Rare B Decays from BaBar

William T. Ford
University of Colorado
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- Introduction: what's "rare"?
- What can we learn?
- Electroweak penguin mediated decays — massive propagators, $\left|V_{t(s,d)}\right|$, ...
- Hadronic two-body decays → CKM angles (CP violating), matrix elements, ...
- Conclusions

Quark couplings in the standard model

Weak isospin doublet members (d', s', b') are mixed flavor states:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

V is the (unitary) Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix.

Unitarity $\Rightarrow$ 4 free parameters, including 1 phase:

$$V \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

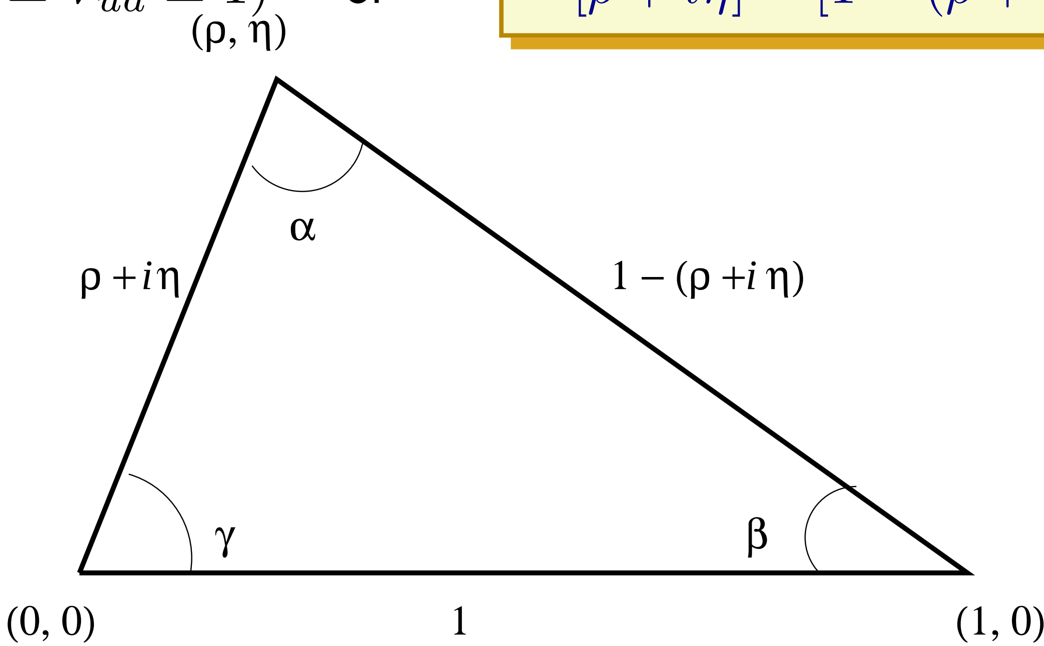
$$\begin{aligned} \lambda &\simeq \sin\theta_c \simeq 0.22 \\ A &\sim 1 \end{aligned}$$

Unitarity Triangle

$V^\dagger V = 1$: $1^{\rm st}$ column $\times$ $(3^{\rm rd}$ column$)^*$ $\rightarrow$

$$V_{ud}V_{ub}^* + V_{td}V_{tb}^* + V_{cd}V_{cb}^* = 0 \qquad \frac{V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}}{V_{cd}V_{cb}^*} + 1 = 0$$

$(V_{tb} \simeq V_{ud} \simeq 1)$ or $-[\rho + i\eta] - [1 - (\rho + i\eta)] + 1 = 0$



Major B decay modes are

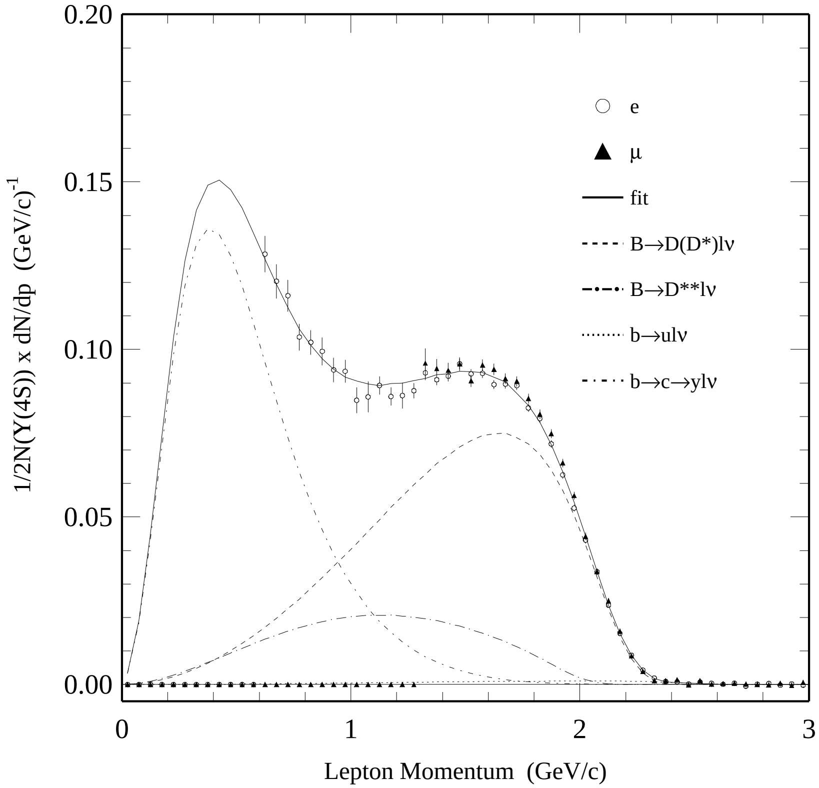
$\boldsymbol{B^0}$	BF	$\boldsymbol{B^+}$	BF	
$D^{(*)-}\ell^+\nu$	6.7%	$D^{(*)0}\ell^+\nu$	7.4%	$b \longrightarrow c$ tree
$D^{(*)-}(1,3)\pi(\pi^0)$	7.9%	$D^{(*)0}(1,3)\pi(\pi^0)$	8.4%	$b \longrightarrow c$ tree
$D^{(*)-}D_s^{(*)+}$	4.8%	$D^{(*)0}D_s^{(*)+}$	6.1%	$b \longrightarrow c$ tree
$\psi^{(\prime)}K^{(*)0}$	0.3%	$\psi^{(\prime)}K^{(*)+}$	0.3%	color suppressed

What is "rare"

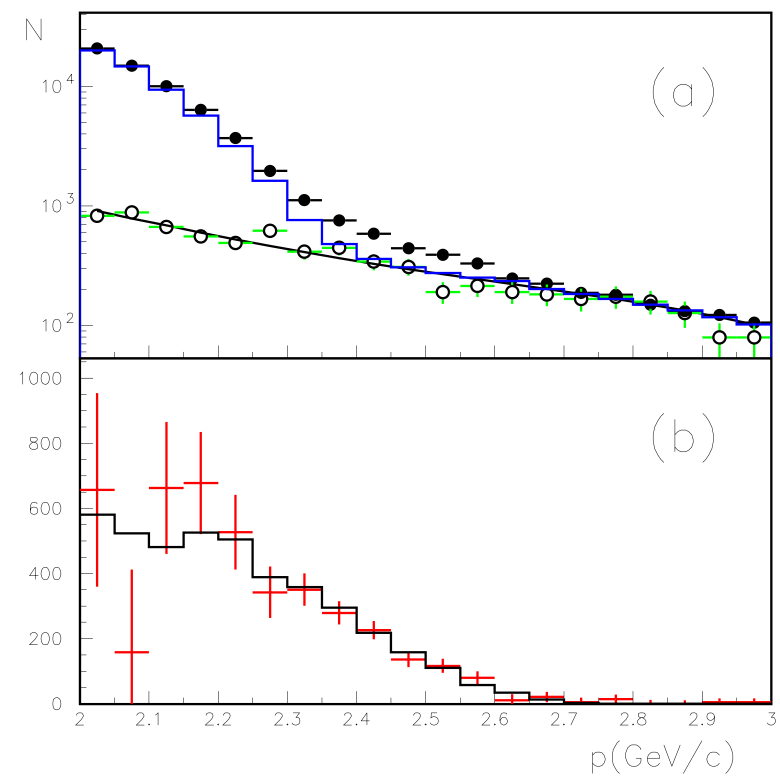
Here we mean modes with neither open nor hidden charm:

$$b \rightarrow u \quad \text{(CKM suppressed)}, \quad |V_{ub}/V_{cb}| \sim 0.06 - 0.10$$

$$b \rightarrow s, d \quad \text{(induced FCNC, penguin loops)}$$



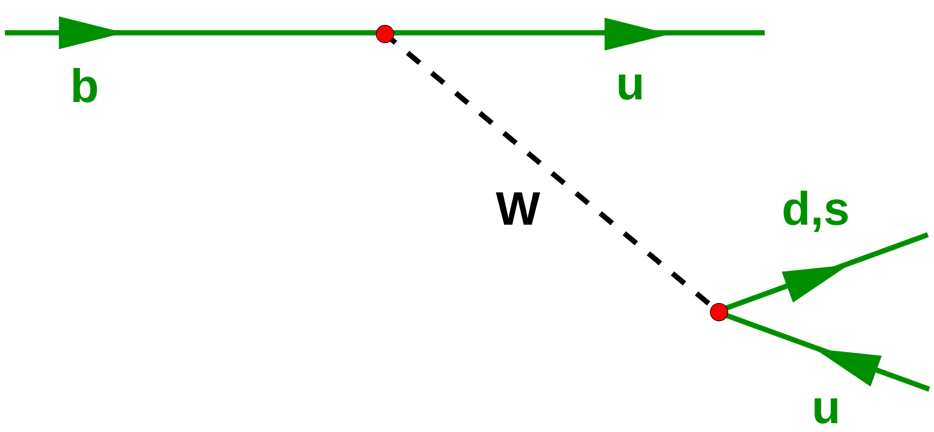
Inclusive lepton spectrum (CLEO)



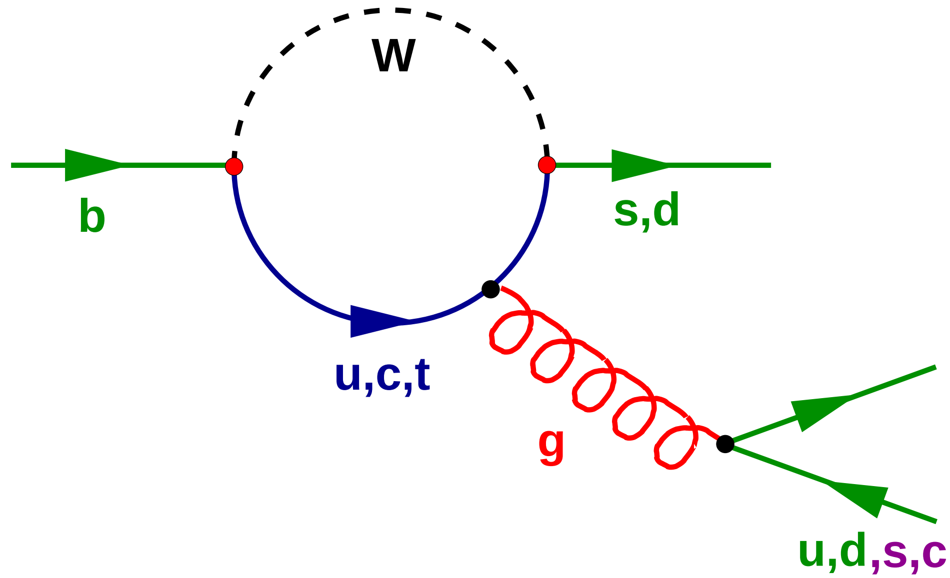
Endpoint region (*BABAR*)

Why focus on RARE B decays?

- Heavy quark systems are relatively amenable to theoretical treatment ($m_b \gg \Lambda_{\mathrm{QCD}}$).
- Need to flesh out S. M. with measurements (currently imprecise) of flavor mixing.
- CKM suppression of $b \to u$ tree diagrams . . .

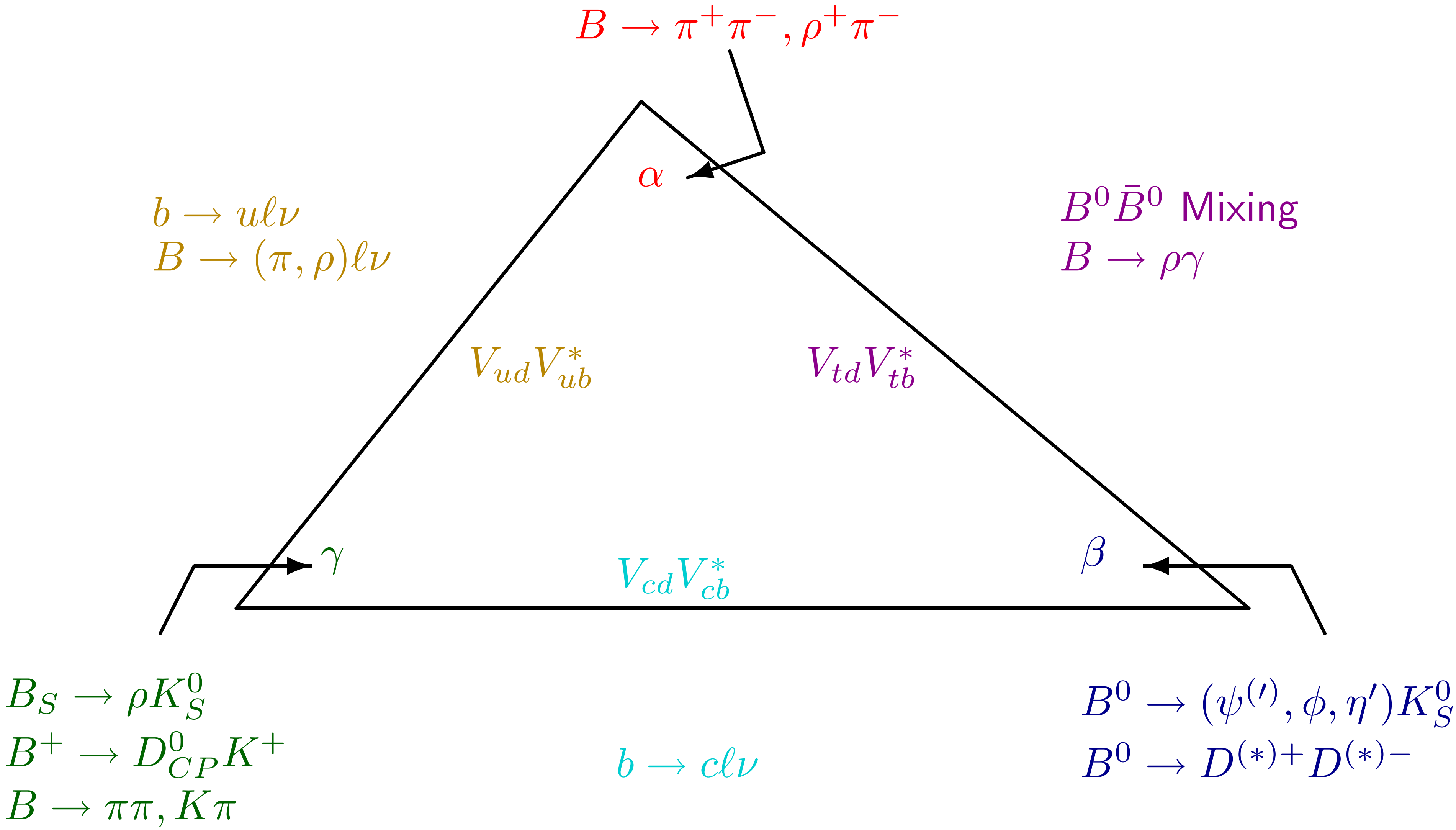


... allows access to penguin terms

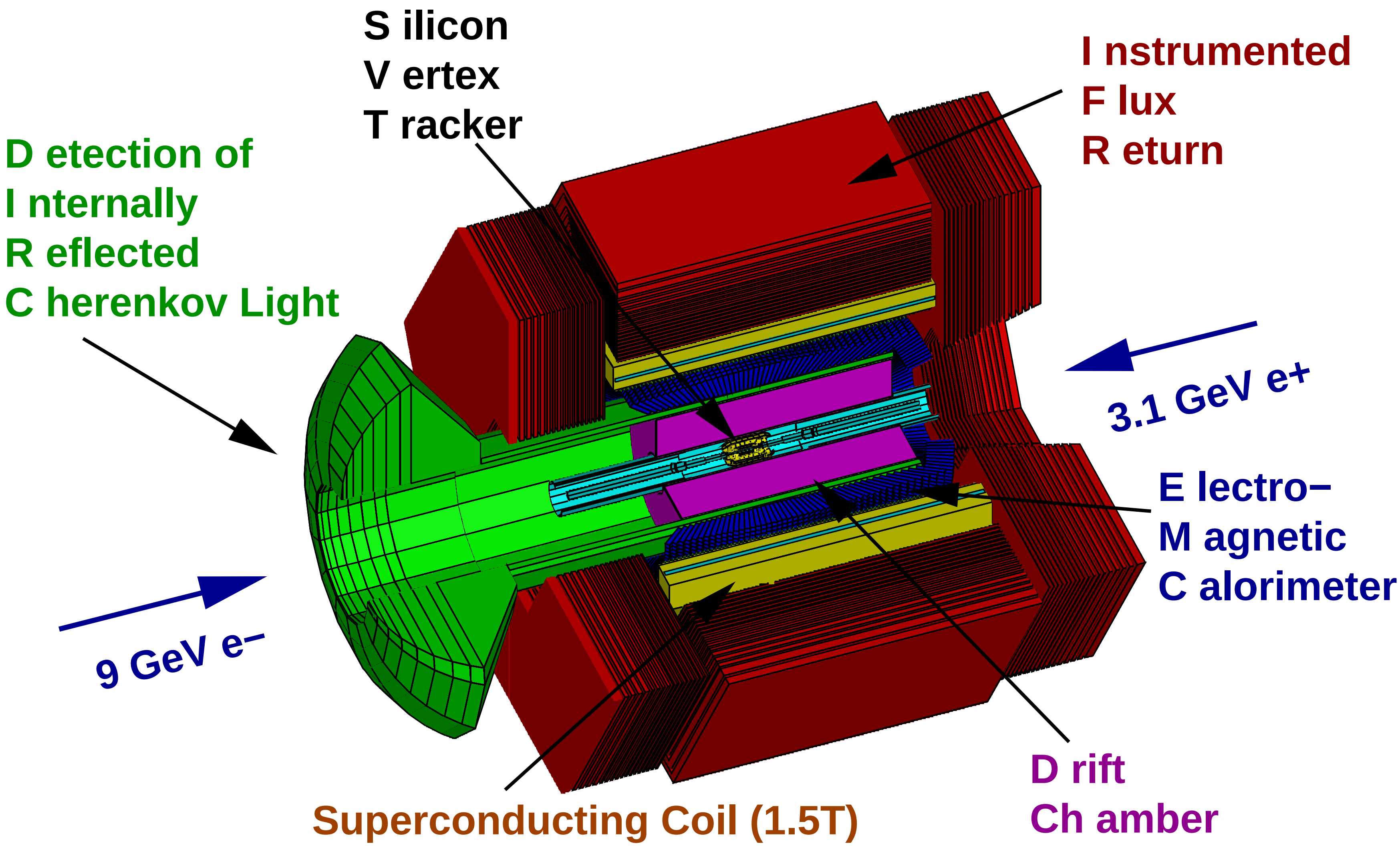


- Particles too massive to appear on-shell can contribute to loops
  - ◇ top quarks, $V_{t(s,d)}$ terms.
  - ◇ Higgs, SUSY, new structure.
- Interfering terms of comparable magnitudes expose phases, e.g., CP violating.
- Penguins complicate CP measurements; need to be understood for interpretation.

Measuring V_{CKM} – $O(\lambda^3/\lambda^2)$ terms

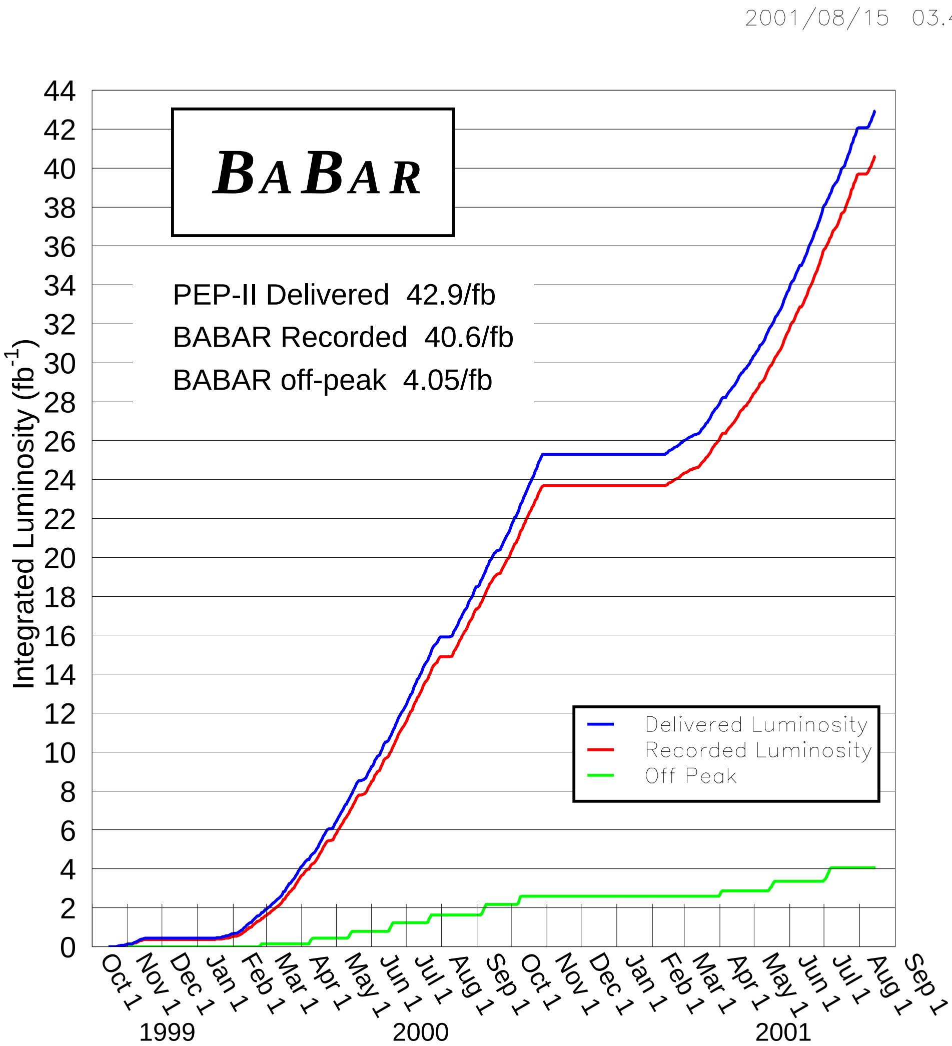


The BABAR detector



BABAR luminosity

- "Run 1", 1999-2000
- $20.7\ \mathrm{fb}^{-1}$ on-$\Upsilon(4S)$
- $2.6\ \mathrm{fb}^{-1}$ off-$\Upsilon(4S)$
- 22.7×10^{6} produced B pairs



Reconstruction of B decays at the $\Upsilon(4S)$

- $\Upsilon(4S) \rightarrow B^0\bar{B}^0,\ B^+B^-$ ~at rest ($p^*_B \simeq 325$ MeV/c)
- $m_B \simeq 5.3\ \mathrm{GeV/c^2}\ = m_{\mathsf{recoil}}$
- Energy, momentum conservation expressed as

$$\Delta E \equiv \sum E^*_i - E^*_{\mathrm{beam}} = 0$$

$$M \equiv (m_{ES} \text{ or } m_{\mathrm{EC}}) \simeq \sqrt{E^{*2}_{\mathsf{beam}} - |\mathbf{p}^*_i|^2} = m_B$$

within resolution. (E^*_{beam} is much better measured than $\sum E^*_i$.)

Typical resolution $M:\ 2.8\ \mathrm{MeV}/c^2,\quad \Delta E:\ 25-30\ \mathrm{MeV}$

- For two-body
  - ◇ daughter $E^* \simeq 2.6$ GeV
  - ◇ daughters nearly back-to-back

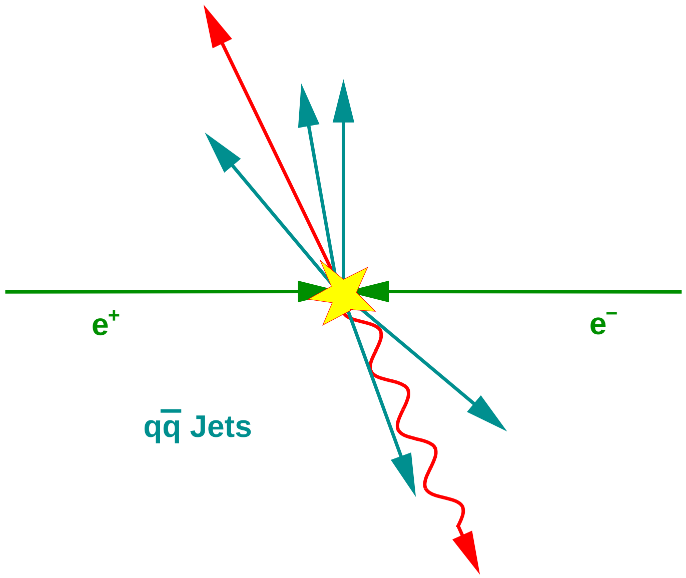
Background rejection

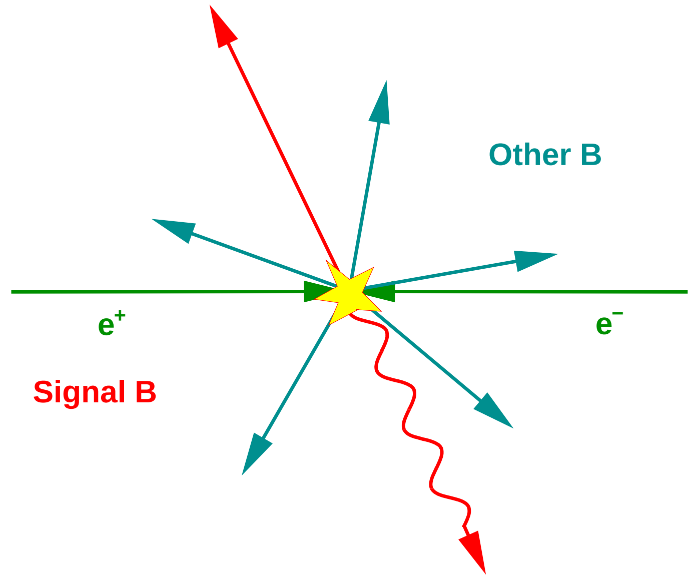
- $b \to c$ background: heavier daughter, lower energy recoil.

  Not a problem for most modes.

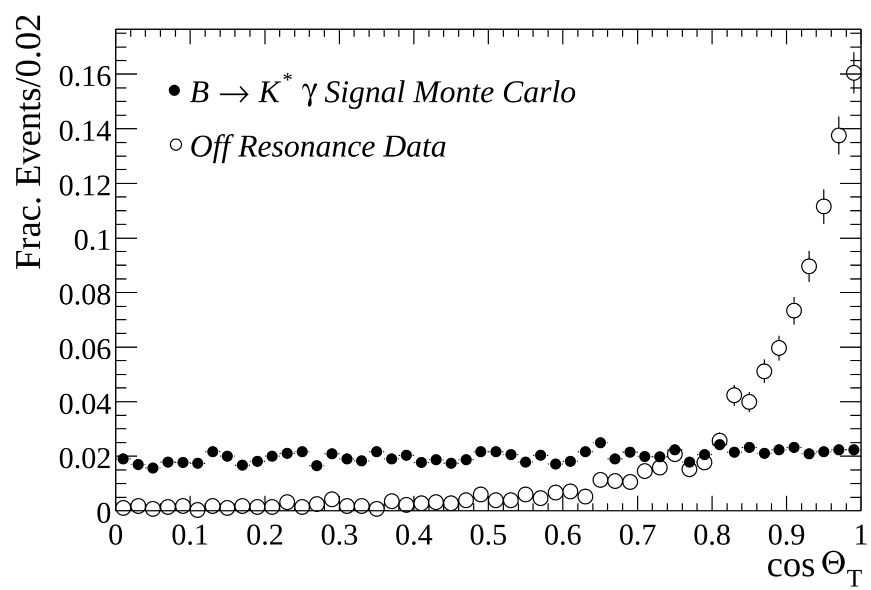
- Continuum background (e.g. two $x = .5$ particles in opposite jets from $e^+e^- \to q\bar{q}$):
  - ◇ Control data with $E_{\text{cm}} < B\bar{B}$ threshold.
  - ◇ Distinguished by event shape.
    - ∗ R_2, ratio of 2nd to zeroth Fox-Wolfram moments (peaks higher for jetty continuum)
    - ∗ B decay axis correlation with jet axis ...

Event shapes



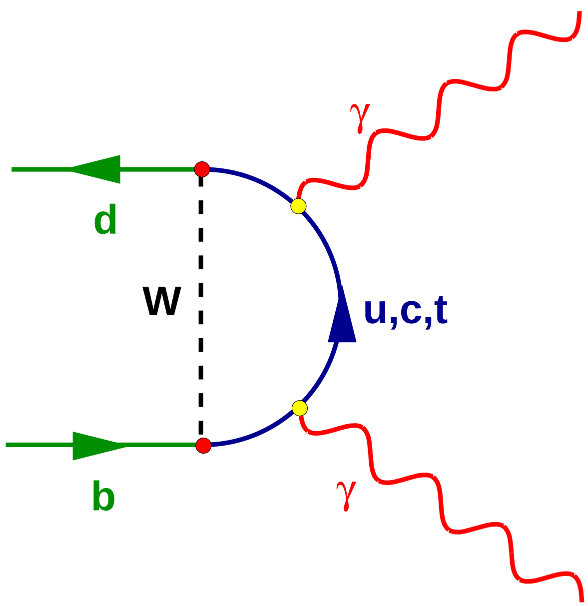


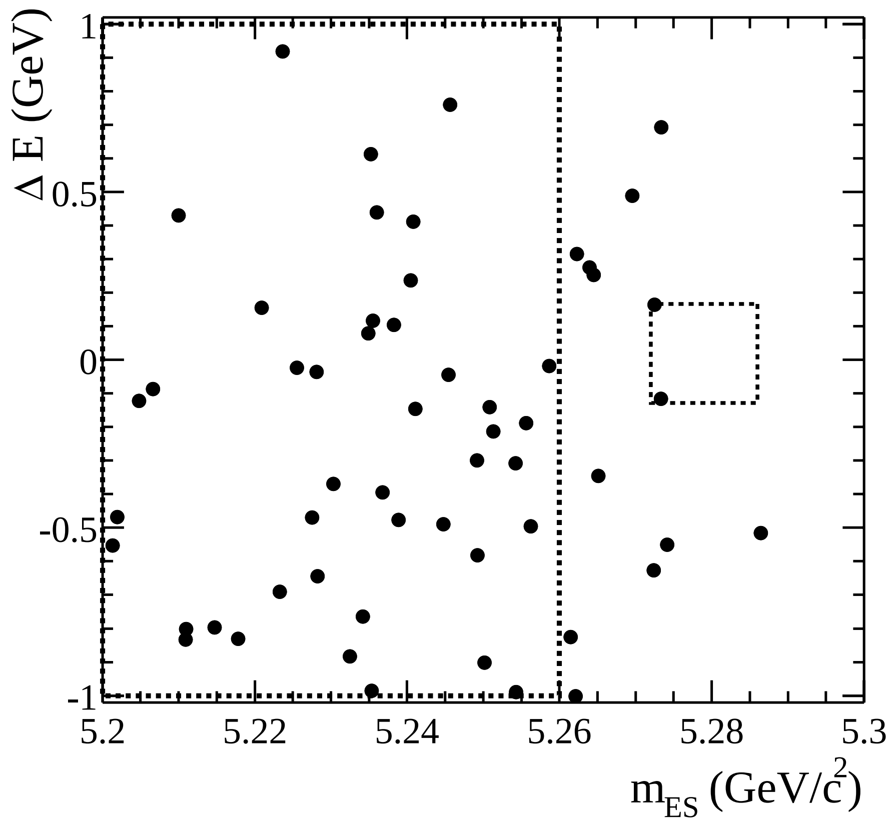
Define angle θ_T between B decay axis and thrust axis of the rest of the event (in $\Upsilon(4S)$ frame)



Electroweak annihilation

Search for $B \to \gamma\gamma$
expectation from S. M.:
$\mathcal{B} \simeq 0.1$ to 2.3×10^{-8}



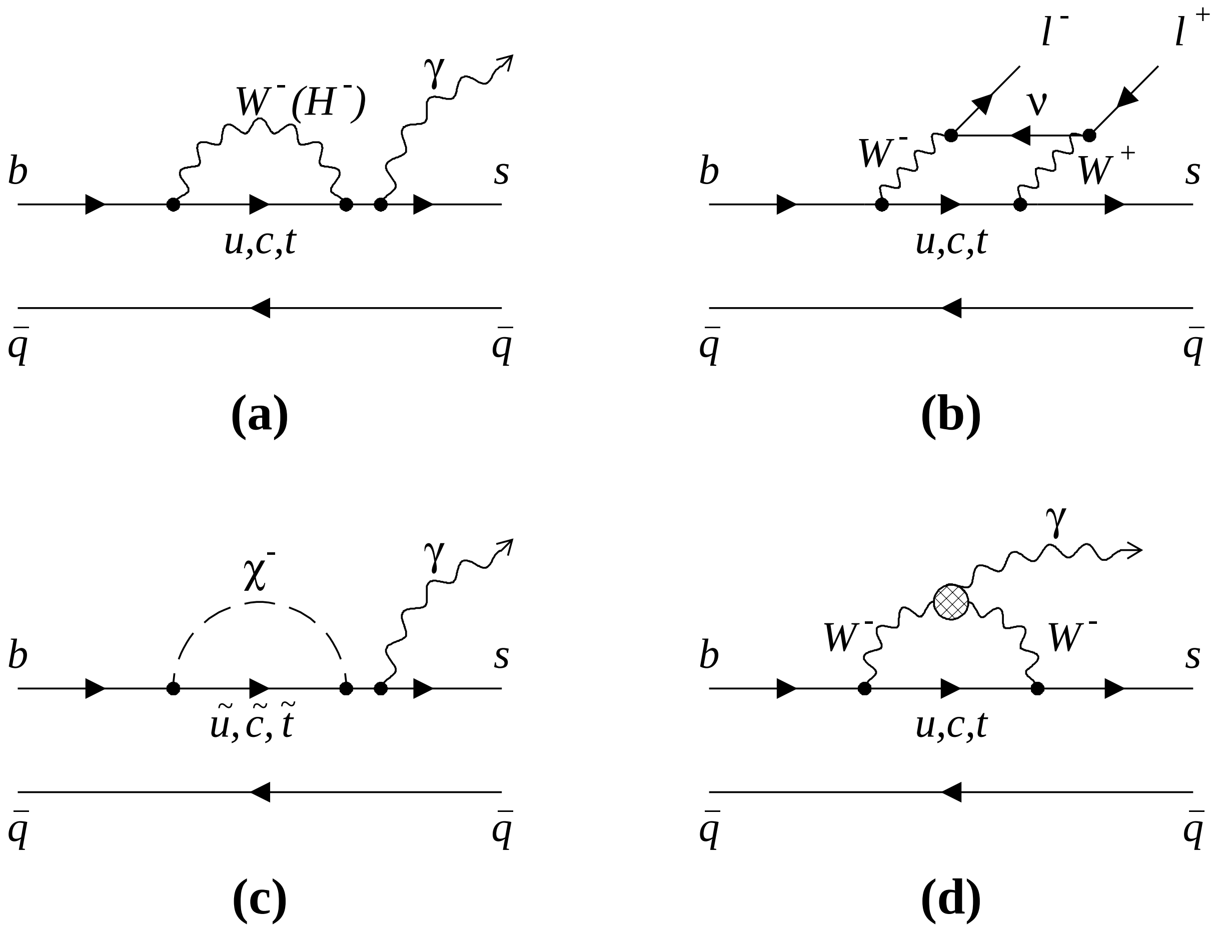


Select γ pairs not in π^0, η
Cut on R_2, $\cos\theta_{\rm T}$, $\cos\theta_B$

$\mathcal{B}(B^0 \to \gamma\gamma) < 1.7 \times 10^{-6}$ (90% CL)

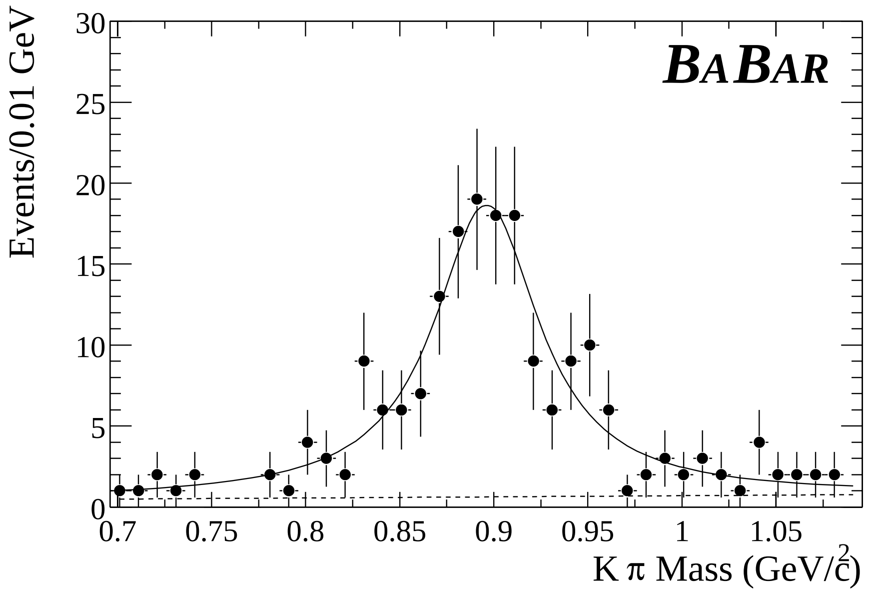
Electroweak penguin processes

$$B \to K^*\gamma,\ B \to (\rho,\omega)\gamma,\ b \to s\gamma,\ B \to K^{(*)}\ell^+\ell^-$$



$B \to K^*\gamma$

- Include $K^{*+} \to K^0_S\pi^+, K^+\pi^0$, $K^{*0} \to K^+\pi^-, K^0_S\pi^0$

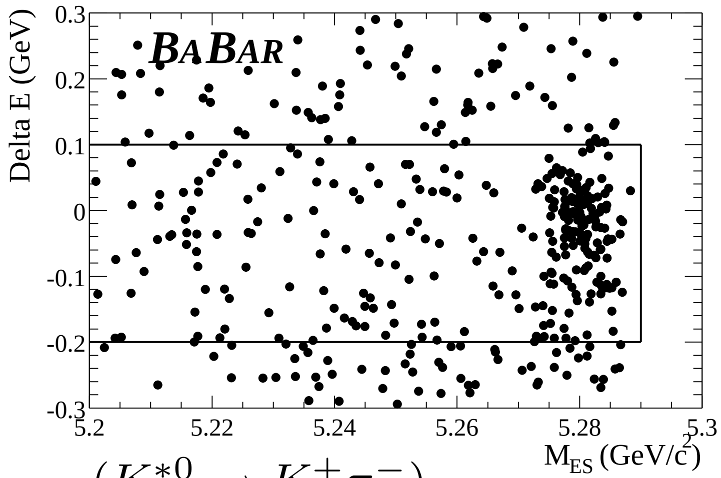


- Select events in
  - ◇ K^* mass peak
  - ◇ $2.30 < E^*_\gamma < 2.85$ GeV
  - ◇ Track, photon, vertex quality
  - ◇ Positive kaon ID from DIRC

- Reduce background with
  - ◇ $|\cos\theta_{\rm T}| < 0.8$
  - ◇ For p^*_B direction wrt beam $\cos\theta^*_B < 0.75$
  - ◇ For K^* decay helicity angle $\cos\theta^*_H < 0.75$

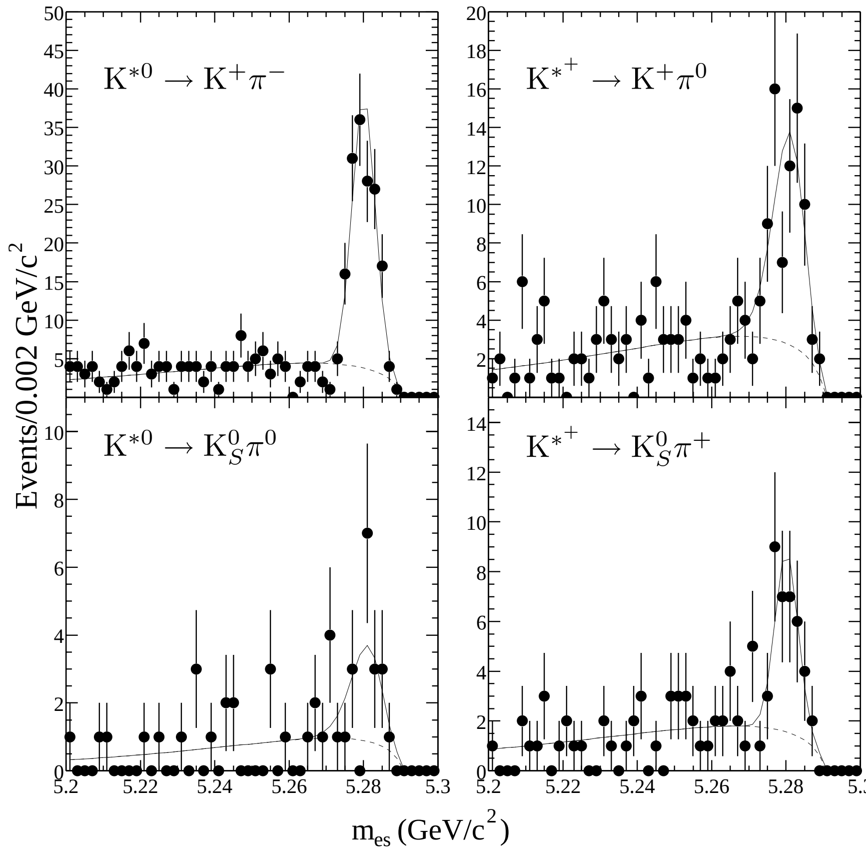
    Both have (for different reasons) $\sin^2\theta$ distribution, vs uniform for BG

Results for $B \to K^*\gamma$



$(K^{*0} \to K^+\pi^-)$

Vigorous theoretical program to compute these.



$$\mathcal{B}(B^- \to K^{*-}\gamma) = (3.92 \pm 0.62 \pm 0.21) \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.23 \pm 0.40 \pm 0.22) \times 10^{-5}$$

theory estimate $(7.1 \pm \sim 2.5) \times 10^{-5}$

In progress: $B \to (\rho, \omega)\gamma$

From the ratios of $b \to d$ to $b \to s$ we determine the top quark CKM couplings:

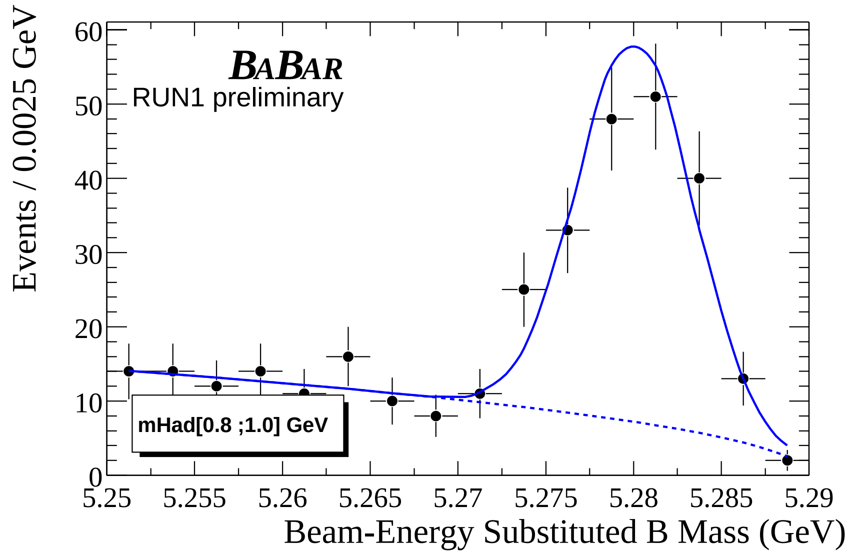
$$\frac{\mathcal{B}(B^- \to \rho^- \gamma)}{\mathcal{B}(B^- \to K^{*-}\gamma)} = \frac{\mathcal{B}(B^- \to \rho^0 \gamma) + \mathcal{B}(B^- \to \omega^0 \gamma)}{\mathcal{B}(B^- \to K^{*-}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right| \xi \Omega$$

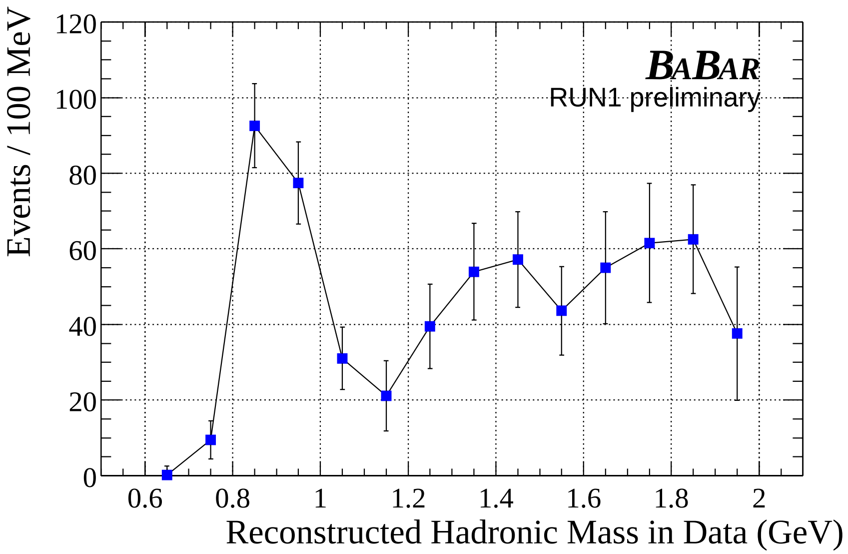
$\xi =$ SU(3)-breaking factor

$\Omega =$ phase space factor

$\Longrightarrow$ bounds on $\left|\frac{V_{td}}{V_{ts}}\right|$

In progress: $b \to s\gamma$

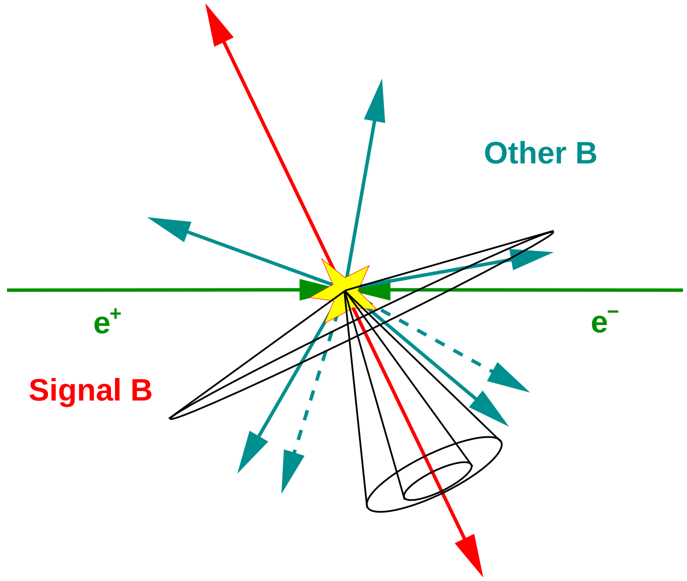




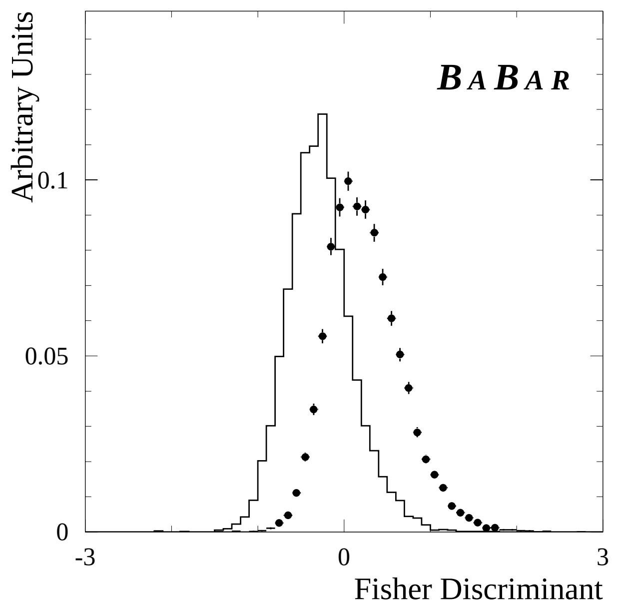
Signal is evident; results still to be quantified.

More on continuum rejection

- θ_T (introduced above)
- θ_B^* (introduced above)
- B decay angle wrt beams θ_{TB}^*
- Energy flow about the decay axis
  - ◇ Conical bins
  - ◇ Legendre moments
- Global event shape (R_2, sphericity)

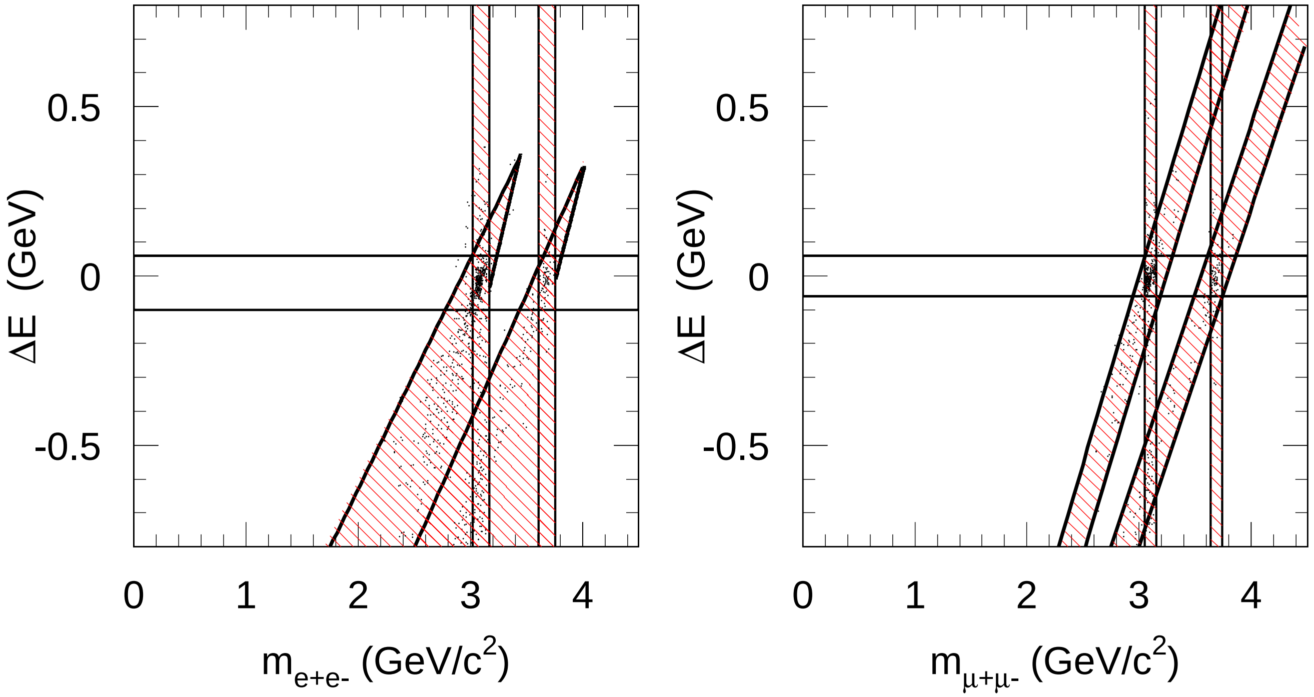


As these are correlated, combine in a Fisher discriminant, $\mathcal{F}$ (or neural network). Typically include conical bins, with or without θ_B^*, θ_{TB}^*.



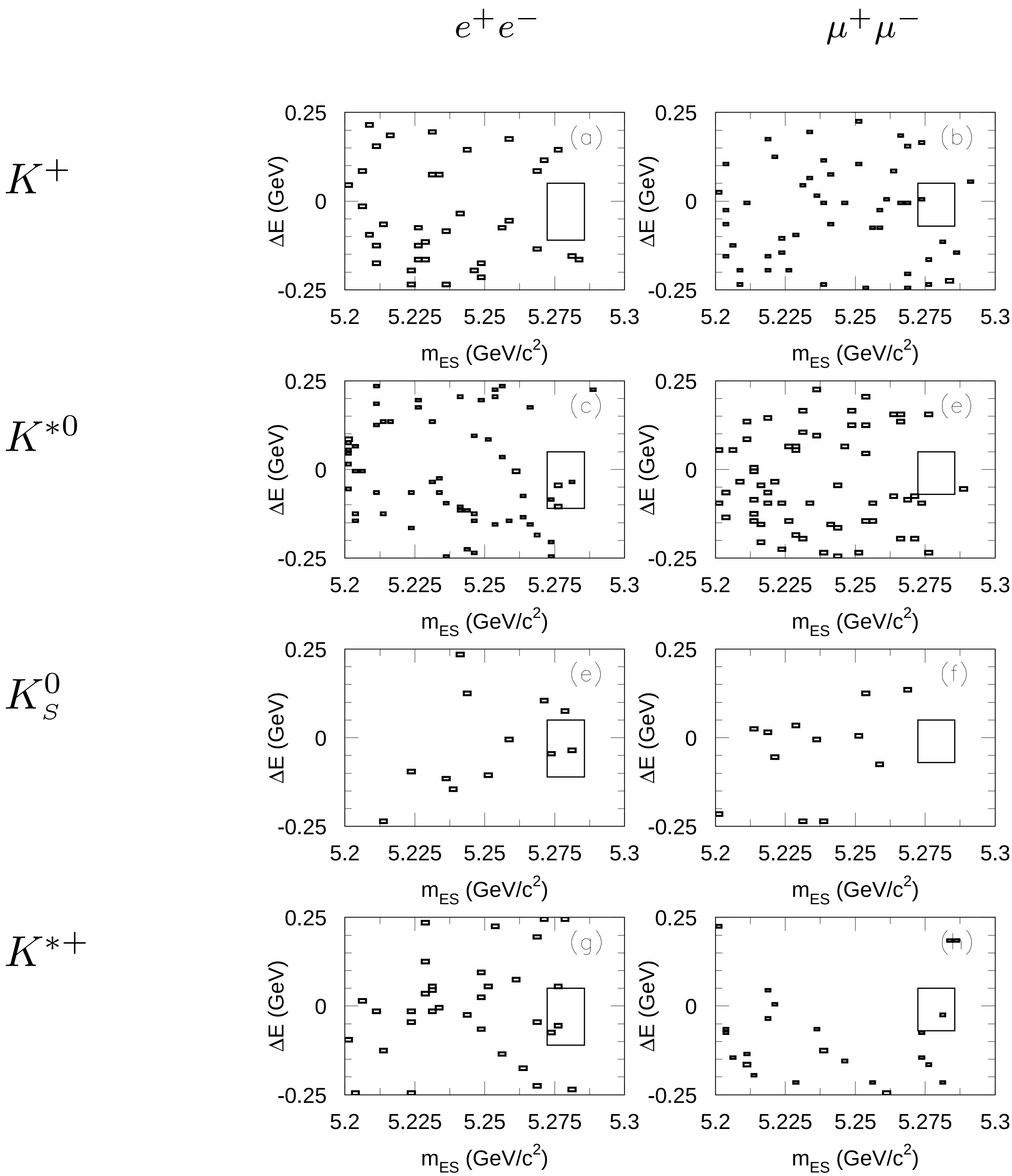
Search for $B \longrightarrow K^{(*)}\ell^+\ell^-$

- Tight PID cuts on all tracks
- Continuum suppression with a Fisher $\mathcal{F}(R_2, \theta_B, \theta_{BT}, m_{K\ell})$
- $B \longrightarrow$ charmonium veto



- Control samples $B \longrightarrow K^{(*)}J/\psi,\ B \longrightarrow K^{(*)}\psi(2S)$

Search for $B \to K^{(*)}\ell^+\ell^-$, cont.



Perform a maximum likelihood fit in these two variables

Search for $B \to K^{(*)}\ell^+\ell^-$, cont.

The Standard Model predictions are based on light quark sum rules, quark models, and QCD sum rules. Find (90% CL upper limits)

$$\begin{aligned} \mathcal{B}(B \to K\ell^+\ell^-) &< 0.8 \times 10^{-6} \quad (\text{theory } 0.3 \text{ to } 0.75 \times 10^{-6}) \\ \mathcal{B}(B \to K^*\ell^+\ell^-) &< 2.5 \times 10^{-6} \quad (1.0 \text{ to } 3.0 \times 10^{-6}) \end{aligned}$$

Limits are close to prediction; improved experimental sensitivity should soon make this decay obervable.

Two body hadronic B decays

Can make ~ 70 combinations among members of lowest-lying pseudoscalar, vector nonets

Representative diagrams

($'$) denotes $\Delta S = 1$

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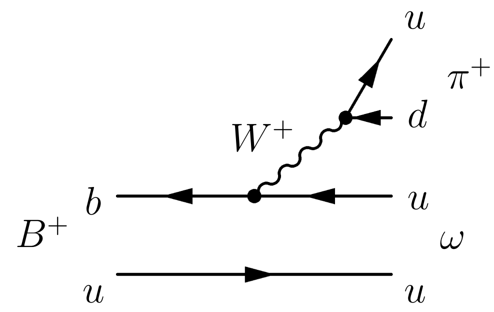
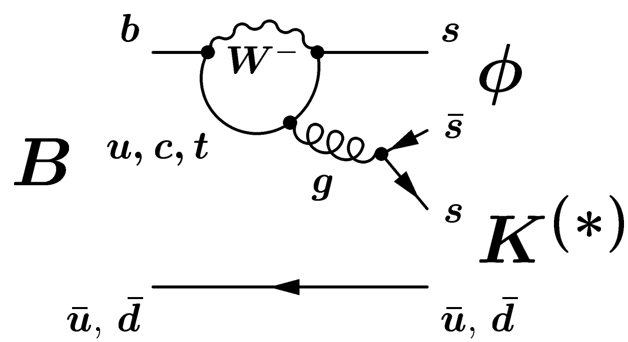
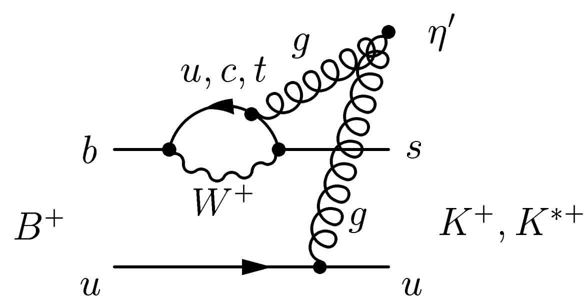


P'

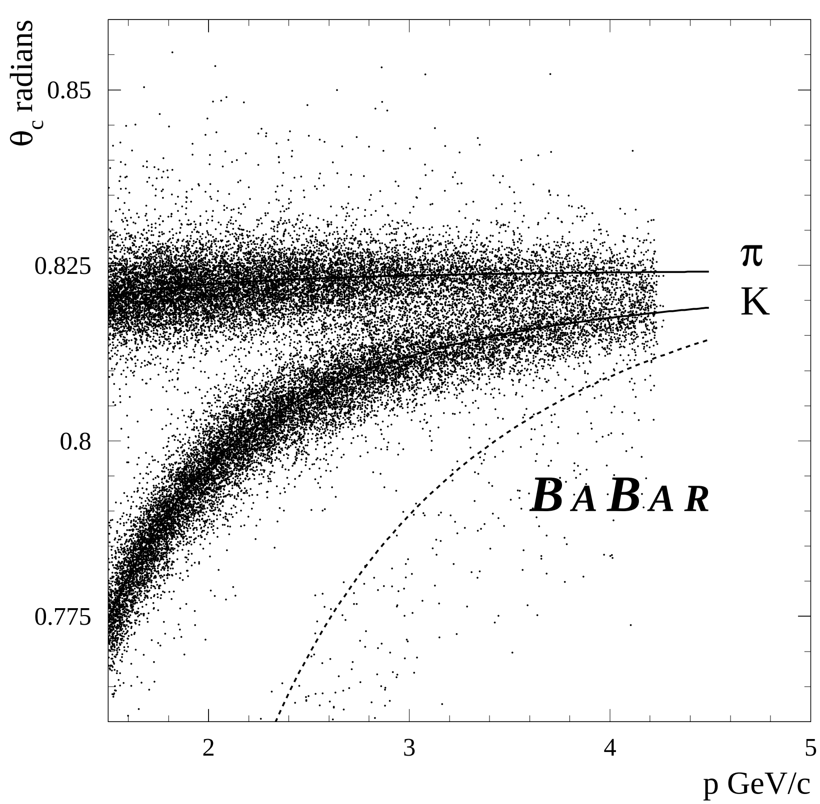


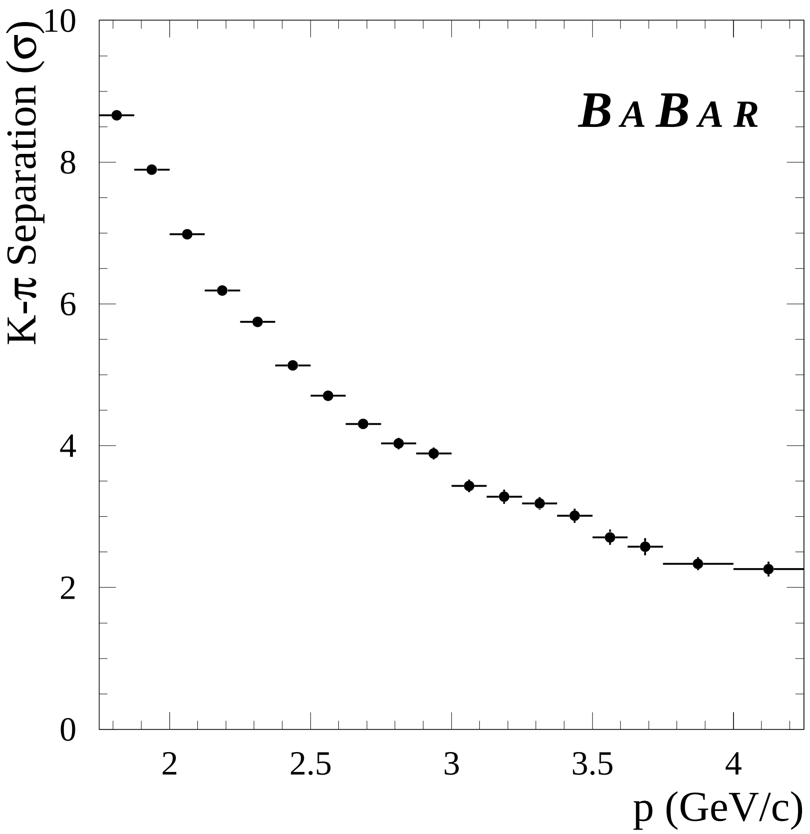
S'



K, π separation

For modes with a charged track recoiling against a light particle, lab momentum is uniformly distributed between about 1.6 and 4.4 GeV/c. DIRC gives K, π separation (measured with $D^0 \to K^+\pi^-$):





Maximum likelihood fit

Results (most analyses) come from maximum of unbinned extended likelihood:

$$\mathcal{L} = \frac{e^{-(\sum n_j)}}{N!} \prod_{i=1}^{N} \mathcal{L}_i$$

Allowing for final states KX and πX,

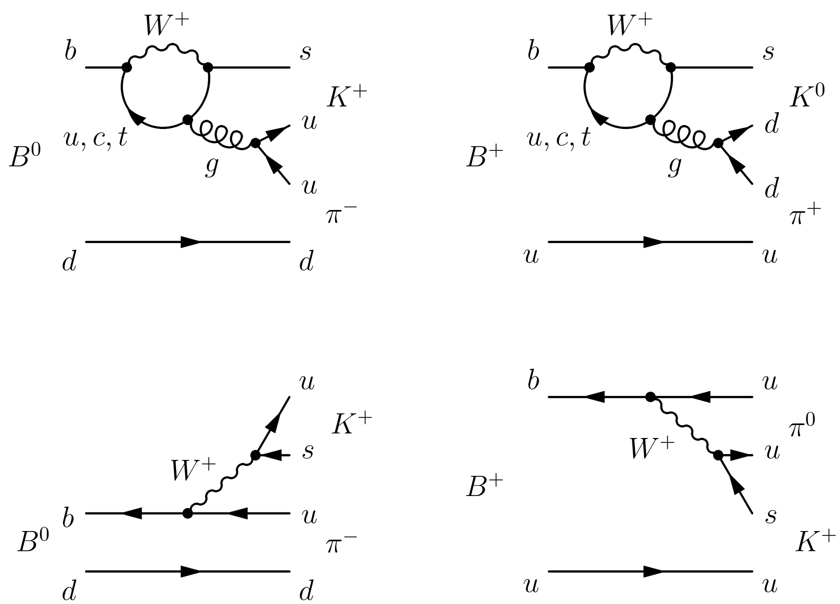
$$\begin{aligned} \mathcal{L}_i &= n_\pi \mathcal{P}_{\pi S}(\mathbf{x}_i) + n_K \mathcal{P}_{KS}(\mathbf{x}_i) && \text{Signals} \\ &+ n_C \left[f_{KC} \mathcal{P}_{KC}(\mathbf{x}_i) + (1 - f_{KC}) \mathcal{P}_{\pi C}(\mathbf{x}_i) \right] && \text{Background} \end{aligned}$$

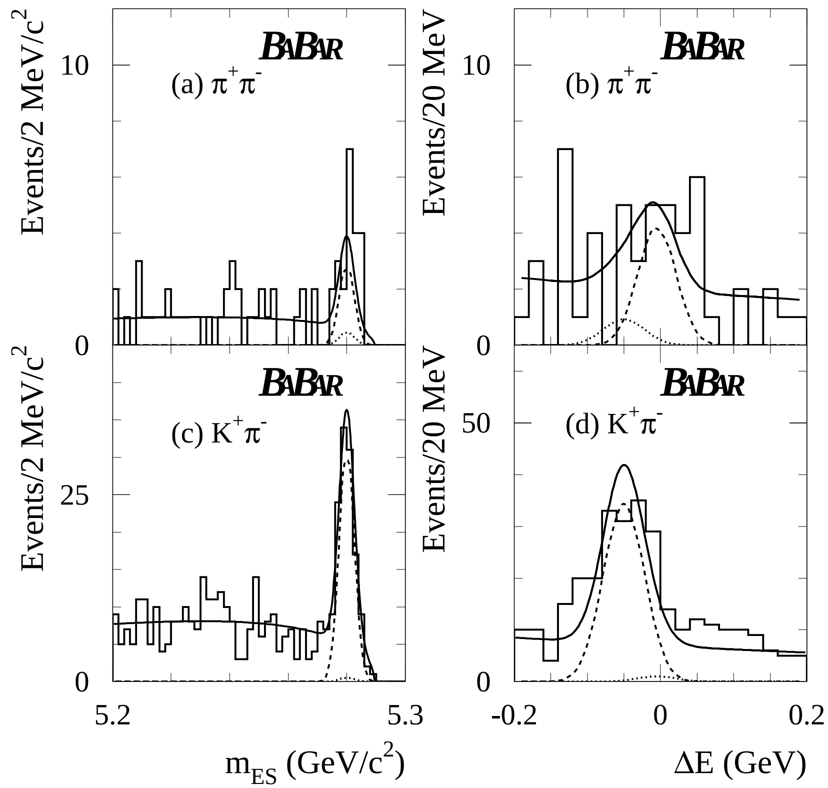
- Input observables for each event include $\mathbf{x}_i = \{M, \Delta E, \mathcal{F},$ resonance masses, helicity angles $\mathcal{H}$, PID pulls$\}$.
- PDF's $\mathcal{P}_{\pi S}$, etc., are products of functions of uncorrelated observables.
- PDF's determined with sideband data and MC.

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

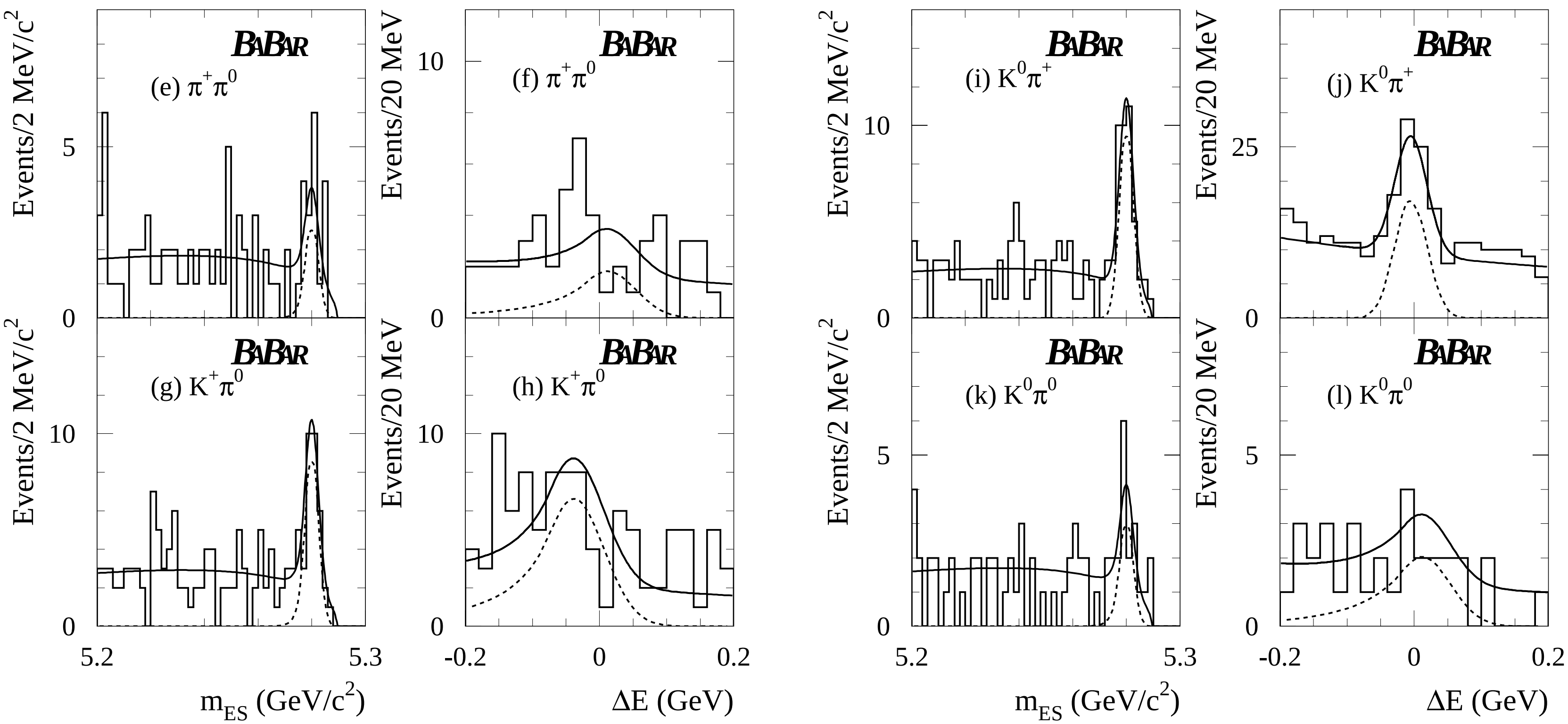
ML fit to M, ΔE, $\mathcal{F}$, PID pulls

(ΔE here computed with π hypothesis of charged tracks)





$B \to (K, \pi)\pi$



$B^+ \to \pi^+\pi^0 \simeq$ pure T

$B^+ \to \pi^+K^0 \simeq$ pure P'

Results for K, π modes

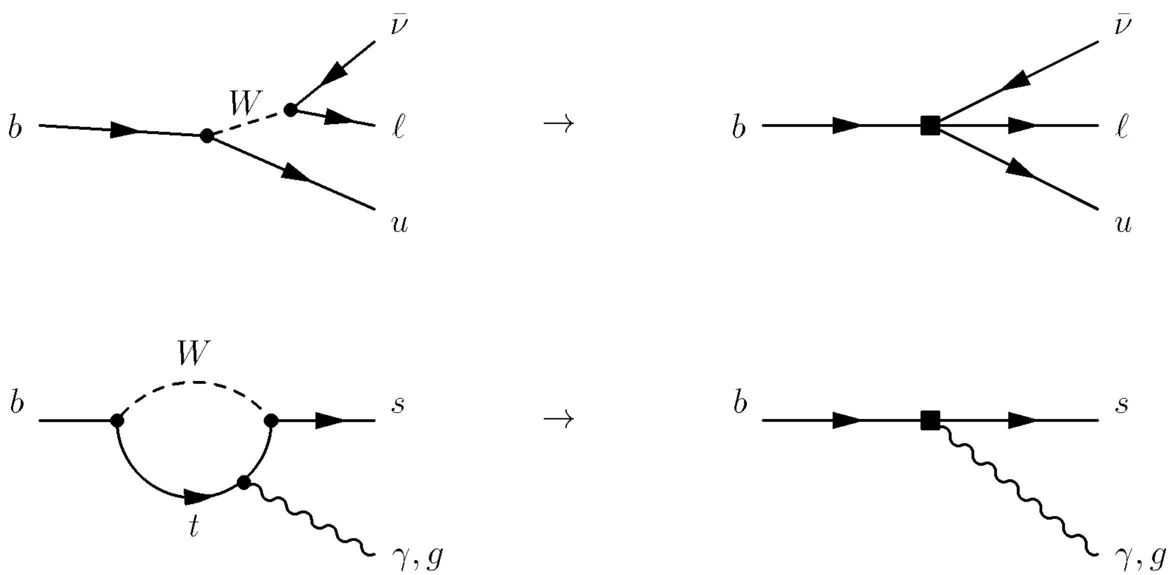
Mode	N_S	S (σ)	$\mathcal{B}(10^{-6})$
$\pi^+\pi^-$	$41 \pm 10 \pm 7$	4.7	$4.1 \pm 1.0 \pm 0.7$
$K^+\pi^-$	$169 \pm 17 \pm 13$	15.8	$16.7 \pm 1.6 \pm 1.3$
K^+K^-	$8.2^{+7.8}_{-6.4} \pm 3.5$	1.3	< 2.5 (90% C.L.)
$\pi^+\pi^0$	$37 \pm 14 \pm 6$	3.4	< 9.6 (90% C.L.)
$K^+\pi^0$	$75 \pm 14 \pm 7$	8.0	$10.8^{+2.1}_{-1.9} \pm 1.0$
$K^0\pi^+$	$59^{+11}_{-10} \pm 6$	9.8	$18.2^{+3.3}_{-3.0} \pm 2.0$
$\overline{K}^0K^+$	$-4.1^{+4.5}_{-3.8} \pm 2.3$	–	< 2.4 (90% C.L.)
$K^0\pi^0$	$17.9^{+6.8}_{-5.8} \pm 1.9$	4.5	$8.2^{+3.1}_{-2.7} \pm 1.2$

Predictions for pure tree, penguin modes (BBNS, current inputs):

$\mathcal{B}(B^+ \to \pi^+\pi^0) = 5.3^{+0.8}_{-0.4} \pm 0.3$

$\mathcal{B}(B^+ \to \pi^+K^0) = 14.1^{+6.4}_{-4.0}$

Effective theory



$$H_{\text{eff}} = -4\frac{G}{\sqrt{2}}V_{tb}V_{ts}^{*}\sum_{i=1}^{10}C_i(\mu)Q_i(\mu) \quad + (s \rightarrow d)$$

Wilson operators Q_i, coefficients C_i, renormalization scale μ

Effective theory, cont.

$$H_{\text{eff}} = -4\frac{G}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) Q_i(\mu) \quad + (s \to d)$$

$$\begin{aligned} i = \text{odd(even)} &\quad \leftrightarrow \quad \text{external(internal)} \\ i = 1, 2 &\quad : \quad W^{\pm}\ (L) \\ i = 3 - 6 &\quad : \quad \text{gluonic penguins } (L, R) \\ i = 7 - 10 &\quad : \quad \text{electroweak penguins } (L, R) \end{aligned}$$

- Renormalization group evolution $\mu = m_W \to m_B$ mixes the operators
- $\sum C_i(\mu) Q_i(\mu)$ scale independent, except for neglected terms in perturbation series
- Inclusive $\langle X \mid Q_i \mid B \rangle \simeq \langle s \mid Q_i \mid b \rangle$

Factorization

$$\langle m_1 m_2 \mid H_2 \mid B \rangle = \langle m_1 \mid J^\mu \mid B \rangle \langle m_2 \mid J_\mu \mid 0 \rangle$$

Uncertainties:

- Unmeasurable non-color singlet terms $\propto 1/N_c \rightarrow \xi$, a free parameter.
- $\langle m_1 \mid J^\mu \mid B \rangle$ depends on form factor(s) $F_{B \rightarrow m_1}$
- Average 4-momentum of virtual gluons and photons in loops
- quark masses

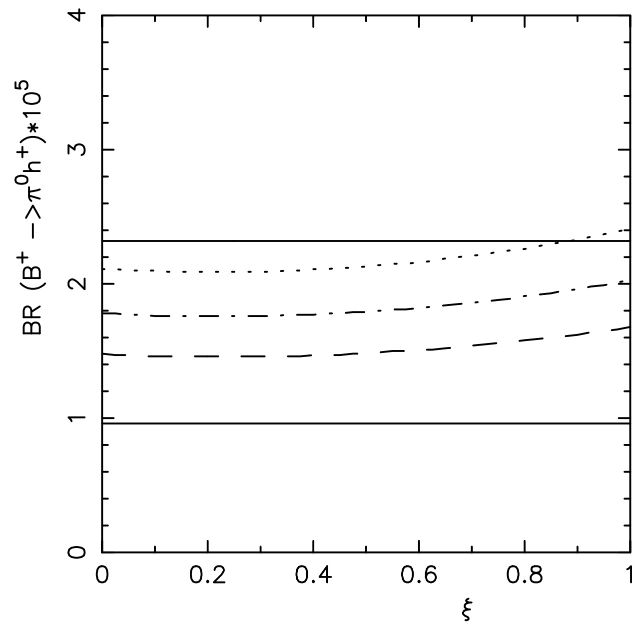
$\mathcal{B}\left(B^0 \rightarrow K^+ \pi^-\right)$

Ali, Kramer, Lü prediction

$(14 \text{ to } 21) \times 10^{-6}$

BABAR:

$(16.7 \pm 1.6 \pm 1.3) \times 10^{-6}$



Bounds on $\gamma_{\rm CKM}$

(Fleisher, Mannel; others): $B^{\pm} \rightarrow \overset{(-)}{K^0} \pi^{\pm}$ is pure penguin.

$$\mathcal{A}_{CP}^{\rm dir} \equiv \frac{\mathcal{B}\left(B^0 \rightarrow K^+\pi^-\right) - \mathcal{B}\left(\bar{B}^0 \rightarrow K^-\pi^+\right)}{\mathcal{B}\left(B^0 \rightarrow K^+\pi^-\right) + \mathcal{B}\left(\bar{B}^0 \rightarrow K^-\pi^+\right)}$$

$$R \equiv \frac{\mathcal{B}\left(\overset{(-)}{B^0} \rightarrow K^{\pm}\pi^{\mp}\right)}{\mathcal{B}\left(\bar{B}^{\pm} \rightarrow \overset{(-)}{K^0} \pi^{\pm}\right)}$$

$$r \equiv \frac{(\rm tree)}{(\rm penguin)}; \quad \delta \equiv \phi_{(\rm tree)} - \phi_{(\rm penguin)}$$

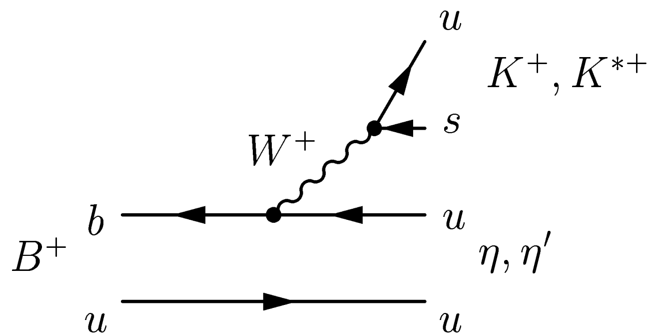
$$\mathcal{A}_{CP}^{\rm dir} = 2\frac{r}{R}\sin\delta\sin\gamma$$

$$R = 1 - 2r\cos\delta\cos\gamma + r^2$$

$$\sin^2\gamma < R = 0.65 \pm 0.38$$

$B \to \eta^{(\prime)} K^{(*)}$

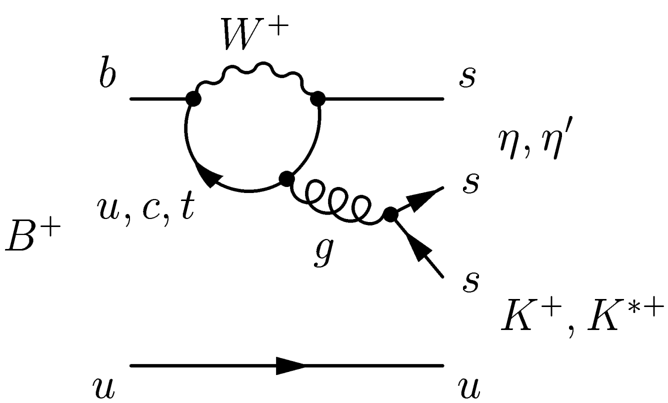
The tree is Cabibbo suppressed:

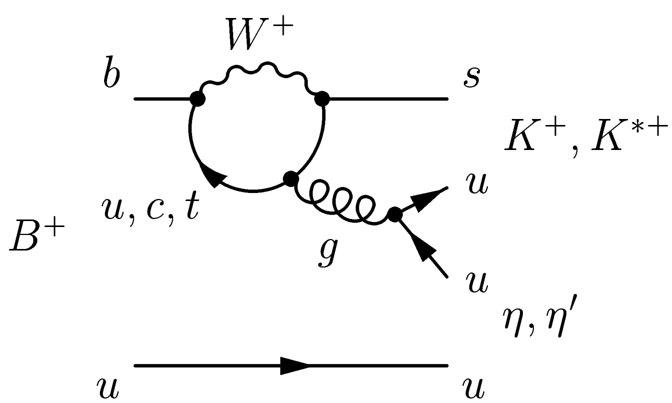


Interference between penguins; conjecture

enhance $B \to \eta K^*$, $B \to \eta' K$

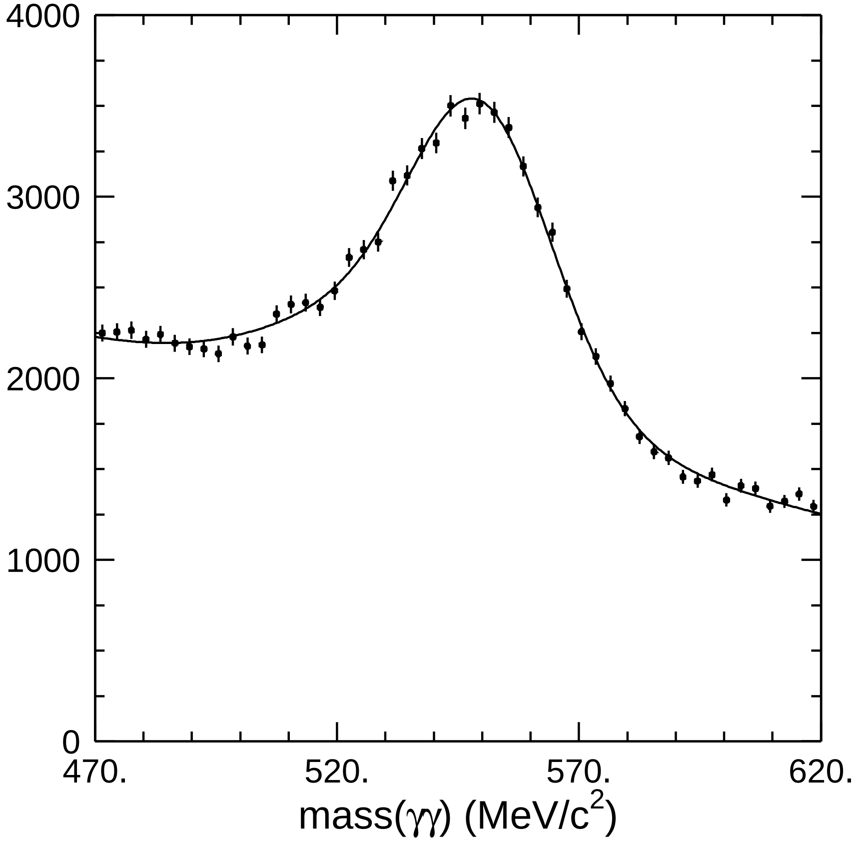
suppress $B \to \eta K$, $B \to \eta' K^*$

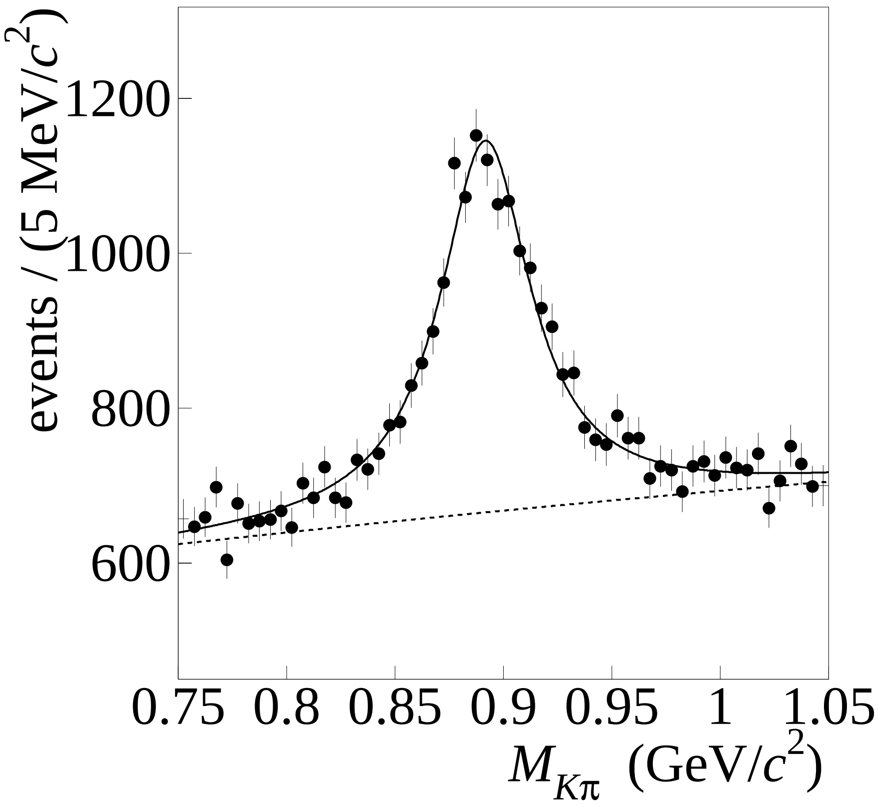




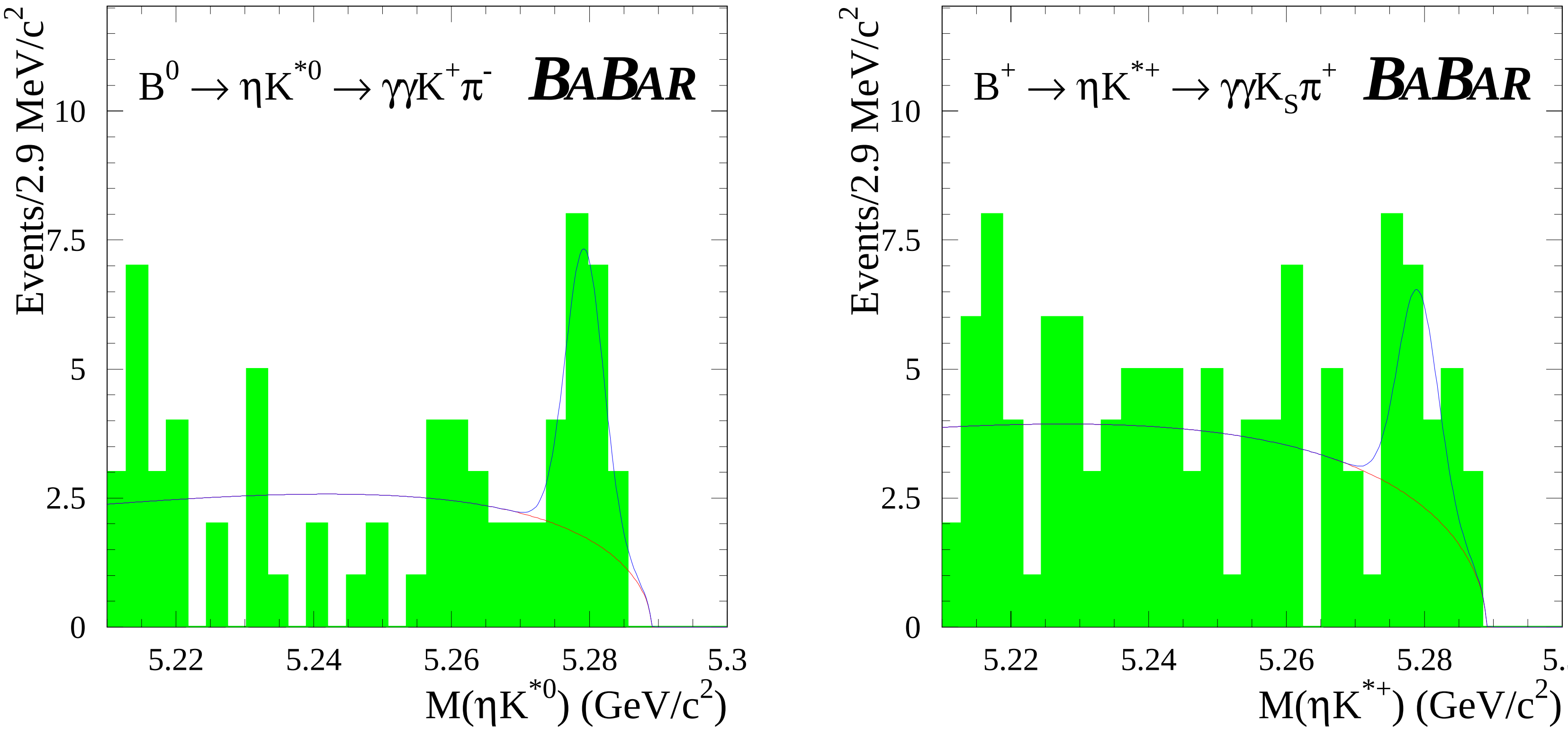
$B \to \eta K^*$

Add $\gamma\gamma$, $K\pi$ mass PDFs to ML fit

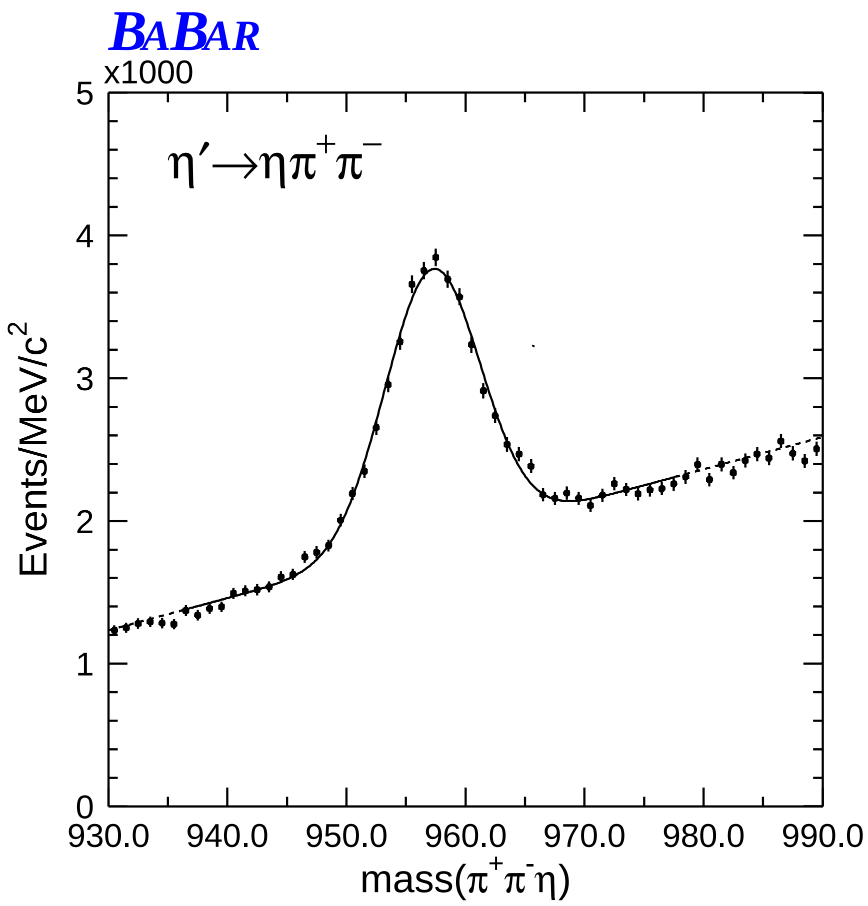


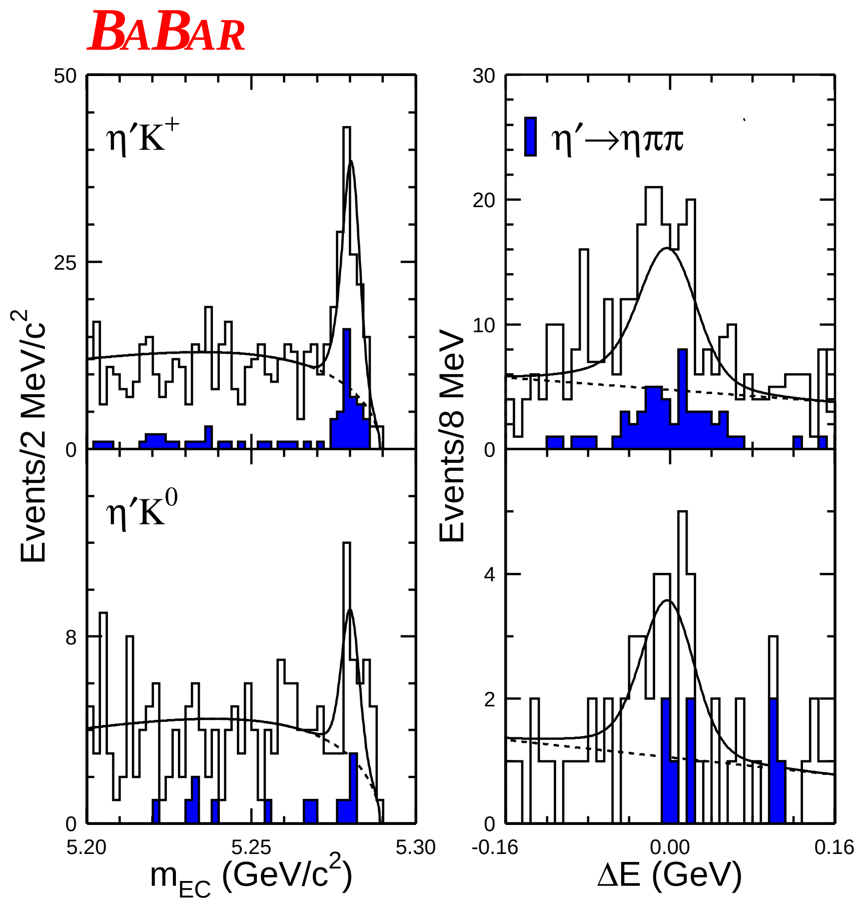


$B \to \eta K^*$


$B^0 \to \eta K^{*0} \to \gamma\gamma K^+\pi^-$
BABAR
Events/2.9 MeV/c²
0
2.5
5
7.5
10
5.22
5.24
5.26
5.28
5.3
M(ηK*0) (GeV/c²)
$B^+ \to \eta K^{*+} \to \gamma\gamma K_S\pi^+$
BABAR
Events/2.9 MeV/c²
M(ηK*+) (GeV/c²)

$B \to \eta' K$

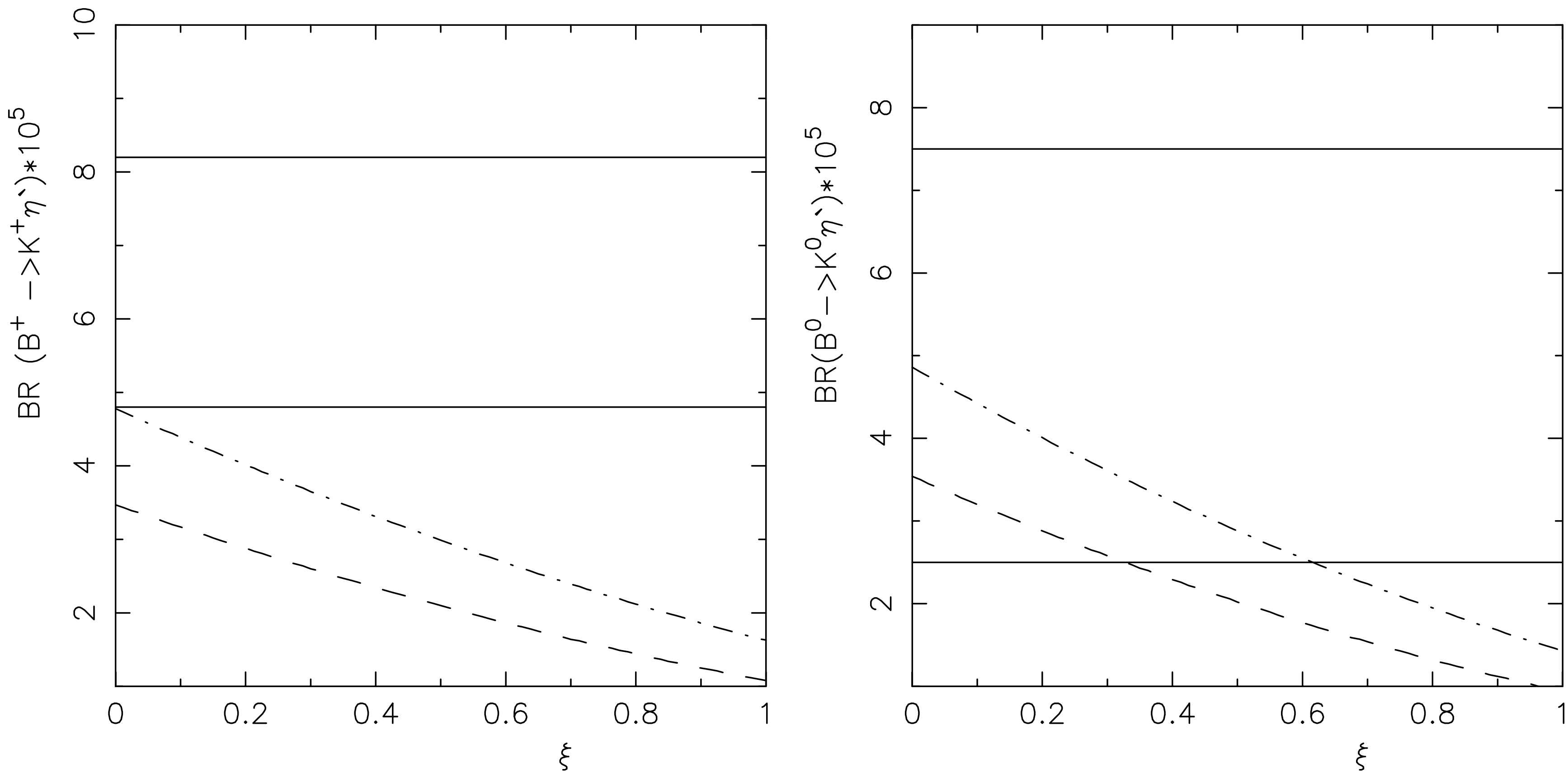

BABAR
x1000
5
4
3
2
1
0
Events/MeV/c2
η′→ηπ+π−
930.0 940.0 950.0 960.0 970.0 980.0 990.0
mass(π+π-η)


BABAR
η′K+
η′K0
η′→ηππ
50
25
0
8
0
30
20
10
0
4
2
0
Events/2 MeV/c2
Events/8 MeV
5.20 5.25 5.30
mEC (GeV/c2)
-0.16 0.00 0.16
ΔE (GeV)

Results for $B \longrightarrow \eta^{(\prime)} K^{(*)}$

Mode	Signal yield	$S(\sigma)$	B/10^{-6}	(90% CL)
ηK^{*0}	20.5 ± 6.0	5.4	$19.8^{+6.5}_{-5.6} \pm 1.7$	
ηK^{*+}	14.3 ± 6.6	3.2	$22.1^{+11.1}_{-9.2} \pm 3.3$	(< 33.9)
$\eta'_{\eta\pi\pi} K^+$	$49.5^{+8.1}_{-7.3}$	15	63^{+10}_{-9}	
$\eta'_{\rho\gamma} K^+$	$87.6^{+13.4}_{-12.5}$	11	80^{+12}_{-11}	
$\eta' K^+$		17	$\mathbf{70 \pm 8 \pm 5}$	
$\eta'_{\eta\pi\pi} K^0$	$6.3^{+3.3}_{-2.5}$	4.7	28^{+15}_{-11}	
$\eta'_{\rho\gamma} K^0$	$20.8^{+7.4}_{-6.5}$	4.2	61^{+22}_{-19}	
$\eta' K^0$		5.9	$\mathbf{42^{+13}_{-11} \pm 4}$	
$\eta'_{\eta\pi\pi} \pi^+$	$5.7^{+3.8}_{-2.8}$	3.2	$7.1^{+4.8}_{-3.5}$	
$\eta'_{\rho\gamma} \pi^+$	$-0.9^{+7.8}_{-6.2}$	0.1	$-0.7^{+6.7}_{-5.3}$	
$\eta' \pi^+$		2.8	$\mathbf{5.4^{+3.5}_{-2.6} \pm 0.8}$	(< 12)

Factorization prediction for $B \to \eta' K$



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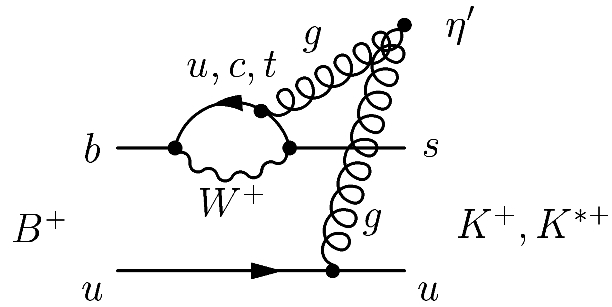
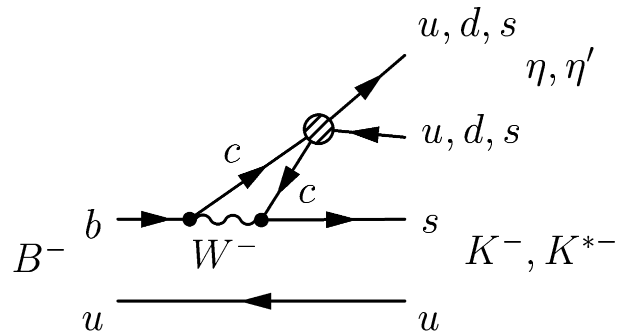
Large rate for $B \to \eta' K$

Has prompted conjectures

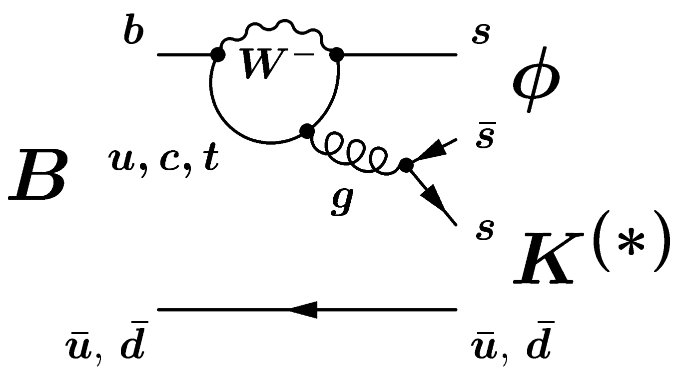
- η' approximates a flavor singlet state
- QCD anomaly, glue coupling to η'



"Charming penguins" — c enhanced in loop:

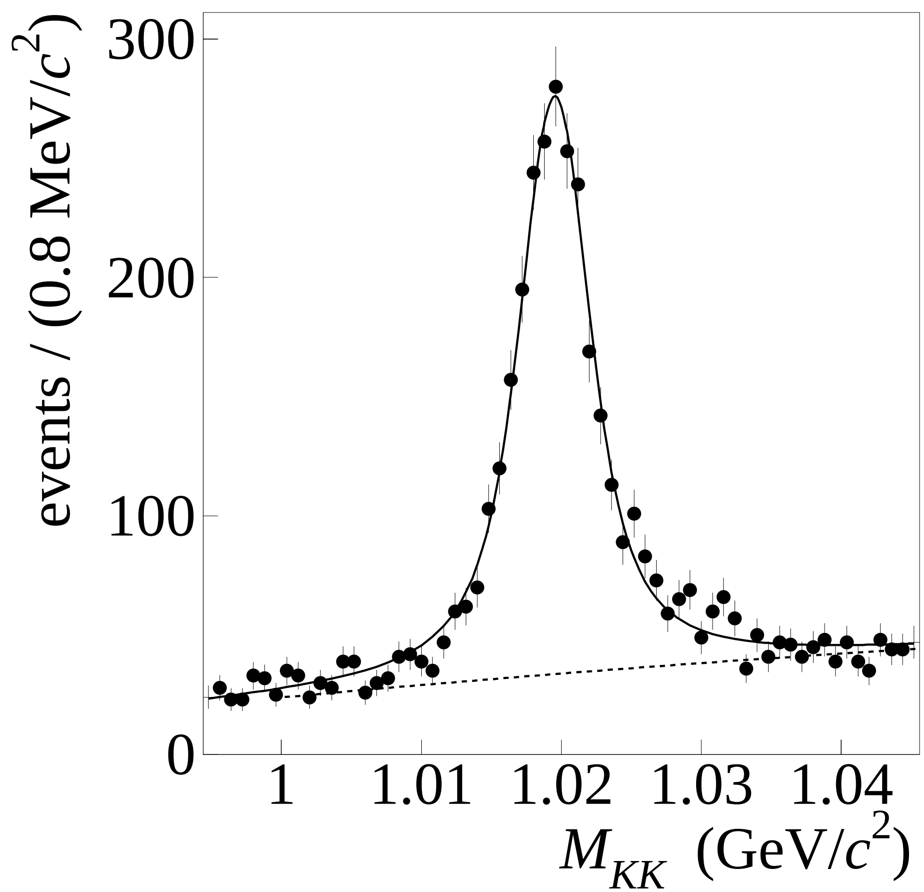


$B \to \phi K^{(*)}$

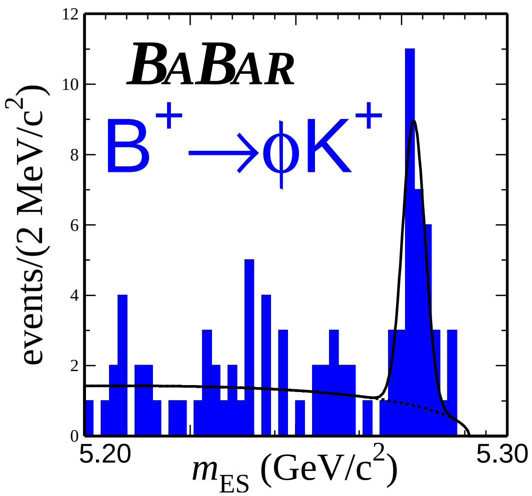


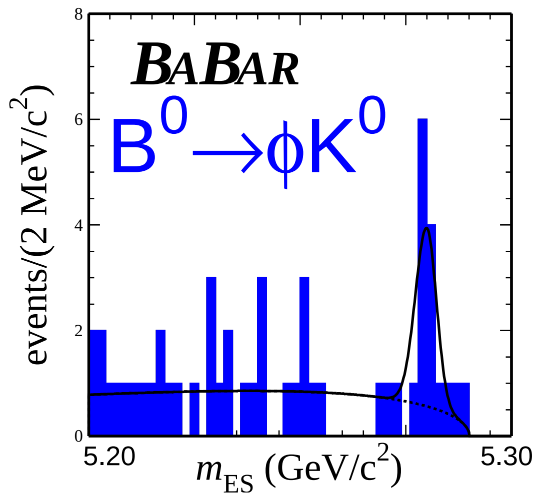
Maximum likelihood fit to
M, ΔE, $\mathcal{F}$, $m(K^+K^-)$

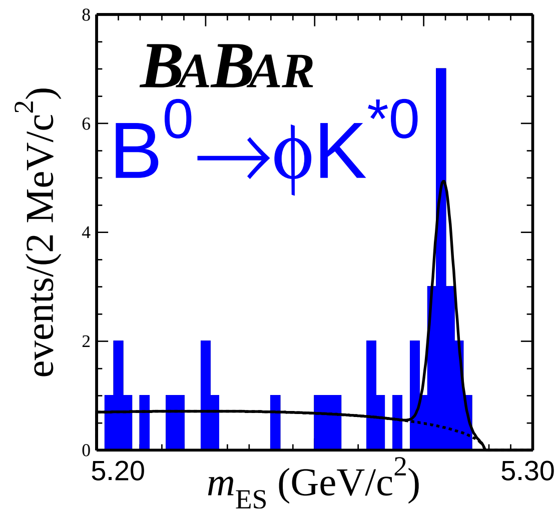
$\mathcal{H}$ for ϕK modes

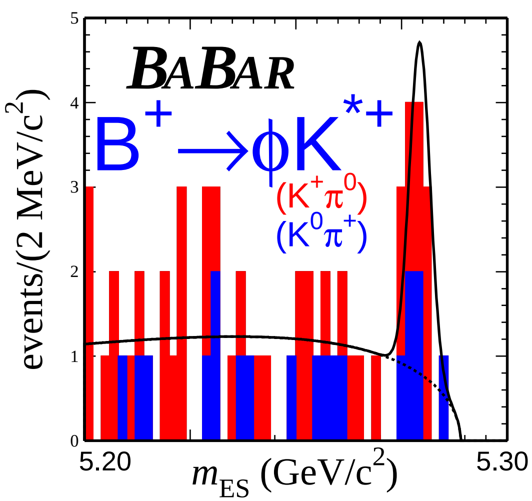


Results for $\phi K^{(*)}$



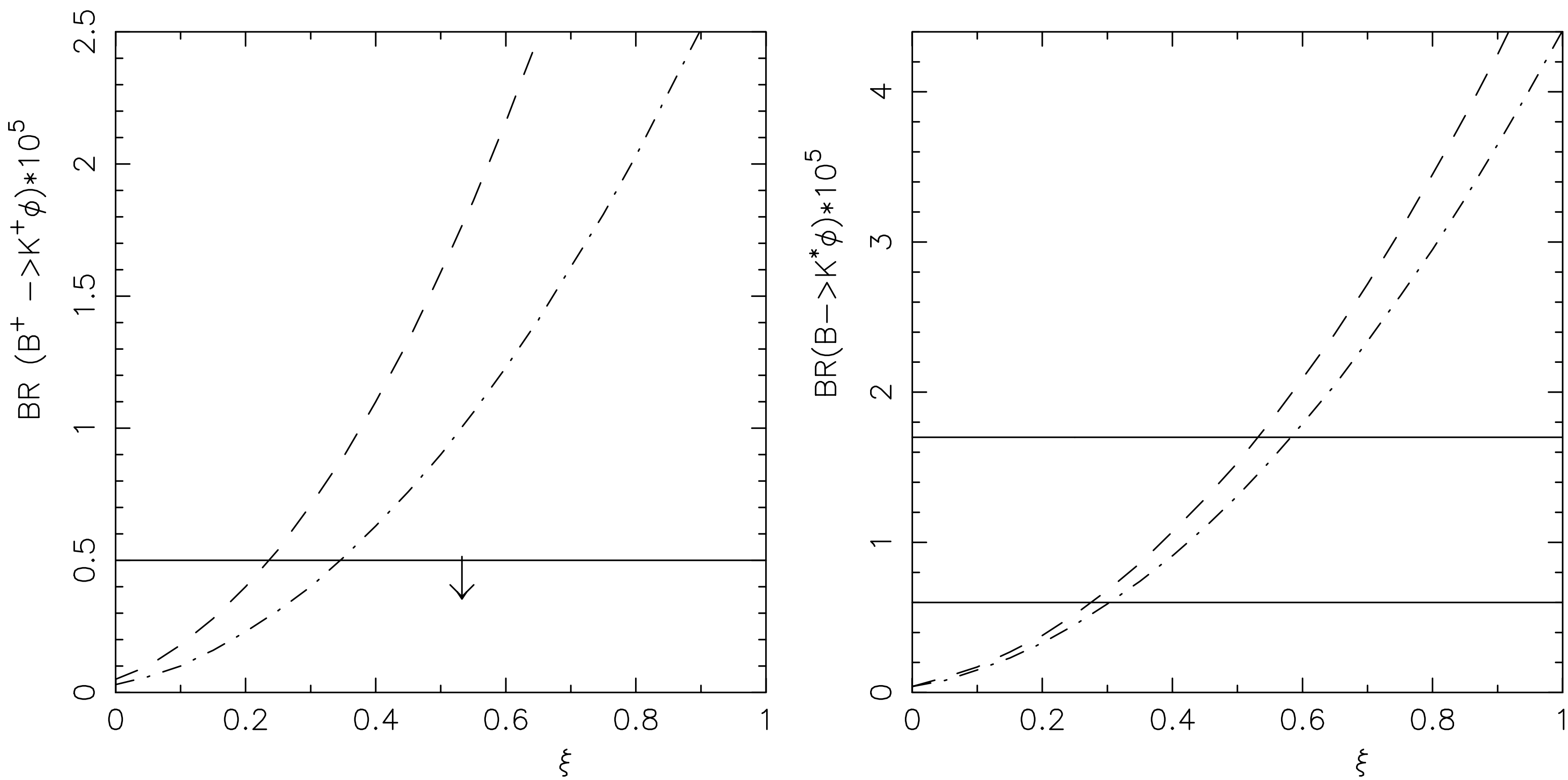






Mode	$n_{\rm sig}$	S	$\mathcal{B}(10^{-6})$
ϕK^+	$31.4^{+6.7}_{-5.9}$	10.5	$7.7^{+1.6}_{-1.4} \pm 0.8$
ϕK^0	$10.8^{+4.1}_{-3.3}$	6.4	$8.1^{+3.1}_{-2.5} \pm 0.8$
ϕK^{*+}	–	4.5	$9.7^{+4.2}_{-3.4} \pm 1.7$
$\phi K^{*+}_{K^+}$	$7.1^{+4.3}_{-3.4}$	2.7	$12.8^{+7.7}_{-6.1} \pm 3.2$
$\phi K^{*+}_{K^0}$	$4.4^{+2.7}_{-2.0}$	3.6	$8.0^{+5.0}_{-3.7} \pm 1.3$
ϕK^{*0}	$20.8^{+5.9}_{-5.1}$	7.5	$8.7^{+2.5}_{-2.1} \pm 1.1$
$\phi \pi^+$	$0.9^{+2.1}_{-0.9}$	0.6	< 1.4 (90% CL)

Factorization prediction for $B^+ \to \phi K^{(*)}$



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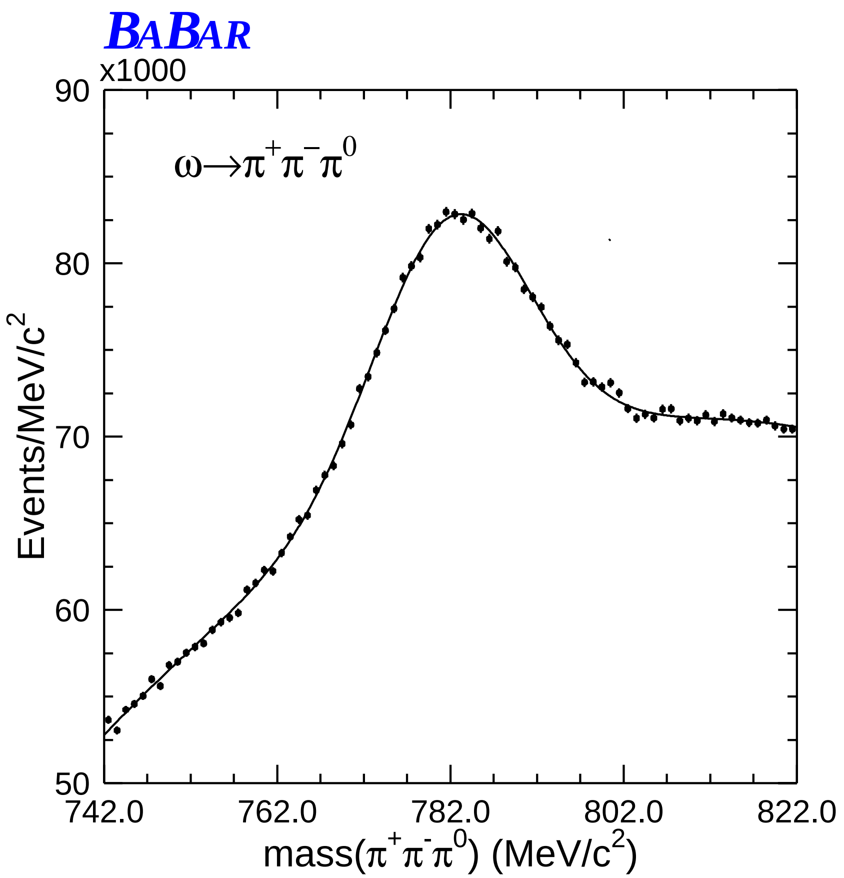
$B \to \omega\pi$, $B \to \omega K$

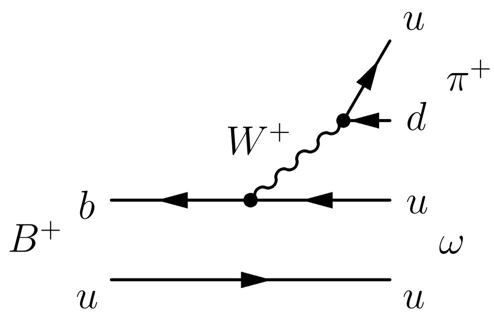
ML fit with m_{EC}, ΔE, $\mathcal{F}$, $m(\pi^+\pi^-\pi^0)$, $\mathcal{H}$, DIRC pull for $B^+ \to \omega h^+$

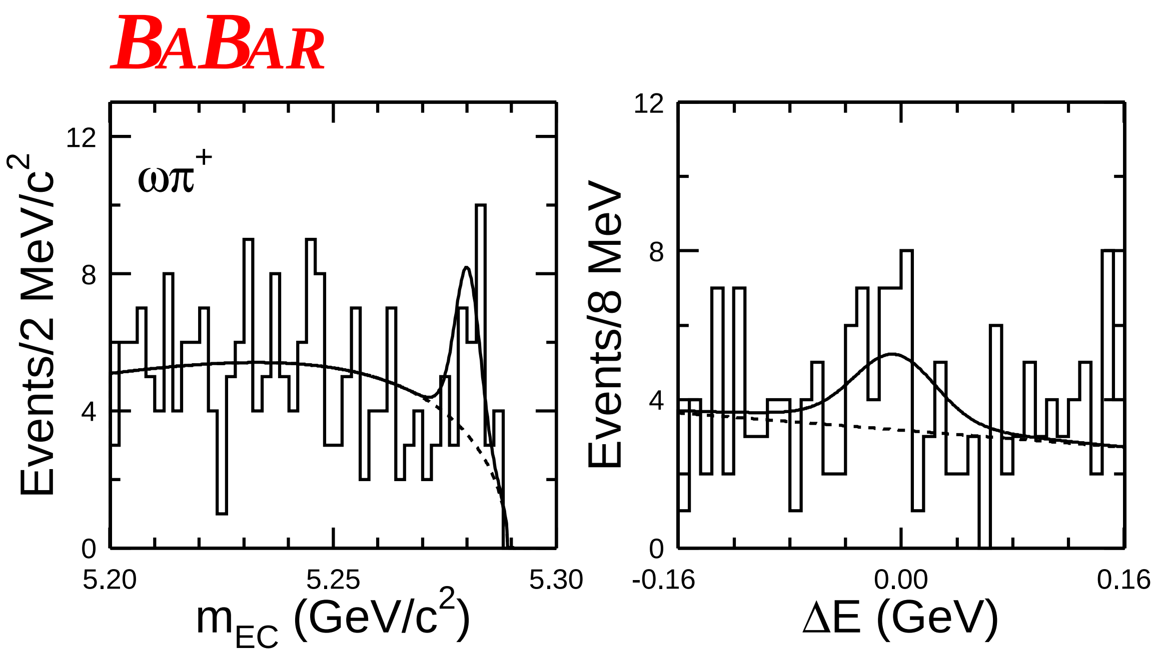
Also analyzed with NN (excluding ΔE), ML fit to NN output and $\Delta E \Longrightarrow$ confirming results (quoted for $B^0 \to \omega\pi^0$).



$B \to \omega\pi$, $B \to \omega K$

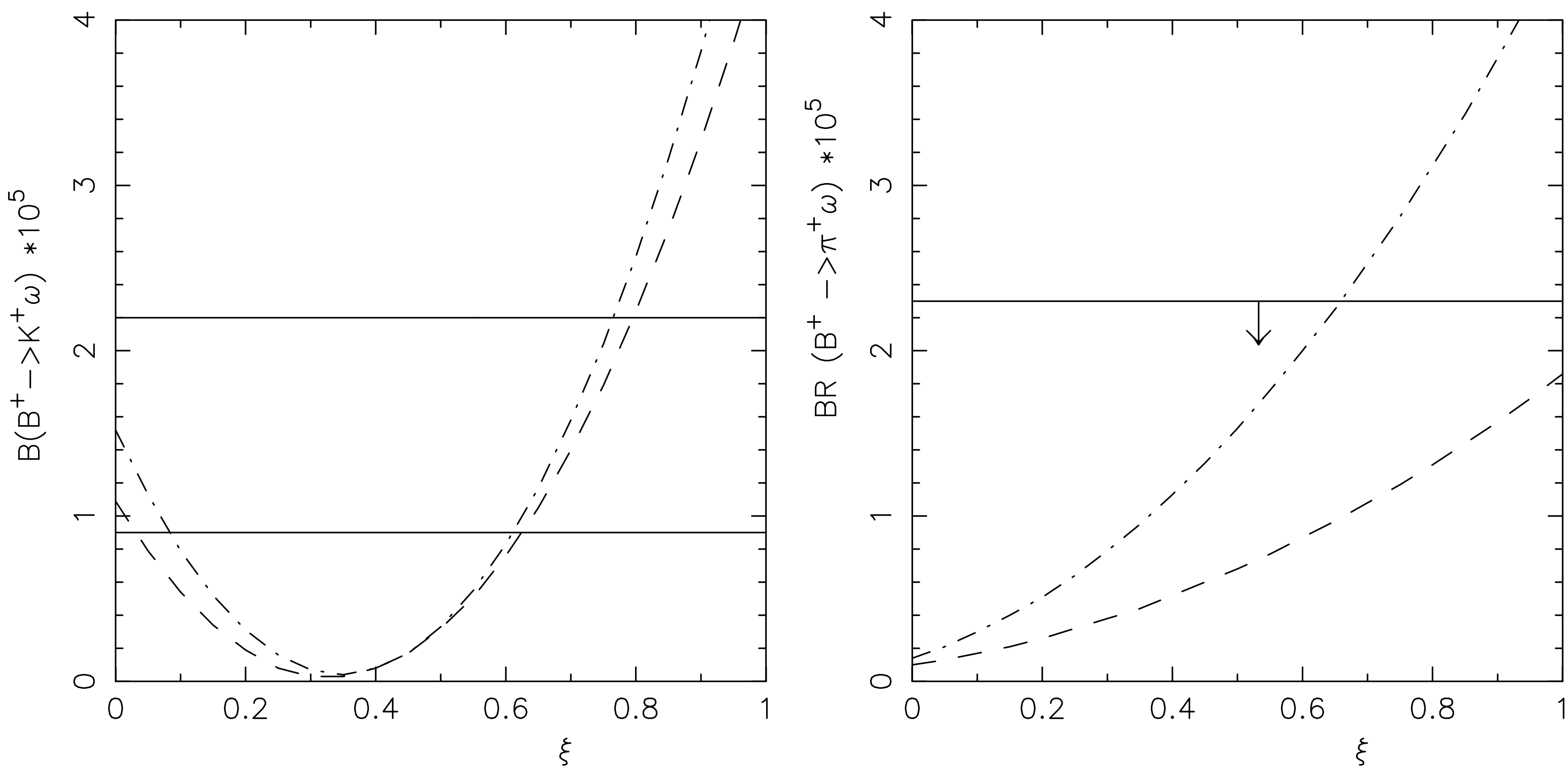
For $B^+ \to \omega\pi^+$ expect the Cabibbo-favored tree to dominate:





Mode	Signal yield	$S(\sigma)$	$\mathcal{B}/10^{-6}$	(90% CL)
ωK^+	$6.4^{+5.6}_{-4.4}$	1.3	$\mathbf{1.4^{+1.3}_{-1.0} \pm 0.3}$	(< 4)
ωK^0	$8.1^{+4.6}_{-3.6}$	3.2	$\mathbf{6.4^{+3.6}_{-2.8} \pm 0.8}$	(< 13)
$\omega\pi^+$	$27.6^{+8.8}_{-7.7}$	4.9	$\mathbf{6.6^{+2.1}_{-1.8} \pm 0.7}$	
$\omega\pi^0$	$-0.9^{+5.0}_{-3.2}$	–	$\mathbf{-0.3 \pm 1.1 \pm 0.3}$	(< 3)

Factorization prediction for $\omega(K, \pi)$



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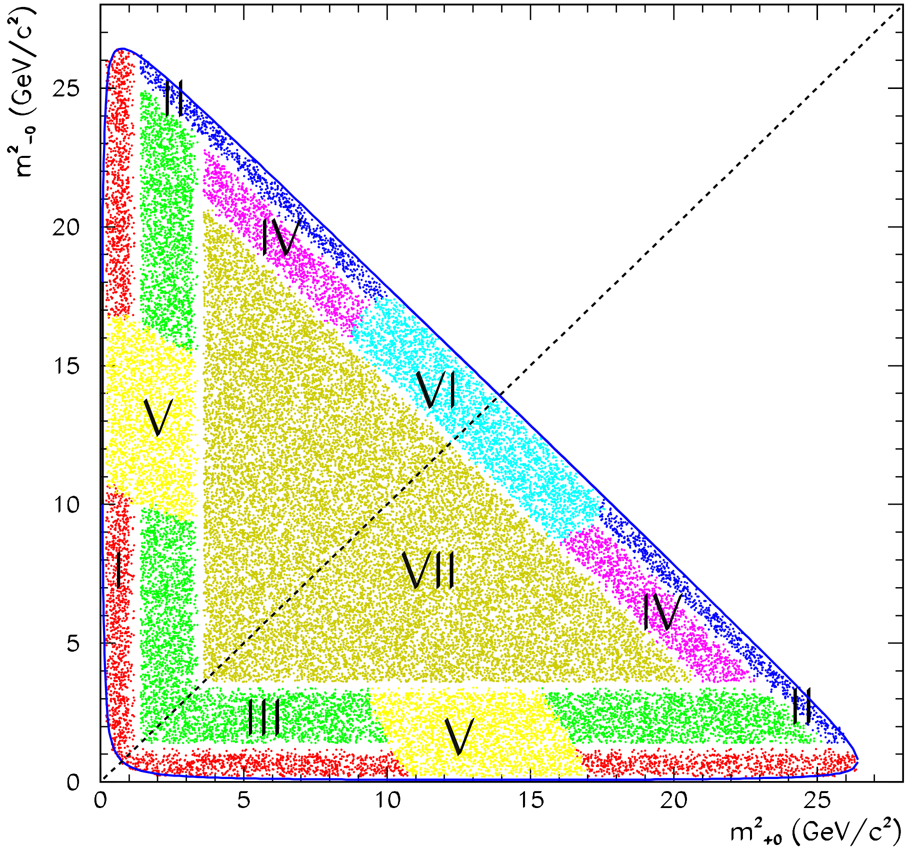
$B^0 \to \pi^+\pi^-\pi^0$

Dalitz plot



$m(\pi^-\pi^0)$ vs $m(\pi^+\pi^0)$

Dotted line is CP symmetry axis

- $\rho^\pm$ along left, bottom
- ρ^0 along diagonal
- $\rho'^\pm$, ρ'^0 along inner bands
- Spin alignment $\Longrightarrow$ $\cos^2\theta_H$ peaking at low, high m
- Charged, neutral $(f^0(400-1200)$ or "σ" scalar in band centers
- Non-resonant $\pi^+\pi^-\pi^0$ in central region

$m(\pi^-\pi^0)$ vs $m(\pi^+\pi^0)$

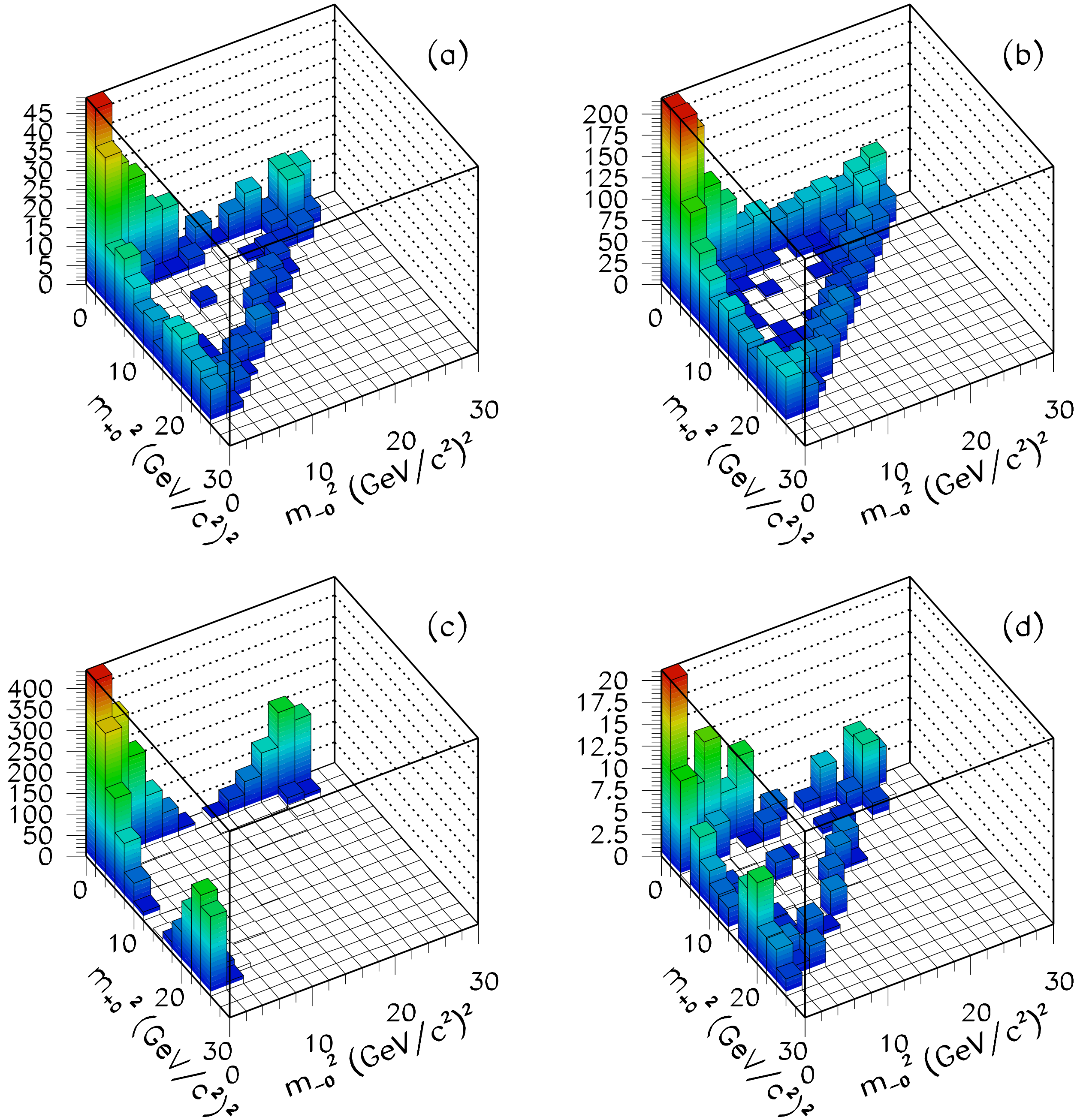
Cut and count

(a) Signal box

(b) GSB

(c) Signal MC

(d) BG-subtr

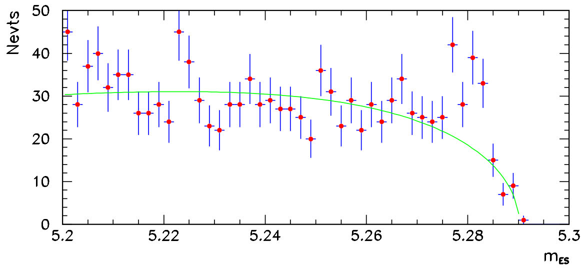


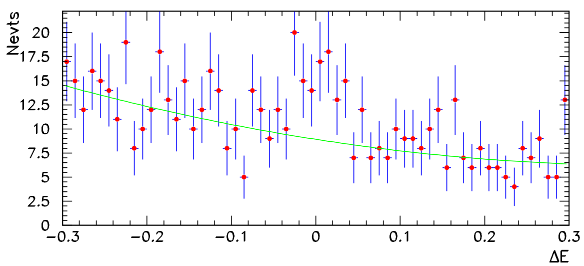
$B^0 \to \pi^+\pi^-\pi^0$

Cuts: $\pi^0 \to \gamma\gamma$ mass, $\cos\theta_T$, $\mathcal{F}$, $\mathcal{H}$

Signal in $B^0 \to \rho^+\pi^-$

m_{ES}, ΔE:





Mode	Net Yield	S (σ)	$\mathcal{B}/10^{-6}$
$\rho^+\pi^-$	$42.8 \pm 11.5 \pm 4.0$		
$\rho^-\pi^+$	$46.2 \pm 11.4 \pm 3.8$		
$\rho^\pm\pi^\mp$		5.01	$28.9 \pm 5.4 \pm 4.3$
$\rho^0\pi^+$	$6.1 \pm 5.8 \pm 2.8$	0.96	$3.6 \pm 3.5 \pm 1.7$
			(< 10.6, 90% CL)

$B^0 \to a_0^+ \pi^-$

Going beyond the lowest-lying meson nonets,

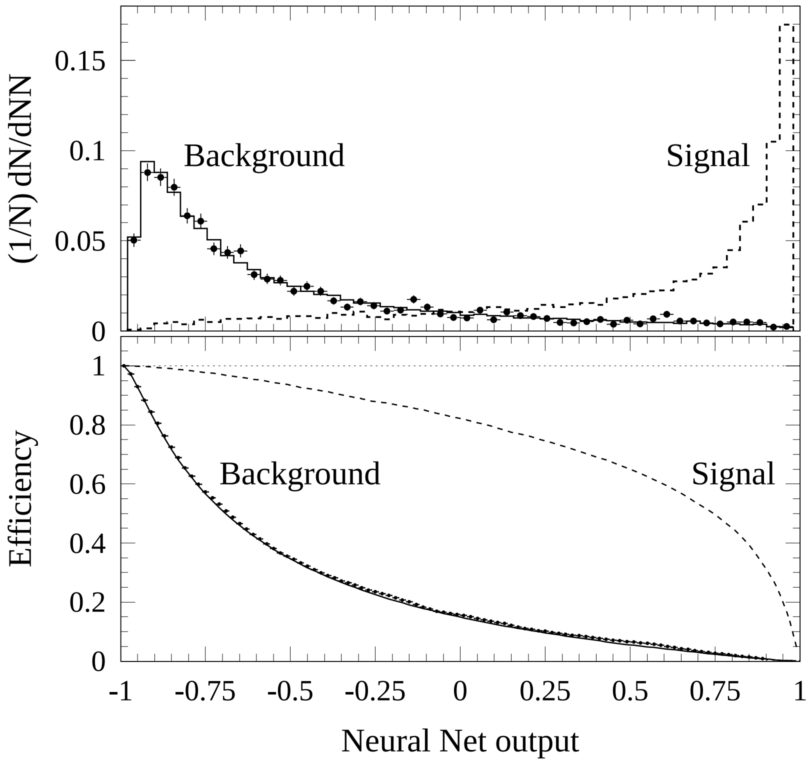
$a_0(980)(\Gamma = 50$ to 100 MeV$/c^2) \to \eta\pi$ ("dominant"); $\eta \to \gamma\gamma$

Continuum rejection Neural Net

- R_2, $\cos\theta_T$, $\cos\theta_B^*$
- three more topological angles
- Legendre moments $L_j^{(c,n)} \equiv \sum_{i_{(c,n)}} p_i \left|\cos\theta_i\right|^j$, $j = 0, 2, 6$

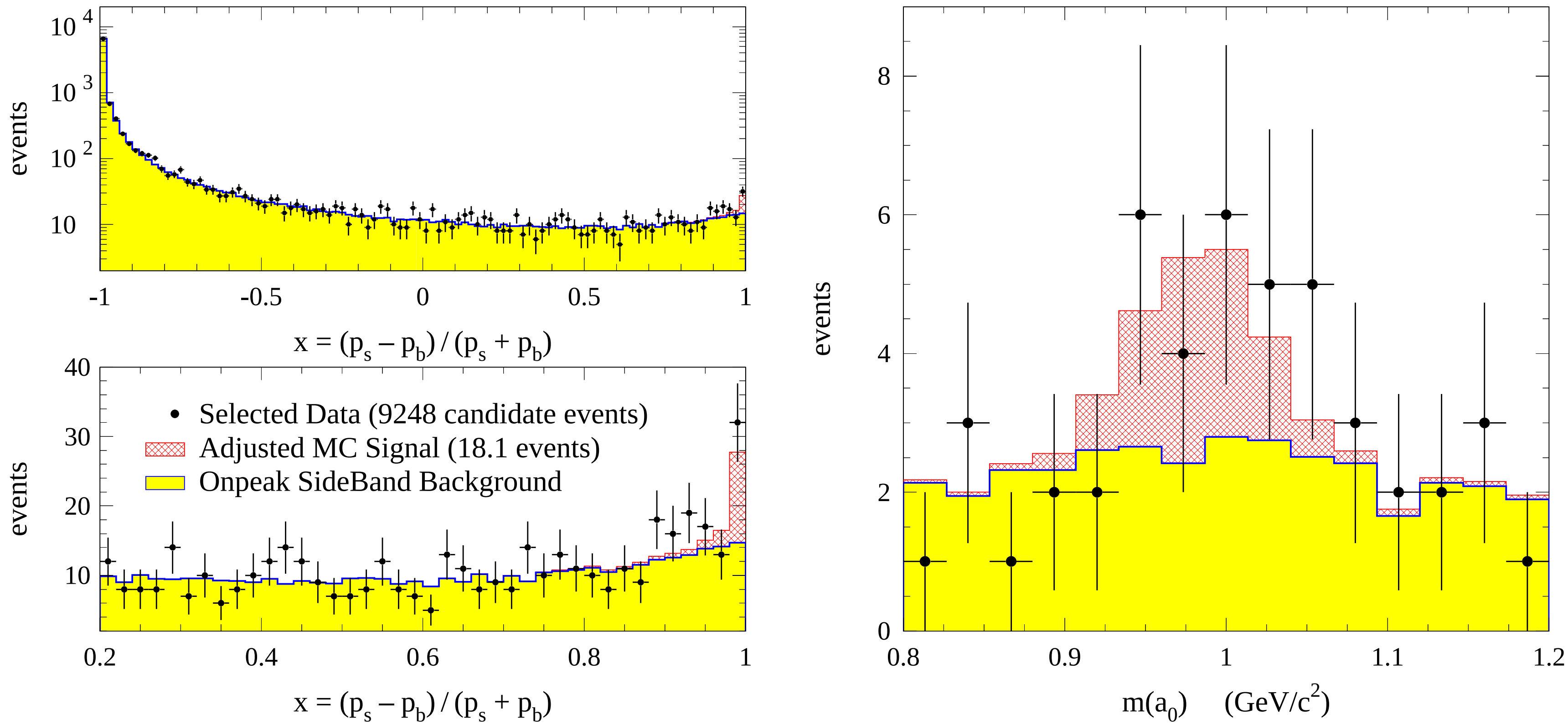
  c: tracks; n: calorimeter clusters,

  θ_i wrt B candidate thrust axis



$B^0 \to a_0^+\pi^-$, cont.

Max. likelihood fit with NN, $m(\gamma\gamma)$, ΔE, $m_{\rm EC}$ (no $m(a_0)$)

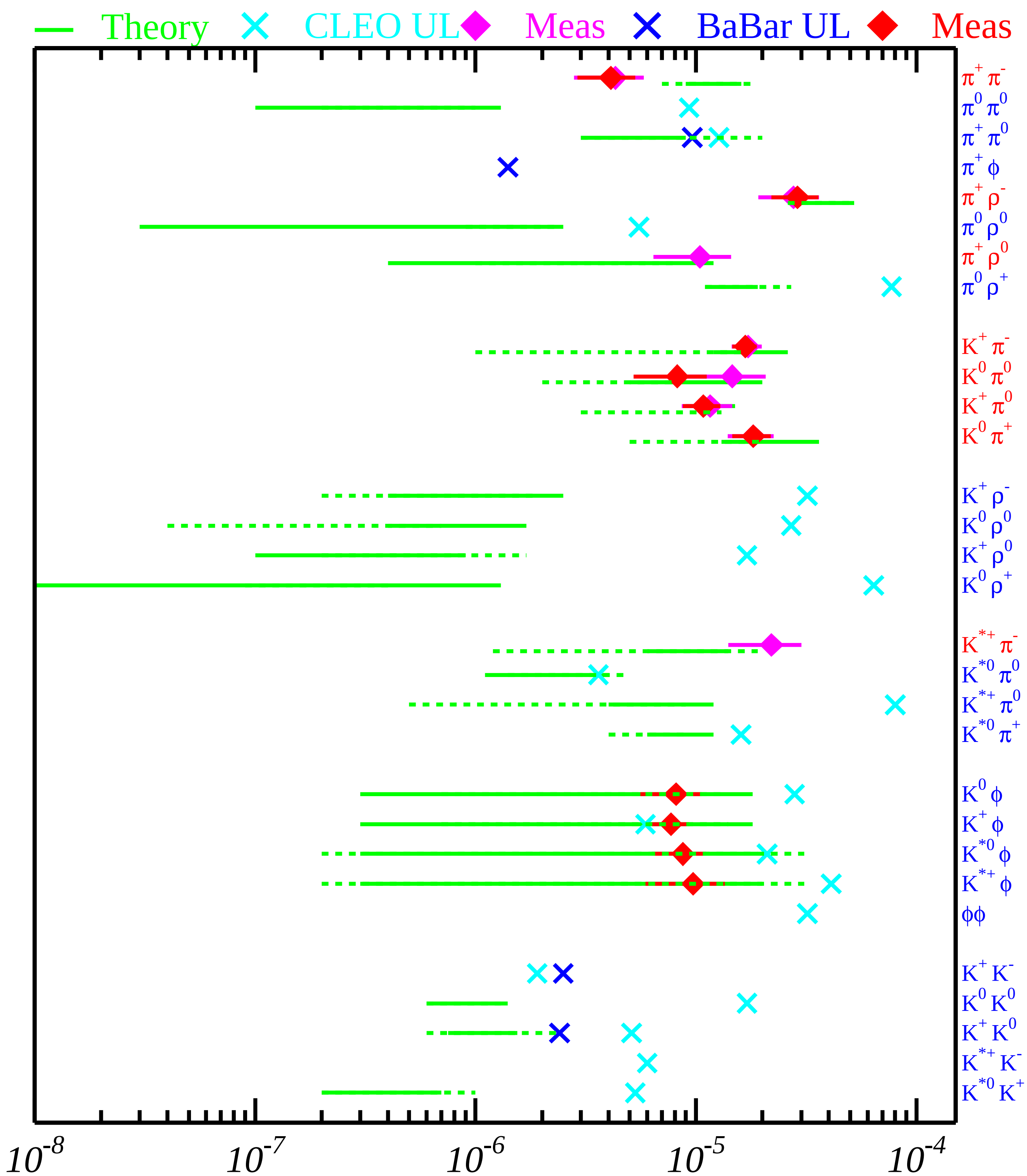


$$\mathcal{B}(B^0 \to a_0^+(a_0^+ \to \eta\pi^+)\pi^-) = (6.2^{+3.0}_{-2.5} \pm 1.1) \times 10^{-6}$$

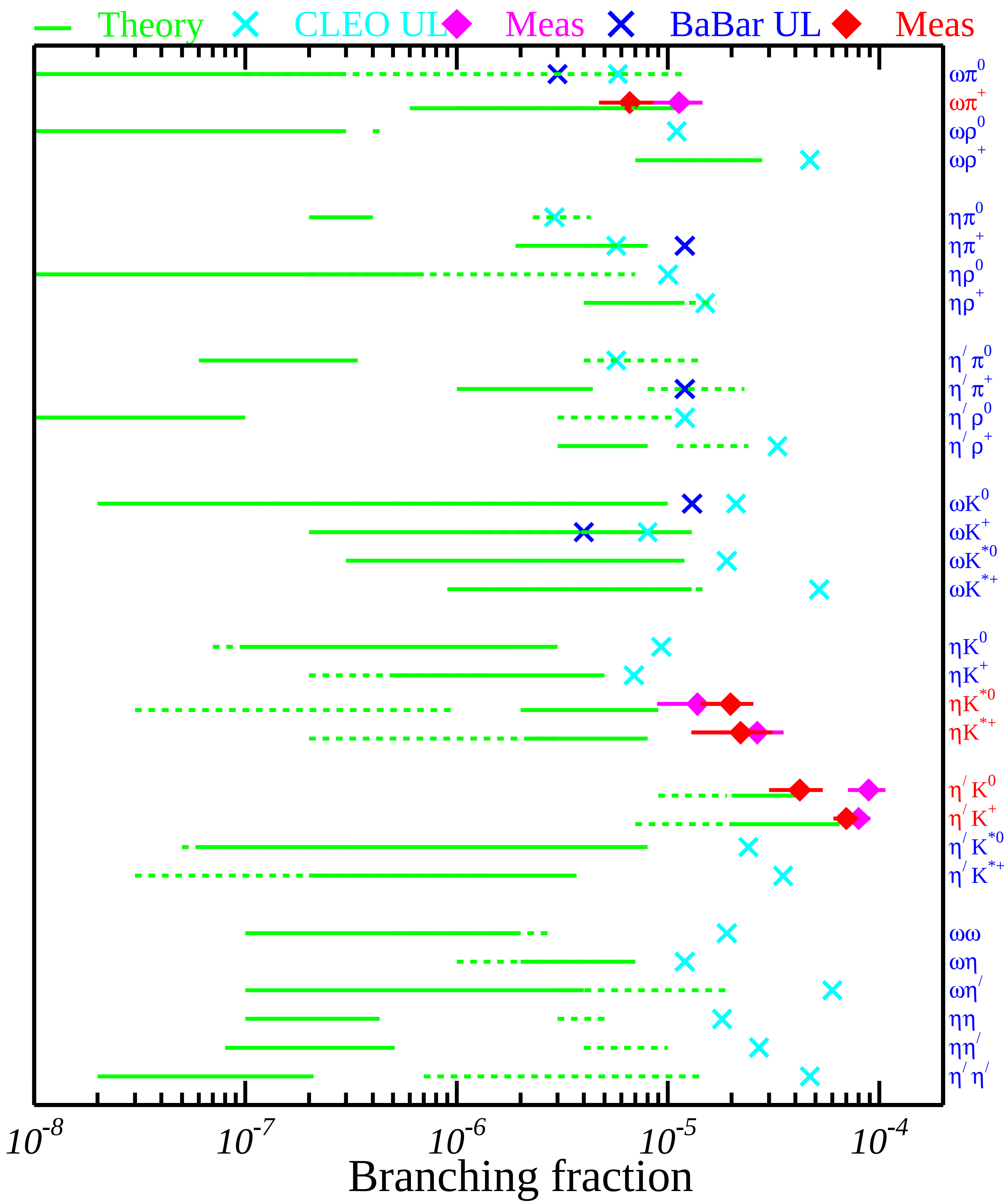
with a statistical signficance, including systematics, of $3.7\ \sigma$.

At 90% CL, $\mathcal{B}(B^0 \to a_0^+(a_0^+ \to \eta\pi^+)\pi^-) < 11.5 \times 10^{-6}$

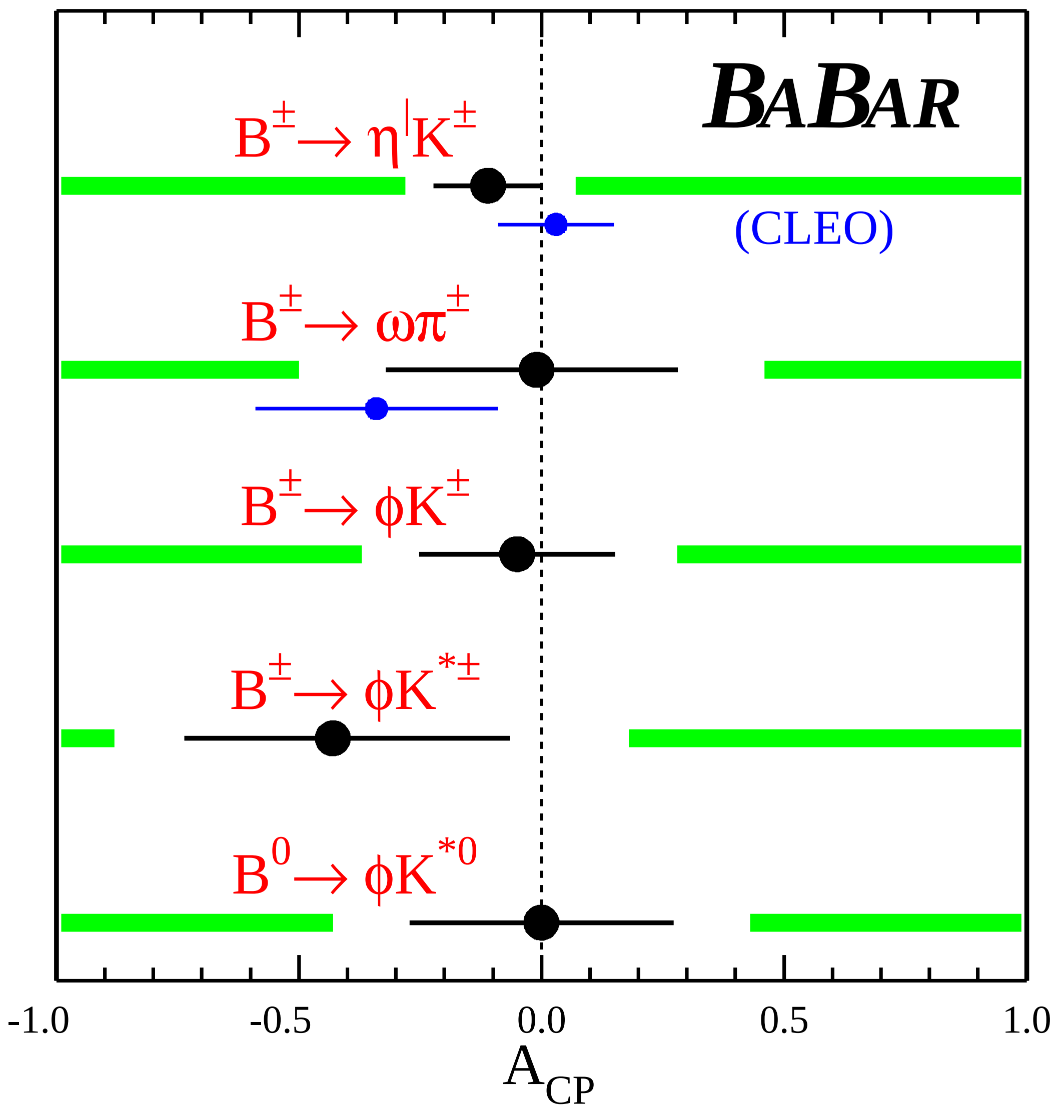
Summary for K, π, ϕ modes



Summary for η, η', ω modes



Direct CP Asymmetries



Near future focus of theory, expt effort

- Reliability of predictions for radiative decays
  - ◇ Constrain new physics in loops
- Reliability of "triangle" relations for CP angles
  - ◇ Control of penguin polution
  - ◇ "Pure" tree, penguin modes
- Charge asymmetries — direct CP
- Time dependent asymmetries — CKM angles
  - ◇ Control of penguin polution
- Role of QCD anomaly, charm enhancement, ...
  - ◇ Large rates for $B \to \eta' K$, inclusive $B \to \eta'$

Conclusions

- Experiments are approaching the $\mathcal{O}(10^{-6})$ decade of branching fractions in B decays.
- ~ 20 exclusive modes observed so far:
  - ◇ $K^*\gamma$
  - ◇ $K\pi$
  - ◇ $\pi\pi$
  - ◇ $K\eta'$
  - ◇ $K^*\eta$
  - ◇ $\pi^+\rho^-$
  - ◇ $\pi^+\omega$
  - ◇ $K^{(*)}\phi$
- Measurements have stimulated much theoretical interest and effort
- More data in hand; much more in the next few years.