ICFP2003
KIAS

BABAR
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Rare B Decays at BaBar

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on behalf of the BaBar Collaboration

- ✓ Purely leptonic decays
- ✓ Radiative decays
- ✓ $b \rightarrow sll$ decays
- ✓ $D^{(*)}K^{(*)}$ decays
- ✓ Charmless hadronic decays

✓All results are preliminary unless journal ref. is given
✓All limit values are 90% CL unless otherwise specified

- This is 2nd experimental talk (must have been 3rd…)
- All are already shown in LP03
- Confusion due to $\alpha\beta\gamma$ vs $\phi_1\phi_2\phi_3$?
  (Don't worry, no triangle in this talk!)

B Decays

B mesons decay lots of different ways :
➔ provide wide range of different physics topics to study

PDG 2002:

$B \rightarrow D + X$	$O(\%)$
$B \rightarrow J/\Psi + X$	$O(10^{-3})$:
$B \rightarrow$ light hadrons	$O(10^{-5})$
$B \rightarrow$ hadrons + γ	?
$B \rightarrow$ lepton pair + X	
…	

This area is referred to as "Rare B decays" during this talk

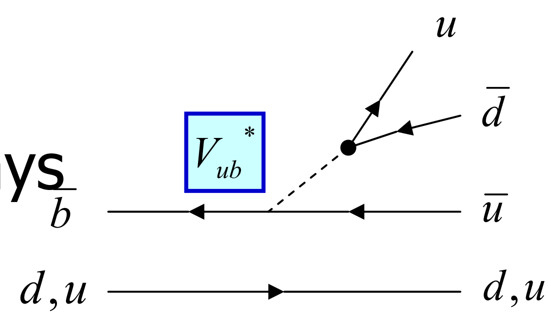
- sensitive to new physics as we probe rarer decay modes
- new physics scenarios already become sensitive

➔ Currently, BaBar and Belle have 10^8 B mesons

What are Rare B Decays? (1)

- Small CKM matrix element

✓ exclusive $b \rightarrow u$ hadronic charmless decays

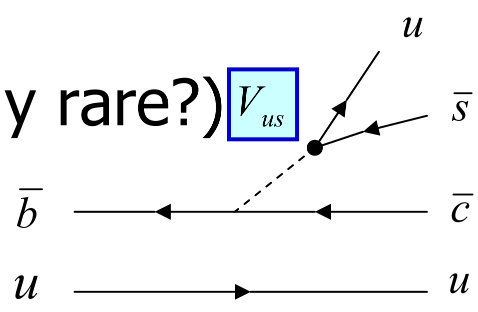


$B^0 \rightarrow \pi^+\pi^-, K^+\pi^-, \ldots$
$B \rightarrow \pi\pi\pi, K\pi\pi, \rho\rho, K^*\rho, \ldots$

$|V_{ub}/V_{cb}| \sim \lambda$

$BR \sim 10^{-5 \sim -6}$

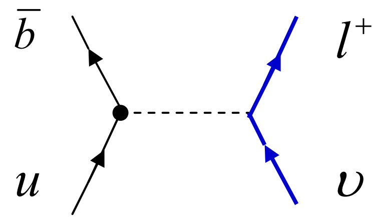
✓ exclusive $b \rightarrow c$ with V_{us} involved (not really rare?)



$B^+ \rightarrow \bar{D}^0 K^+, \ldots$

$BR \sim 10^{-4 \sim -5}$

✓ exclusive $b \rightarrow u$, purely leptonic $f_B |V_{ub}|$



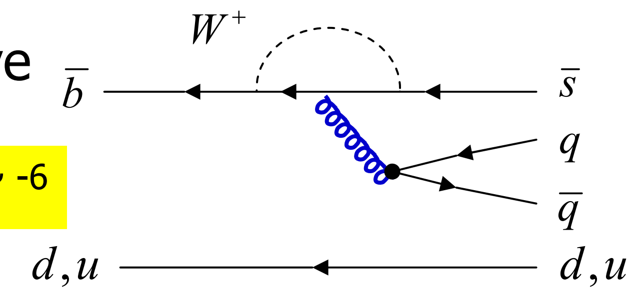
$B^+ \rightarrow l^+\nu$

$BR \sim 10^{-5 \sim -12}$

What are Rare B Decays? (2)

- Leading diagram involves a quantum loop ("penguin" loop)

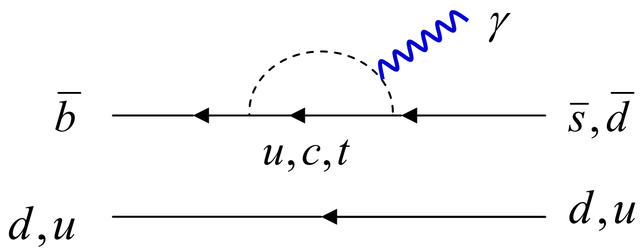
✓ gluonic loop: $b \rightarrow s$ gluon ($\bar{q}q$) exclusive



$B \rightarrow \phi K^*$ … (pure gluonic loop)
$B \rightarrow K\pi$, $K\eta'$ (gluonic + small tree)

$BR{\sim}10^{-5 \sim -6}$

✓ radiative loop: $b \rightarrow (s,d)\ \gamma$

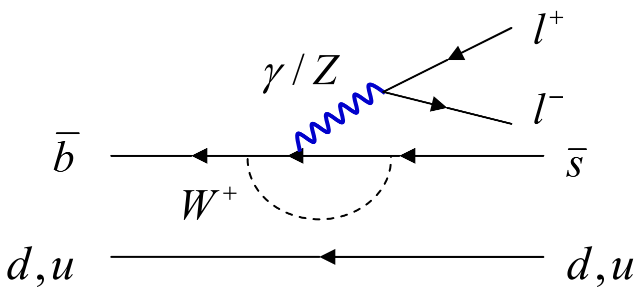


$B \rightarrow K^*\gamma, \rho\gamma, \omega\gamma$
$B \rightarrow s\gamma$

exclusive ($b \rightarrow s,d\ \gamma$)
inclusive ($b \rightarrow s\ \gamma$)

$BR{\sim}10^{-5 \sim -7}$
$B\ {\sim}10^{-4}$

✓ electroweak loop



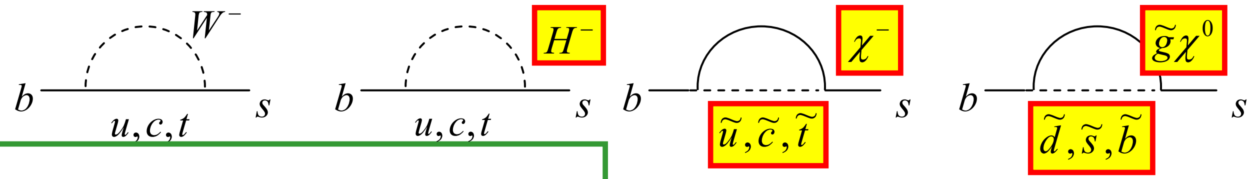
$B \rightarrow K\ \bar{\nu}\nu$, $K\ \bar{l}\, l$

$BR{\sim}10^{-6}$

Motivations

• Hints for new physics

: new particles in loops



might show up in:

✓different (higher) rates than SM only

✓different CP violation than SM only

✓different differential distribution than SM only

• Constrain & test Standard Model

✓ Sides of the unitary triangle: radiative decays

$|V_{td}/V_{ts}|$: $B \to K^*\gamma$, $\rho\gamma$ complements B^0 mixing studies ($\Delta m_{d,s}$)

QCD: inclusive $b \to s\gamma$ (photon spectrum) → HQET parameters, useful for V_{ub}

• Search for direct CPV

✓ Direct CP asymmetry occurs if $B \to f$ (any final state) with at least two (SM or New Physics) amplitudes with different weak and strong phases:

Outline of the talk

- Purely leptonic decays
  - Exclusive $\tau\nu$ search
- Radiative decays
  - Exclusive $K^*\gamma$ BRs, $\rho\gamma$ and $\omega\gamma$ searches
- $B \to X_s ll$ decays
  - $K^{(*)}\ ll\ BR$
  - Inclusive $X_s\ ll$
  - search for $B \to K \bar{\nu}\nu$
- $D^{(*)}K^{(*)}$ decays
  - $B^- \to D^{*0}K^-$
- Charmless hadronic decays
  - $B \to hh$
  - Inclusive $B \to hhh$, $B \to Khh$

$f_B |V_{ub}|$

$|V_{td}|/|V_{ts}|$

sides of triangle

angle γ

angle α

Hints for new physics ?

Talk by Ko

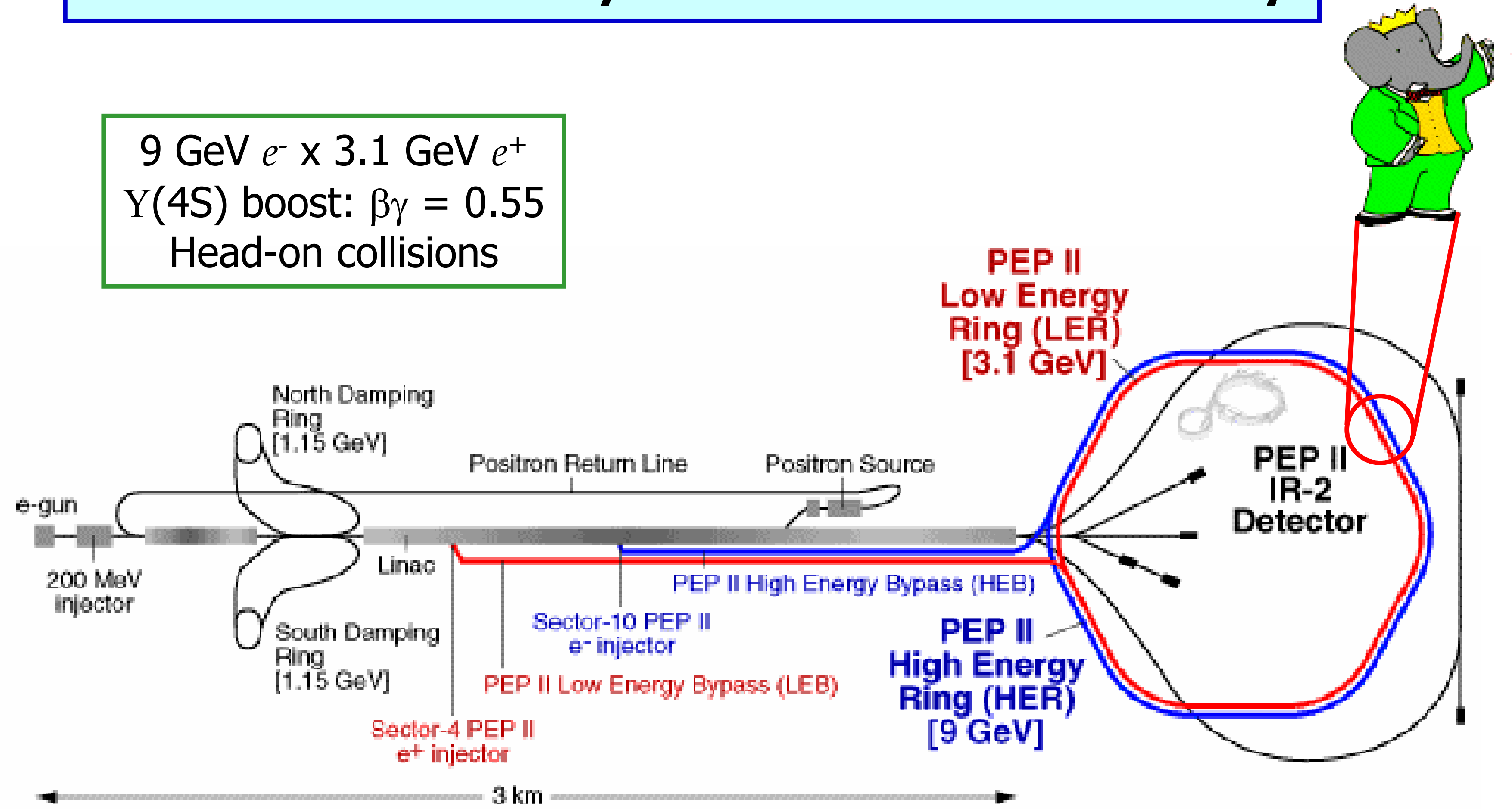
Talks by J.P.Lee, Yamada, Vaidya

Talk by Li, J. Chay

Talks by Du, Yang, Yoshikawa, S. Baek, Sechul Oh

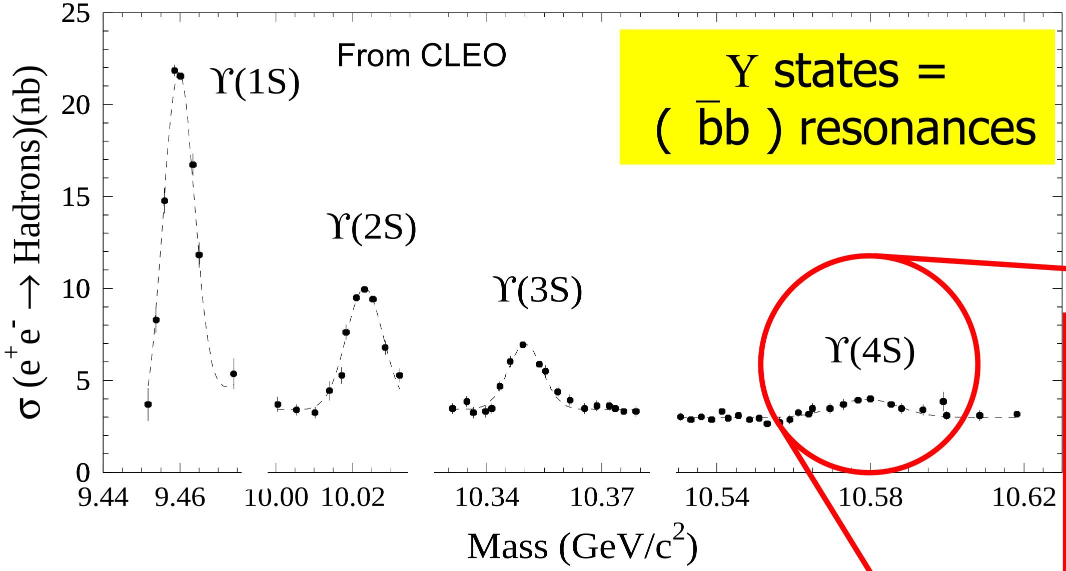
The PEP-II Asymmetric B Factory

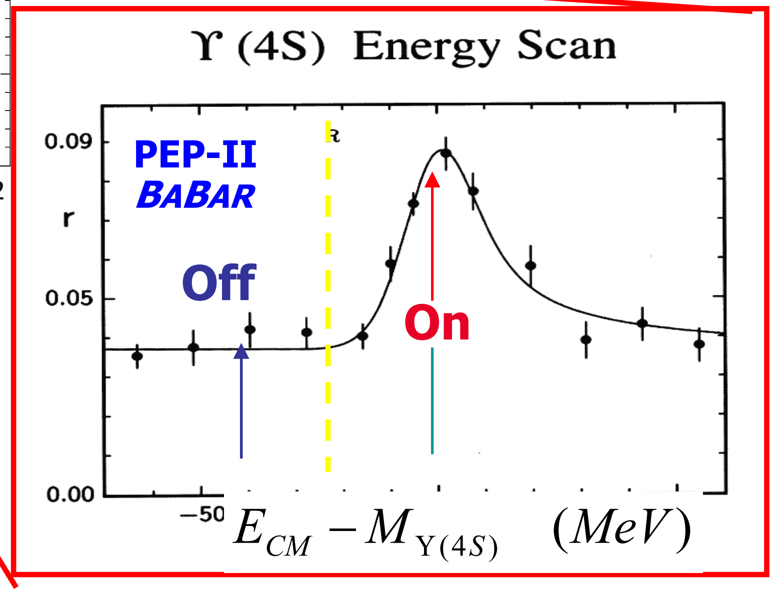
9 GeV e^- x 3.1 GeV e^+
$\Upsilon(4S)$ boost: $\beta\gamma = 0.55$
Head-on collisions



Located in the 2.2 km PEP tunnel
at the Stanford Linear Accelerator Center

e^+e^- collisions at BABAR



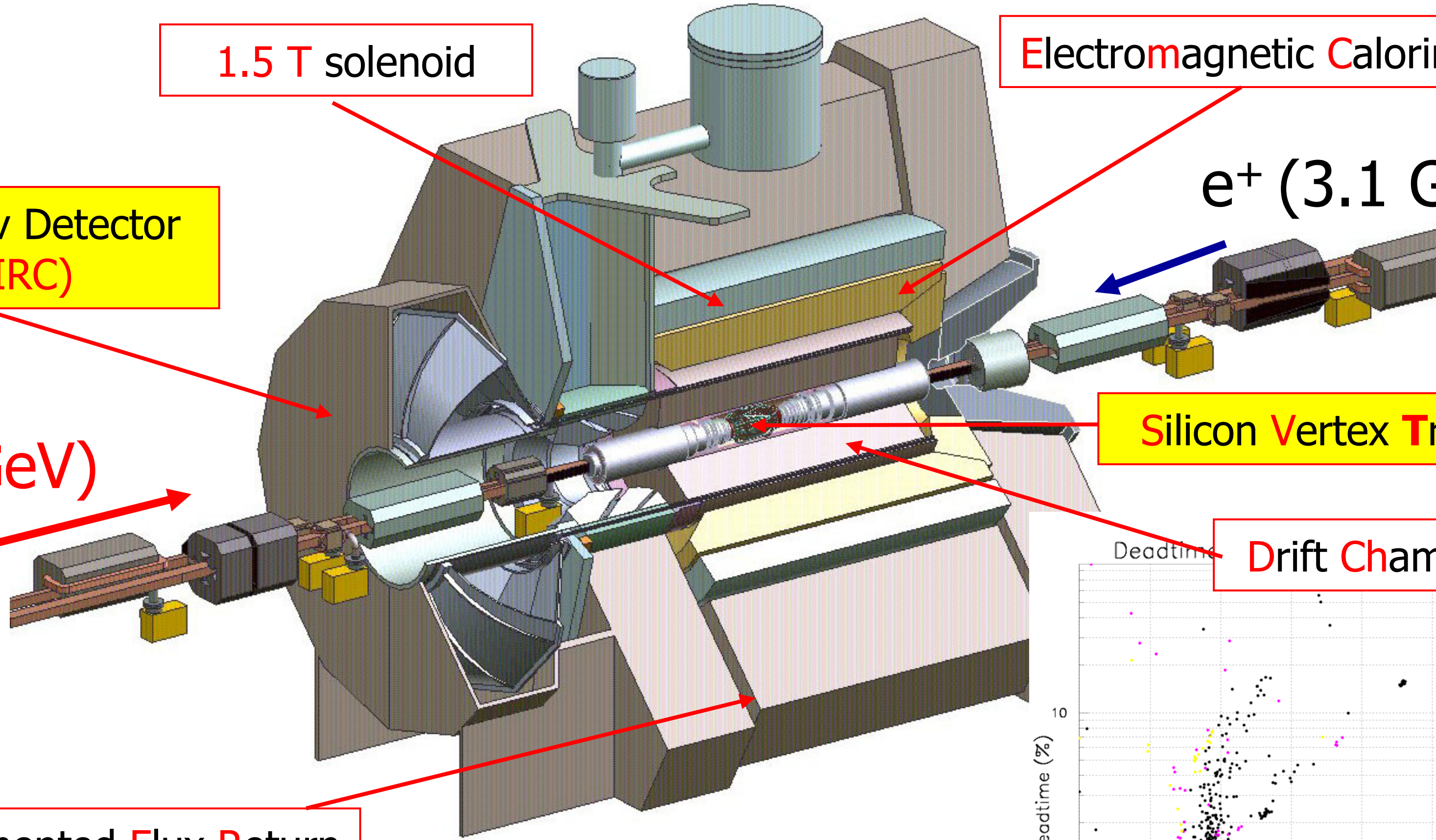


Cross sections at Υ(4S):

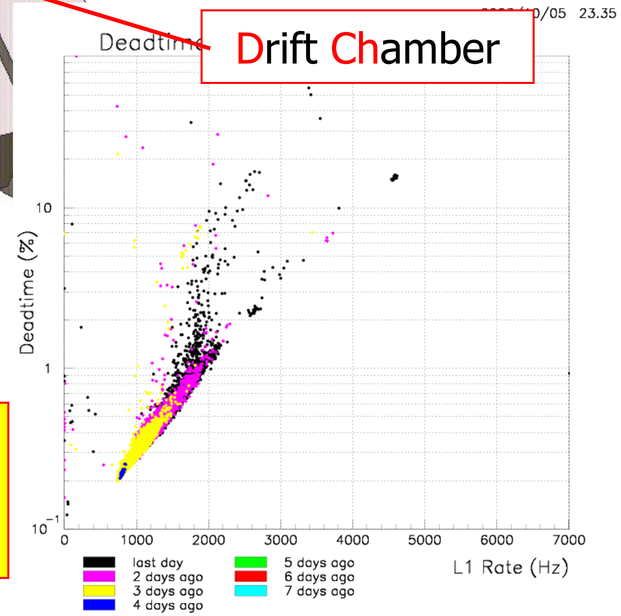
- $b\bar{b}$ ~ 1.1 nb
- $c\bar{c}$ ~ 1.3 nb
- $d\bar{d}$ ~ 0.3 nb
- $s\bar{s}$ ~ 0.3 nb
- $u\bar{u}$ ~ 1.4 nb
- $\tau^+\tau^-$ ~ 0.9 nb

BABAR collected 91.6/fb in Runs 1 and 2, and a further 33.8/fb in Run3

The BABAR Detector

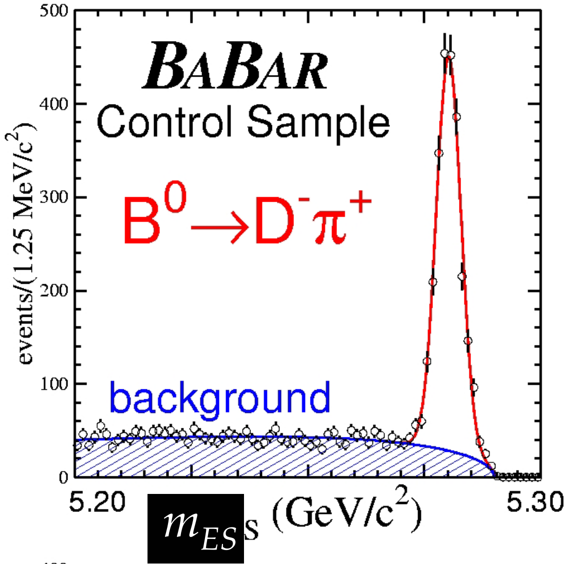


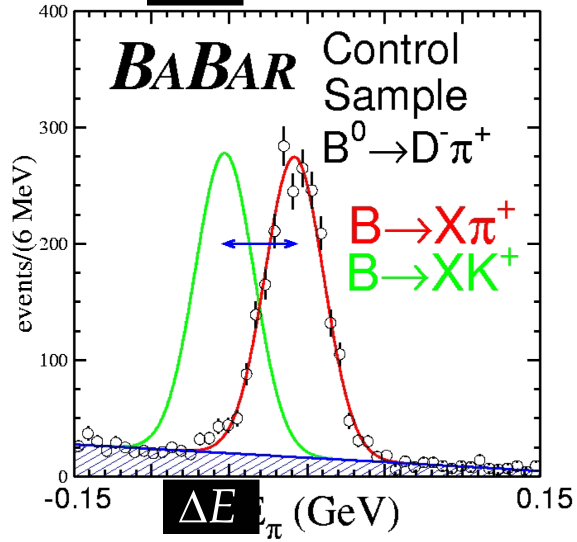
Dedicated front end electronics, DAQ, trigger systems



Experimental Tools

kinematical variables to select B





$$m_{ES} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2 / E_i^2 - p_B^2}$$

$\sigma(m_{ES}) \approx 2.6$ MeV/c^2

$\sqrt{s}$: e^+e^- CM energy

$(E_i, \boldsymbol{p}_i)$: four momentum of initial e^+e^- system

$\boldsymbol{p}_B$: B candidate momentum

} lab frame

$$\Delta E = E_B^* - E_{beam}^*$$

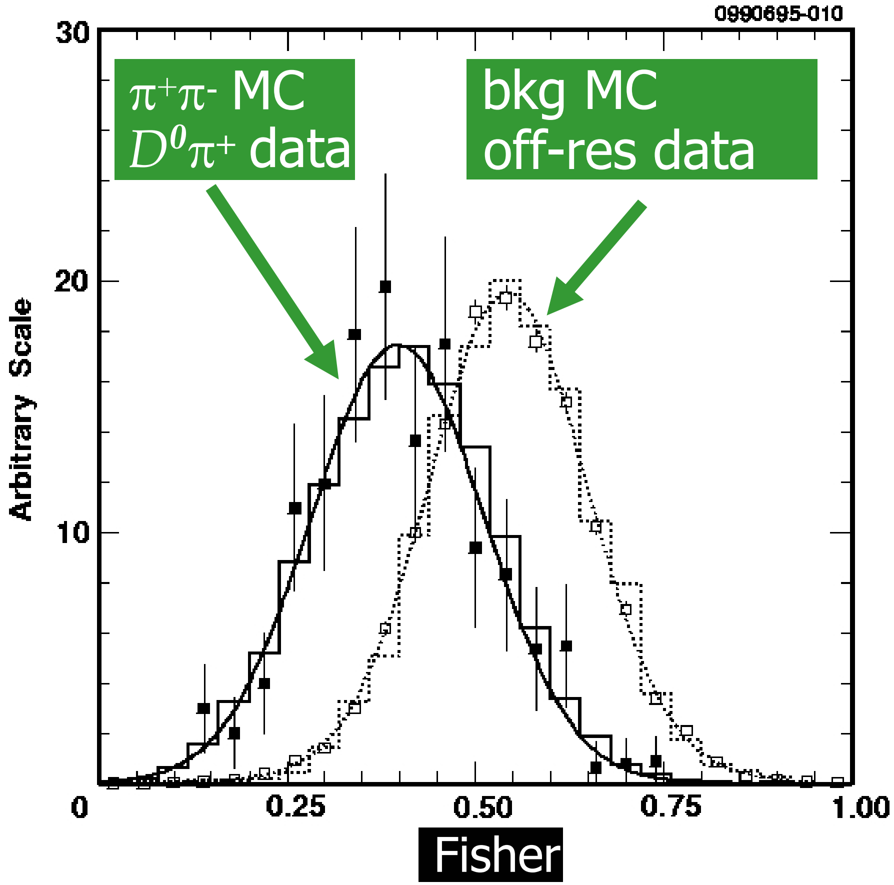
$\sigma(\Delta E) \approx 20$ MeV

but can be worse with π^0, ν…

Most of them are pioneered by CLEO!

Experimental Tools

Continuum suppression



- Moments (Fox-Wolfram moments) Thurst, helicity angle (if available)…
- Occasionally, some of correlated variables are inputs to multivariate techniques (Neural network, Fisher discriminator…)

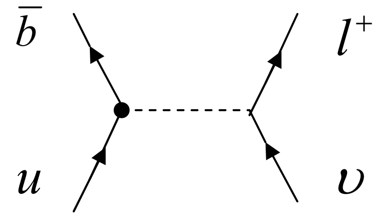
Purely leptonic decays

$B^+ \rightarrow l^+ \nu$

predictions for $B \rightarrow l\ \nu$ are especially clean – good test of SM

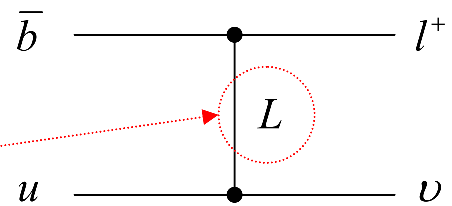
SM: W-annihilation decays with V_{ub} vertex

$$BR(B^+ \rightarrow l^+ \upsilon) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$



✓ BR is very small for $l = e,\mu$ (helicity suppression)
✓ BR ($B \rightarrow \tau\nu$) ~ 250 BR ($B \rightarrow \mu\nu$) but experimentally more difficult (multiple neutrinos)

A good place look for new physics
: charged Higgs   Hou, PRD 48 2342 (1993)
  leptoquark   Valencia, Willenbrock PRD 50 6843 (1994)



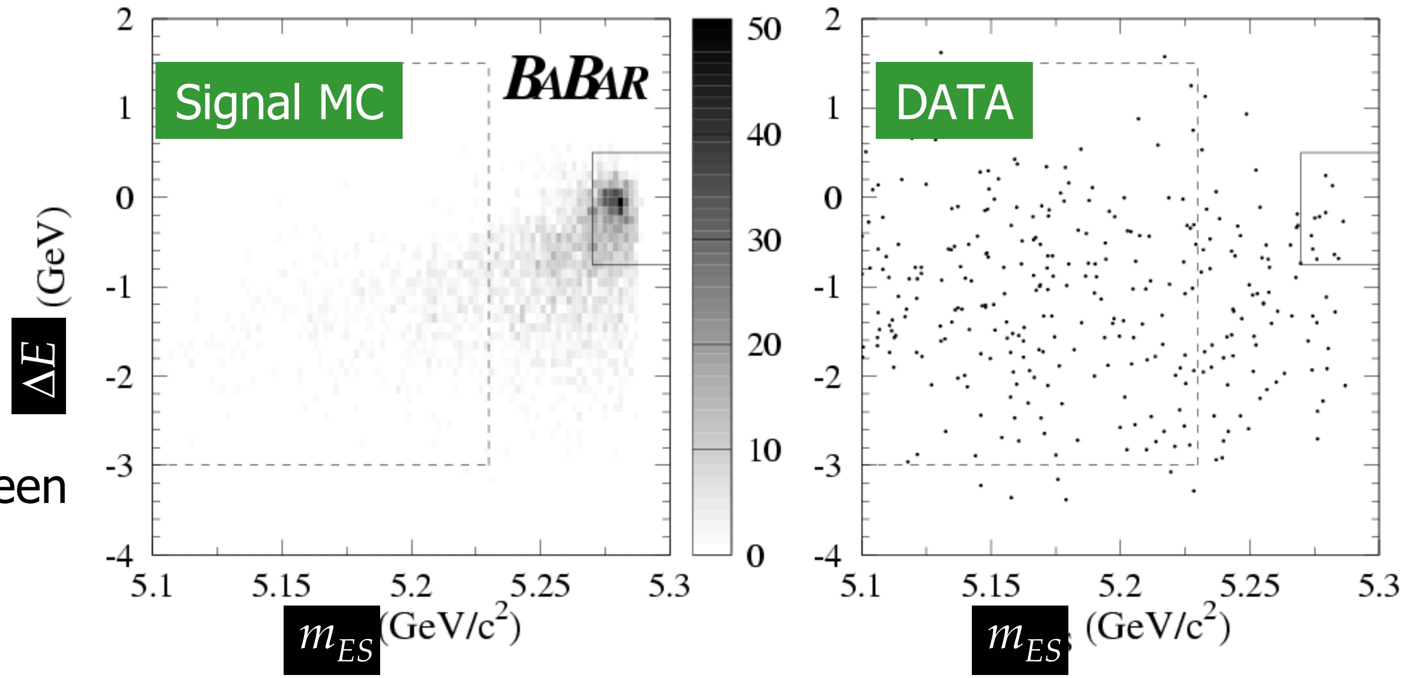
Purely leptonic decays

$B^+ \rightarrow \mu^+ \nu$

Selection:
- ✓ Event shape cuts
- ✓ Select mono-energetic muons
- ✓ ΔE and m_{ES} cuts

$BR(B^+ \rightarrow \mu^+\nu) <$ 6.6 x 10^{-6} (EPS03, 81/fb)

SM : $BR \sim 4 \times 10^{-7}$



11 events seen
BKG = 5.0+1.8-1.4

$B^+ \rightarrow \tau^+ \nu$

Purely leptonic decays

BaBar reconstructs the other B by:

$B^- \rightarrow D^0 l^- \bar{\nu} + X$ — semi-leptonic tag

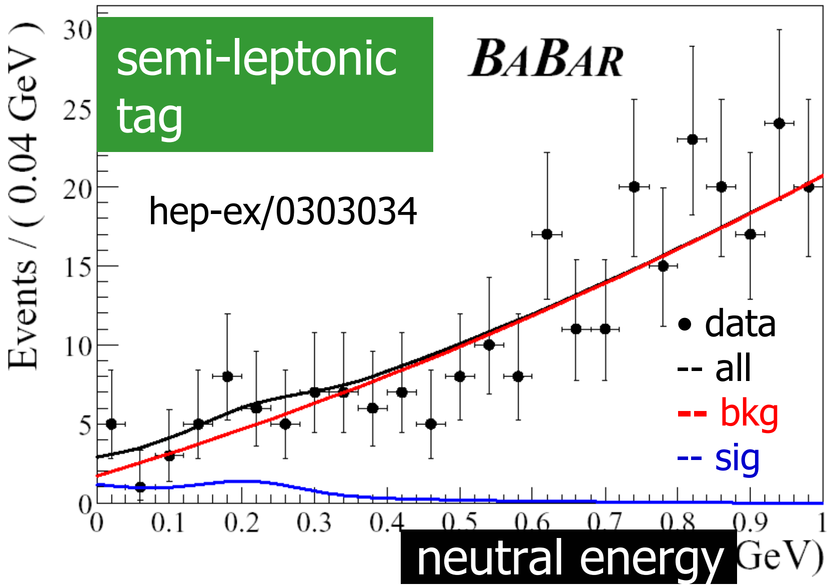
$B^- \rightarrow D^{(*)0} + n_1\pi^{\pm} + n_2K^{\pm} + n_3\pi^0 + n_4K^0_s$ — hadronic tag

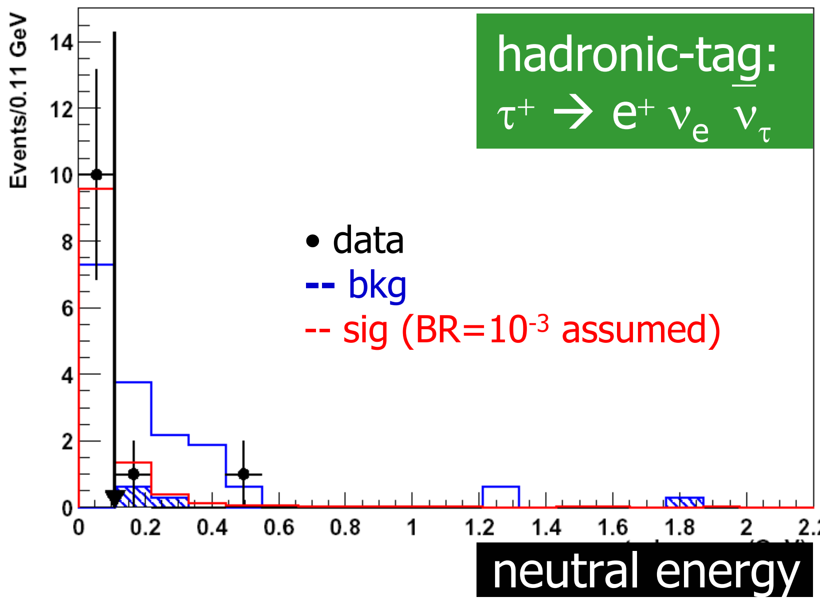
And look for τ decays of :

hadronic "-tag" {
- $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$
- $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
- $\tau^+ \rightarrow \pi^+ \bar{\nu}$
- $\tau^+ \rightarrow \pi^+\pi^0 \bar{\nu}$
- $\tau^+ \rightarrow \pi^+\pi^-\pi^+ \bar{\nu}$

(the first two: semi-leptonic -tag)

hep-ex/0304030





$BR(B \rightarrow \tau\nu) < 7.7\times10^{-4}$ (had.-tag)
$BR(B \rightarrow \tau\nu) < 4.9\times10^{-4}$ (semi.-tag)

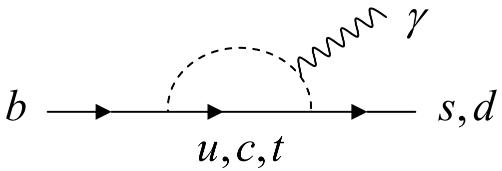
$BR(B \rightarrow \tau\nu) < 4.1\times10^{-4}$ (combined)

SM : BR ~ 4 x 10^{-5}

So far, we covered...

- Purely leptonic decays $f_B \mid V_{ub} \mid$
  - Exclusive $\tau\nu$ search

- Radiative decays
  - Exclusive $K^*\gamma$ BRs, $\rho\gamma$ and $\omega\gamma$ searches $\mid V_{td} \mid / \mid V_{ts} \mid$
- $B \rightarrow X_s ll$ decays
  - $K^{(*)}\ ll\ BR$
  - Inclusive $X_s\ ll$
  - search for $B \rightarrow K\ \bar{\nu}\nu$
- $D^{(*)}K^{(*)}$ decays
  - $B^- \rightarrow D^{*0}K^-$
- Charmless hadronic decays
  - $B \rightarrow hh$
  - Inclusive $B \rightarrow hhh$, $B \rightarrow Khh$



$b \to s\,\gamma$

Wilson coefficients: contain short distance physics only

$$H_{eff} \propto \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

Long-distance contributions are here

- Loop diagrams can accommodate heavy new particles (SUSY, H^+)

- Formulated in an effective Hamiltonian:

$$\Gamma(b \to s\gamma) = \frac{G_F^2 \alpha_{em} m_b^5}{32\pi^4} \left| V_{ts}^* V_{tb} \right|^2 \left(\left| C_7^{eff} \right|^2 + O(1/m_b, 1/m_c) \right)$$

Can be normalized with $b \to cl\nu$: ($G_F^2 m_b^5 \,|\, V_{ts}{}^* V_{tb} \,|^2$ cancels by assuming $|\,V^*_{ts} V_{tb}\,| = |\,V_{cb}\,|$)

- Probe new physics through Wilson coefficient $|\,C_7\,|$,

NLO calculation for SM and various new physics scenarios available

- A_{cp} in $B \to X_s\,\gamma$

A_{cp} can be significant if new CPV phase in $b \to s\gamma$

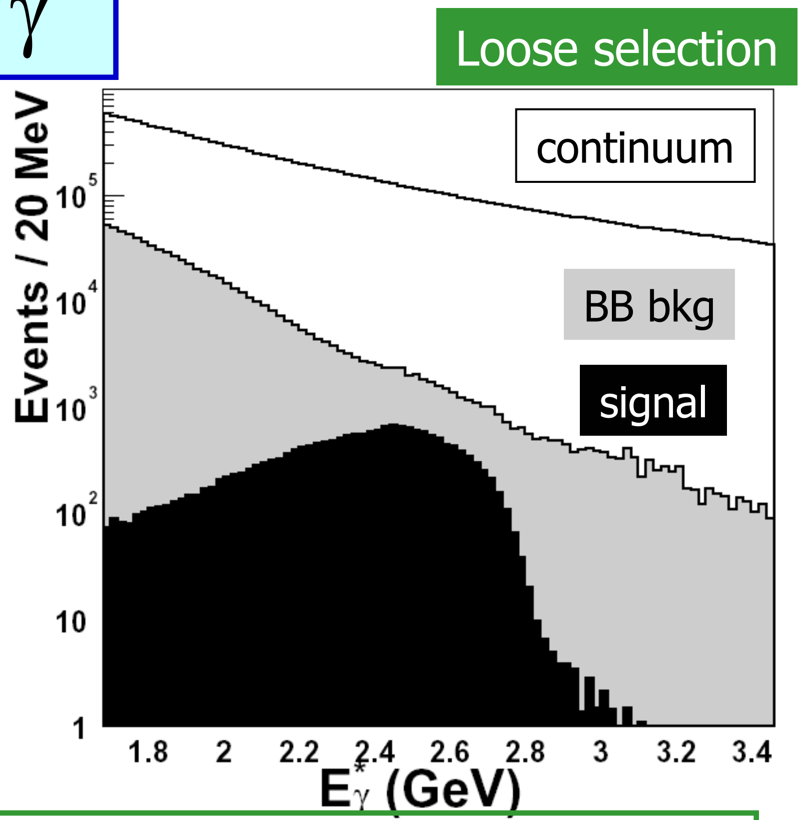
very small (<1%) in SM

- Photon spectrum

: expected to be $\delta(E_\gamma - m_b/2)$, smeared due to perturbative gluon brem + non-perturbative b quark motion

: a precise measurement of the photon spectrum allows to determine $|\,V_{ub}\,|$

$B \rightarrow X_s \gamma$



- Pioneered by CLEO (1993)
  E_γ over huge bkg (from non $\bar{B}B$ pairs)
  π^0,η backgrounds from B decays

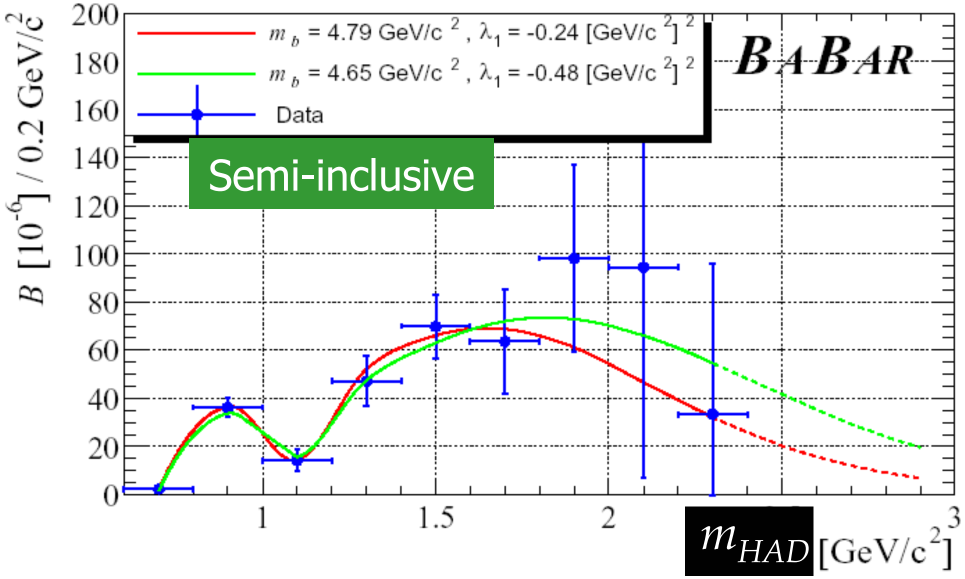
- Two issues in extracting $BR(B \rightarrow X_s \gamma)$
  Subtracting $B \rightarrow X_d \gamma$
  Correcting inefficiency due to E_γ cut

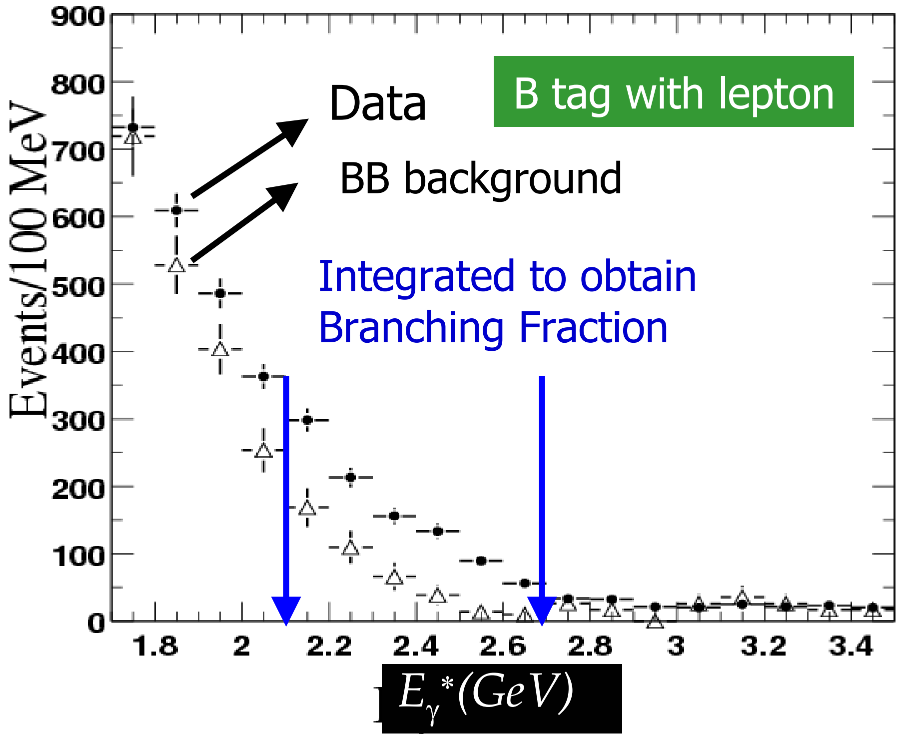
- BaBar uses two different techniques:

✓Semi-inclusive (pseudo-reconstruction) : reconstruct 12 exclusive modes obtain a hadronic mass spectrum with shape by Kagan and Neubert EPJ C7 5(1999) → extract E_γ moments and BR

✓Inclusive γ measurement + B tag with lepton
  require E_γ > 2.1 GeV
  require a high momentum lepton (from the other B)

$B \to X_s \gamma$ BRs



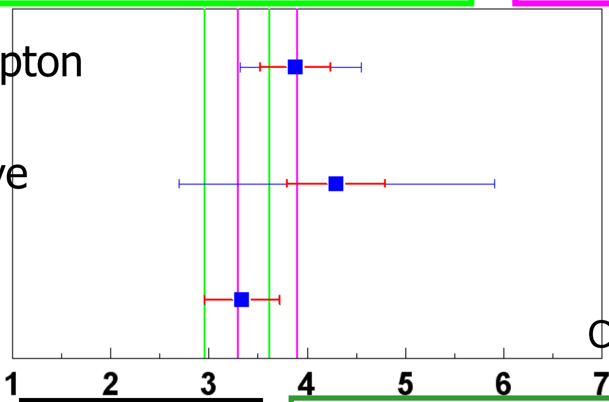


SM: Kagan and Neubert (hep-ph/9805303) | Gambino and Misiak (hep-ph/0104034)

BaBar B tag with lepton (hep-ex/0207076) — $(3.88 \pm 0.36 \pm 0.37 + 0.43 - 0.23) \times 10^{-4}$

BaBar Semi-inclusive (hep-ex/0207074) — $(4.3 \pm 0.5 \pm 0.8 \pm 1.3) \times 10^{-4}$

World Average — $(3.34 \pm 0.38) \times 10^{-4}$



$BR \times 10^4$

C.Jessop SLAC-PUB-9610 including CLEO/Belle/ALEPH

No deviations from SM: many constraints on new physics scenarios
To further reduce errors: Theory need to go from NLO to NNLO
Experiments need to lower E_γ (more data)

Exclusive radiative decays

$B \to K^*\gamma$

Experimentally very clean signal but large theoretical errors for BRs ($B \to K^*$ form factor calculations)

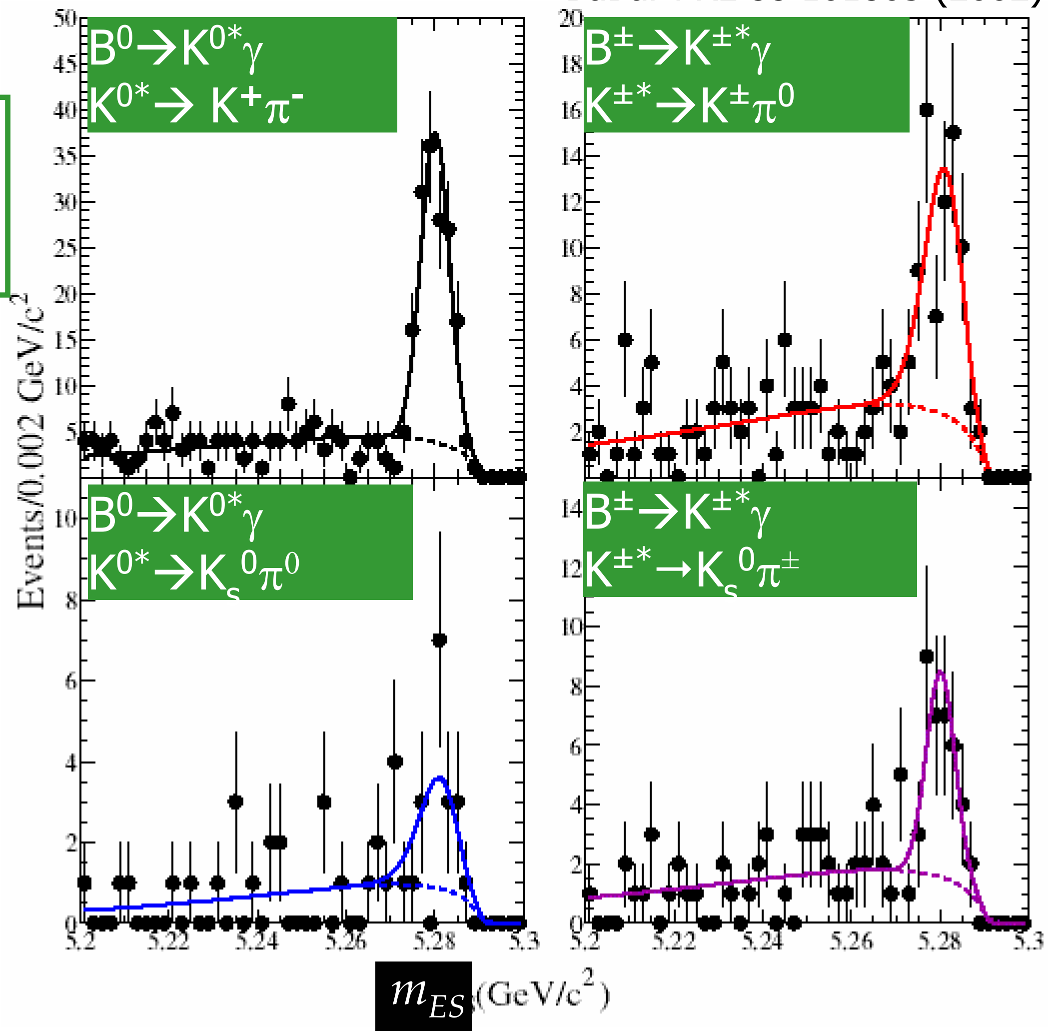
Selection:
- ✓require a high energy photon
- ✓reconstruct K^* candidates
- ✓remove continuum background

Mode	BR x 10^5
$B^0 \to K^{*0}\gamma$	4.23 ± 0.40 (stat) ± 0.22 (sys)
$B^\pm \to K^{*\pm}\gamma$	3.83 ± 0.62 (stat) ± 0.22 (sys)

Bosch and Buchalla (hep-ph/0106081):
SM predicts $BR \sim (7 \pm 2) \times 10^{-5}$, $A_{CP} < 1\%$

Theoretical debates: form factors from LCSR, lattice, and extraction from exp. consistent?

BaBar PRL 88 101805 (2002)



$$A_{CP} = \frac{B(\bar{B} \to \bar{K}^*\gamma) - B(B \to K^*\gamma)}{B(\bar{B} \to \bar{K}^*\gamma) + B(B \to K^*\gamma)}$$

= -0.044 ±0.076(stat) ±0.012 (sys) → consistent with zero

Exclusive radiative decays

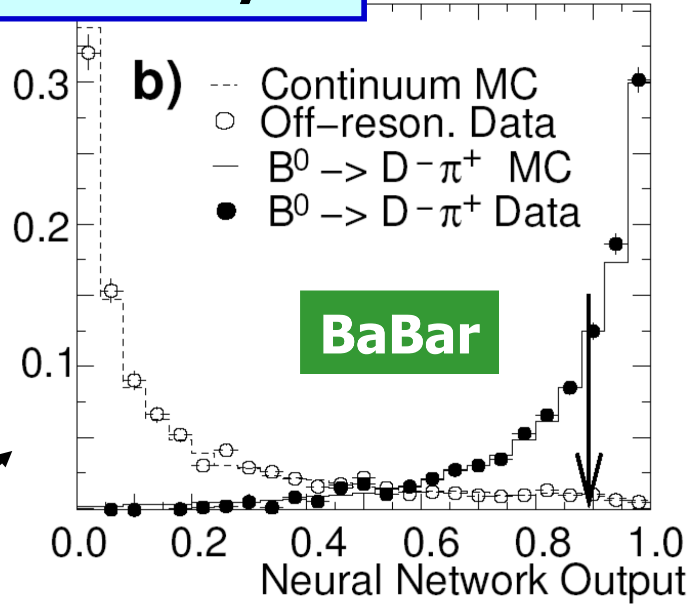
$B \to \rho(\omega)\gamma$

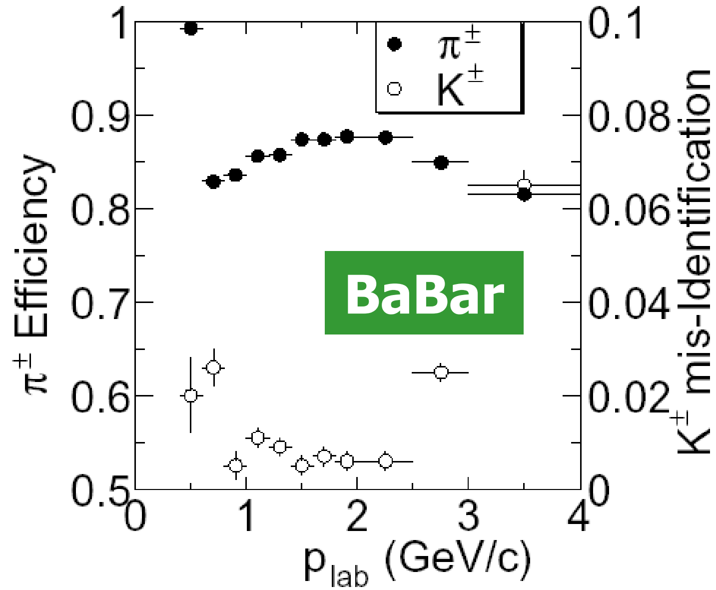
SM: $BR \sim 10^{-6}$

- $b \to d\gamma$ mode
  Mode to measure $|V_{td}/V_{ts}|$ independently from $\Delta m_d/\Delta m_s$

- Worse background from continuum than the case of $K^*\gamma$
  : Optimized neural network of event shapes, helicity, z vertex displacement, etc… (1 hidden layer of 10 nodes)

- Kaon rejection from $B \to K^*\gamma$ important
  : 80 % pion efficiency with 1-2 % kaon fake





Exclusive radiative decays

hep-ex/0306038:
78/fb

Limits on $B \rightarrow \rho(\omega)\gamma$

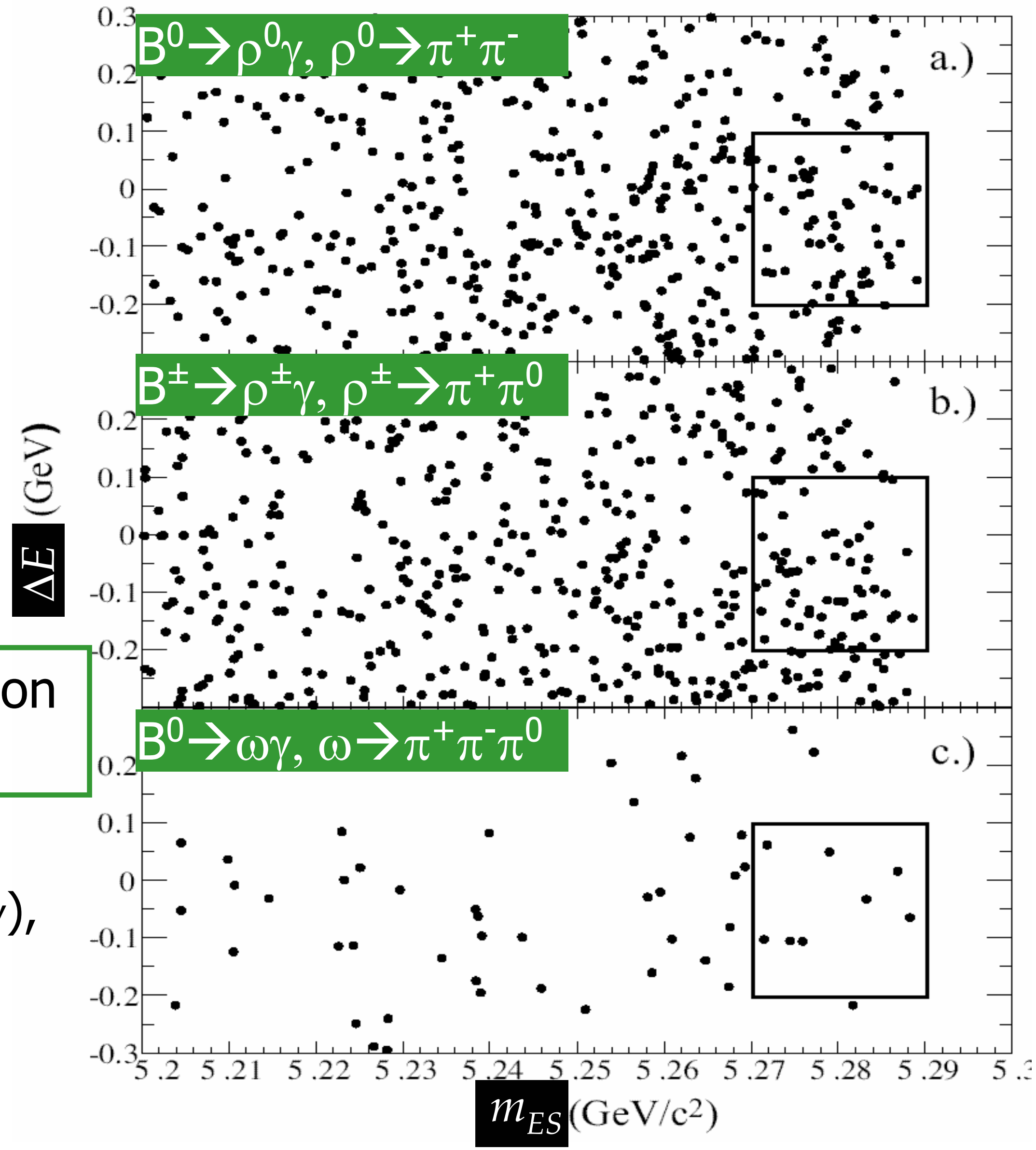
no evidence of signal observed

Mode	$BR \times 10^6$
$B^0 \rightarrow \rho^0 \gamma$	< 1.2
$B^\pm \rightarrow \rho^\pm \gamma$	< 2.1
$B^0 \rightarrow \omega \gamma$	< 1.0

Since SM $BR \sim 10^{-6}$, the observation seems just around the corner!

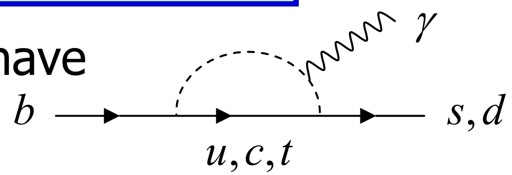
Using isospin relation:
$\Gamma(B \rightarrow \rho\gamma) = \Gamma(B^+ \rightarrow \rho^+\gamma) = 2\Gamma(B^0 \rightarrow \rho^0\gamma)$,

$BR(B \rightarrow \rho\gamma) < 1.9 \times 10^{-6}$



Exclusive radiative decays

Limits on $|V_{td}/V_{ts}|$ usually comes $\Delta m_d/\Delta m_s$ but we also have



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

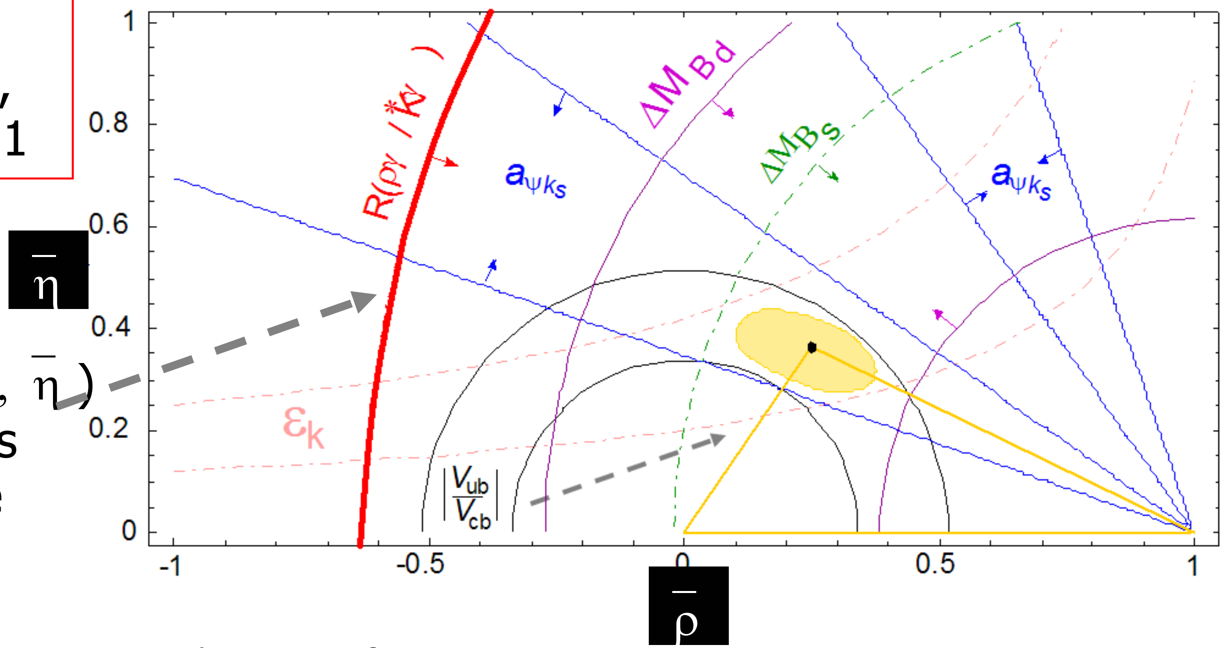
Ali and Parkhomenko
EPJ C23 89 (2002)

ζ: radio of the form factors
ΔR: calculated to leading order in α_s and Λ_{QCD}/m_H

$BR(B\to\rho\gamma)/BR(B\to K^*\gamma)$ < 0.047
and with
Using LCSR: ζ = 0.76 ±0.10,
ΔR = 0.015±0.011

gives a loose bound in the ($\bar{\rho}$, $\bar{\eta}$) plane : not competitive to ones from Δm measurements at the moment

Ali and Lunghi EPJ C26 195 (2002)



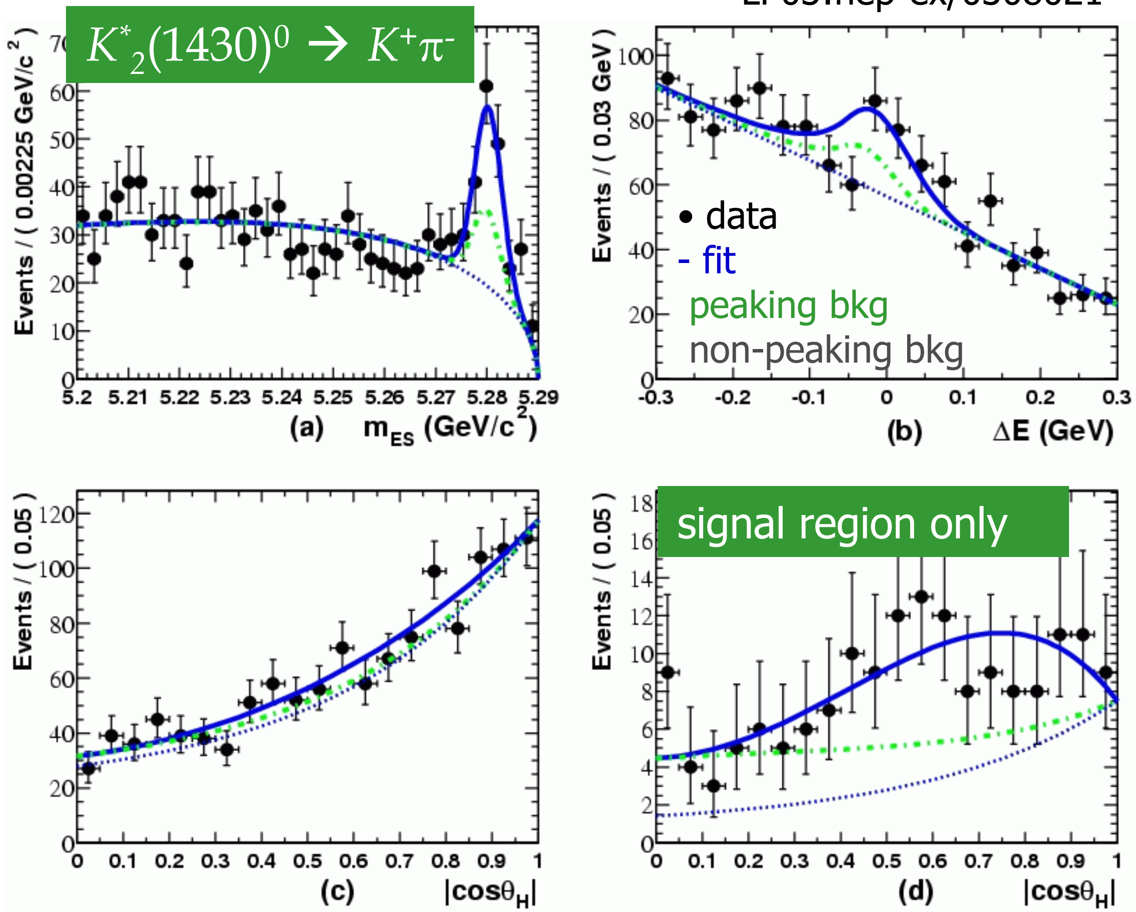
Exclusive radiative decays

$B \rightarrow K^*_2(1430)\gamma$

CLEO and Belle observed this mode previously

$K^*_2(1430) \rightarrow K\pi$ (50%)

LP03:hep-ex/0308021



θ_H : the angle of K in the rest frame of K^*_2 w.r.t. the flight direction of K^*_2 (helicity angle)

- ✓ Background suppression
  ➔neural network ($cos\theta_T$, $cos\theta_B$, p^*_{track}, p^*_γ,sphericity, Fox-Wolfram moments)
- ✓ Likelihood fit to m_{ES}, ΔE, and $\cos\theta_H$ simultaneously

5.8 σ for $K^*_2(1430)^0\gamma$
$K^*_2(1430)^0 \rightarrow K^+\pi^-$

4.1 σ for $K^*_2(1430)^+\gamma$
$K^*_2(1430)^+ \rightarrow K^+\pi^0, K^0\pi^+$

Exclusive radiative decays

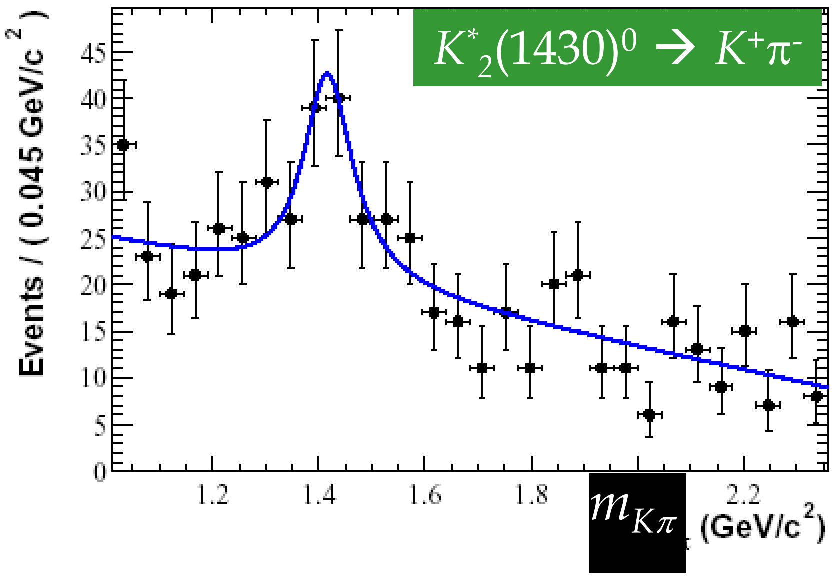
$B \rightarrow K^*_2(1430)\gamma$

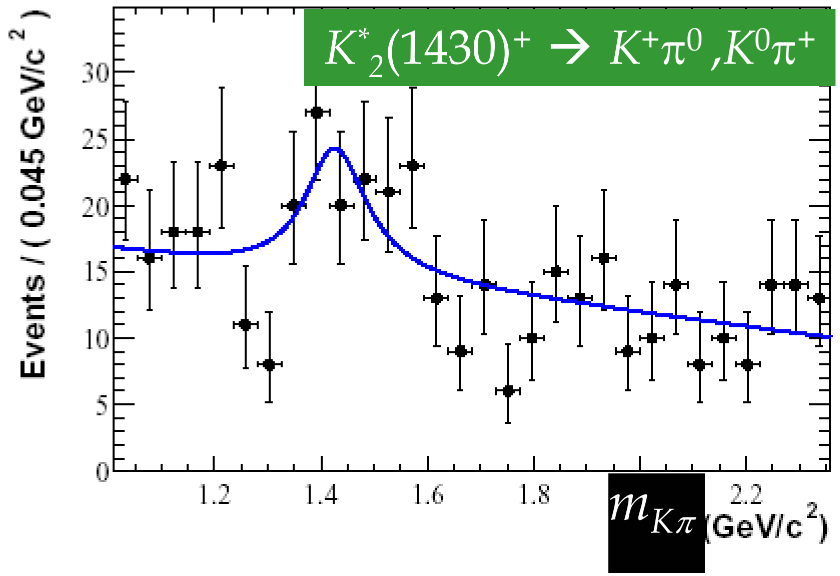
Branching fraction mesurements

Mode	BR x 10^5
$B^0 \rightarrow K^{0*}_2(1430)\gamma$	1.22±0.25±0.11
$B^\pm \rightarrow K^{\pm *}_2(1430)\gamma$	1.44±0.40±0.13

SM: (17.3 ± 8.0) x 10^{-6}

Veseli and Olsson, relativistic form-factor model PLB **367** 309 (1996)



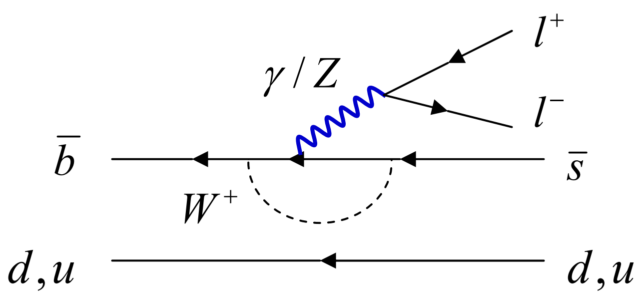


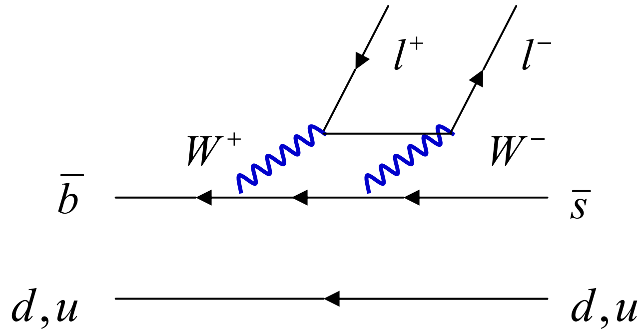
So far, we covered…

- Purely leptonic decays $f_B |V_{ub}|$
  Exclusive $\tau\nu$ search
- Radiative decays
  Exclusive $K^*\gamma$ BRs, $\rho\gamma$ and $\omega\gamma$ searches $|V_{td}|/|V_{ts}|$

- $B \rightarrow X_s ll$ decays
  $K^{(*)}\ ll\ BR$
  Inclusive $X_s\ ll$
  search for $B \rightarrow K \bar{\nu}\nu$
- $D^{(*)}K^{(*)}$ decays
  $B^- \rightarrow D^{*0}K^-$
- Charmless hadronic decays
  $B \rightarrow hh$
  Inclusive $B \rightarrow hhh$, $B \rightarrow Khh$

$b \to s\, l^+ l^-$ decays





Usually formulated as a function of $s=q^2/m^2_b=(m(ll)/m_b)^2$

$$\frac{d\Gamma(b \to s l^+ l^-)}{ds} = \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3}(1-s)^2$$

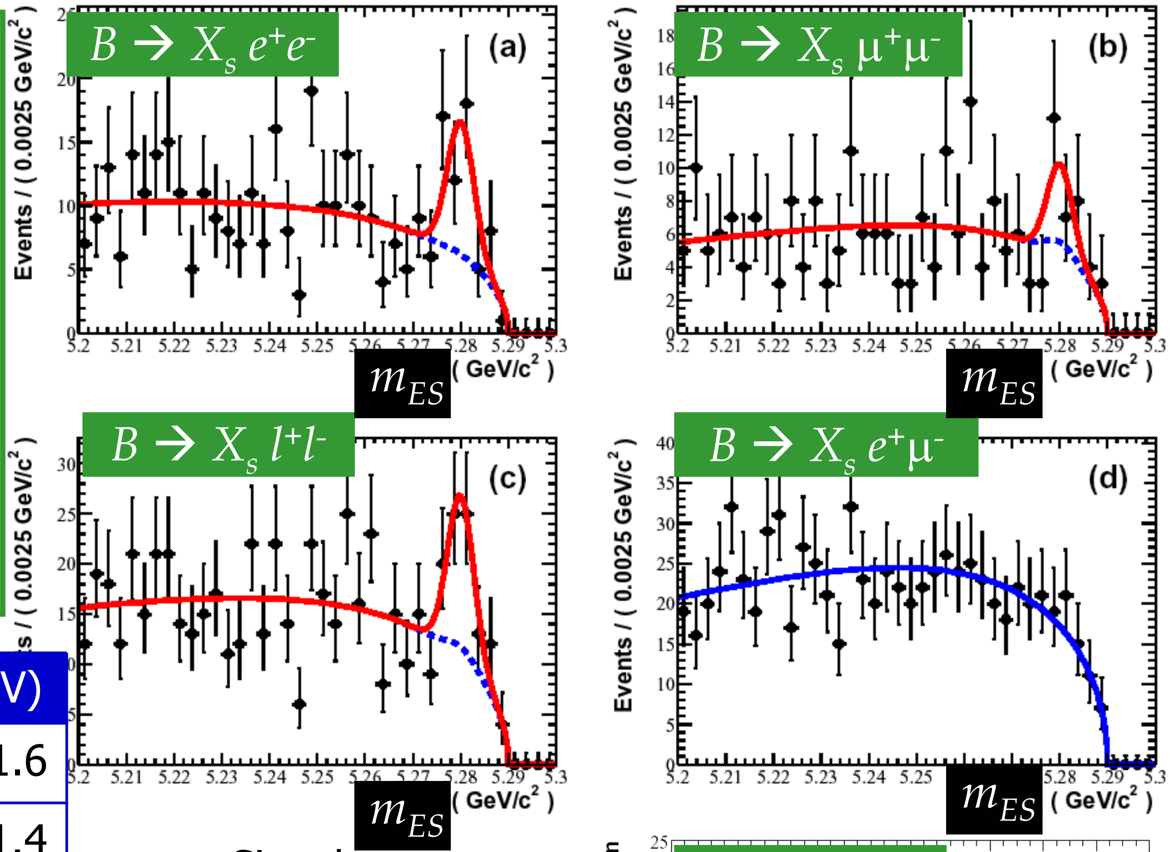
$$\times\left[(1+2s)\left(\left|C_9^{eff}\right|^2+\left|C_{10}^{eff}\right|^2\right)+4\left(1+\frac{2}{s}\right)\left|C_7^{eff}\right|^2+12\,\mathrm{Re}\left(C_7^{eff} C_9^{eff}\right)\right]+corr.$$

- NNLO calculations (up to $\bar{c}c$ threshold) available
- Sensitive to C_9, C_{10} and sign(C_7) (C_7 from $b \to s\gamma$)
- q^2 distribution, forward-backward asymmetry (A_{FB}) may reveal new physics

Inclusive $B \rightarrow X_s l^+l^-$

LP03: hep-ex/0308016, 82 fb^{-1}

- $l = e, \mu$ ($p_e > 0.5$, $p_\mu > 0.8$ GeV)
- Form $B \rightarrow X_s l^+l^-$ candidates by adding $K^\pm$ or K_s^0 and up to two $\pi^\pm$
- No more than one π^0
- In total, 10 different topologies considered
- $m(X_s) < 1.8$ GeV
- $m(l^+l^-) > 0.2$ GeV
- likelihood fits to m_{ES}



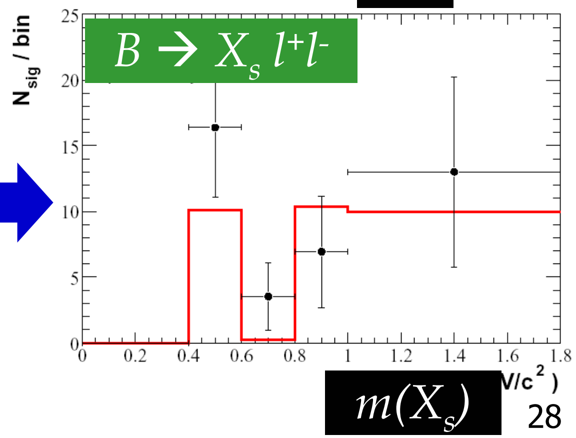
Mode	BR x 10^6 ($m(l^+l^-)$>0.2 GeV)
$B \rightarrow X_s e^+e^-$	6.6±1.9+1.9-1.6
$B \rightarrow X_s \mu^+\mu^-$	5.7±2.8+1.7-1.4
$B \rightarrow X_s l^+l^-$	6.3±1.6+1.8-1.5

With ($m(l^+l^-) > 0.2$ GeV),

SM prediction: (4.15 ± 0.7) x 10^{-6} for both e,μ

agreement with SM at 1 σ level

- Signal contributions from across a range of hadronic mass
- No deviation from SM so far



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

LP03: hep-ex/0308042 113.1 fb^{-1}

$K(*)$: K^+, K^0_s, K^{*+}, K^{*0}
l^+l^-: e^+e^-, $\mu^+\mu^-$

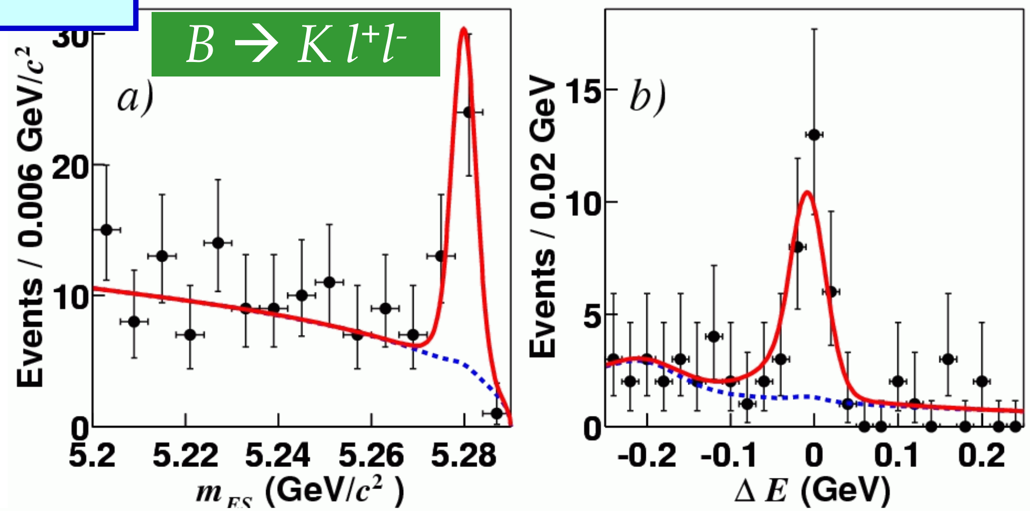
In total 8 final states

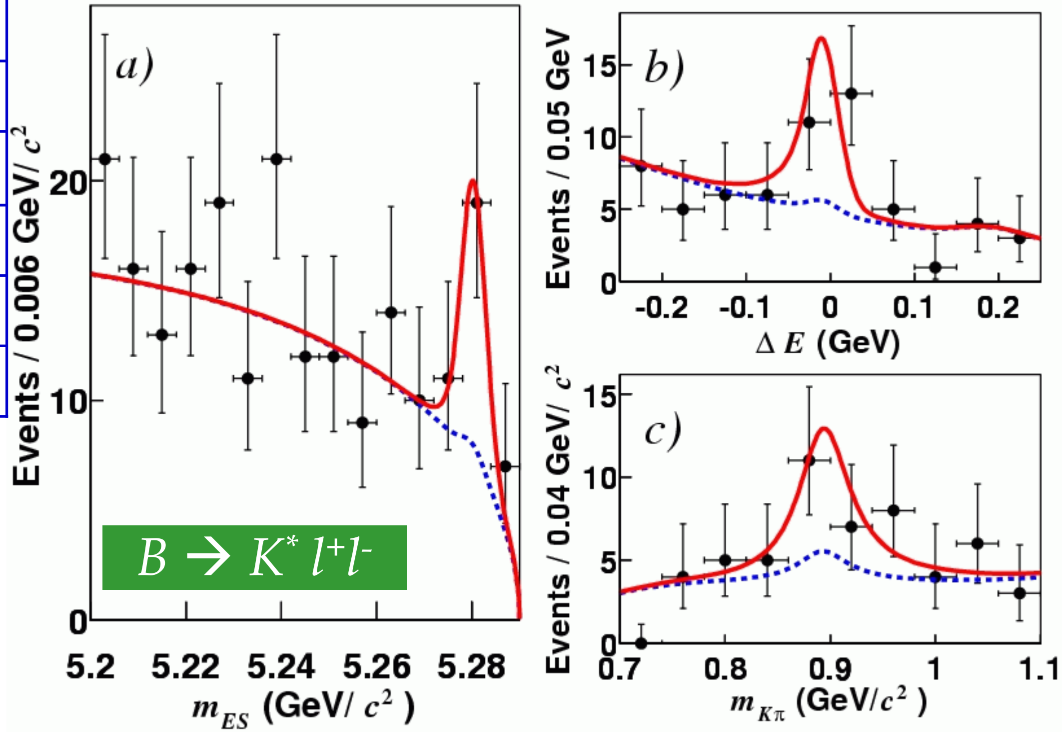
2D fit (m_{ES}, ΔE) for Kll mode
3D fit (m_{ES}, ΔE, $m_{K\pi}$) for K^*ll mode

Mode	$BR \times 10^6$
$B \to Ke^+e^-$	0.74 +0.18-0.16 ± 0.05
$B \to K\mu^+\mu^-$	0.45 +0.23-0.19 ± 0.04
$B \to K^*e^+e^-$	0.98 +0.50-0.42 ± 0.11
$B \to K^*\mu^+\mu^-$	1.27 +0.76-0.61 ± 0.16
$B \to Kl^+l^-$	0.65 +0.14-0.13 ± 0.04
$B \to K^*l^+l^-$	0.88 +0.33-0.29 ± 0.10

SM (Ali *et al*, PRD 66 034002 (2002))
$B \to Kl^+l^-$ (0.35 ± 0.12) x 10^{-6}
$B \to K^*l^+l^-$ (1.19 ± 0.39) x 10^{-6}

→ Data consistent with SM (Note: Zhong *et-al*, hep-ph/0206013 predicts slightly differently)





$B \to X_s\, l^+l^-$ BRs

Next goal is to measure *BR*s more precisely and differential distributions (A_{FB}, q^2)

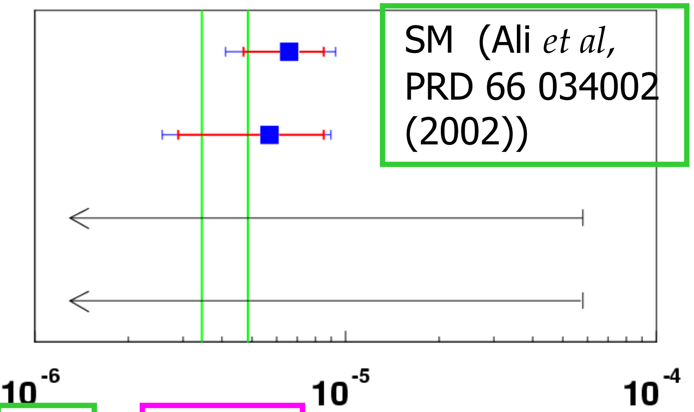
BaBar
hep-ex/0308016

$B \to X_s\, l^+l^-$ (e^+e^-)

$B \to X_s\, l^+l^-$ $(\mu^+\mu^-)$

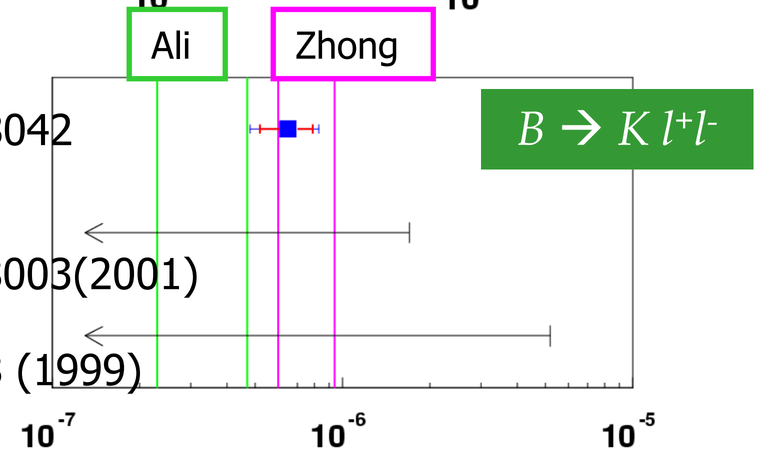
CLEO (e^+e^-)

$(\mu^+\mu^-)$



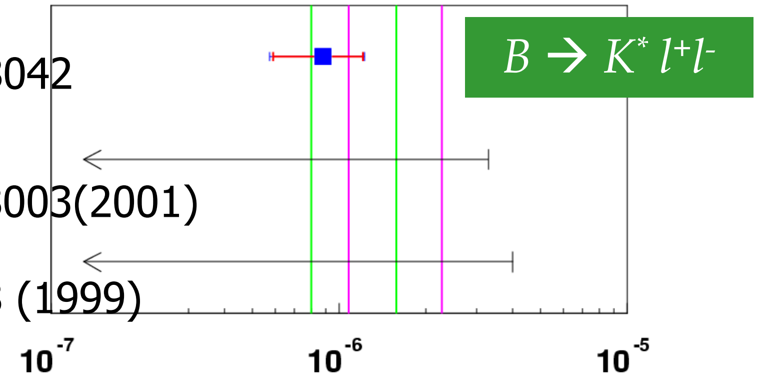
BaBar
hep-ex/0308042

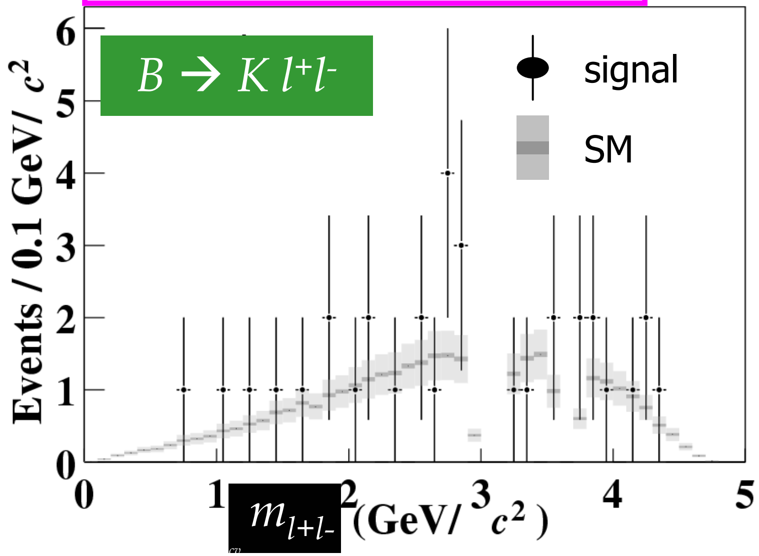
CLEO
PRL 87 1818003(2001)
CDF
PRL 83 3378 (1999)

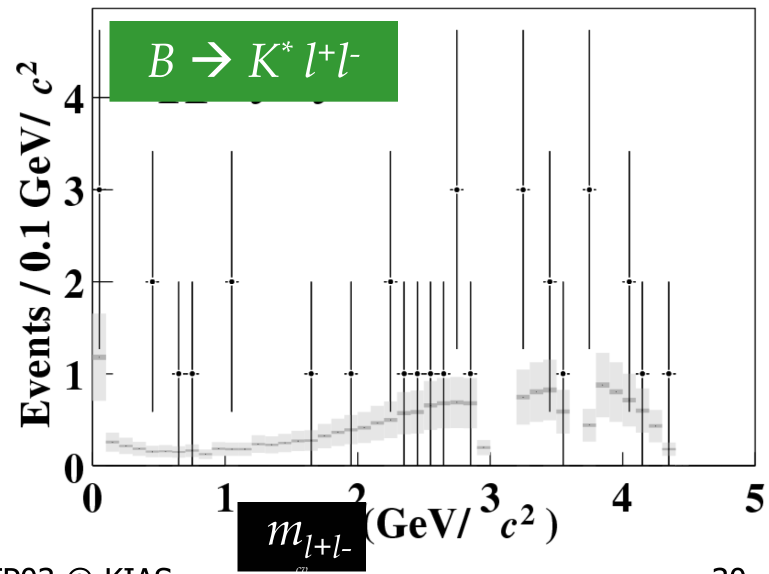


BaBar
hep-ex/0308042

CLEO
PRL 87 1818003(2001)
CDF
PRL 83 3378 (1999)







$b \to s \ \bar{\nu}\nu$

- The decay $B \to X_s \ \bar{\nu}\nu$ is theoretically cleanest (no photon-penguin), but experimentally difficult)

- SM predicts
  - ✓ $BR(B \to X_s \ \bar{\nu}\nu)$ = (3.5 ± 0.7) x 10^{-5}
    Buras hep-ph/9806417
  - ✓ $BR(B^+ \to K^+ \ \bar{\nu}\nu)$ = (0.38 +0.12-0.06) x 10^{-5}
    Buchalla et al, PRD 63 014015 (2001)

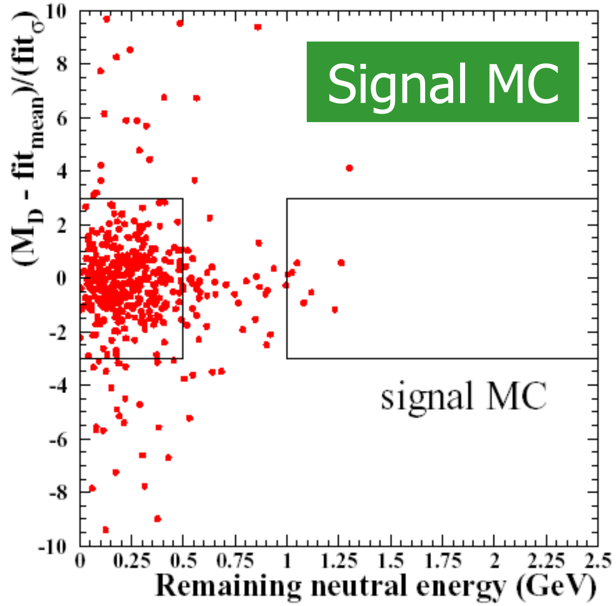
$B \to K \ \bar{\nu}\nu$

- BaBar looked at the exclusive mode $B \to K \ \bar{\nu}\nu$
- Two undetected neutrinos ➔ The other side of B must be tagged
- BaBar uses two methods for B reconstruction

Semi-leptonic tag | Hadronic tag

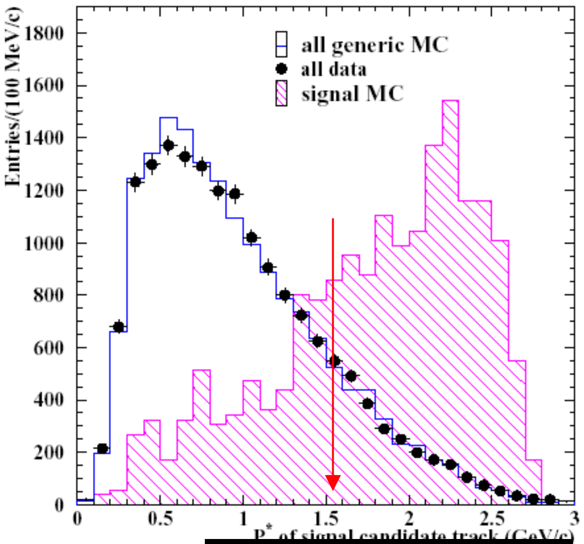
$B \rightarrow K \nu\bar{\nu}$

2 events seen
BKG = 2.2

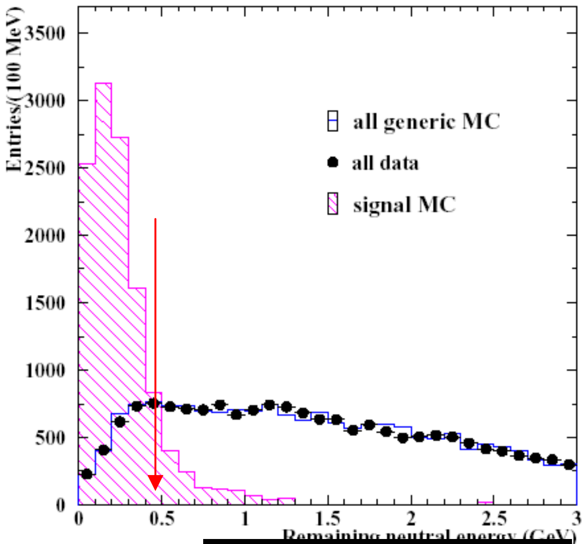


Semi-leptonic tag ($B^- \rightarrow D^0 l^- \bar{\nu} X$)

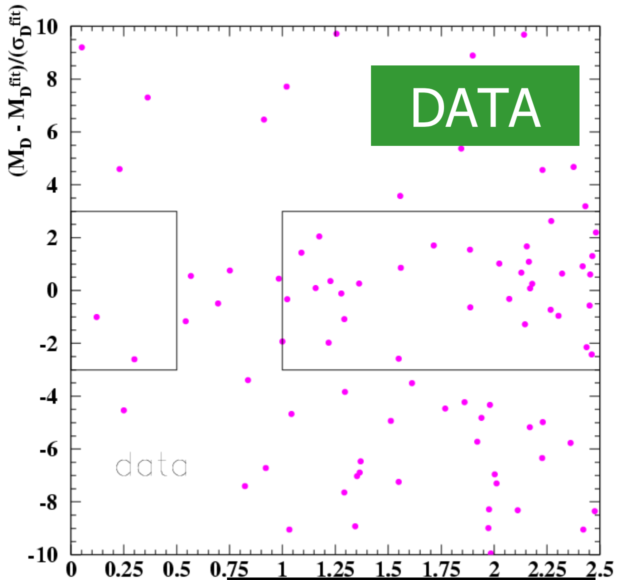
✓Select semi-leptonic decays (0.5%)
✓Signal side B
  only one track w/ p^*_K > 1.5 GeV
  E_{left} < 0.5 GeV



p^* of candidate track



remaining neutral E



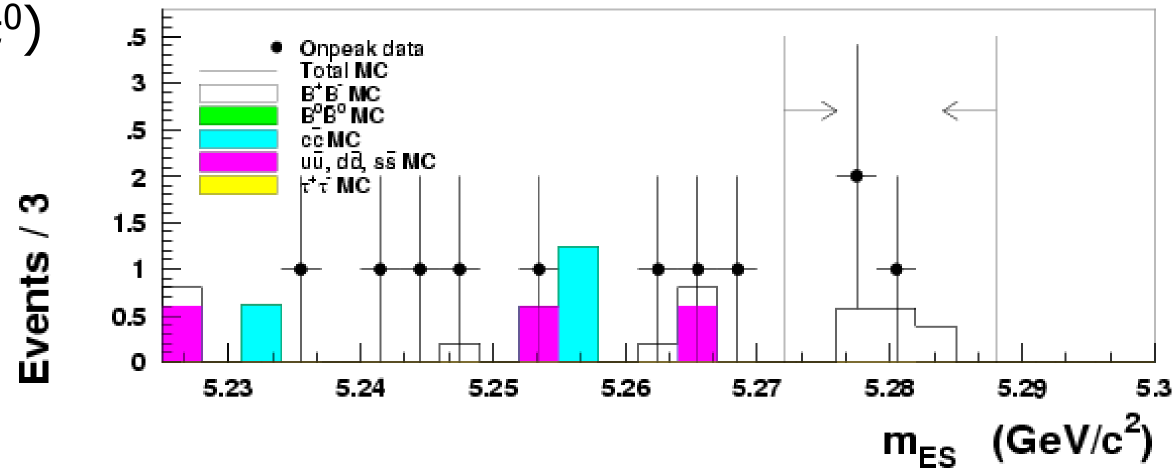
remaining neutral E

$B \rightarrow K \nu\bar{\nu}$

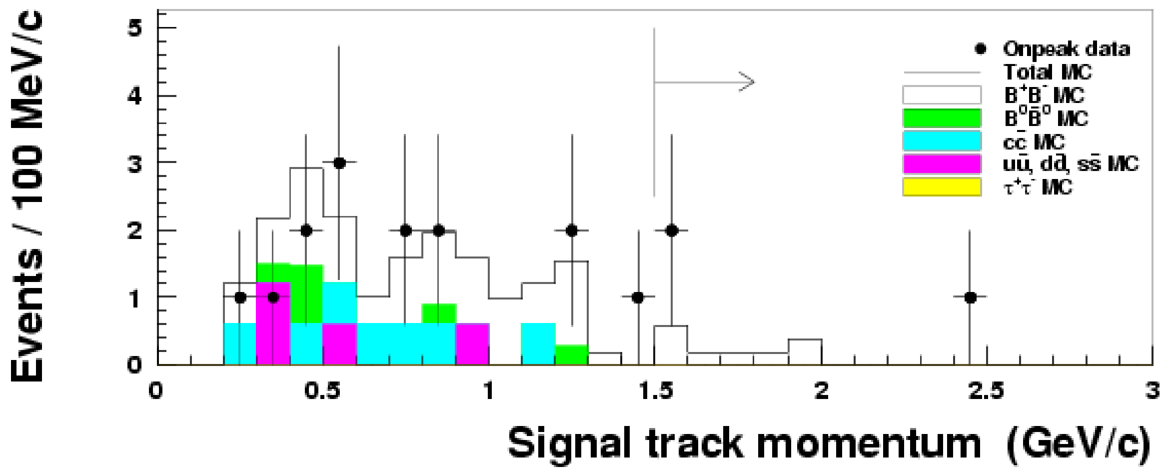
Hadronic tag ($B^- \rightarrow D^0 X^-$)

3 events seen
BKG = 2.7 ± 0.8

✓Signal side B : similar to semi-leptonic case (but remove π^0)
✓Select Hadronic decays (0.13%)

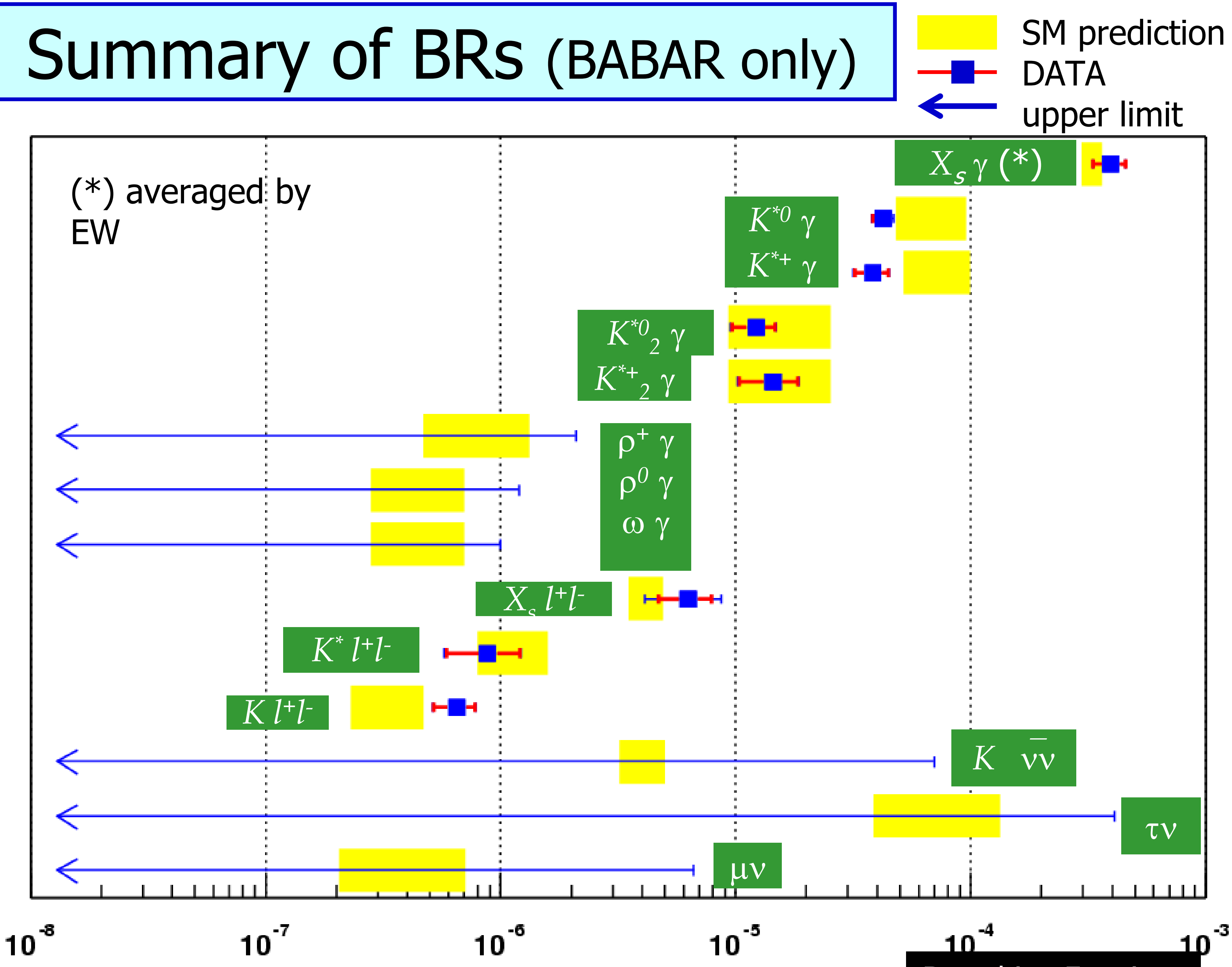


Method	BR x 10^4
Hadronic tag	< 0.94
Semi-leptonic	< 1.05
Combined	< 0.70



SM: $BR \sim 10^{-6}$

Summary of BRs (BABAR only)

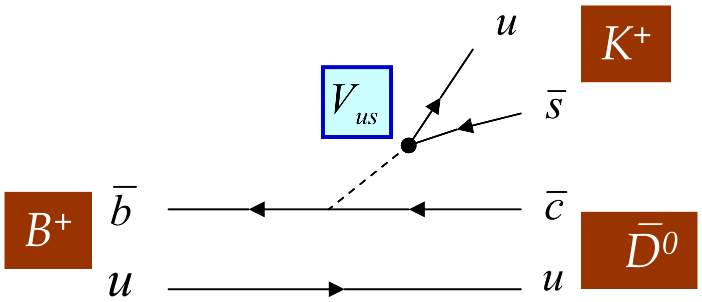


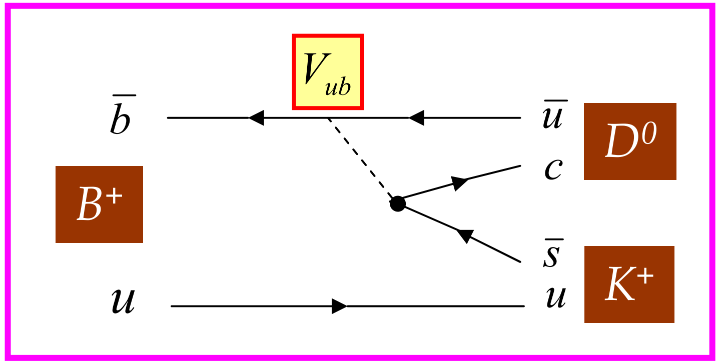
So far, we covered…

- Purely leptonic decays $f_B \,|\, V_{ub} \,|$
  - Exclusive $\tau\nu$ search
- Radiative decays
  - Exclusive $K^*\gamma$ BRs, $\rho\gamma$ and $\omega\gamma$ searches $|\, V_{td} \,|/|\, V_{ts} \,|$
- $B \rightarrow X_s ll$ decays
  - $K^{(*)}\, ll\ BR$
  - Inclusive $X_s\ ll$
  - search for $B \rightarrow K\ \bar{\nu}\nu$

- $D^{(*)}K^{(*)}$ decays
  - $B^- \rightarrow D^{*0}K^-$
- Charmless hadronic decays
  - $B \rightarrow hh$
  - Inclusive $B \rightarrow hhh$, $B \rightarrow Khh$

Angle γ and $B \rightarrow D_{CP}K$



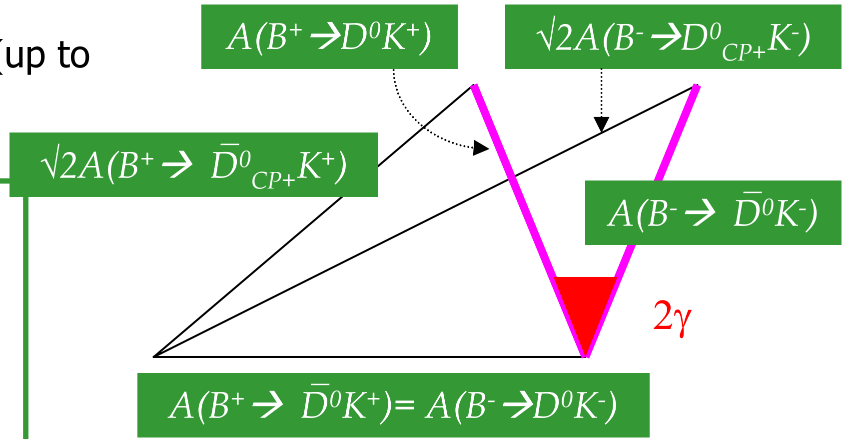


color suppressed

triangle is squashed

$$D^0_{CP^\pm} = \frac{1}{\sqrt{2}}\left(| D^0 > \pm | \overline{D}^0 > \right)$$

Related with γ angle (up to discrete ambiguities)



- Presently the amount of data is insufficient to measure more amplitude triangles
- We can look for a time integrated direct CP asymmetry

$$A_{CP} = \frac{B(B^- \rightarrow D^0_{CP} K^-) - B(B^+ \rightarrow D^0_{CP} K^+)}{B(B^- \rightarrow D^0_{CP} K^-) + B(B^+ \rightarrow D^0_{CP} K^+)}$$

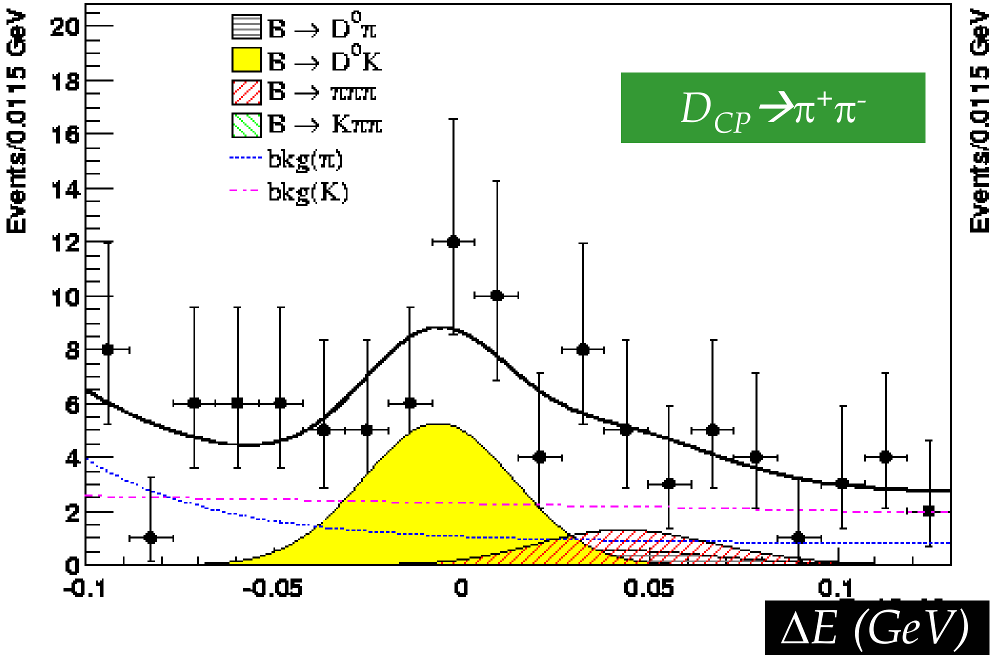
$$= \frac{\pm 2r \sin\delta \sin\gamma}{1 \pm 2r \cos\delta \cos\gamma + r^2}$$

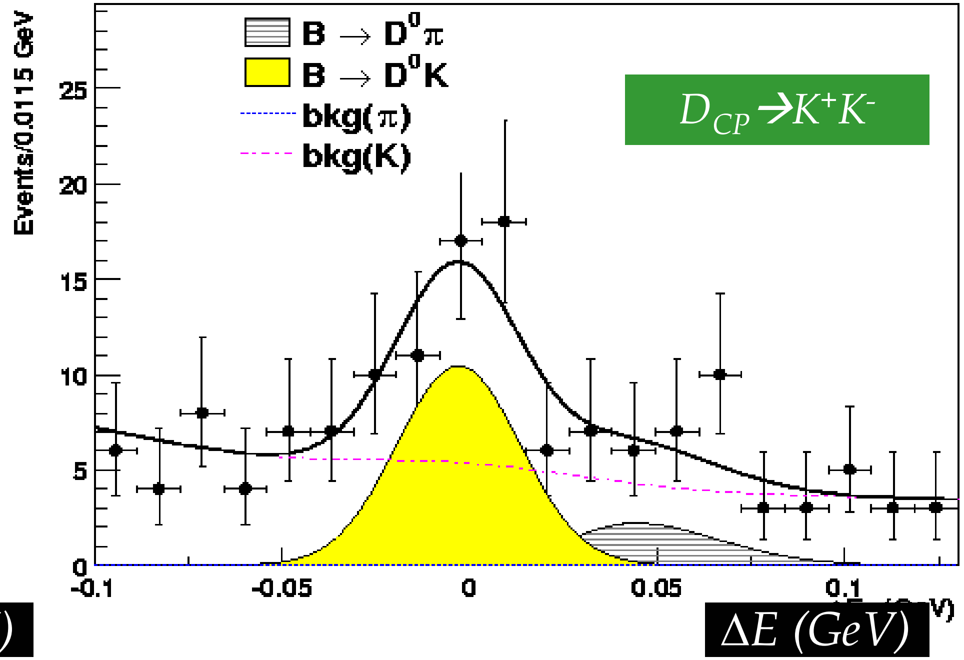
Requires selecting CP eigenstates:
CP +: $\pi^+\pi^-$, K^+K^-
CP - : K^0_s ($\pi^0, \varphi, \omega, \eta, \eta', \ldots$)

$B^- \to D_{CP=+1} K^-$

Look for $D_{CP} \to K^+K^-$ and $\pi^+\pi^-$ (CP=+1)
Likelihood fits (m_{ES}, ΔE, particle ID (for KK), $m(D^0)$ (for $\pi\pi$)) in order to extract BRs

EPS03: 81.8/fb





$$R_{(CP)} = \frac{B(B^- \to D^0_{CP} K^-) + B(B^+ \to D^0_{CP} K^+)}{B(B^- \to D^0_{CP} \pi^-) + B(B^+ \to D^0_{CP} \pi^+)}$$

ratio of Cabibbo-suppressed to -favored BRs

= (8.8 ± 1.6 ± 0.5) x 10 $^{-2}$

A_{CP} = 0.07 ± 0.17 ± 0.06 → No sizable DCPV seen

Summary of $B \rightarrow D^{(*)}K^{(*)}$

Mode	R_+	A_+
$B^- \rightarrow D^0_{CP}K^-$	1.06 ± 0.26 ± 0.17	0.17 ±0.23 ±0.08

Parameterization from hep-ph/0306308
Belle measured R_- and A_- as well

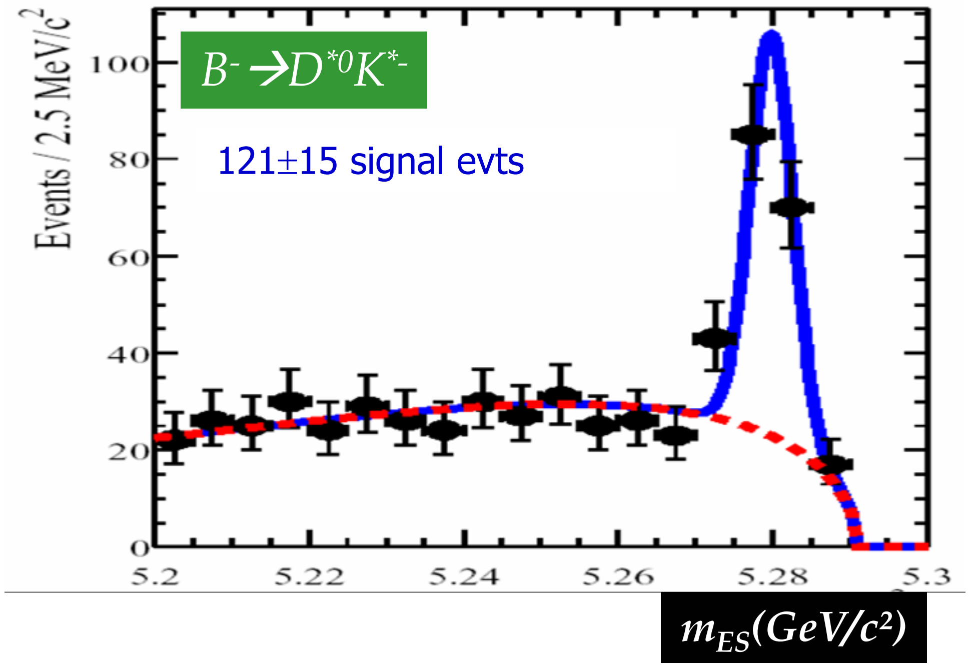
$$R_{\pm} \equiv \frac{B(B^- \to D^0_{CP}K^-) - B(B^+ \to D^0_{CP}K^+)}{B(B^- \to D^0 K^-)}$$

A_+ is A_{CP} for CP=+1, A_- for CP=-1

Mode	BR
$B \rightarrow D^0K^*$	(6.3 ± 0.7 ± 0.4) x 10^{-4}
$B^0 \rightarrow \bar{D}^0K^{*0}$	(3.0 ± 1.3 ± 0.6) x 10^{-5}
$B^0 \rightarrow \bar{D}^0K^0$	(3.4 ± 1.3 ± 0.6) x 10^{-5}
$B^- \rightarrow D^{*0}K^{*-}$	(8.3 ± 1.1 ± 1.0) x 10^{-4}

B-$\rightarrow D^{*0}K^{*-}$ is a vector-vector decay
longitudinal polarization measured to be :
Γ_T/Γ = 0.86 ± 0.06 ± 0.03

EPS03 79.1/fb



• Current experimental errors are too large for simultaneous extraction of γ, ratio of $b \rightarrow c$ and $b \rightarrow u$ amplitudes (r_{DK}) and the strong phase

So far, we covered…

- Purely leptonic decays $f_B |V_{ub}|$
  - Exclusive $\tau\nu$ search
- Radiative decays
  - Exclusive $K^*\gamma$ BRs, $\rho\gamma$ and $\omega\gamma$ searches $|V_{td}|/|V_{ts}|$
- $B \to X_s ll$ decays
  - $K^{(*)} ll$ BR
  - Inclusive $X_s ll$
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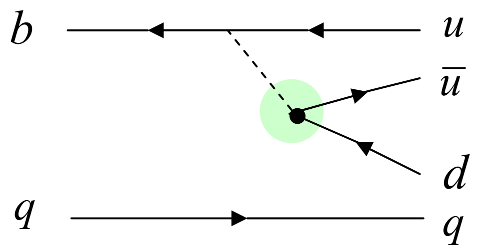
- $D^{(*)}K^{(*)}$ decays
  - $B^- \to D^{*0}K^-$

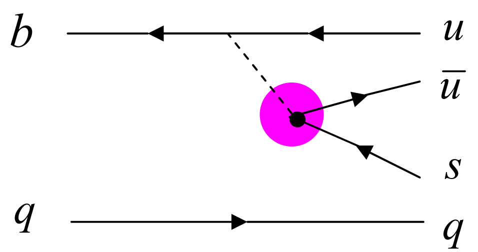
- Charmless hadronic decays
  - $B \to hh$
  - Inclusive $B \to hhh$, $B \to Khh$

Charmless hadronic decays

Tree diagrams



$B \to \pi\pi$: $(\pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0)$
$B \to \rho\pi$, $B \to \rho\rho$, $a_1\pi$, …

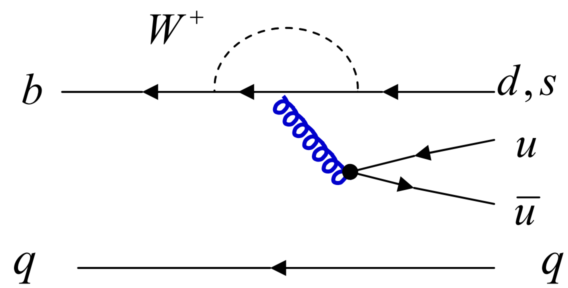


$B \to K\pi$: $(K^+\pi^-, K^0\pi^+, K^0\pi^0\ldots)$

CKM suppressed

Unfortunately, tree diagrams are not alone: penguins (gluonic and electroweak) can also lead to the same final states:

+



Data indicate gluonic penguins are large and complicate extraction of α

Interference of T & P results in Direct CPV and sensitivity to γ

Charmless hadronic decays

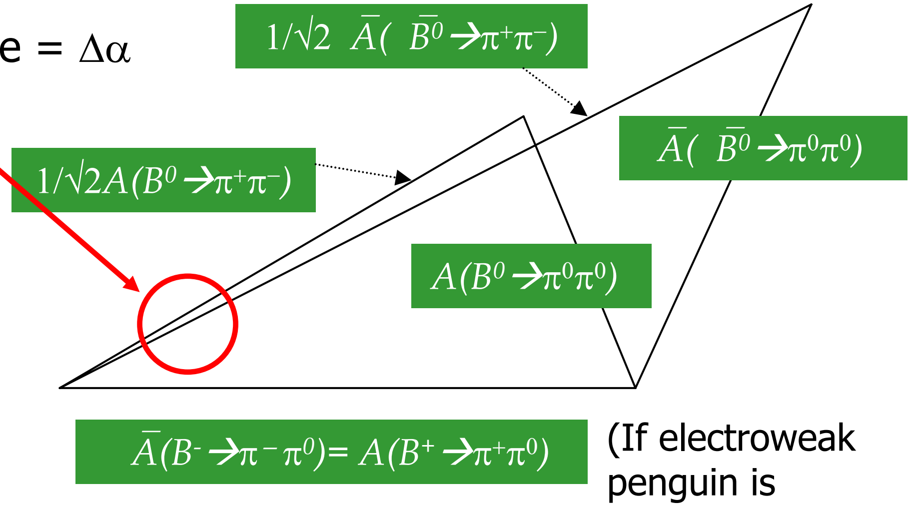
$B \to \pi\pi$

Two isospin relationships for the decay amplitudes of B and $\bar{B}$ mesons into 2 pions
➔ Angle between the two triangle = $\Delta\alpha$

We need:

$BR(B^0 \to \pi^+\pi^-)$ $\quad BR(\bar{B}^0 \to \pi^+\pi^-)$
$BR(B^\pm \to \pi^\pm\pi^0)$
$BR(B^0 \to \pi^0\pi^0)$ $\quad BR(\bar{B}^0 \to \pi^0\pi^0)$

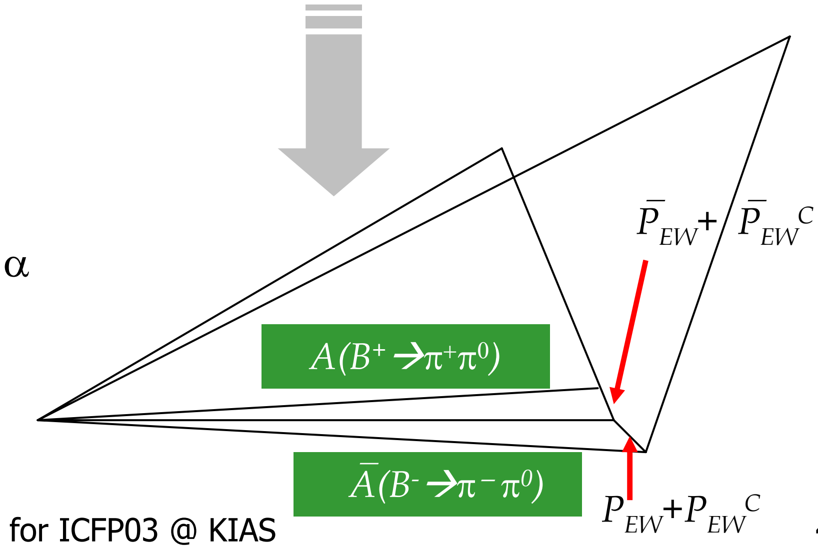
to measure the sides of the triangles



(If electroweak penguin is neglected)

- One expects $BR(B \to K\pi)/BR(B \to \pi\pi)$ ~ 5 % only tree is assumed
- But measured $BR(B \to K\pi)/BR(B \to \pi\pi)$ ~ 4

➔ penguins are significant



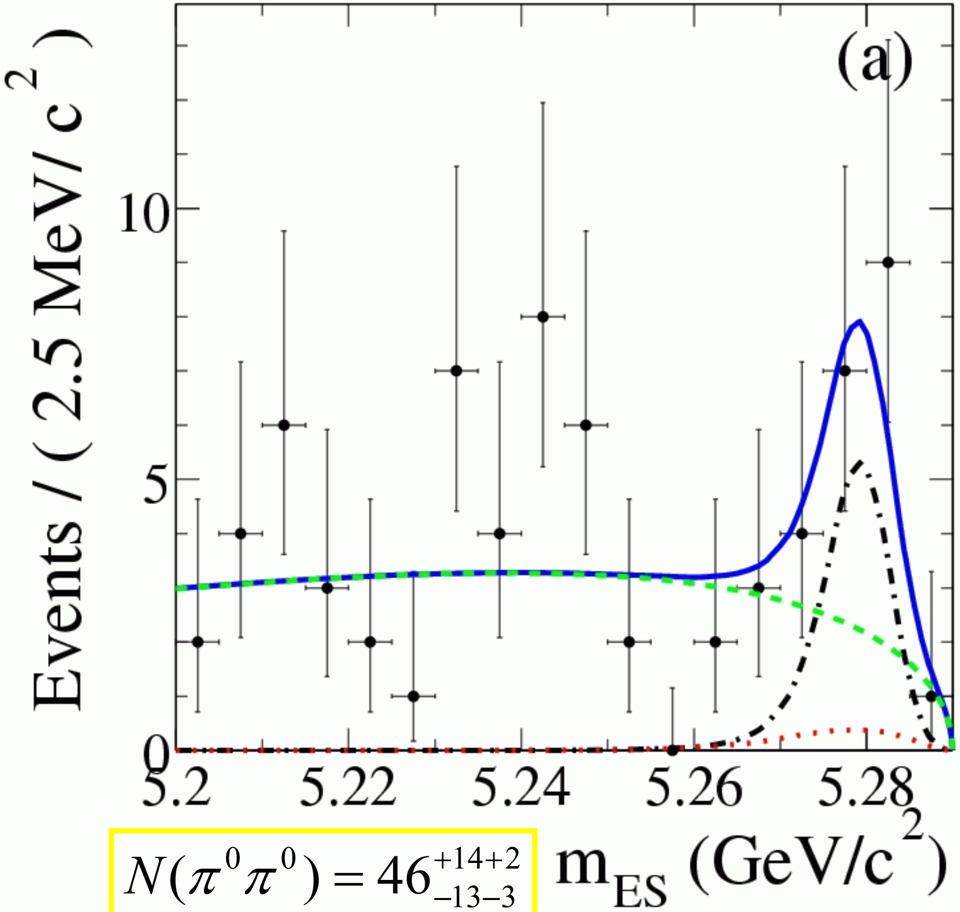
Two triangles no longer have a common base
➔ no single measurement is likely to give the value α

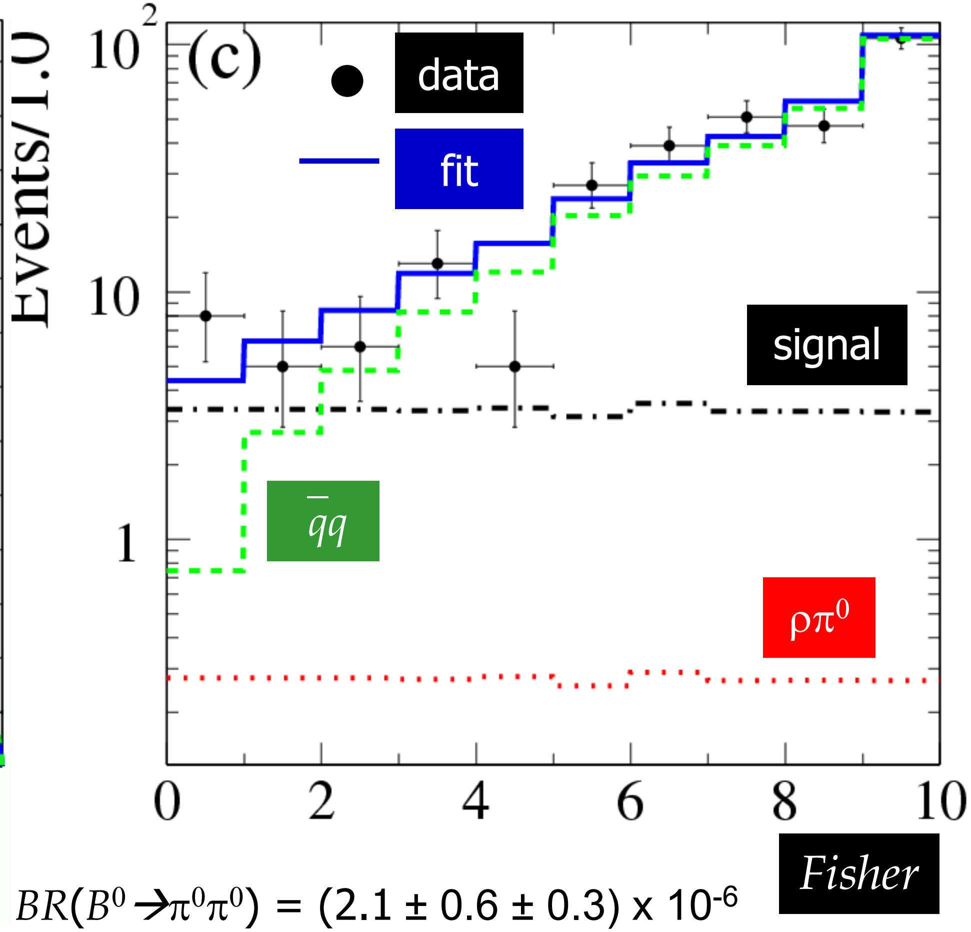
Quinn and Grossman (hep-ph/9712306) suggest a boundary

$$\sin^2 \Delta\alpha \le \frac{BR(B^0 \to \pi^0\pi^0)}{BR(B^\pm \to \pi^\pm\pi^0)}$$

$B \rightarrow \pi^0\pi^0$

- ✓ Used the full data set (113/fb) LP03
- ✓ Major backgrounds include continuum and $B \rightarrow \rho^{\pm}\pi^0$
- ✓ maximum likelihood fit (m_{ES}, ΔE, Fisher) to extract the signal yield





$N(\pi^0\pi^0) = 46^{+14+2}_{-13-3}$

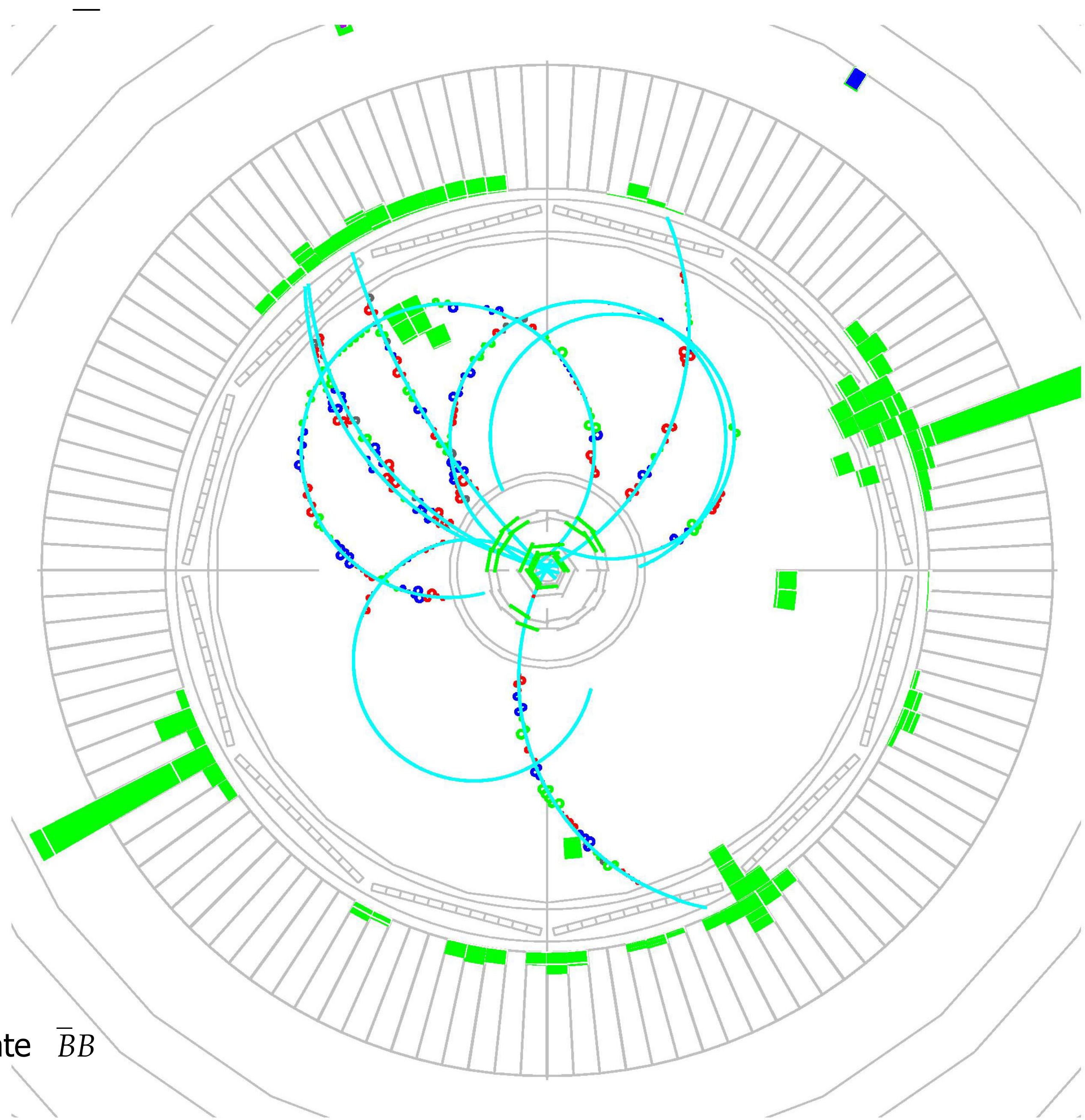
$BR(B^0 \rightarrow \pi^0\pi^0) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-6}$

significance : 4.2 σ → "observation"

SM: BR~ (0.3 – 1.1) x 10^{-6}

(averaged over B^0 and $\bar{B}^0$ decays)

$B \rightarrow \pi^0\pi^0$



Event display of a candidate $\overline{B}B$ event with one $B \rightarrow \pi^0\pi^0$

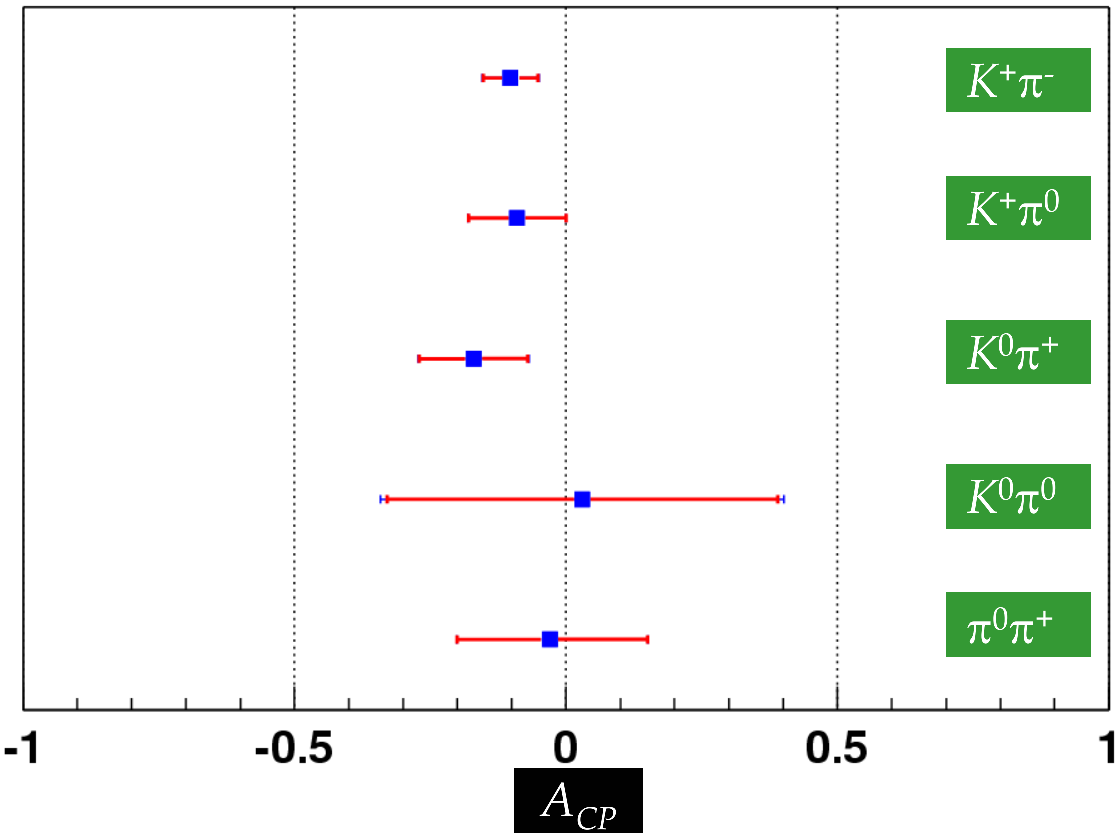
Summary of $B \to hh$, including $\pi^0\pi^0$

Measured Branching Fractions

Mode	$BR \times 10^6$	
$K^+\pi^-$	17.9 ± 0.9	± 0.7
$K^0\pi^-$	20.0 ± 1.6	± 1.0
$K^+\pi^0$	12.8 +1.2-1.1	± 1.0
$K^0\pi^0$	10.4 ±1.5	± 0.8
$\pi^+\pi^-$	4.7 ±0.6	± 0.2
$\pi^+\pi^0$	5.5 +1.0-0.9	± 0.6
$\pi^0\pi^0$	2.1 ±0.6	± 0.3
K^+K^-		< 0.6
$K^+ \bar{K}^0$		< 2.2
$K^0 \bar{K}^0$		< 1.6

Search for direct CP

No significant A_{CP} has been observed yet, but precision limited by statistics



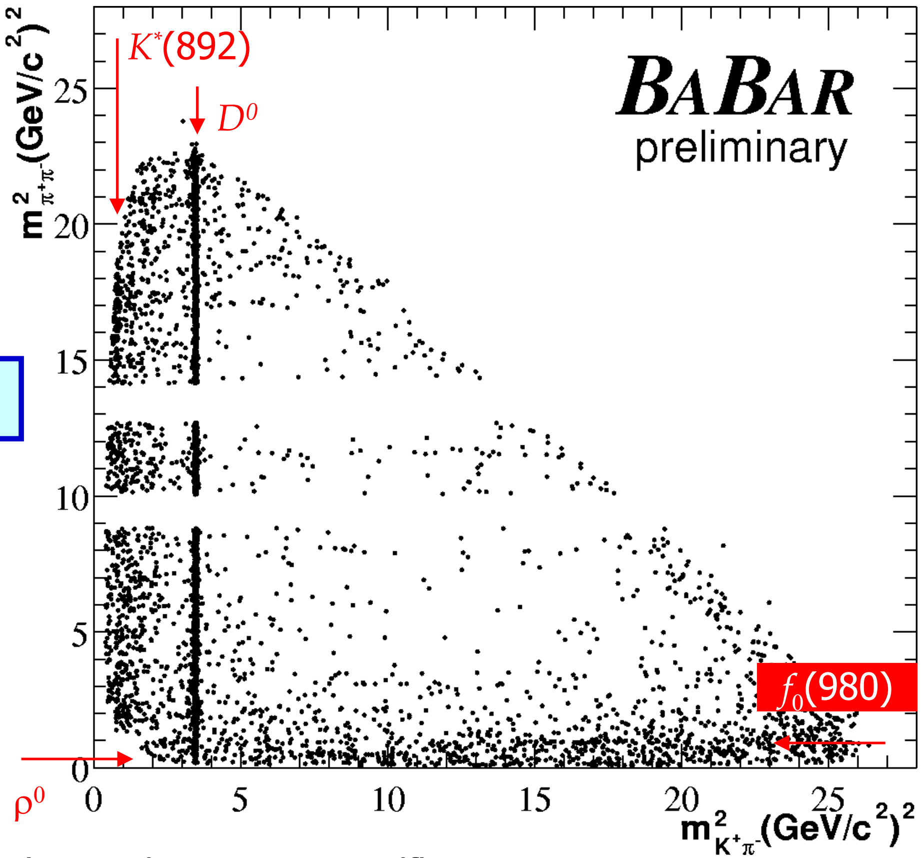
Inclusive $B^+ \rightarrow h^+h^-h^+$, exclusive $K^+\pi^+\pi^-$

direct CP ➔ angle γ Blanco et al, PRL 86, 2720 (2001) help for α Snyder and Quinn, PRD 48, 2139 (1993)

- ✓ BaBar inclusive $B^+ \rightarrow h^+h^-h^+$
- ✓ veto D^0, J/ψ, ψ(2S), χ_{c0} mesons
- ✓ efficiency varies across Dalitz plot
- ✓ cross-feed between modes taken into account

Modes	$BR \times 10^6$	A_{CP}
$B^+ \rightarrow \pi^+\pi^-\pi^+$	10.9±3.3±1.6	-0.39±0.33±0.12
$B^+ \rightarrow K^+\pi^-\pi^+$	59.1±3.8±3.2	0.01±0.07±0.03
$K^{*0}\pi^+$	10.3±1.2±2.8	$B^+ \rightarrow K^+\pi^+\pi^-$
f_0K^+	9.2±1.2±2.4	
$\chi_{c0}K^+$	1.46±0.35±0.12	
higher $K^{*0}\pi^+$	25.1±2.0±9.0	
higher f_0K^+	< 12	
ρ^0K^+	< 6.2	
$\pi^+\pi^-\pi^+$ *non res*	< 17	
$B^+ \rightarrow K^+K^-K^+$	29.6±2.1±1.6	0.02±0.07±0.03
$B^+ \rightarrow K^+K^-\pi^+$	< 6.3	
$B^+ \rightarrow K^-\pi^+\pi^+$	< 1.8	
$B^+ \rightarrow K^+K^+\pi^-$	< 1.3	

$B^+ \rightarrow K^+\pi^+\pi^-$ Dalitz plot study



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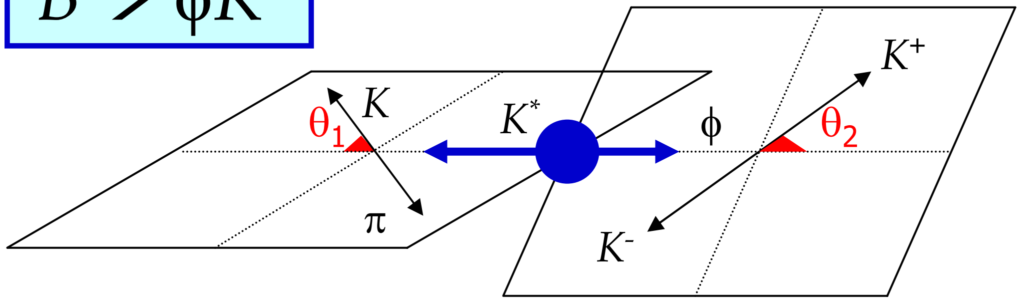
vector-vector decays

$B \rightarrow \phi K^*$



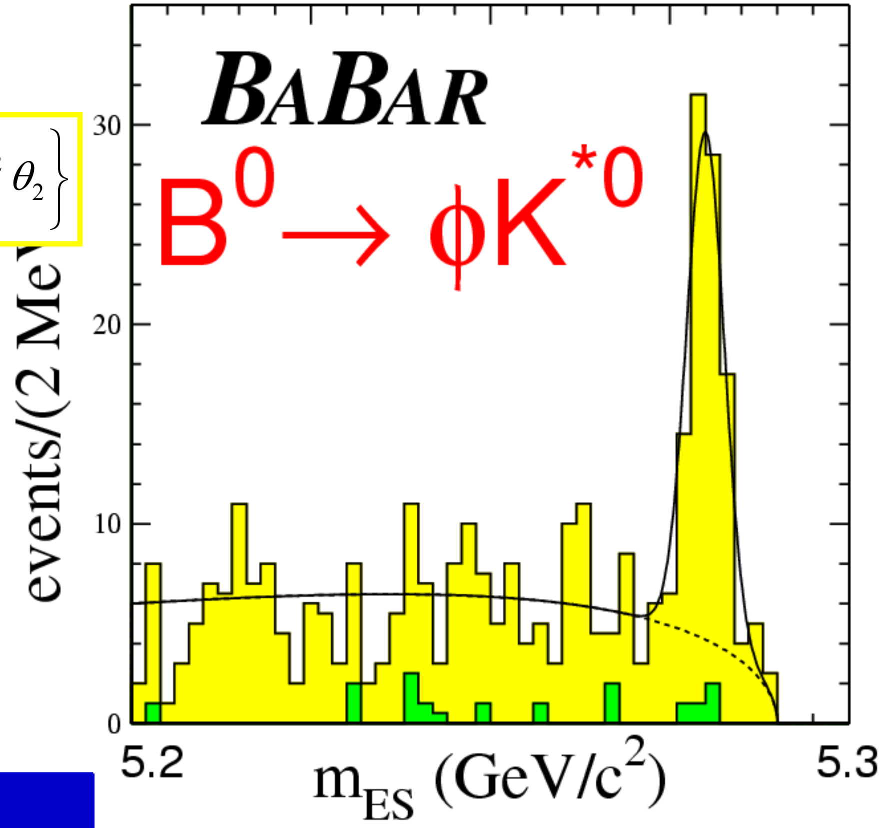
vector-vector decay : not a CP eigenstate
→ angular analysis to separate CP odd/even
$(f_L=\Gamma_L/\Gamma)$

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_1 d\cos\theta_2}\frac{9}{4}\left\{\frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2+f_L\cos^2\theta_1\cos^2\theta_2\right\}$$

✓ provides additional information about decay dynamics and δ (Kramer, Palmer PRD45 193 (1992), Chen et al, PRD 66 054012 (2002))

✓ A_{CP} in ϕK^*(pure penguin) is sensitive to new physics (Hinchliffe, Kersting PRD 63 015003 (2001))

✓ likelihood fits (m_{ES}, ΔE, Fisher, m_{K^*}, m_ϕ, θ_1,θ_2) to extract BR, f_L, A_{CP} simultaneously



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Mode	$BR \times 10^6$	f_L (%)	A_{CP}
$B^0 \rightarrow K^{*0}\phi$	11.2±1.3±0.8	65± 7±2	0.04±0.12±0.02
$B^+ \rightarrow K^{*+}\phi$	12.7+2.2-2.0±1.1	46±12±3	0.16±0.17±0.03

vector-vector decays

$B \to \rho K^* \; \rho\rho$

$B \to \rho K^*$: dominated by penguin? direct CP?
$B \to \rho\rho$: angle α

- ✓ similar angular analysis as in $B \to K\phi$
- ✓ first observation for $B \to \rho^+\rho^-$ (LP03)
  - likelihood fit (m_{ES},ΔE,Fisher,$m\rho_+$,$m\rho_-$, θ_1,θ_2)
  - simultaneous fit to signal yield and f_L
  - reconstruction efficiency low : 4%
  - signal yield : 93+23-21±9
  - significance > 5 σ

Mode	BR x 10^{-6}	f_L (%)	A_{CP}
$B^+ \to \rho^0 K^{*+}$	10.6+3.0-2.6±2.4	96+4-15±4	0.20+0.32-0.29±0.04
$B^+ \to \rho^+\rho^-$	27.0+7-6±5-7	99+1-7±3	-
$B^+ \to \rho^+\rho^0$	22.5+5.7-5.4±5.8	97+3-7±4	-0.19±0.23±0.03
$B^0 \to \rho^0 \rho^0$	< 2.1	-	-

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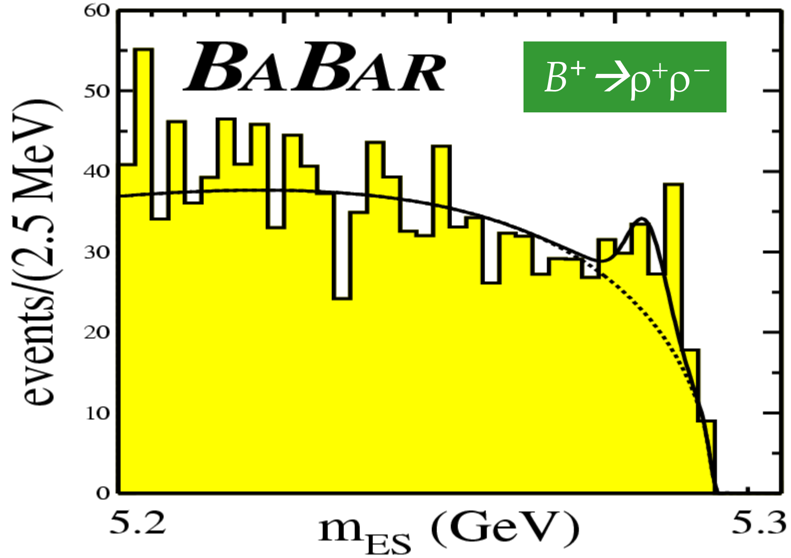

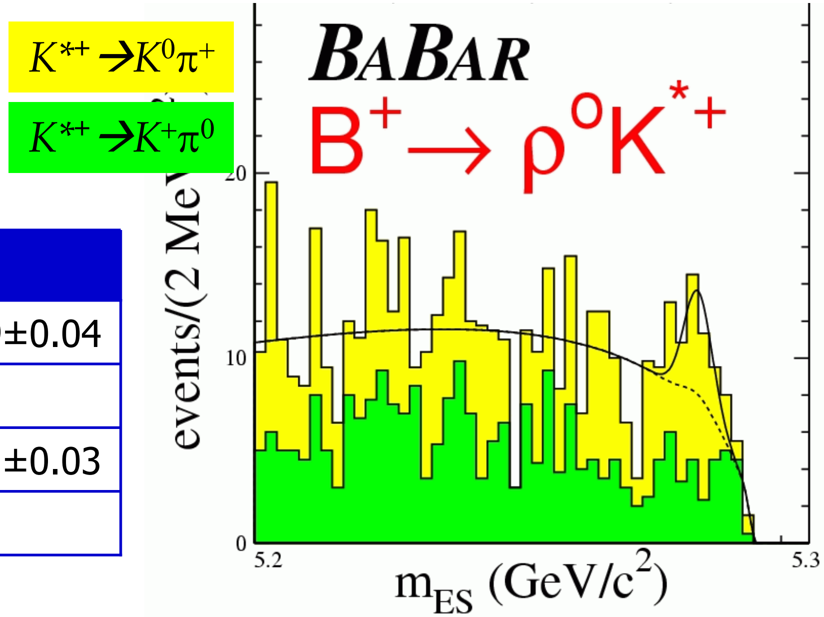

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Charmless hadronic decays - Summary

$B^{\pm}$		B^{0}	
Mode	BR x 10^6	Mode	BR x 10^6
$\eta' K^+$	76.9±3.5±4.4	$\eta' K^0$	55.4±5.2±4.0
ηK^+	2.8±0.8±0.2	ηK^{*0}	19.8+6.5-5.6±1.7
ηK^{*+}	22.1+11.1-9.2±3.3	ηK^0	< 4.6
ωK^+	5.0±1.0±0.4		
$K^{*0}\pi^+$	10.3±1.2+1.0-2.7		
$K^+\pi^+\pi^-$	59.1±3.8±3.2	$K^0\pi^+\pi^-$	47.0±5.0±6.0
$K^+K^-K^+$	29.6±2.1±1.6	$K^0K^-K^+$	-
$K^+K^0_sK^0_s$	-	$K^+K^0_sK^0_s$	-
$\rho^0\pi^+$	24.0±8.0±3.0	$\rho^-\pi^+$	22.6±1.8±2.2
$\omega\pi^+$	5.4±1.0±0.4	ρ^-K^+	7.3±1.3±1.3
$\eta\pi^+$	4.2±1.0±0.3	ωK^0	5.3±1.3±0.5
$K^+\phi$	10.0±0.9±0.5		
$\pi^+\phi$	< 0.38		

(grey box) Belle has results in these channels

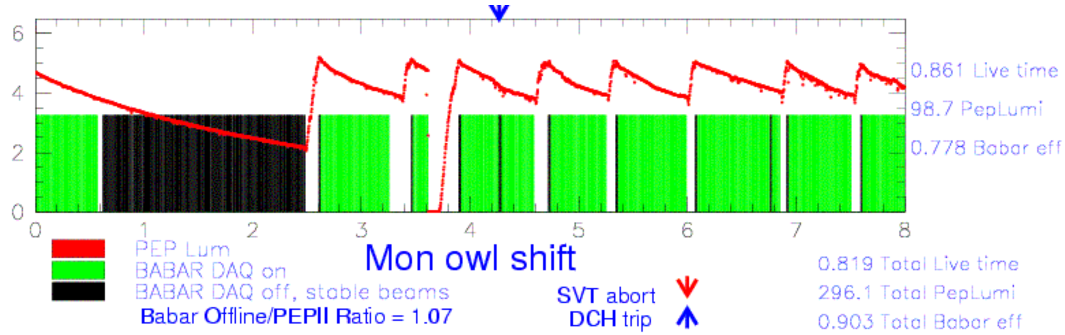
So, we are done

- Purely leptonic decays $f_B |V_{ub}|$
  - Exclusive $\tau\nu$ search
- Radiative decays
  - Exclusive $K^*\gamma$ BRs, $\rho\gamma$ and $\omega\gamma$ searches $|V_{td}|/|V_{ts}|$
- $B \to X_s ll$ decays
  - $K^{(*)}\ ll\ BR$
  - Inclusive $X_s\ ll$
  - search for $B \to K\ \bar{\nu}\nu$
- $D^{(*)}K^{(*)}$ decays
  - $B^- \to D^{*0}K^-$
- Charmless hadronic decays
  - $B \to hh$
  - Inclusive $B \to hhh$, $B \to Khh$

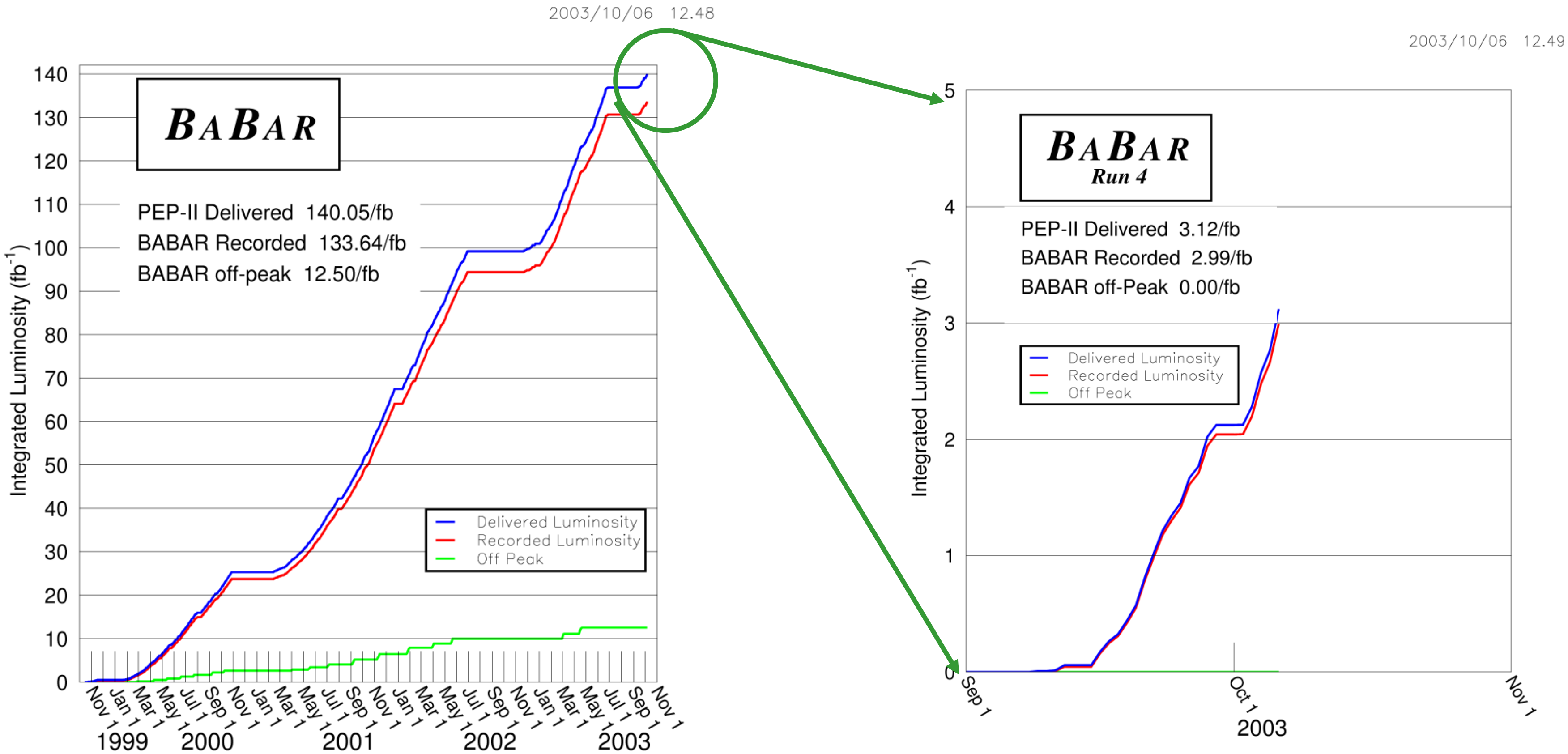
Summary

- 10^8 B mesons provide unique opportunity to study rare B decays
- Purely leptonic decays approaching SM predictions
- Radiative decays
  - many studies were done (BR, γ spectrum, new physics scenarios)
  - important to lower E_γ cut
- $B \rightarrow X_s ll$ decays
  - Most of decay modes identified
  - Need to get differential distributions
- $D^{(*)}K^{(*)}$ decays
  - Lots more data is needed to extract angle γ
- Charmless hadronic decays
  - $\pi^0\pi^0$ observed
  - Still lots more data is needed for angle α
- No hints of new physics in rates, A_{CP}, and distributions **yet**

Prospects



- BaBar is back in operation since September
- We expect to have more data: 500/fb in 2006

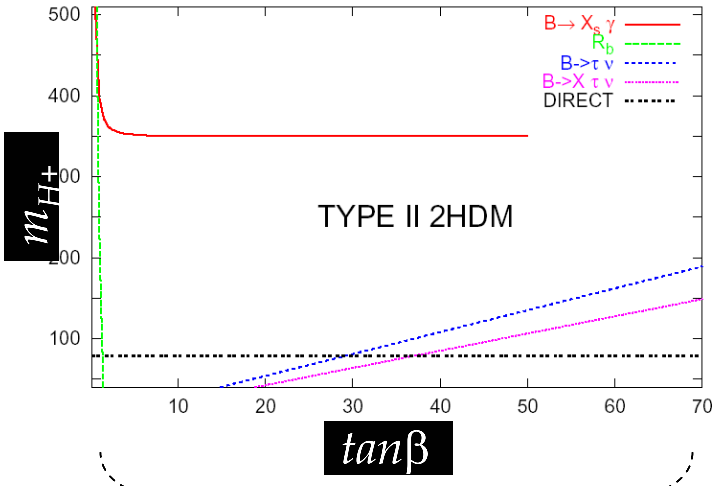


Backup

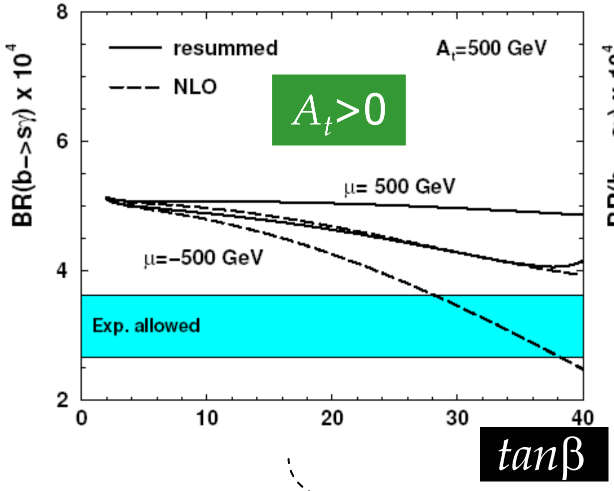
$B \to s\,\gamma$ beyond SM

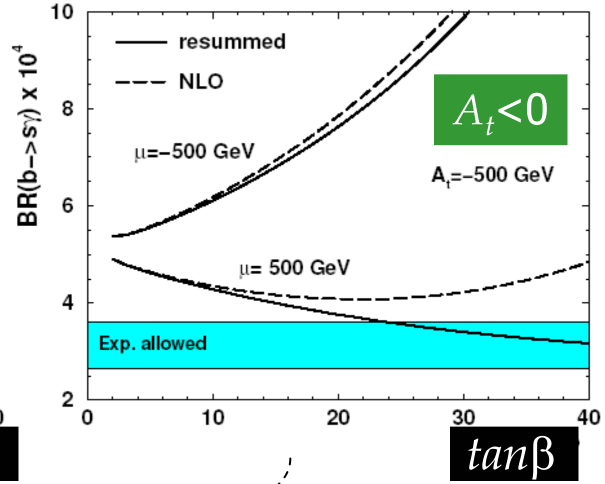
See more on talk by Vaidya (Thu) Yamada (Fri)

2HDM



MSSM ($m(H^{+})$=200 GeV, $m(stop)$=250 GeV, others 800 GeV)





Lower bounds on type II 2HDM m_{H+}
Much more restrictive than direct search by LEP

(Gambino and Misiak, NPB 611 338(2001))
: m_H > 280 GeV if renormalization scheme dependence is introduced

BR in a MSSM scenario (Carena et al, PLB 499 141 (2001),
A_t : stop mixing parameter)
$A_t\mu>0$: constructive interference btw SM and charged Higgs
$A_t\mu<0$: destructive

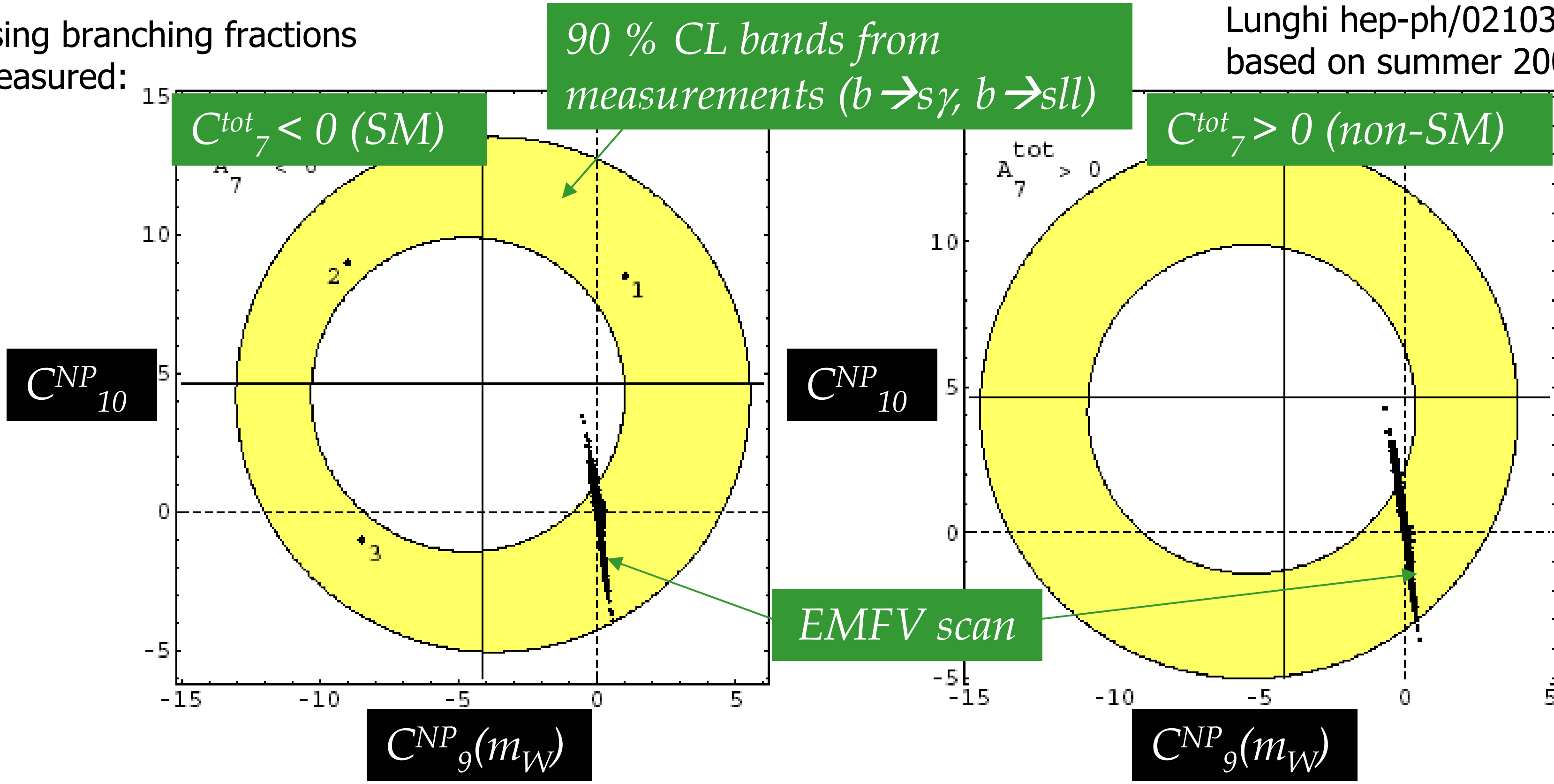
➔ If $A_t\mu>0$: model requires very heavy super-partners
If $A_t\mu<0$: model favors large tanβ
(SLAC-PUB-9604)

Type I: u and d quarks get masses from the same Higgs doublet
Type II: u quark gets from Yukawa couplings to H_2, d gets from couplings to H_1

Constraints on C_7 and C_{10}

Using branching fractions measured:

Lunghi hep-ph/0210379, based on summer 2002 data



- Studied on variants of SUSY (to NNLO)
- Cutting out some non-SM C_9 and C_{10} space from $b \to sl^+l^-$ with a $|C_7|$ constraint from $b \to s\gamma$
- But sign of C_7 is not determined yet

➡ There is room to improve constraints by measuring BRs more precisely