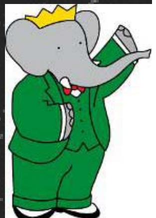
Seeking a Needle in a Haystack

Recent Results from the B-Factory Experiments

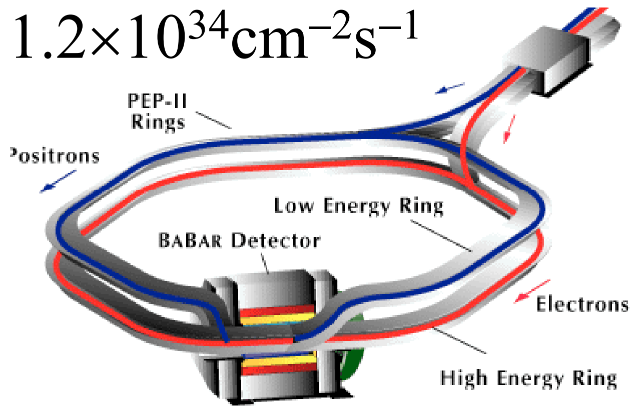
Klaus Honscheid
Ohio State University
XIII Mexican School of Particles and Fields 2008

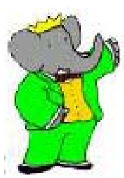


The Two Asymmetric Energy B Factories

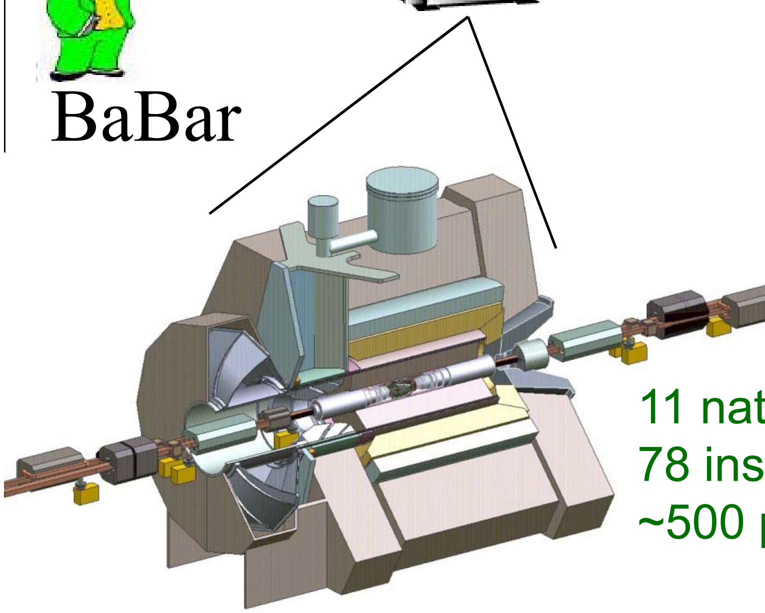
PEP-II at SLAC

9 GeV (e^-) × 3.1 GeV (e^+)
peak luminosity:
$1.2\times10^{34}\text{cm}^{-2}\text{s}^{-1}$



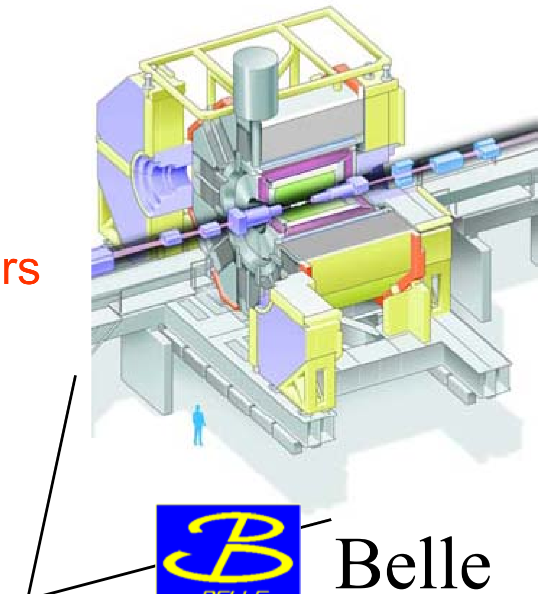


BaBar

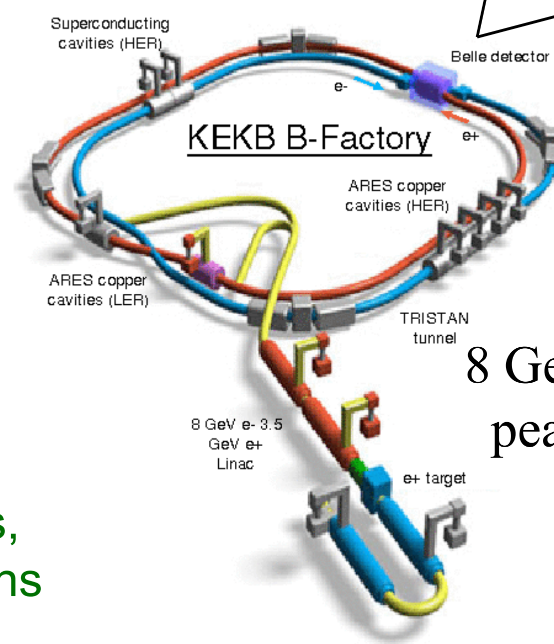


11 nations,
78 institutes,
~500 persons

14 countries,
59 institutes,
~400 collaborators



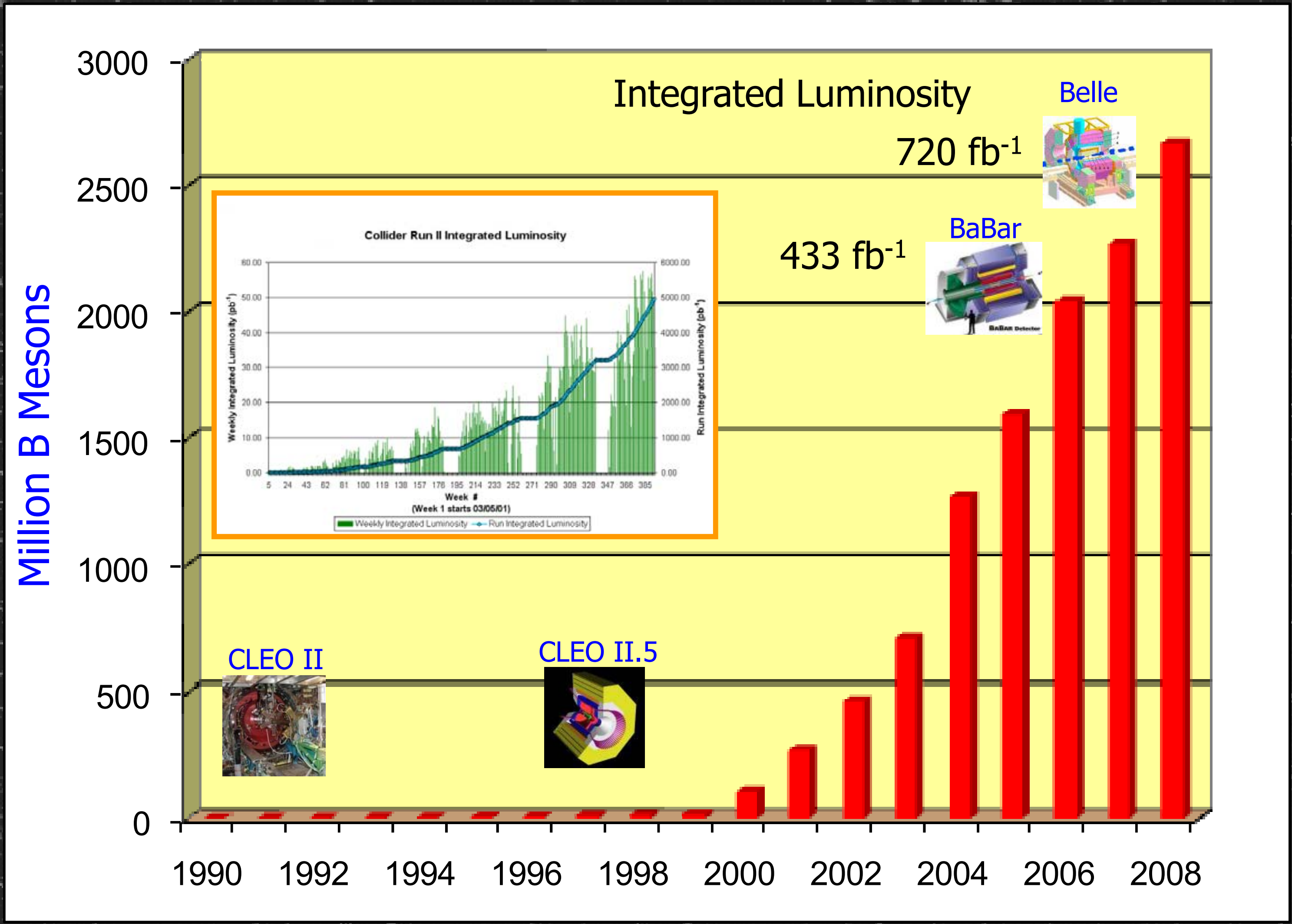
Belle



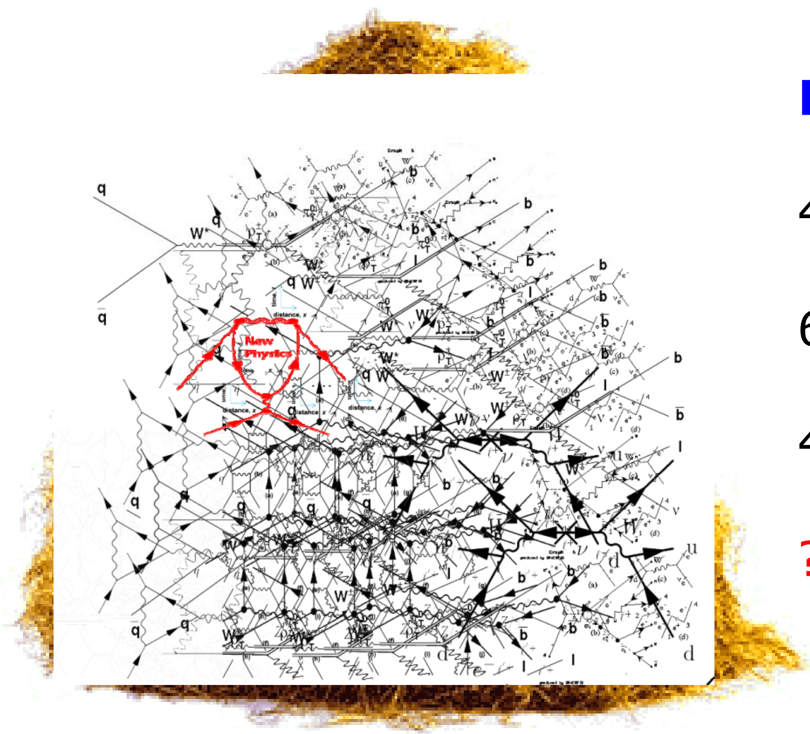
KEKB at KEK

8 GeV (e^-) × 3.5 GeV (e^+)
peak luminosity:
$1.7\times10^{34}\text{cm}^{-2}\text{s}^{-1}$

Experimental Landscape (ca 2008)



Precision Physics and Rare Events



BaBar collected:

480 million $\Upsilon(4S) \rightarrow B\bar{B}$

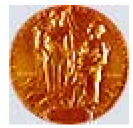
630 million $e^+e^- \rightarrow c\bar{c}$

460 million $e^+e^- \rightarrow \tau^+\tau^-$

??? New Physics

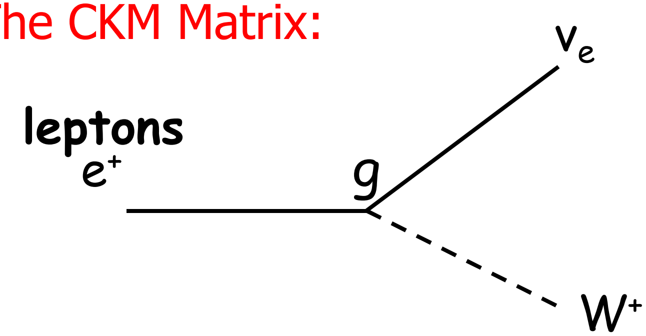
Heavy Flavors and the Weak Sector of the SM

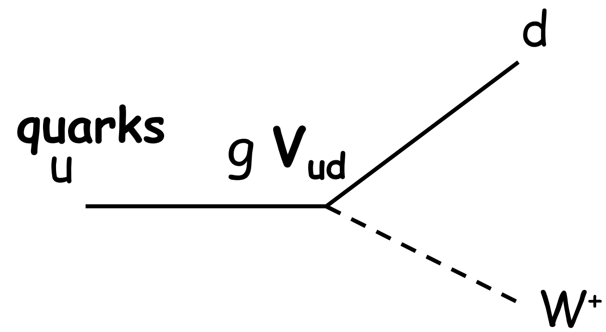
In the Standard model the weak eigenstates differ from the mass eigenstates.



The Nobel Prize in Physics 2008

The CKM Matrix:

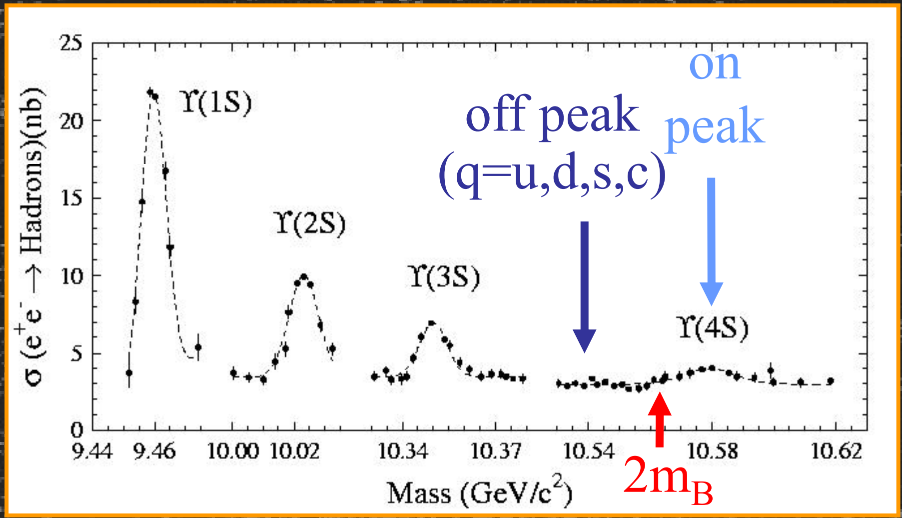


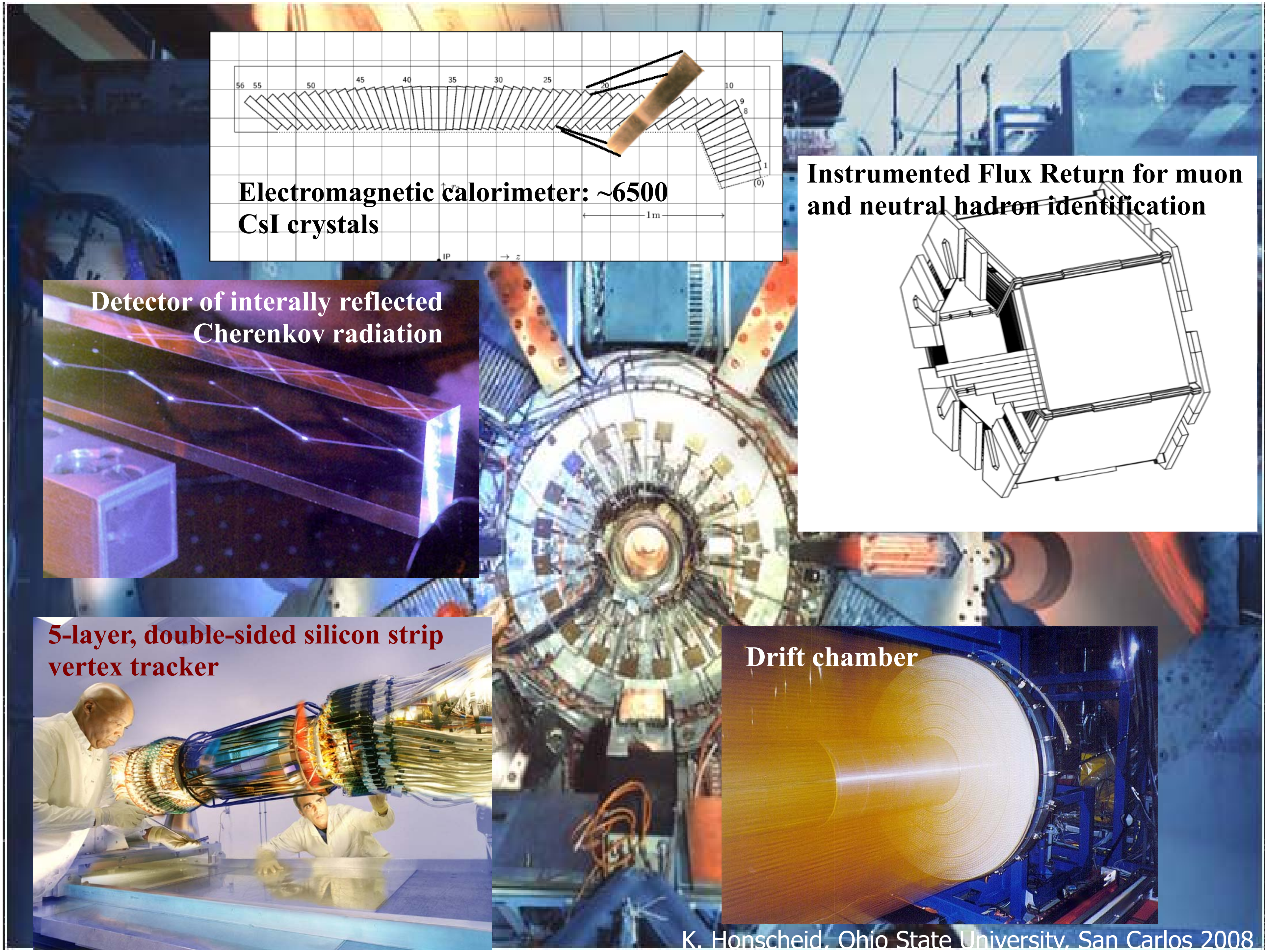


$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Experimental setting: $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$

- 20 MeV above BB threshold; no additional pions
- B mesons have small speed β ~ 0.06 in Y(4S) frame
- Decay products of B and $\bar{B}$ overlap in detector
- $e^+e^- \rightarrow q\bar{q}$ continuum decays also produced
- At asymmetric B factories, B vertices differ by 260μm



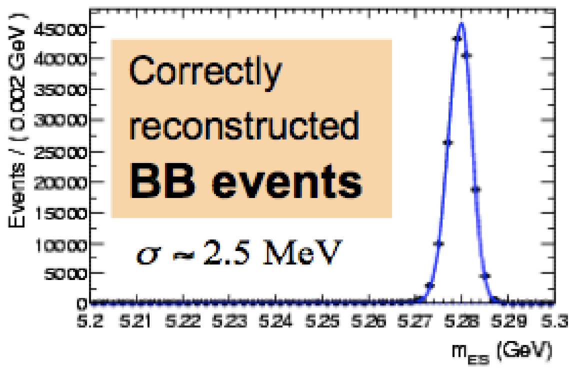

Electromagnetic calorimeter: ~6500
CsI crystals
Instrumented Flux Return for muon
and neutral hadron identification
Detector of interally reflected
Cherenkov radiation
5-layer, double-sided silicon strip
vertex tracker
Drift chamber

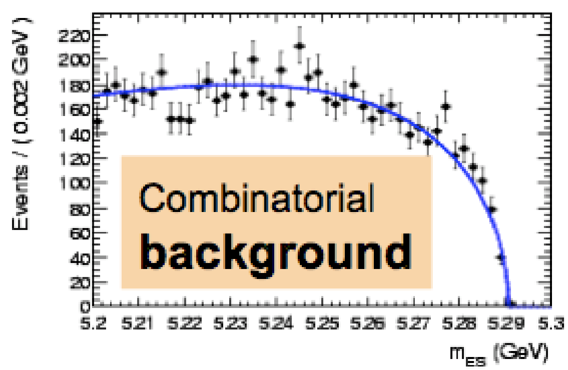
Experimental Techniques: B meson reconstruction

Exploit kinematics of $e^+e^- \to \Upsilon(4S) \to B\bar{B}^0$ for signal selection

Beam-energy substituted mass

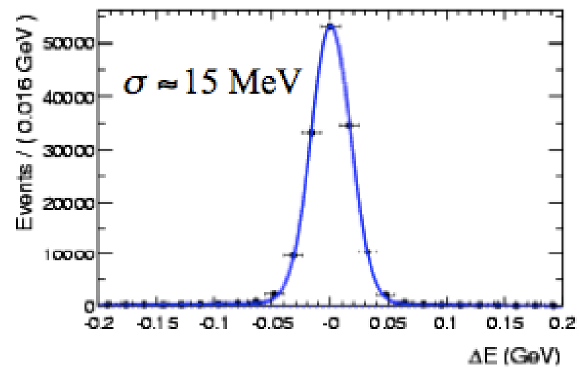
$$m_{ES} = \sqrt{E^{*\,2}_{beam} - p^{*\,2}_{B}}$$

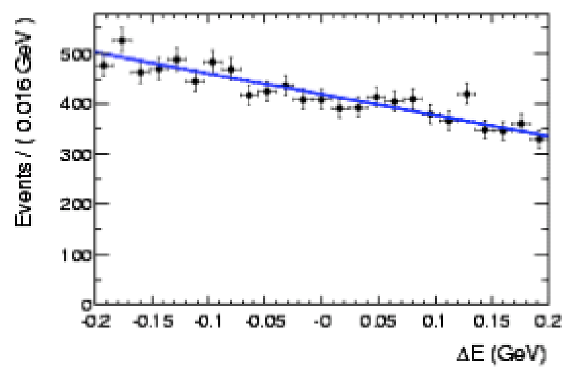




Energy difference

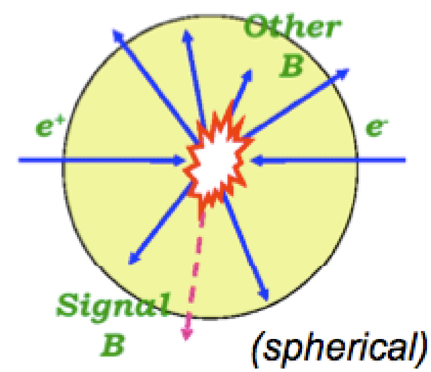
$$\Delta E = E^*_B - E^*_{beam}$$

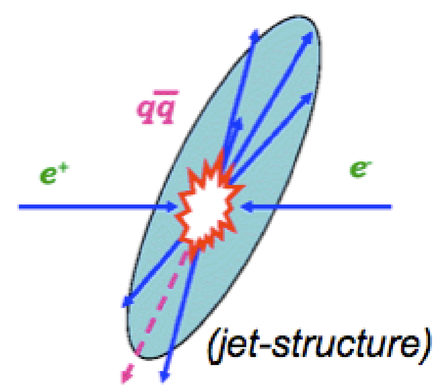




Event topology

(multivariate methods)



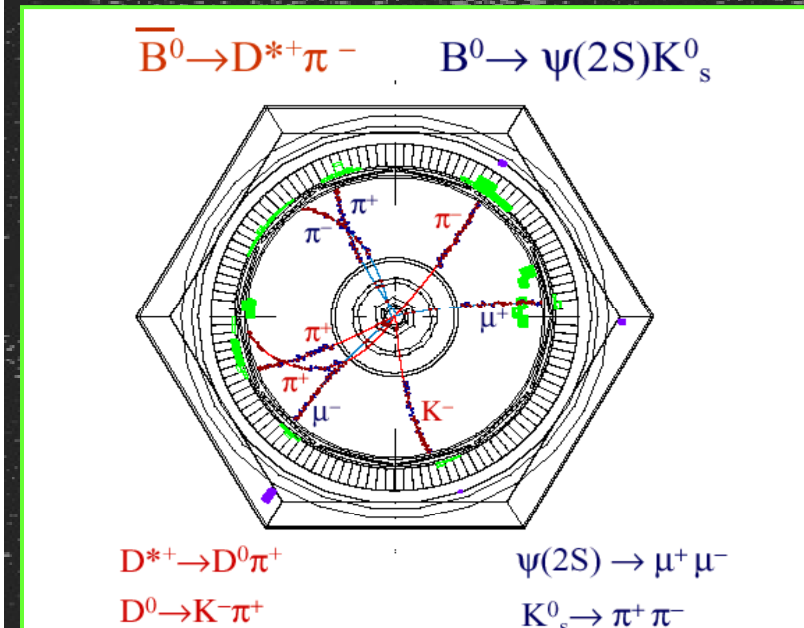


Experimental Techniques: Single B Meson Beams

Lots of interesting modes include one or more neutrinos.

"Beams" with a single, monochromatic B and without c, QED etc would be very useful for : $B \to \tau\nu$, $B \to \nu\nu$, $B \to K\nu\nu$,…

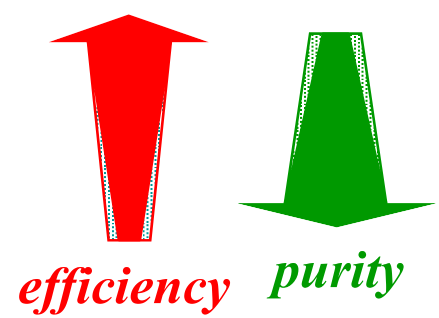
Fully reconstruct one of the Bs and study the remaining of the event ➔ closed kinematics, missing energy reconstruction



Tag types

Semileptonic $D^{(*)}l(\nu\pi)$
$5K/fb^{-1}$

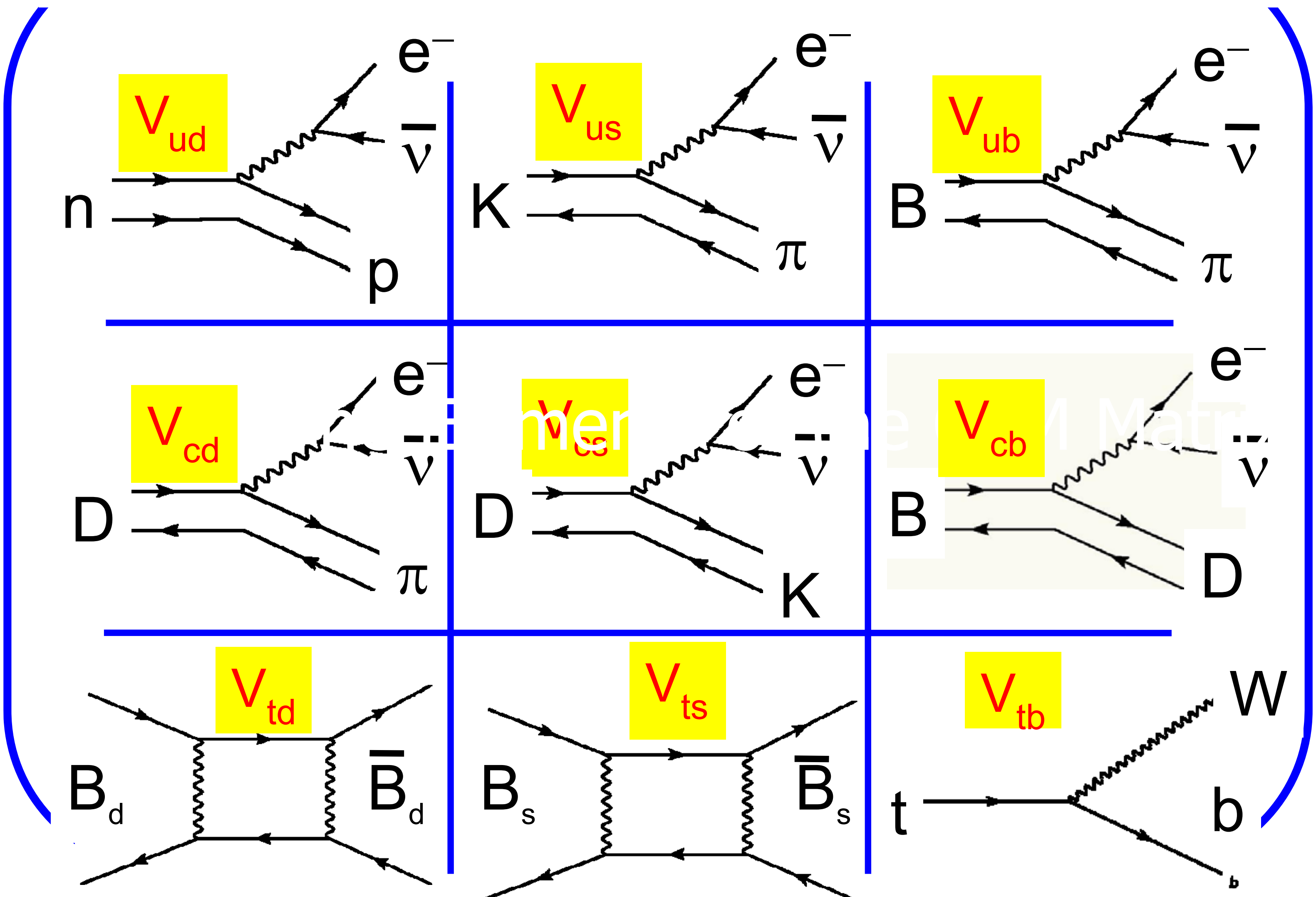
Hadronic $D^{(*)}X$
$3K/fb^{-1}$



$X = n\pi + m\pi^0 + pK + qK_s$

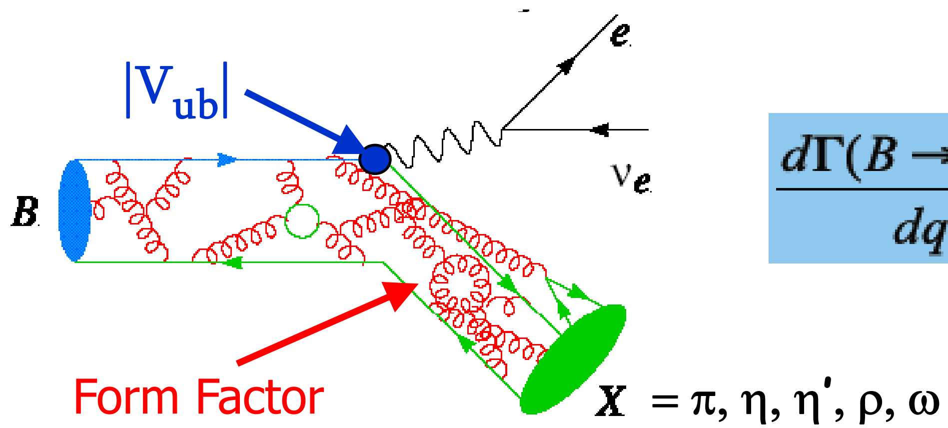
Part 1: The Elements of the CKM Matrix

4 Fundamental parameters of the Standard Model
They cannot be predicted but can be measured



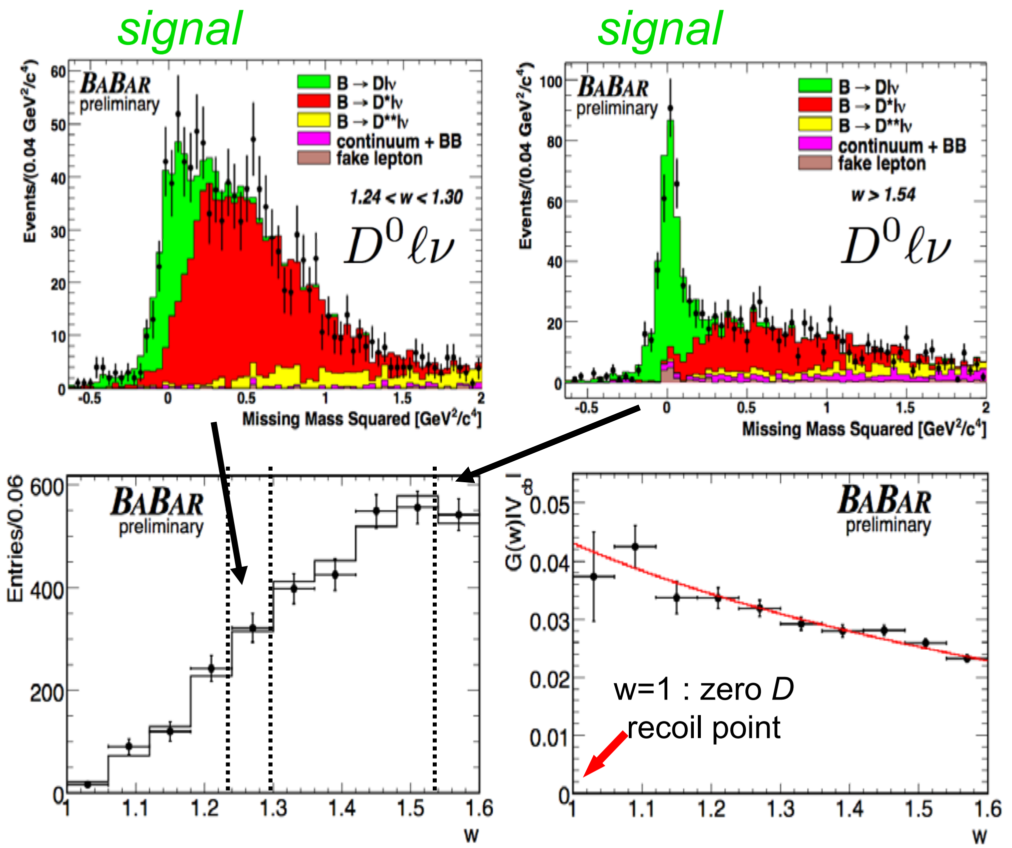
The CKM Elements $|V_{ub}|$ and $|V_{cb}|$

- The determination of the $|V_{ub}|$ and $|V_{cb}|$ relies on semileptonic decays → only one hadronic current
- Tree decays – insensitive to NP
- Two complementary approaches:
  - **Exclusive**: **X** fully reconstructed
    - Need form factor normalization (non-perturbative)
  - **Inclusive**: sum over many **X** states, with at most partial reconstruction of the **X** system
    - Use OPE in $(1/m_b)^n$



$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2}=\frac{G_F^2}{24\pi^3}|V_{ub}|^2\,p_\pi^3\,|f_+(q^2)|^2$$

$B \to D l \nu$ in the recoil of fully reconstructed B_{tag}



- Fully reconstructed "tag" B meson.
  - Signal B 4-vector known.
  - Neutrino kinematics fully constrained.
  - Excellent w resolution.
  - Very clean signal.
- Consistent with other methods
  - Larger stat uncertainty
  - Smaller systematic
- $>2\sigma$ $|V_{cb}|$ exclusive vs inclusive discrepancy remains…

$$w = V_B \cdot V_D = \frac{(M_B^2 + M_D^2 - q^2)}{(2M_B M_D)}$$

Fit results

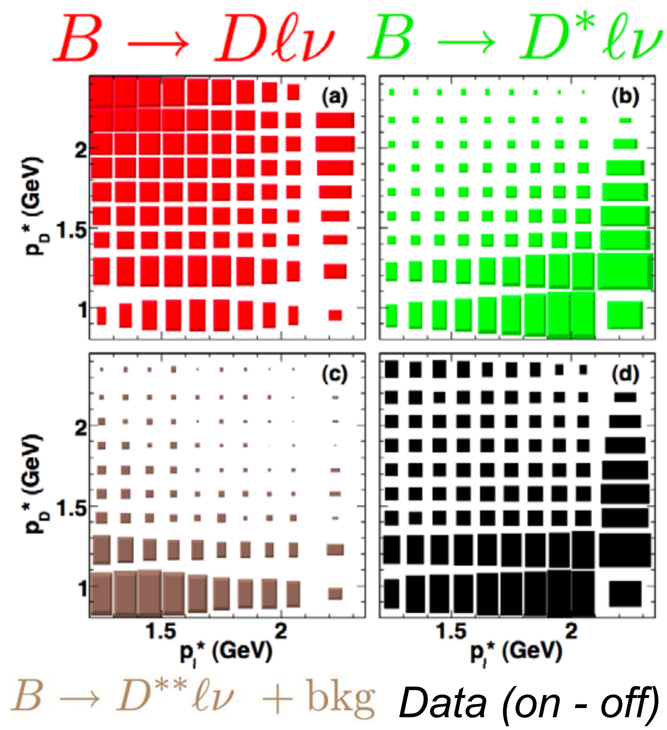
$$\text{shape}: \rho^2 = 1.20 \pm 0.09 \pm 0.04$$

$$\text{intercept}: \mathcal{G}(1)|V_{cb}| = (45.6 \pm 3.3 \pm 1.6) \times 10^{-3}$$

$$|V_{cb}| = (39.8 \pm 1.8 \pm 1.3 \pm 0.9) \times 10^{-3}$$

$|V_{cb}|$: Global fit of $B \to DX l\nu$

- Reconstruct $D^0 l$ and $D^+ l$ pairs (slow π from D^* not required).
- Binned 3D χ^2 fit to p_l, p_D, and cosine of angle between B and Dl, all in CM frame.
- Fit for BFs and form factor slopes.



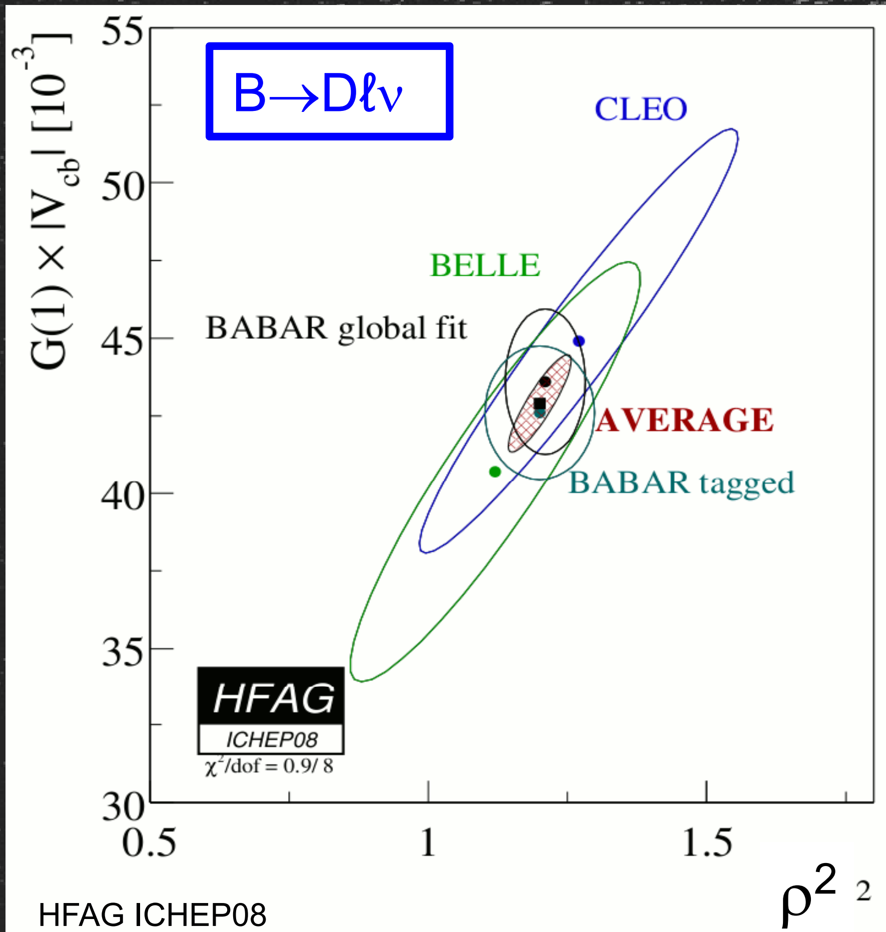
$$\mathcal{G}(1)|V_{cb}| = (44.1 \pm 0.8 \pm 2.2) \times 10^{-3}$$
$$\mathcal{F}(1)|V_{cb}| = (35.6 \pm 0.2 \pm 1.2) \times 10^{-3}$$

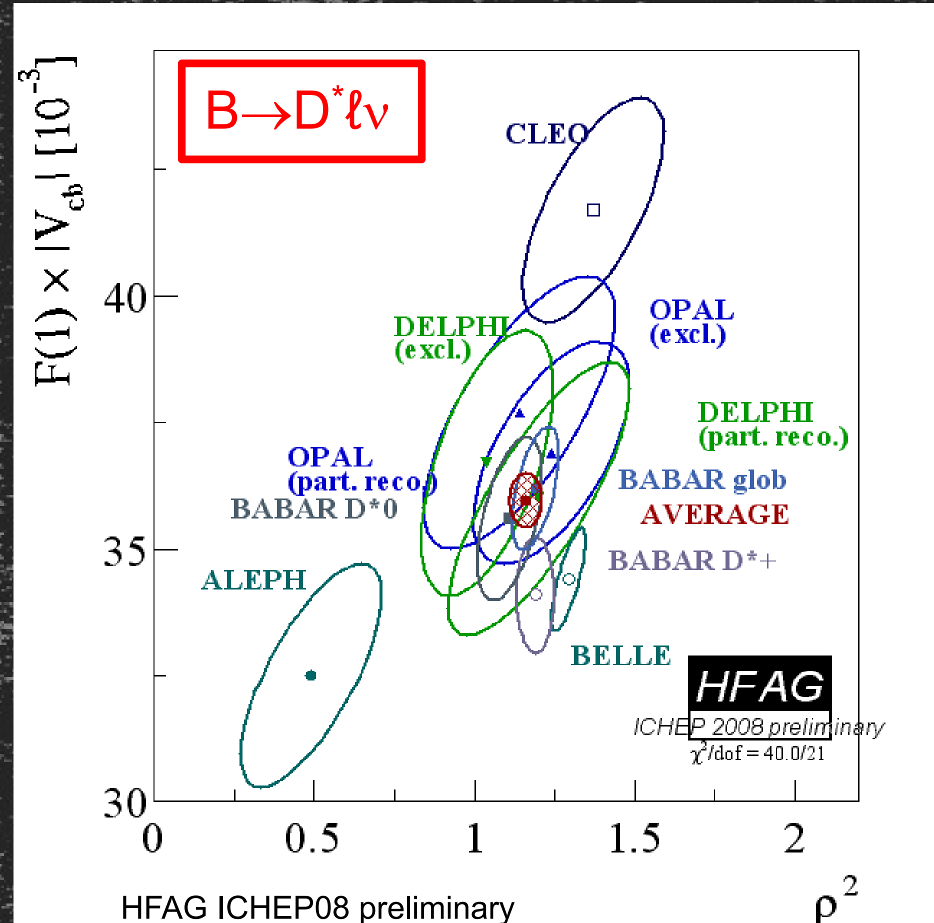
Lattice QCD : Form factor norm. at zero recoil.

$G(1)|V_{cb}|$ meas. twice as precise as world average!

$$D^*\ell\nu : \ |V_{cb}| = (38.3 \pm 0.2 \pm 1.3 \pm 0.9) \times 10^{-3}$$
$$D\ell\nu : \ |V_{cb}| = (40.8 \pm 0.8 \pm 2.1 \pm 0.9) \times 10^{-3}$$

$|V_{cb}|$ from $B \to D^{(*)}\ell\nu_\ell$ Decays





$G(1)|V_{cb}| = (42.9 \pm 1.6) \times 10^{-3}$

for $G(1) = 1.074 \pm 0.018 \pm 0.016$

(M.Okamoto et al NPPS 140, 461 (2005))

$|V_{cb}| = (39.7 \pm 1.4_{exp} \pm 0.9_{theo}) \times 10^{-3}$

$F(1)|V_{cb}| = (35.97 \pm 0.53) \times 10^{-3}$

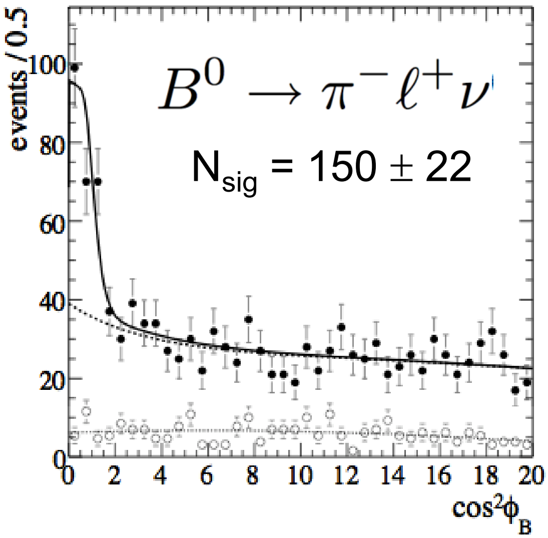
for $F(1) = 0.924 \pm 0.012 \pm 0.019$

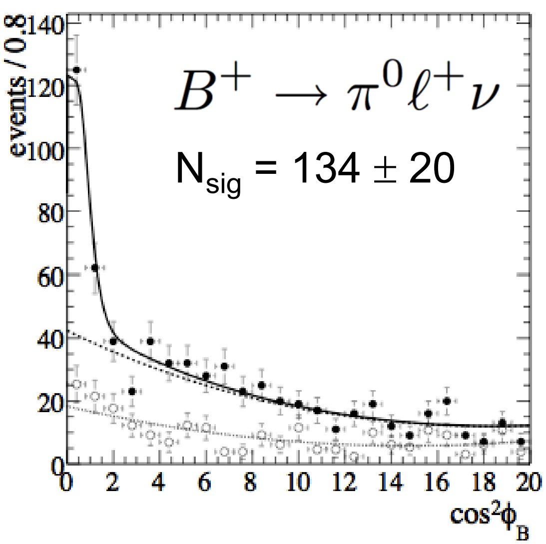
(J.Laiho) arXiv:0710.1111 [hep-lat]

$|V_{cb}| = (38.7 \pm 0.6_{exp} \pm 0.9_{theo}) \times 10^{-3}$

$B \to \pi \ell \nu$ with semileptonic tag

arXiv:0805.2408 [hep-ex]

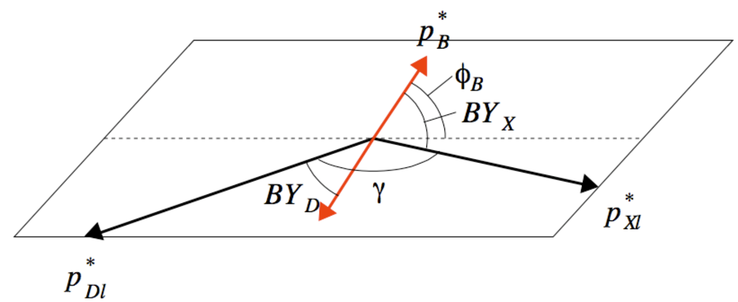




0805.2408 [hep-ex]

348 fb^{-1}

- 383 million $B\bar{B}$ pairs
- Tag one B in $D^{(*)}l\nu$.
- Require a πl pair in rest of event and nothing else.
- Fit $\cos^2\phi_B$ in bins of q^2.



Combined result

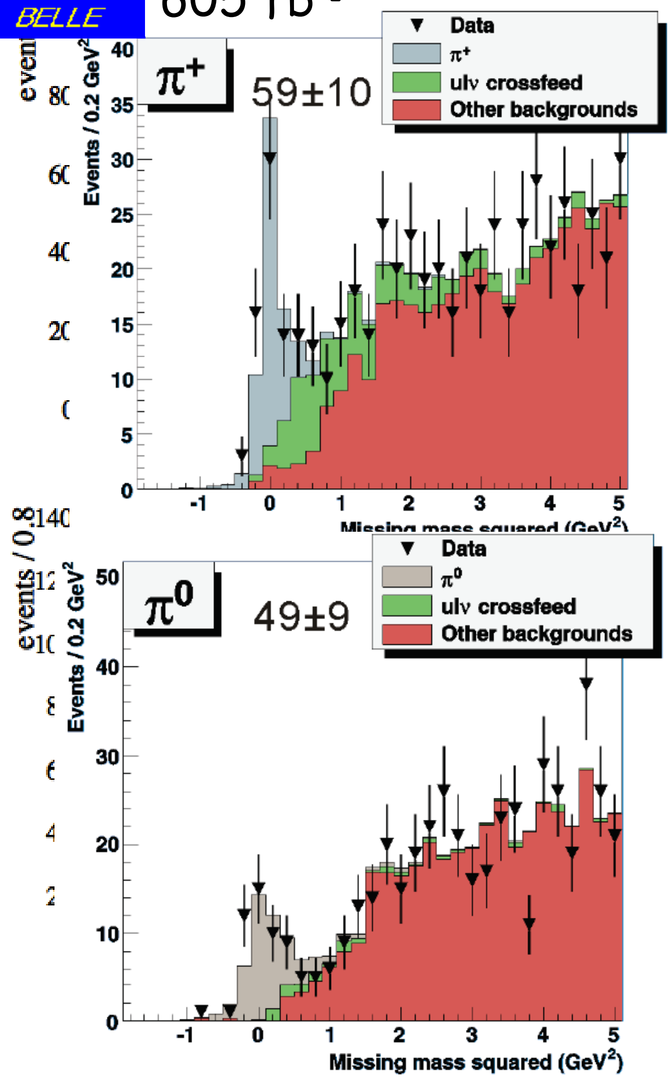
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.54 \pm 0.17 \pm 0.09) \times 10^{-4}$$

- Consistent with world average.
- Inclusive vs exclusive $|V_{ub}|$ agreement acceptable.

$B \to \pi \ell \nu$ with semileptonic tag

Presented at ICHEP08

605 fb^{-1}



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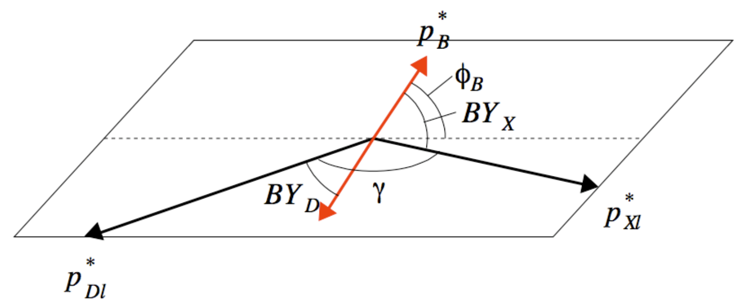

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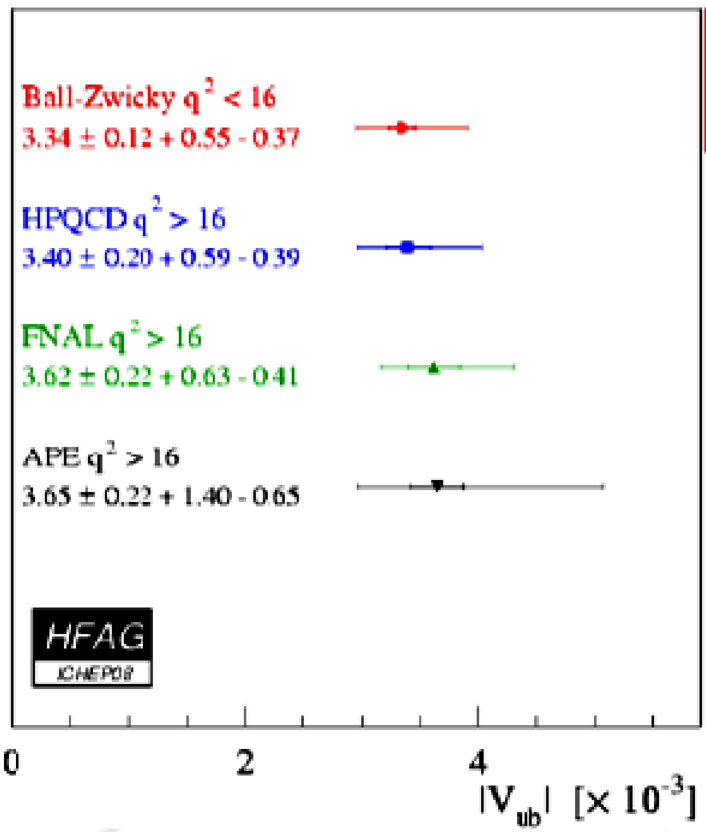
$|V_{ub}|$ from $B \to \pi \ell \nu$



Light-Cone Sum Rules (LCSR)
P. Ball, R. Zwicky
Phys. Rev. D71:014015 (2005)

Consistent with new LCSR result:
Duplancic, Khodjamirian, Mannel, Melic, Offen, 0801.1796 [hep-ph]

Unquenched Lattice QCD
E. Gulez et al. Phys.Rev.D73, 074502 (2006), Erratum-ibid.D75:119906,2007

Unquenched Lattice QCD
Okamoto et al., Nucl. Phys. Proc. Suppl.140:461-463, 2005

Quenched Lattice QCD
A. Abada et al. Nucl. Phys. B 619 (2000) 565-587

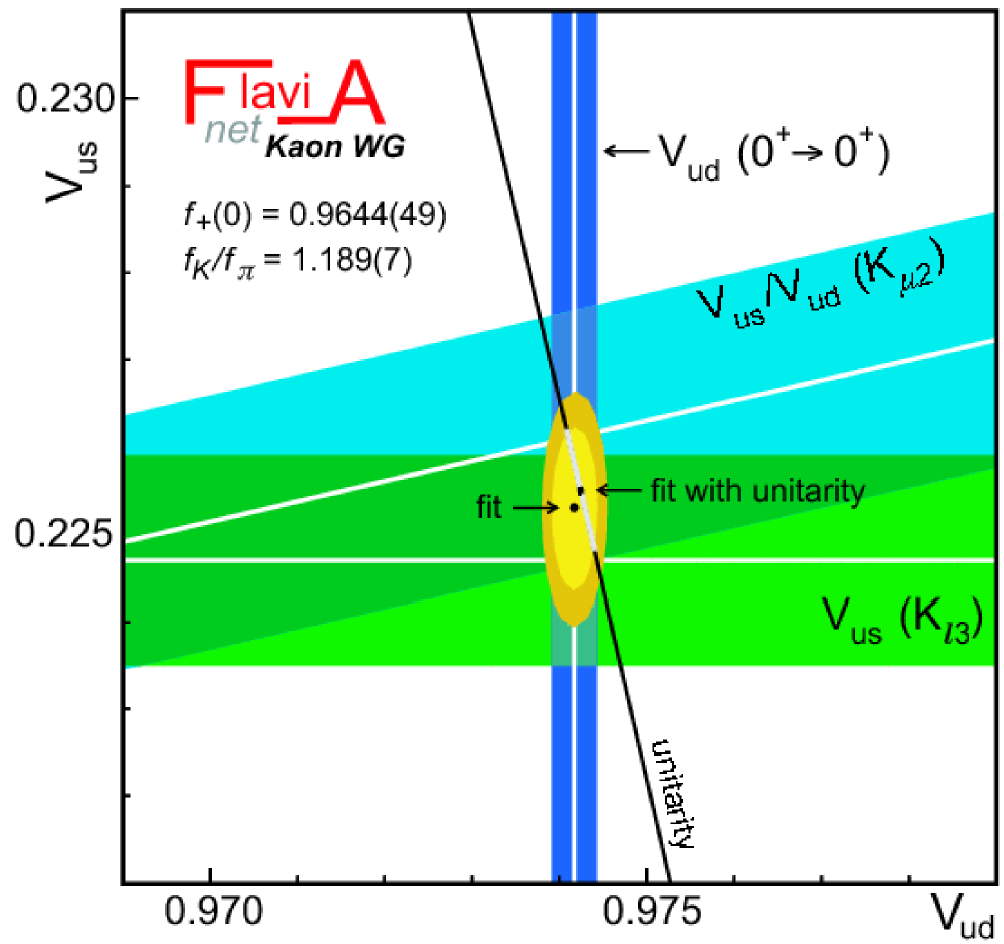
$|V_{ub}| = 3.44\,^{+0.22}_{-0.17} \times 10^{-3}$ (CKMfitter)

Theory lags behind experiments
$\delta|V_{ub}|/|V_{ub}|^{exp} \sim 5\%$
$\delta|V_{ub}|/|V_{ub}|^{f+(0)} \sim \,^{+17\%}_{-11\%}$ (e.g HPQCD & FNAL)

LCSR, unquenched and quenched LQCD give consistent results !

Experimental q^2 data are used to improve form factors (several methods)

Unitarity of the First Row



Fit results, without constraint:

$|V_{ud}| = 0.97417(26)$

$|V_{us}| = 0.2253(9)$

χ^2/ndf=0.65/1(42%)

$|V_{ud}|^2+|V_{us}|^2=0.9998(6)$

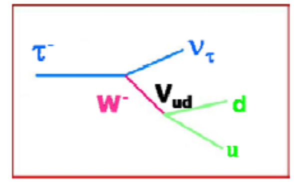
(neglecting $|V_{ub}|$)

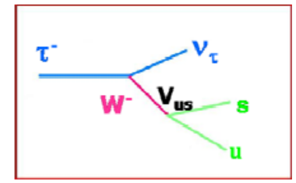
Fit results, unitarity constr.: **$|V_{us}|=0.2255(7)$** χ^2/ndf = 0.80/2 (67%)

$|V_{us}|$ from τ decays

$|V_{us}|$ from the hadronic τ decays in final states with kaons

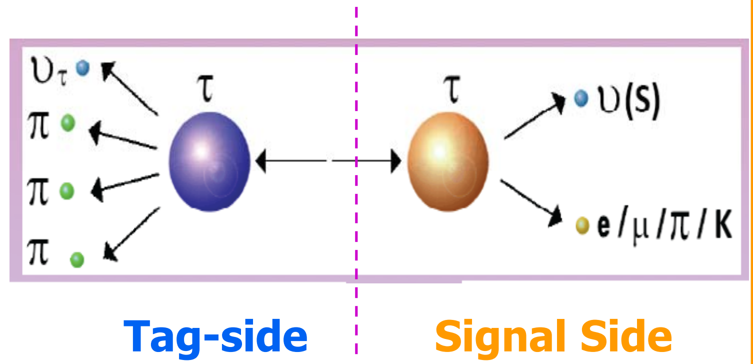
$$\frac{B(\tau^- \to K^- \nu_\tau)}{B(\tau^- \to \pi^- \nu_\tau)} = \frac{f_K^2}{f_\pi^2}\frac{|V_{us}|^2}{|V_{ud}|^2}\frac{(1-m_K^2/m_\tau^2)^2}{(1-m_\pi^2/m_\tau^2)^2}$$





BaBar, Preliminary

$$\frac{\mathcal{B}(\tau \to K^-\nu_\tau)}{\mathcal{B}(\tau \to \pi^-\nu_\tau)} = 0.06531 \pm 0.00056 \pm 0.00093$$



Assume universal couplings

Using f_K/f_π=1.189 ±0.007 from Lattice QCD

E.Follana *et al.* Phys. Rev. Lett. 100, 062002 (2007)

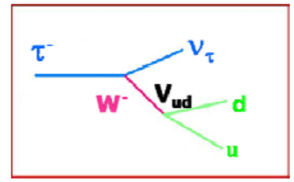
$|V_{us}| = 0.2255 \pm 0.0023$

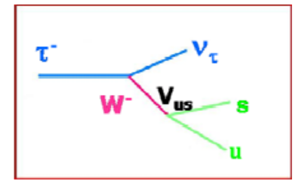
Consistent with $|V_{us}|$ from $K_{\ell 3}$,$K_{\ell 2}$

$|V_{us}|$ from τ decays

$|V_{us}|$ from the hadronic τ decays in final states with kaons

$$\frac{B(\tau^- \to K^- \nu_\tau)}{B(\tau^- \to \pi^- \nu_\tau)} = \frac{f_K^2}{f_\pi^2} \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{(1-m_K^2/m_\tau^2)^2}{(1-m_\pi^2/m_\tau^2)^2}$$





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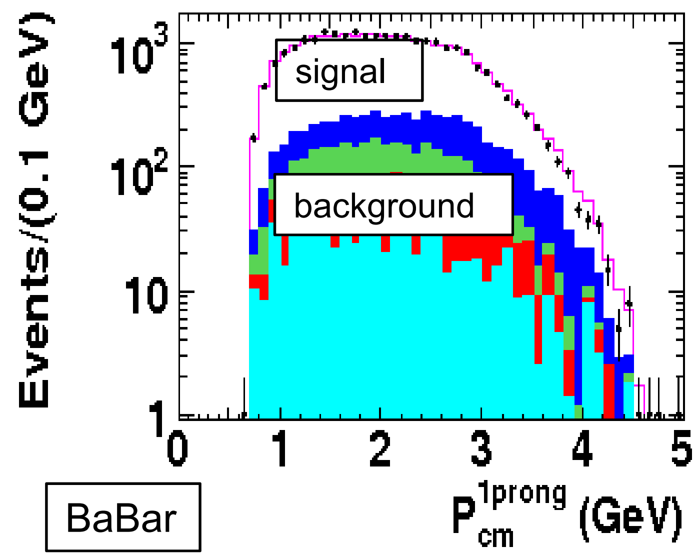
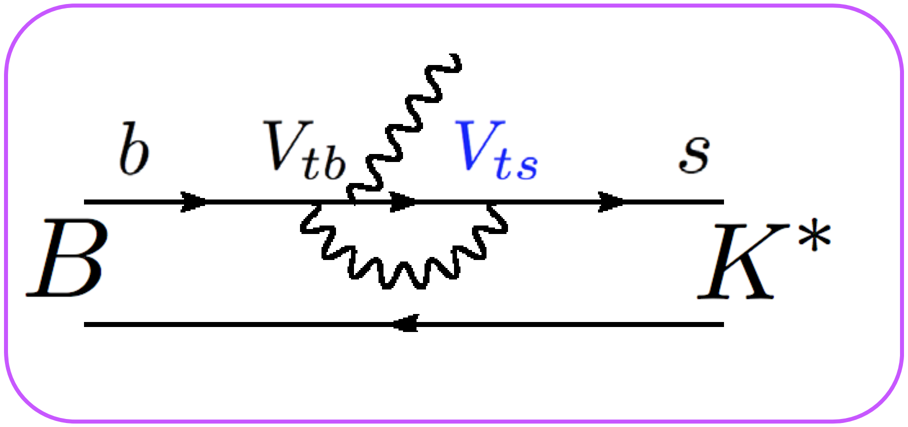
$|V_{us}| = 0.2255 \pm 0.0023$

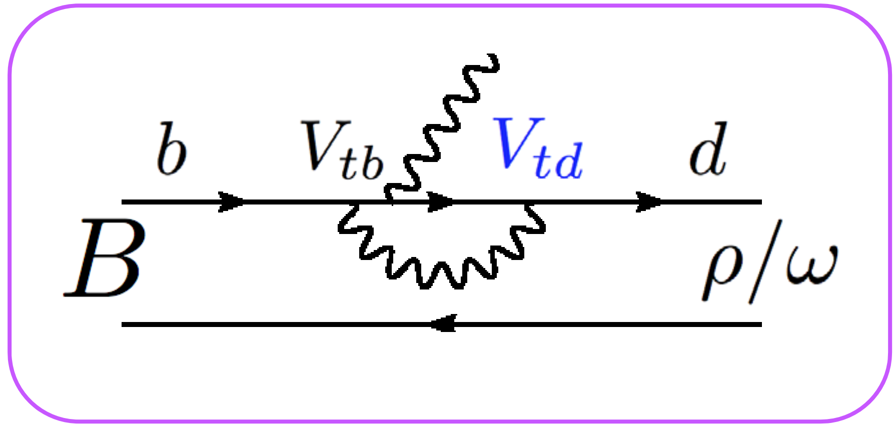
Consistent with $|V_{us}|$ from $K_{\ell 3}, K_{\ell 2}$

$\tau \to K^- \nu$



$|V_{td}/V_{ts}|$ from $b \to d\,\gamma$





$$\frac{\mathcal{B}[B \to \rho(\omega)\gamma]}{\mathcal{B}(B \to K^*\gamma)} = S \left| \frac{V_{td}}{V_{ts}} \right|^2 \left(\frac{1 - m^2_{\rho(\omega)}/M_B^2}{1 - m^2_{K^*}/M_B^2} \right)^3 \zeta^2 [1 + \Delta R]$$

S = 1 for ρ^+, 1/2 for ρ^0 or ω.

Form factor ratio

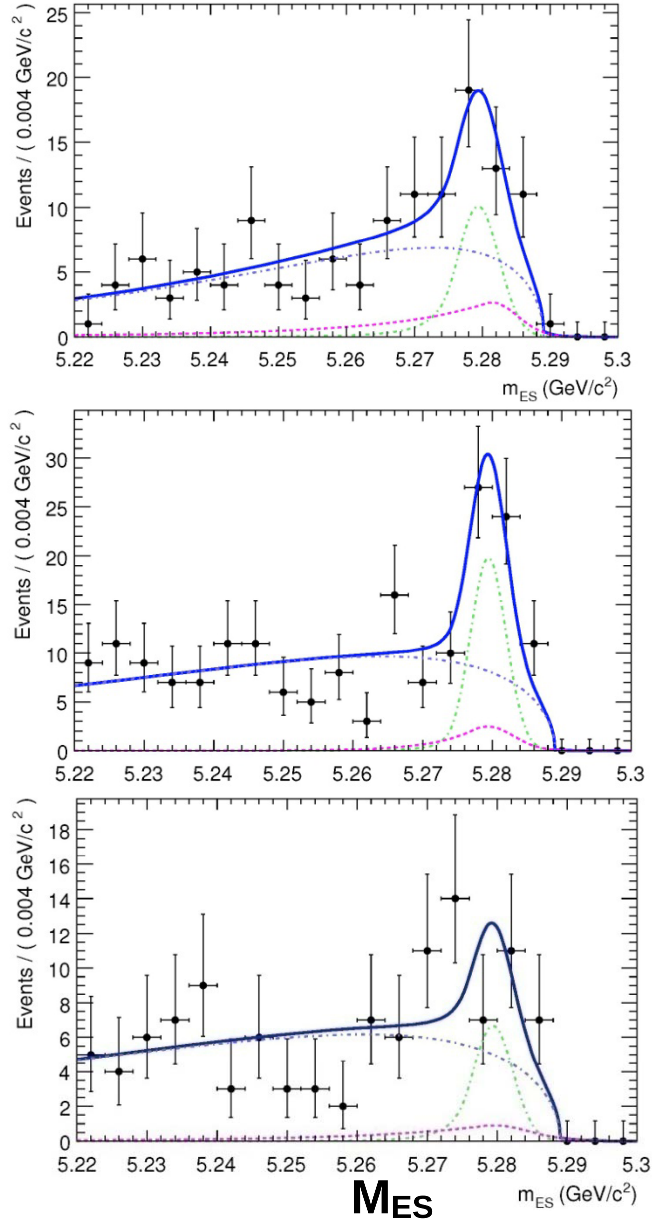
Annihilation contribution

Branching ratios of order 10^{-6}.
Very challenging!

$|V_{td}/V_{ts}|$:B->rho/omega gamma

423fb^{-1}

preliminary



	Significance	B(x10^{-6}) ± stat ± sys
$B^+ \rightarrow \rho^+\gamma$	3.2σ	$1.20^{+0.42}_{-0.37} \pm 0.20$
$B^0 \rightarrow \rho^0\gamma$	5.4σ	$0.97^{+0.24}_{-0.22} \pm 0.06$
$B^0 \rightarrow \omega^0\gamma$	2.2σ	$< 0.9(90\% C.L.)$ or $0.50^{+0.27}_{-0.23} \pm 0.09$

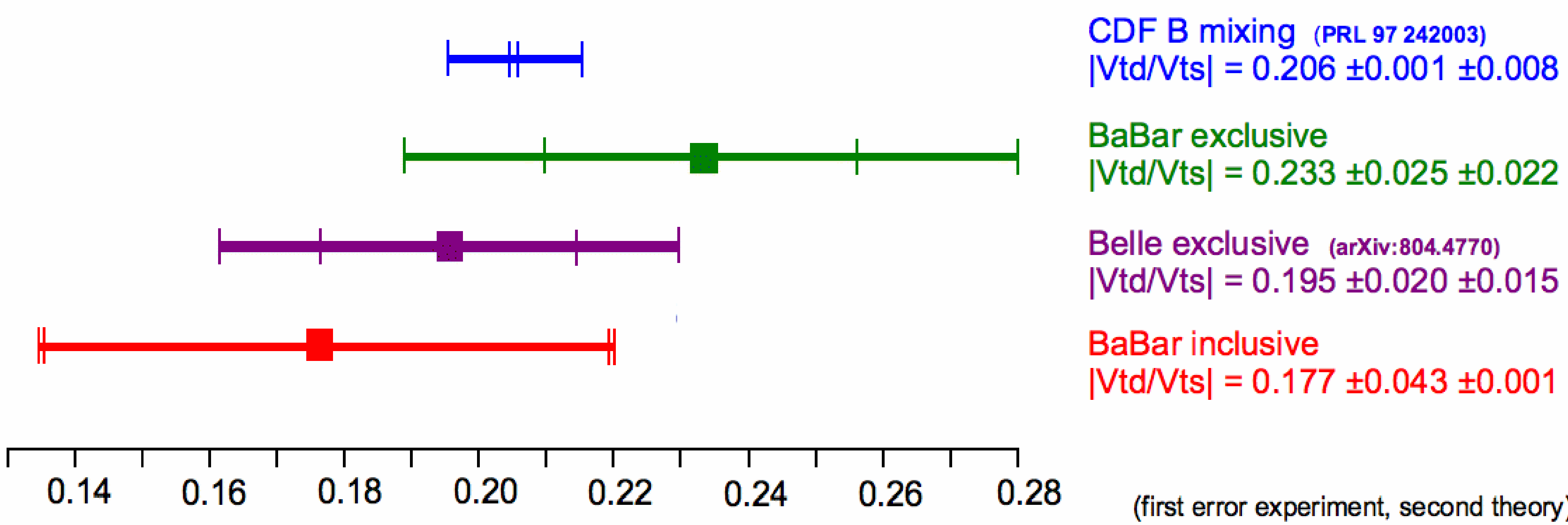
Results Consistent with SM and previous measurments

Comparison of $|V_{td}/V_{ts}|$ measurements

347fb[-1]
preliminary

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.177 \pm 0.043(\exp.) \pm 0.001(th.)$$

(Ali,Asatrian & Greub PLB 429,87,1998)

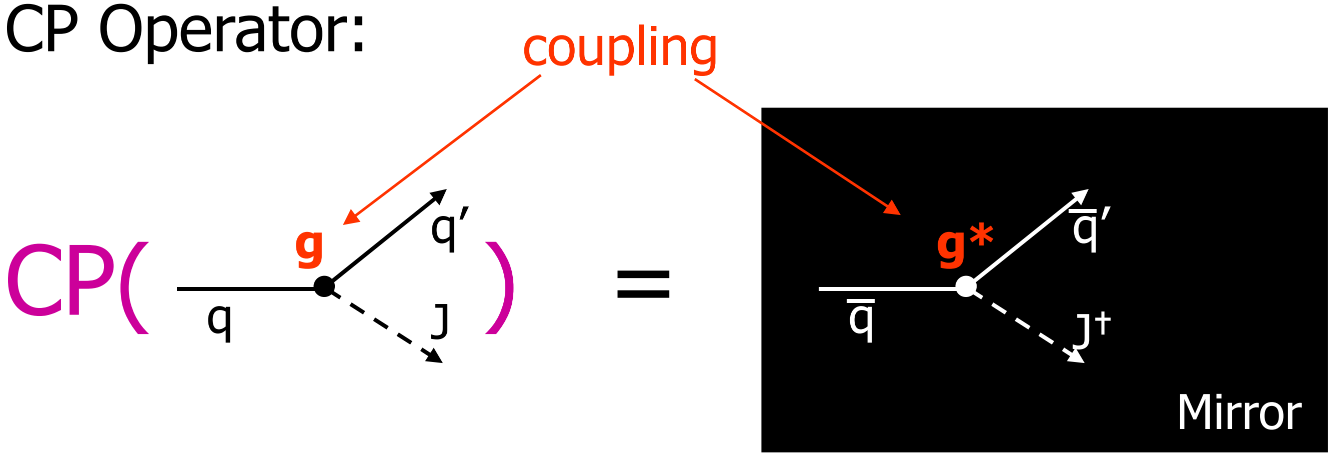


Theory error in BaBar $B \rightarrow X_d\gamma$ does not include error for using ~50% of states - i.e does heavy quark duality still hold ?

Part 2: CP Violation in the Standard Model

CP Violation in the Standard Model

CP Operator:



To incorporate CP violation

$$g \neq g^*$$

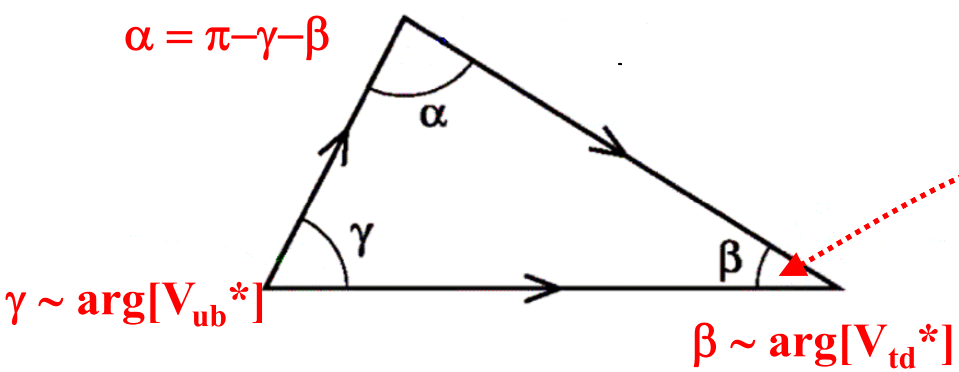
(coupling has to be complex)

CP Violation in the SM: The CKM Matrix

- The CKM matrix V_{ij} is unitary with 4 independent fundamental parameters
- Unitarity constraint from 1st and 3rd columns: $\Sigma_i V^*_{i3} V_{i1} = 0$

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

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

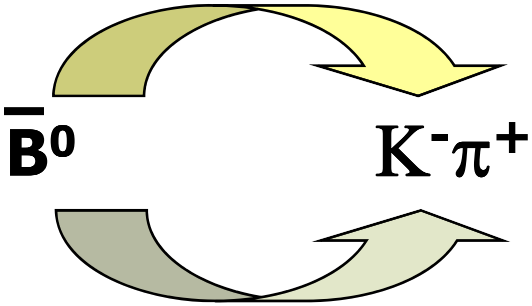


CKM phases
(in Wolfenstein convention)

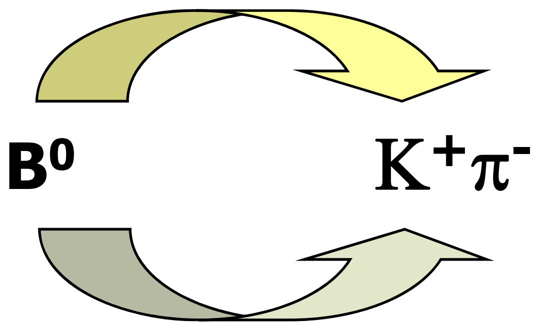
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

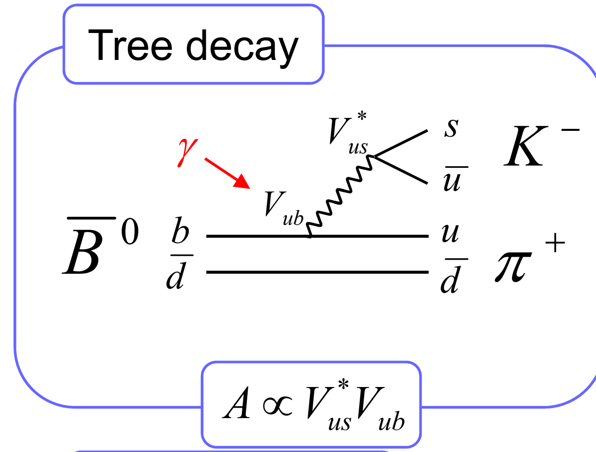
Interfering Amplitudes in $B^o \to K\pi$ Decays

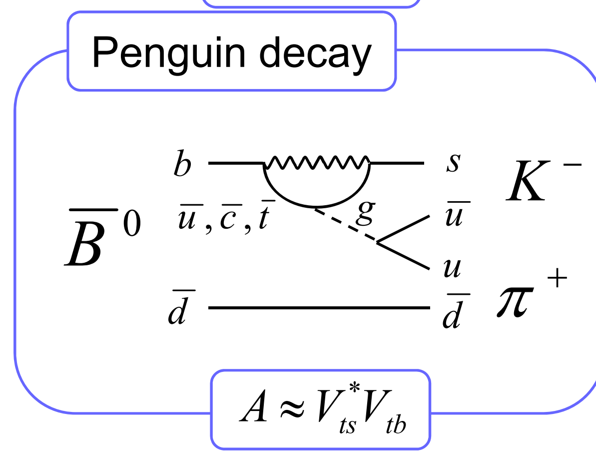


$$A_1 = a_1\, e^{i\phi_1}\, e^{i\delta_1}$$
$$\oplus$$
$$A_2 = a_2\, e^{i\phi_2}\, e^{i\delta_2}$$



$$\overline{A}_1 = a_1\, e^{-i\phi_1}\, e^{i\delta_1}$$
$$\oplus$$
$$\overline{A}_2 = a_2\, e^{-i\phi_2}\, e^{i\delta_2}$$





Interference $\to (A_1 + A_2)^2 \neq (\overline{A}_1 + \overline{A}_2)^2$

Asymmetry $= \dfrac{\Gamma(B) - \Gamma(\overline{B})}{\Gamma(B) + \Gamma(\overline{B})} = \dfrac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} \approx 2 \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$ $= 0$

CP Violation in $B^o \rightarrow K\pi$ Decays

467 x 10^6 B^0 Mesons

↓

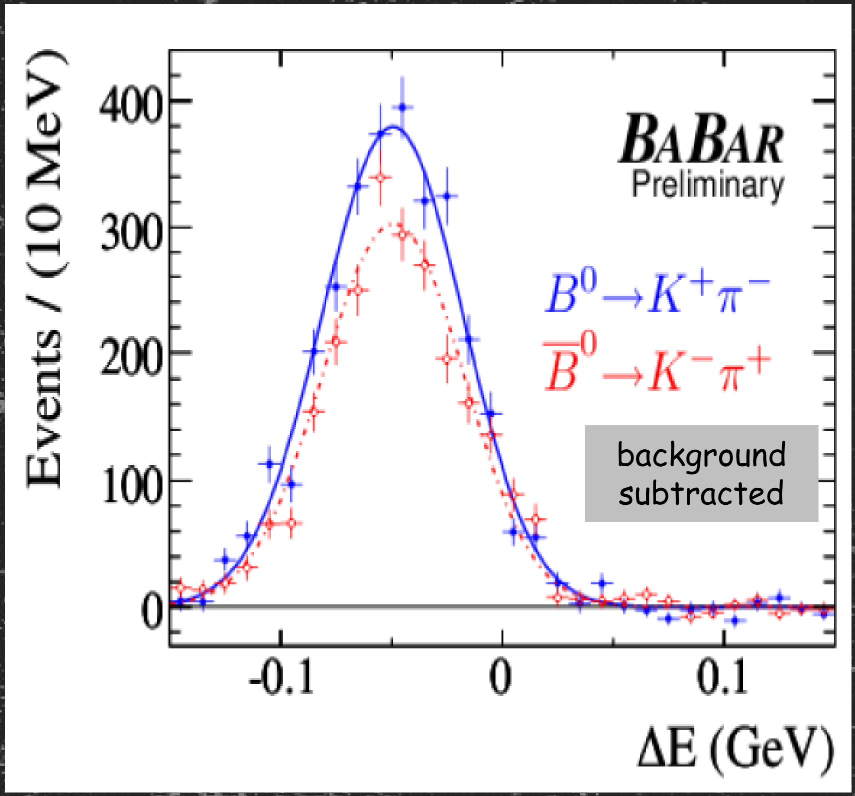
Count $B^0 \rightarrow K^+\pi^-$ Decays

467 x 10^6 $\bar{B}^0$ Mesons

↓

Count $\bar{B}^0 \rightarrow K^-\pi^+$ Decays

Is $N(B^0 \rightarrow K^+\pi^-)$ equal to $N(\bar{B}^0 \rightarrow K^-\pi^+)$?



CP Violation in $B^o \to K\pi$ Decays

467 x 10^6 B^0 Mesons

↓

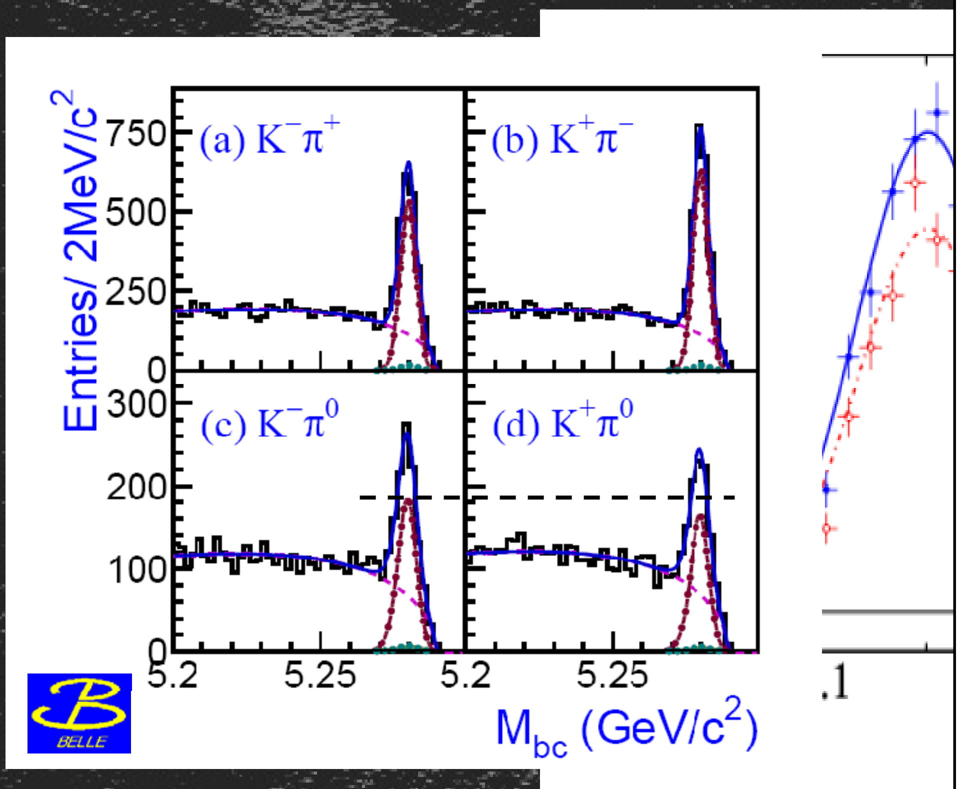
Count $B^0 \to K^+\pi^-$ Decays

467 x 10^6 $\bar{B}^0$ Mesons

↓

Count $\bar{B}^0 \to K^-\pi^+$ Decays

Is $N(B^0 \to K^+\pi^-)$ equal to $N(\bar{B}^0 \to K^-\pi^+)$?



$$A_{CP} = \frac{Br(\bar{B} \to \bar{f}) - Br(B \to f)}{Br(\bar{B} \to \bar{f}) + Br(B \to f)}$$

$$A_{cp}(K^+\pi^-) = \begin{cases} -0.107 \pm 0.016 \,^{+0.006}_{-0.004} & \text{BaBar} \\ -0.094 \pm 0.018 \pm 0.008 & \text{Belle} \\ -0.086 \pm 0.023 \pm 0.009 & \text{CDF} \\ -0.04 \pm 0.16 \pm 0.02 & \text{CLEO} \end{cases}$$

$\Rightarrow -0.098 \,^{+0.012}_{-0.011}$ @ 8.1σ AVG

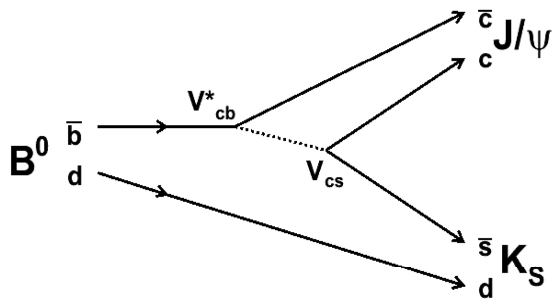
$$A_{cp}(K^+\pi^0) = \begin{cases} +0.030 \pm 0.039 \pm 0.010 & \text{BaBar} \\ +0.07 \pm 0.03 \pm 0.01 & \text{Belle} \\ -0.29 \pm 0.23 \pm 0.02 & \text{CLEO} \end{cases}$$

$\Rightarrow +0.050 \pm 0.025$ @2.0σ AVG

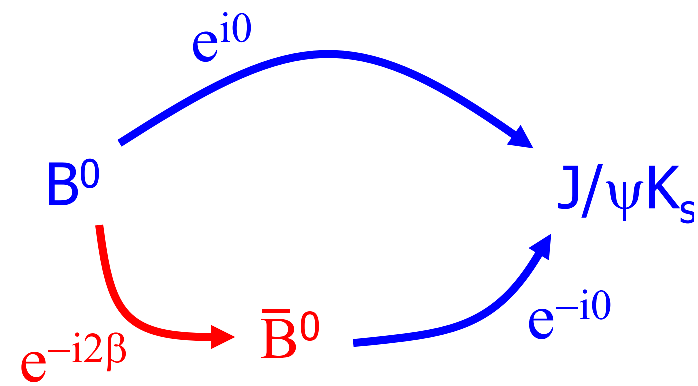
$\Delta A_{K\pi} = A_{cp}(K^+\pi^-) - A_{cp}(K^+\pi^0)$
$= -0.147 \pm 0.028$ @ 5.3σ

Mixing Induced CP violation

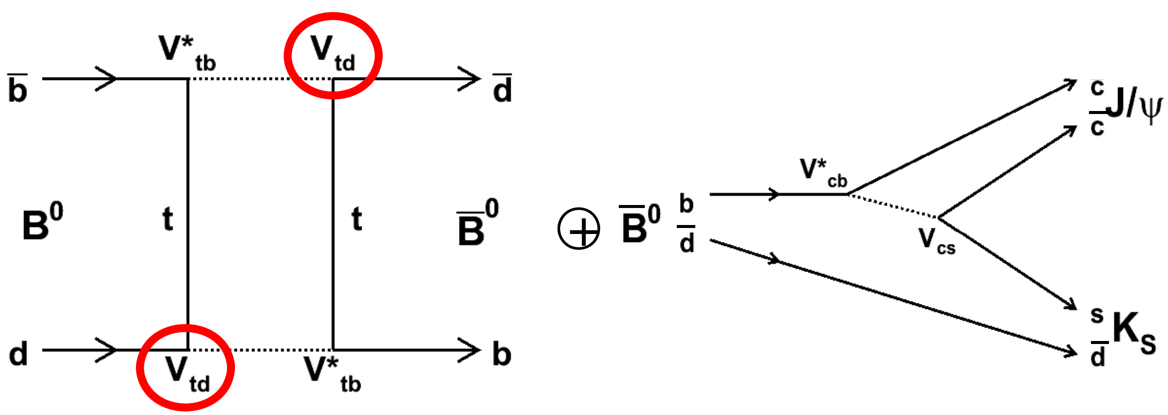
Golden mode $B^0 \to J/\psi K_s$:CP eigenstate, high rate, theoretically clean



No weak phase



Two V_{td} vertices $e^{-i2\beta}$

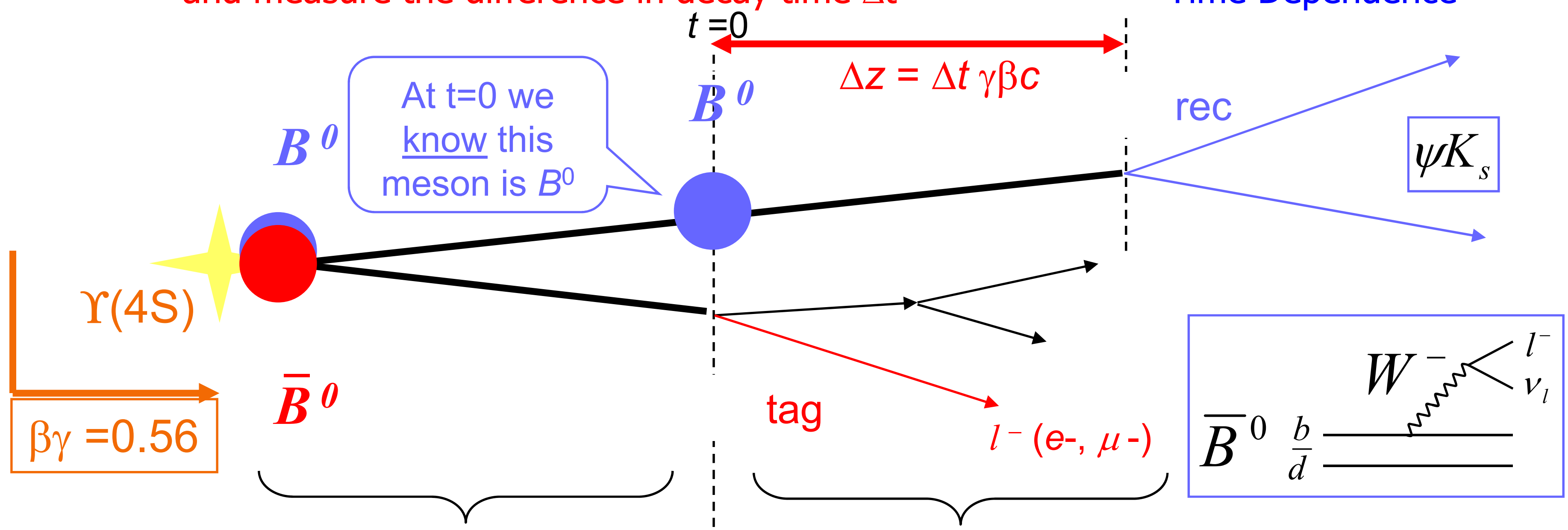


Two Amplitudes ➡ Interference ➡ $A_{CP} \sim \sin 2\beta$

A Complication: Quantum Coherence

We need to know the flavor of the *B* at a reference t=0 and measure the difference in decay time Δt

Flavor Tagging
Time Dependence



The two mesons oscillate coherently : at any given time, if one is a B^0 the other is necessarily a $\bar{B}^0$

In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson : $l^- = \bar{B}^0 \quad l^+ = B^0$.

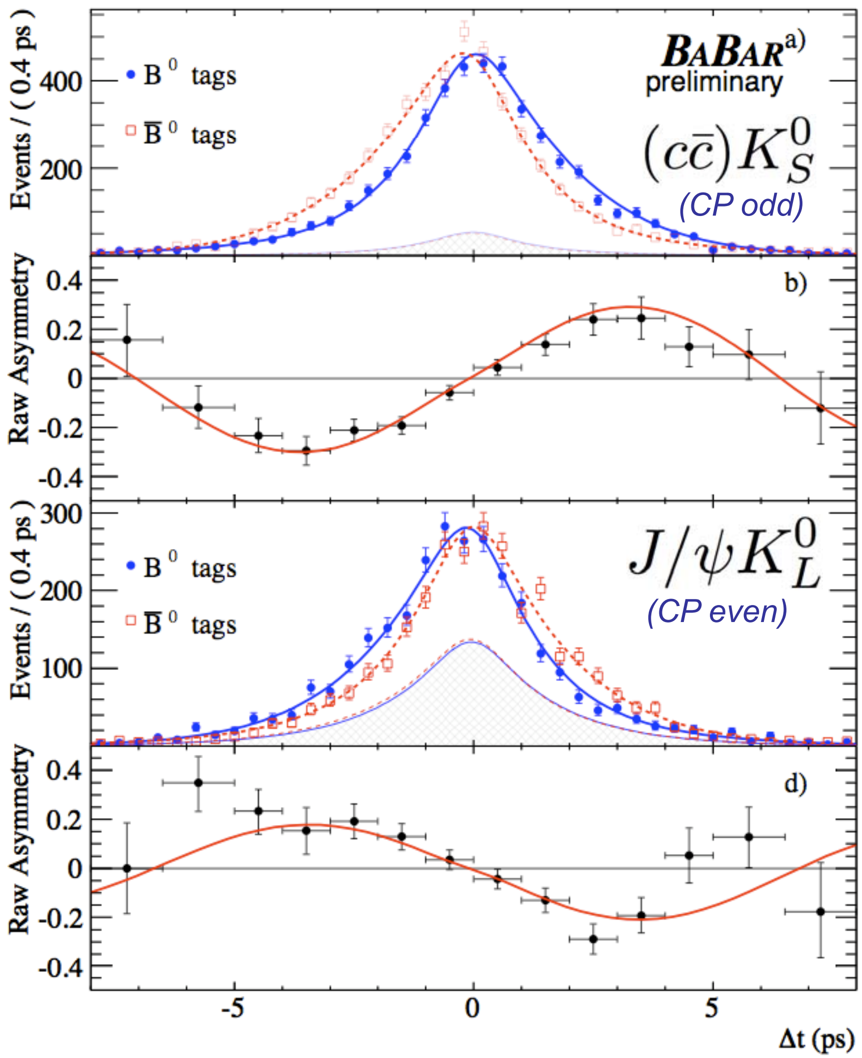
Δt picoseconds later, the B^0 (or perhaps its now a $\bar{B}^0$) decays.

Time dependent asymmetry $A_{CP} = S_{CP}\sin(\Delta m \Delta t) - C_{CP}\cos(\Delta m \Delta t)$

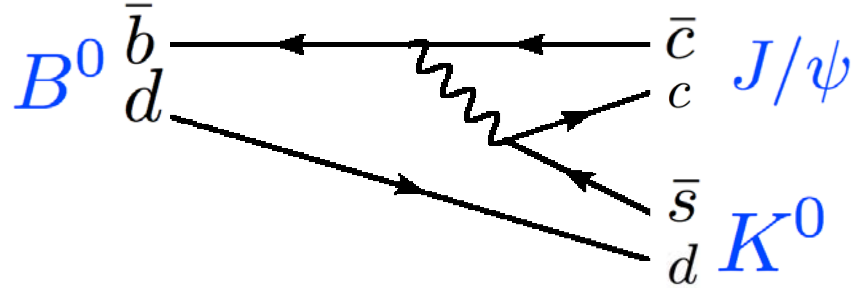
$S_{CP} = -f_{CP}\sin 2\beta$ ($f_{CP} = \pm 1$), C_{CP} "direct" CP violation = 0 for $J/\psi K$

sin2β from $B^0 \to J/\psi K^0$

Final analysis: 465 M BB



One dominant decay amplitude



No direct CPV expected

$$S_{J/\psi K^0_S} \approx \sin 2\beta \ , \quad C_{J/\psi K^0_S} \approx 0$$

Theoretical uncertainty in predictions ~1%

$$S_{(c\bar{c})K^0} = 0.691 \pm 0.029 \pm 0.014$$
$$C_{(c\bar{c})K^0} = 0.027 \pm 0.020 \pm 0.016$$

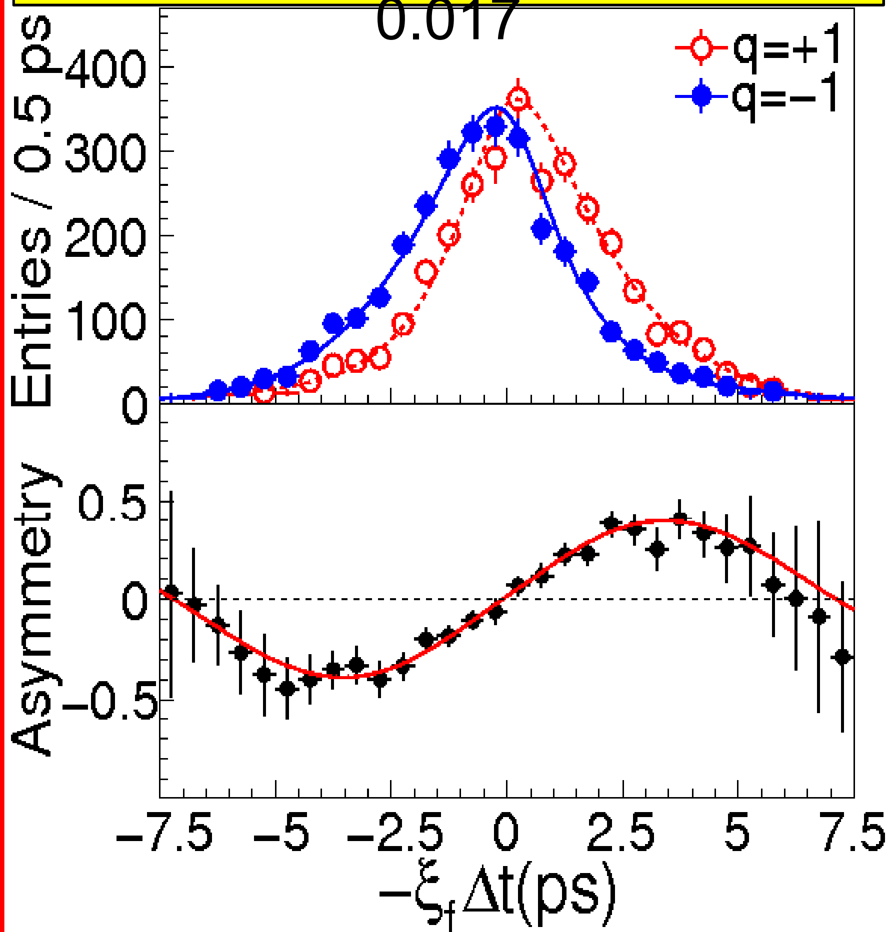
stat. *syst.*

Still statistics limited!

Consistent with Belle measurement

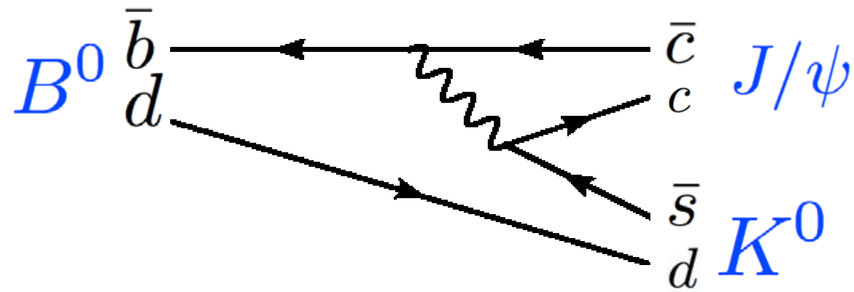
sin2β from $B^0 \to J/\psi K^0$

$\sin(2\varphi_1) = 0.642 \pm 0.031 \pm 0.017$



PRL 98 (2007) 031802

One dominant decay amplitude



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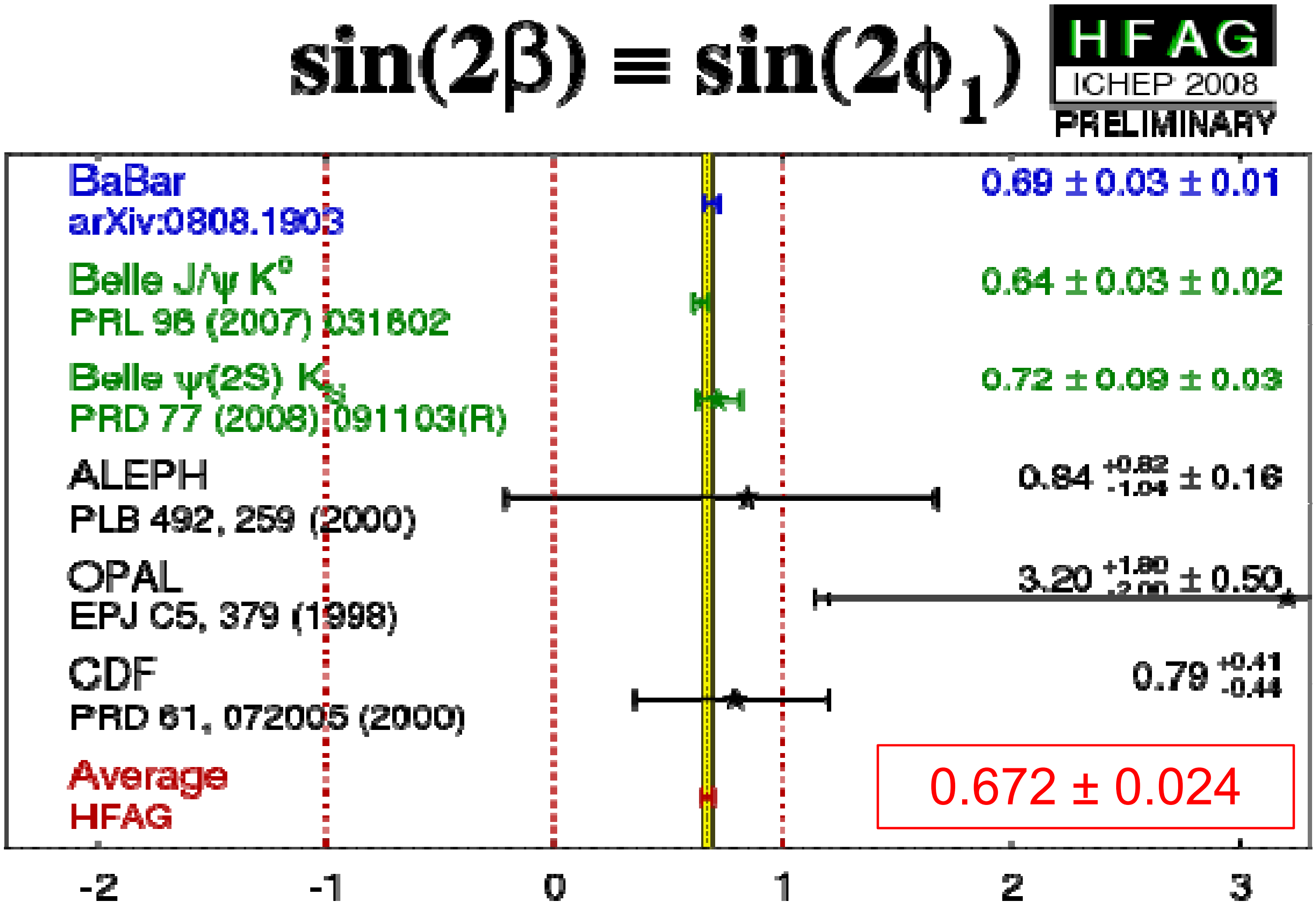
stat. *syst.*

Still statistics limited!

Consistent with Belle measurement

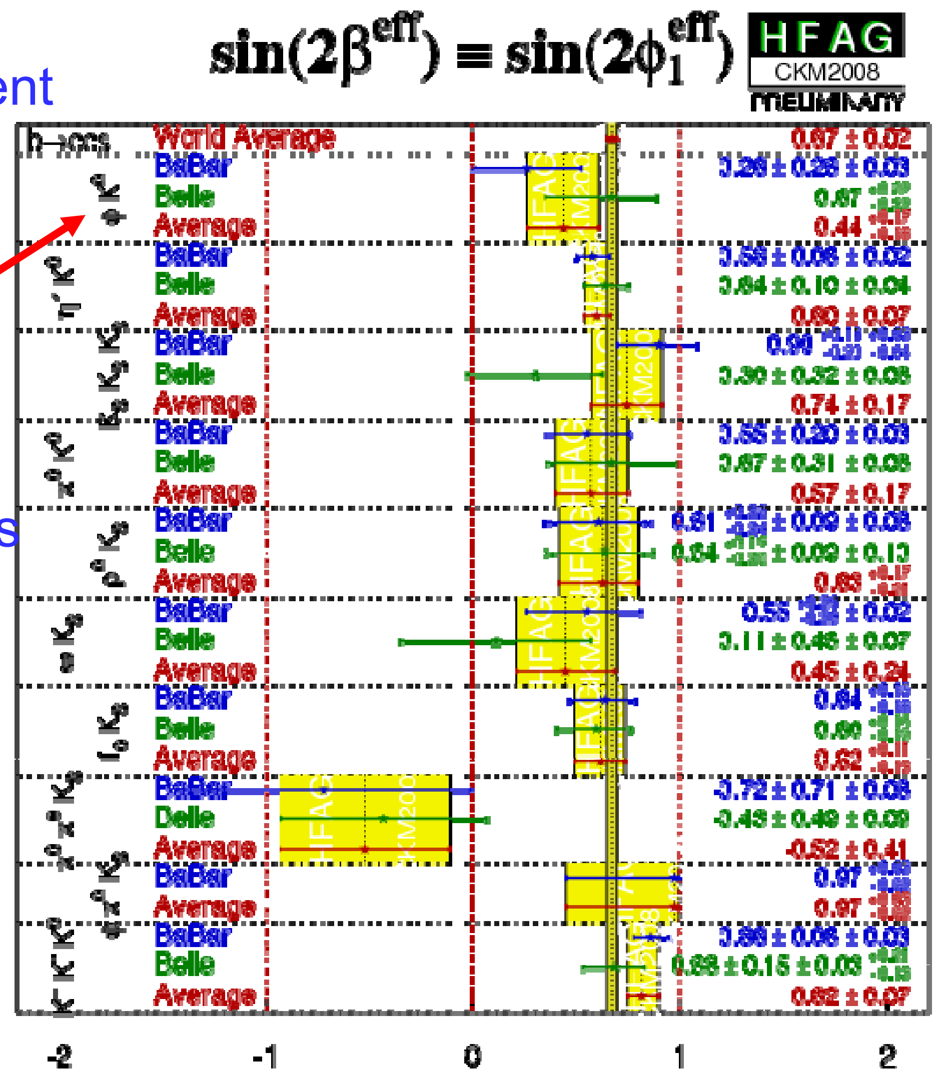
Compilation of Results



Is sin(2β) universal?

- Decays mediated by several different quark-level transitions probe 2β
  - $b \to c\bar{c}s$ (eg. J/ψ K_S)
  - $b \to c\bar{c}d$ (eg. J/ψ π^0)
  - $b \to c\bar{u}d$ (eg. D_{CP} π^0)
  - $b \to q\bar{q}s$ (eg. φ K_S)
- Consistency of measurements tests the Standard Model
- Today's situation :

  no smoking gun

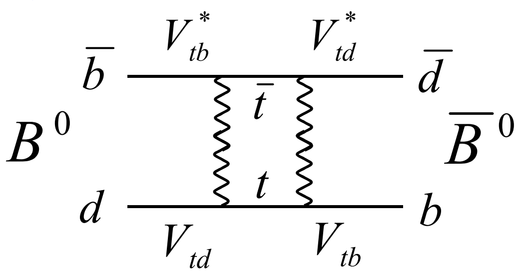


NB. Dalitz plot analyses for $\pi^+\pi^-K_S$ and $K^+K^-K_S$

Let's try this for the next angle: α

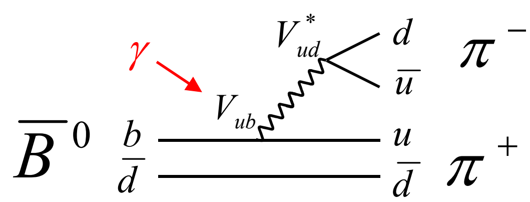
- Access to α from the interference of a $b \to u$ decay (γ) with $B^0 B^0$ mixing (β)

$B^0\bar{B}^0$ mixing



$q/p \propto V_{tb}^* V_{td} / V_{tb} V_{td}^*$

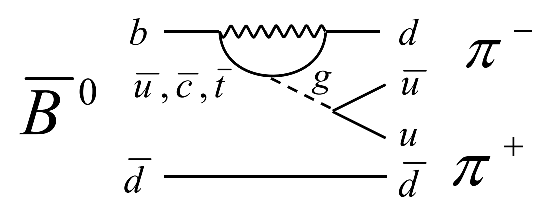
Tree decay



$A \propto V_{ud}^* V_{ub}$

$\oplus$

Penguin decay



$A \approx V_{td}^* V_{tb}$

$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$S = \sin(2\alpha)$$

$$C = 0$$

$$\lambda = e^{i2\alpha} \frac{T + P e^{+i\gamma} e^{i\delta}}{T + P e^{-i\gamma} e^{i\delta}}$$

$$S = \sqrt{1 - C^2} \sin(2\alpha_{eff})$$

$$C \propto \sin\delta$$

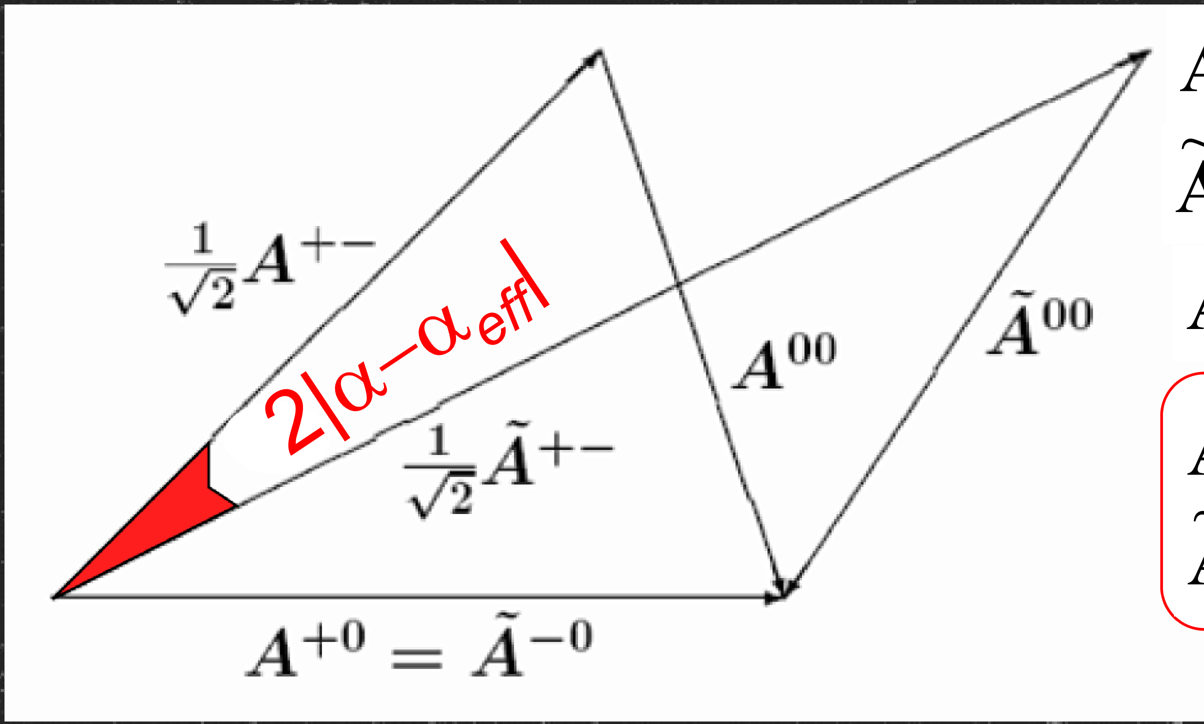
How can we obtain α from α_{eff} ?

Time-dep. asymmetry : $A_{\pi\pi}(\Delta t) = S_{\pi\pi} \sin(\Delta m_d \Delta t) - C_{\pi\pi} \cos(\Delta m_d \Delta t)$

NB : T = "tree" amplitude P = "penguin" amplitude

How to estimate $|\alpha-\alpha_{eff}|$: Isospin analysis

- Use SU(2) to relate decay rates of different *hh* final states ($h \in \{\pi,\rho\}$)
- $B \to hh$ can have I=0 or 2 but gluonic penguins only contribute to I=0 (by $\Delta I=1/2$ rule) $\Rightarrow A^{+0} = \tilde{A}^{-0}$
- Need to measure several related B.F.s
- Works for $\pi\pi$, $\rho\rho$, $\rho\pi$ systems

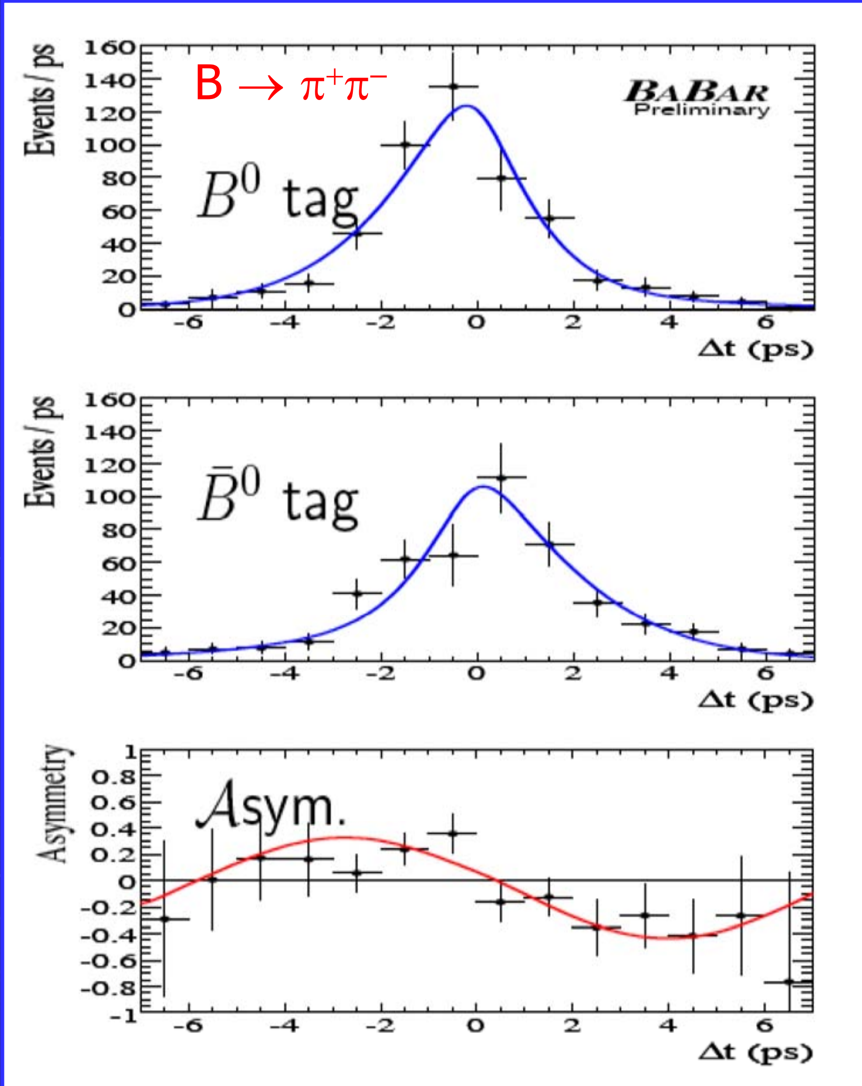


$$\mathbf{A}^{+-} = A(B^0 \to \pi^+\pi^-)$$
$$\tilde{\mathbf{A}}^{+-} = A(\overline{B}^0 \to \pi^+\pi^-)$$
$$\mathbf{A}^{+0} = A(B^+ \to \pi^+\pi^0)$$
$$\mathbf{A}^{00} = A(B^0 \to \pi^0\pi^0)$$
$$\tilde{\mathbf{A}}^{00} = A(\overline{B}^0 \to \pi^0\pi^0)$$

Limiting factor in analysis

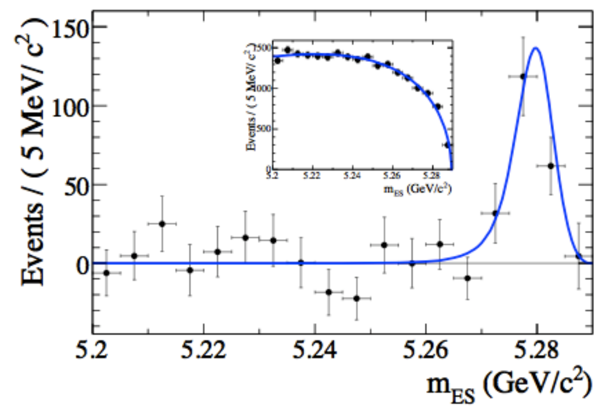
Gronau, London : PRL**65**, 3381 (1990)

Alpha: B → ππ system



$$B^0 \longrightarrow \pi^0\pi^0$$

Branching fraction and time-integrated CP asymmetry.



$\mathcal{B}^{00} = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$

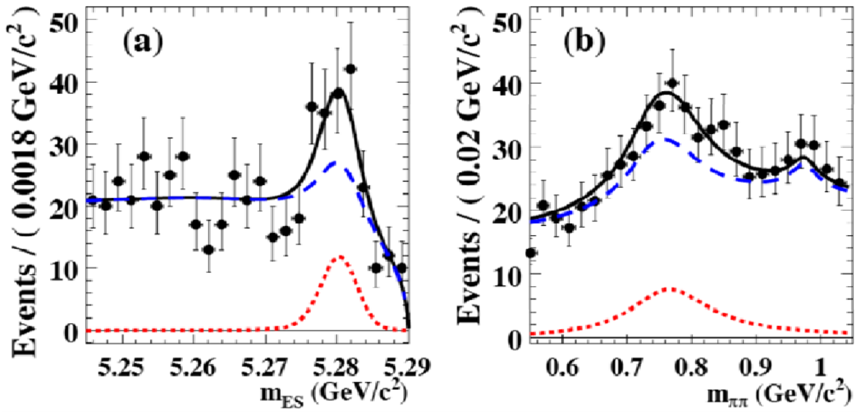
S^{00} not possible (no vertex)

$C^{00} = -0.43 \pm 0.26 \pm 0.05$

Final analysis: 465 M BB

Alpha: $B \to \rho\rho$ system

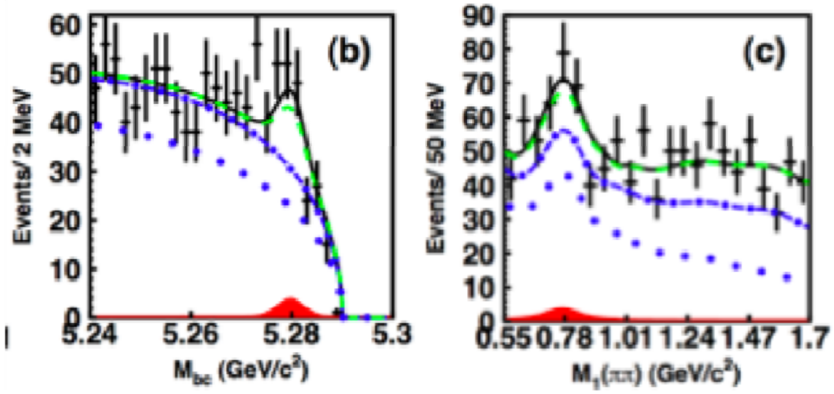
New from BaBar: $B^0 \to \rho^0\rho^0$ (arXiv:0807.4977)



$$\mathcal{B} = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$$
$$f_L = 0.75^{+0.11}_{-0.14} \pm 0.04$$
$$S^{00} = +0.3 \pm 0.7 \pm 0.2$$
$$C^{00} = +0.2 \pm 0.8 \pm 0.3$$

3.1σ evidence for $\rho^0\rho^0$

New from Belle: $B^0 \to \rho^0\rho^0$: $\mathcal{B} = (0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$

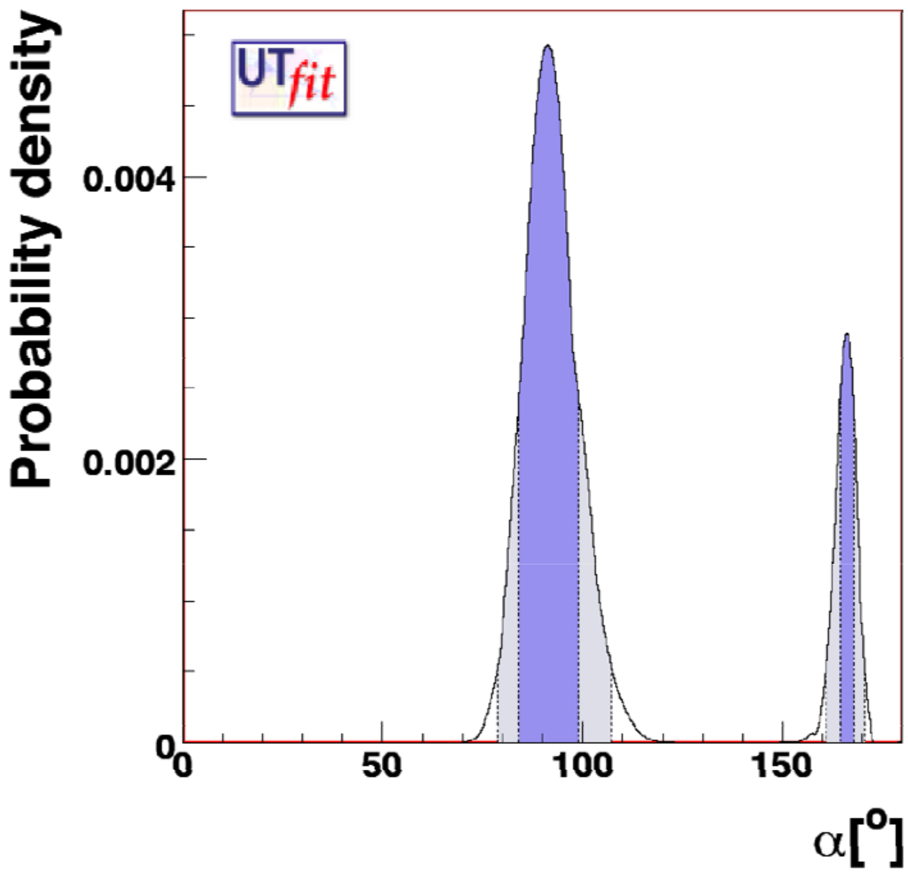


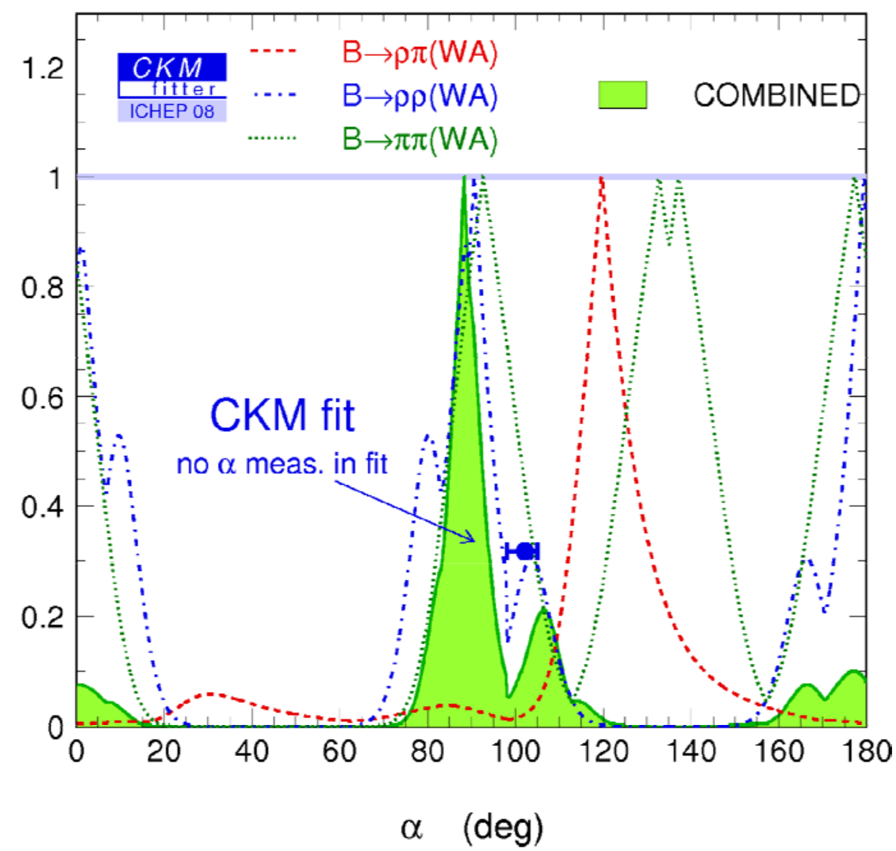
World averages:

$$\mathcal{B}_{\rho 0 \rho 0} = (0.72 \pm 0.28) \times 10^{-6}$$
$$\mathcal{B}_{\rho + \rho -} = (24.2 \pm 3.2) \times 10^{-6}$$

$\mathcal{B}(\rho^0\rho^0) << \mathcal{B}(\rho^+\rho^-)$

Summary for α





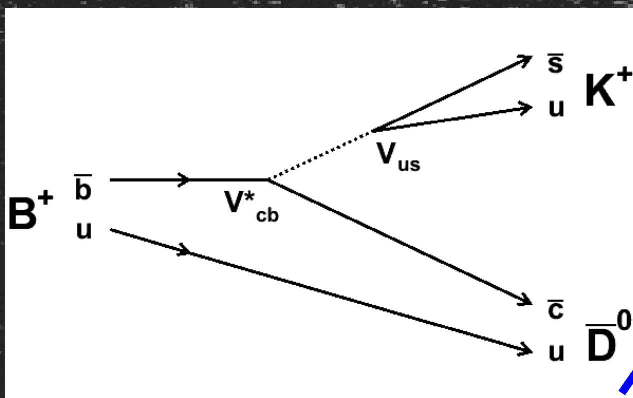
SM solution: $\alpha=(91\pm8)^\circ$

$\alpha \in [83.5\ ;\ 94.0]^\circ$ @ 68% CL

$\gamma = \arg[V_{ub}^*]$: CP violation in DK modes

GLW: Gronau, London, Wyler (2001)
ADS: Atwood, Dunietz, Soni (1997)
GGSZ: Giri, Grossman, Soffer, Zupan (2003)

E.g. $B^+ \to D^0 / \overline{D}{}^0 K^+$



B^+

e^{i0} → $\overline{D}{}^0 K^+$ → e^{i0}

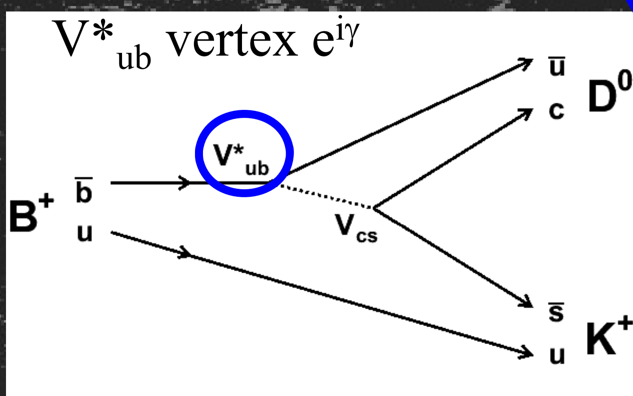
$e^{i\gamma}$ → $D^0 K^+$ → e^{i0}

D decays do not involve V_{ub} or V_{td}: no contribution to phase

$\overline{D}{}^0/D^0 \to$ CP state (GLW)

$\overline{D}{}^0/D^0 \to K^-\pi^+/K^+\pi^-$, CA/DCS (ADS)

$\overline{D}{}^0/D^0 \to K_S\pi^+\pi^-$, Dalitz (GGSZ)



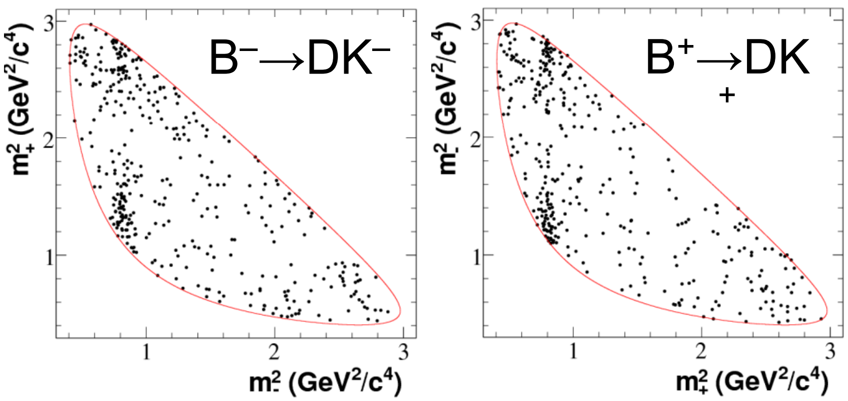
Relative phase = $e^{-i\gamma}$

$B^\pm \to DK$: no time dependence; extract γ from rates and CP asymmetries but $b \to u$ amplitude is small (for example r_B (DK^-) = 0.16 ± 0.05 ± 0.01 ± 0.05 Belle)

$B \to D^{(*)}K^{(*)}$ with $D \to K_S\pi^+\pi^-$ Dalitz Plot Analysis

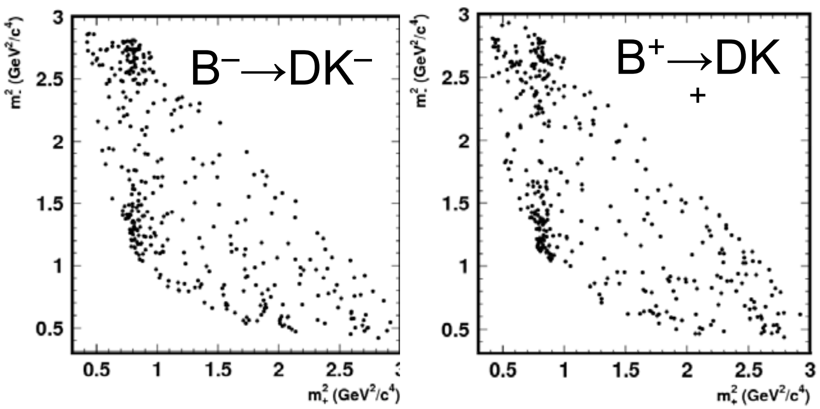
Giri, Grossman, Soffer & Zupan, PRD 68 (2003) 054018 & Belle

BABAR PRD 78 (2008) 034023



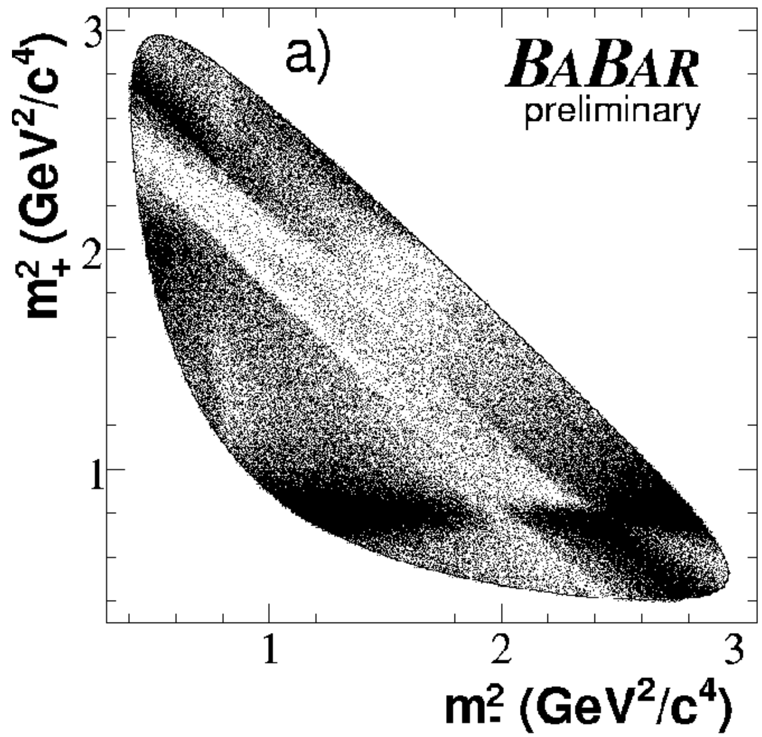
$\gamma = (76 \pm 22 \pm 5 \pm 5)°$

Belle arXiv:0803.3375

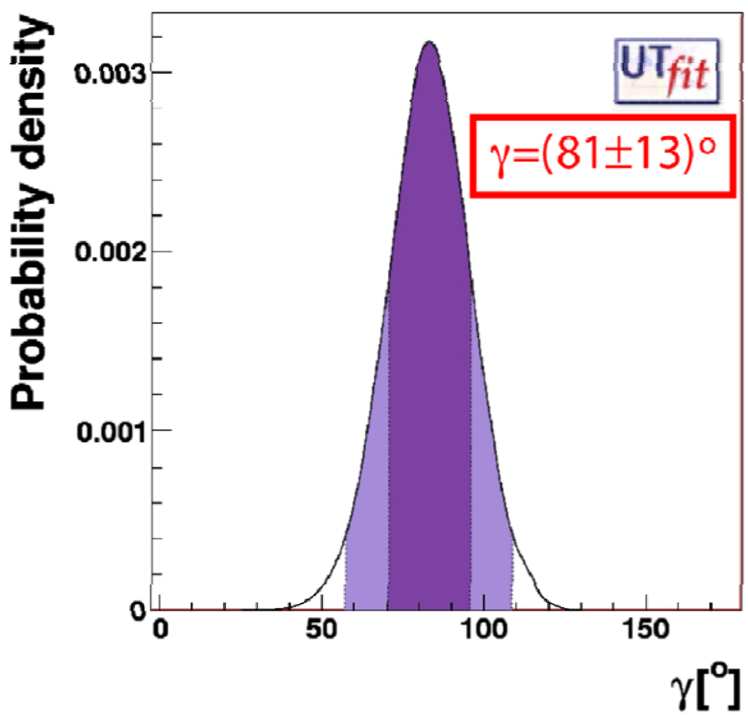


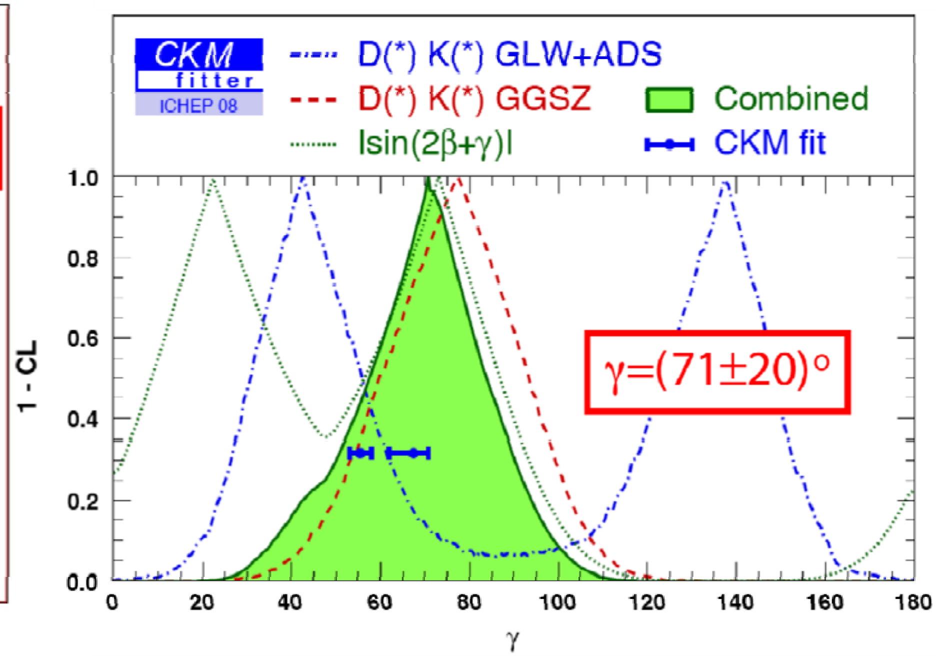
$\varphi_3 = (76\,^{+12}_{-13} \pm 4 \pm 9)°$

Map out Dalitz plot from all $D^0 \to K_s\pi^+\pi^-$ decays

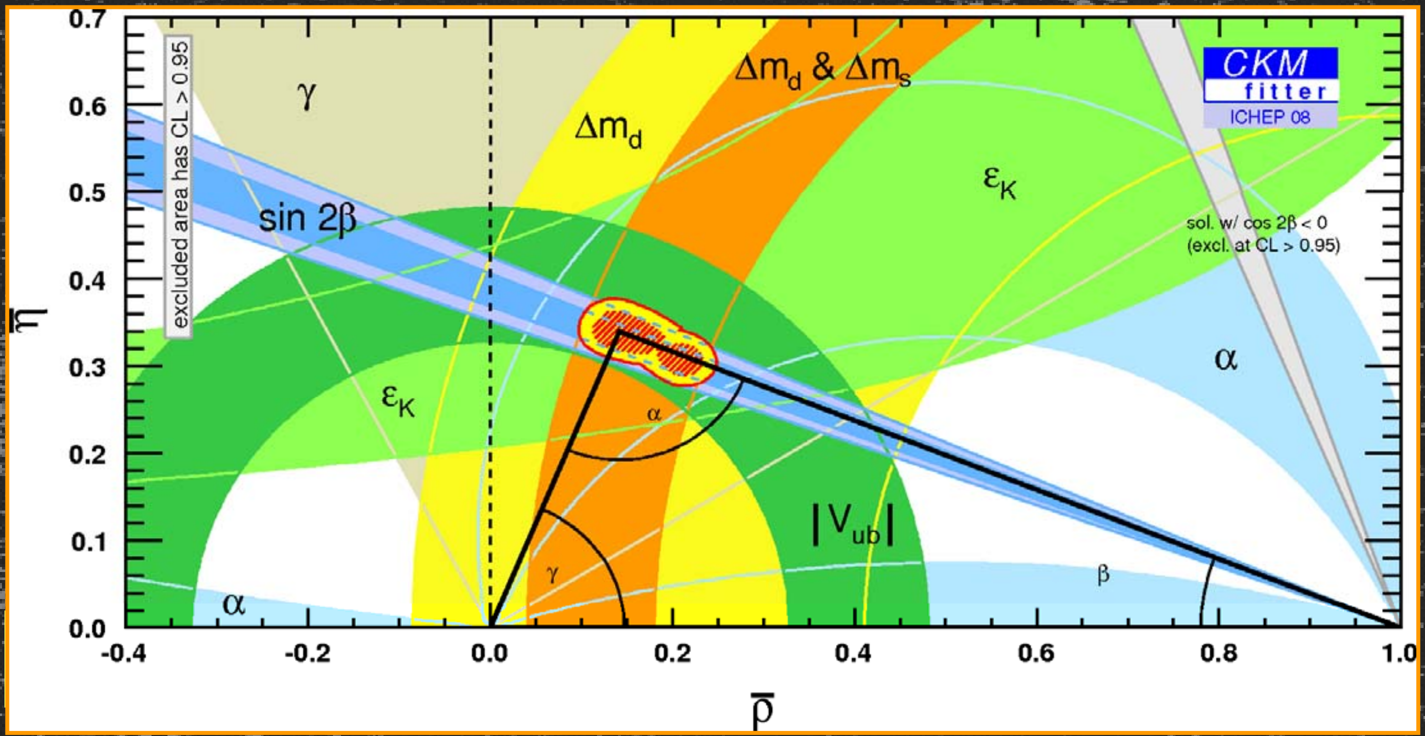


Summary for γ



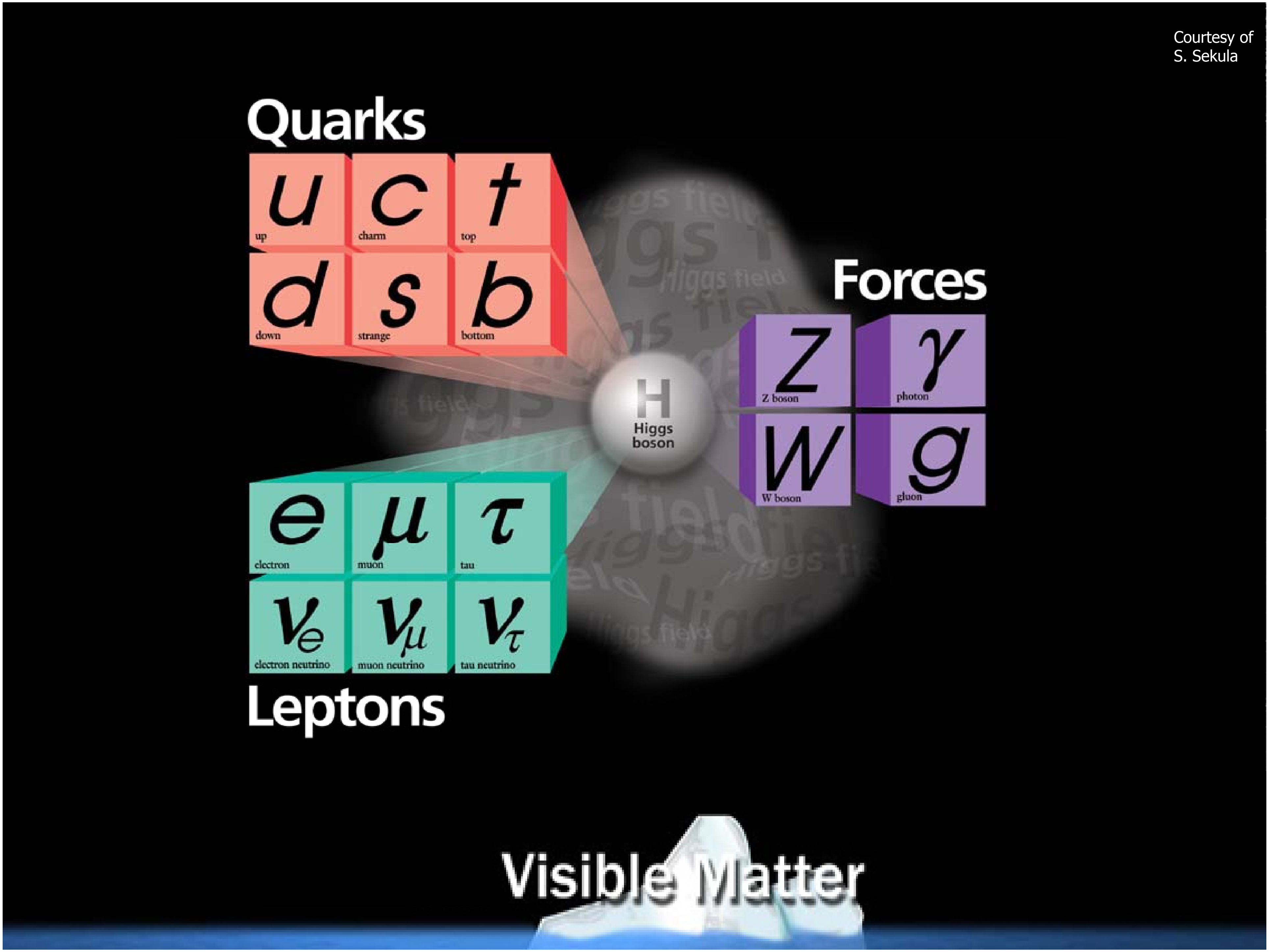


The CKM Model has passed the experimental test

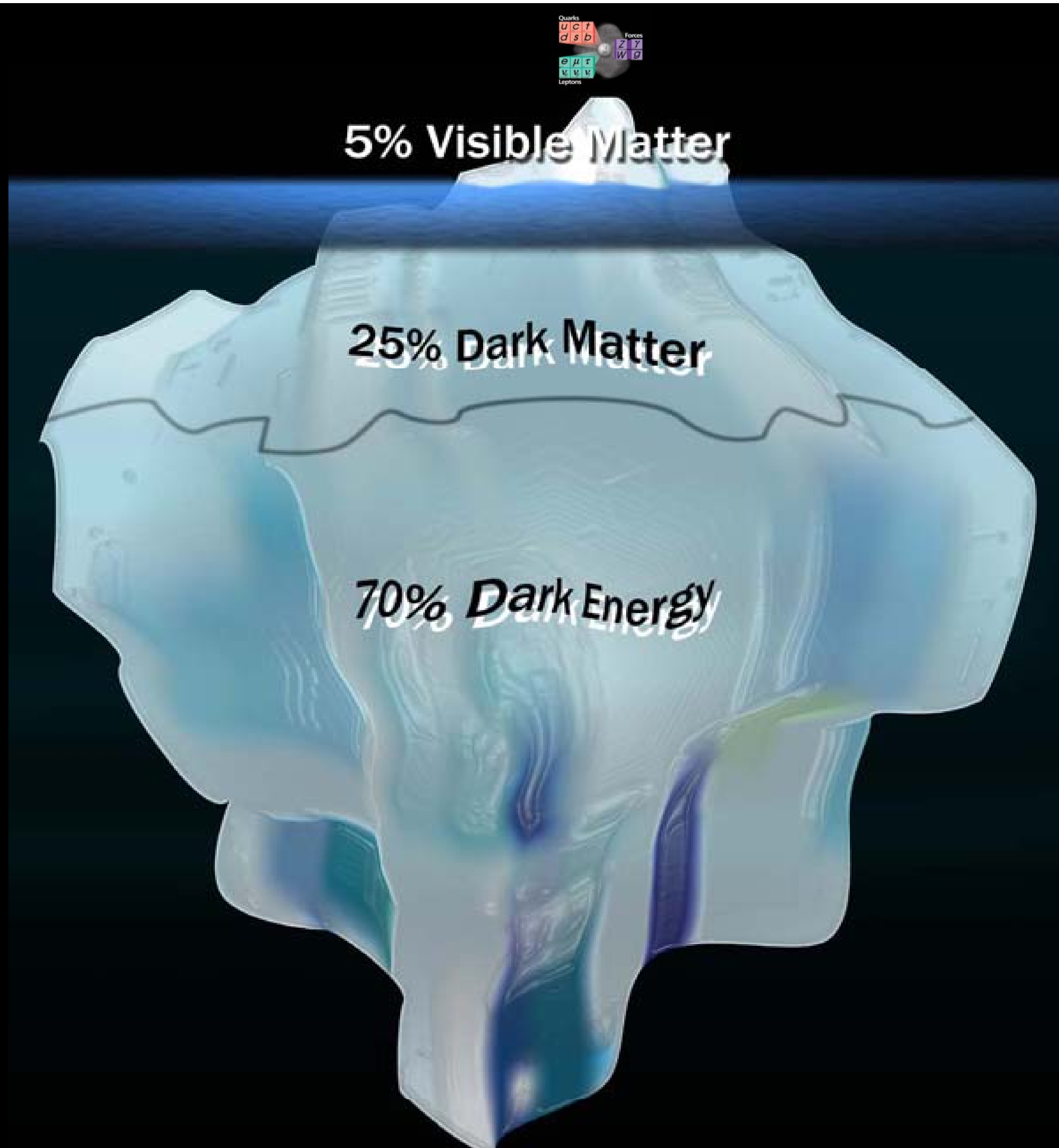


New Targets

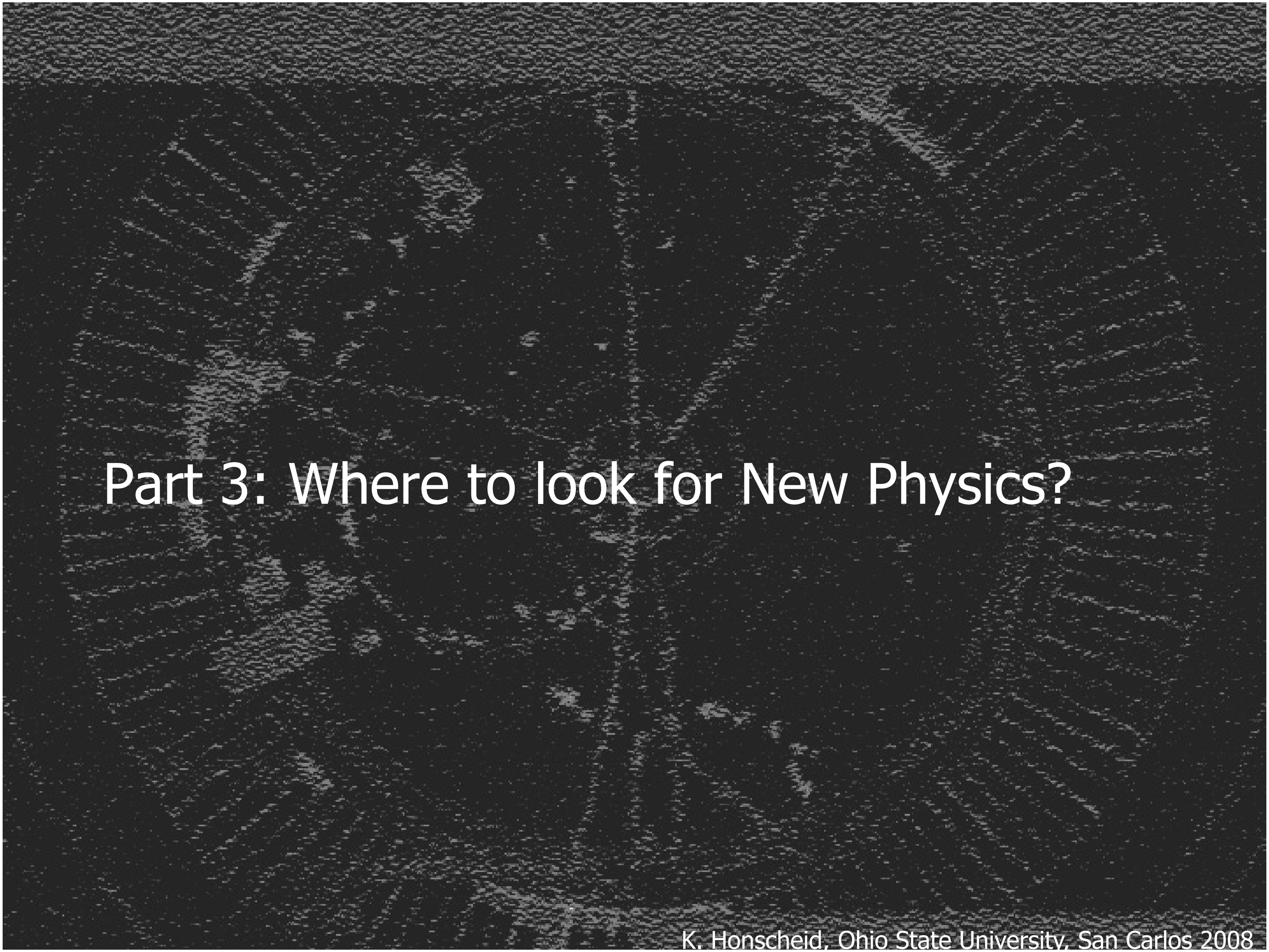
- Effects of TeV new physics → deviations from SM
- LFV and new source of CPV
- Hidden flavor symmetry and its breaking


Courtesy of S. Sekula
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs field
Visible Matter

Courtesy of
S. Sekula

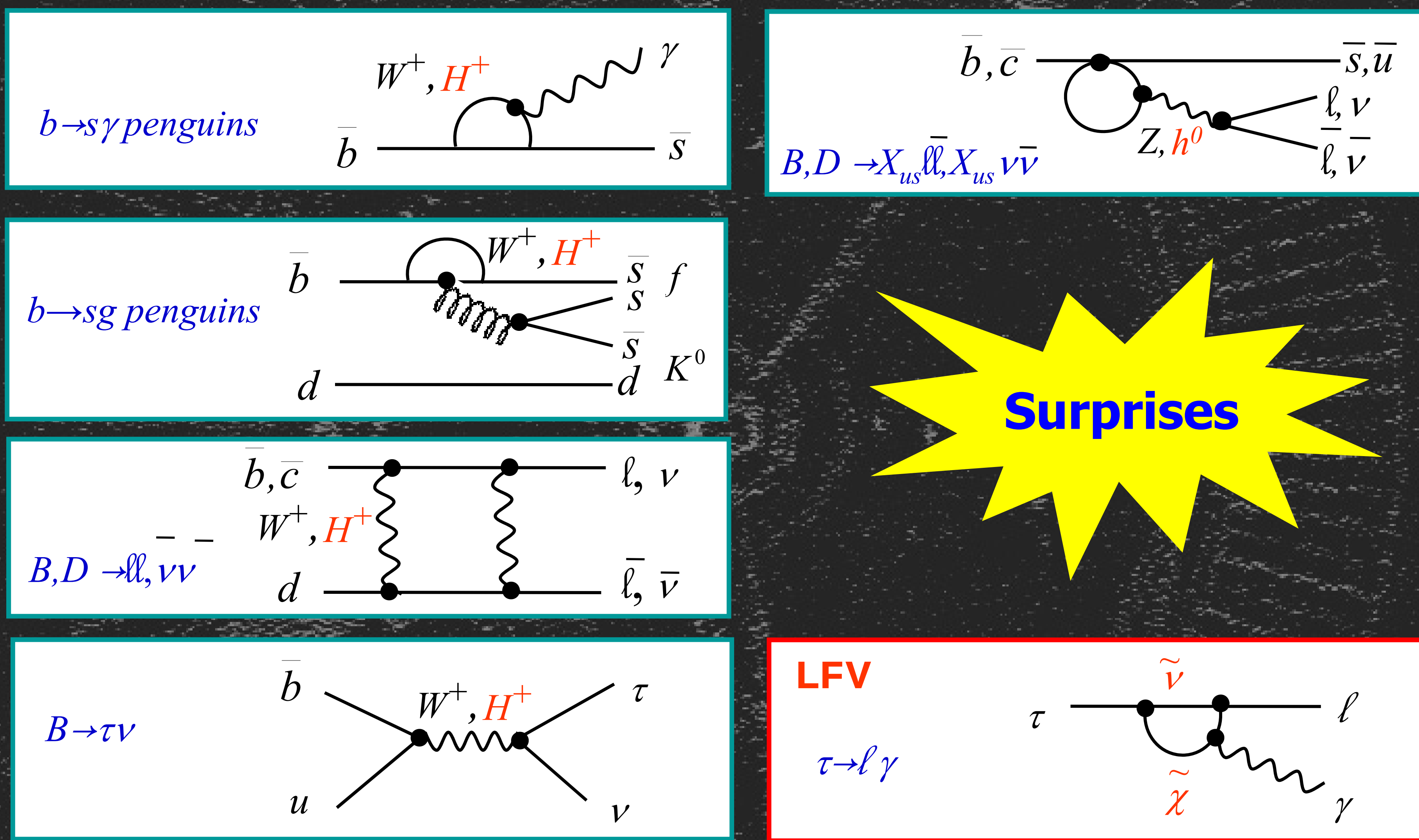


Can we find evidence for New Physics in Heavy Flavor Decays?



Part 3: Where to look for New Physics?

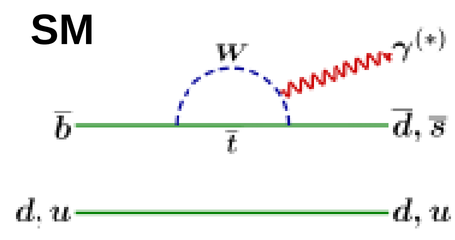
Experimental Strategies

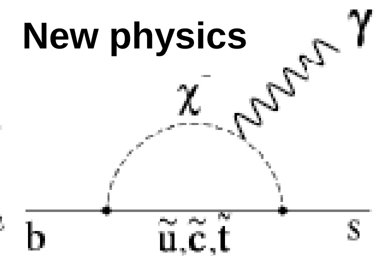


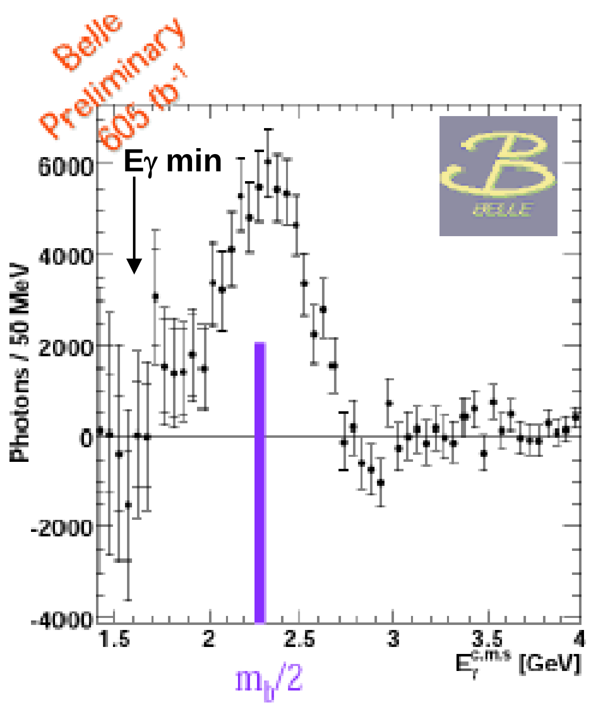
Inclusive $B \to X_s \gamma$ Branching Fraction

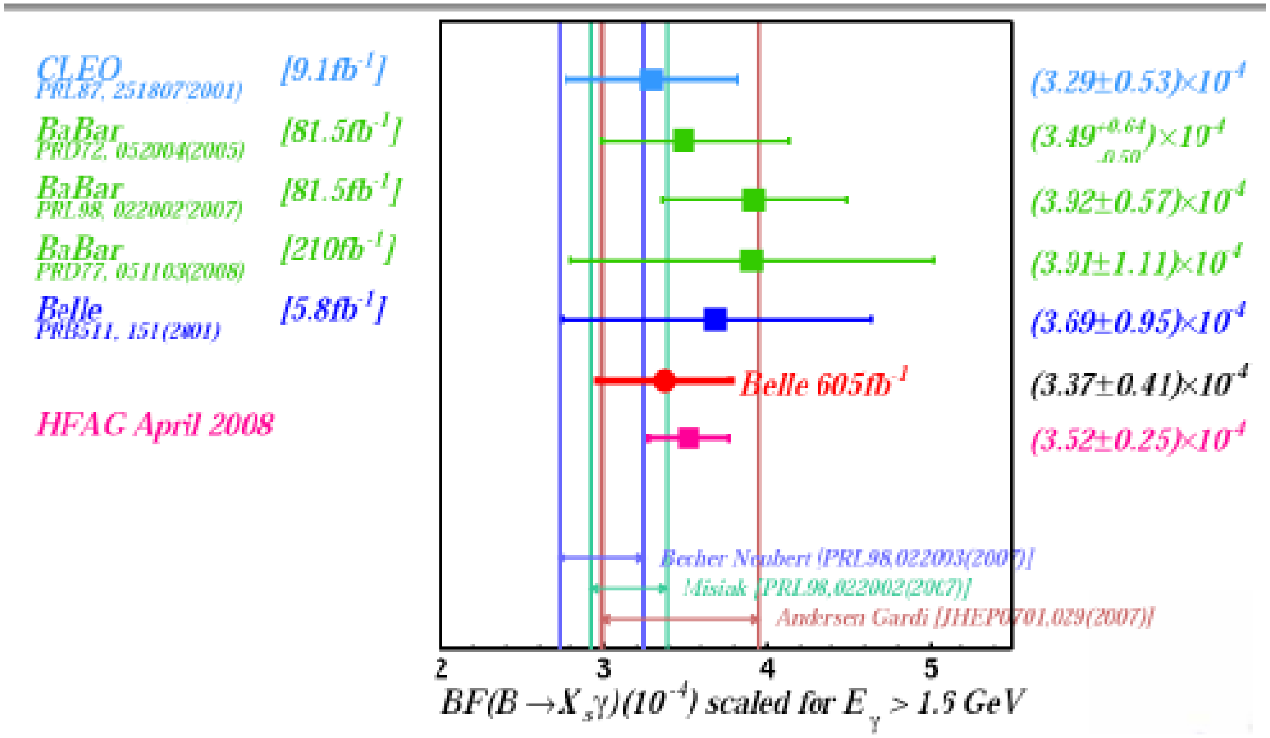
Belle update with E_γ >1.7 GeV:

arXiv:0804.1580









SM NNLO calculation:

$\mathcal{B}(B \to X_s\gamma)\,|_{E_\gamma > 1.6\ \text{GeV}} =$

$(3.15\pm0.23)\times10^{-4}$	Misiak et al.
$(2.98\pm0.26)\times10^{-}$	Becher Neubertv
$(3.47\pm0.49)\times10^{-4}$	Anderson Gardi

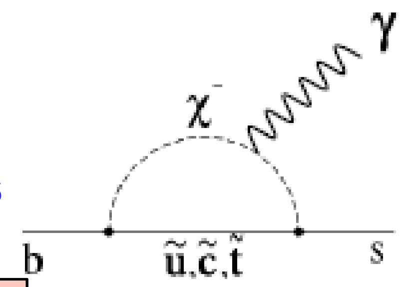
HFAG 2008:

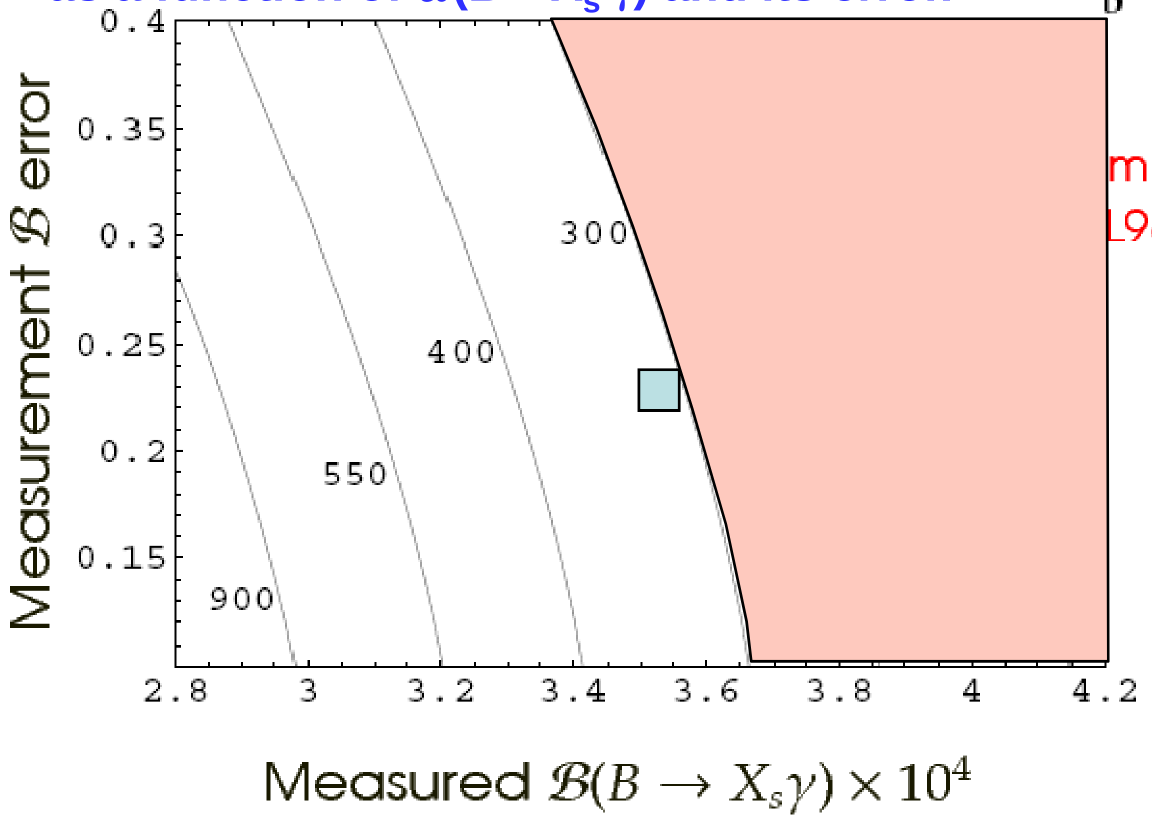
$\mathcal{B}(B \to X_s\gamma)\,|_{E_\gamma > 1.6\ \text{GeV}}$

$= (3.52\pm0.25)\times10^{-4}$

Charged Higgs Bound

The 95% lower bound of charged Higgs mass as a function of $\mathcal{B}(B \rightarrow X_s\, \gamma)$ and its error.

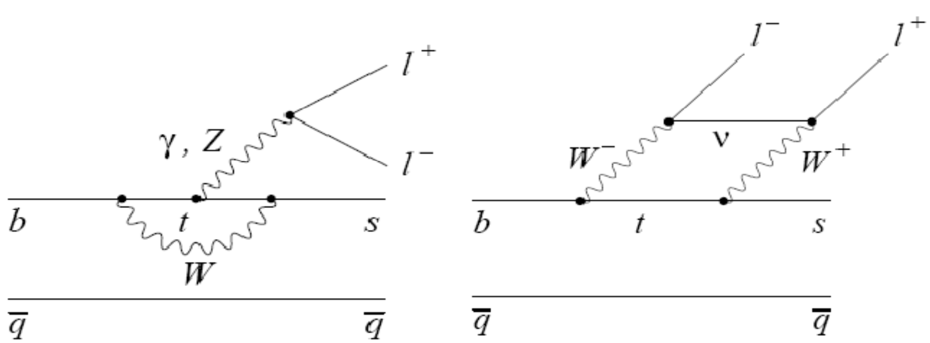




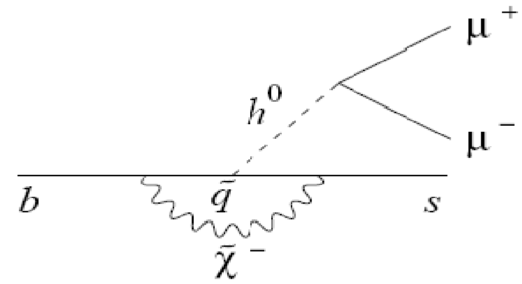
m Misiak et al,
L98,022002('07)

M_{H^+} > 300 GeV/c² @ 95% C.L. for all tanβ

EW Penguins: $B\to Kl^+l^-$, $B\to K^*l^+l^-$, and $B\to X_s l^+l^-$



- With l^+l^- pair, can produce both pseudoscalar and vector mesons
- SM: $Br(B \to K l^+l^-) \sim 4 \times 10^{-7}$ (± 30% theory) ~3 times that for K*



$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} (V_{tb}V_{ts}^*) \sum_{i=1}^{10} C_i O_i$$

New Physics affects

Rates, Asymmetries (AFB, CP), μμ/ee ratio

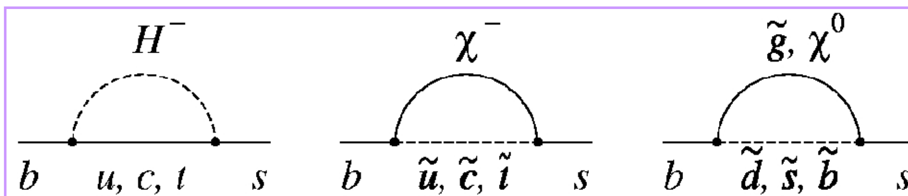
Short-distance physics appears in the Wilson coefficients.

C_7, C_9, C_{10} important for $b \to s\, l^+l^-$

Magnitude of $|C_7| \approx 0.33$ known from $B \to X_S\gamma$, but sign not constrained.

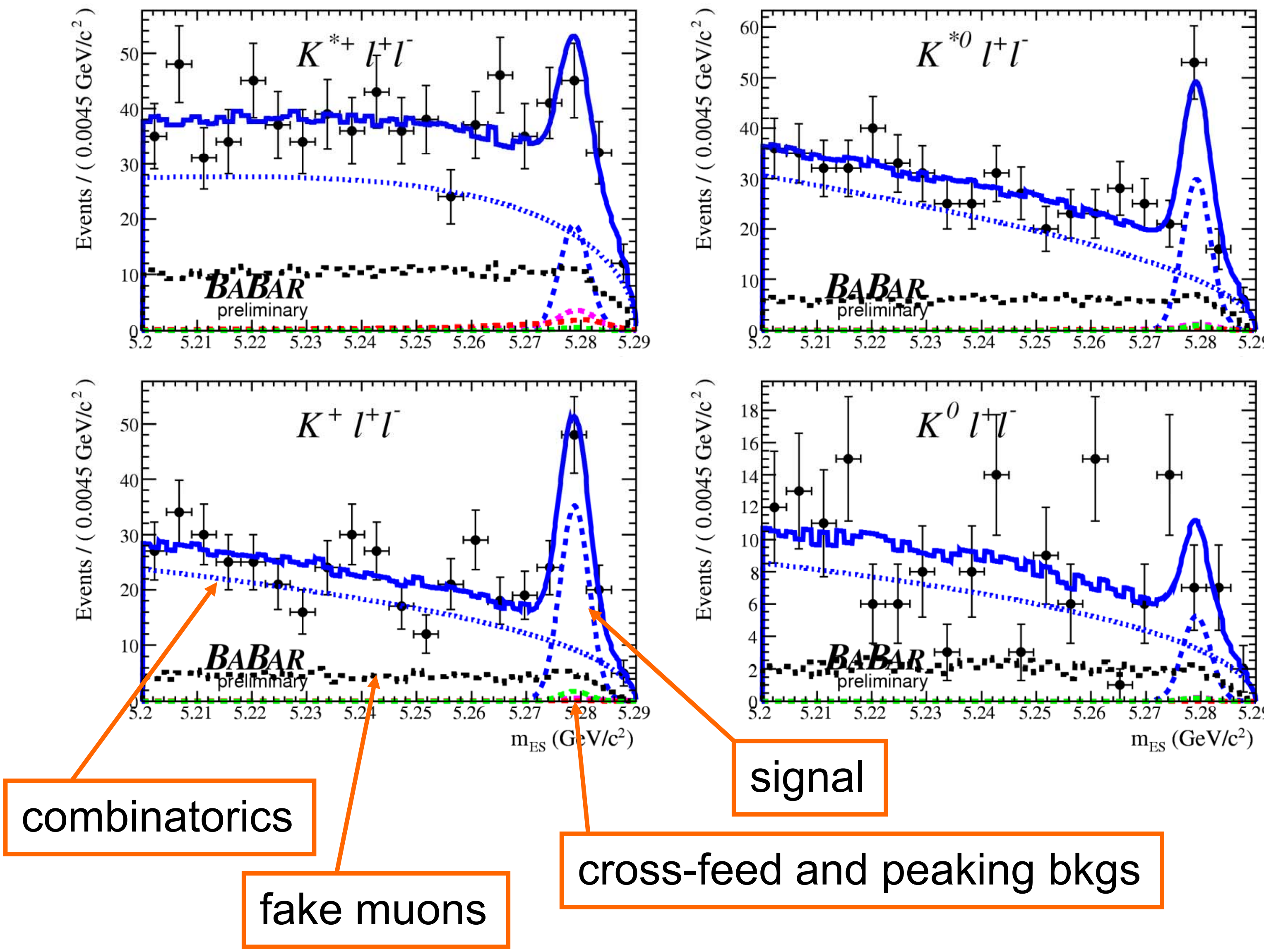
$|C_9|^2 + |C_{10}|^2$ constrained by $b \to s\, l^+l^-$ BF, but not relative sign.

New physics may modify the C's or introduce additional terms (e.g., scalar, pseudoscalar)



$B \to K^{(*)} l^+ l^-$ Signals

349 fb^{-1}

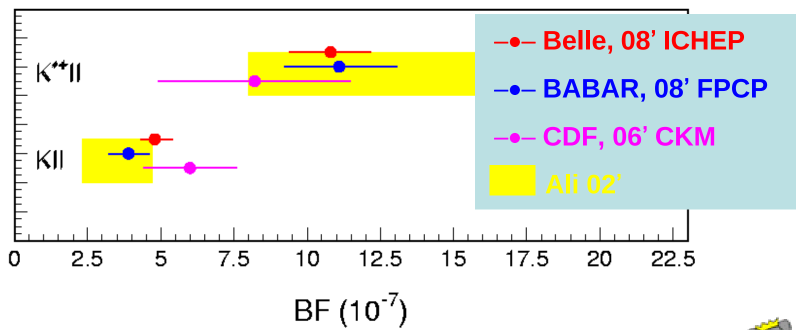


ΔE cuts applied

Good agreement with SM BF

657M

- Obtain partial BF in 6 bins in q^2; extrapolate the total BF.
- $BF(B \to K^*ll) = (10.8 \pm 1.0 \pm 0.9) \times 10^{-7}$
- $BF(B \to Kll) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$



- $BF(B \to K^*ll) = (11.1 \pm 1.9 \pm 0.7) \times 10^{-7}$
- $BF(B \to Kll) = (3.9 \pm 0.7 \pm 0.2) \times 10^{-7}$

384M

photon pole

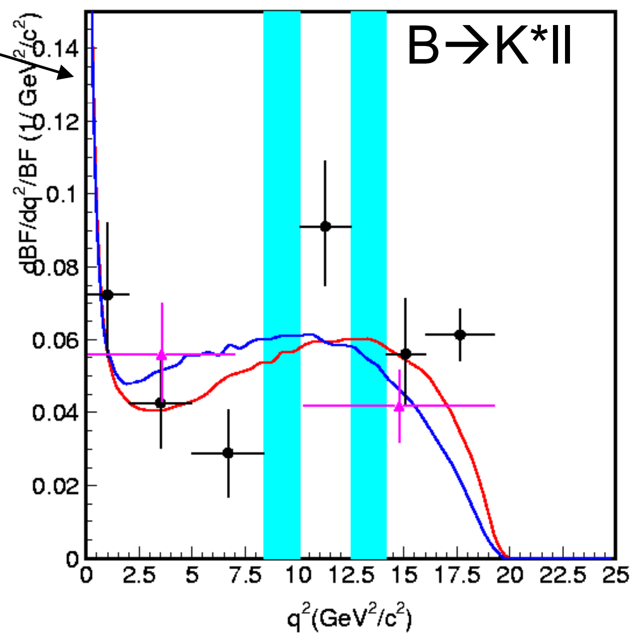
Veto events in the J/ψ and ψ′ regions

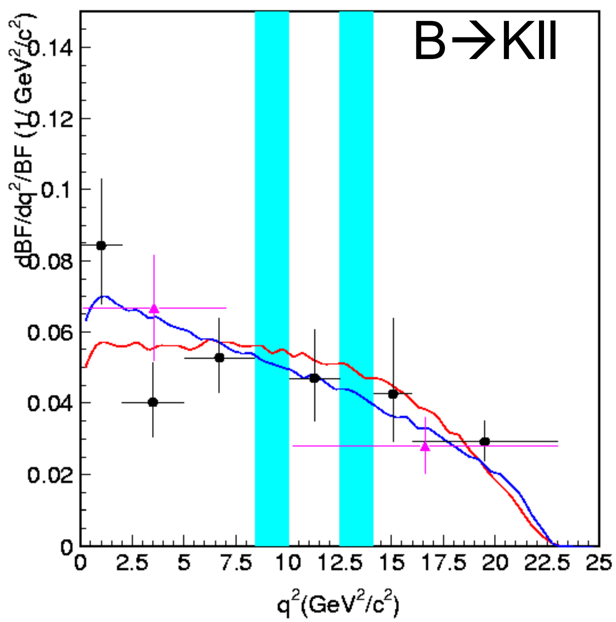
–●– **Belle, ICHEP 08**

–●– **BABAR, FPCP 08**

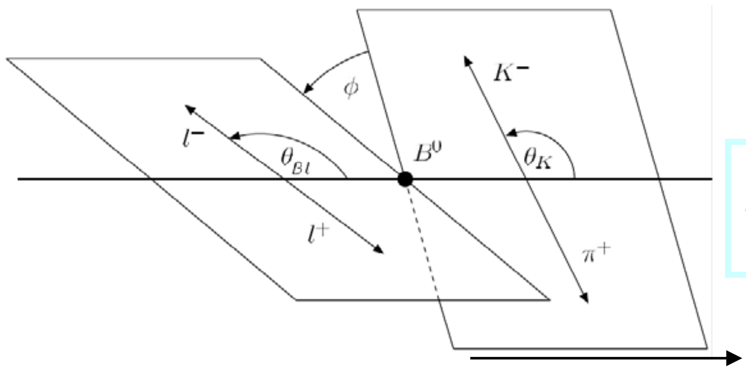
–– **Melikhov et. al (quark model, PLB 410, 1997)**

–– **Ali (PRD 66, 034002, 290, 2002)**

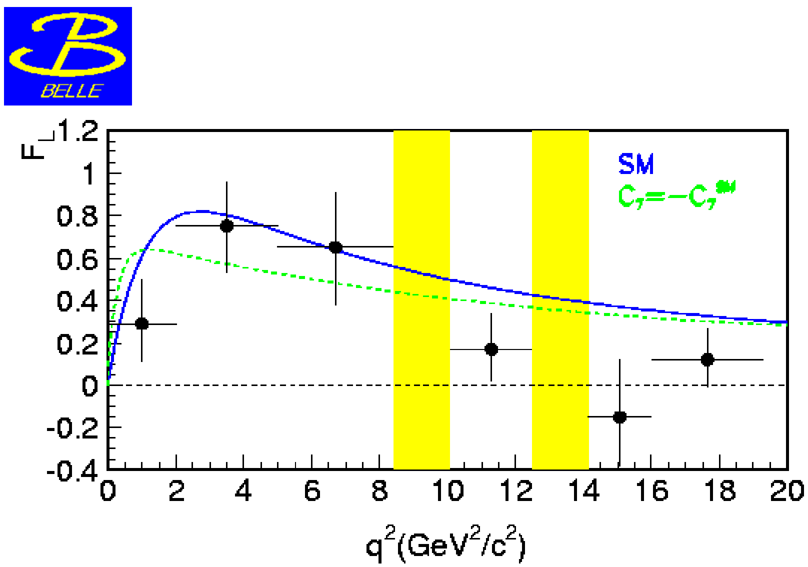


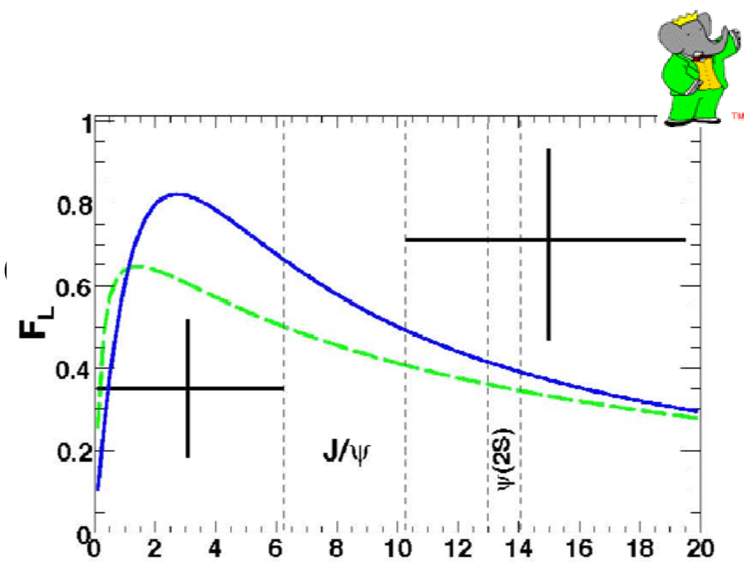


K* Longitudinal Polarization



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$



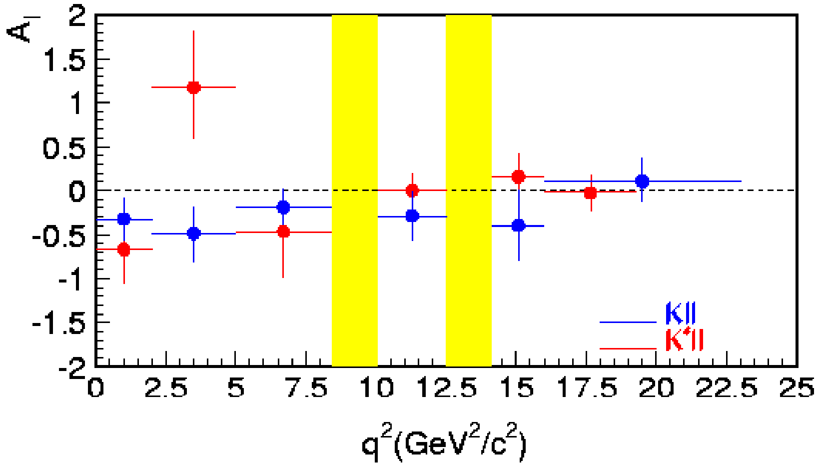


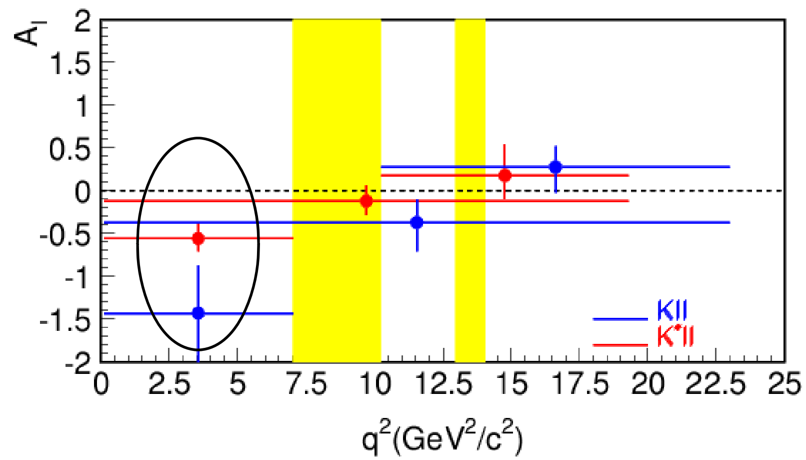
Unexpectedly Large Isospin Asymmetry?

Belle ICHEP 2008

BABAR arXiv:0807.4119

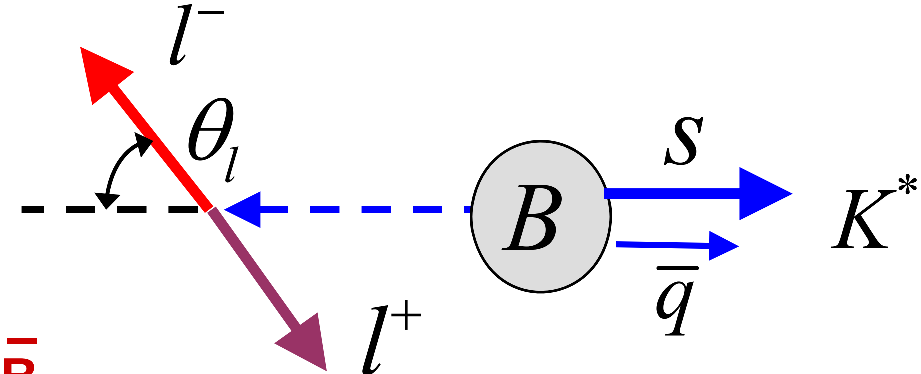
$$A_I \equiv \frac{\mathrm{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - (\frac{\tau_0}{\tau_+})\mathrm{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}{\mathrm{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + (\frac{\tau_0}{\tau_+})\mathrm{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}$$





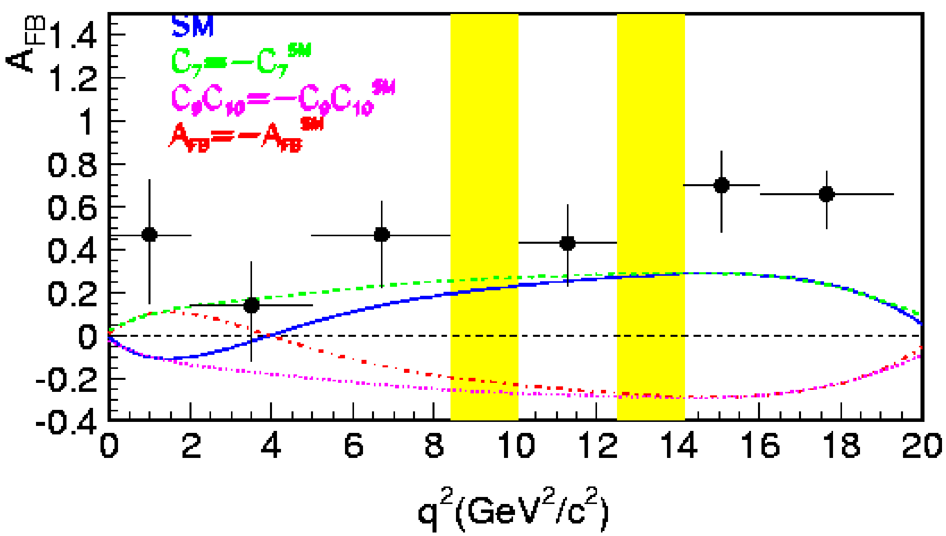
Expected to be small in SM (Feldman and Matias, JHEP 0301, 074 (2003))

Anomalous $A_{FB}(q^2)$ in $B \to K^{(*)} ll$?

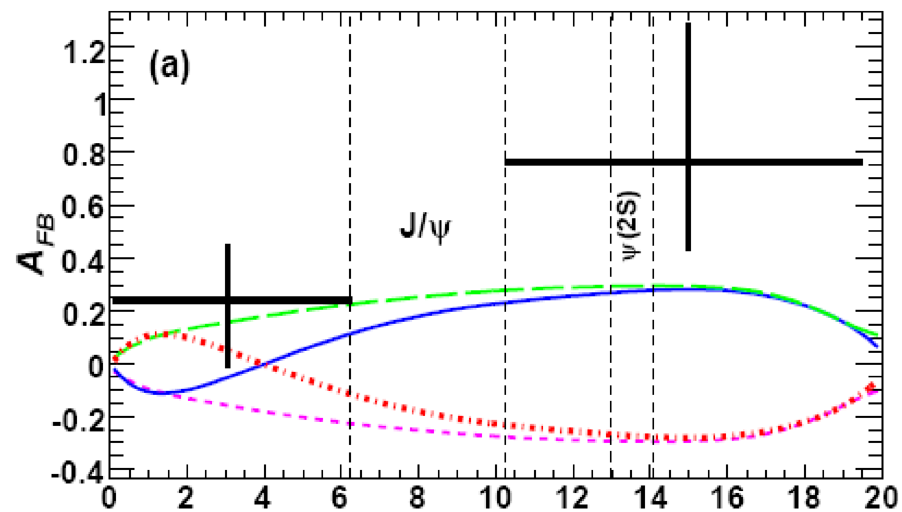


Lepton angular distribution in $l^+ l^-$ rest frame

657 M $B\bar{B}$



384 M $B\bar{B}$



Data show positive A_{FB} at low q^2, while the SM predicts negative A_{FB}.

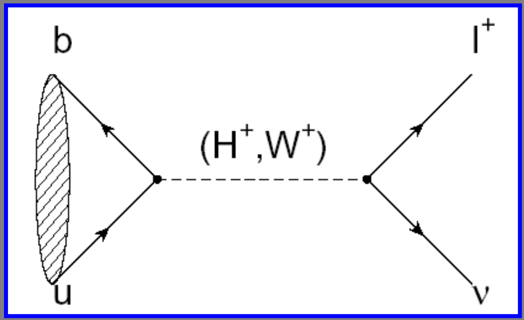
At high q^2, data above the SM expectation.

Search for B→ τν

- SM decay proceeds via W-annihilation diagram

$$\mathcal{B}^{SM}(B^+ \to \tau^+\nu_\tau) = 9.3 \times 10^{-5} \left[\frac{f_{B+}}{196\ MeV}\right]^2 \left[\frac{|V_{ub}|}{0.00367}\right]^2$$

- B (B→τν)= $(0.78\ ^{+0.09}_{-0.13})$ x 10-4 (CKM fitter 2008 prediction)



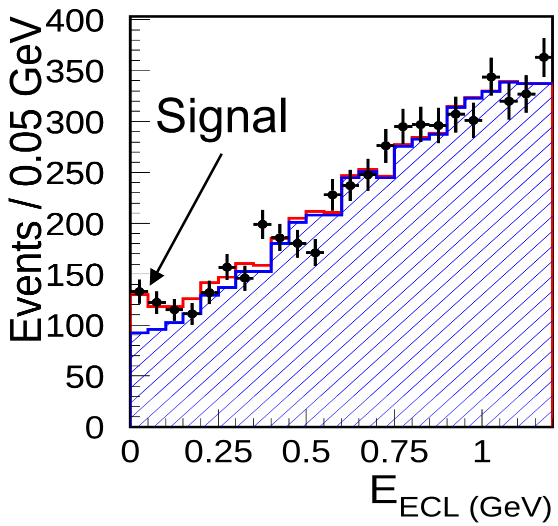
- Sensitive to new physics charged current
- Analysis:
  - Undetected neutrinos result in large missing energy and few kinematic constraints – high background.
  - Reduce the background by reconstructing the second B ("tag B") in the event in the copious decay mode $B^- \to D^{*0} l^- \nu_l$
  - Reconstruct $B^+ \to \tau^+ \upsilon_\tau$ with $\tau^+ \to l^+ \nu \nu_{bar}$ or $\tau^+ \to h^+ \nu$, where h = π, ρ, or a_1
  - Require no additional charged tracks in the event

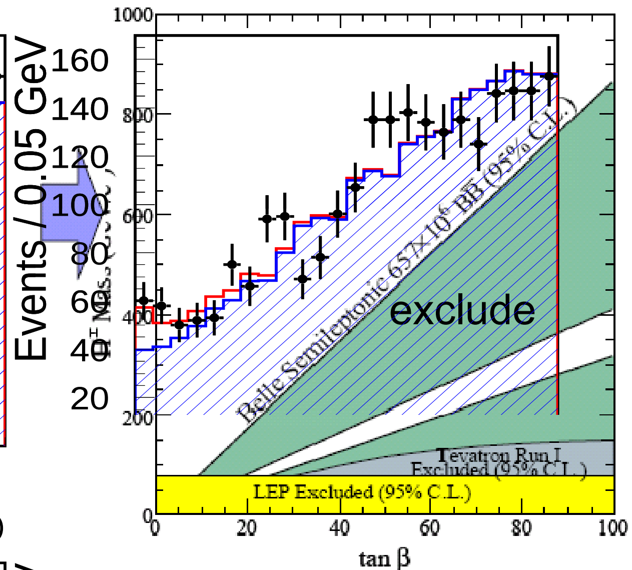
New Belle Result on $B^+ \to \tau^+ \nu$

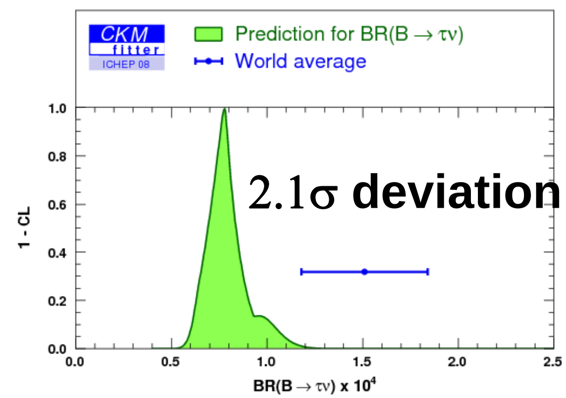
Method: Tag B on one side (hadronic tag or $D^{(*)}$ l ν tag)

Look for τ signature with “extra” energy in the ECAL

Use 657 M BB with $D^{(*)}$l ν tag







Note that interference is destructive in 2HDM (type II). $\mathcal{B} > \mathcal{B}_{SM}$ implies that H^+ contribution dominates

$$N_{sig} = 154^{+36}_{-35}\ \text{(stat)}\ {}^{+20}_{-22}\ \text{(syst)}$$

$$\Rightarrow \mathcal{B}(B \to \tau\nu) = (1.65^{+0.38}_{-0.37}{}^{+0.35}_{-0.37})\text{x}10^{-4}$$

3.8σ

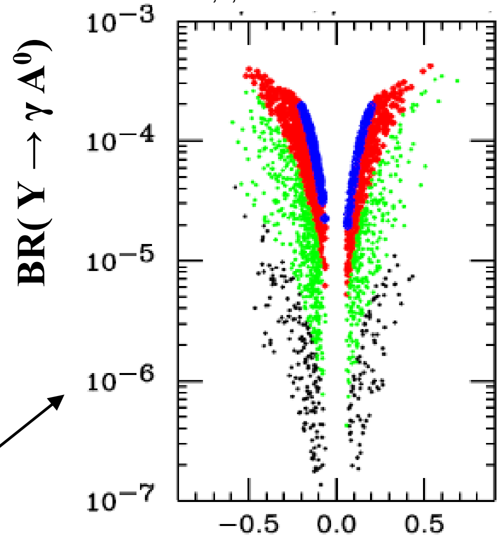
It doesn’t have to be a B meson decay

Can we find a light Higgs before the LHC is repaired?

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) adds a Higgs singlet [*] → extra Higgs boson, A^0, ***can be light.***

$$Y(3S) \to \gamma A^0; A^0 \to \chi\chi\,(invisible)$$

Channel could dominate for a light component of the dark matter (χ)



The fraction of the A^0 which is non-singlet

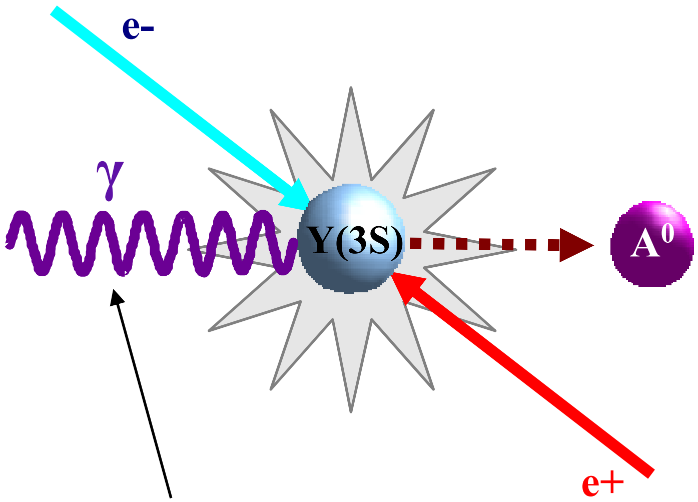
<u>Parameter Scan</u>
blue points: $m_A < 2m_\tau$
red points: $2m_\tau < m_A < 7.5$ GeV
green points: 7.5 GeV $< m_A <$ 8.8 GeV
black points: 8.8 GeV $< m_A <$ 9.2 GeV

Best limits come from recent CLEO search for $A^0 \to \mu\mu, \tau\tau$

hep/ex arXiv:0807.1427

[*] c.f. PRL 95:041801,2005 and PRD 76:051105,2007

Experimental Approach



Search for an invisibly-decaying particle recoiling against a single photon

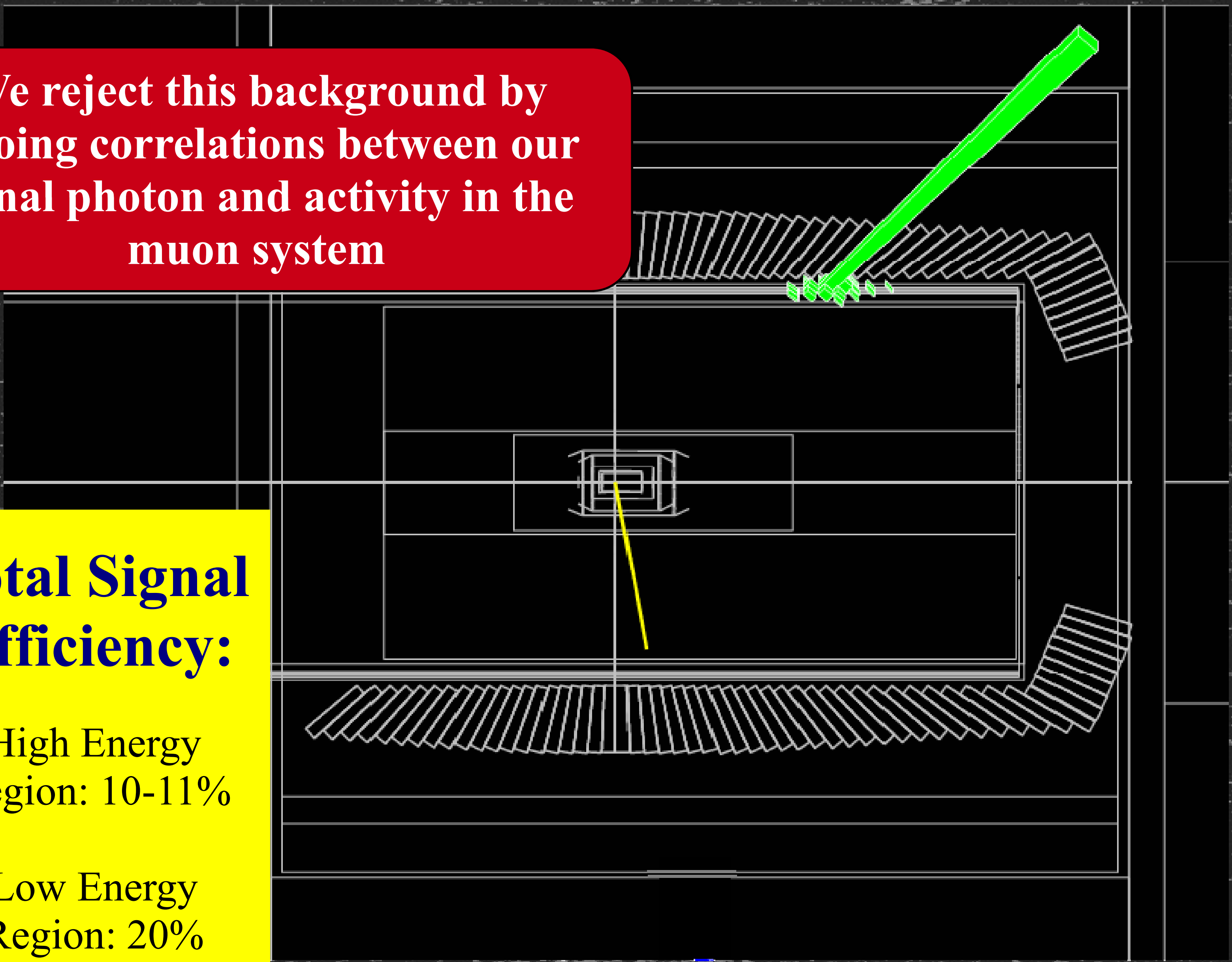
Photon Selection:

- EMC shower shape, acceptance, etc.
- Veto events where there is activity in the muon system opposite the photon (veto e+ e- $\rightarrow \gamma\gamma$)
- Veto photons in regions where the muon system has gaps

Additional Constraints

- No activity in the tracking system (track veto)
- Maximum energy requirement on remaining photons (<100 MeV total energy)

A Υ(3S) → γ + Invisible Candidate



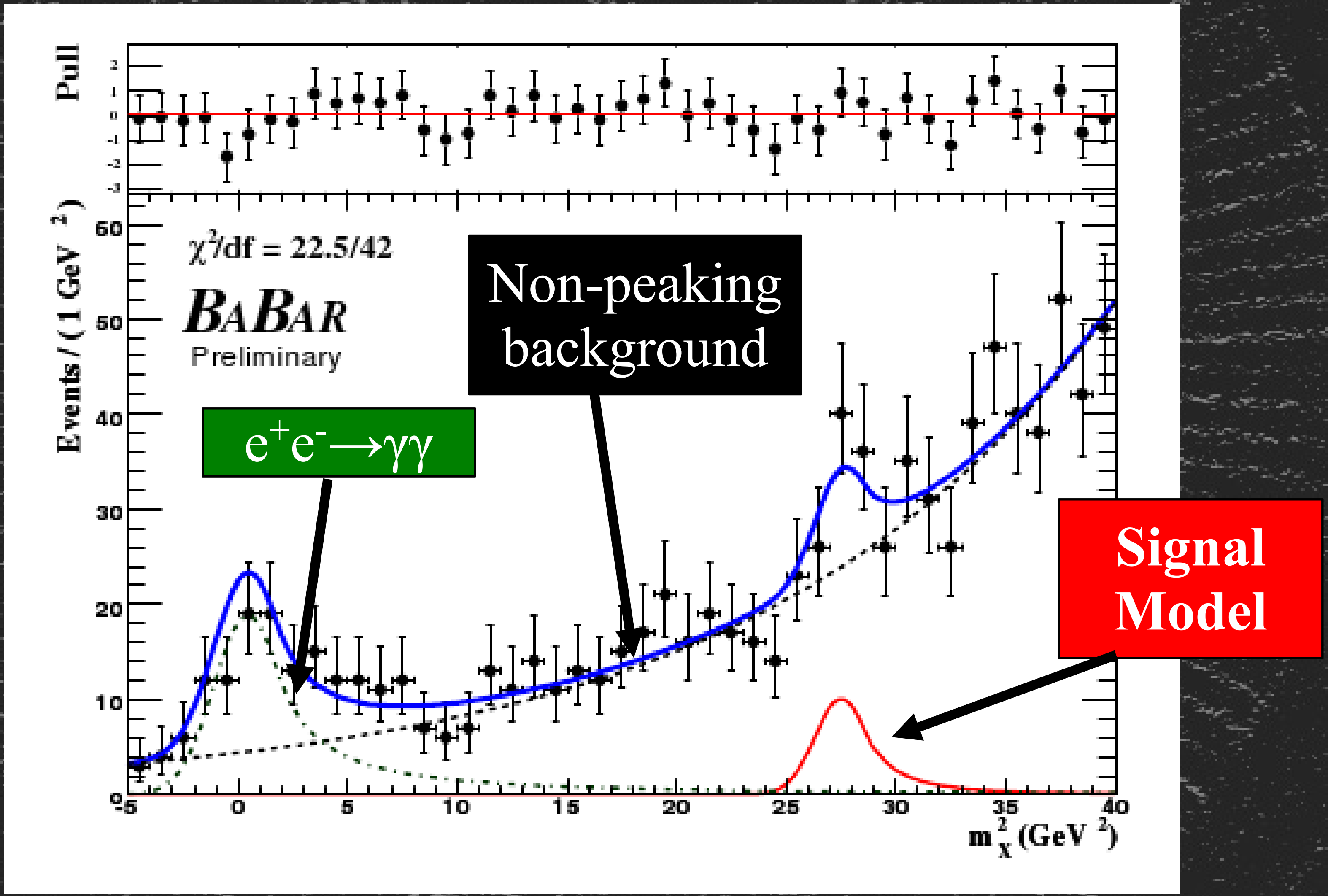
We reject this background by vetoing correlations between our signal photon and activity in the muon system

Total Signal Efficiency:

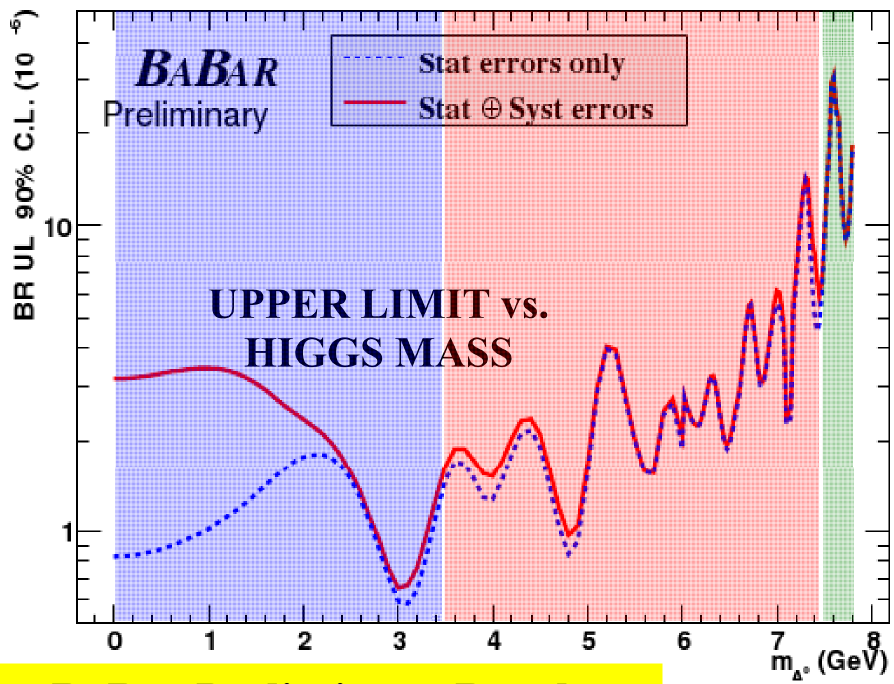
High Energy Region: 10-11%

Low Energy Region: 20%

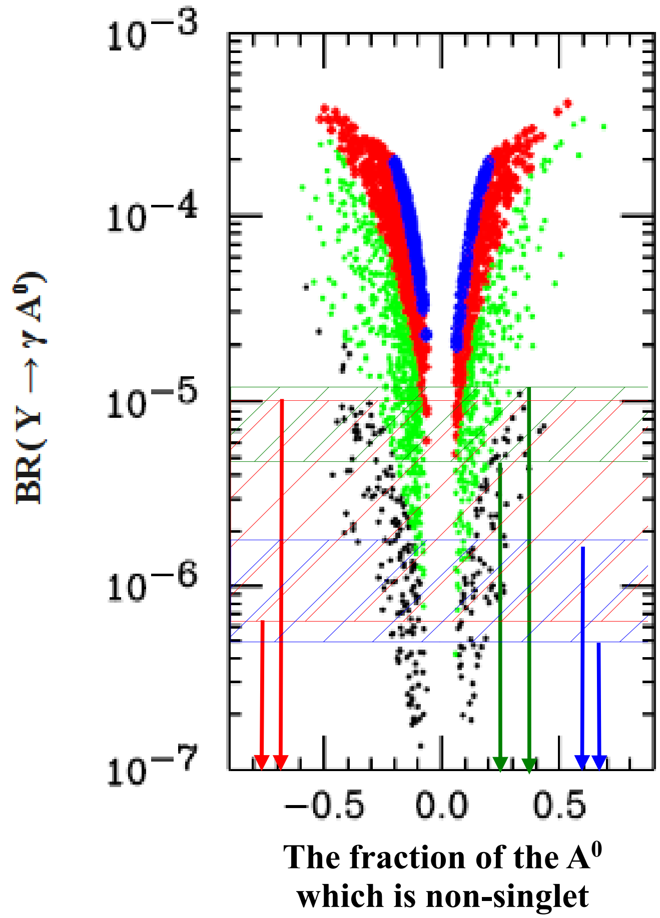
A Snapshot: Fits to the Photon Spectrum



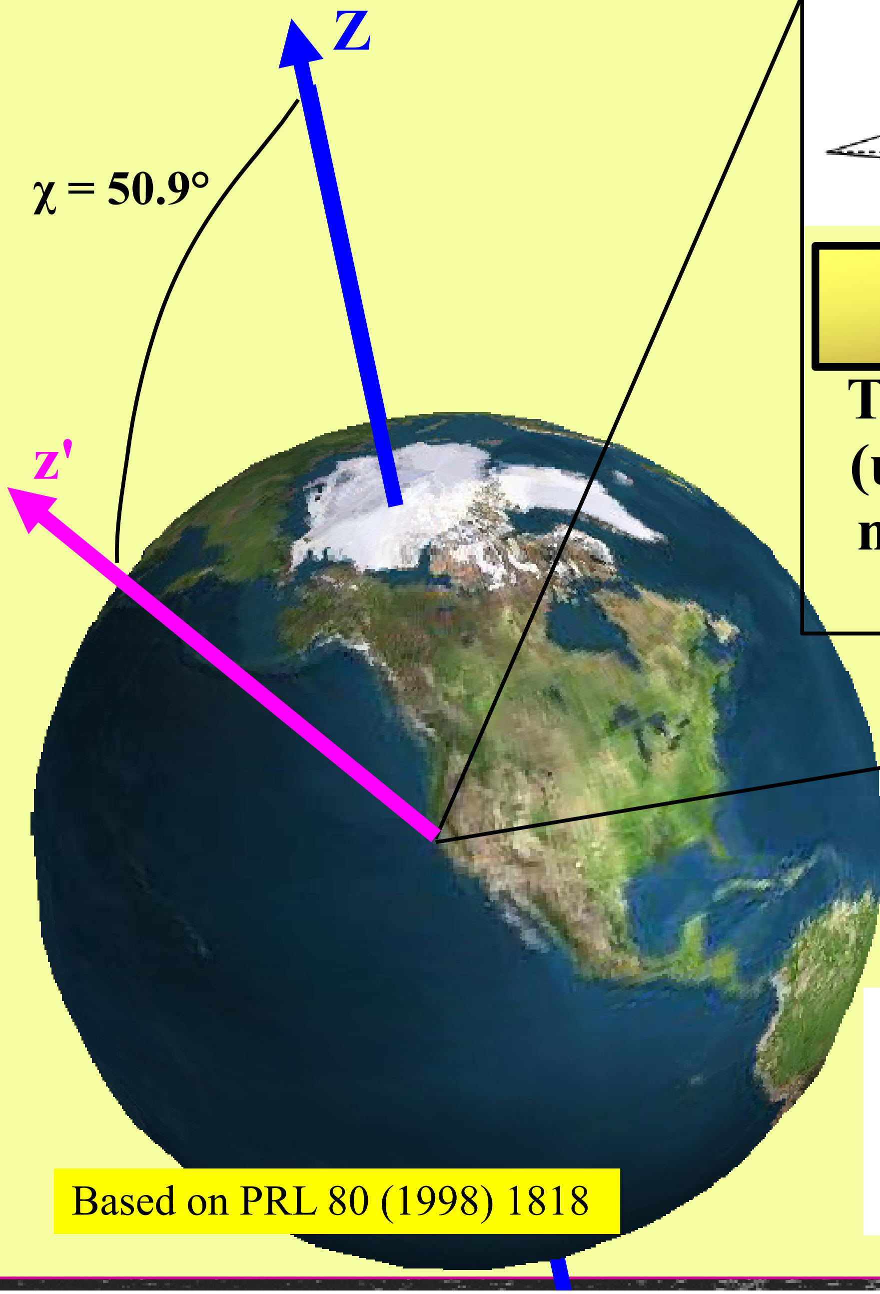
Results for Υ(3S) → γ + Invisible

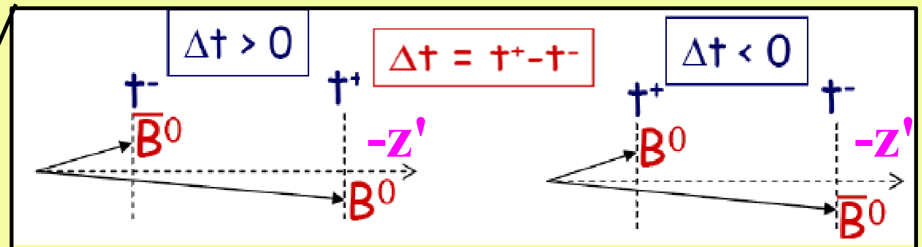


BaBar Preliminary Result:
arXiv:0808.0017 [hep-ex]



CPT Invariance





$$Prob\left(B^0 \to B^0\right)\left(|\Delta t|\right) = Prob\left(\overline{B}^0 \to \overline{B}^0\right)\left(|\Delta t|\right)$$

Required by CPT Invariance

Test CPT invariance of B-mixing (using dileptons) by studying the mixing asymmetry as a function of the sidereal day.

Measure $A_{CP/CPT}(|\Delta t|) =$

$$\frac{Prob(\overline{B}^0 \to \overline{B}^0)(|\Delta t|) - Prob(B^0 \to B^0)(|\Delta t|)}{Prob(\overline{B}^0 \to \overline{B}^0)(|\Delta t|) + Prob(B^0 \to B^0)(|\Delta t|)}$$

$$\frac{N(\ell^+,\ell^-)(\Delta t < 0) - N(\ell^+,\ell^-)(\Delta t > 0)}{N(\ell^+,\ell^-)(\Delta t < 0) + N(\ell^+,\ell^-)(\Delta t > 0)}$$

Based on PRL 80 (1998) 1818

Results

$$|B_L> \;= p\sqrt{1-z}\,|B^0> \;+ q\sqrt{1+z}\,|\overline{B}^0>$$

$$|B_H> \;= p\sqrt{1+z}\,|B^0> \;- q\sqrt{1-z}\,|\overline{B}^0>$$

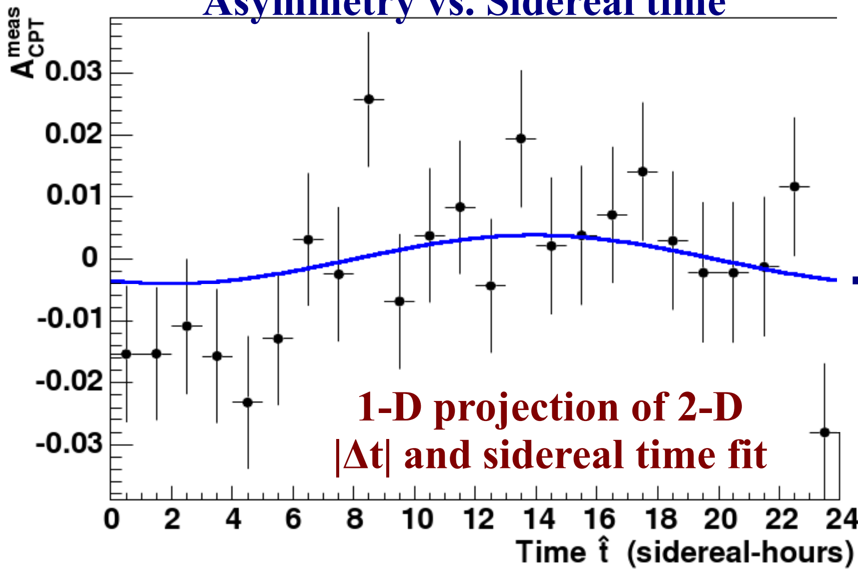
$A_{CP/CPT}$ Measures:

$$z = \frac{\beta^{\mu}\Delta a_{\mu}}{\Delta m - i\Delta\Delta/2}$$

Interpretation of measurement

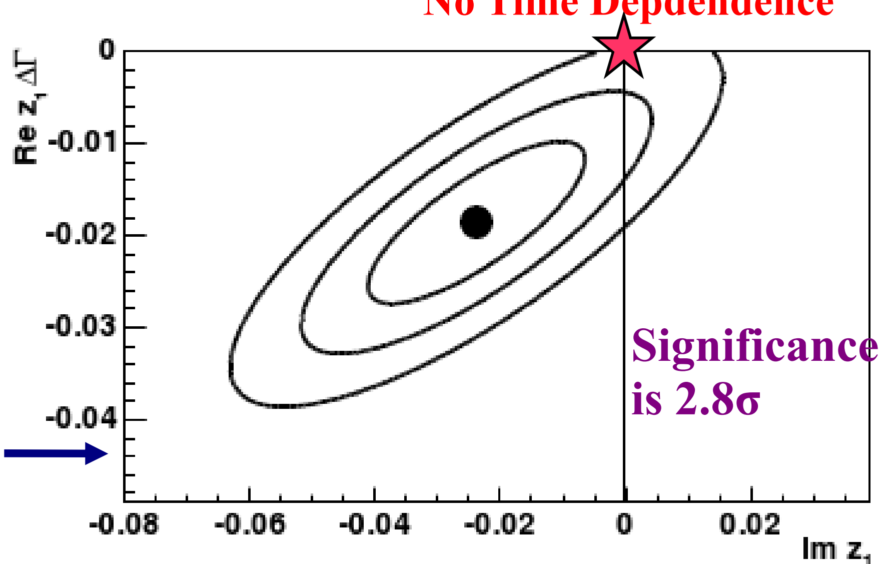
$$\Delta\Gamma \times \mathrm{Re}(z) = \Delta\Gamma \times \mathrm{Re}(z)_0 + \Delta\Gamma \times \mathrm{Re}(z)_1 \cos(\Omega T + \varphi_r)$$
$$\mathrm{Im}(z) = \mathrm{Im}(z)_0 + \mathrm{Im}(z)_1 \cos(\Omega T + \varphi_i)$$

Asymmetry vs. Sidereal time



1-D projection of 2-D |Δt| and sidereal time fit

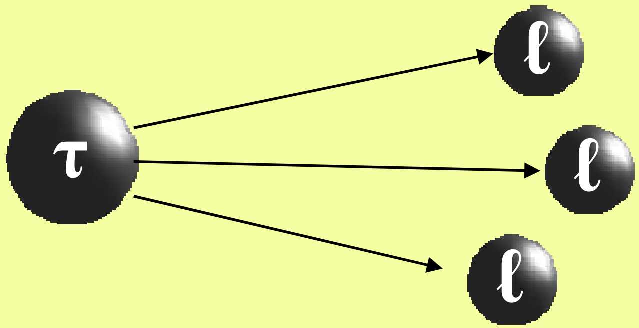
No Time Depdendence



Significance is 2.8σ

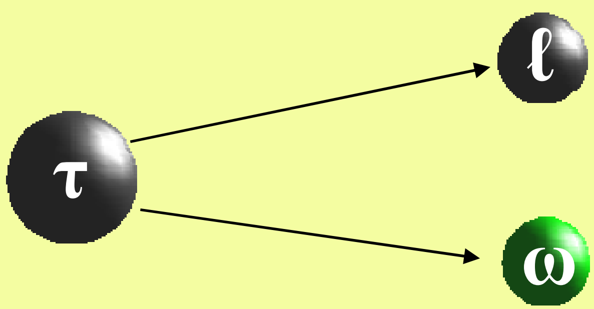
PRL 100:131802,2008.

Recent BaBar Searches for LFV: $\tau\to 3\ell$ and $\tau\to\ell\omega$



Search for tri-lepton final states with 6 distinct combinations of electrons and muons

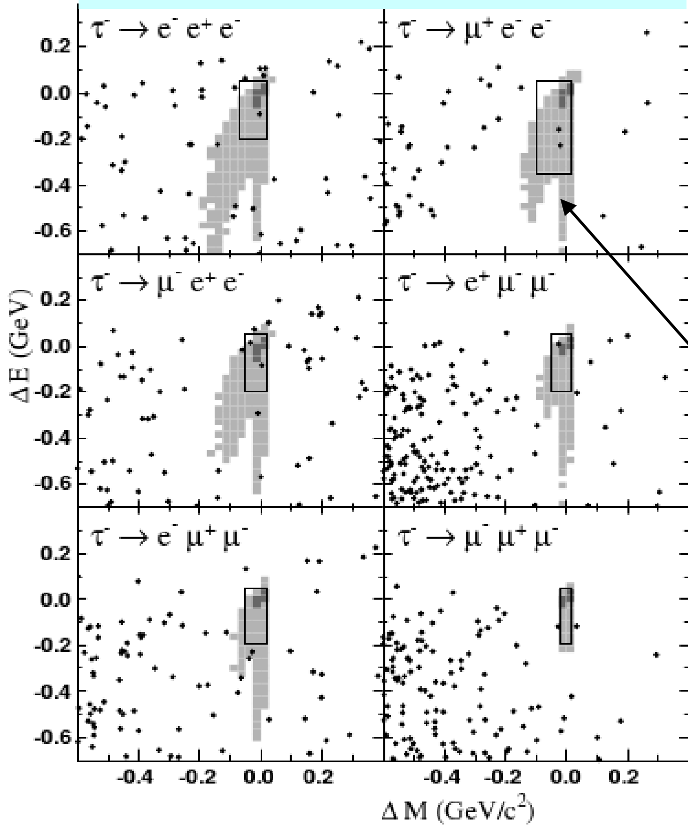
	$\mathcal{B}(\tau\to\ell\ell\ell)$
SM+ν-mixing (PRL95(2005)41802,EPJC8(1999)513)	10^{-14}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-9}
MSSM+seesaw (PRD66 (2002) 057301) $\mathcal{B}(\tau\to\mu\gamma):\mathcal{B}(\tau\to\mu\mu\mu):\mathcal{B}(\tau\to\mu\eta)$ = 1.5 : 1 : 8.4	

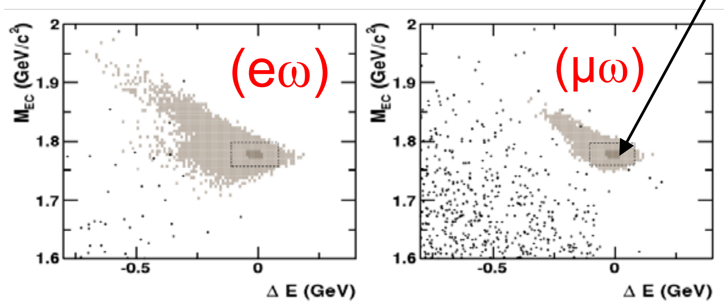


Search for $\tau^+\to l^+\omega$ (using electron and muon final states and $\omega\to\pi^+\pi^-\pi^0$). Observation of either is an unambiguous sign of new physics.

LFV Results

~350 Million τ-pairs





Event Selection: "1-prong" +

(3ℓ)	(ℓω)
$\Delta E = E^*_{Rec} - E^*_\tau$	ΔE
$\Delta M = M_{rec.} - m_\tau$	m_{EC}: τ mass with the τ energy constrained to $E_{beam}/2$

Expect ~1 bkg. event per channel
Signal efficiency is 2-10% per channel.
Results consistent with background

broad shaded area indicates regions containing 90% of signal events

We find no evidence for these decays
90% CL upper limits:
$(4\text{-}8)\times10^{-8}$ (3ℓ)
and
1×10^{-7} (ℓω)

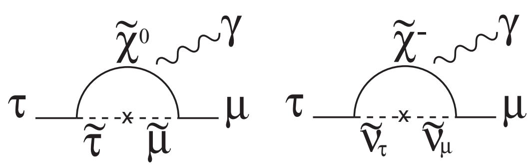
PRL 100:071802,2008

PRL 99:251803,2007

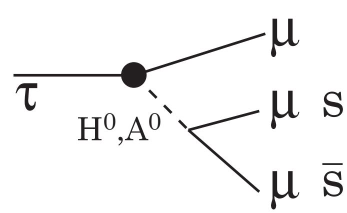
Lepton Flavor Violation in τ Decay

- **Forbidden in SM but various new physics models predict $\mathcal{B}$ as high as 10^{-8}**

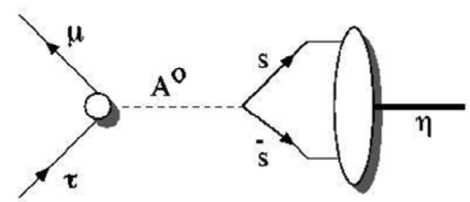
SUSY

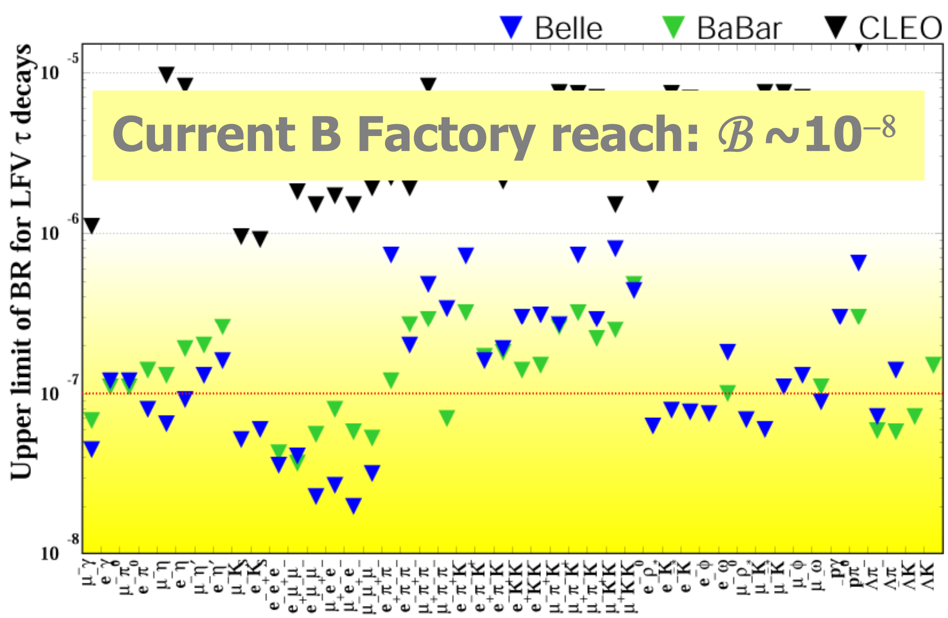


SUSY Higgs

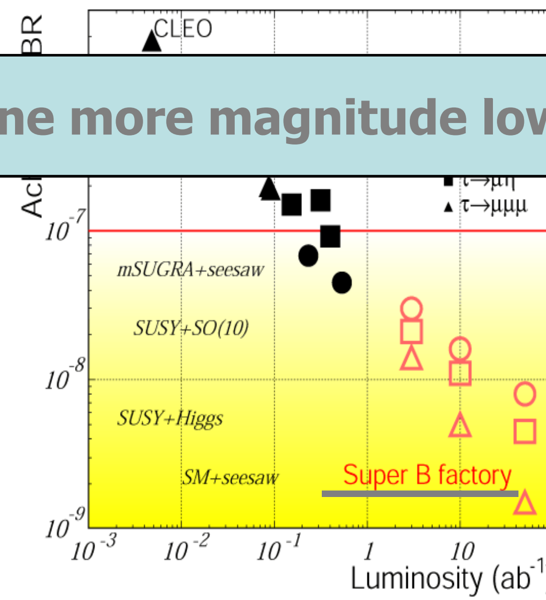


MSSM





Current B Factory reach: $\mathcal{B} \sim 10^{-8}$



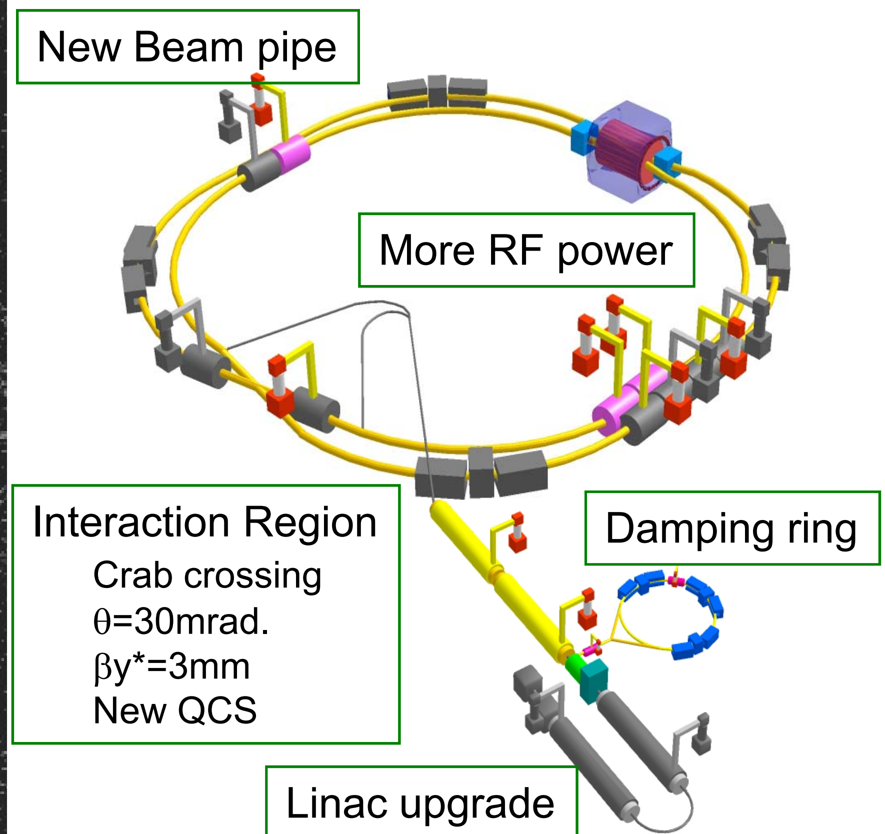
one more magnitude lower

Part 4: Where do we go from here?

Where do we go from here?

- BaBar is complete
- Belle
  - Start Y(5S) run (+ some 2S)
  - Shutdown for upgrade
- CLEO-c is complete
- Tevatron
  - 8 fb^{-1} (2009)
- The near term future will be in Europe: LHCb
- Will there be a new accelerator dedicated to heavy flavor physics?

LHCb is waiting for data



KEK

$L = 4\times10^{35}/cm^2\ /sec$

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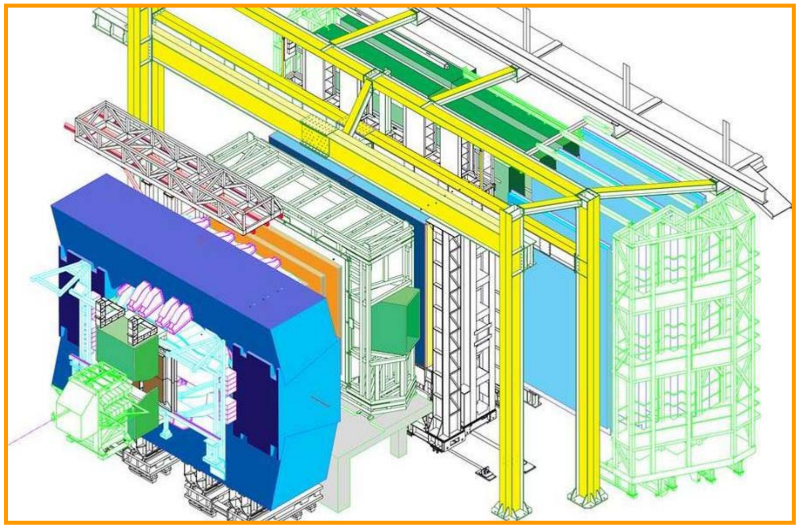
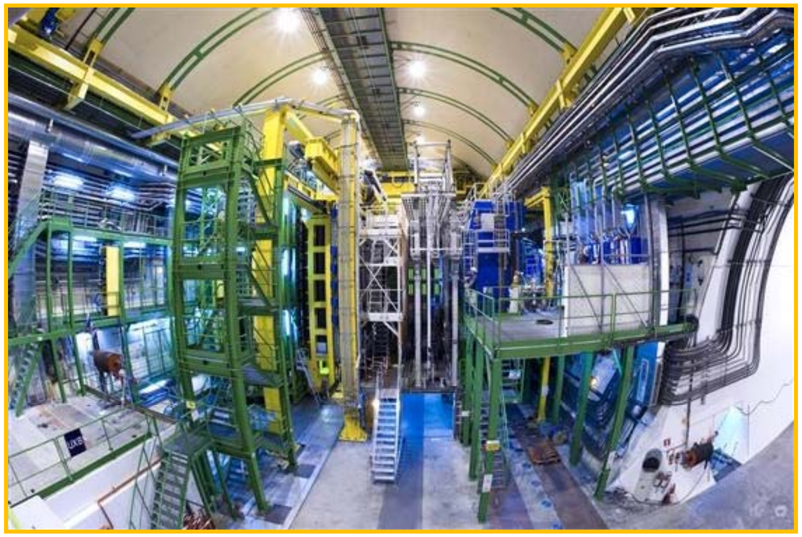




If we had 50 times more data...

With 75 ab^{-1} of data we could ask:

Are there new *CP*-violating phases in *b,c* or τ decay ?

Are there new right-handed currents ?

Are there new loop contributions to flavor-changing neutral currents

Are there new Higgs fields ?

Is there lepton flavor violation?

Is there new flavor symmetry that elucidates the CKM hierarchy ?

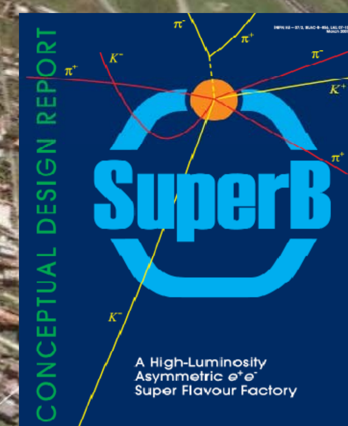
Site of the proposed Super-B Factory in Italy

Campus of Tor Vergata University in Rome

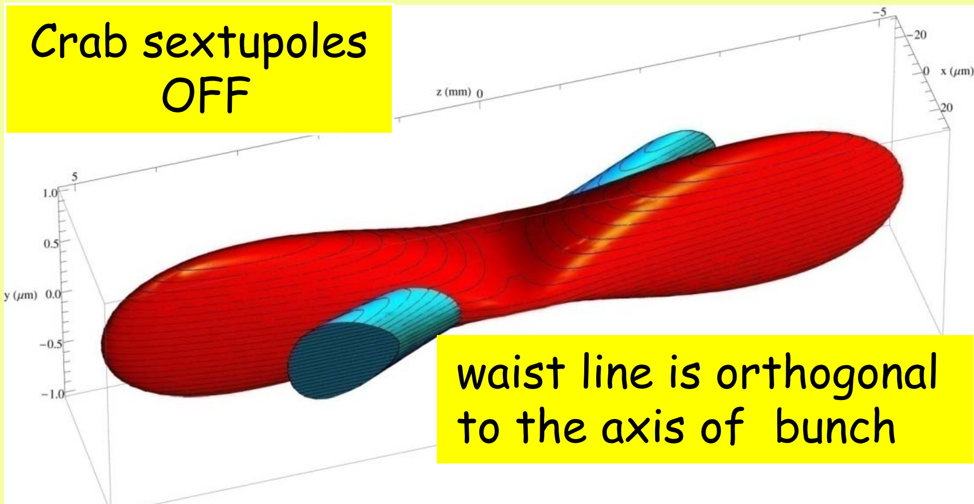
Site of the proposed Super-B Factory in Italy

Campus of Tor Vergata University in Rome

- Very high initial luminosity, 10^{36}
- It is asymmetric : 4 on 7 GeV
- Ring magnets, RF, vacuum componens can reused from PEP-II
- Reuse BaBar magnet, CsI as the basis for an upgraded detector
- Polarized beams possible
- Flexible design: Υ region, charm & tau threshold regions
- Time scales
  - European Roadmap process (2008-2009) (INFN, ECFA, CERN Strategy Group) INFN→Ministry
  - Regione Lazio funded digging the SuperB tunnel!
  - Luminosity in 2015

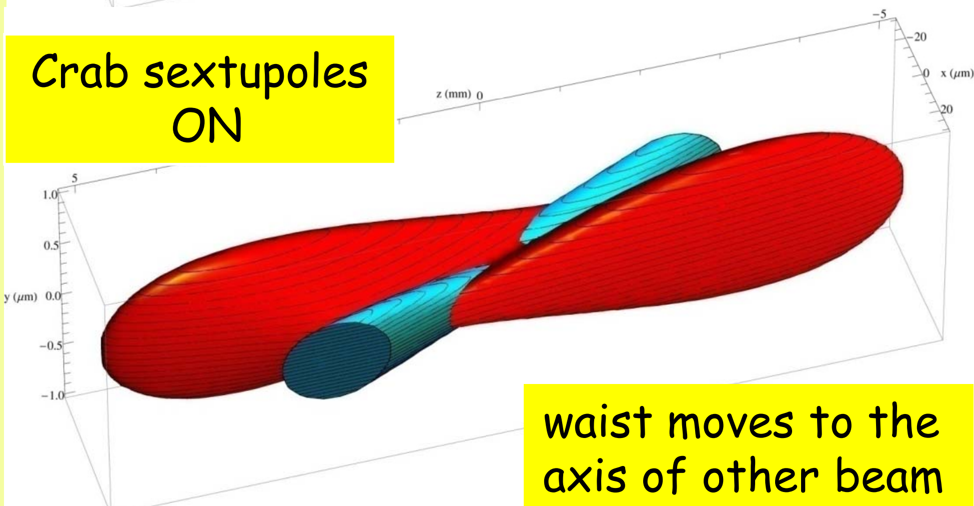


New Design for New Physics



Crab sextupoles OFF

waist line is orthogonal to the axis of bunch

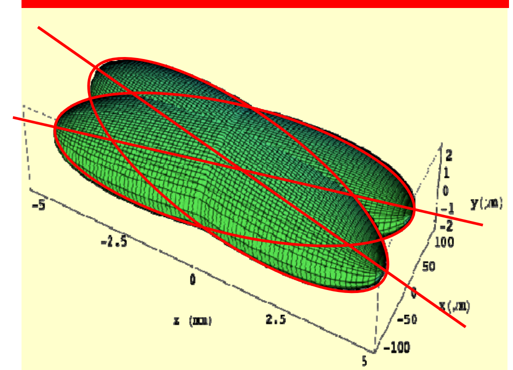


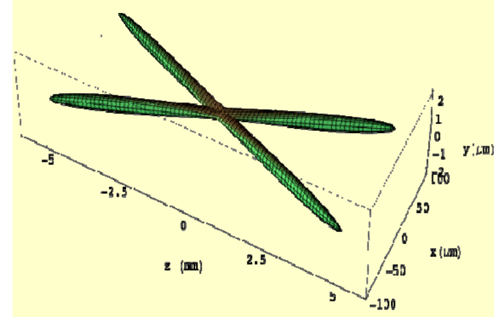
Crab sextupoles ON

waist moves to the axis of other beam

All particles from both beams collide in the minimum β_y region, with a net luminosity gain

IP beam distributions for KEKB





IP beam distributions for Super*B* *(without transparency conditions)*

Summary

- The 2 B-Factories continue to produce a wealth of new physics results
- CP Violation in the B sector is firmly established
- The CKM paradigm is established as the source of CP violation & flavor mixing in the SM

  Wolfenstein parameterization: $\lambda \sim 0.23, A \sim 0.8, \rho \sim 0.2, \eta \sim 0.4$

- Precision measurements of the magnitudes of the CKM elements are now available (experimental uncertainties)
  - $\sigma(|V_{cb}|) \sim$ 2-3%
  - $\sigma(|V_{ub}|) \sim$ 5%
  - $\sigma(|V_{td}|) \sim$ 1-2%
- New upper limits for rare decays as low as 10^{-8}
- We are still looking for that needle in the haystack…