir}_{K^+K^-}, \mathcal{A}^{mix}_{K^+K^-})$		0.02
$\frac{\mathcal{BR}(B^0\to\pi^+\pi^-)}{\mathcal{BR}(B^0\to K^+\pi^-)}$	0.264 ± 0.011	0.006
$\frac{\mathcal{BR}(B^0\to K^+K^-)}{\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.020 \pm 0.008 \pm 0.006$	0.005
$\frac{f_s\,\mathcal{BR}(B^0_s\to K^+K^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.347 \pm 0.020 \pm 0.021$	0.006
$\frac{f_s\,\mathcal{BR}(B^0_s\to \pi^+K^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.071 \pm 0.010 \pm 0.007$	0.004
$\frac{f_s\,\mathcal{BR}(B^0_s\to \pi^+\pi^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.007 \pm 0.004 \pm 0.005$	0.002
$\frac{f_{\Lambda_b}\,\mathcal{BR}(\Lambda_b\to p\pi^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.0415 \pm 0.0074 \pm 0.0058$	0.0016
$\frac{f_{\Lambda_b}\,\mathcal{BR}(\Lambda_b\to pK^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.0663 \pm 0.0089 \pm 0.0084$	0.0018

Flavour oscillations, CP violation and Nobel Prizes

1964 – Discovery of CP violation in K^0 system

1980 – Nobel Prize to Cronin and Fitch



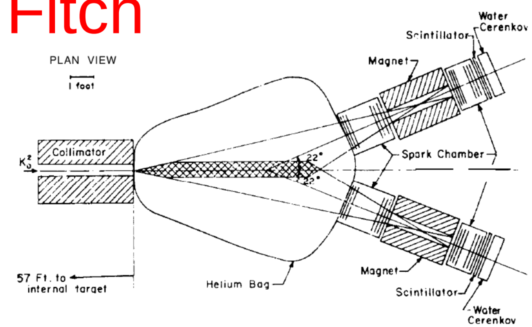


Fig. 1. Plan view of the apparatus as located at the A. G. S.

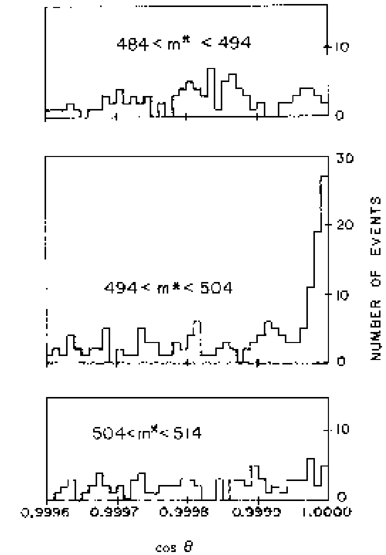


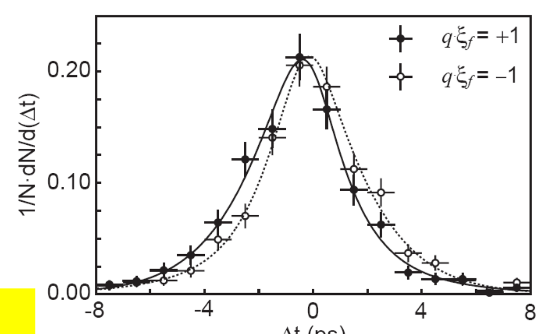
FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.

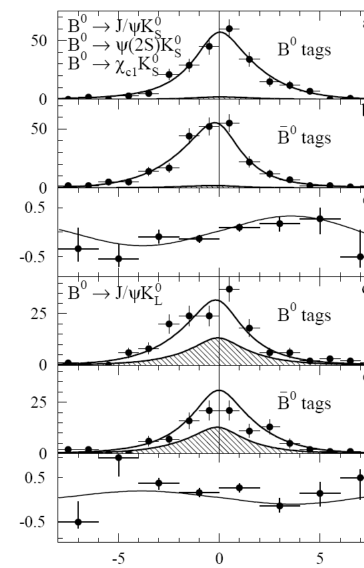
PRL 13 (1964) 138

2001 – Discovery of CP violation in B_d system

2008 – Nobel Prize to Kobayashi and Maskawa

Prog.Theor.Phys. 49 (1973) 652





Belle PRL 87 (2001) 091802

BABAR PRL 87 (2001) 091801

Flavour oscillations, CP violation and Nobel Prizes

1964

1980

2001

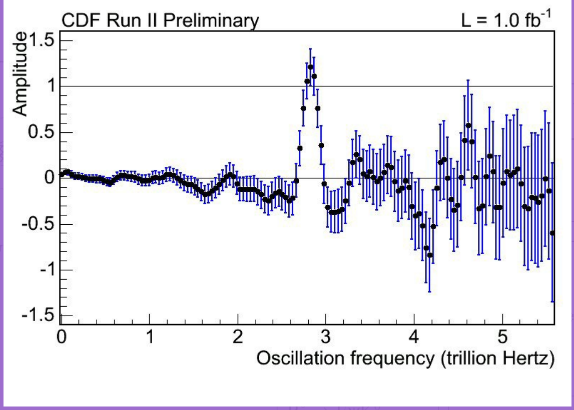
2008

Discovery of oscillations → discovery of CP violation → Nobel Prize can take 30 years

CPV so far seen in only 2 of 4 neutral flavoured mesons

2006 Discovery of B_s oscillations

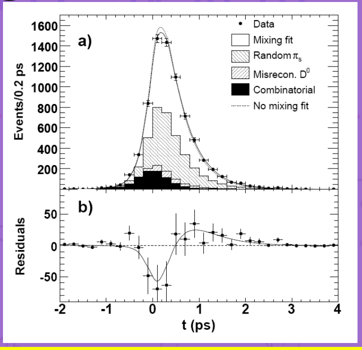
CDF PRL 97 (2006) 242003

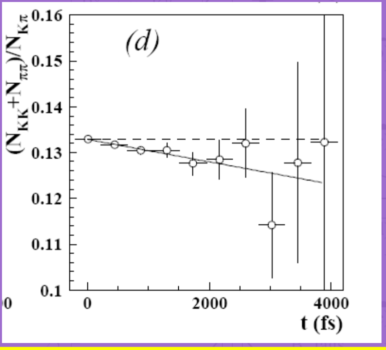


no discovery of CP violation yet

2007 Discovery of charm oscillations

no CP violation yet





BABAR PRL 98 (2007) 211802

Belle PRL 98 (2007) 211803

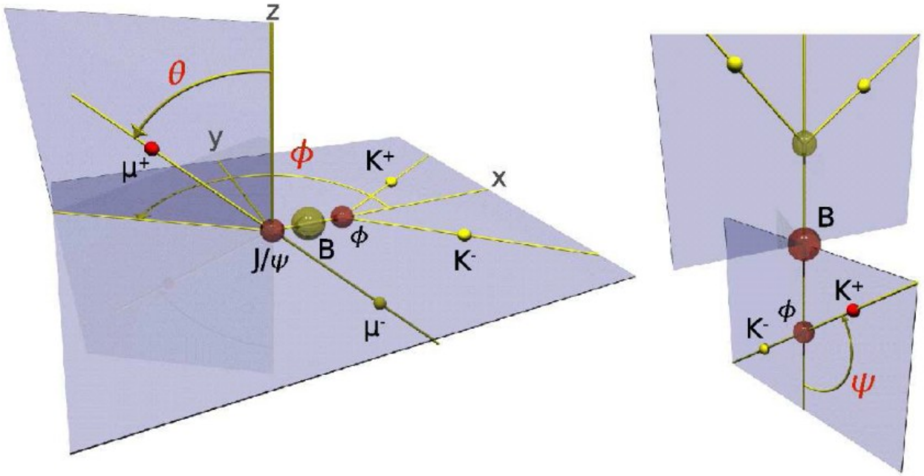
Prog.Theor.Phys. 49 (1973) 652

Belle PRL 87 (2001) 091802

BABAR PRL 87 (2001) 091801

Φ_s ($B_s \to J/\psi\varphi$)

K.Gibson at Beauty 2009



VV final state

- three helicity amplitudes
- → mixture of CP-even and CP-odd
- disentangled using angular &
  - time-dependent distributions
- → additional sensitivity
- many correlated variables
- → complicated analysis

2004

- CDF: measurement of ΔΓ/Γ
- D0 measurement in 2005

2006

- D0: first untagged analysis for Φ_s
- CDF analysis in 2007
- CDF: first measurement of Δm_s

2007

- CDF: first flavour tagged analysis
- D0 measurement in 2008

2008/9

- First attempts at averages → → →
  - official CDF/D0 combination
- Updated results ... both now 2.8/fb

Φ_s ($B_s \rightarrow J/\psi\varphi$)

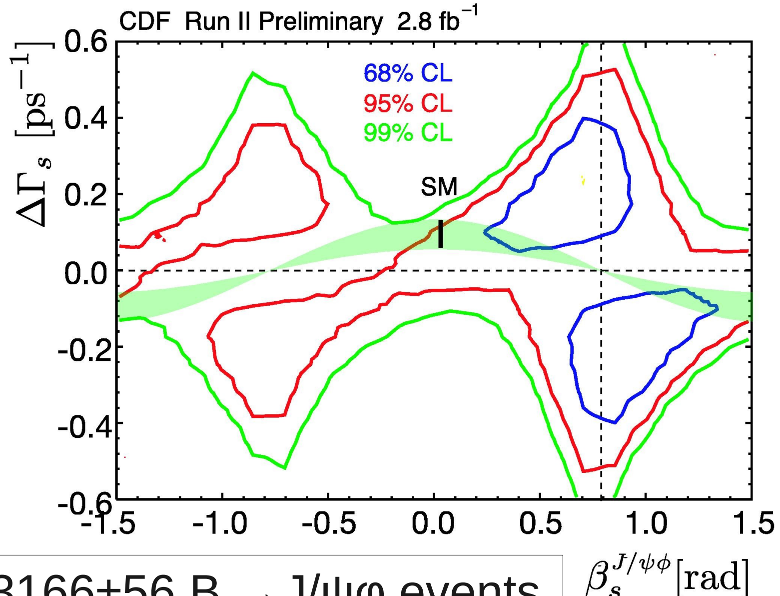
G.Punzi at EPS 2009

Tevatron measurements using tagged $B_s \rightarrow J/\psi\varphi$

Angular analyses of vector-vector final state

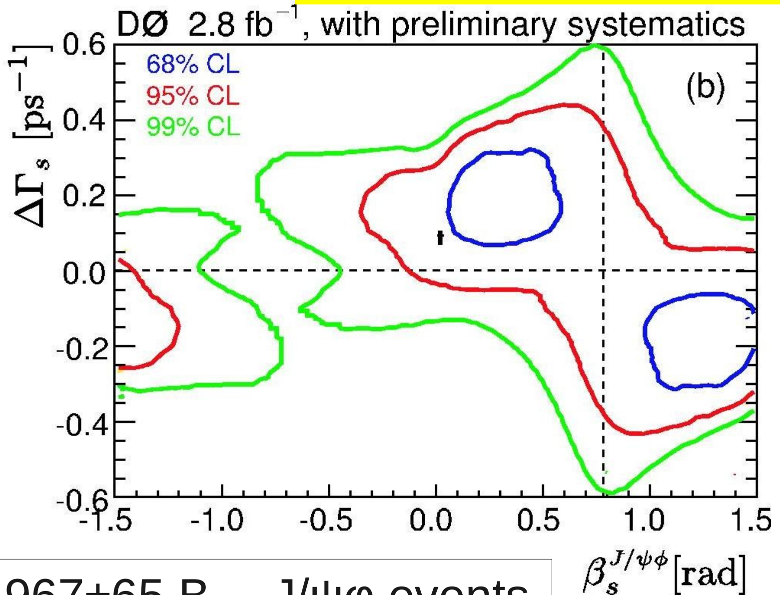
Results depend on $\Delta\Gamma$

CDF note 9787



3166±56 $B_s \rightarrow J/\psi\varphi$ events

D0 5928-CONF



1967±65 $B_s \rightarrow J/\psi\varphi$ events

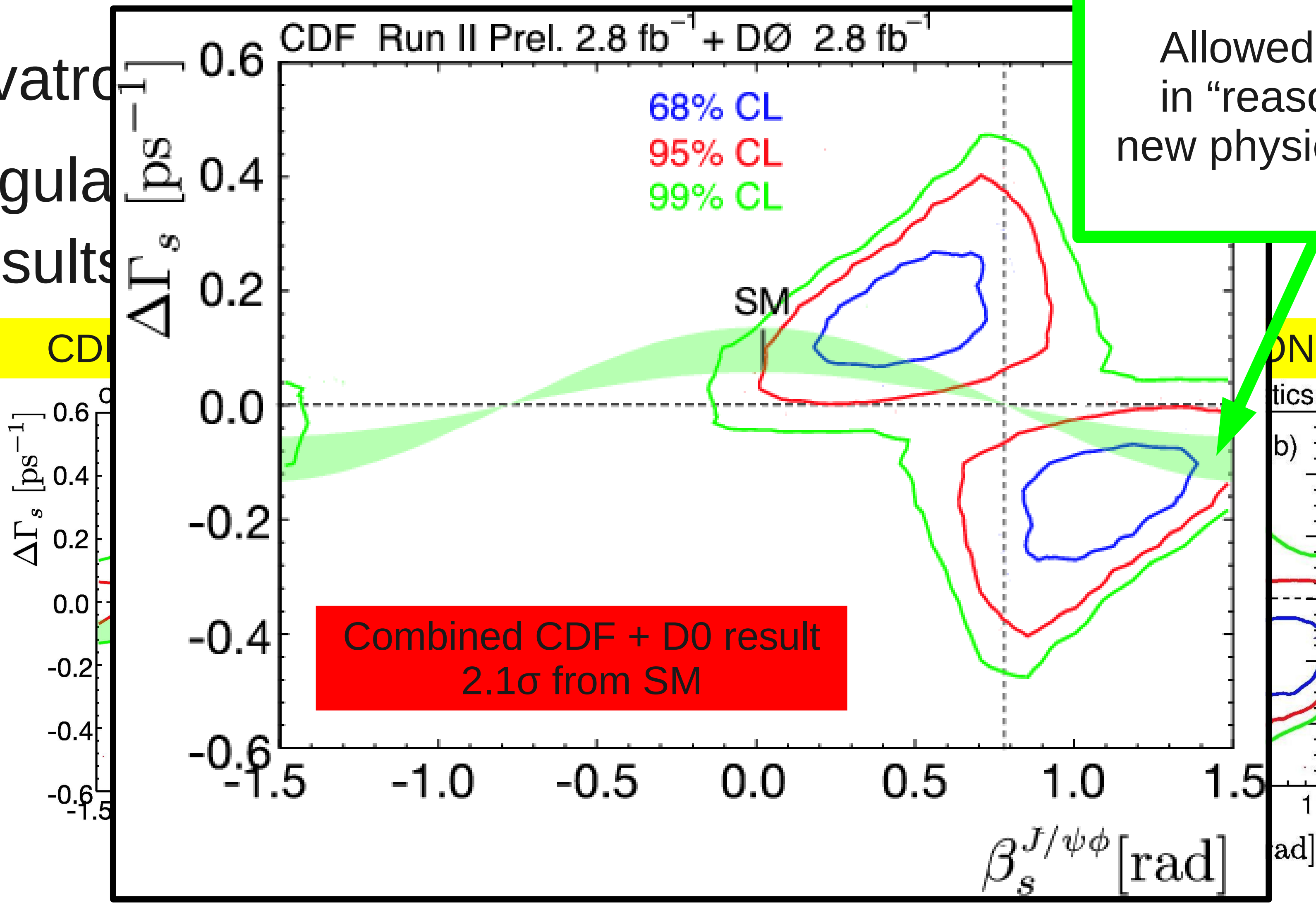
Φ_s ($B_s \to J/\psi\varphi$)

Tevatro

Angula

Results

CD ... NF



Allowed values in "reasonable" new physics models

Combined CDF + D0 result
2.1σ from SM

68% CL interval: Φ_s in [0.27, 0.59]∪[0.97, 1.30] rad

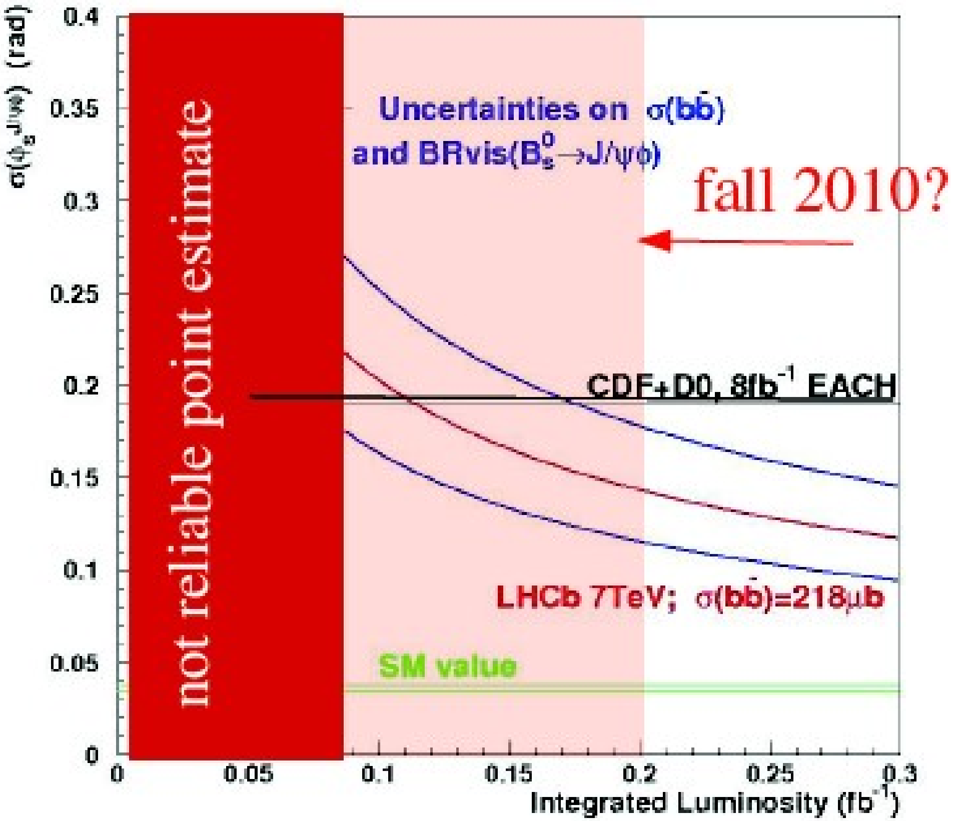
95% CL interval: Φ_s in [0.10, 1.42] rad

LHCb

G.Lanfranchi at Firenze
LHCb Collaboration meeting

ϕs: where we could be in ~14 months

LHCb: ϕs statistical sensitivity



LHCb with 0.2 fb^{-1}:

→ σ(2βs)< σ(Tevatron)

→ 5σ NP discovery if 2βs=0.8

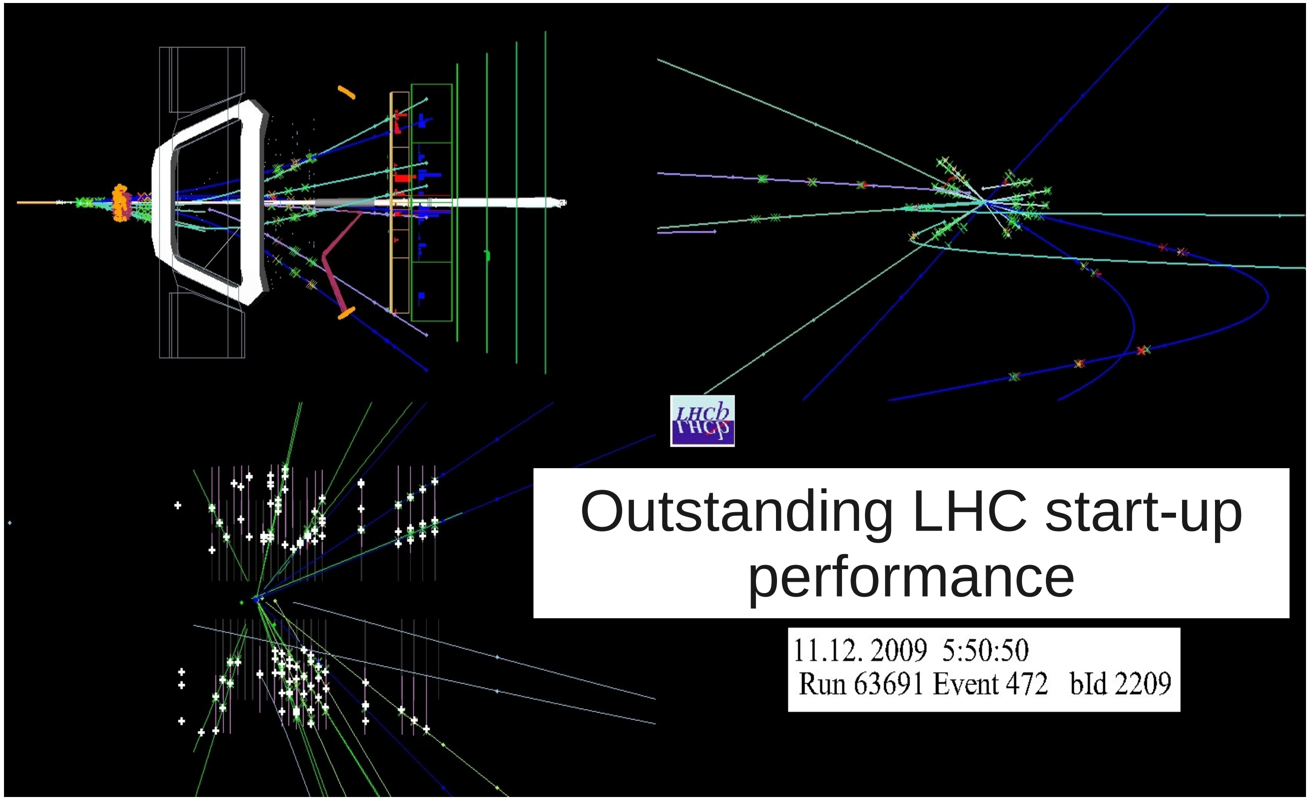
Competition with CDF/D0 for the first [true] evidence of NP is started.....

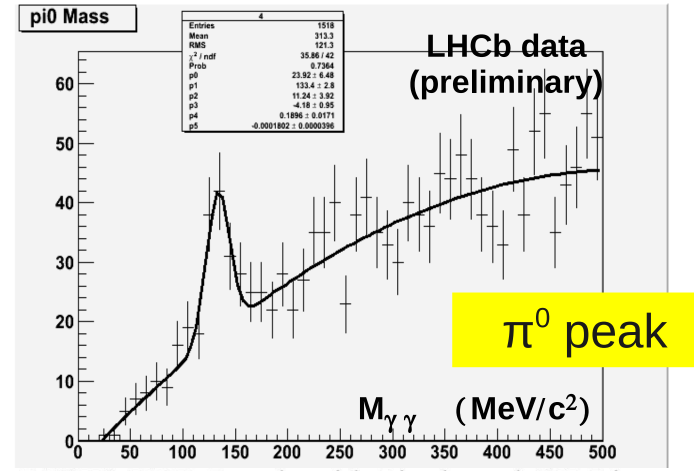
... Time is ticking.......

Very high priority for Tevatron updates next summer

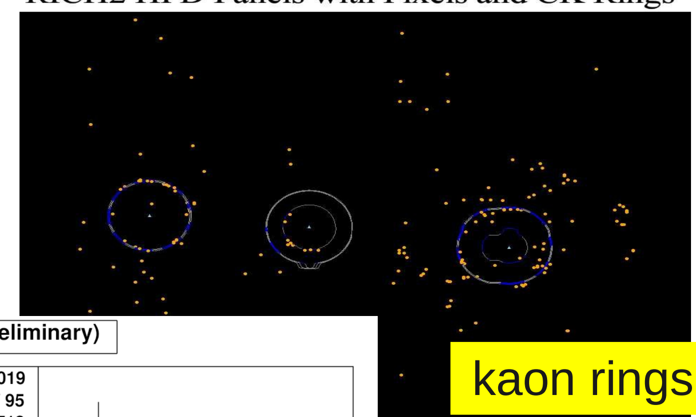
LHCb

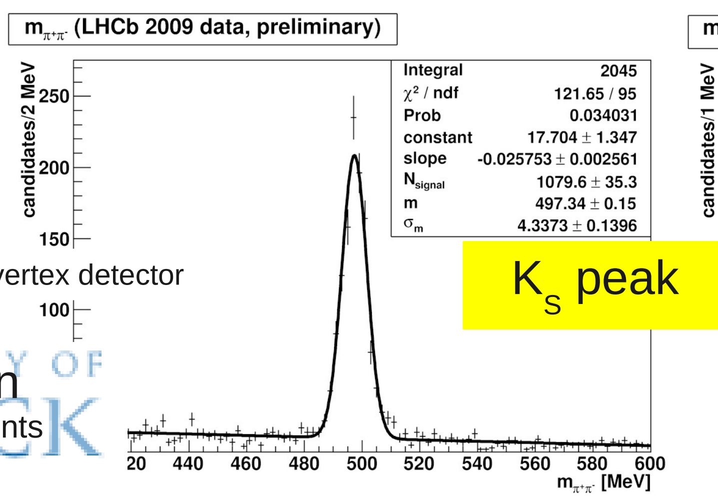
Status of LHCb at end 2009

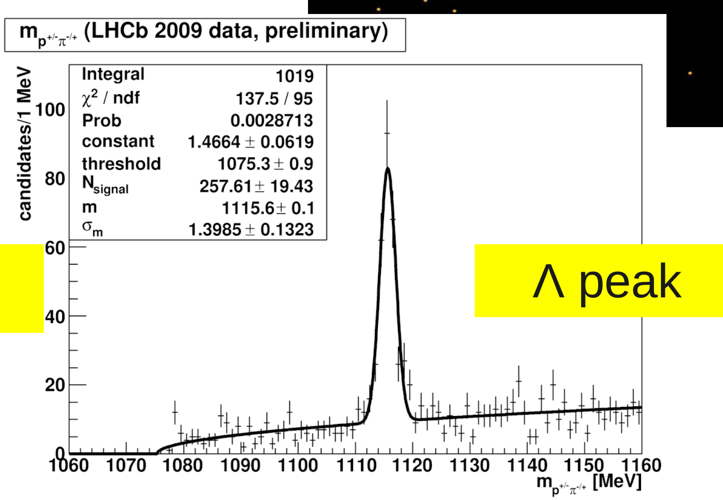




RICH2 HPD Panels with Pixels and CK Rings







"long tracks" - including vertex detector

Tim Gershon
B physics experiments

CKM Matrix – Magnitudes

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

Measurement of $|V_{ub}|$ and $|V_{cb}|$

Possibilities:

- exclusive hadronic B decays, eg. $B^0 \to D_s^+ \pi^-$
  - large theoretical (hadronic) uncertainties
- exclusive semileptonic B decays, eg. $B^0 \to \pi^- e^+ \nu$
  - moderate theoretical (hadronic) uncertainties
- inclusive semileptonic B decays, eg. $B^0 \to X_u e^+ \nu$
  - experimentally challenging
- leptonic B decays, eg. $B^+ \to \tau^+\nu$
  - experimentally challenging

For $|V_{cb}|$, best constraints from inclusive $B \to X_c l\nu$ analysis

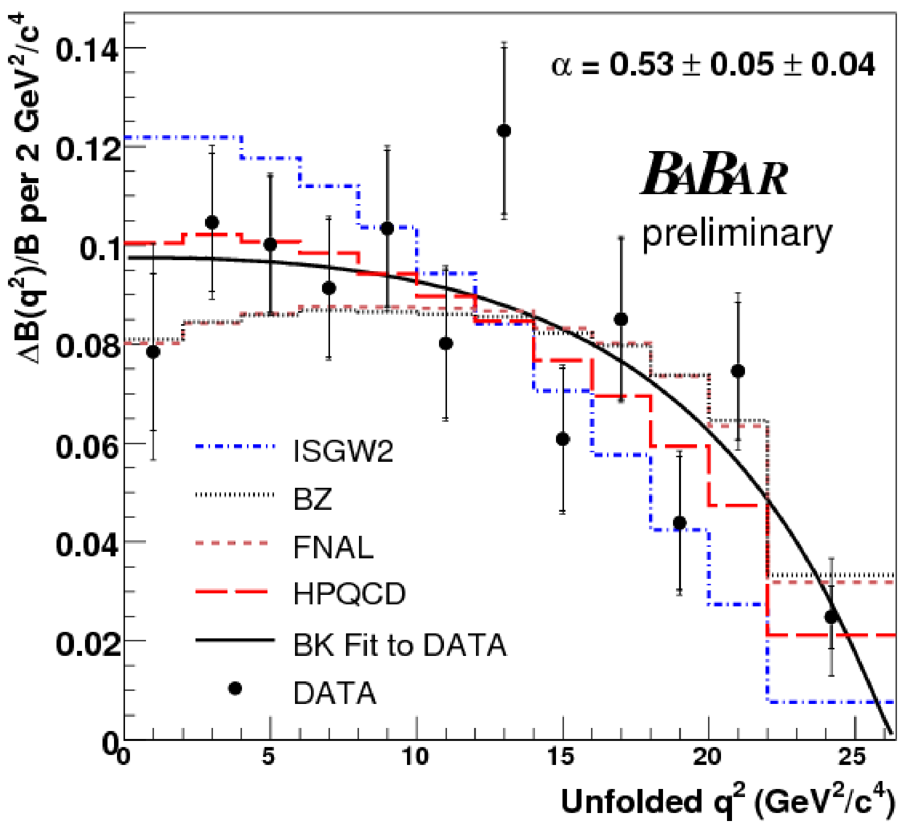
- extract theoretical parameters from fit to moments of decay distributions in $m(X_c)$ & q^2
- PDG 2008 gives $|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}$

BaBar (eg. PRL 97 (2006) 171803)
Belle (eg. PRD 78 (2008) 032016)
and others

$|V_{ub}|$ - exclusive semileptonic decays

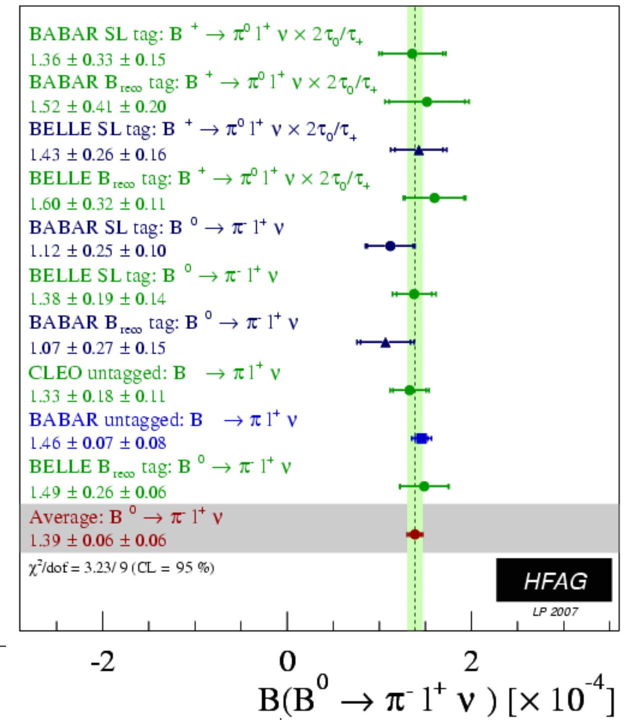
$B^0 \rightarrow \pi^- l^+ \nu$

PRL 98 (2007) 091801

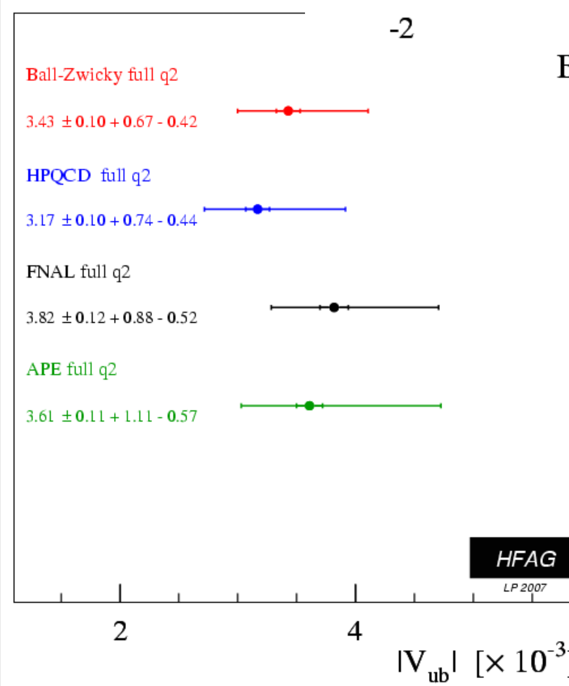


$B(B^0 \rightarrow \pi l \nu) = (1.46 \pm 0.07 \pm 0.08) \times 10^{-4}$

$|V_{ub}| = (4.1 \pm 0.2 \pm 0.2\ ^{+0.6}_{-0.4}) \times 10^{-3}$



Extraction of $|V_{ub}|$ with different theoretical approaches



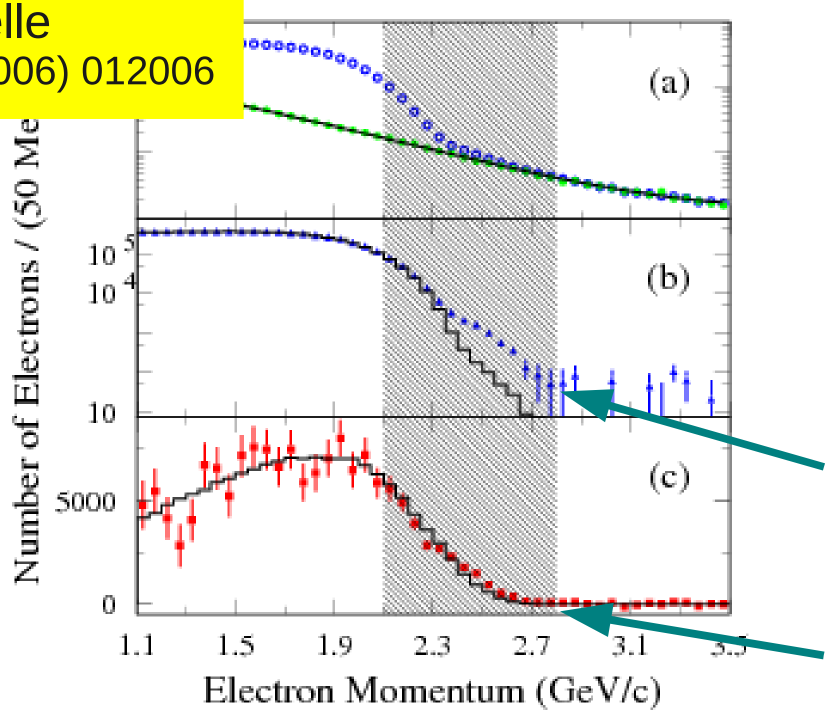
$|V_{ub}|$ - inclusive semileptonic decays

Problem for inclusive $B^0 \to X_u\, l^+ \nu$: background from $B^0 \to X_c\, l^+ \nu$

Solution:

- cut on E_l (lepton endpoint), $M(X_u)$ or some combination thereof
- cuts introduce theoretical uncertainty

Belle
PRD 73 (2006) 012006

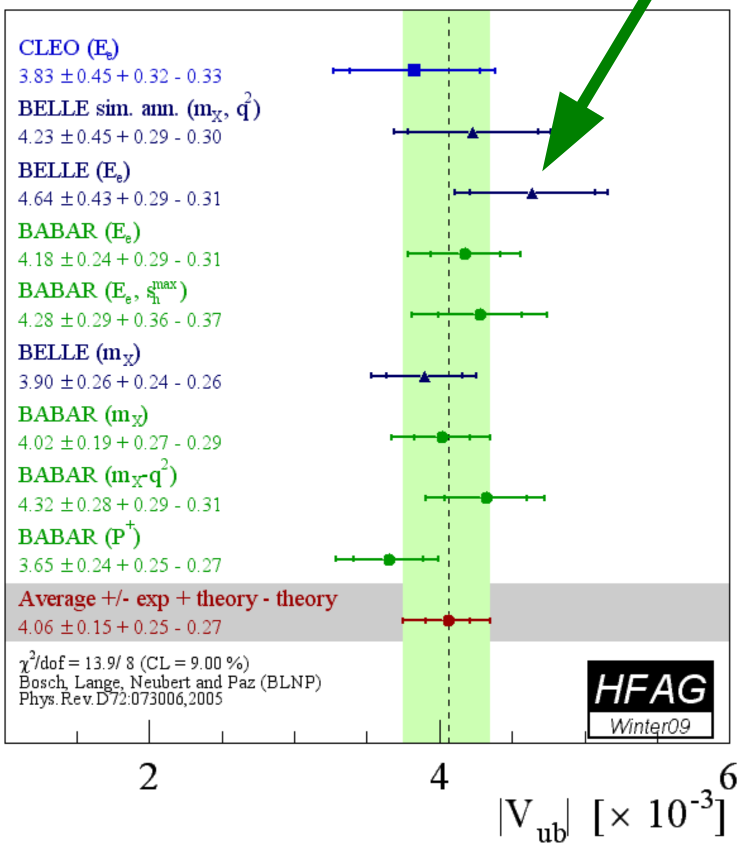


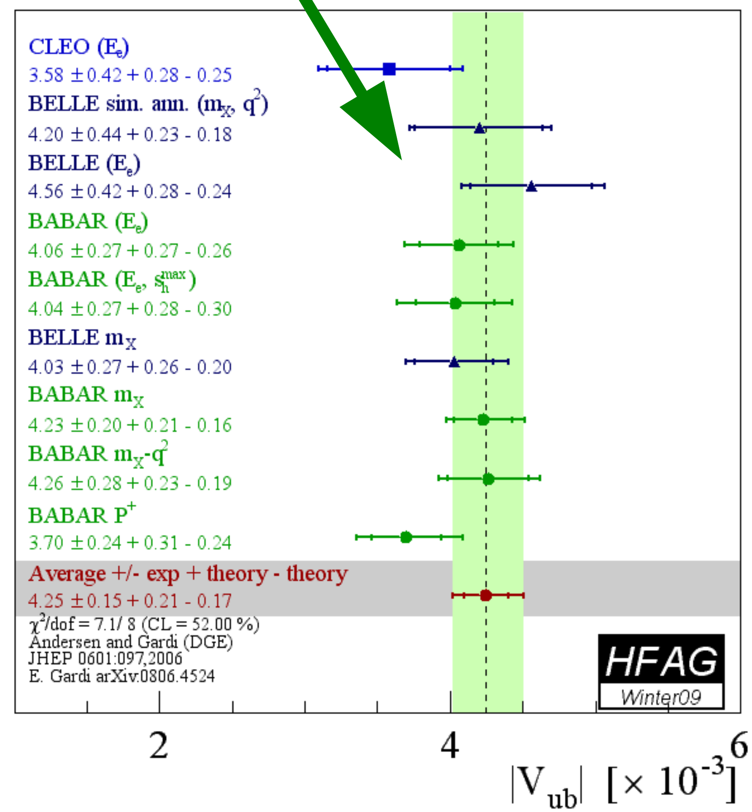
$\mathcal{B}(B \to X_u e \nu) =$
$(2.27 \pm 0.26_{exp}\ ^{+0.33}_{-0.28}\ _{SF} \pm 0.17_{theory}) \times 10^{-3}$

$|V_{ub}| =$
$(4.44 \pm 0.25_{exp}\ ^{+0.42}_{-0.38}\ _{SF} \pm 0.22_{theory}) \times 10^{-3}$

$|V_{ub}|$ inclusive - compilation

Different theoretical approaches



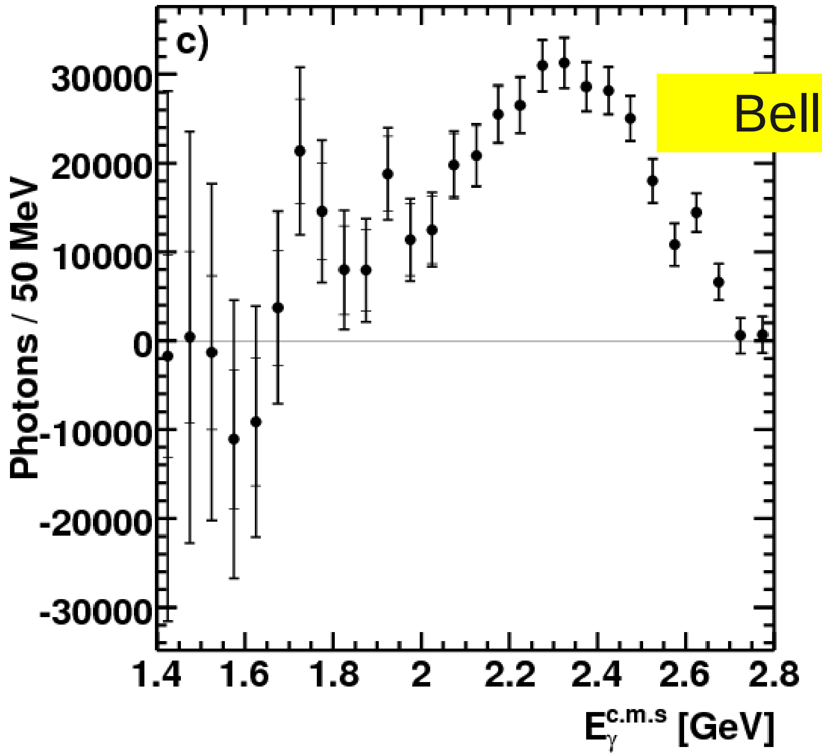


Significant experimental and theoretical problems to make a single average for |Vub|

Rare B Decays

b→sγ rate and photon energy spectrum

Archetypal FCNC probe for new physics



Belle PRL 103 (2009) 241801

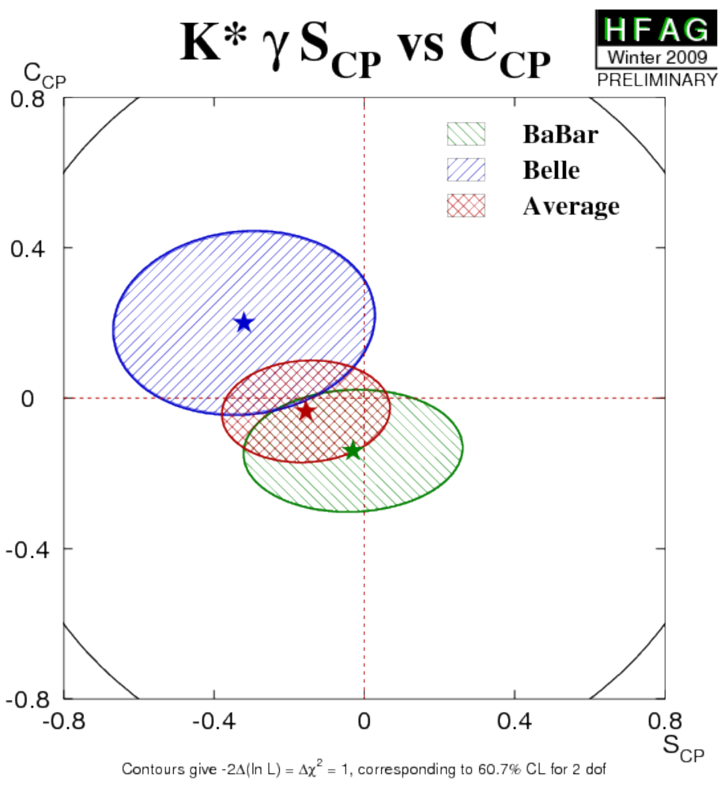
$$B(B\to X_s\gamma)_{E_\gamma>1.7\ GeV}=(3.45\pm0.15\pm0.40)\times10^{-4}$$

consistent with the SM prediction

$b \rightarrow s\gamma$ photon polarisation measurement

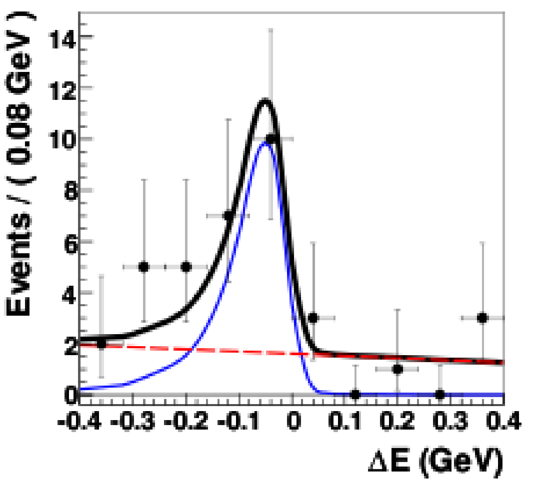
Search for time-dependent asymmetry

- Observable effect requires NP: left-handed current & new CP phase



Excellent prospects for LHCb with $B_s \rightarrow \varphi\gamma$

Belle PRL 100 (2008) 121801



Can also use, eg., $B \rightarrow K^{*}e^{+}e^{-}$ (low q^2)

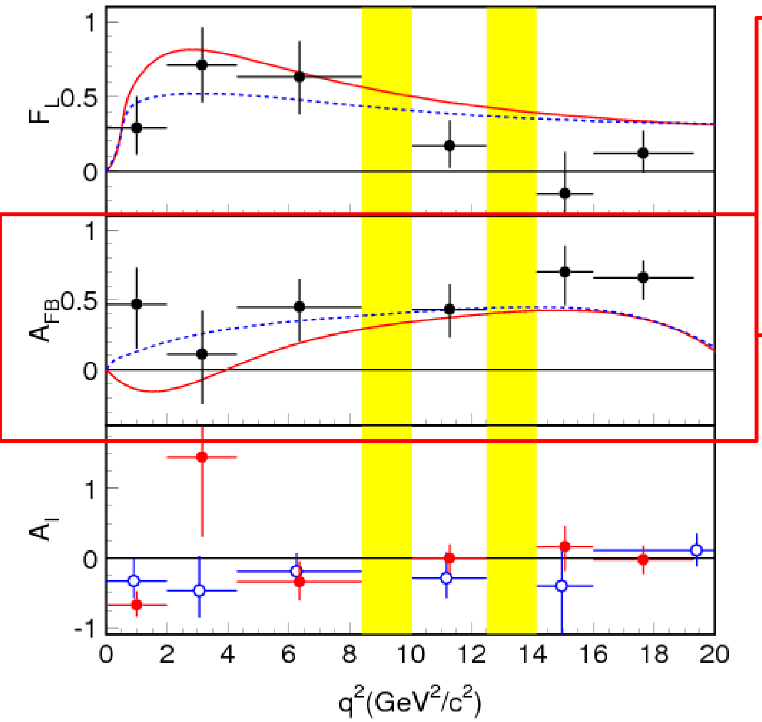
Kinematic distributions in B→K*ll

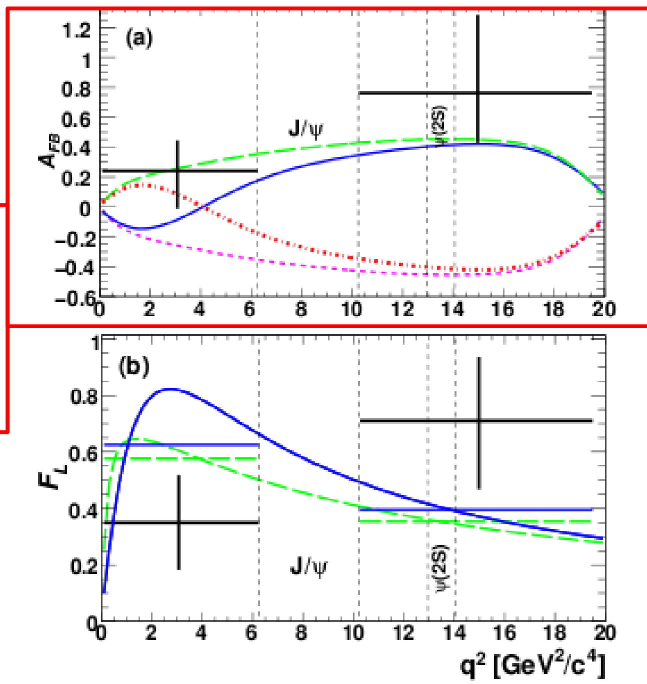
Zero-crossing point of forward-backward asymmetry cleanly predicted in SM and sensitive to NP corrections

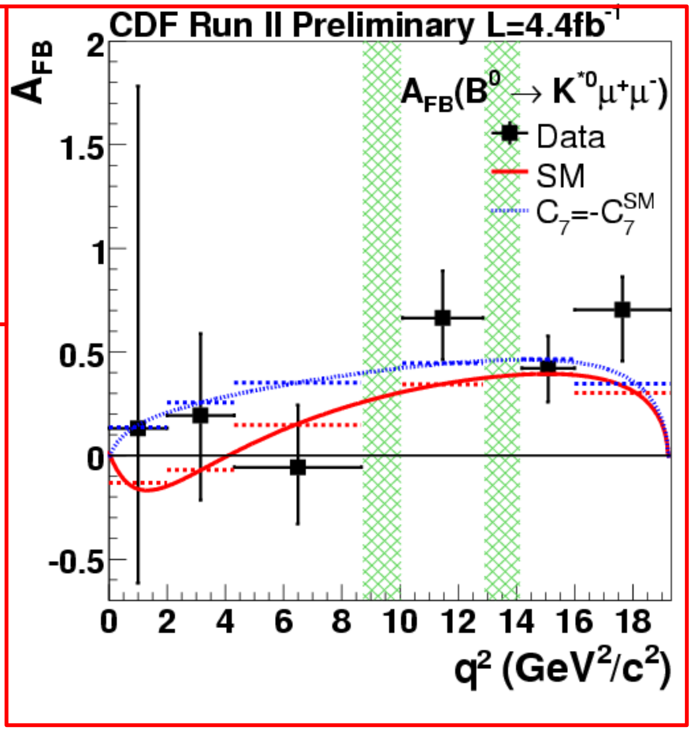
Belle PRL 103 (2009) 171801

BABAR PRD 79 (2009) 031102(R)

CDF note 09-11-12





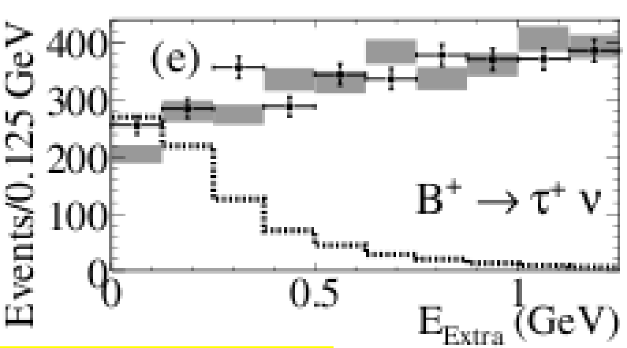


Interesting hints but much better precision required
another good opportunity for LHCb

Leptonic B Decays

$B^+ \to l^+\nu$ decays helicity-suppressed in SM: probe for effects of charged-Higgs mediated NP

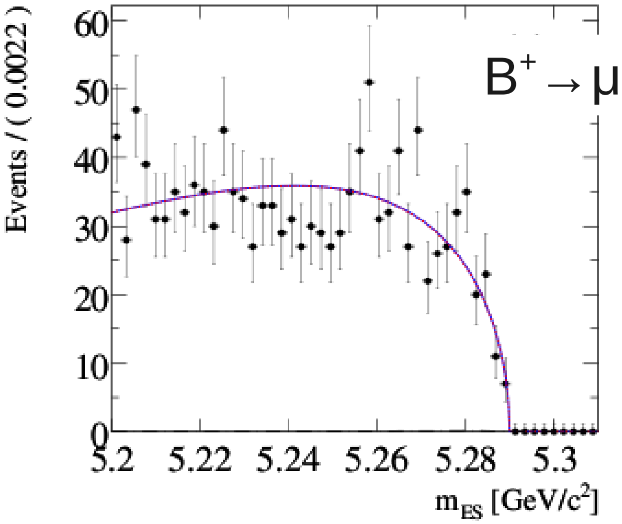
BaBar arXiv:0912.2453 [hep-ex]
See also BABAR PRD 77 (2008) 011107
Belle 0809.3834 [hep-ex] &
PRL 97 (2006) 251802



T.Iijima at LP'09

World average
$\mathcal{B}(B \to \tau\nu) = (173 \pm 35) \times 10^{-6}$
Consistent with (1σ above) SM prediction

BaBar PRD 79 (2009) 091101(R)
See also Belle PLB 647 (2007) 67



$\mathcal{B}(B \to \mu\nu) < 1.7 \times 10^{-6}$
Sensitivity approaching SM level

These modes require a Super Flavour Factory

$B_s \to \mu\mu$

Potential new physics discovery channel
for CDF / D0 / LHCb / ATLAS / CMS

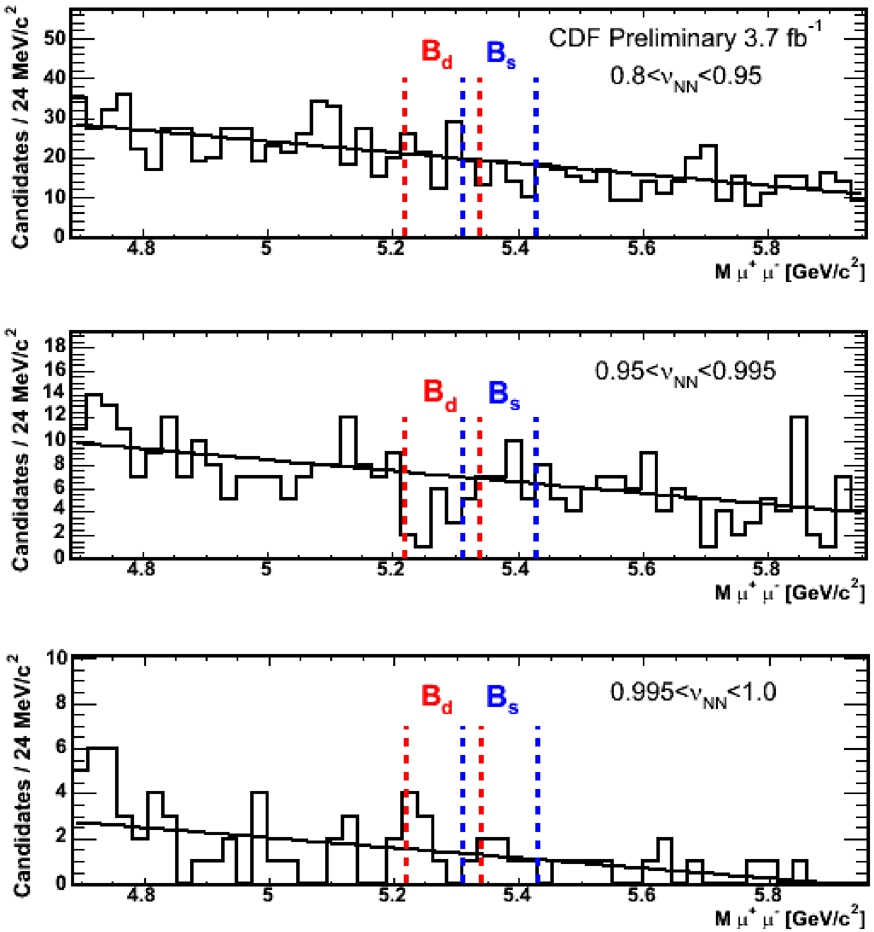
CDF Public Note 9892

New upper limits from CDF (3.7/fb):

$\mathcal{B}(B_s \to \mu\mu) < 4.3 \times 10^{-8}$ @95% CL

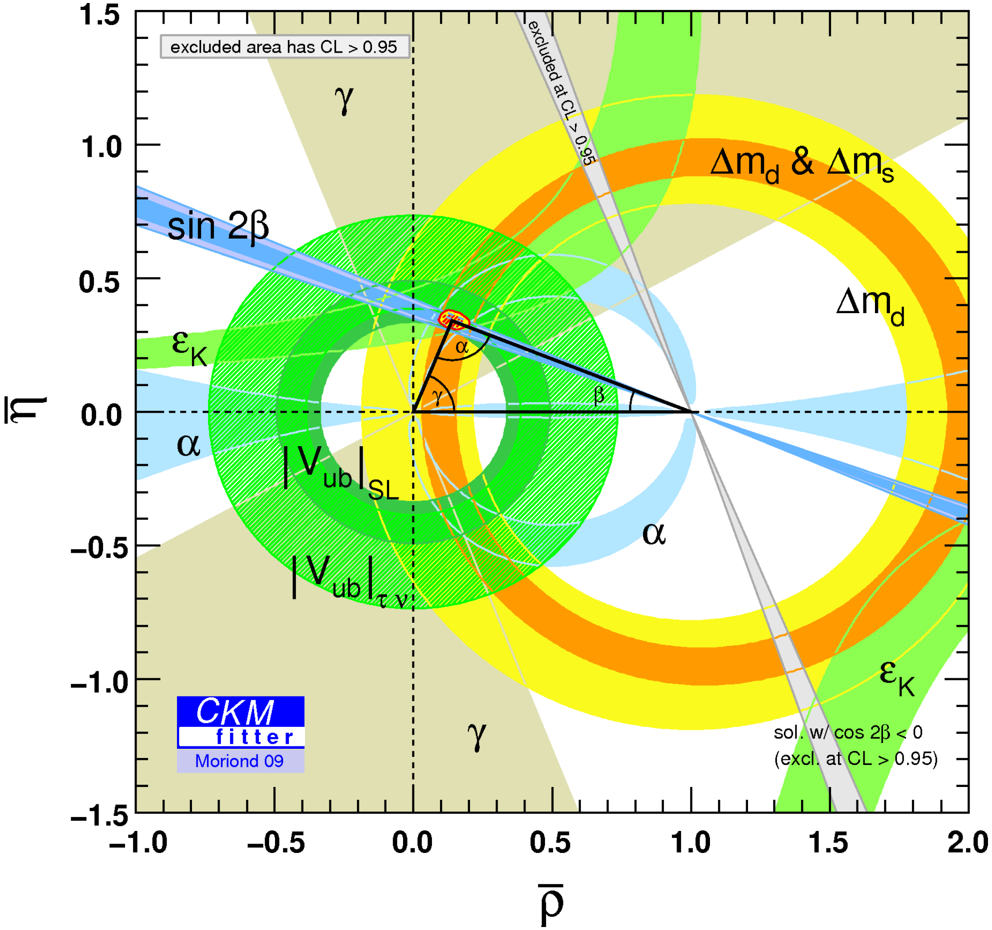
$\mathcal{B}(B_d \to \mu\mu) < 7.6 \times 10^{-9}$ @95% CL

Still some way above SM prediction

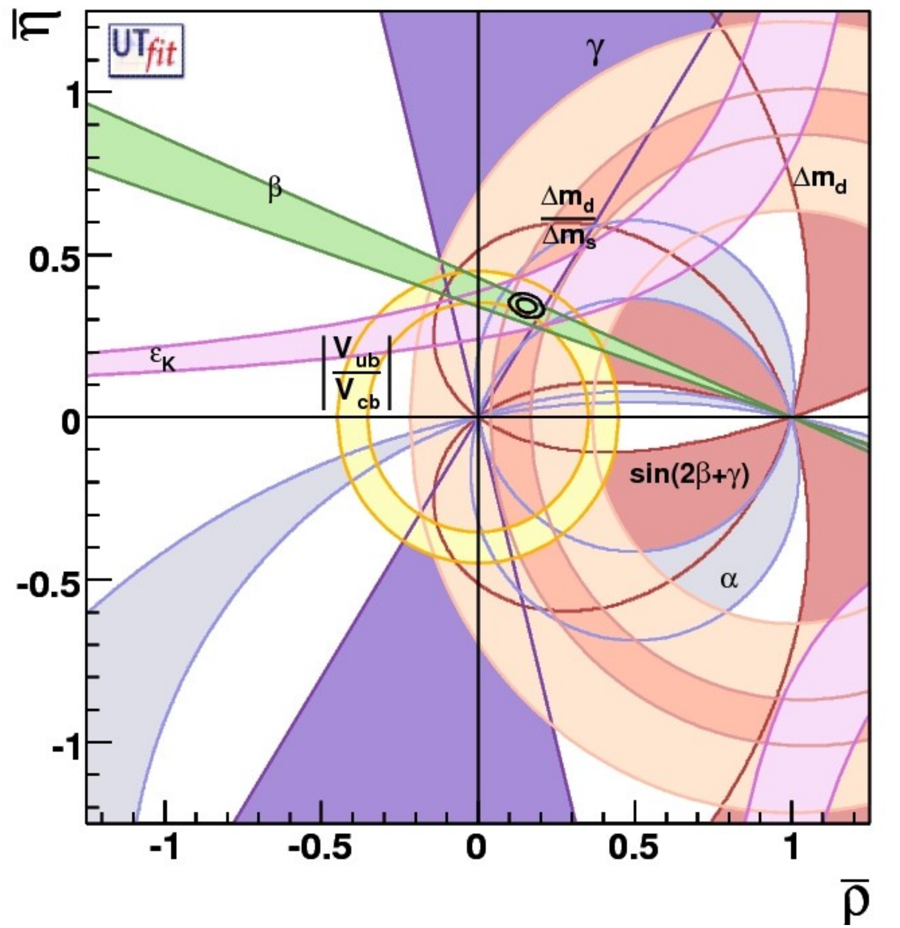


Putting it all together – Unitarity Triangle

http://ckmfitter.in2p3.fr/



http://www.utfit.org/



Summary

- Progress in B physics continues apace
  - BaBar, Belle, CDF, D0
- No smoking gun for new physics

  … but several exciting hints
  - tension in CKM fits
  - $\Delta A_{CP}(K\pi)$
  - Φ_s ($B_s \rightarrow J/\psi\varphi$)
  - $A_{FB}(K^*l^+l^-)$
- Excellent prospects for the next few years and beyond
  - LHCb, ATLAS, CMS
  - Belle2, SuperB, LHCb upgrade

Summary

How good are the prospects for New Physics discovery in the B system before WHEPPXII (2012)?

- If large NP effects are present (still possible!)
- If LHC operation runs reasonably smoothly
- If LHCb collaboration understands detector performance

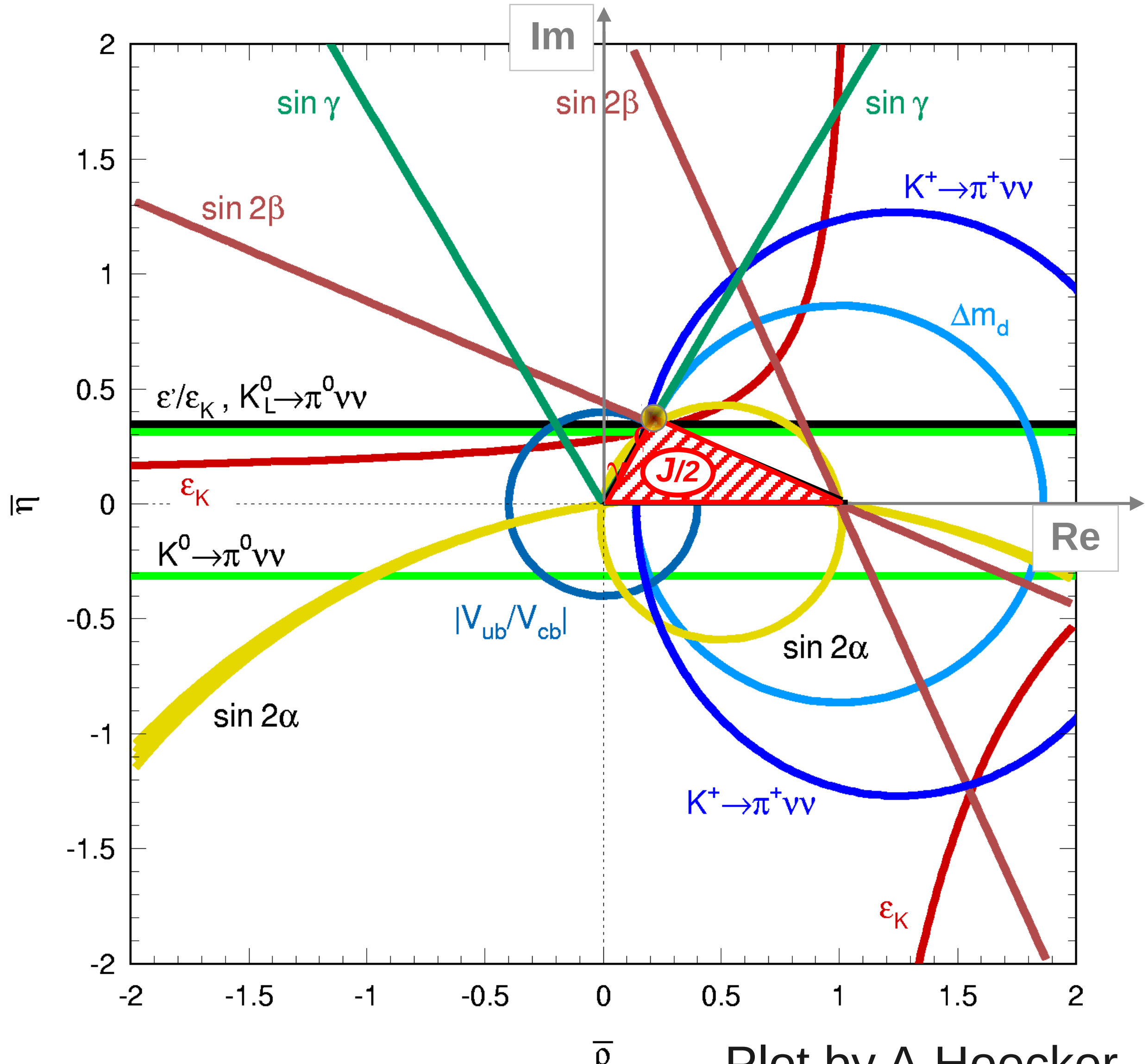
(also ATLAS & CMS if large NP in $B_s \to \mu^+\mu^-$)

(let's be optimistic)

… then the prospects are good!

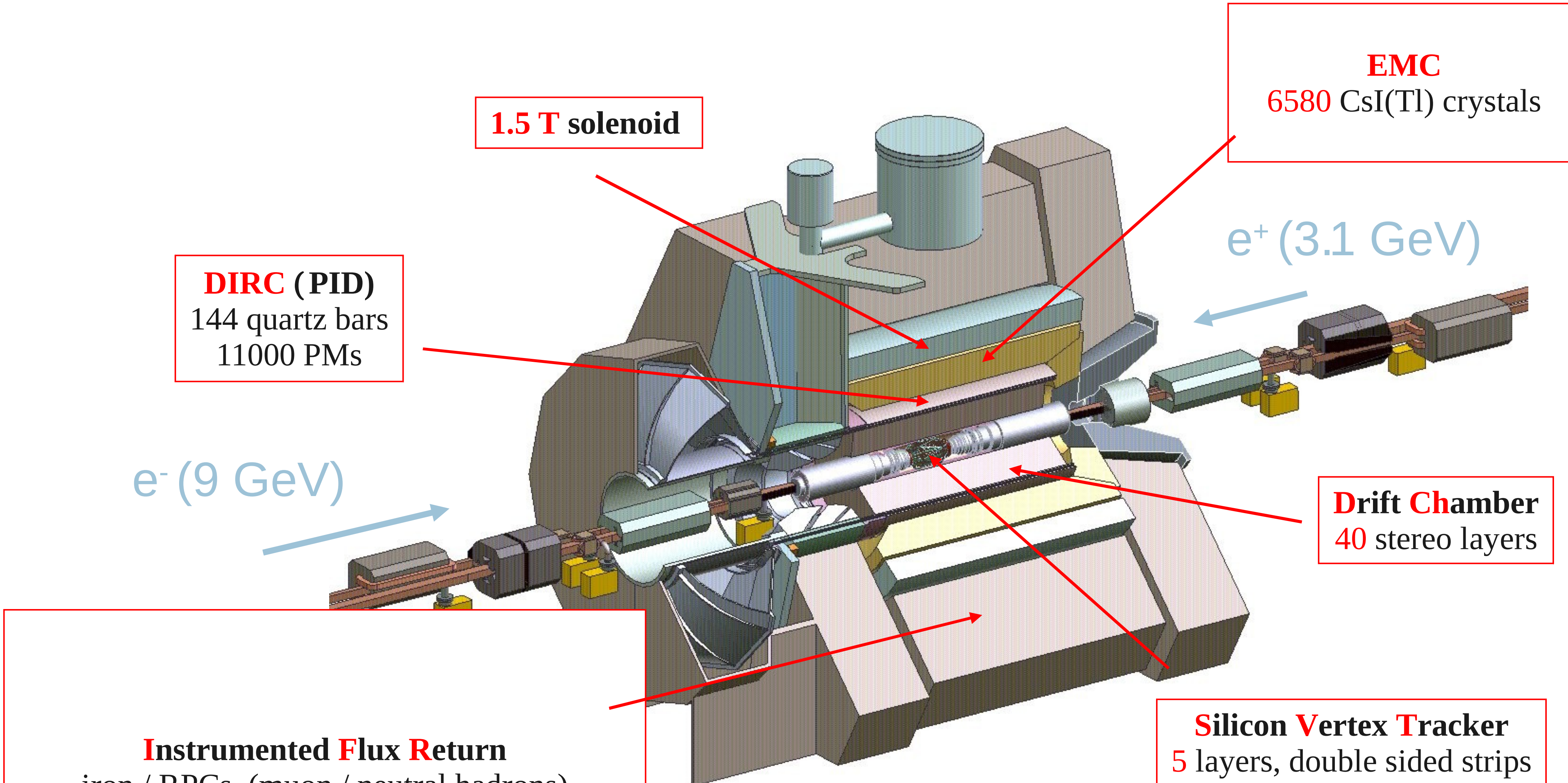
Back-up Material

All measurements must agree



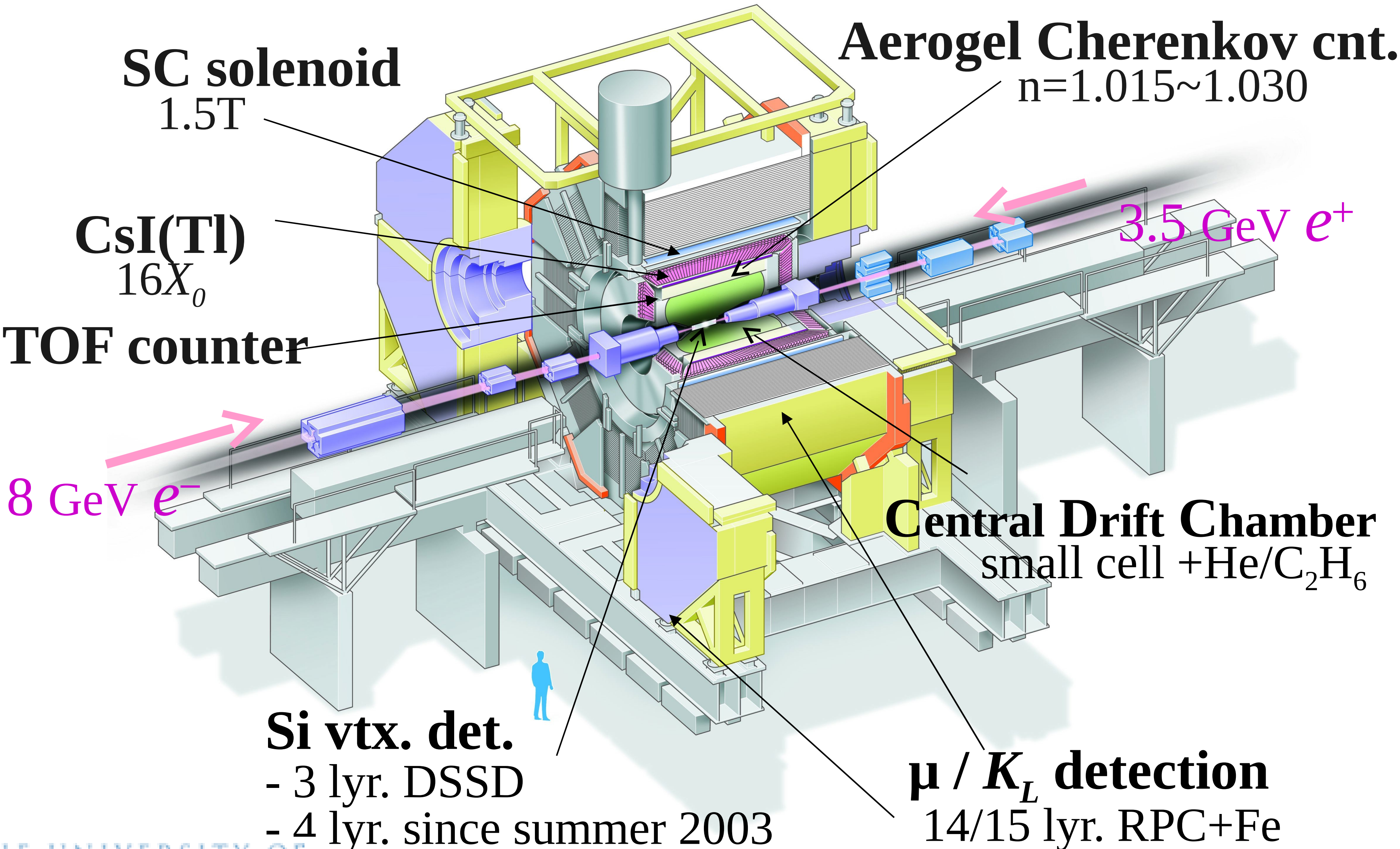
Plot by A.Hoecker

BABAR Detector

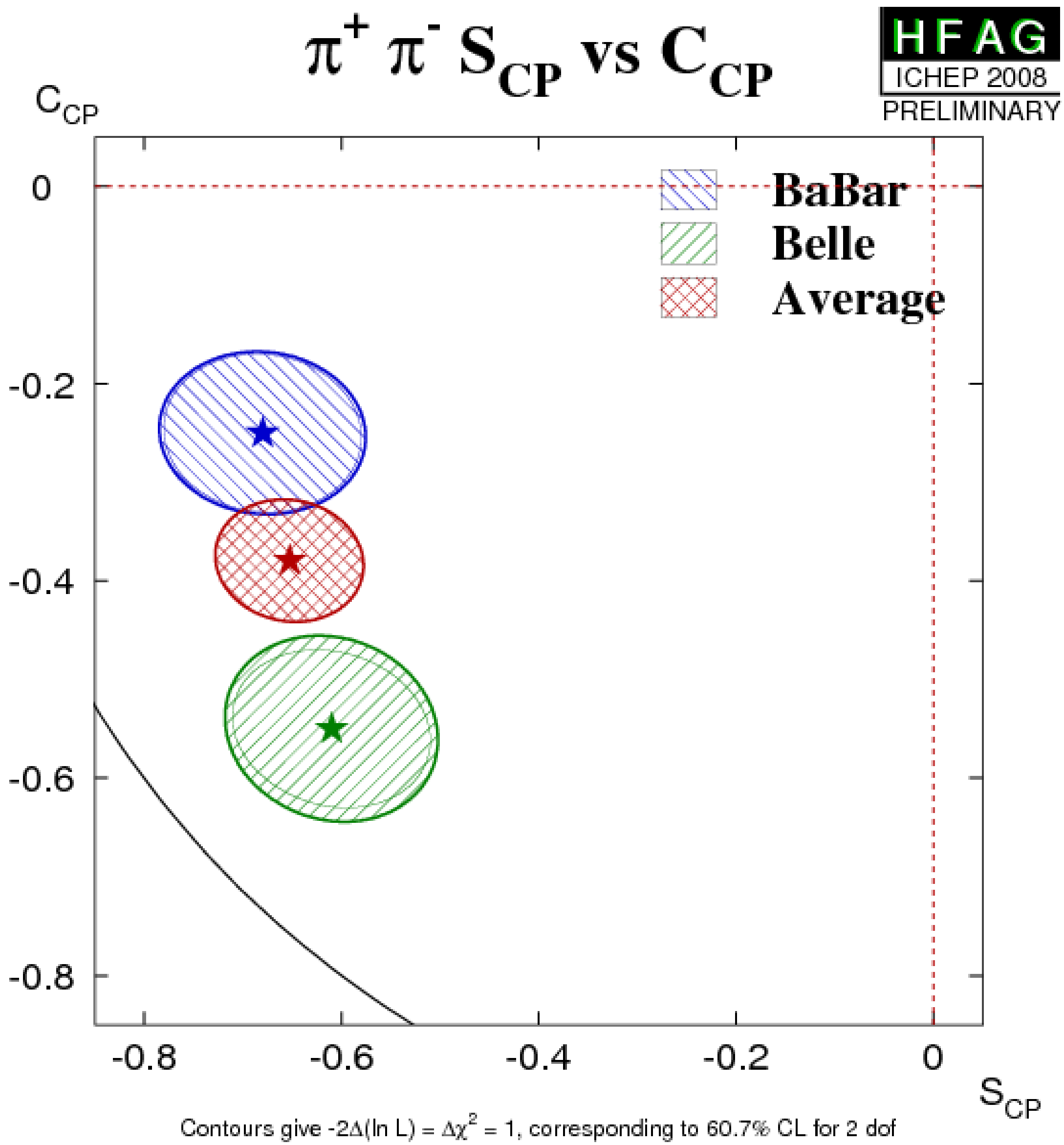


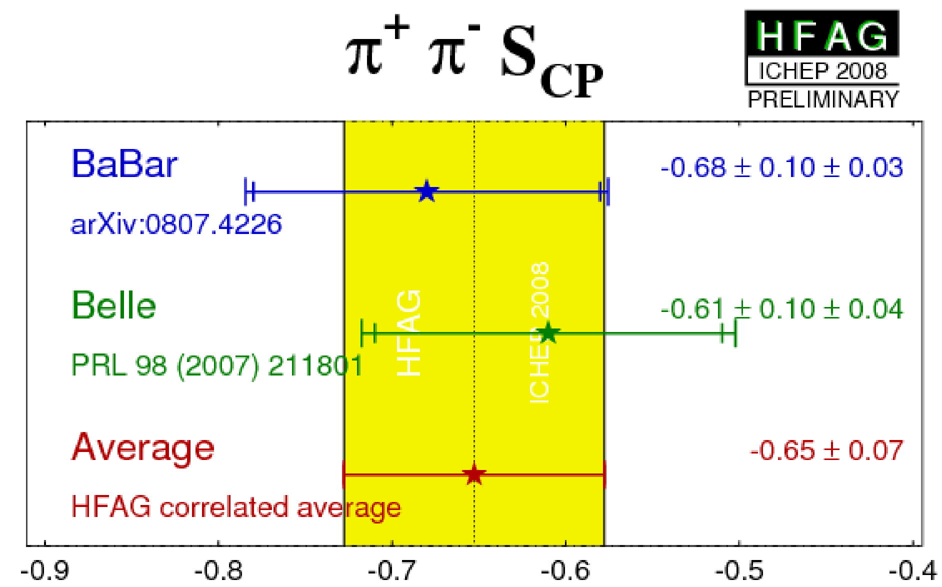
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)
2/6 replaced by LST in 2004
Rest of replacement in 2006

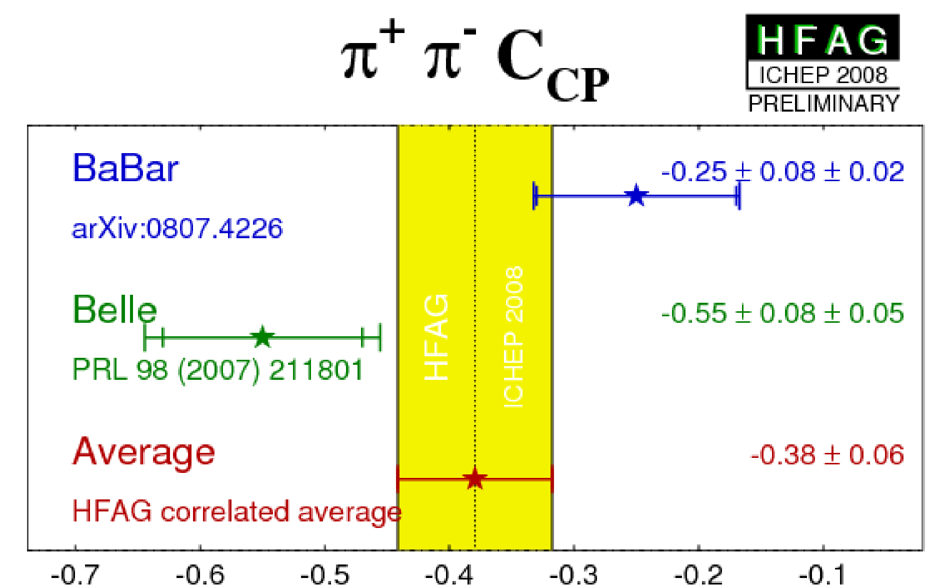
Belle Detector



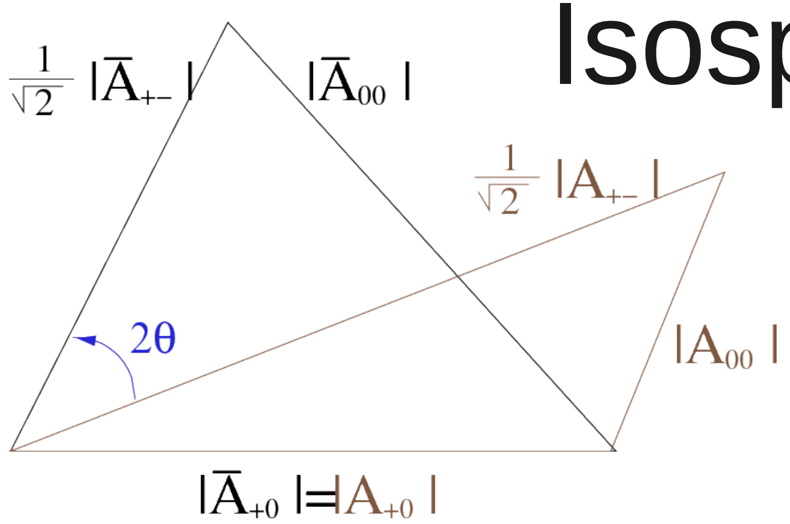
$B^0 \to \pi^+\pi^-$ -- Experimental Situation



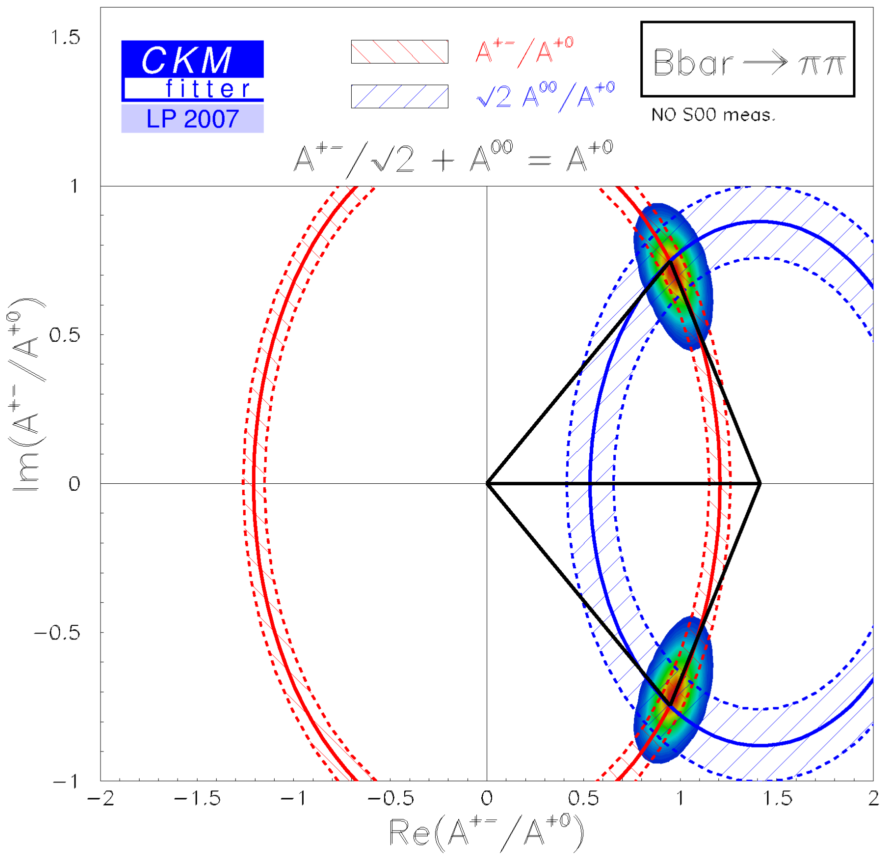


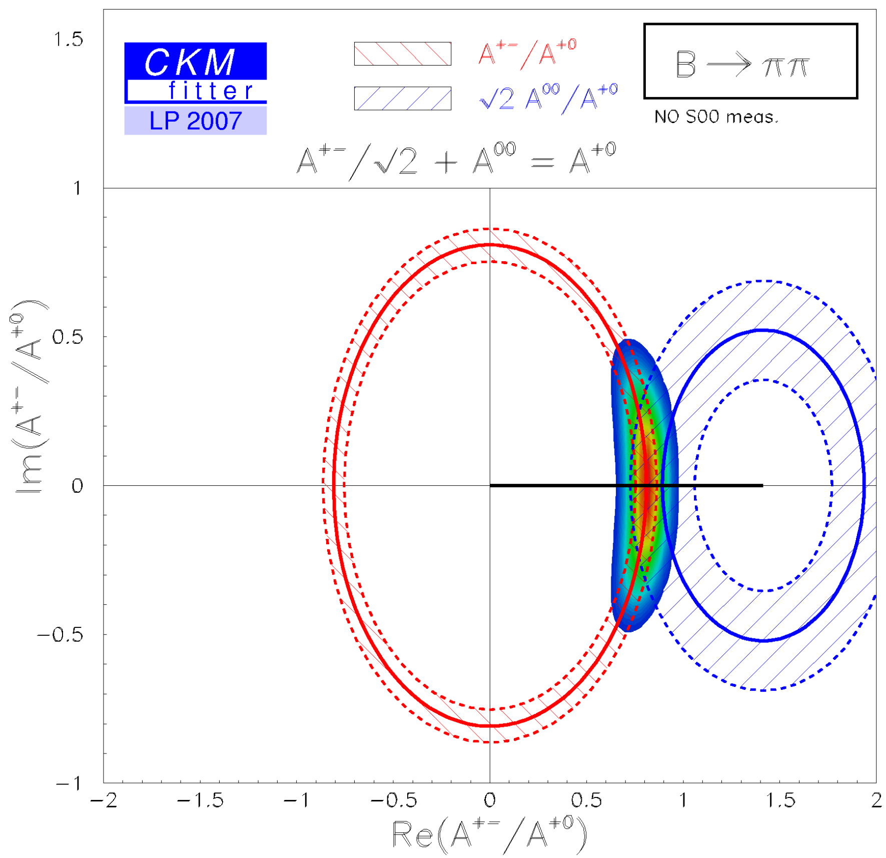


Isospin analysis

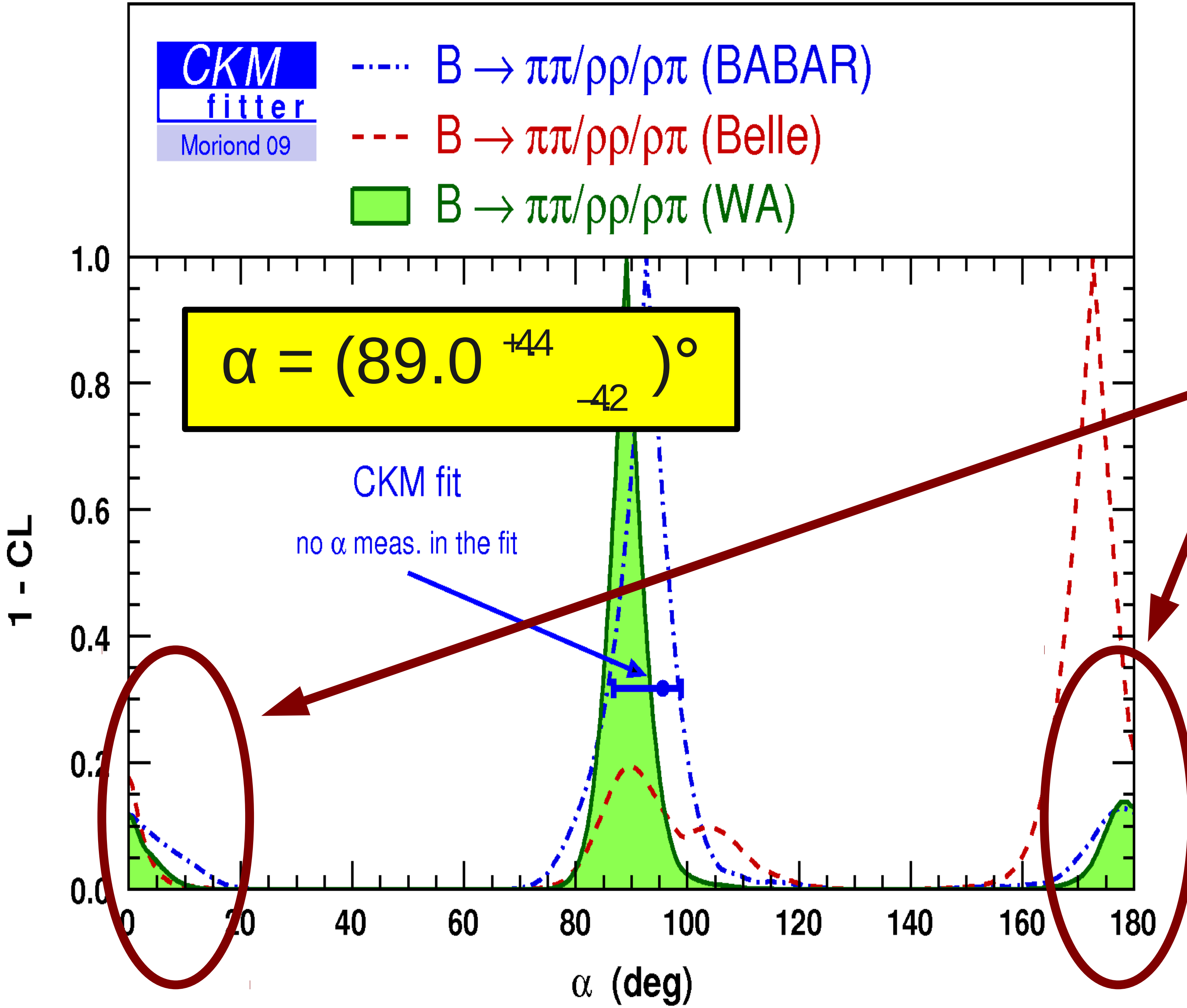


- Use triangle construction to find difference between "α_{eff}" and α (θ)
- Requires measurement of rates and asymmetries of $B^+ \to \pi^+\pi^0$ & $B^0 \to \pi^0\pi^0$





Measurement of α



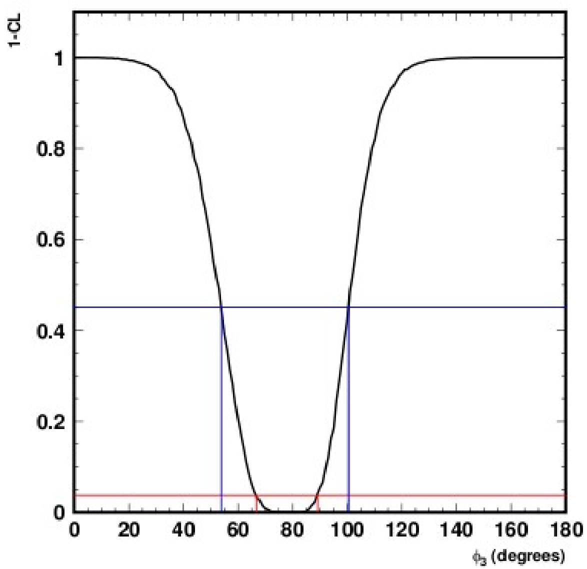
THESE SOLUTIONS RULED OUT BY OBSERVATION OF DIRECT CP VIOLATION IN B → ππ

Latest results on B→DK : (ii) Dalitz

- D decays to (e.g.) $K_S\pi^+\pi^-$ - enhanced sensitivity to γ due to interference of various resonances in the Dalitz plot
- Update from Belle including D*K, D*→Dγ
- Combined with existing results on DK; D*K, D*→$D\pi^0$; all with D→$K_S\pi^+\pi^-$

- Combined results for all modes:
  - $\phi_3 = 78.4^{\circ}{}^{+10.8^\circ}_{-11.6^\circ} \pm 3.6^\circ(\text{syst}) \pm 8.9^\circ(\text{model})$
  - $r_{DK} = 0.160^{+0.040}_{-0.038} \pm 0.011(\text{syst})^{+0.050}_{-0.010}(\text{model})$
  - $r_{D^*K} = 0.196^{+0.072}_{-0.069} \pm 0.012(\text{syst})^{+0.062}_{-0.012}(\text{model})$
- CP violation significance: 3.5σ (including systematic and model uncertainty).

Belle D→$K_S\pi\pi$
A.Poluektov at EPS'09



Model independent B→DK Dalitz measurements

Use CP-tagged CLEOc data to measure average D^0–$\bar{D}^0$ phase difference

CLEO-c Results: c_i & s_i

NEW

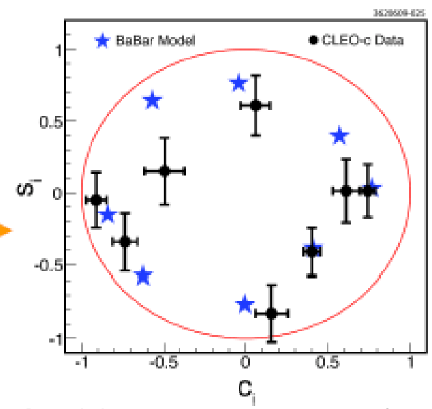
[Phys Rev. D 80, 032002 (2009)]

A.Powell at Beauty 2009

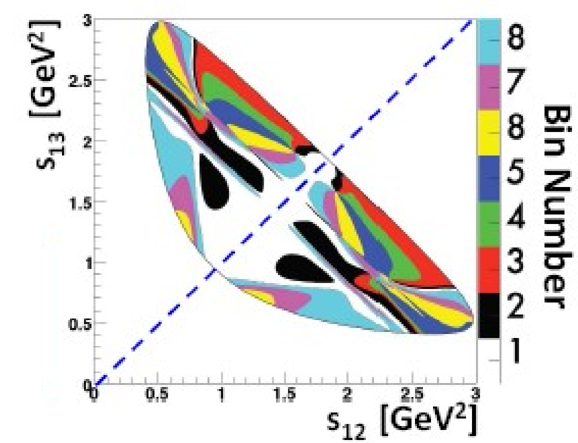
- Result ± stat ± sys ± ($K_L\pi\pi$ $K_S\pi\pi$ syst)

i	c_i	s_i
1	$0.743 \pm 0.037 \pm 0.022 \pm 0.013$	$0.014 \pm 0.160 \pm 0.077 \pm 0.045$
2	$0.611 \pm 0.071 \pm 0.037 \pm 0.009$	$0.014 \pm 0.215 \pm 0.055 \pm 0.017$
3	$0.059 \pm 0.063 \pm 0.031 \pm 0.057$	$0.609 \pm 0.190 \pm 0.076 \pm 0.037$
4	$-0.495 \pm 0.101 \pm 0.052 \pm 0.045$	$0.151 \pm 0.217 \pm 0.069 \pm 0.048$
5	$-0.911 \pm 0.049 \pm 0.032 \pm 0.021$	$-0.050 \pm 0.183 \pm 0.045 \pm 0.036$
6	$-0.736 \pm 0.066 \pm 0.030 \pm 0.018$	$-0.340 \pm 0.187 \pm 0.052 \pm 0.047$
7	$0.157 \pm 0.074 \pm 0.042 \pm 0.051$	$-0.827 \pm 0.185 \pm 0.060 \pm 0.036$
8	$0.403 \pm 0.046 \pm 0.021 \pm 0.002$	$-0.409 \pm 0.158 \pm 0.050 \pm 0.002$

- Statistical uncertainties dominant
- c_i better determined than s_i
- Results also available for c_i' & s_i'
- Broad agreement with model predictions



[Model = BABAR PRL 95 121802 (2005)]



[Model = BABAR PRL 95 121802 (2005)]

- γ Uncertainty: $\sigma_{\text{CLEO-input}}(\gamma)$ = 1.7°
  (recall model error = 7°)

LHCb sensitivity to γ

δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9

Numbers assume nominal LHC performance

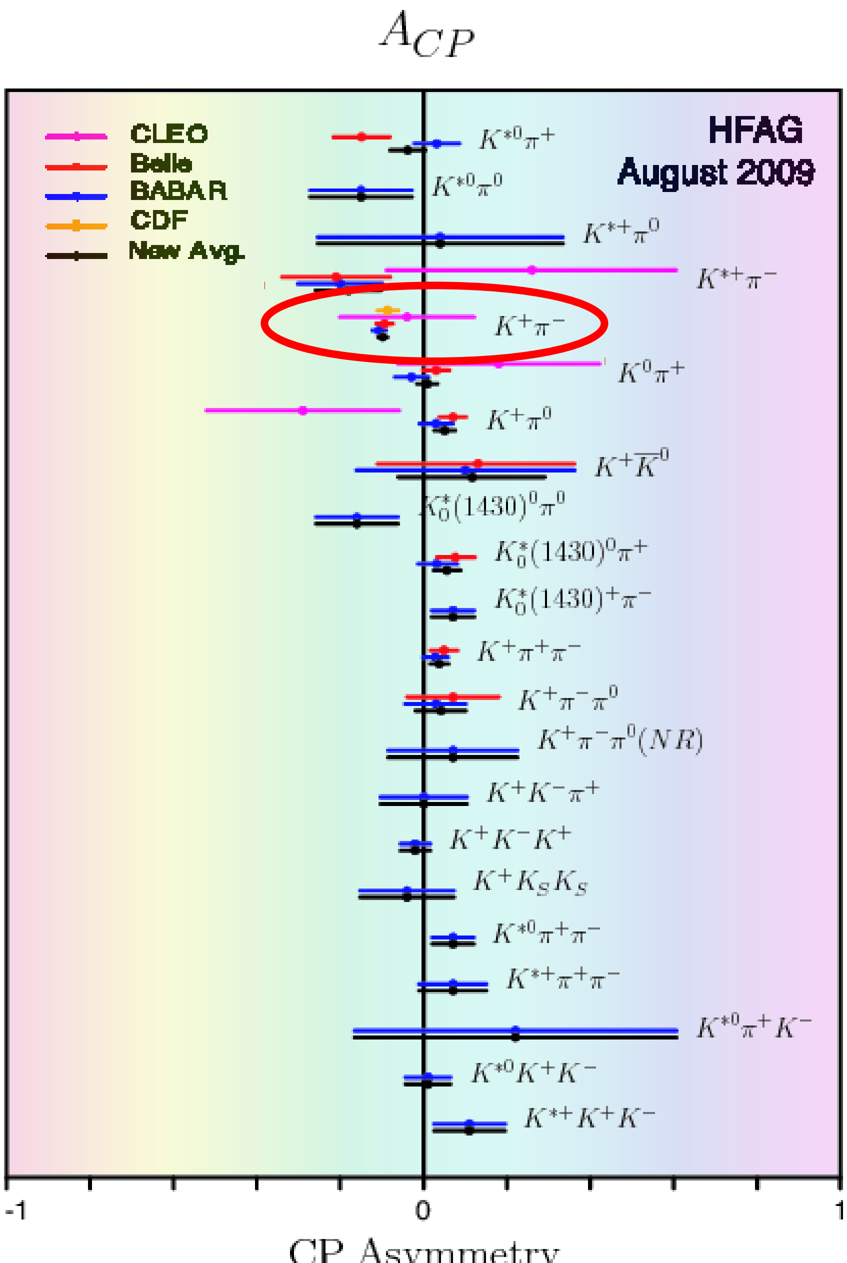
Sensitivity to δ_{B0} inherent to $B^0 \rightarrow DK^{*0}$ ("quasi-two-body") analysis

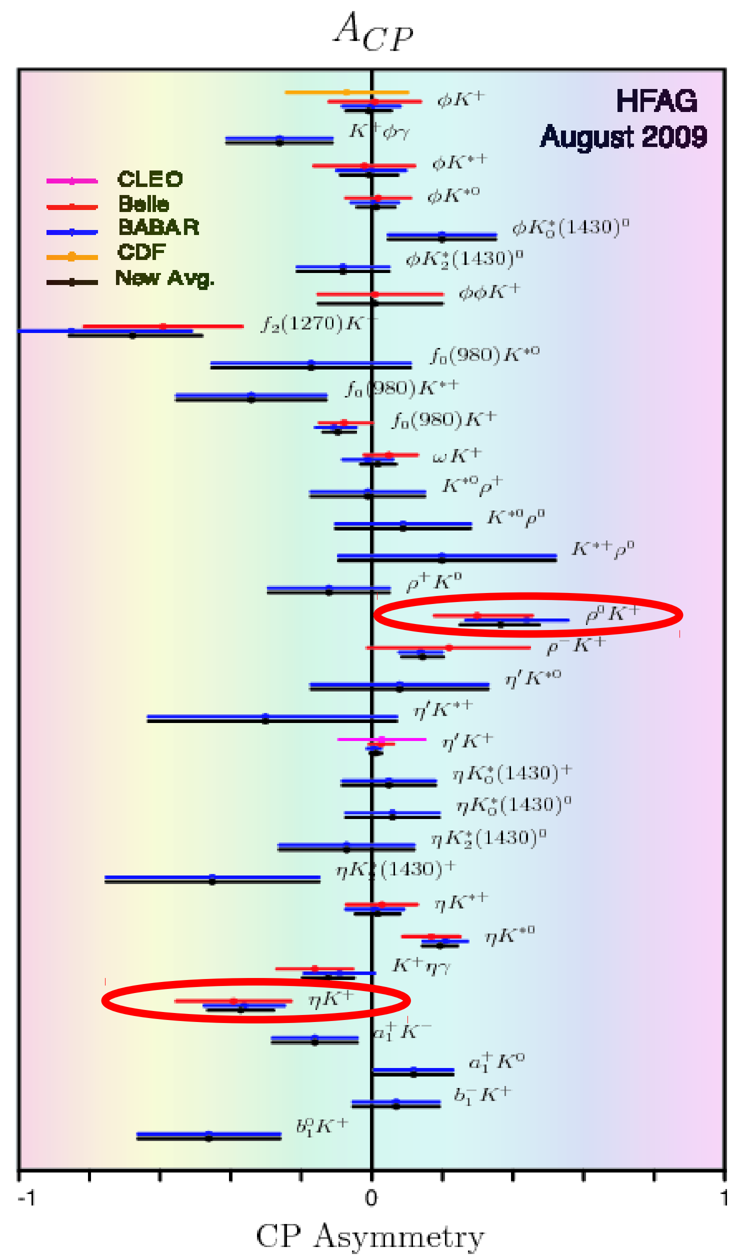
Precision can be further improved:

- CLEOc results on $D \rightarrow K\pi\pi^0$ allow it to be used in ADS analysis
- $B^0 \rightarrow DK\pi$ Dalitz plot analysis gives improved sensitivity to γ with reduced dependence on δ_{B0}

T.G. Phys. Rev. D 79 (2009) 051301(R)
T.G. & M.Williams, Phys. Rev. D 80 (2009) 092002

Direct CP asymmetries in charmless hadronic B decays

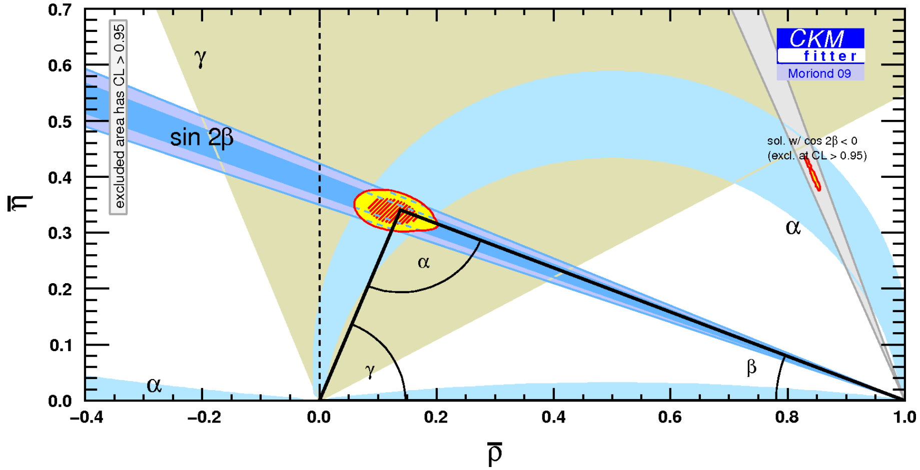




NB. DCPV also observed in $B\to\pi^+\pi^-$ time-dependent analysis

Prospects for Unitarity Triangle angles

http://ckmfitter.in2p3.fr/



Refine understanding of α

$B^+ \to \rho^+\rho^0$ from Belle

Improve γ measurement

good prospects for LHCb

Resolve Kπ puzzle

need better $K_S\pi^0$ measurement: Belle2 & SuperB

Improve $B_s \to hh$ measurements

more to come from CDF; then LHCb (plus e^+e^- Υ(5S) data)

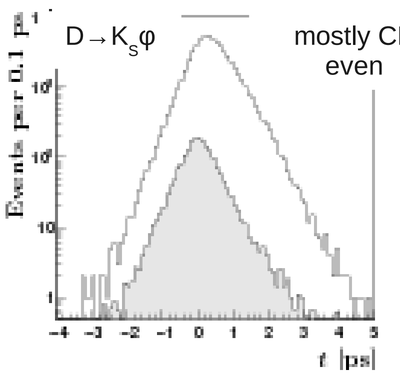
Charmless hadronic B decay Dalitz plot analyses

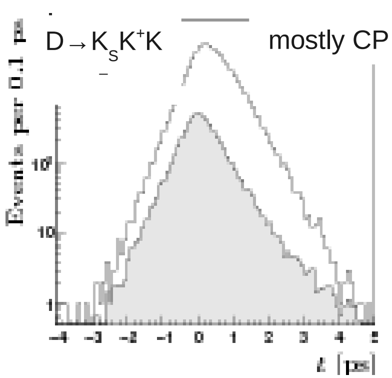
CDF, LHCb, Belle2, SuperB

Charm mixing and CP violation

Results from BABAR, Belle, CDF, CLEO

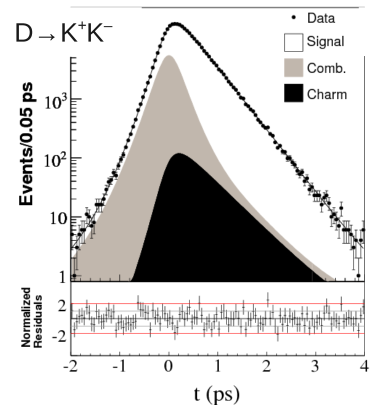
Belle arXiv:0905.4185 [hep-ex]

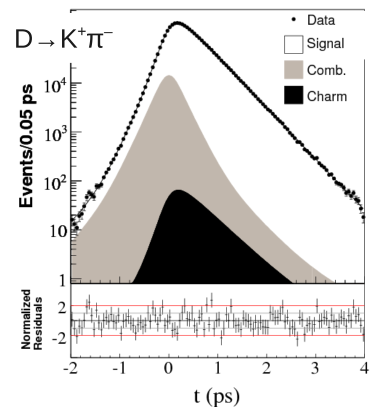




$y_{CP} = (0.11 \pm 0.61\ (stat) \pm 0.52\ (syst))\%$

BABAR arXiv:0908.0761 [hep-ex]





$y_{CP} = (1.12 \pm 0.26\ (stat) \pm 0.22\ (syst))\%$

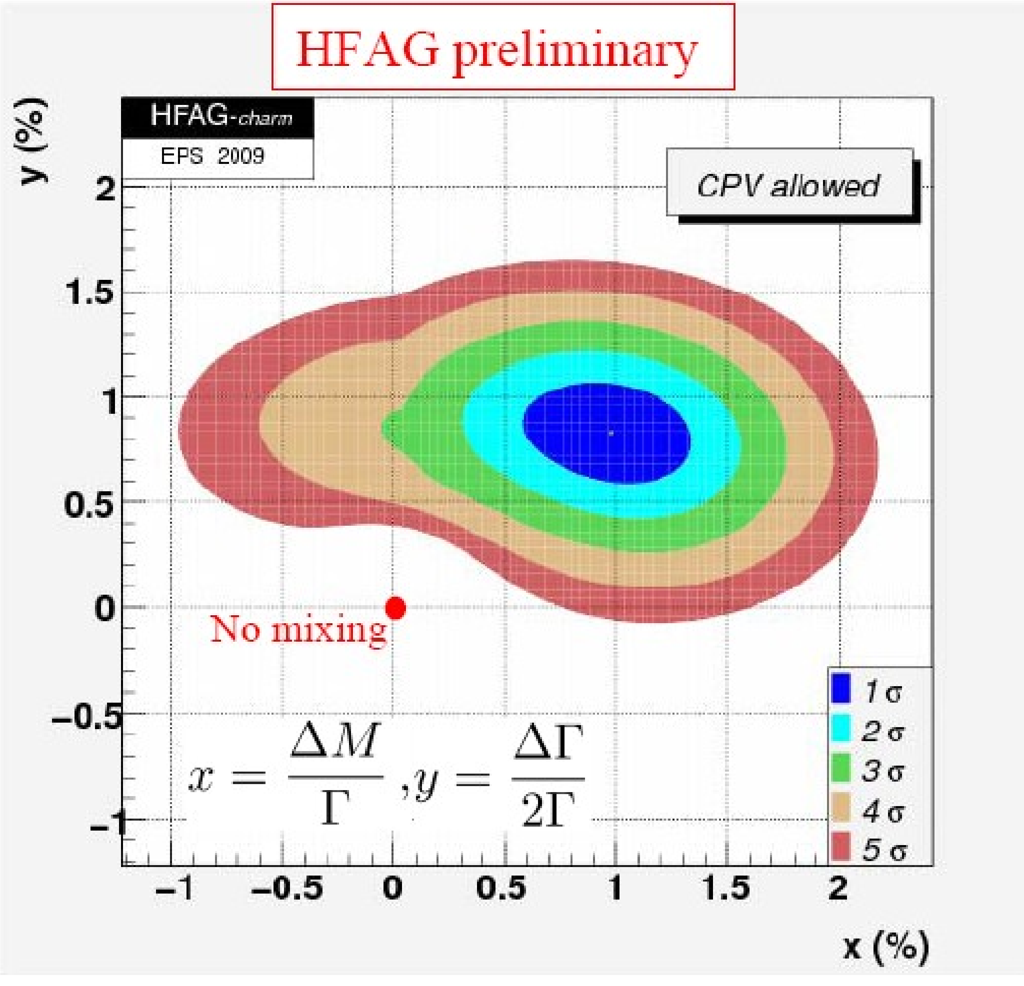
$y_{CP} \sim \Delta\Gamma$ and modified by CP violation in mixing

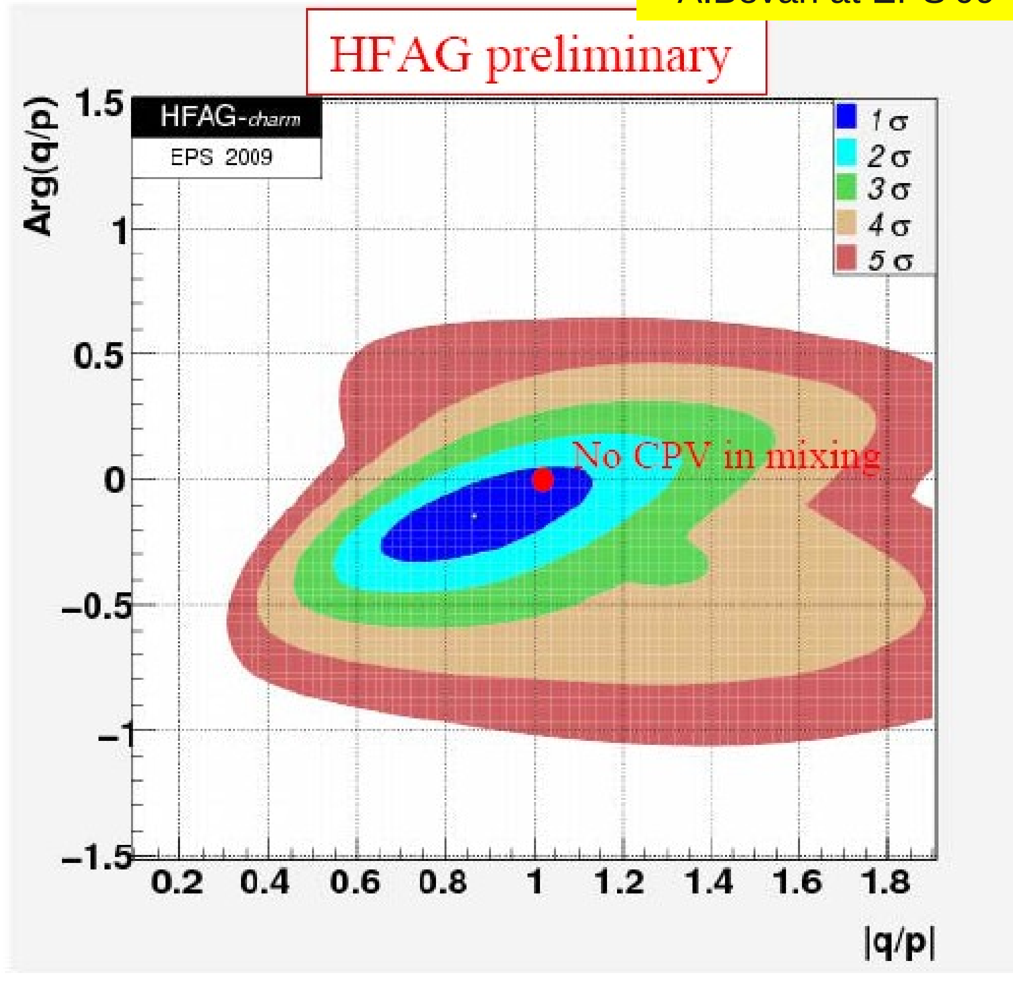
Charm mixing and CP violation

Including results from BABAR, Belle, CDF, CLEO(c), FOCUS

Latest new results Belle arXiv:0905.4185 [hep-ex] BABAR arXiv:0908.0761 [hep-ex]

A.Bevan at EPS'09

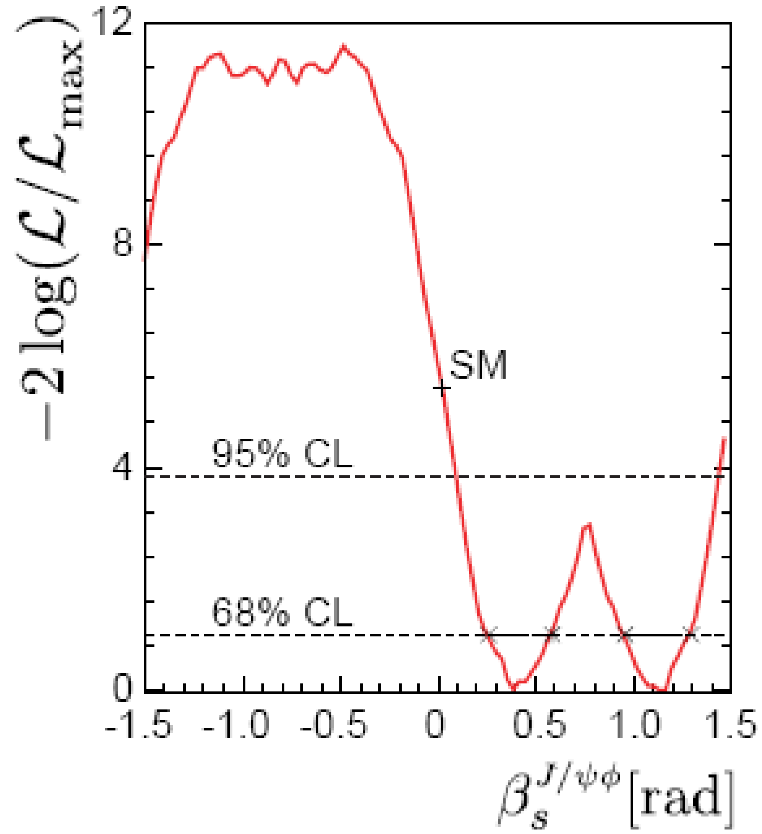




Mixing established (though still no single measurement > 5σ)

No indication of CP violation

Φ_s ($B_s \to J/\psi\varphi$)



68% CL interval [0.27, 0.59]∪[0.97, 1.30] rad
95% CL interval is [0.10, 1.42] rad

Combination of results

Latest combination huge improvement on previous efforts

- The two experiments perform very similar analyses
- Two dimensional ($\Delta\Gamma_s$ *vs*. φ_s) log-likelihoods are added

But, $B_s \rightarrow J/\psi\varphi$ is not a two-dimensional problem

- Consistency of results on other variables?
- Higher dimensional combination would be better
- Most practical way is simultaneous fit of both data sets
- Work ongoing ...

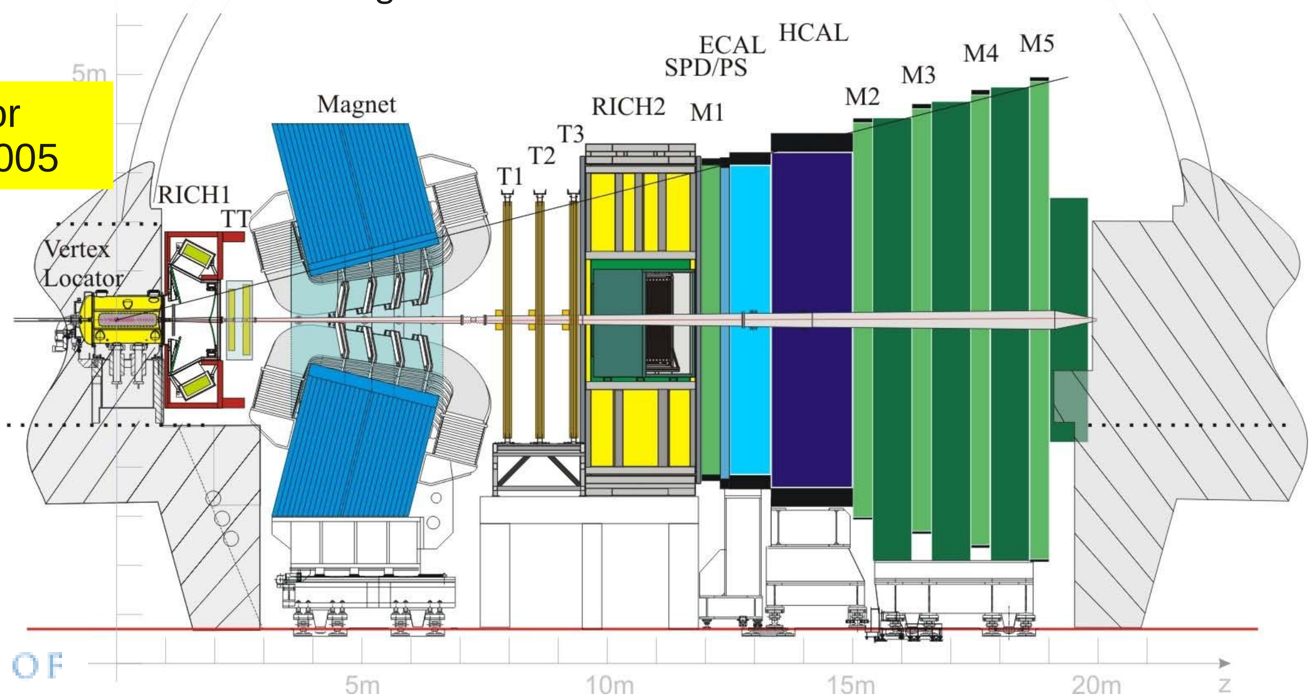
Future prospects for CP violation in B_s and charm oscillations

More results still to come from B factories & Tevatron

LHCb will improve world's best measurements with 1 year of data (at nominal luminosity)

excellent prospects for $B_s \to J/\psi\phi$ and $D^0 \to hh$ with early data

The LHCb Detector
JINST 3 (2008) S08005



CKM Matrix – Magnitudes

PDG 2008
See also S.Prell at LP'09

semileptonic / leptonic kaon decays
hadronic tau decays

superallowed $0^+ \rightarrow 0^+$ β decays

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97418 \pm 0.00027 & 0.2255 \pm 0.0019 & (3.93 \pm 0.36) \times 10^{-3} \\ 0.230 \pm 0.011 & 1.04 \pm 0.06 & (41.2 \pm 1.1) \times 10^{-3} \\ (8.1 \pm 0.6) \times 10^{-3} & (38.7 \pm 2.3) \times 10^{-3} & > 0.74 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

semileptonic / leptonic charm decays

B_d oscillations

B_s oscillations

single top production

theory inputs (eg., lattice calculations) required

$|V_{ub}|$ inclusive - M_X analysis

Best current measurement PRL 95, 241801 (2005)

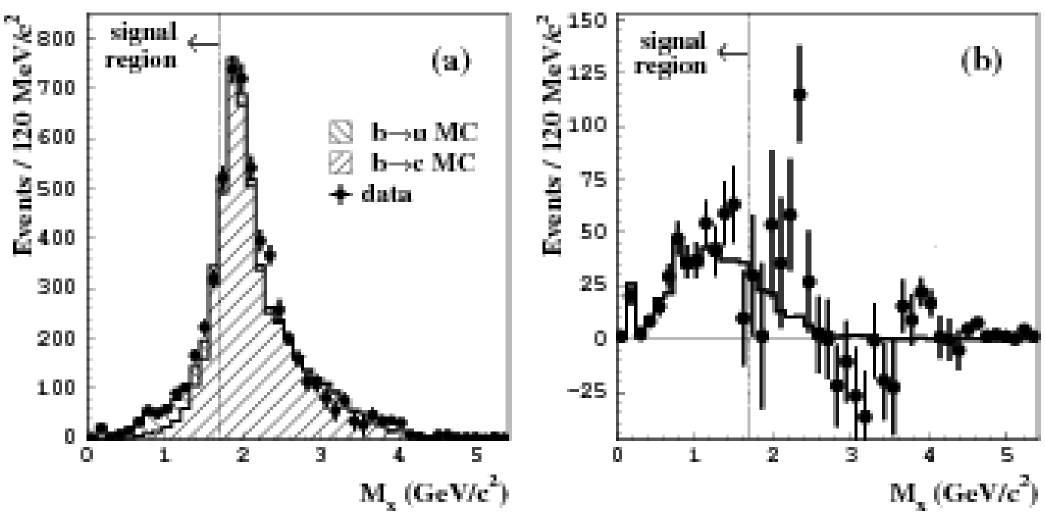


FIG. 3: M_X distribution (no q^2 requirement) with fitted contributions from $X_c\ell\nu$ and $X_u\ell\nu$: (a) before and (b) after subtracting the $X_c\ell\nu$ contribution (symbols with error bars), shown with the prediction for $X_u\ell\nu$ (MC, histogram).

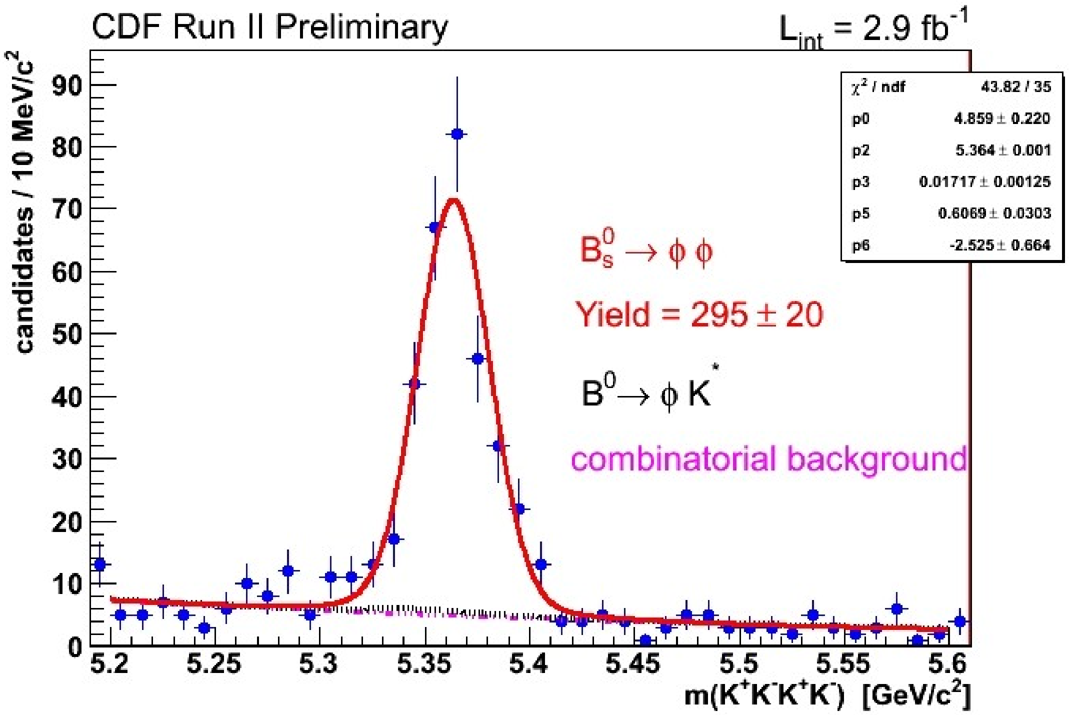
$|V_{ub}| = (4.09 \pm 0.19 \pm 0.20 \pm 0.15 \pm 0.18) \times 10^{-3}$

$B_s \to \varphi\varphi$

New hadronic $b \to s$ penguin dominated decay mode

Approximately as clean theoretically as $B \to \varphi K_s$

CDF preliminary
See D.Tonelli at Beauty'09



Prospects for rare B decays

Excellent prospects for LHCb for many important channels

$B_s \rightarrow \mu\mu$, $B \rightarrow K^*ll$, $B_s \rightarrow \varphi\gamma$, etc.

ATLAS and CMS can also contribute for some channels

Many more important channels can only be studied in e^+e^- environment : Belle2 & SuperB

$B \rightarrow \tau\nu$, inclusive measurements, $B \rightarrow K_S\pi^0\gamma$, $B \rightarrow K\nu\nu$, etc.