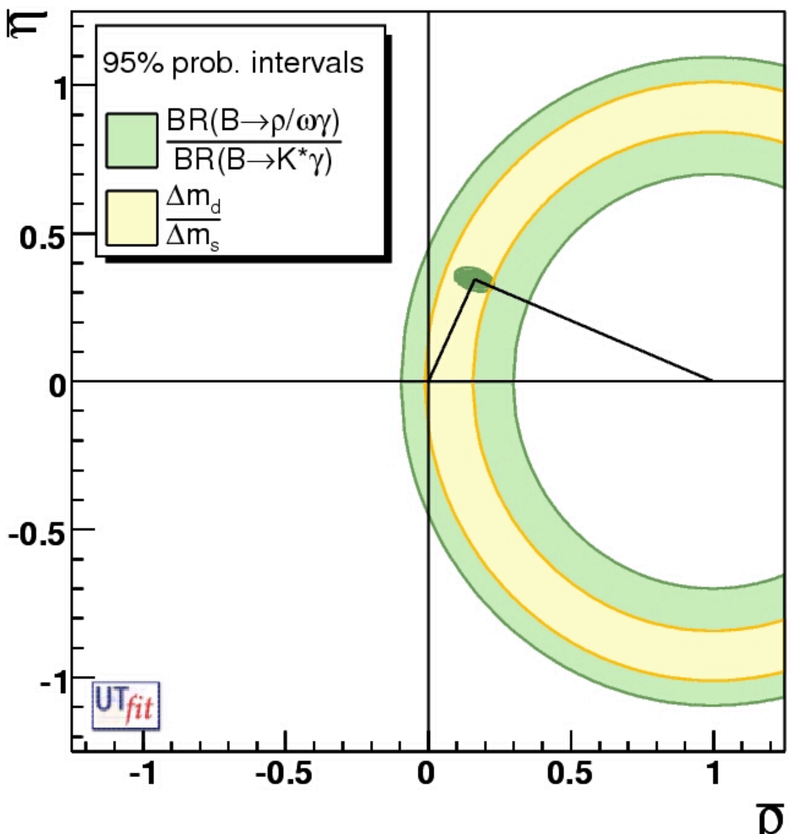
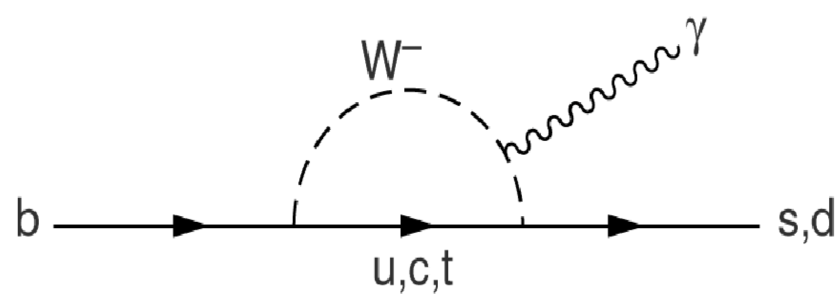
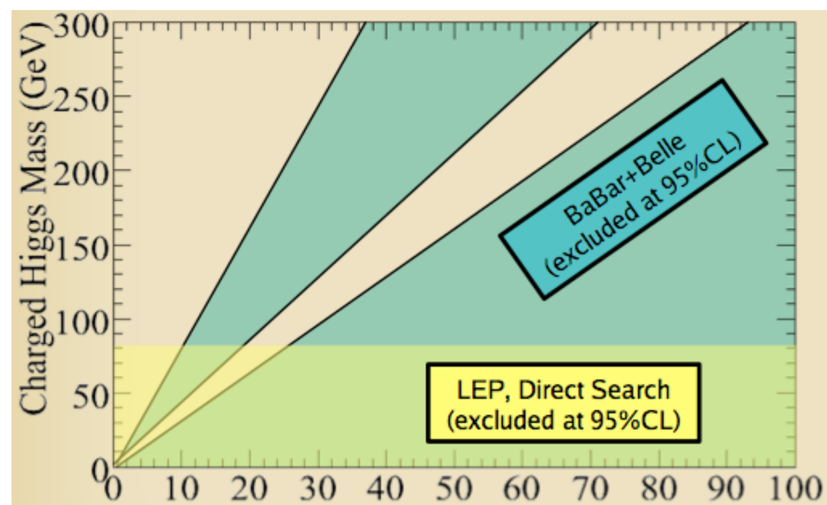
Searching for New Physics in B Decays

Gabriella Sciolla (MIT)







KEK seminar - December 18, 2006

What is "New Physics"

- Standard Model: 1971-present
  - 35 years of success with no major failure
    - Minor failure: neutrinos have mass
- Reasons to believe SM is incomplete
  - Hierarchy problem / Fine tuning…
- Many extensions have been proposed
  - SUSY, Extra dimensions,... $\rightarrow$ New Physics
- The roads to New Physics
  - Direct searches (Tevatron $\rightarrow$LHC)
  - Indirect searches
    - Study of CP violation and rare B decays
    - Electric Dipole Moment
    - g-2,…

Outline

- Constraints on New Physics from CP violation
  - CP violation in the Standard Model
    - Why should we expect New Physics?
  - The beauty of the Unitarity Triangle
    - Measurements of angles
    - Measurements of sides

      ** New measurement of R_t in $B \to \rho\gamma$ from BaBar**

      (submitted to PRL last week)

- Constraints to New Physics from rare B decays
  - Example: $B \to \tau\nu$ and $B \to s\gamma$

- Summary and conclusion

CP violation

- What is CP?

$$CP = C \times P$$

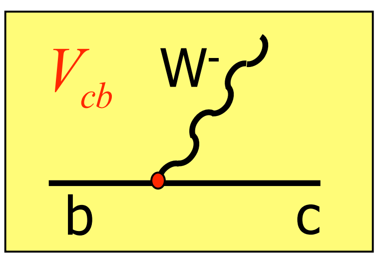
C: Charge Conjugation Particle → Anti-particle	P: Parity Inverts space coordinates

- Why is CP violation interesting?
  - Crucial ingredient to explain the matter-dominated universe
    - A. Sakharov (1967)
  - Measures two fundamental parameters of Standard Model
    - ρ and η
  - May hold the key to uncover the first signs of New Physics
    - e.g.: MSSM has 43 new CP violating phases!

CP violation in the Standard Model

- Discovered by Fitch and Cronin in 1964 in K_L decays
- Introduced in Standard Model in 1973 by Kobayashi and Maskawa
- In KM mechanism, CP violation originates from a <u>complex phase</u> in the quark mixing matrix (CKM matrix)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^6)$$



A,λ (Cabibbo angle): very well measured
ρ,η: poorly known until recently

Going beyond CKM

The (many) strengths of CKM

- ✓ Simple explanation of CPV in SM
- ✓ It is very predictive: only one CPV phase
- ✓ It accommodates all experimental results
  - Indirect CP violation in $K \rightarrow \pi\pi$ and $K_L \rightarrow \pi l \nu$
  - Direct CP violation in $K \rightarrow \pi\pi$
  - CP violation in the B system

New Physics models have several sources of CP violation

- Exploit CKM prediction power -->use CPV as probe for New Physics

Measure CP violation in channels <u>theoretically well understood</u> and look for deviations w.r.t. SM expectations

The Unitarity Triangle

Unitarity of CKM implies: $V^{\dagger}V = 1$ → 6 unitarity conditions

Of particular interest:

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

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

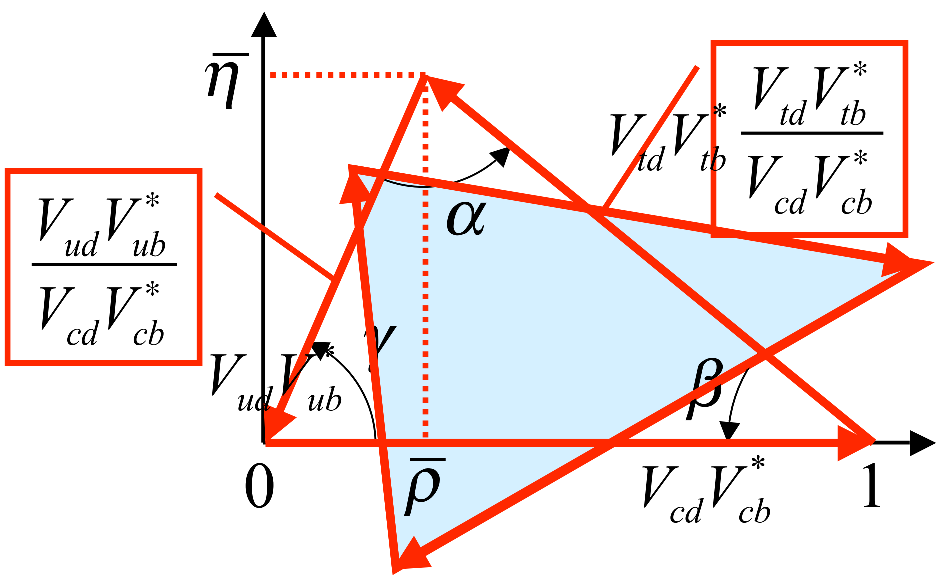
All sides are ~ O(1) → possible to measure both sides and angles!

- CP asymmetries in B meson decays measure α, β and γ
- Sides from semileptonic B decays, B mixing, rare B decays

The Unitarity Triangle

Unitarity of CKM implies: $V^{\dagger}V = 1$ → 6 unitarity conditions

Of particular interest: $$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



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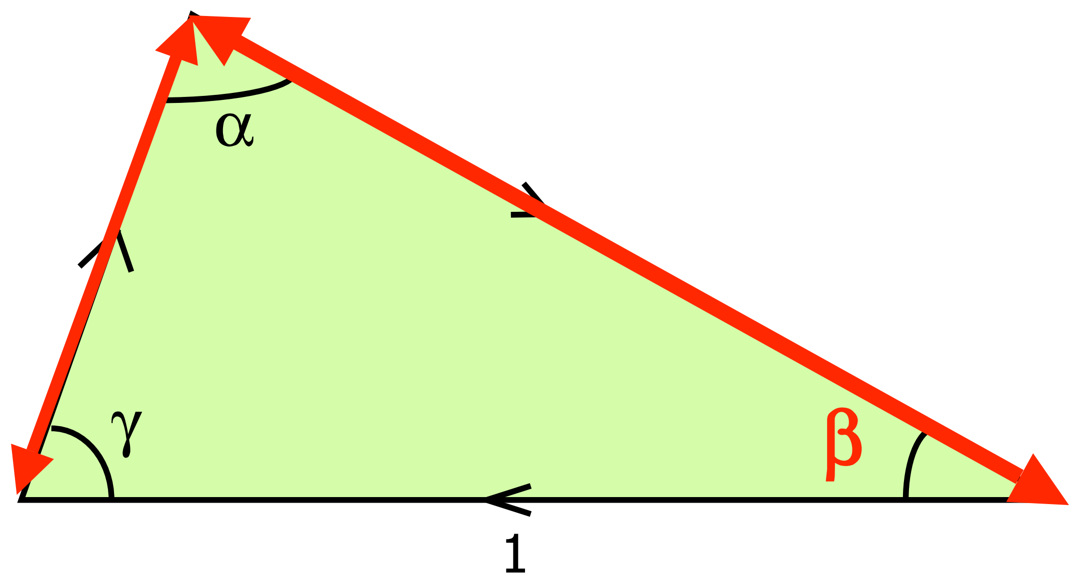
Standard Model parameters (ρ,η)

To precisely determine the parameters of the Standard Model (ρ,η), all we need is a precise measurement of 2 quantities, e.g.: 2 sides.



But additional measurement are essential to look for New Physics

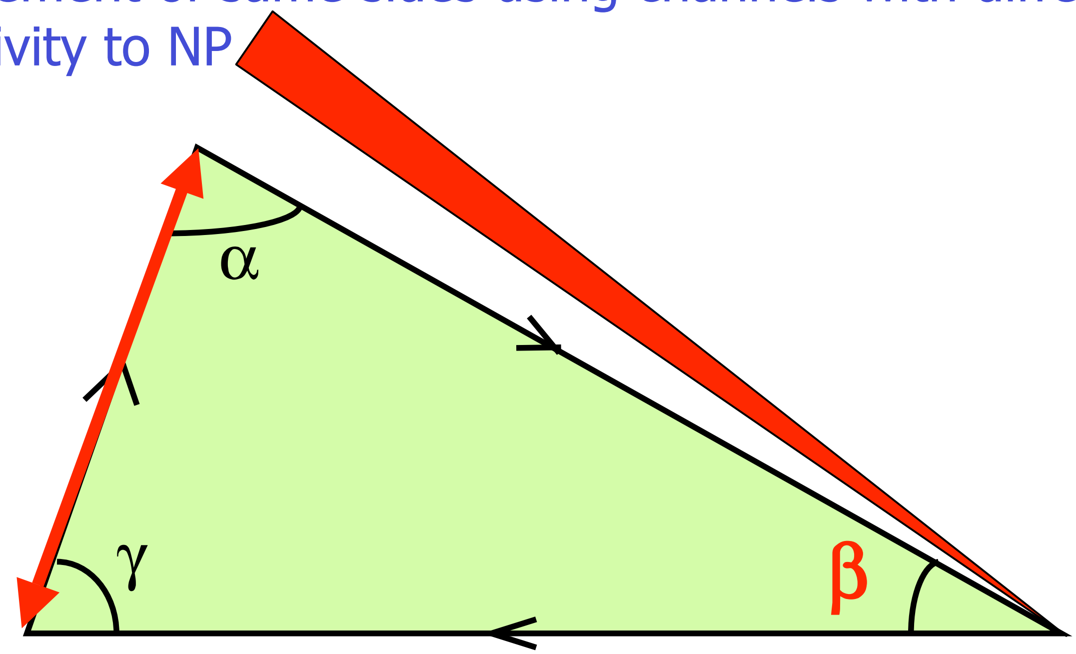
Redundancy, redundancy, redundancy!

3 ways to look for New Physics:

a) Sides vs angles

b) Measurement of same angle using channels with different sensitivity to NP

c) Measurement of same sides using channels with different sensitivity to NP



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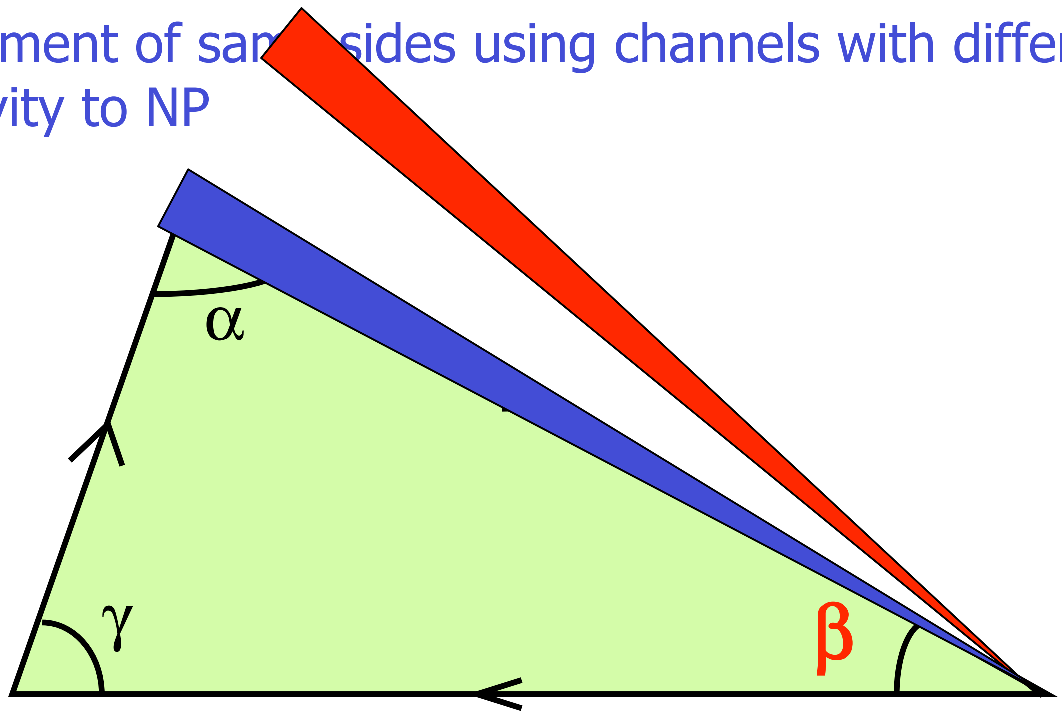

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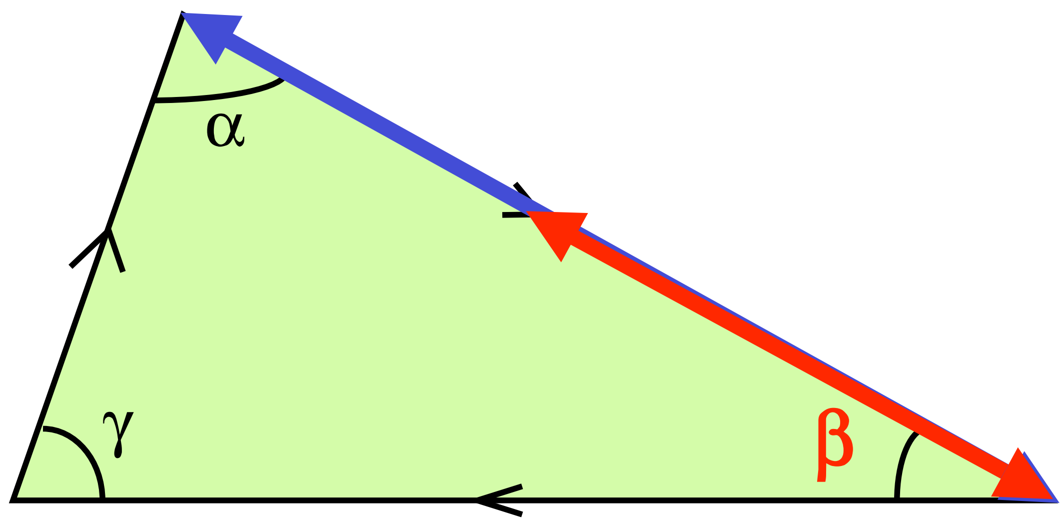
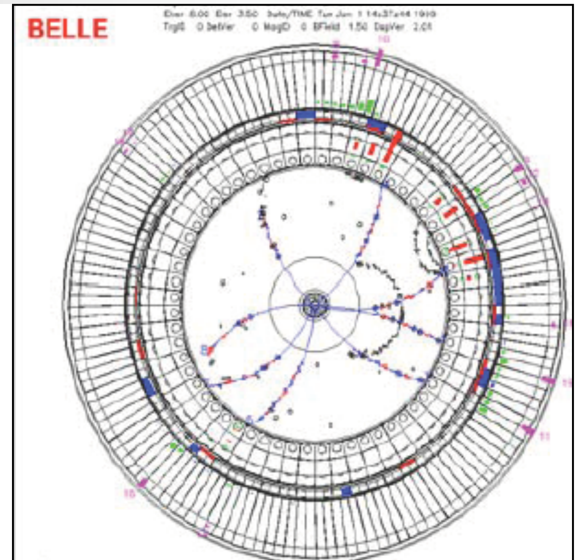
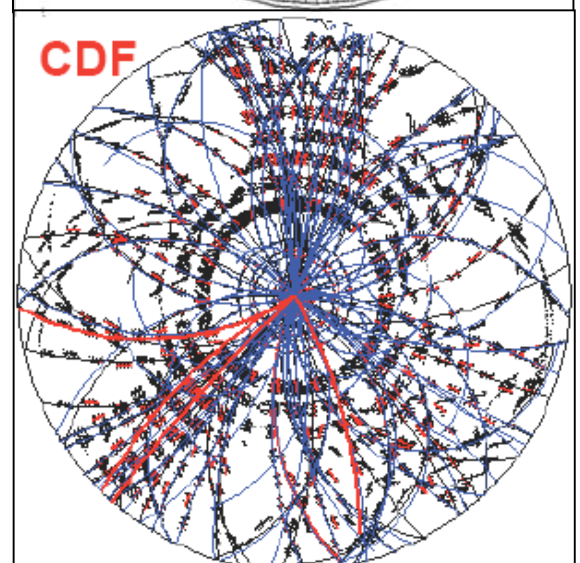


The experiments:

B factories vs Tevatron

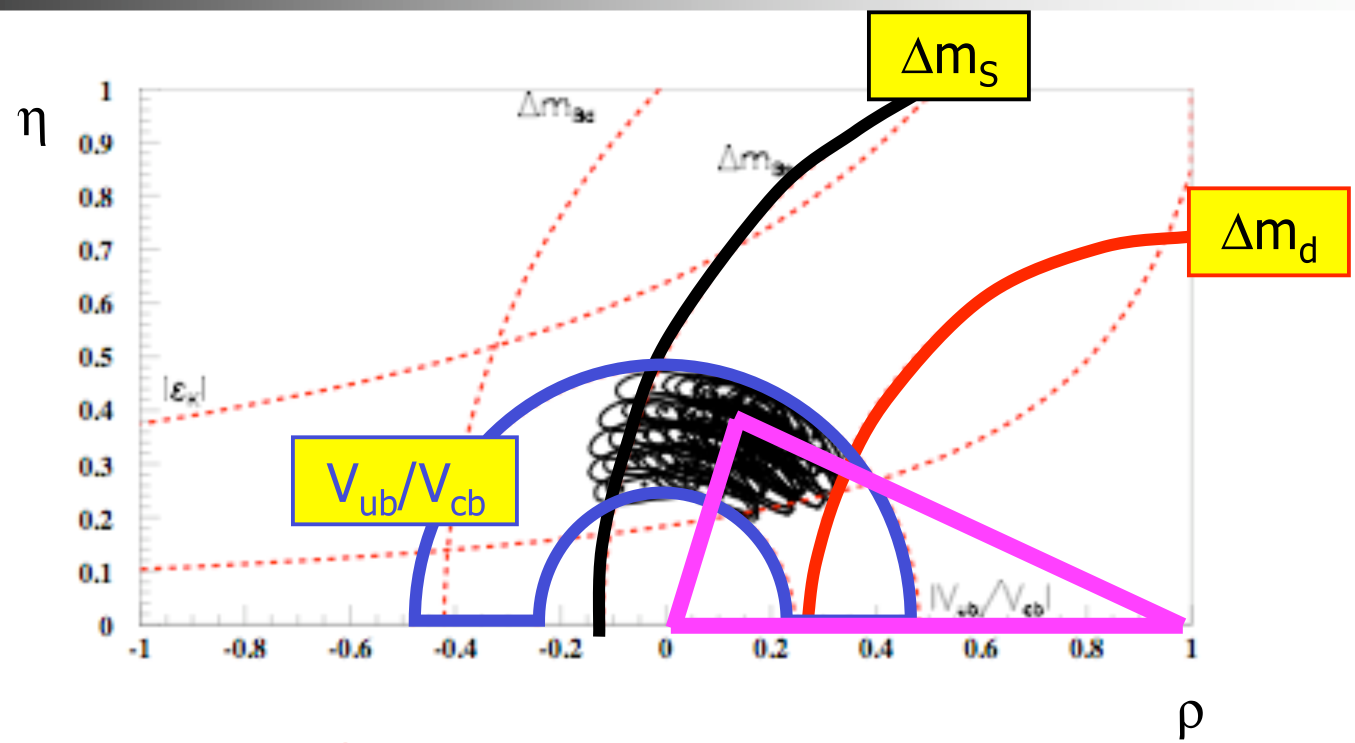
	B factories	Tevatron
Experiments	BaBar at SLAC Belle at KEK	D0 and CDF $p\bar{p}$ @ $\sqrt{s} \sim 2$ TeV
Trigger	$\sigma_{b\bar{b}} : \sigma_{q\bar{q}} \sim 1:4$	$\sigma_{b\bar{b}} : \sigma_{inelastic} \sim 1:10^3$
Multiplicity	$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$	High!
Luminosity	L > 10^{34} $cm^{-2}s^{-1}$ 400/700 fb^{-1} (BaBar/Belle)	L~10^{32} $cm^{-2}s^{-1}$ high x-sections →high rates
B hadrons	B^0,B^+ with $\beta\gamma$~0.5	B_S , Λ_b , B_C ,...





Complementary capability

The Unitarity Triangle in 1999



3 ways to look for New Physics:

a) Sides vs. angles

b) Angle vs. angle

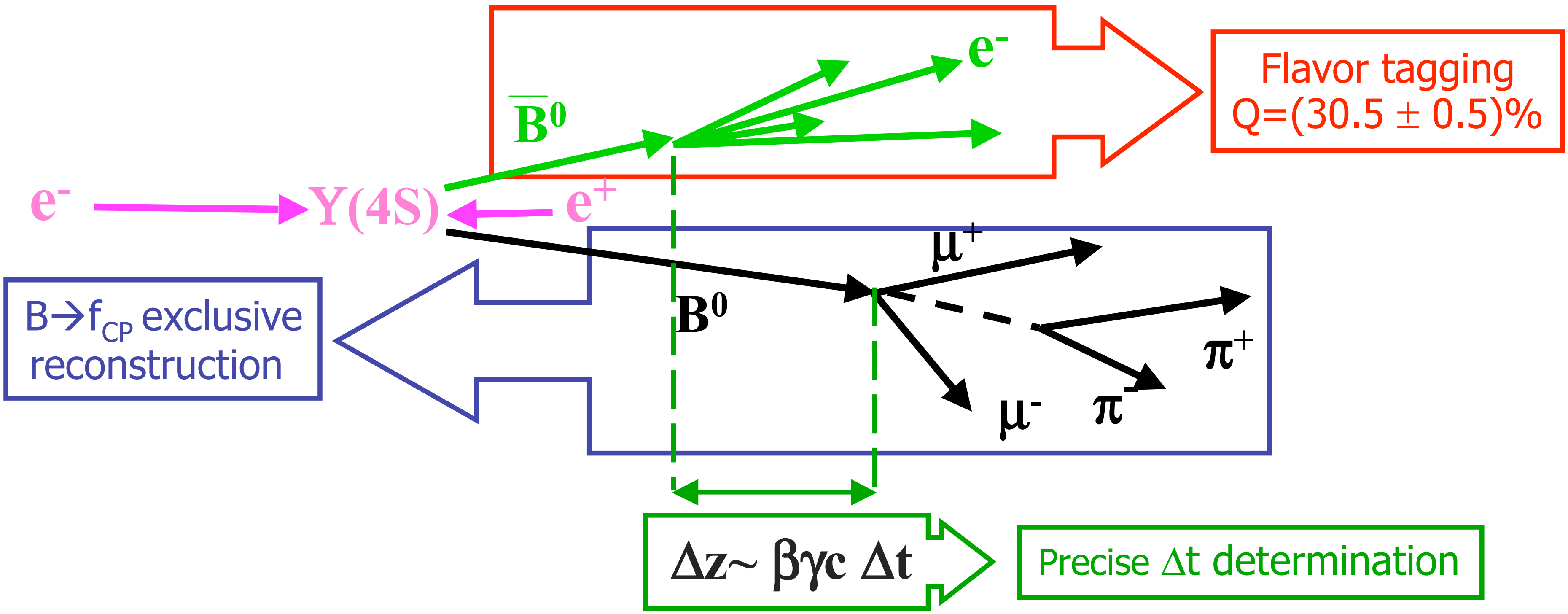
c) Side vs. side

Some measurement of the sides, but no angles!

First goal of the B factories:
measure the angles of UT

Time dependent CP asymmetry:

$$A_{CP}(t) = \frac{N(\overline{B}^0(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\overline{B}^0(t) \to f_{CP}) + N(B^0(t) \to f_{CP})}$$

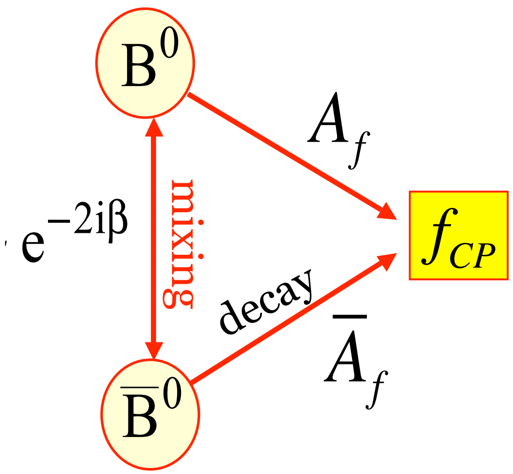


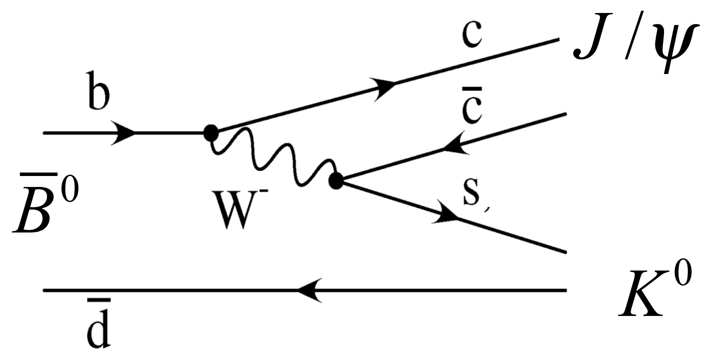
CP violation in B^0 decays: sin2β

For some modes, the amplitude of the $A_{CP}(t)$ is directly and simply related to the angles of the UT

Textbook example: $B^0 \to J/\Psi K_S$

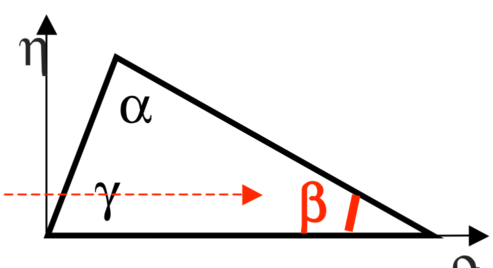
$t = 0$ $\quad t$





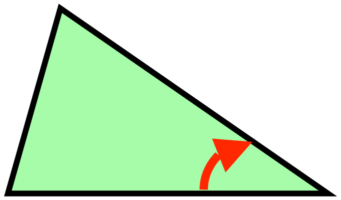
$$\lambda = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)_{B^0_{mix}} \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)_{decay} \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)_{K^0_{mix}} = e^{-i2\beta}$$

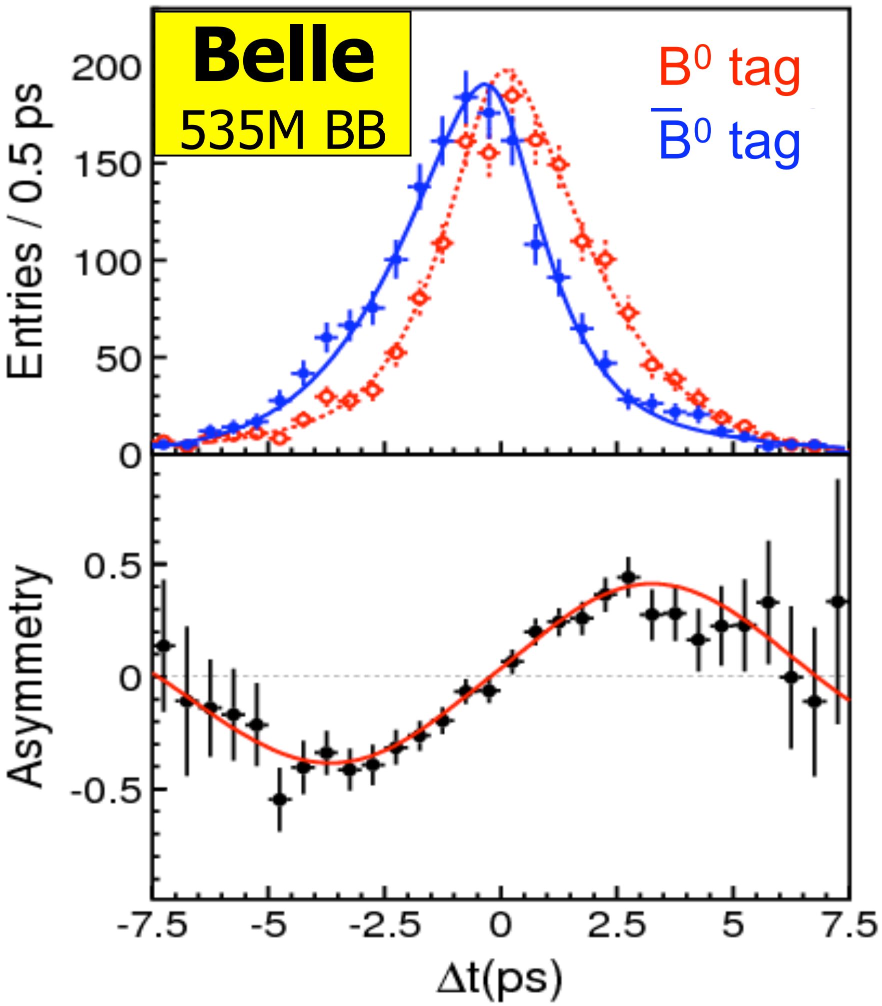
$$A_{CP}(t) = \sin 2\beta \sin \Delta m t$$

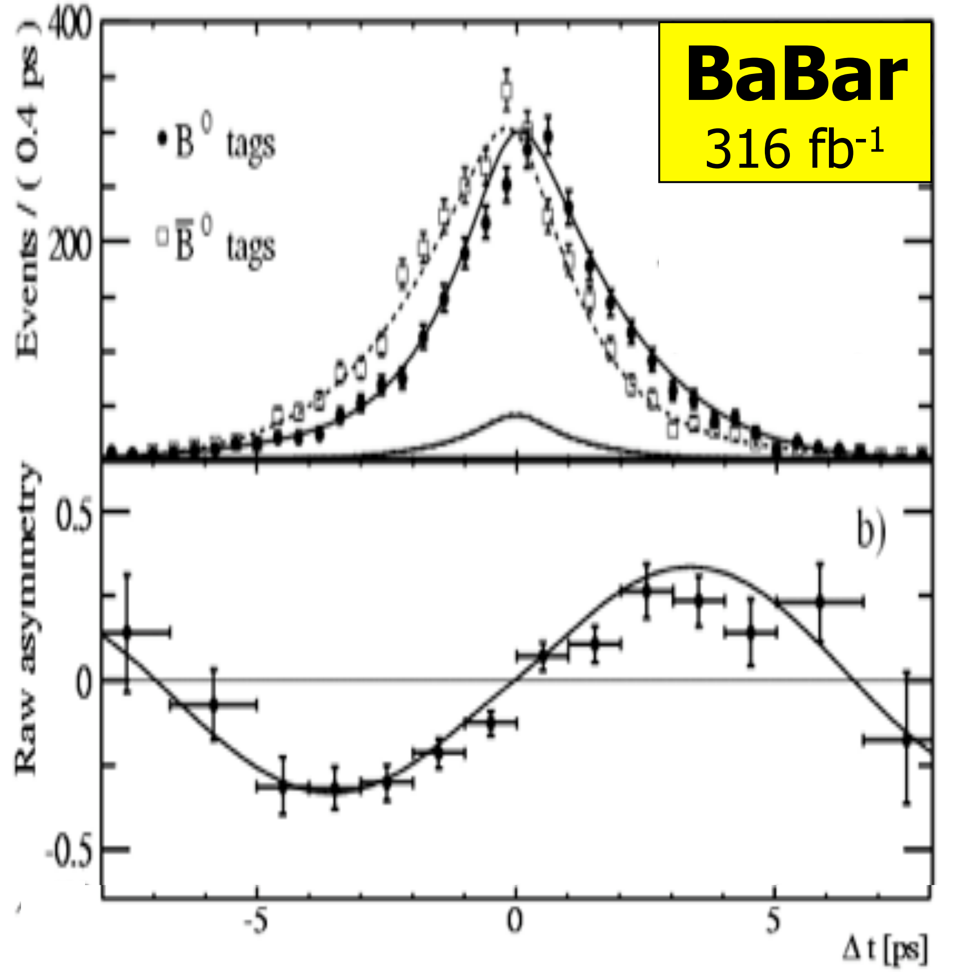


The golden mode for β:

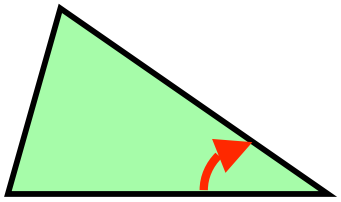
sin2β in $B^0 \rightarrow J/\psi\ K^0$

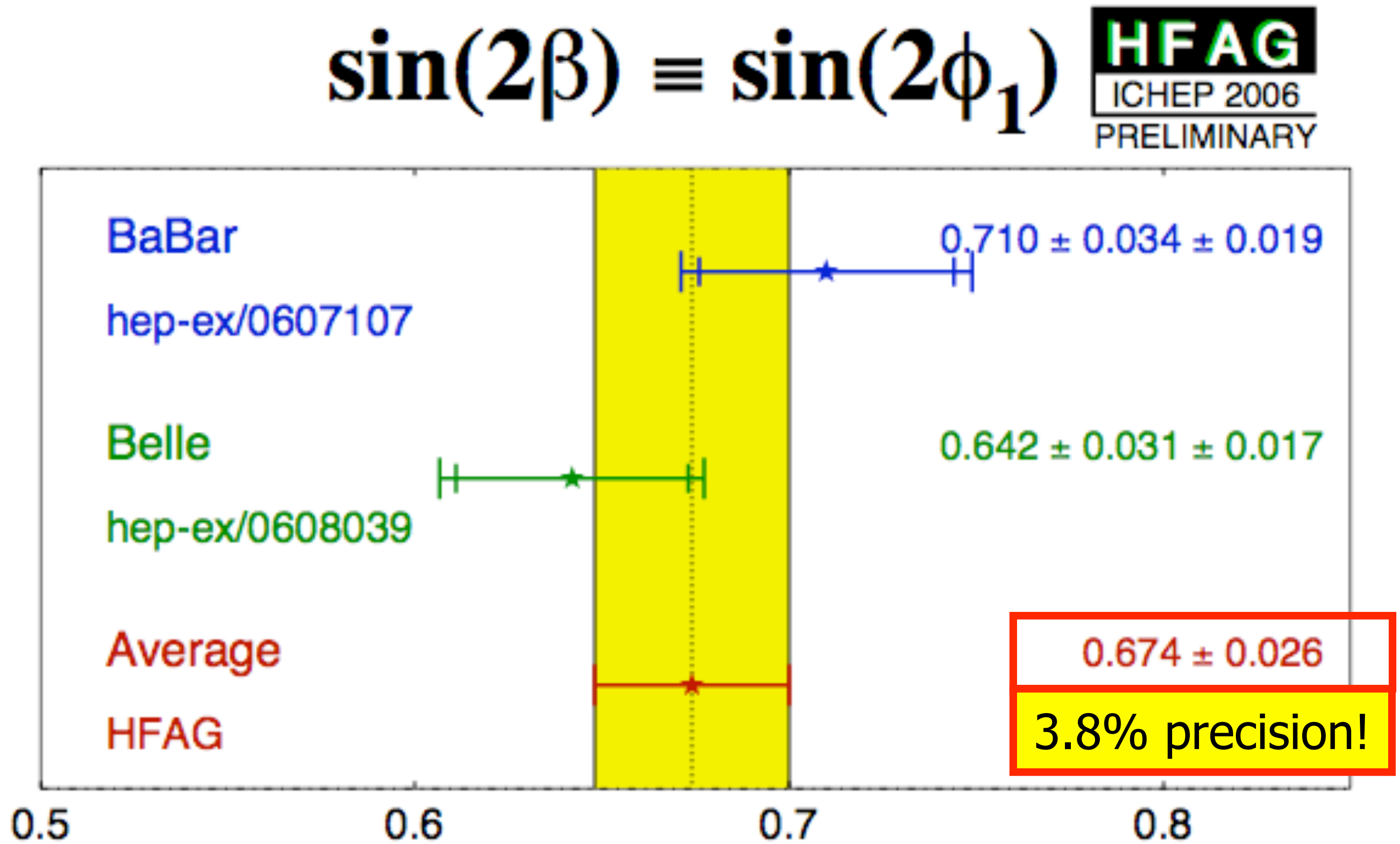




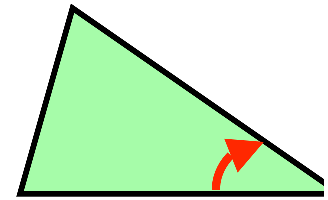


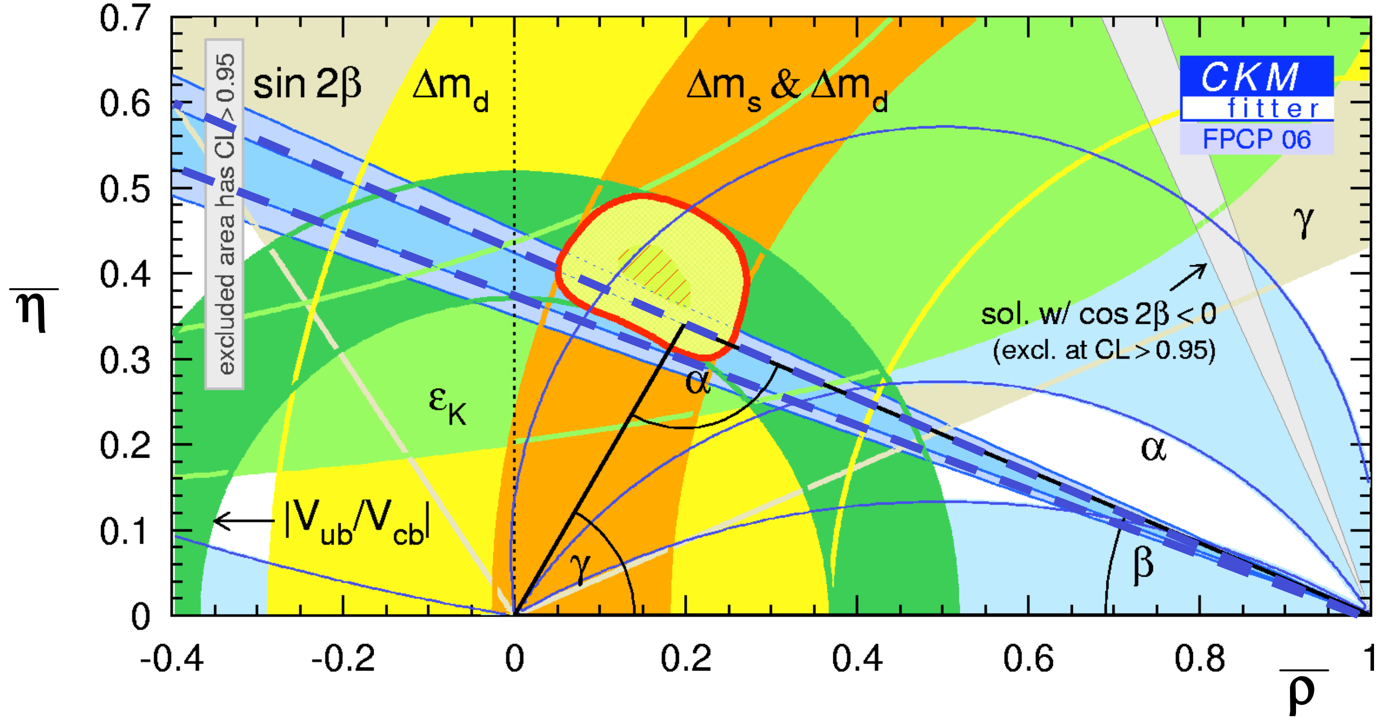
The golden mode for β:
sin2β in $B^0 \rightarrow$ Charmonium K^0

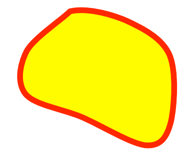




NP test #1: sides vs. angles







95% CL
from "sides"

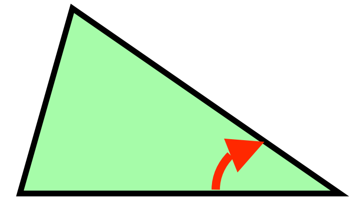
sin2β vs indirect UT constraints: pretty good agreement!

CKM mechanism is the dominant source of CPV at low energies

- New Physics does not show up in the golden mode →SM reference
  - Compare with sin2β in independent modes with different sensitivity to NP

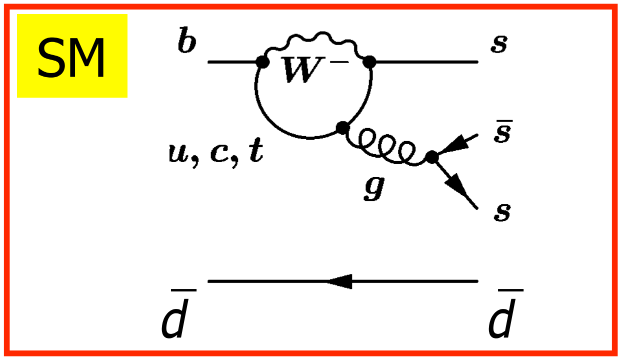
An independent measurement of β:

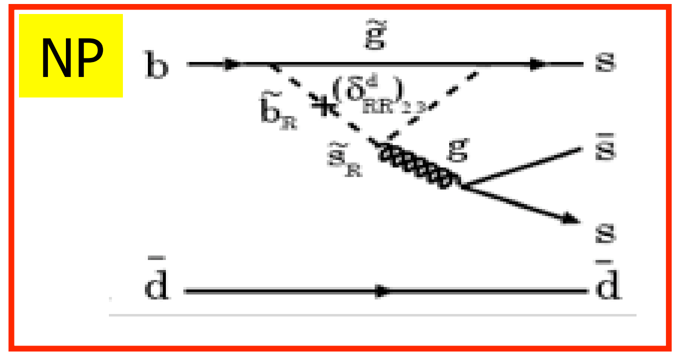
The Penguin Modes



Decays dominated by gluonic penguin diagrams

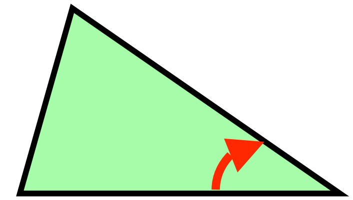
- The typical example: $B^0 \rightarrow \phi K_S$

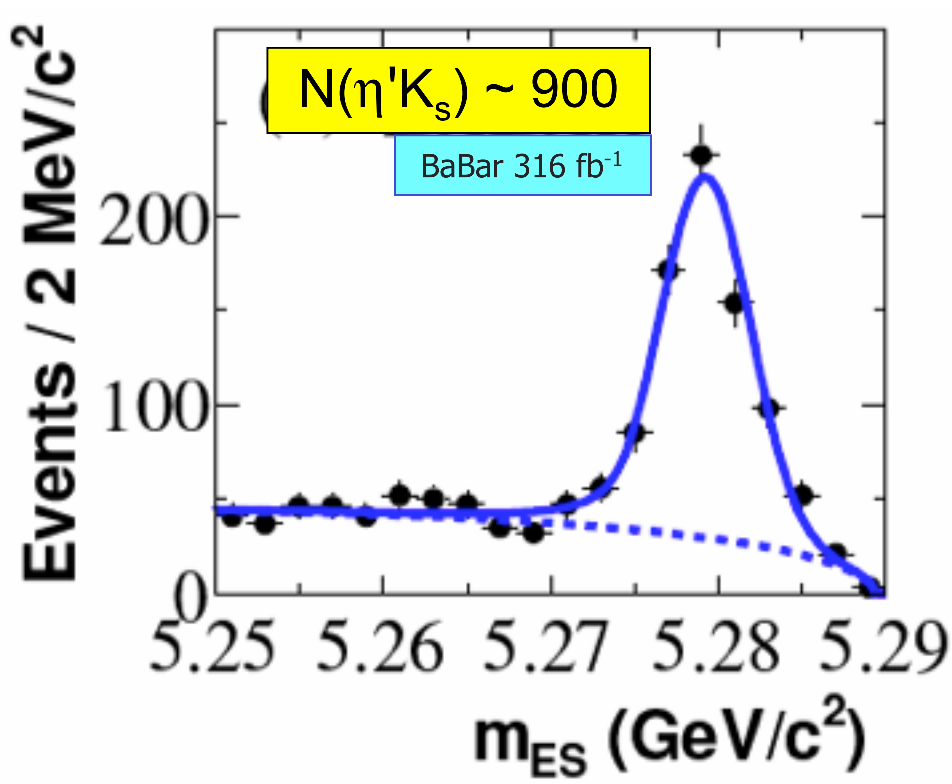


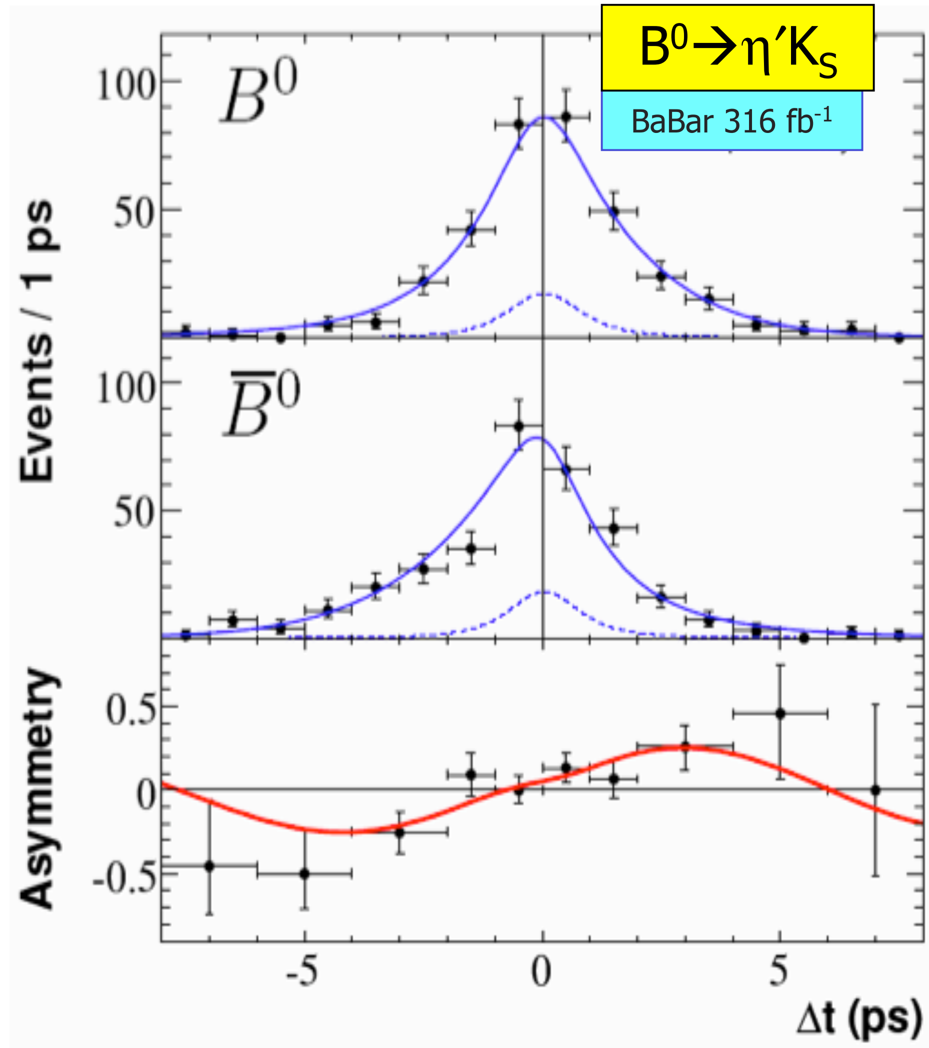


  - No tree level contributions: theoretically clean
  - SM predicts: $A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$
- Impact of New Physics could be significant
  - New particles could participate in the loop → new CPV phases
- Low branching fractions (10^{-5})
  - Measure A_{CP} in as many $b \rightarrow s q\bar{q}$ penguins as possible!
    - φK^0, $K^+ K^- K_S$, $\eta' K_S$, $K_S \pi^0$, $K_S K_S K_S$, ωK_S, $f_0(980) K_S$

The silver penguin: $B^0 \rightarrow \eta' K^0$



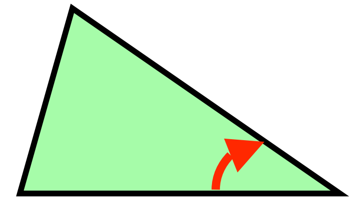


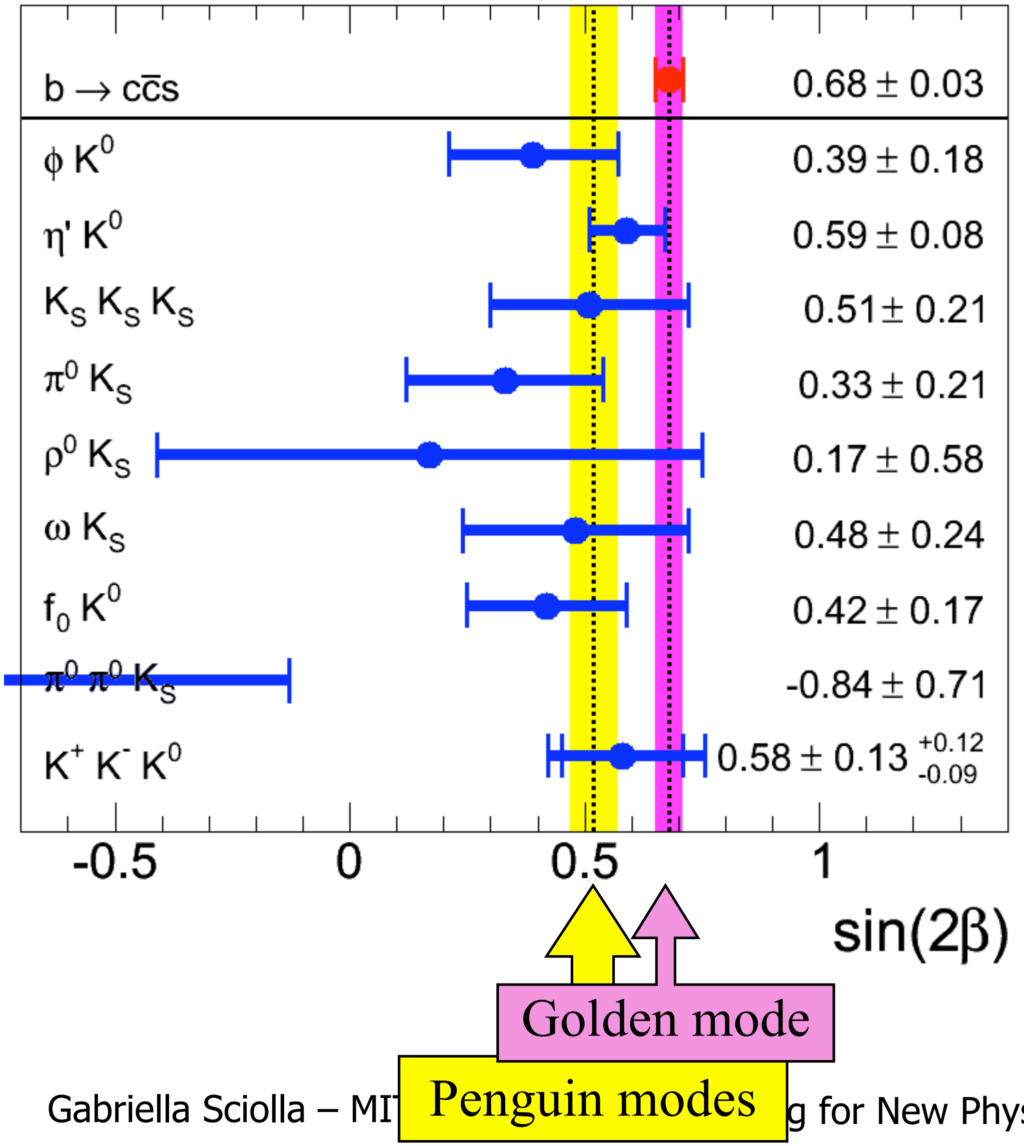


$$S_{\eta' K^0} = 0.55 \pm 0.11 \pm 0.02$$

BaBar 316 fb^{-1}

NP test #2:
β in penguins vs golden mode





BaBar + Belle average

A trend is visible

- although each measurement is compatible with $J/\Psi K_S$…

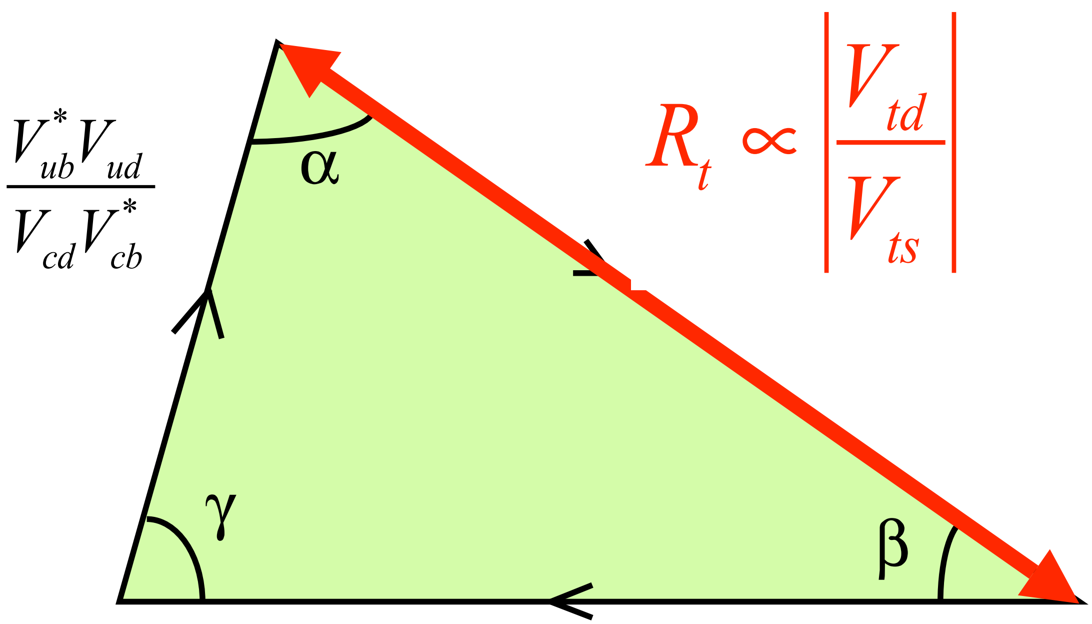
Naïve average: 0.52±0.05

- ~2.6σ

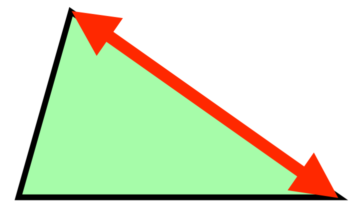
Statistical errors still large…

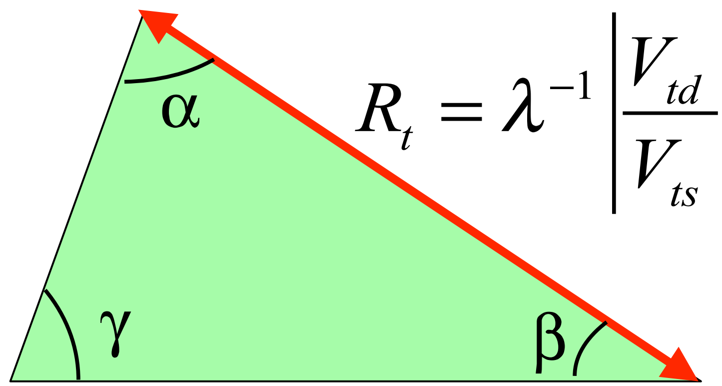
- More statistics will help

NP test #3: sides vs. sides

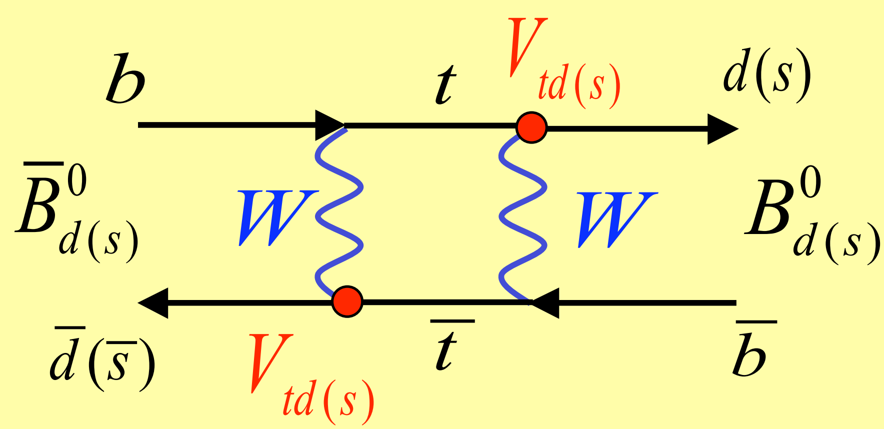


The measurement of R_t





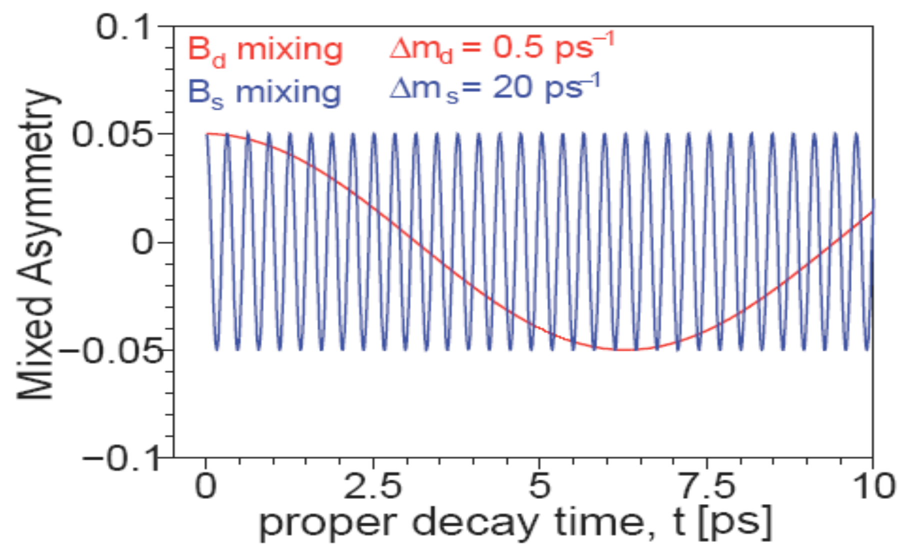
$$R_t = \lambda^{-1}\left|\frac{V_{td}}{V_{ts}}\right|$$



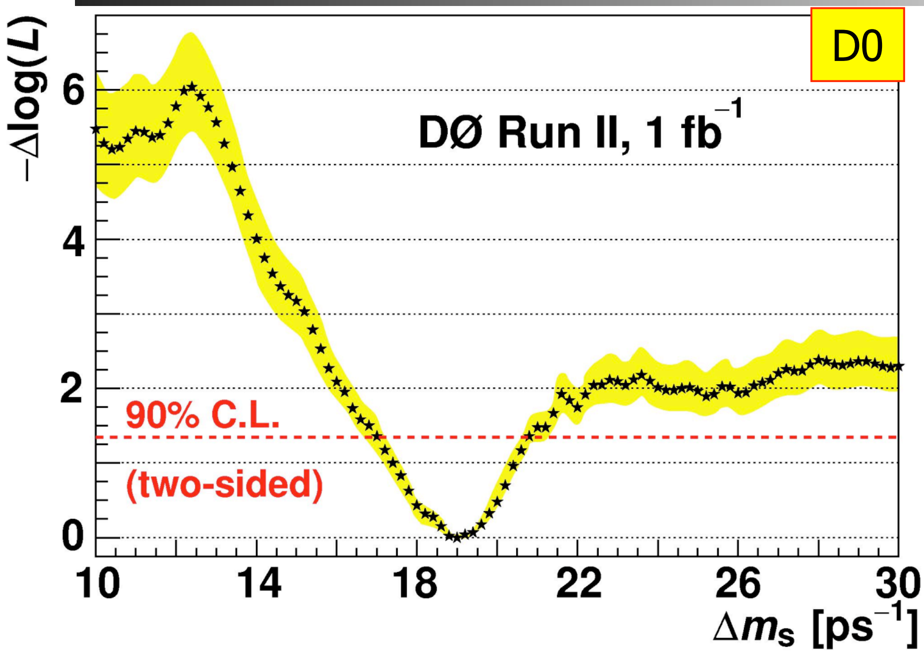
- B_s/B_d oscillations

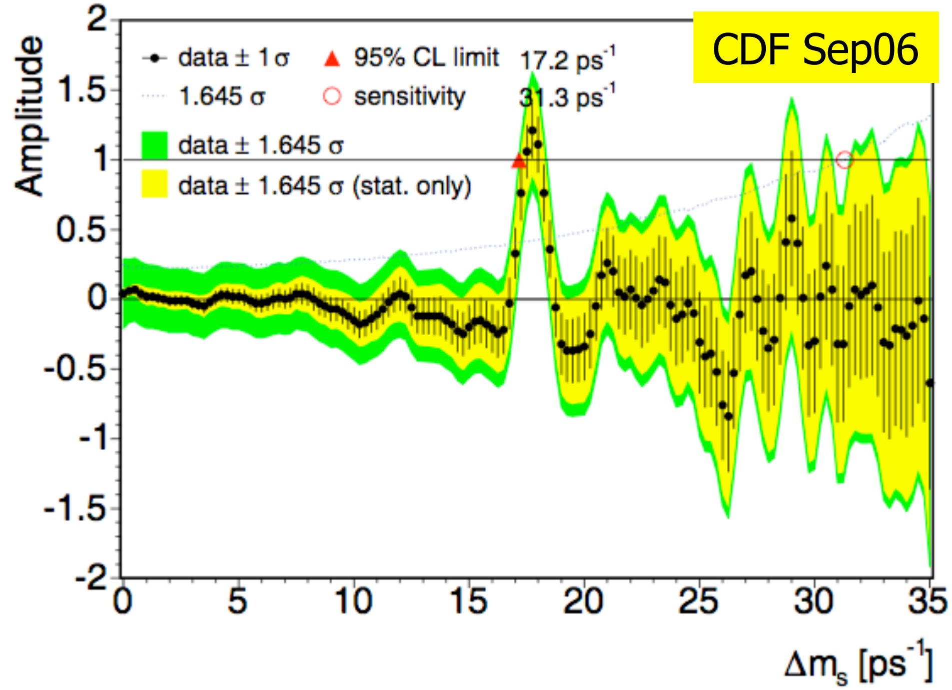
$$\frac{\Delta m_d}{\Delta m_s} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

  - Theory error ~4% (Lattice)
  - Δm_d is precisely measured
  - But B_s mixing is very hard…



Recent Tevatron results





$17 < \Delta m_s <$ 21 ps^{-1} @ 90% CL

D0

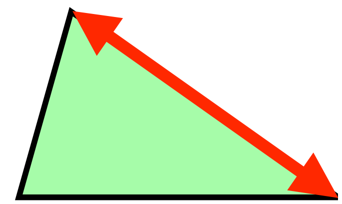
$$\Delta m_S = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$$

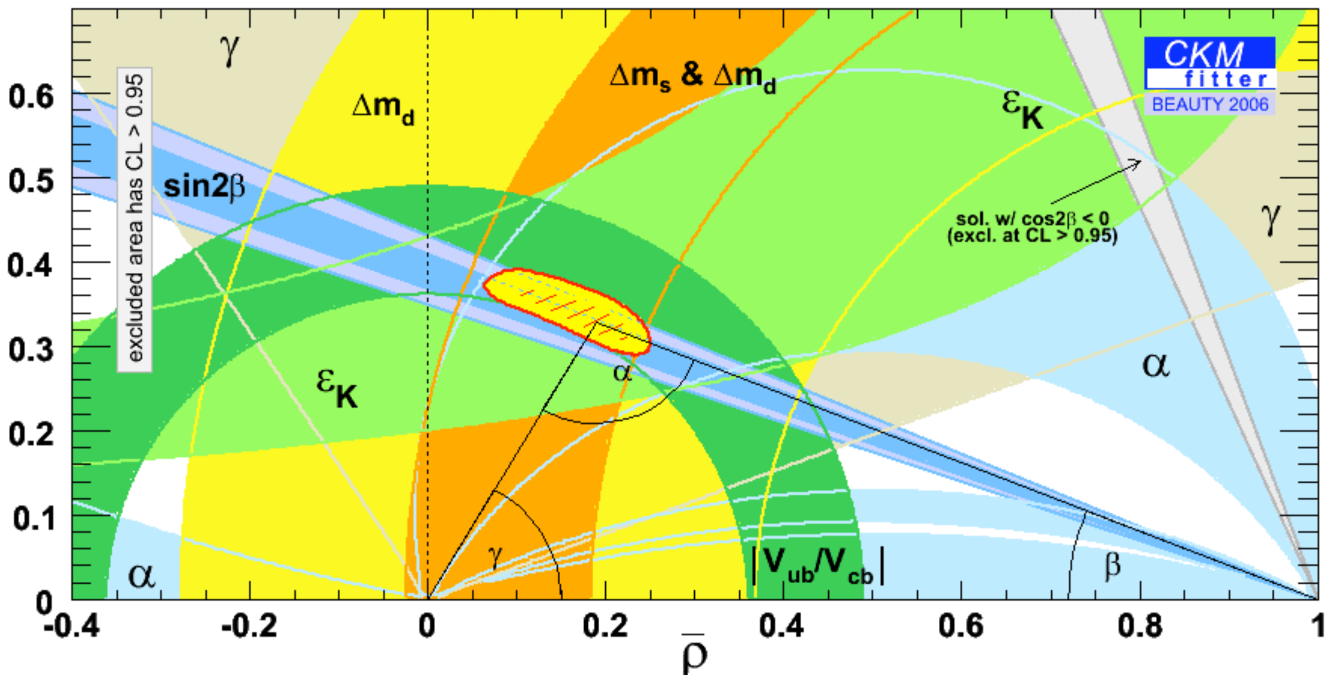
CDF

$$\Rightarrow \left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

Precision ~4%
dominated by theory error

What do we learn from mixing?

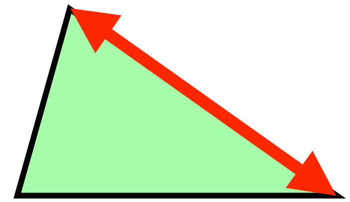




- One precise measurement of R_t improves our knowledge of the SM parameters (ρ,η)
- To go beyond the SM we need to be able to compare this measurement with independent constraints
  - Measurements of angle γ not mature enough for meaningful comparison

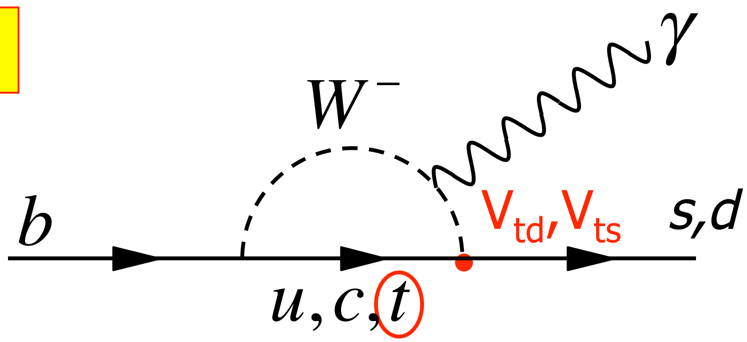
Need for independent measurement of V_{td}/V_{ts} with different sensitivity to New Physics

R_t from $B \to \rho\gamma$ and $B \to K^*\gamma$

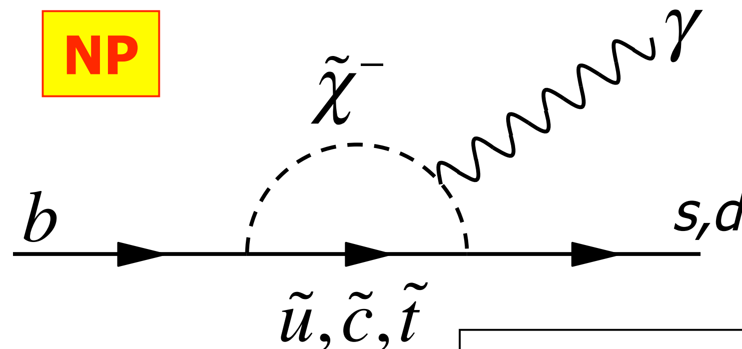


- Radiative penguin decays with $b \to d\gamma$ and $b \to s\gamma$

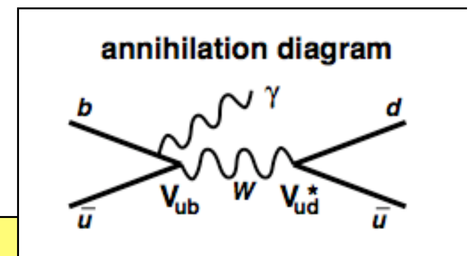
SM



NP



- In the SM, the ratio of BFs measures $|V_{td}/V_{ts}|$
  - Theory errors on $|V_{td}/V_{ts}|$~7.4%

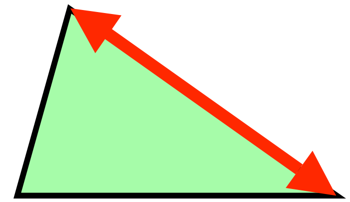


$$\frac{BF(B \to (\rho/\omega)\gamma)}{BF(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{m_B^2 - m_\rho^2}{m_B^2 - m_{K^*}^2}\right)^3 \zeta^2 (1 + \Delta R)$$

Light Cone Rum Rules

- New Physics Beyond the SM could take part in the loop and modify BFs…

B→ργ: analysis overview

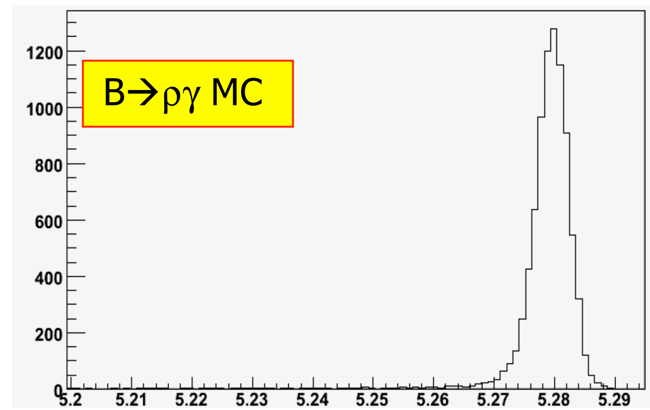


- Two body decay
  - $p_\gamma^{CM} \sim m_B/2$
- Exclusive meson reconstruction
  - $\rho^0 \to \pi^+\pi^-$
  - $\rho^+ \to \pi^+\pi^0$
  - $\omega \to \pi^+\pi^-\pi^0$
- Exclusively reconstruct B meson
  - Beam energy constrained mass m_{ES}

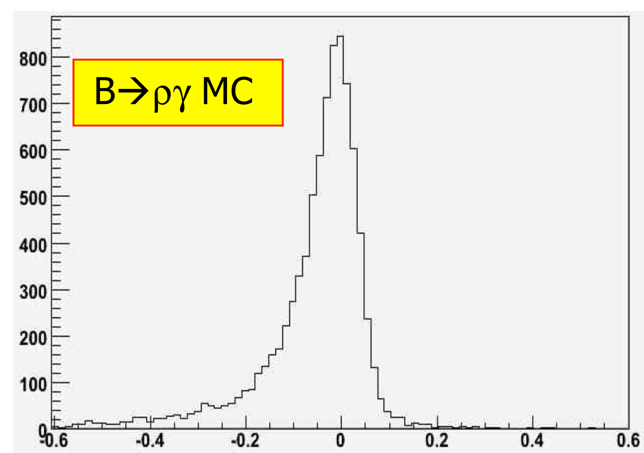
$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

  - Impose energy conservation: $\Delta E \sim 0$

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

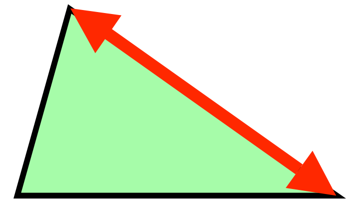


m_{ES} (GeV)/c^2

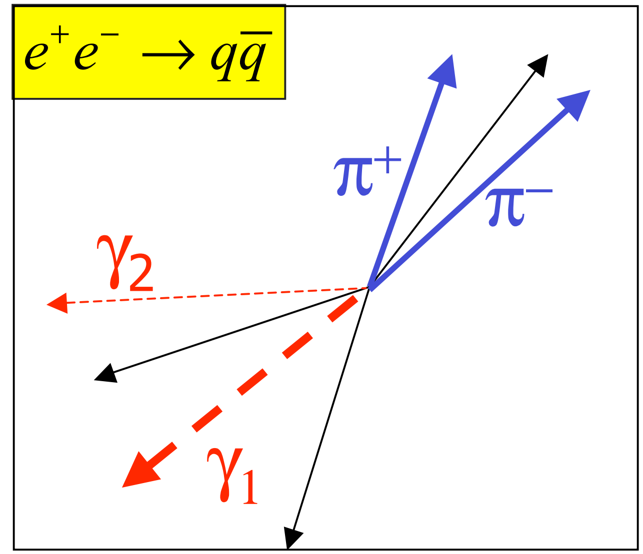


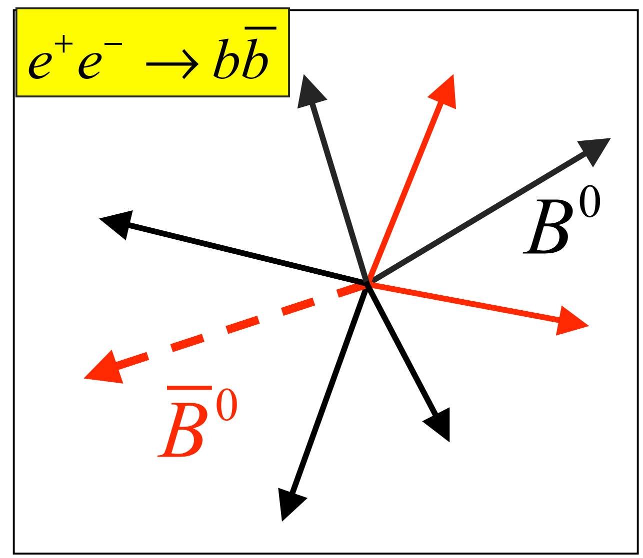
ΔE (GeV)/c^2

$B \to \rho\gamma$: challenges

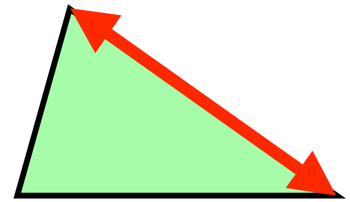


- Very small Branching Fractions
  - $B^0 \to \rho^0\gamma \sim 0.5 \times 10^{-6}$
  - $B^+ \to \rho^+\gamma \sim 1 \times 10^{-6}$
- Combinatorics from random pions
  - $\Gamma(\rho) \sim 150$ MeV
- Background from $B \to K^*\gamma$
  - Pion identification is a must
- Huge continuum background due γ from $\pi^0\ (\eta) \to \gamma_1\gamma_2$
  - NN for continuum suppression is key
  - Veto photons from $\pi^0\ (\eta)$ decays

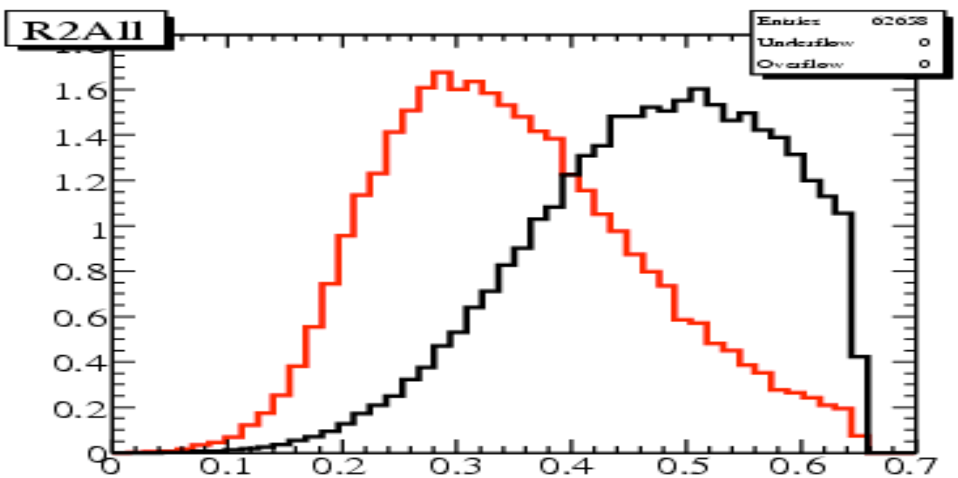


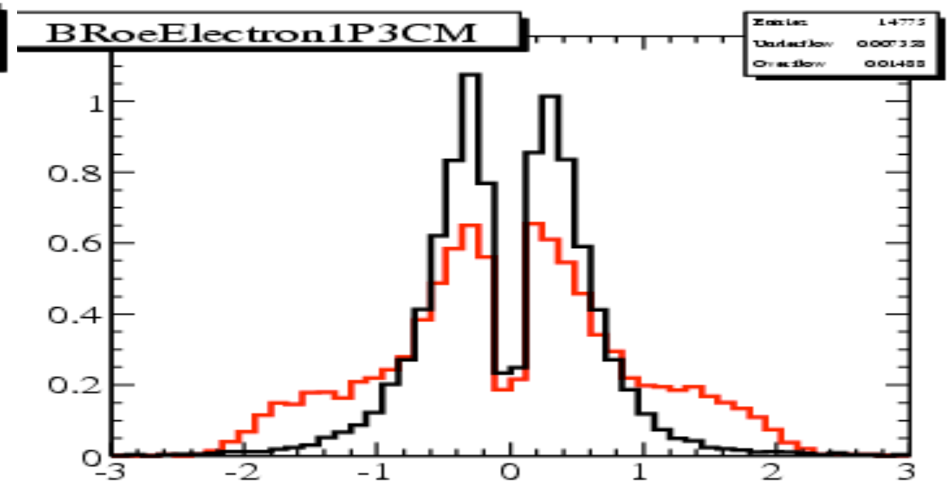


NN for continuum suppression



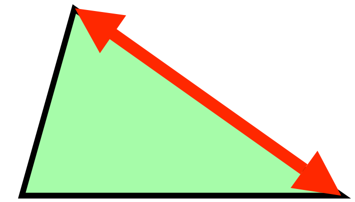
- Identify discriminating variables (30+)
  - Shape variables (e.g.: R2)
  - Properties of B decays (e.g.: Δz)
  - Decay products of other B (e.g.: p_{CMS} of leptons)

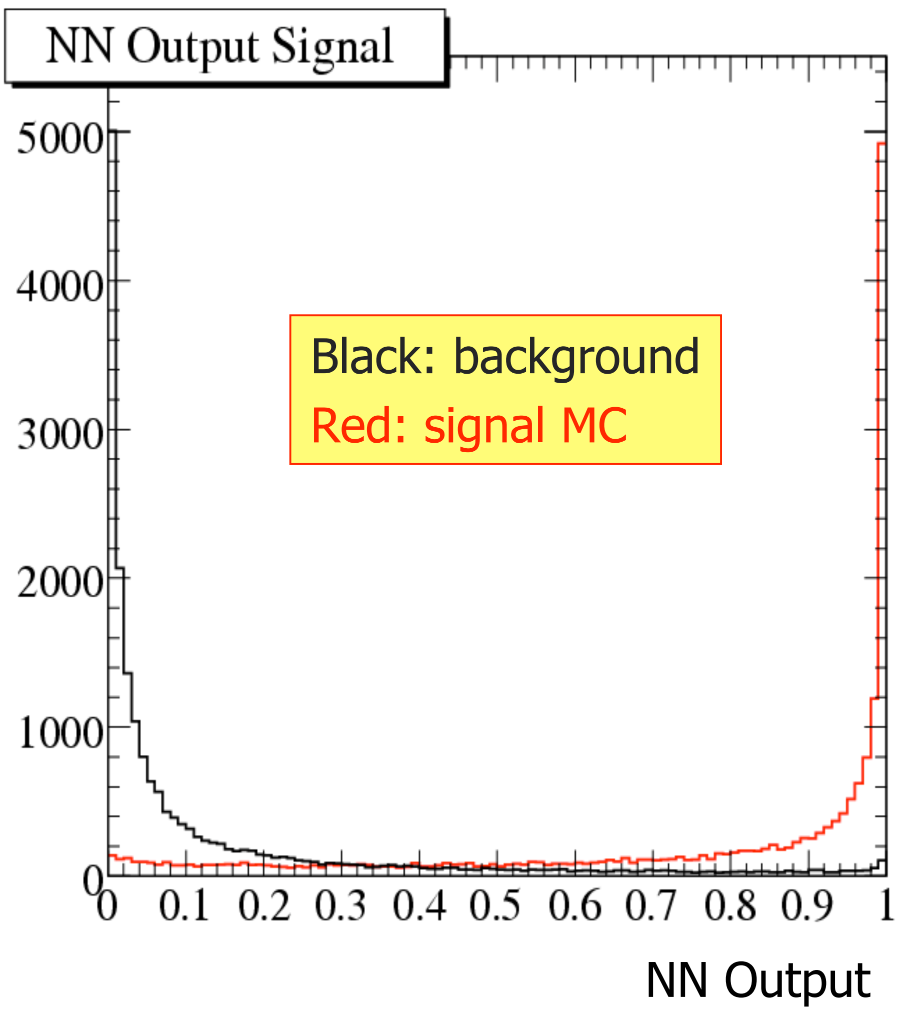


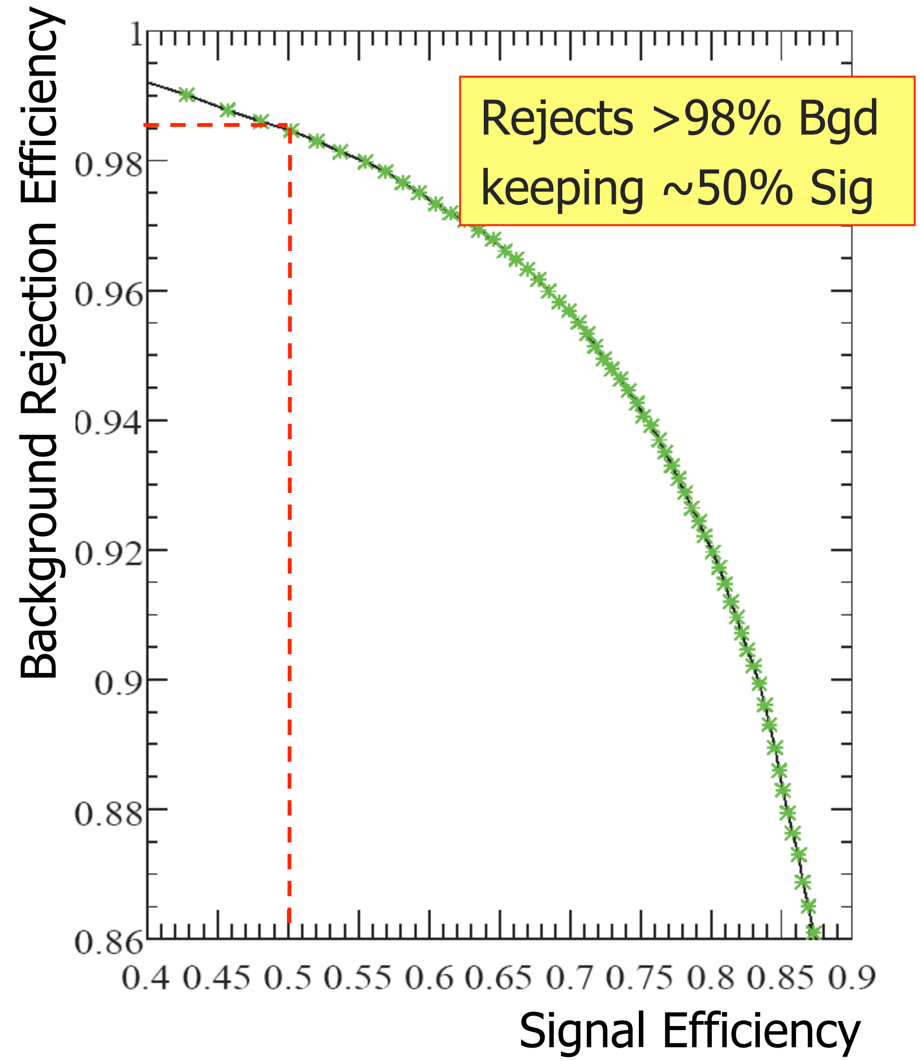


Black: Continuum MC
Red: Signal MC

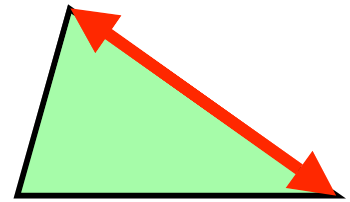
NN Output and performance

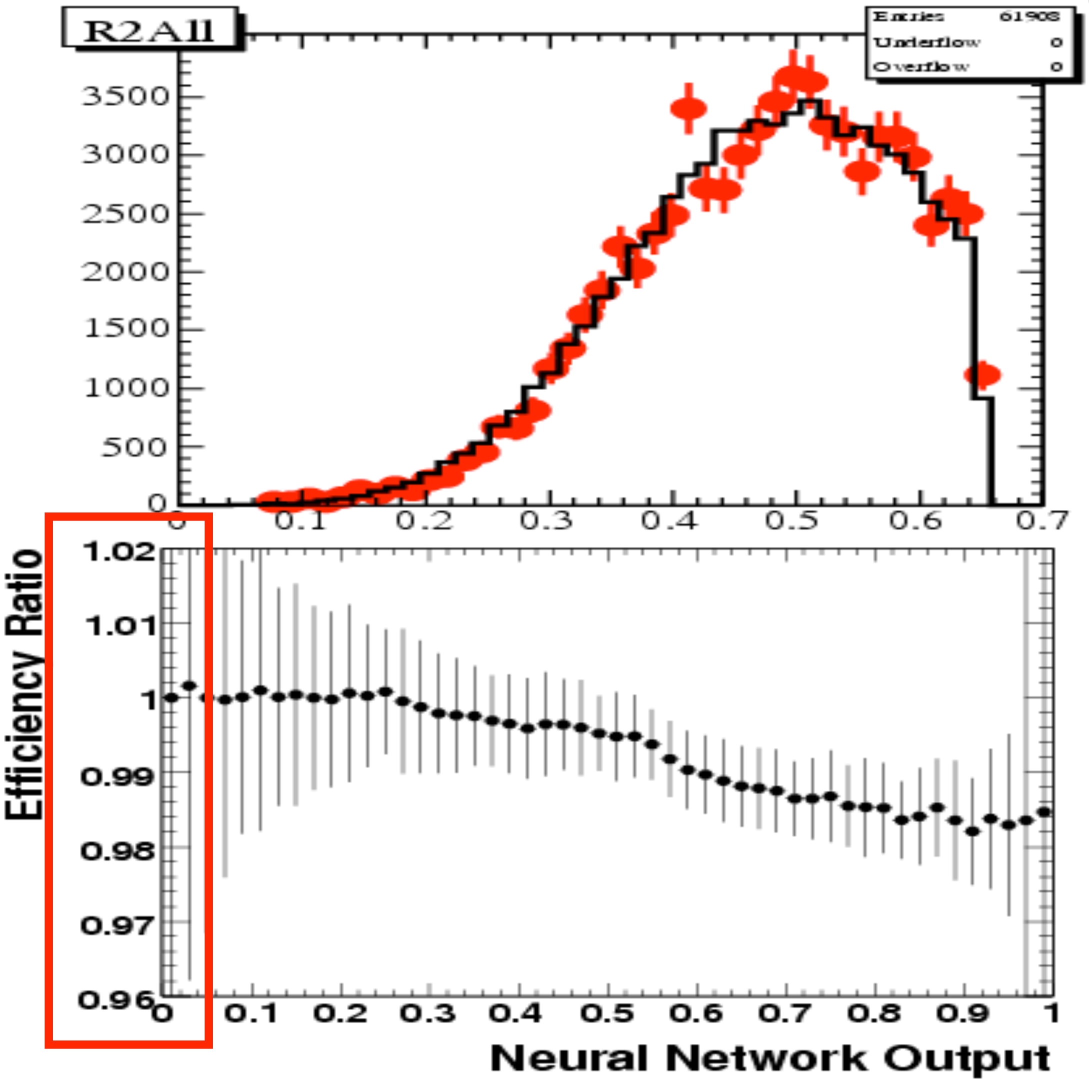






NN systematics





Background shape validation:
Black: continuum MC
Red: off-peak DATA

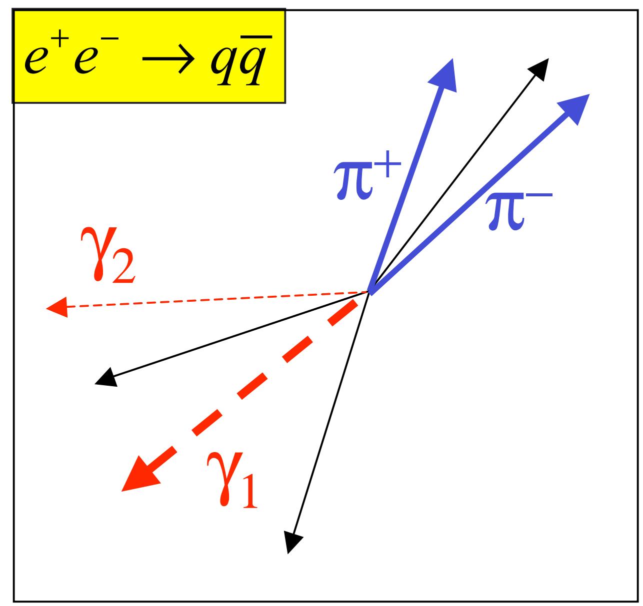
Signal NN shape validation.
$B \to D\pi$ control sample: N_{nsig}/NN_{Back}

Systematics: ~1 %

π^0 and η veto

- Explicitly rejects photon coming from $\pi^0\,(\eta) \rightarrow \gamma_1\gamma_2$
  - Suppress both continuum and B backgrounds

- Method
  - Combine γ candidate with all other photons (γ_i) in event
  - Obtain pdf(mass($\gamma\gamma_i$),$E_{\gamma i}$)'s for signal and π^0/η in continuum MC
  - Cut on likelihood ratio



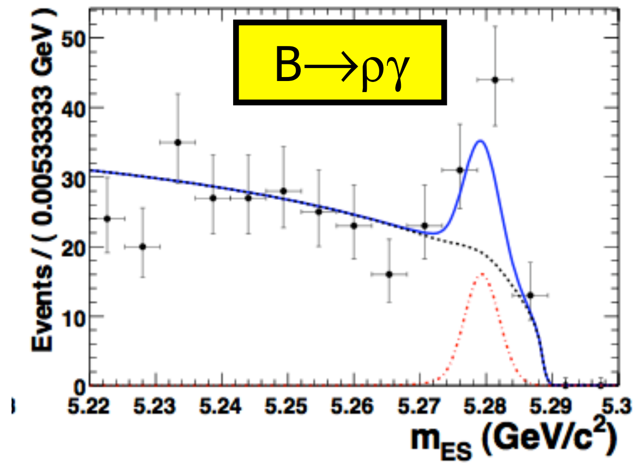
hep-ex/0612017

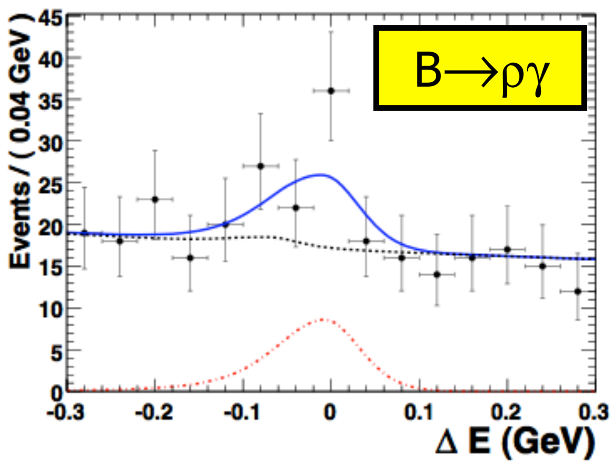
Signal extraction - BaBar

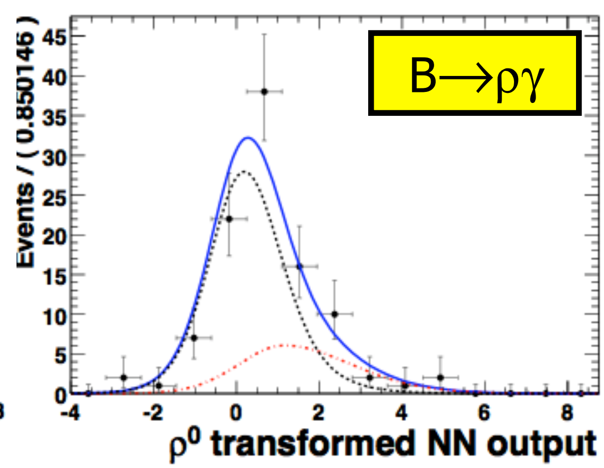
Maximum likelihood fit to signal + background (continuum + B)

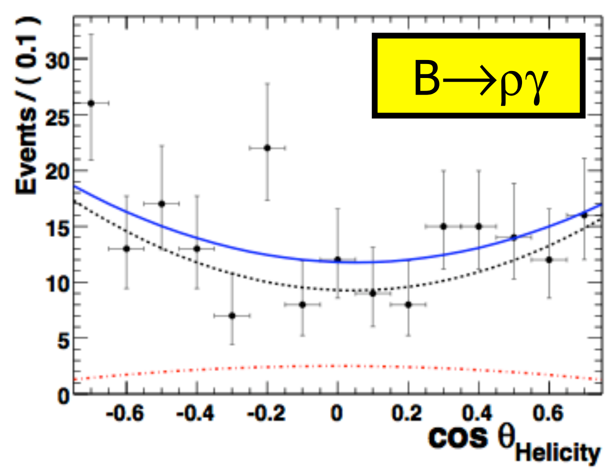
- $B \rightarrow \rho\gamma$: 4D fit to m_{ES}, ΔE, NN, $\theta_{helicity}$
- $B \rightarrow \omega\gamma$: 5D fit includes Dalitz angle

-- Signal
-- Background
— S+B









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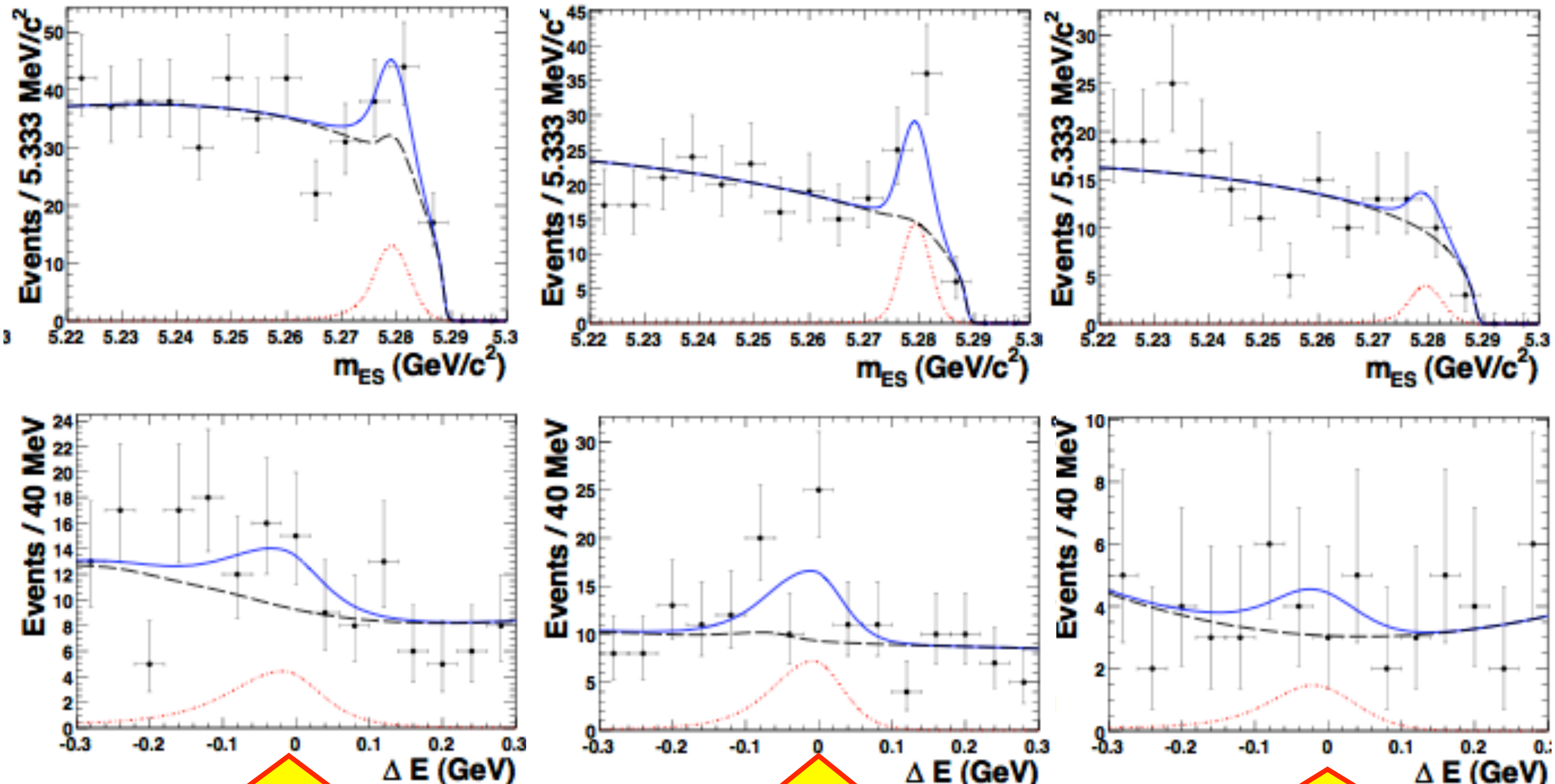
BaBar new results (316 fb^{-1})



$B^+ \to \rho^+\gamma$
3.8σ

$B^0 \to \rho^0\gamma$
4.9σ

$B^0 \to \omega\gamma$
2.1σ

hep-ex/0612017

BaBar new results (316 fb^{-1})

$Mode$	N_{signal}	$Significance$	$BF(10^{-6})$
$B^+ \to \rho^+\gamma$	$42.0^{+14.0}_{-12.7}$	3.8σ	$1.10^{+0.37}_{-0.33} \pm 0.09$
$B^0 \to \rho^0\gamma$	$38.7^{+10.6}_{-9.8}$	4.9σ	$0.79^{+0.22}_{-0.20} \pm 0.06$
$B^0 \to \omega\gamma$	$11.0^{+6.7}_{-5.6}$	2.2σ	$0.40^{+0.24}_{-0.20} \pm 0.05$
Combined BF		6.4σ	$1.25^{+0.25}_{-0.24} \pm 0.09$

19%

- First evidence of $B^+ \to \rho^+\gamma$
- Best measurement of all of these BFs
- Isospin test:

$$\frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 = -0.35 \pm 0.27$$

✓ Consistent with 0: isospin symmetry

Phys.Rev.Lett.96:221601,2006

Belle's results (370 fb^{-1})

$Mode$	N_{signal}	$Significance$	$BF(10^{-6})$
$B^+ \to \rho^+\gamma$	8.5	1.6σ	$0.55^{+0.42+0.09}_{-0.36-0.08}$
$B^0 \to \rho^0\gamma$	20.7	5.2σ	$1.25^{+0.37+0.07}_{-0.33-0.06}$
$B^0 \to \omega\gamma$	5.7	2.3σ	$0.56^{+0.34+0.05}_{-0.27-0.10}$
Combined	36.9	5.1σ	$1.32^{+0.34+0.10}_{-0.31-0.09}$

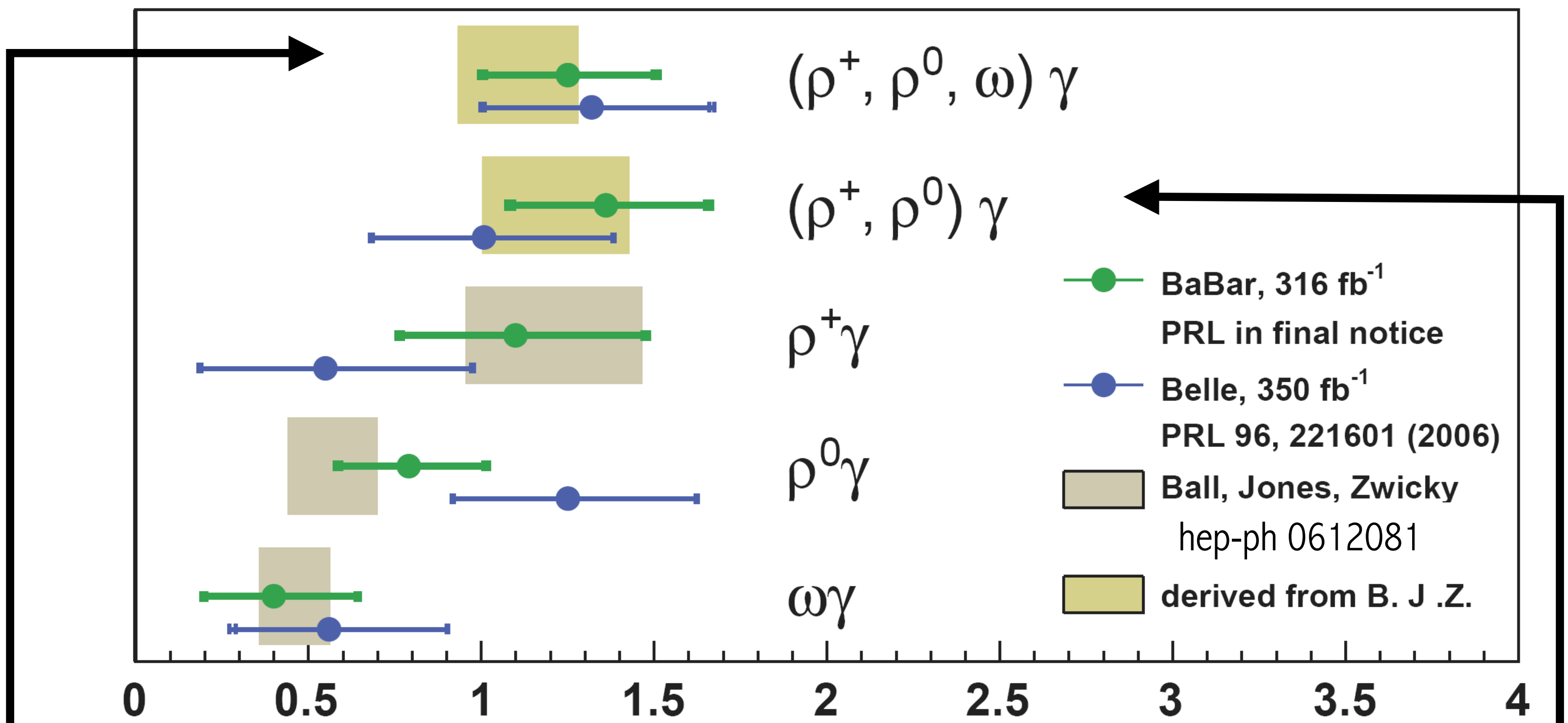
25%

- First observation of $B^0 \to \rho^0\gamma$
- Isospin test
  - Important because isospin conservation is assumed in combined fit
  - Probability of a larger isospin violation <4.9%

SM expectation

$B^+ \sim 1.0 \times 10^{-6}$
$B^0 \sim 0.5 \times 10^{-6}$

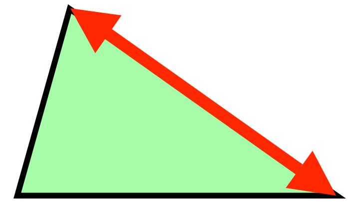
Summary of results: BaBar vs Belle



Isospin-constrained combined fits:

- Combine 3 modes to reduce stat. error
- Combine only ρ modes to reduce theory error
    - ω not a member of iso-triplet!

What do we learn? B→(ρ/ω)γ

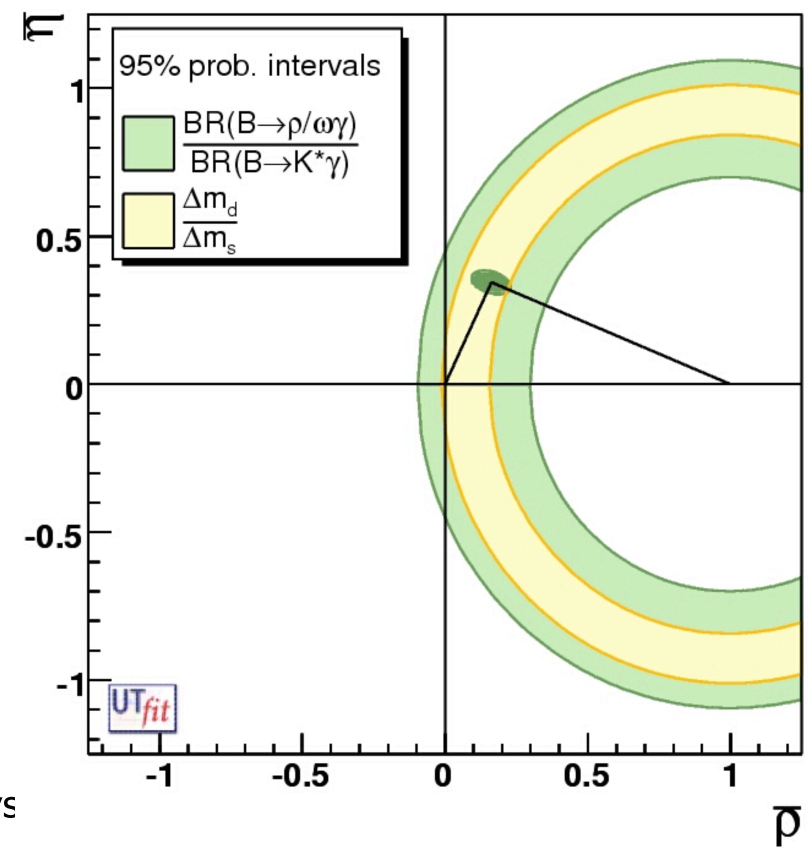


	$BaBar(10^{-6})$	$Belle(10^{-6})$	$Average(10^{-6})$
$BF[B \to (\rho/\omega)\gamma]$	$1.25^{+0.25}_{-0.24} \pm 0.09$	$1.32^{+0.34+0.10}_{-0.31-0.09}$	$1.28^{+0.20}_{-0.19} \pm 0.06$

B→(ρ/ω)γ

$$\left|\frac{V_{td}}{V_{ts}}\right|_{\rho/\omega\gamma} = 0.202^{+0.017}_{-0.016}(\text{exp}) \pm 0.015(\text{th})$$

8.2% 7.4%

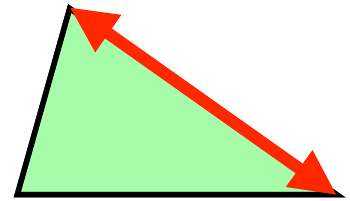


Note:

- BaBar+Belle average
- Ball, Jones, Zwicky (hep-ph 0612081)

In excellent agreement with mixing

What do we learn? B→ργ



	$BaBar(10^{-6})$	$Belle(10^{-6})$	$Average(10^{-6})$
$BF(B \to \rho\gamma)$	$1.36^{+0.29}_{-0.27} \pm 0.10$	$1.01^{+0.37}_{-0.32} \pm 0.07$	$1.22^{+0.23}_{-0.21} \pm 0.05$

B→ργ

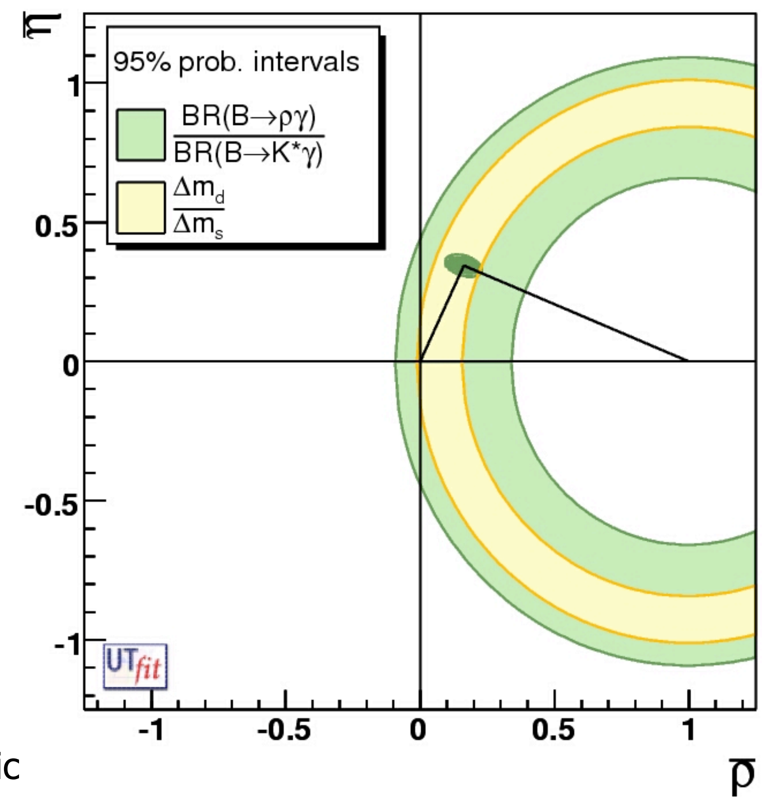
$$\left|\frac{V_{td}}{V_{ts}}\right|_{\rho\gamma} = 0.197^{+0.019}_{-0.018}(\text{exp}) \pm 0.015(\text{th})$$

9.4% (exp) 7.5% (th)

Note:

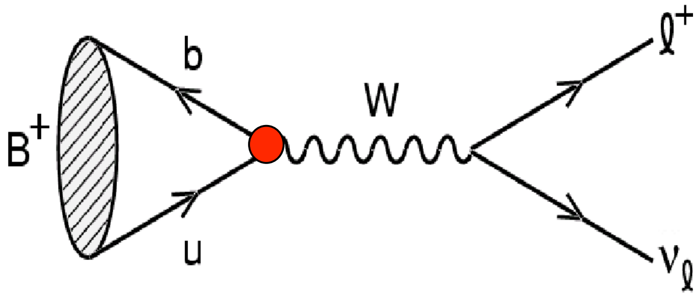
- BaBar's BF(B→ργ) from combined fit
- Belle's BF(B→ργ) from isospin average
- Ball, Jones, Zwicky (hep-ph 0612081)

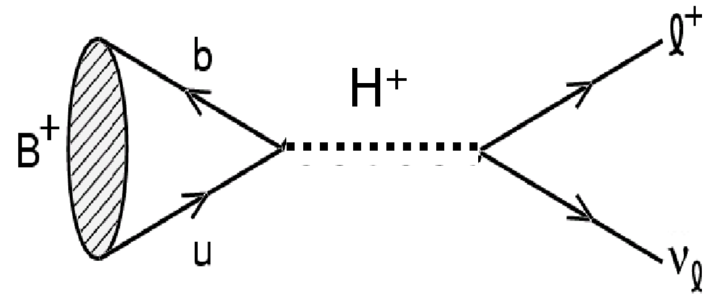
Still in good agreement with mixing



New Physics at the B factories outside the UT
$B^+ \to \tau^+ \nu_\tau$

- Standard Model





$$BF(B^+ \to \tau^+ \nu) = \frac{G_F{}^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B \sim 10^{-4}$$

f_B^2 → Lattice QCD

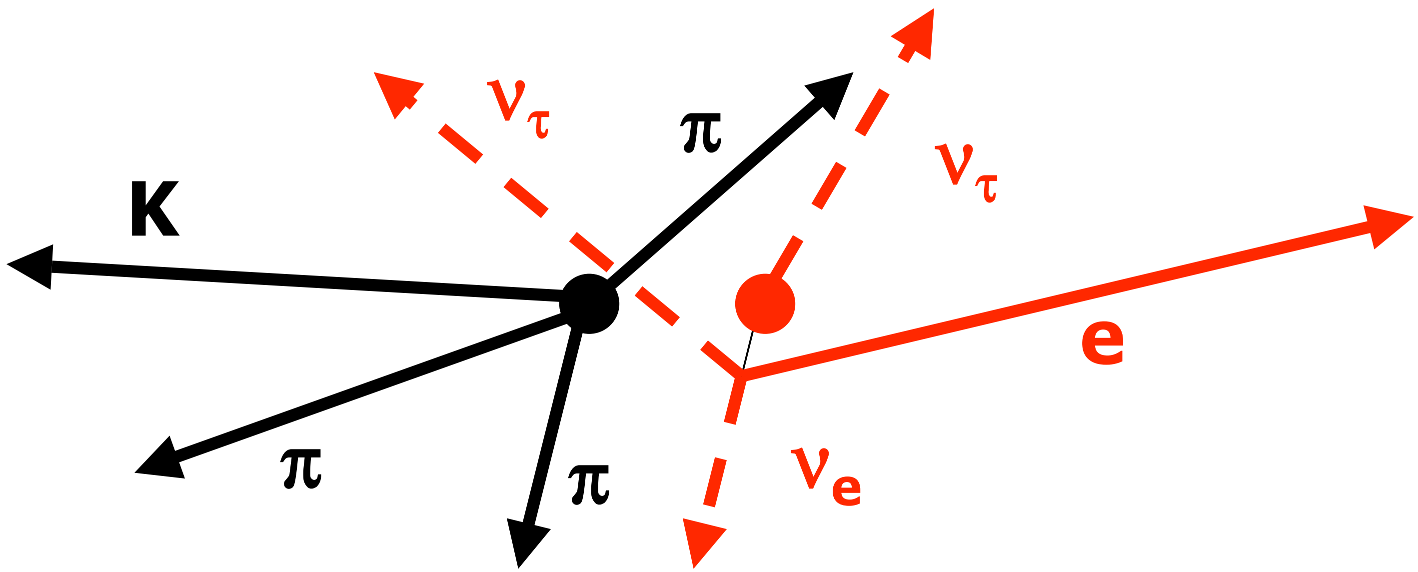
- New Physics, e.g. Type II 2 Higgs Doublet Model

$$BF(B^+ \to \tau^+ \nu) = BF(B^+ \to \tau^+ \nu)_{SM} \times \left(1 - \tan^2\beta \frac{m_{B^+}^2}{m_{H^+}^2}\right)^2$$

$B^+ \to \tau^+ \nu$: analysis technique

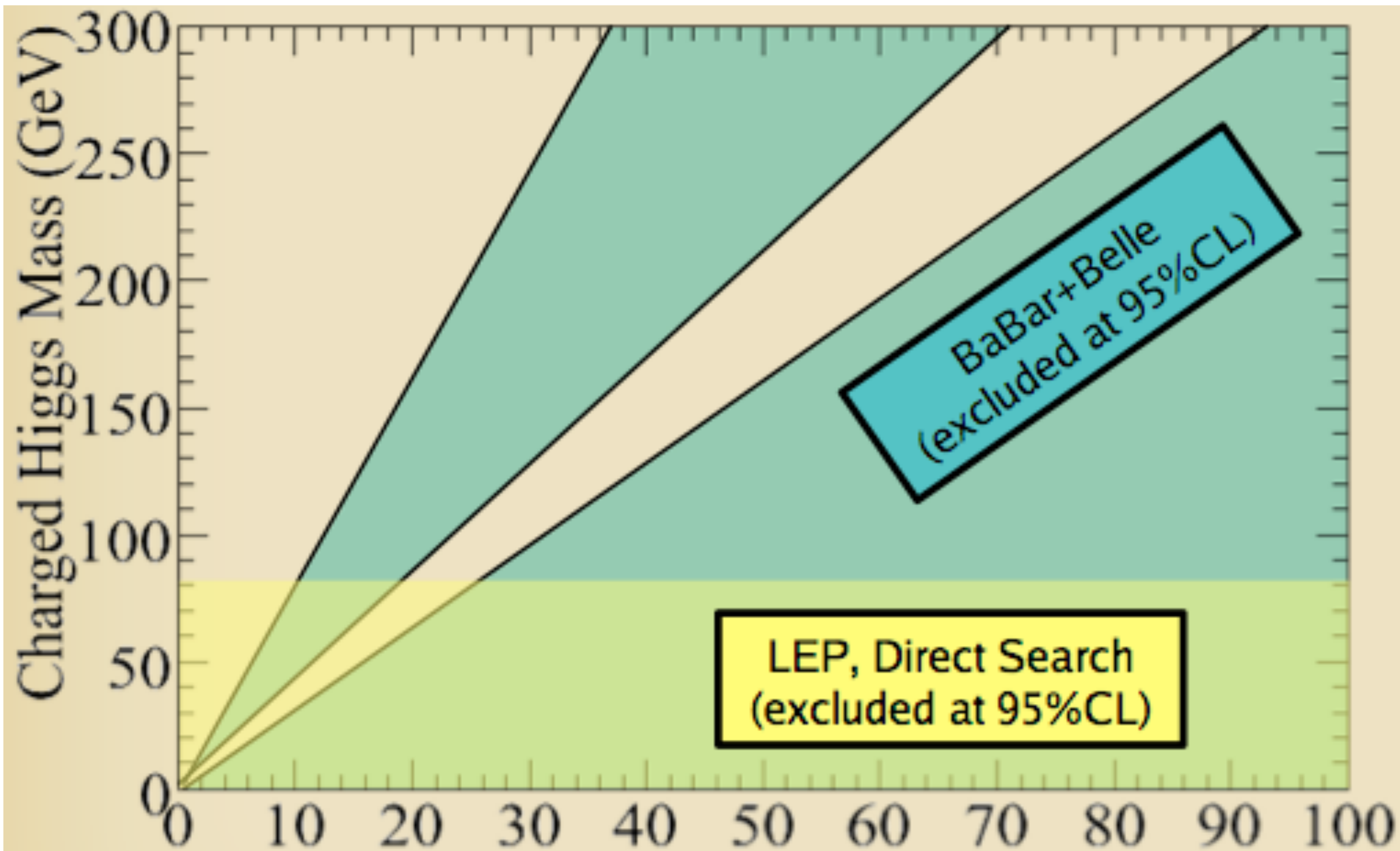
- Exclusive reconstruction of the other B in the event
- All particles left in the event must belong to the other B
- τ^+ reconstructed in the following final states:

$$\tau^+ \to \rho^+ \nu, \mu^+ \nu\nu, e^+ \nu\nu, \pi^+ \nu\nu$$



Constraints on NP from $B \to \tau\nu$

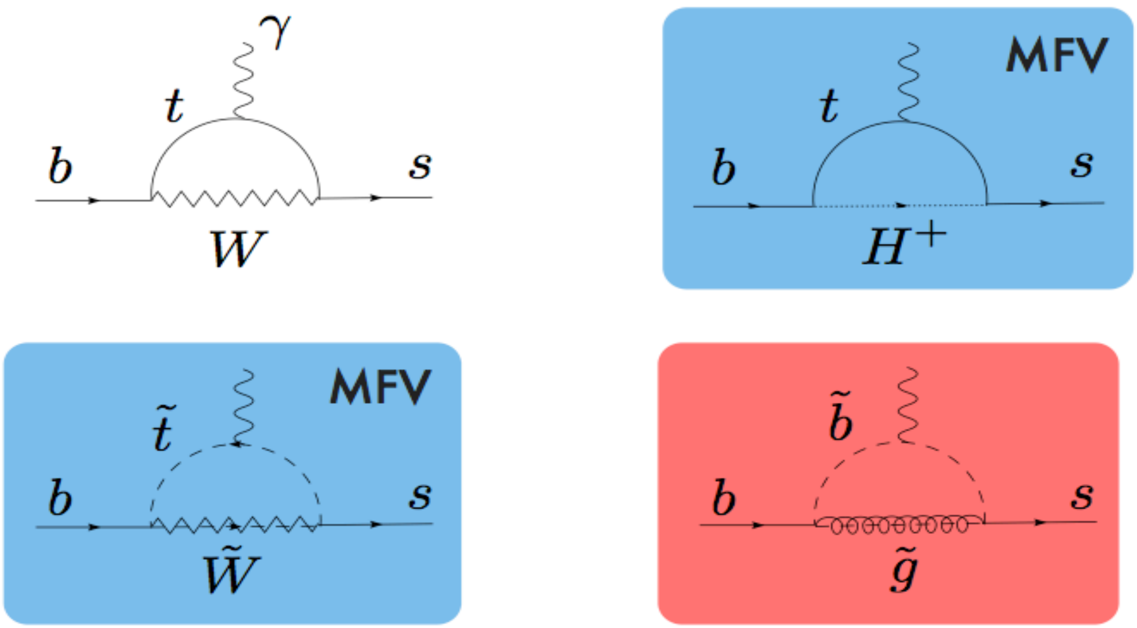
Average of latest BaBar + Belle results:



tanβ

Inclusive BF(b→s γ)

- A sensitive probe of New Physics
  - Example: diagrams contributing in MSSM

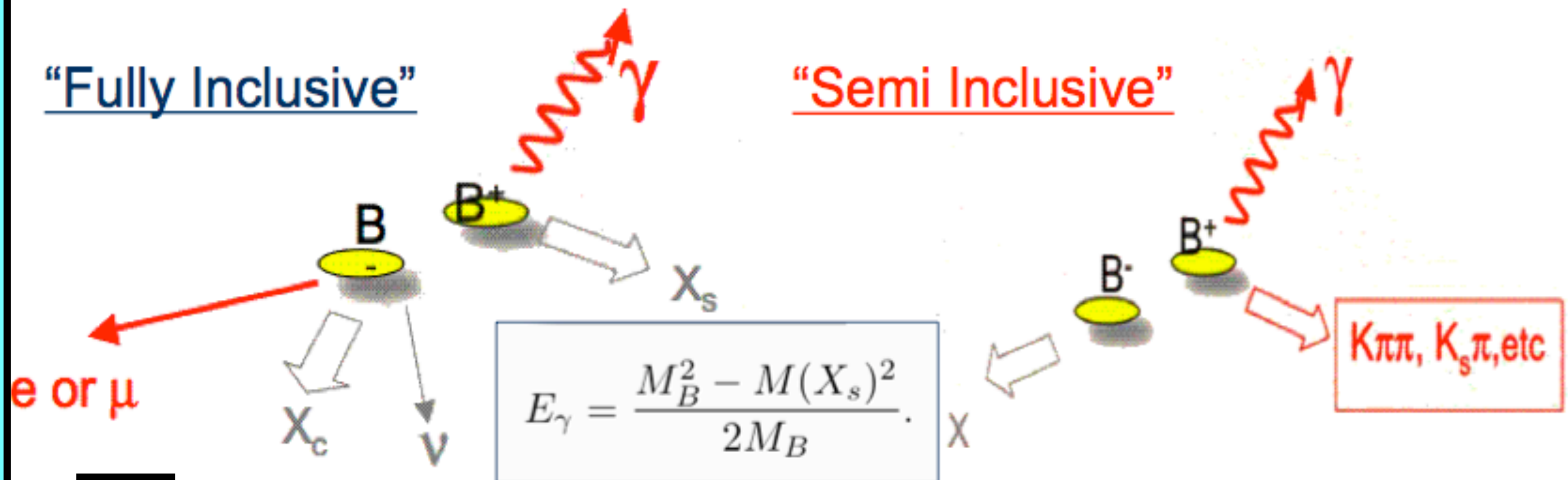


- Many variables can be measured
  - Inclusive BF (b→s g), direct A_{CP}, Time Dependent A_{CP}, …

Henning Flaecher

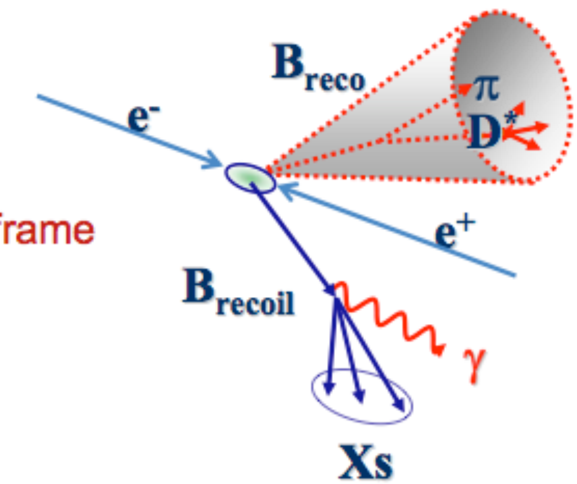
$B \to s\gamma$: experiment

Present



Future

- Hadronic Decay of one B meson is fully reconstructed
  - 4-momentum, charge and flavour determined
  - Enables measurement of A_{CP}
  - Photon energy measured in B rest frame
- BF normalisation obtained from Breco sample
  - Small efficiency extrapolation



Bounds on M_{H+} in Type II 2HDM

Theory error~ 7%

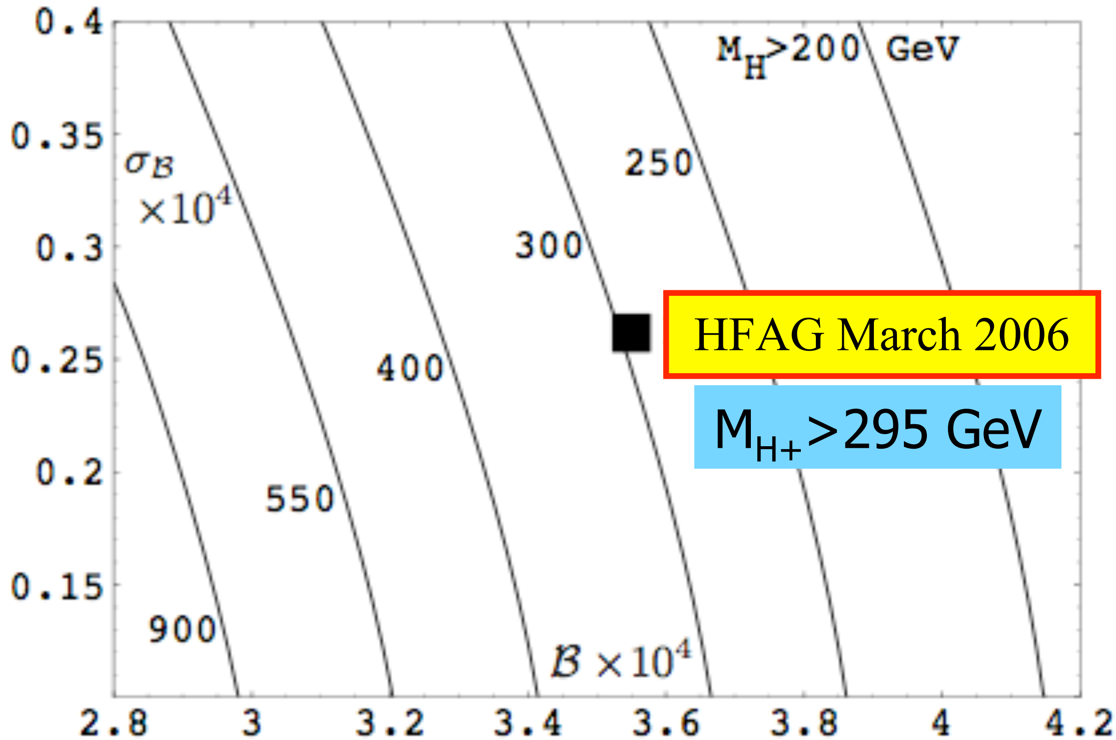
Theory NNLO $B(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$

Experiment $B(B \to X_s \gamma) = (3.55 \pm 0.24 \pm 0.10 \pm 0.03) \times 10^{-4}$

Exp. error ~7%

95% CL lower bound on M_{H+} as a function of experimental central values (x) and errors (y)

Misiak et al, hep-ph/0609232



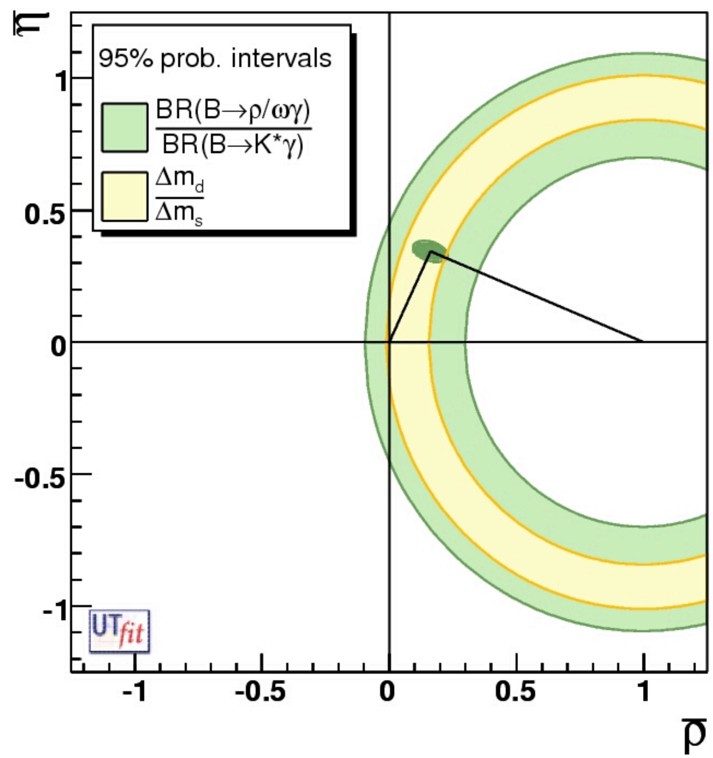
Conclusion

- The abundant and clean dataset from the B factories allows us to test the SM in many different ways
  - Sides vs. Angles
  - Angles: trees vs. penguins
  - Sides: B mixing vs $B \to \rho\gamma$ (New!)
- Rare decays add independent constraints
  - E.g.: $B \to \tau\nu$ or $B \to s\gamma$
- New Physics is still hiding:

  … should we give up hope?

$$\frac{m_W}{\Lambda_{NP}} \sim \frac{100\ \text{GeV}}{1\ \text{TeV}} \sim 10\%$$

  - Precision of ~few% needed



- Can these precisions ever be reached?
  - Almost there for several measurements

… data set will more than double by 2008!

How well do we know SM parameters?

95% CL in 2001

95% CL now