Rare B decays and direct CP violation at BABAR

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on behalf of the BABAR collaboration

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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Rare B decays

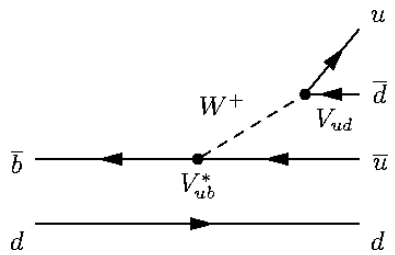
Decays that are suppressed by either:

- **Small CKM matrix element:** $|V_{ub}/V_{cb}| \approx \lambda$

  ✓**exclusive b→u hadronic decays:**

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

  Br ≈ 10^{-5} ,10^{-6}

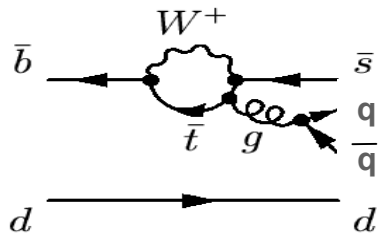


- **Leading diagram involves a loop:** $\frac{\alpha_s}{4\pi}$ or $\frac{\alpha_{QED}}{4\pi}$

  ✓**gluonic penguin: b→ s gluon(→qq) (exclusive)**

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

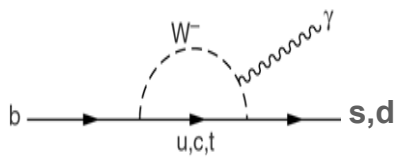
  Br ≈ 10^{-5} ,10^{-6}



  ✓**radiative penguin: b→ s,d γ (exclusive and inclusive)**

  $B \to K^*\gamma$, ρ γ
  b→s γ

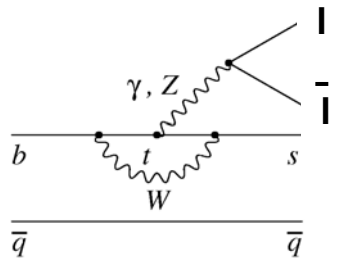
  Exclusive (b→ s,d γ) : Br ≈ $10^{-5,6,7}$
  Inclusive (b→ s γ) : Br ≈ 10^{-4}



  ✓**electroweak penguin: b→ s Z,γ(→ll) (exclusive)**

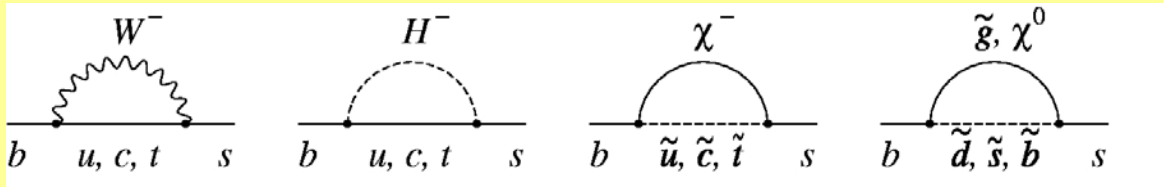
  B→Kνν

  Br ≈ 10^{-6}



Motivation

- New physics particles in loops:



might show up in:

Different (higher) rates than SM only

- Constrain SM
  - Time-dependent CPV: **See R.Faccini's talk**
    sin2α: B→ππ,ρπ, sin2β: B→η'K, ΦK*
  - Rates:
    $|V_{td} / V_{ts}|$: B→K*γ, ρ γ
  - QCD:
    HQET parameters: b→s γ spectrum

Different CP violation than SM only:

Direct CPV asymmetries **require at least two (SM or NP) amplitudes with different weak phases:**

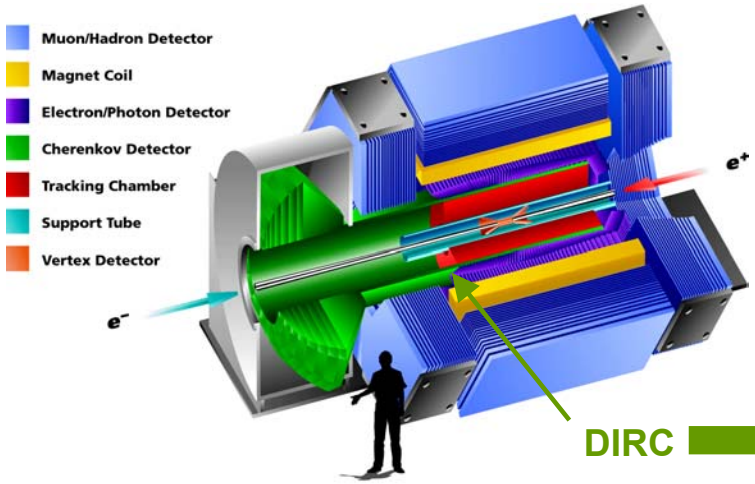
$$B^0, B^+ \xrightarrow{A_f} f \neq \bar{B}^0, B^- \xrightarrow{\bar{A}_{\bar{f}}} \bar{f}$$

$$A_f = \sum_k A_k e^{i\delta_k} e^{i\phi_k} \qquad \bar{A}_{\bar{f}} = \sum_k A_k e^{i\delta_k} e^{-i\phi_k}$$

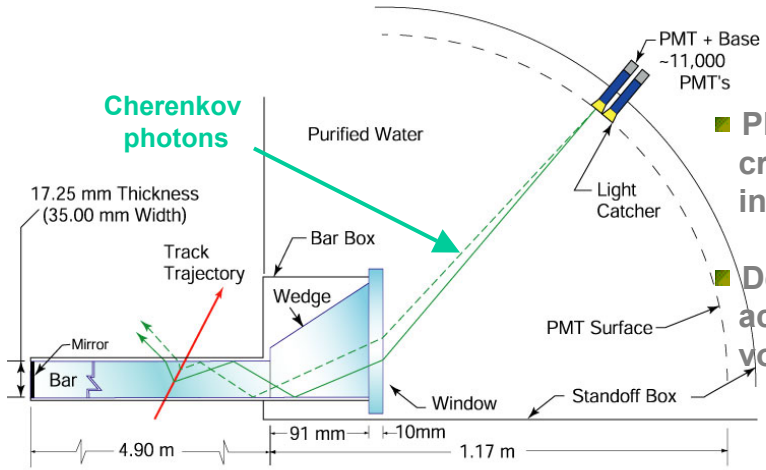
Strong phase (CP-conserving) **Weak phase (CP violating)**

$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = -4A_1A_2 \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

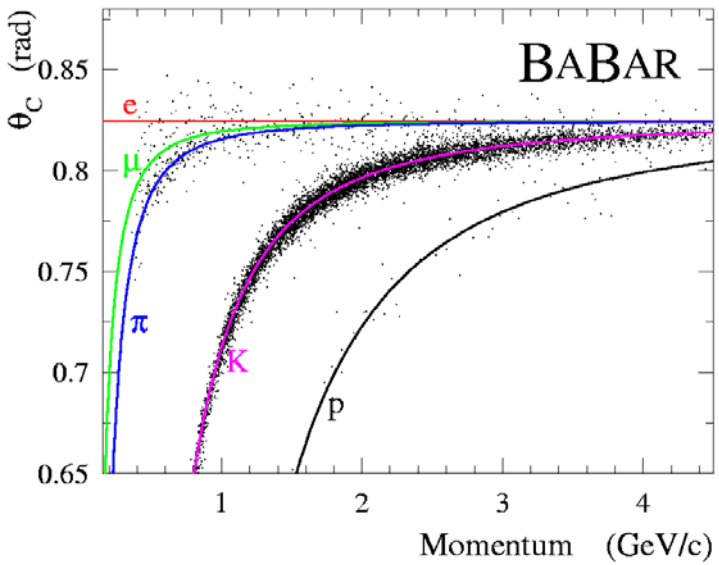
Particle identification:
Detection of Internally Reflected Cherenkov light



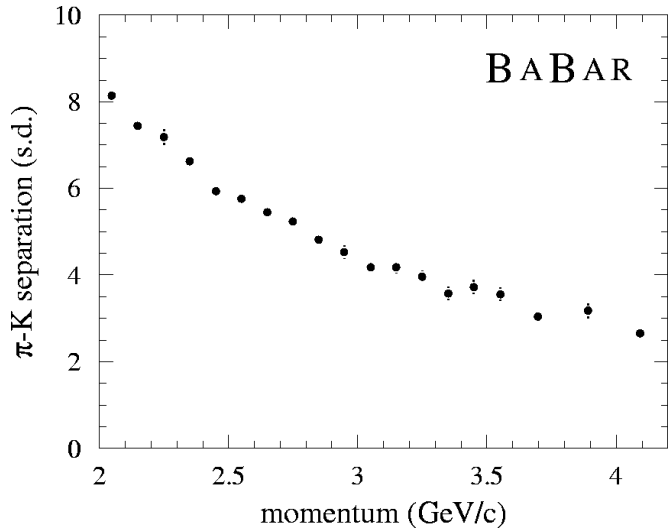
Particle ID important for rare decays (especially K-π)
New kind of Cherenkov detector:



- Photons are created AND guided in quartz bars
- Detection OUTSIDE acceptance volume



K-π separation still 2.5σ at p=4GeV/c



Kinematic variables at a B factory, Continuum background rejection

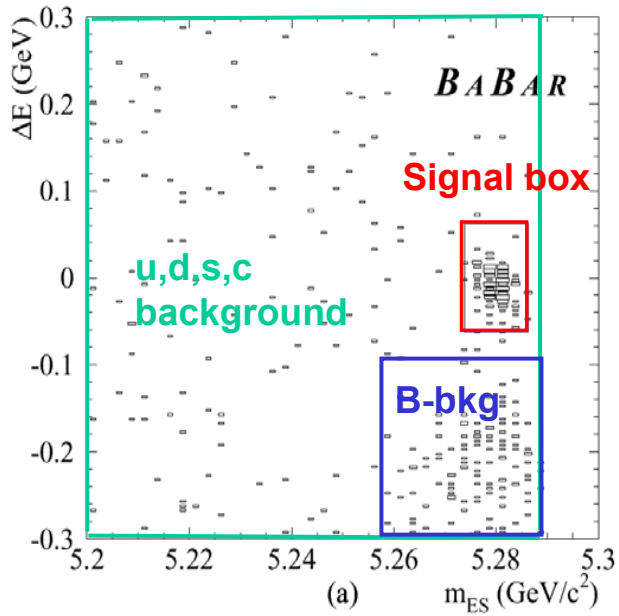
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ ⇒ **B produced almost at rest in $\Upsilon(4S)$ c.m.s.**

Kinematics:

Use beam energy to improve resolution: energy and momentum conservation gives

$$\Delta E = E_B^* - E_{beam}^* \rightarrow 0 \quad \text{for signal}$$

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}} \rightarrow m_B = 5.279\ \text{GeV}/c^2$$



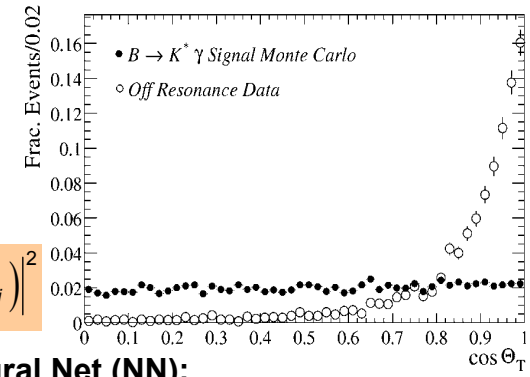
Topology:

B decays: isotropic ⇔ Continuum (u,d,s,c): jet-like

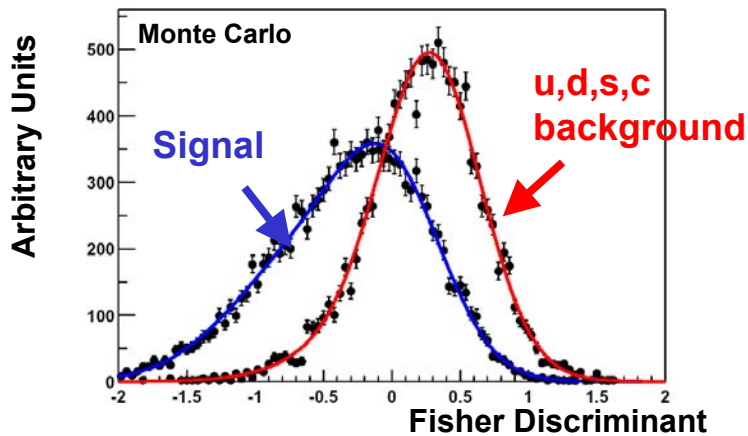
Examples of topological variables using these properties:

- **$\cos\theta_T$: angle between thrust of signal and rest of the event**
- **L_0, L_2: momentum-weighted monomials**

$$L_0 = \sum_{i=ROE} p_i \quad , L_2 = \sum_{i=ROE} p_i \left|\left(\cos\theta_{T_B,i}\right)\right|^2$$



Used in a Fisher or a Neural Net (NN):



small CKM matrix element (Vub)

NEW !

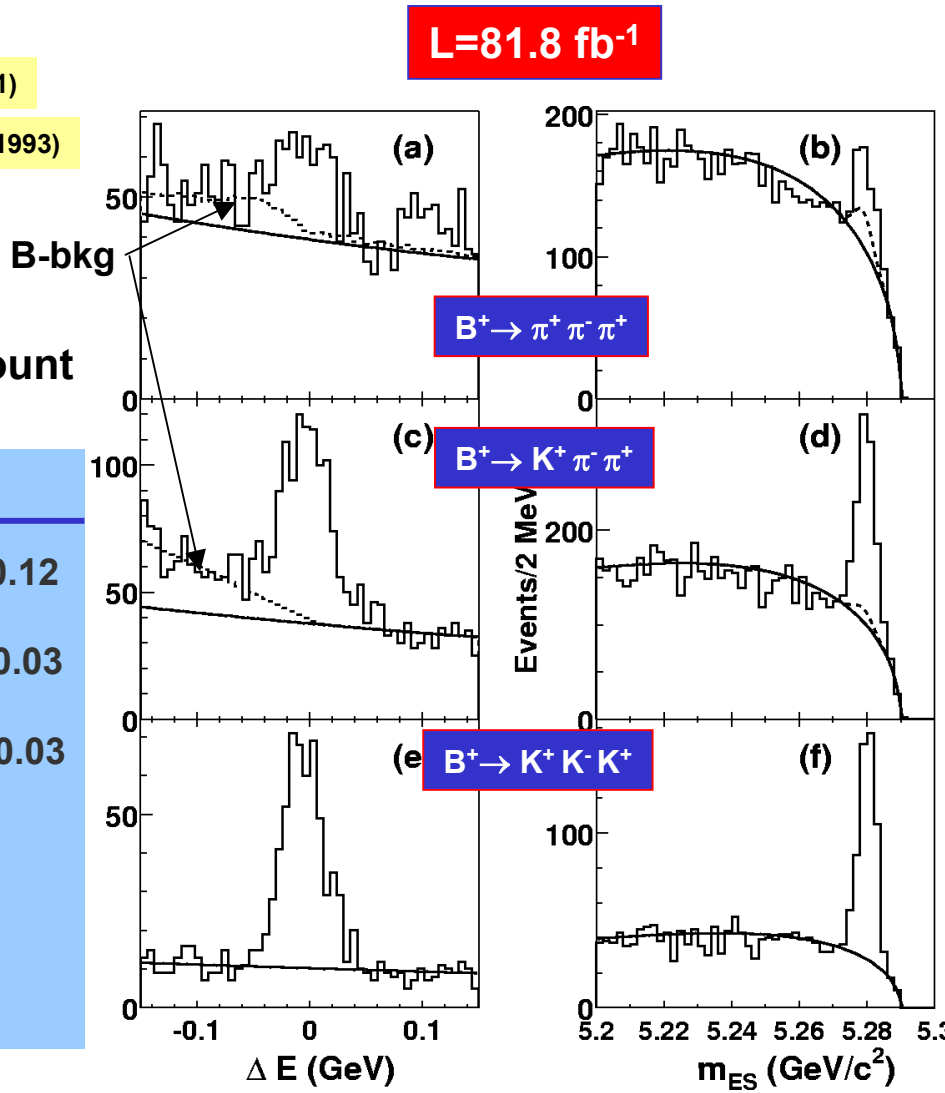
Inclusive rates and direct CP violation in $B^+ \to h^+h^-h^+$ ($h=\pi,K$)

direct CPV, angle γ Blanco et al, Phys.Rev.Lett.86,2720(2001)

help for angle α Snyder and Quinn, Phys.Rev.D48,2139(1993)

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

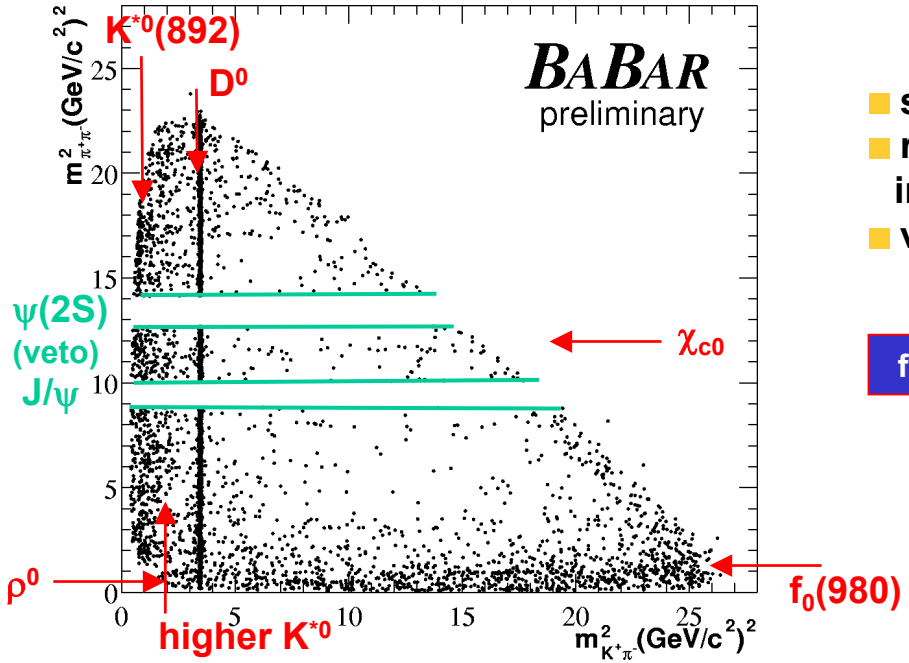
	Br (10^{-6})	A_{CP}
$B^+ \to \pi^+ \pi^- \pi^+$	$10.9 \pm 3.3 \pm 1.6$	$-0.39 \pm 0.33 \pm 0.12$
$B^+ \to K^+ \pi^- \pi^+$	$59.1 \pm 3.8 \pm 3.2$	$0.01 \pm 0.07 \pm 0.03$
$B^+ \to K^+ K^- K^+$	$29.6 \pm 2.1 \pm 1.6$	$0.02 \pm 0.07 \pm 0.03$
$B^+ \to K^+ K^- \pi^+$	< 6.3	N/A
$B^+ \to \pi^+ K^- \pi^+$	< 1.8	N/A
$B^+ \to K^+ \pi^- K^+$	< 1.3	N/A



small CKM matrix element (Vub)

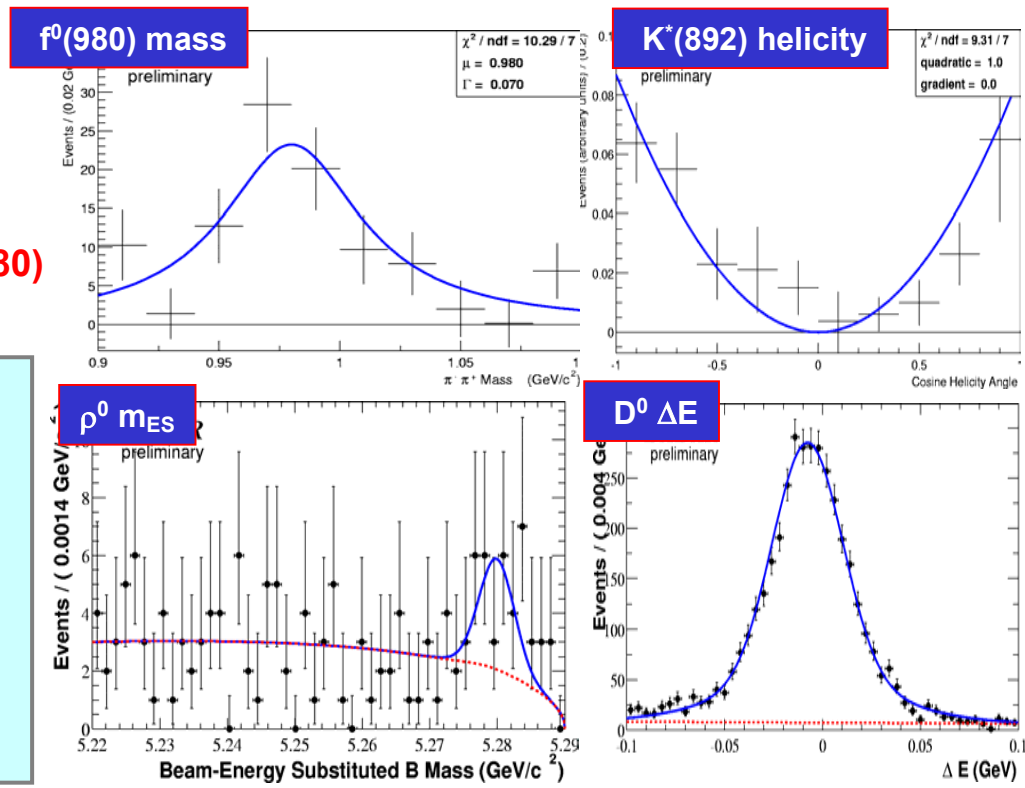
NEW !

Exclusive branching fractions of $B^+ \to K^+ \pi^- \pi^+$



L=56.4 fb^{-1}

- split Dalitz plot in zones
- reject resonance crossing regions (where interferences are the strongest)
- veto J/ψ, ψ(2S), parameterize other B bkg



	Br (10^{-6})
$B^+ \to K^{*0}(892)\pi^+$, $K^{*0} \to K^+ \pi^-$	$10.3 \pm 1.2\ ^{+1.0}_{-2.7}$
$B^+ \to f_0(980)K^+$, $f_0 \to \pi^+\pi$	$9.2 \pm 1.2\ ^{+2.1}_{-2.6}$
$B^+ \to \chi_{c0}\ K^+$, $\chi_{c0} \to \pi^+\pi$	$1.46 \pm 0.35 \pm 0.12$
$B^+ \to D^0\pi^+$, $D^0 \to K^+ \pi^-$	$184.6 \pm 3.2 \pm 9.7$
$B^+ \to$ higher $K^{*0}\pi^+$, $K^{*0} \to K^+ \pi^-$	$25.1 \pm 2.0\ ^{+11.0}_{-5.7}$
$B^+ \to \rho^0(770)K^+$, $\rho^0 \to \pi^+\pi$	< 6.2
$B^+ \to K^+ \pi^- \pi^+$ (non resonant)	< 17
$B^+ \to$ higher fK^+, $f \to \pi^+\pi$	< 12

small CKM matrix element (Vub)

NEW !

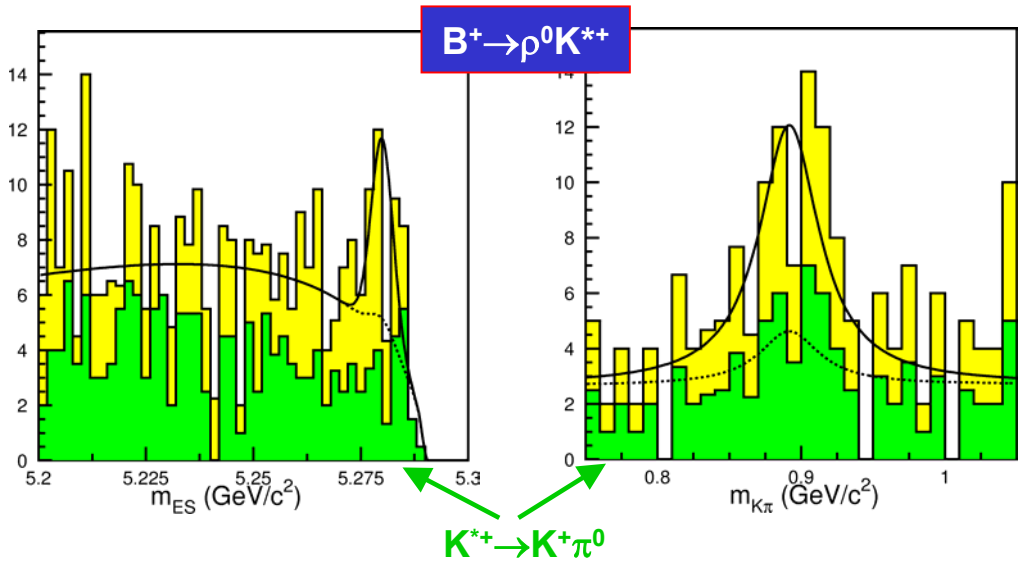
Br of $B^+ \to \rho^0 \rho^+$, $\rho^0 K^{*+}$

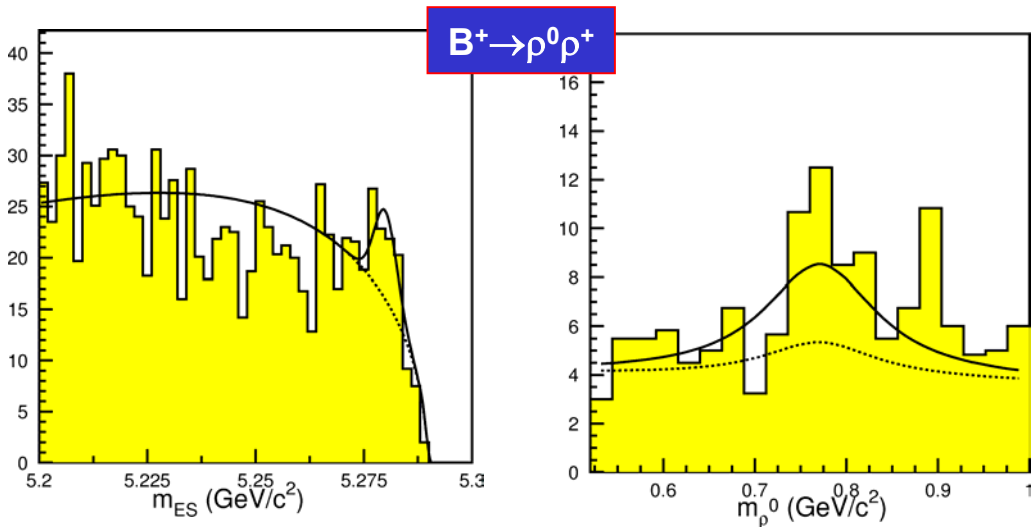
- **Interest:**
  $B \to \rho\rho$ modes: angle α
  $B \to \rho K^*$: dominated by penguin ?

- **Reconstruction:**
  - **$K^{*+} \to K^+ \pi^0$, $K^0 \pi^+$**
  - **(charmed) B bkg accounted for in fit**
  - **average efficiency over transverse and longitudinal components**

$$Br\left(B^+ \to \rho^0 \rho^+\right) = \left(9.9^{+2.6}_{-2.5} \pm 2.5\right).10^{-6}$$

$$Br\left(B^+ \to \rho^0 K^{*+}\right) = \left(7.7^{+2.1}_{-2.0} \pm 1.4\right).10^{-6}$$

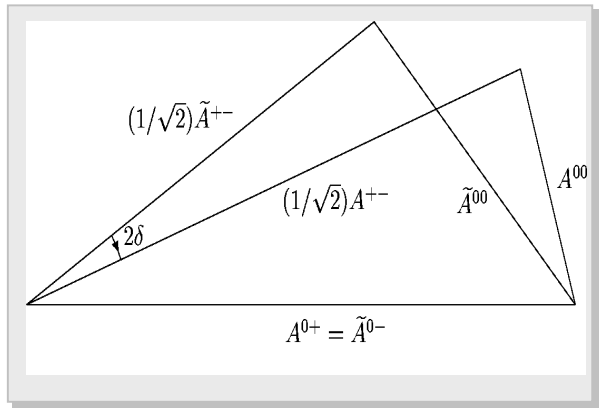




small CKM matrix element (Vub)

Isospin analysis in B→ππ

Amplitude relations (isospin symmetry):



CPV time dependent analysis in $B^0 \to \pi^+\pi^-$ measures α_{eff}

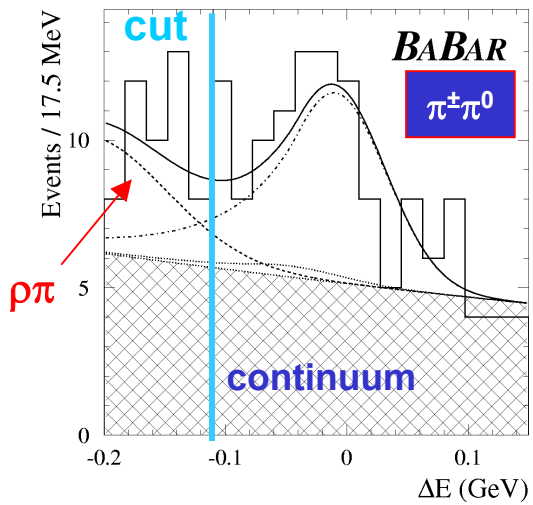
Need other ππ decays + isospin symmetry to get α:

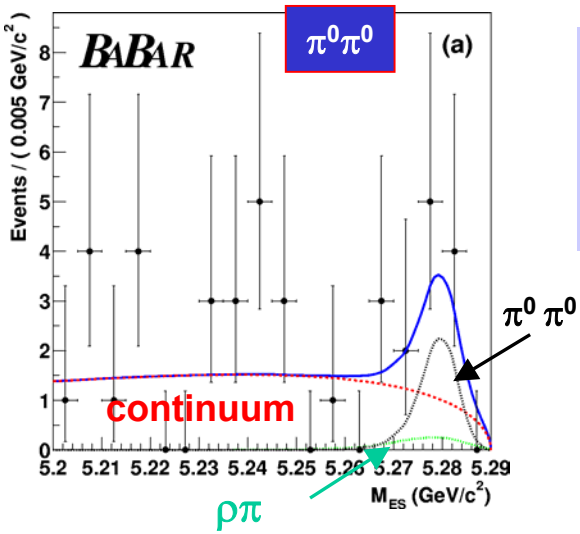
BRs $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$ (limit)

CP asymmetries $A_{CP}(\pi^\pm\pi^0)$, $S_{\pi\pi}$, $C_{\pi\pi}$ → See R.Faccini's talk

All measured:

L=81.8 fb^{-1}





$B^0 \to \pi^+\pi^-$	$(4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$
$B^+ \to \pi^+\pi^0$	$(5.5\ ^{+1.0}_{-0.9} \pm 0.6) \times 10^{-6}$
$B^0 \to \pi^0\pi^0$	$< 3.6 \times 10^{-6}$ @ 90%CL
$A_{CP}(\pi^+\pi^0)$	$-0.03\ ^{+0.18}_{-0.17} \pm 0.02$

$|\alpha - \alpha_{eff}| < 51°$

@ 90%CL

small CKM matrix element (Vub)

Summary of B→hh (h=π,K) decays

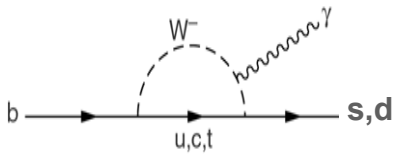
L=81.8 fb^{-1}

Mode	N_{events}	Br (10^{-6})	A_{CP}
$B^0 \to \pi^+\pi^-$	157±19	4.7 ±0.6 ±0.2	
$B^0 \to K^+\pi^-$	589 ±30	17.9 ±0.9 ±0.6	-0.102 ±0.050 ±0.016
$B^0 \to K^+K^-$	<15.9	<0.6 (90% CL)	
$B^+ \to \pi^+\pi^0$	125 ±22 ±10	5.5 ±1.0 ±0.6	-0.03 ±0.18 ±0.02
$B^+ \to K^+\pi^0$	239 ±22 ±6	12.8 ±1.2 ±1.0	-0.09 ±0.09 ±0.01
$B^+ \to K^0\pi^+$	172 ±17 ±9	17.5 ±1.8 ±1.3	-0.17 ±0.10 ±0.02
$B^0 \to K^0\pi^0$	86 ±13 ±3	10.4 ±1.5 ±0.8	0.03 ±0.36 ±0.09
$B^0 \to \pi^0\pi^0$	23 ±10	<3.6 (90% CL)	
$B^+ \to K^+K^0$	<10	<1.3 (90% CL)	

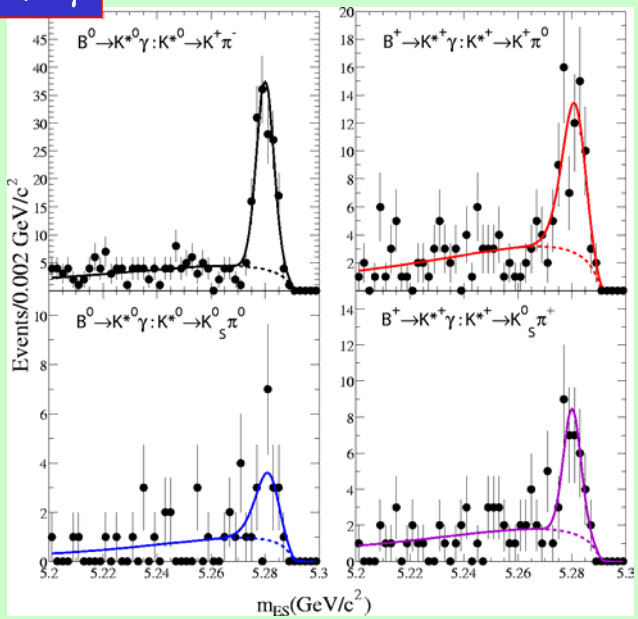
Radiative penguin

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

(Cabibbo favoured) (Cabibbo suppressed)



$B \to K^* \gamma$



Similarities:

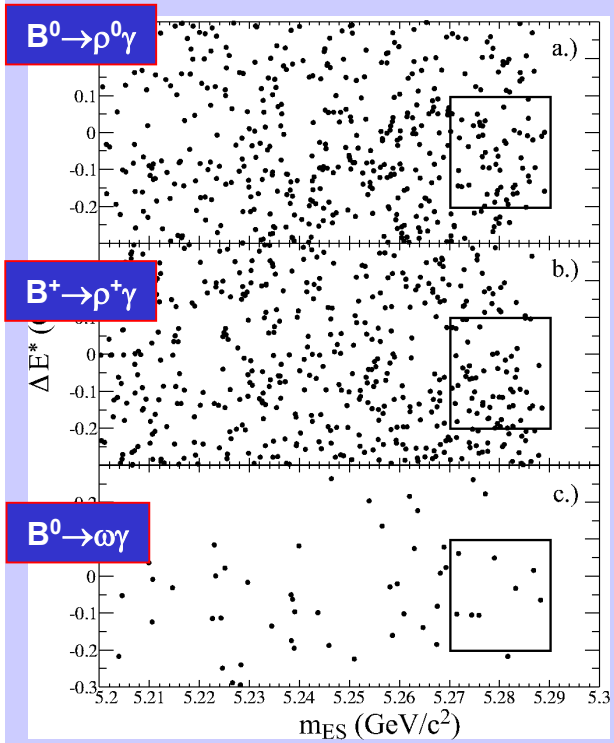
- High momentum γ
- Veto γ coming from π^0, η

For $B \to K^* \gamma$, reconstruct:
- $K^{*0} \to K^+\pi^-$, $K^0\pi^0$
- $K^{*+} \to K^+\pi^0$, $K^0\pi^+$

$B^0 \to \rho^0\gamma$

$B^+ \to \rho^+\gamma$

$B^0 \to \omega\gamma$



	Prediction	Measurement	
L=20.7 fb⁻¹			
$B^0 \to K^{*0}(K^+\pi^-, K^0_S\pi^0)\gamma$	7.5 ± 3.0	$4.23 \pm 0.40 \pm 0.22$	10^{-5}
$B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\gamma$	7.5 ± 3.0	$3.83 \pm 0.62 \pm 0.22$	
$A_{CP}(K^*(K^+\pi^-, K^+\pi^0, K^0_S\pi^+)\gamma$	<0.005	$-0.17 < A_{CP} < 0.08$	
L=78 fb⁻¹			
$B^0 \to \rho^0(\pi^+\pi^-)\gamma$	0.5 – 0.75	< 1.4	10^{-6}
$B^+ \to \rho^+(\pi^+\pi^0)\gamma$	0.8 – 1.5	< 2.3 @ 90%CL	
$B^0 \to \omega(\pi^+\pi^-\pi^0)\gamma$	0.5 – 0.75	< 1.2	

$|V_{td}/V_{ts}| < 0.36$

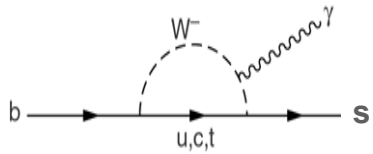
@ 90%CL

Prediction from Ali, Parhhomonko Eur.Phys.J C23,89(2002)

1σ range from CKM fits:
$0.17 < |V_{td}/V_{ts}| < 0.22$
(Höcker et al, EPJC, 21, 225(2001))

Radiative penguin

Semi-inclusive b→sγ

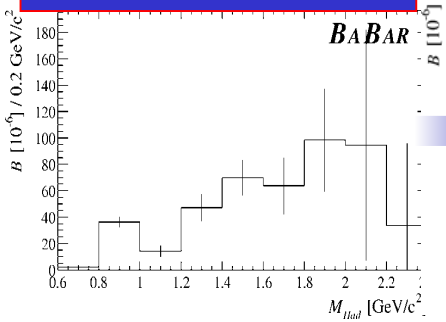


L=20.7 fb^{-1}

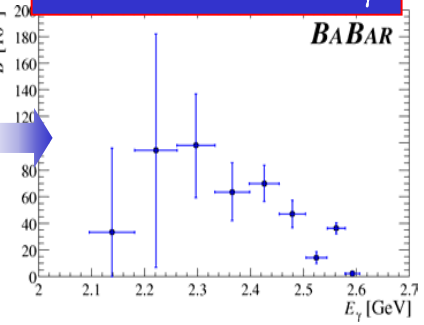
- "Semi-inclusive" = K + 1 to 3 pions
- E_γ obtained from hadronic invariant mass
- Fit E_γ spectrum moments to extract HQET parameters:

$$m_B = m_b + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_b} + \ldots$$

Br as a function of M_{had}



Br as a function of E_γ



$$\mathrm{Br}(b \to s\gamma) = \left(4.3 \pm 0.5(\mathrm{stat}) \pm 0.8(\mathrm{syst}) \pm 1.3(\mathrm{model})\right).10^{-4}$$

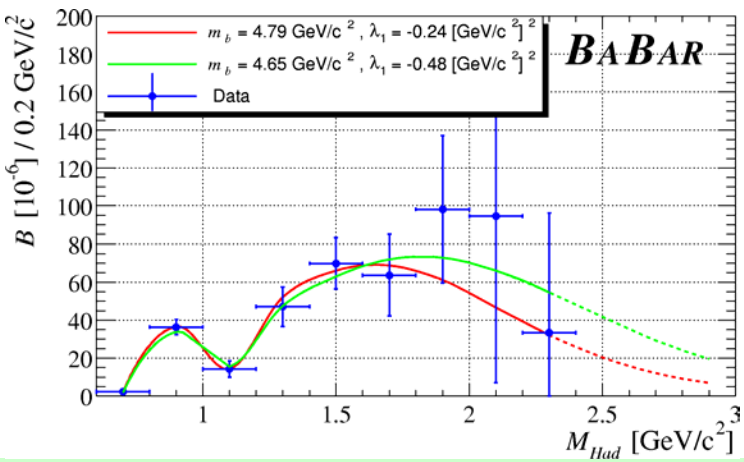
$\bar{\Lambda}$: energy of the light degrees of freedom

λ_1 : Kinetic energy of b quark Fermi motion in B meson

λ_2 : Hyperfine chromo-magnetic interaction → (known from B-B* mass spliting)

Enter theoretical predictions of V_{ub}, V_{cb} from inclusive decays

$$\left\langle E_\gamma^n \right\rangle = f\left(\bar{\Lambda}, \lambda_1, \lambda_2\right)$$



Ligeti, Luke, Manohar, Wise, PRD 60,034019(1999)
Kagan and Neubert, EPJ C7,5(1999)

$$\bar{\Lambda} = 0.37 \pm 0.09(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \pm 0.10(\mathrm{model})\ \mathrm{GeV/c^2}$$

$$m_b = 4.79 \pm 0.08(\mathrm{stat}) \pm 0.10(\mathrm{syst}) \pm 1.3(\mathrm{model})\ \mathrm{GeV/c^2}$$

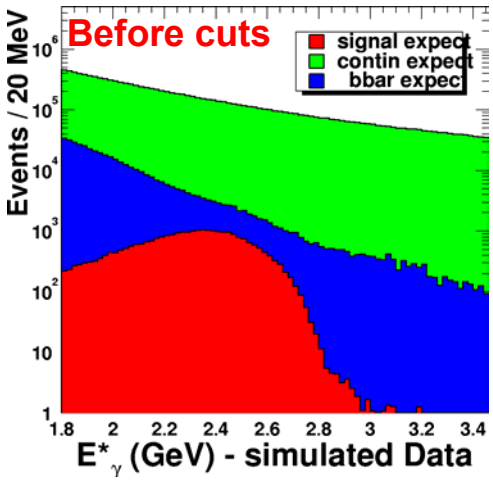
$$\lambda_1 = -0.24^{+0.03}_{-0.04}(\mathrm{stat}) \pm 0.02(\mathrm{syst})^{+0.15}_{-0.21}(\mathrm{model})\ \left[\mathrm{GeV/c^2}\right]^2$$

Radiative penguin

Fully inclusive b→sγ

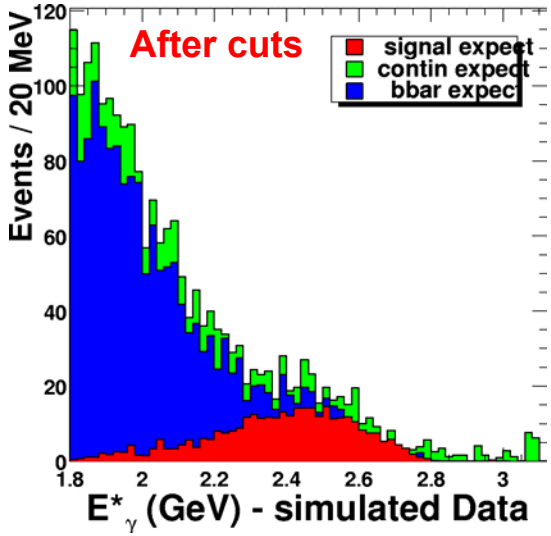
L=54.6 fb^{-1}

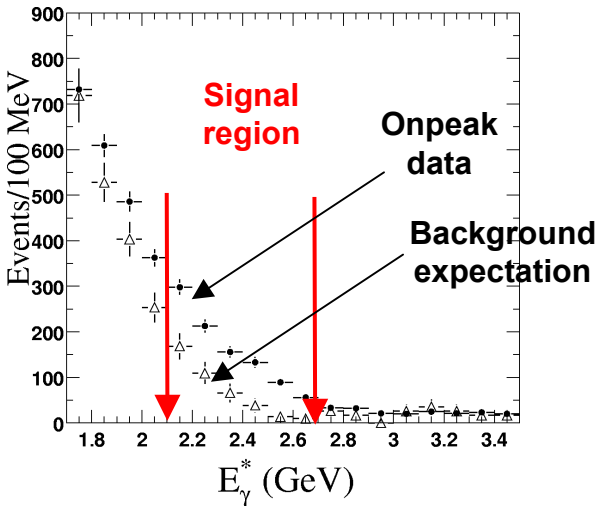
Continuum and B bkg are orders of magnitude larger than the signal:



Require semi-leptonic decay on the other side:

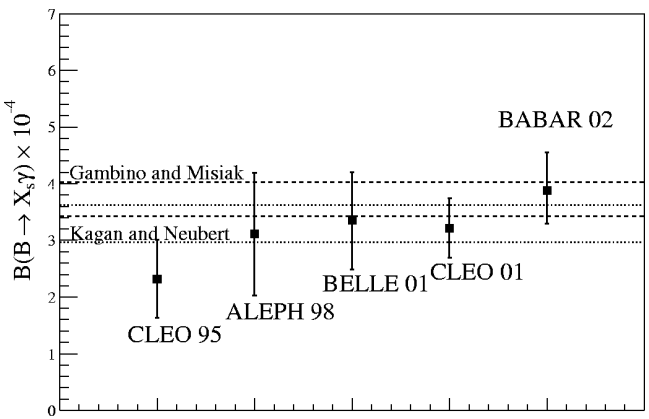
- **high p* lepton: p*(e,μ) > 1.3,1.55 GeV**
- **large missing energy (ν): E_{miss}>1.2 GeV**





$$\mathrm{Br}(B \to X_s\gamma) = \left(3.88 \pm 0.36(\mathrm{stat}) \pm 0.37(\mathrm{syst})^{+0.43}_{-0.23}(\mathrm{model})\right).10^{-4}$$

543 net signal events



Gluonic penguin

Br and A_{CP} in $B \to \eta' K$

NEW this year !

L=81.9 fb^{-1}

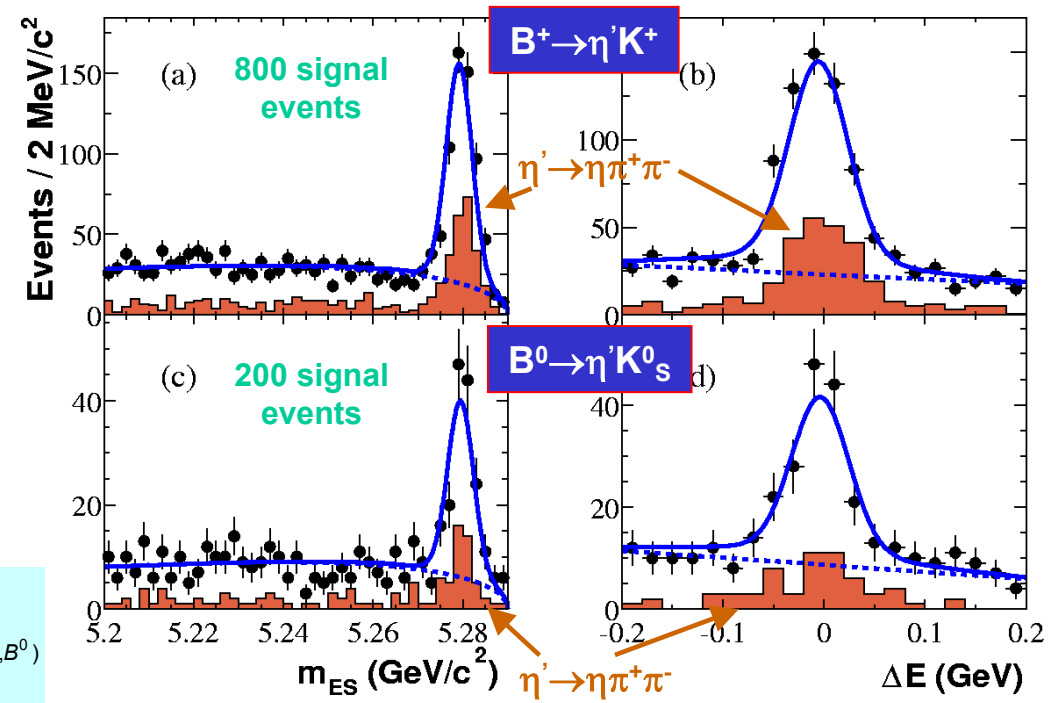
- Reconstruct $\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$
- Main bkg: continuum
- Small B bkg to $\rho^0\gamma$

$Br(B^+ \to \eta' K^+) = (76.9 \pm 3.5 \pm 4.4)\ 10^{-6}$
$Br(B^0 \to \eta' K^0) = (55.4 \pm 5.2 \pm 4.0)\ 10^{-6}$
$A_{CP}(B^+ \to \eta' K^+) = 0.037 \pm 0.045 \pm 0.011$

$-0.04 < A_{CP}(B^+ \to \eta' K^+) < 0.11$ @ 90%CL

$$\frac{\Gamma(B^+ \to \eta' K^+)}{\Gamma(B^0 \to \eta' K^0)} = 1.22 \pm 0.13_{stat} \pm 0.05_{syst} \pm 0.05_{\tau(B^+,B^0)}$$

Compatible with isospin symmetry



These Brs are higher than expected:
$Br(B^+ \to \eta' K^+) \approx 6\times Br(B^+ \to \pi^0 K^+)$??

- Flavour singlet part of η'
- Intrinsic charm content in η'
- η' from gluon fusion
- New physics…

Time-dependent CP analysis: sin2β in the SM

See R.Faccini's talk

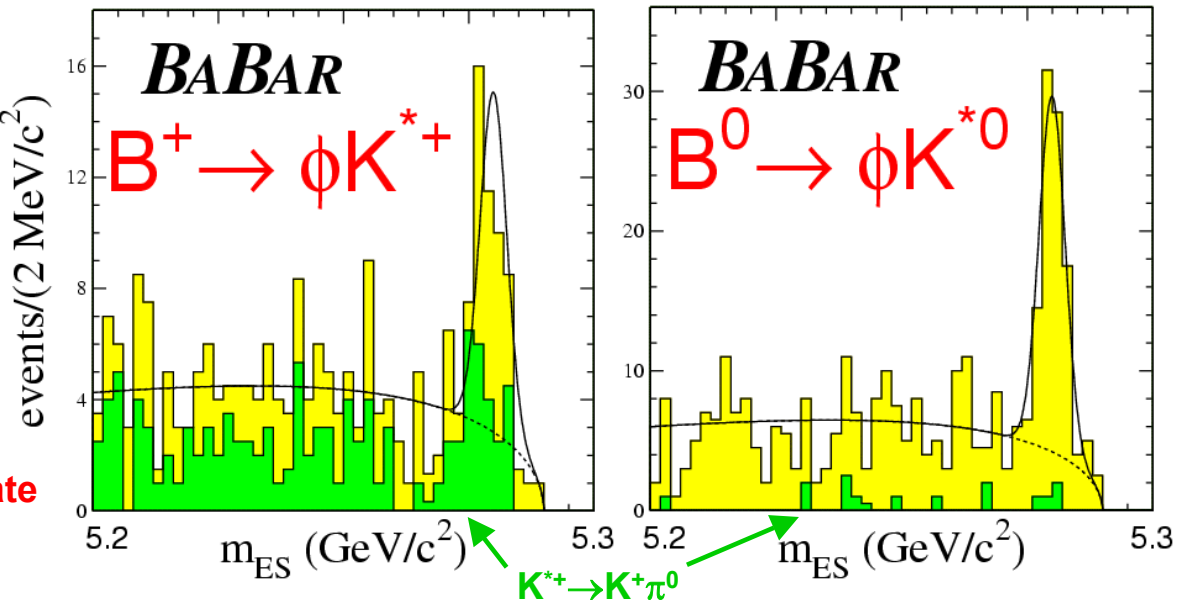
Gluonic penguin

NEW !

Br and A_{CP} in $B \to \Phi K^*$

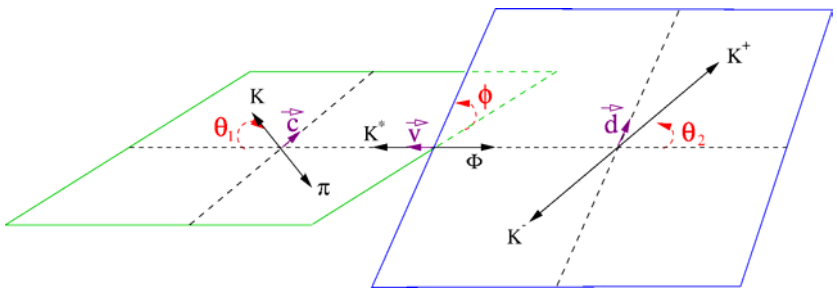
L=81.9 fb^{-1}

- Reconstruct $\phi \to K^+K^-$,
  $K^{*0} \to K^+\pi^-$, $K^0\pi^0$
  $K^{*+} \to K^+\pi^0$, $K^0\pi^+$
- Main bkg: continuum
- Low B bkg because ϕ is narrow
  (veto $B \to D(K\pi, K\pi\pi)\pi$)



Vector-vector decay: not a CP eigenstate

angular analysis to separate CP-odd/even (for now, simplified due to low statistics: separate longitudinal component)



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

$$Br(B^0 \to \phi K^{*0}) = (11.1^{+1.3}_{-1.2} \pm 1.1).10^{-6}$$
$$Br(B^+ \to \phi K^{*+}) = (12.1^{+2.1}_{-1.9} \pm 1.5).10^{-6}$$

$$\Gamma_L/\Gamma(B^0 \to \phi K^{*0}) = 0.65 \pm 0.07 \pm 0.04$$
$$\Gamma_L/\Gamma(B^+ \to \phi K^{*+}) = 0.46 \pm 0.12 \pm 0.05$$

$$A_{CP}(B^0 \to \phi K^{*0}) = 0.04 \pm 0.12 \pm 0.02$$
$$A_{CP}(B^+ \to \phi K^{*+}) = 0.16 \pm 0.17 \pm 0.04$$

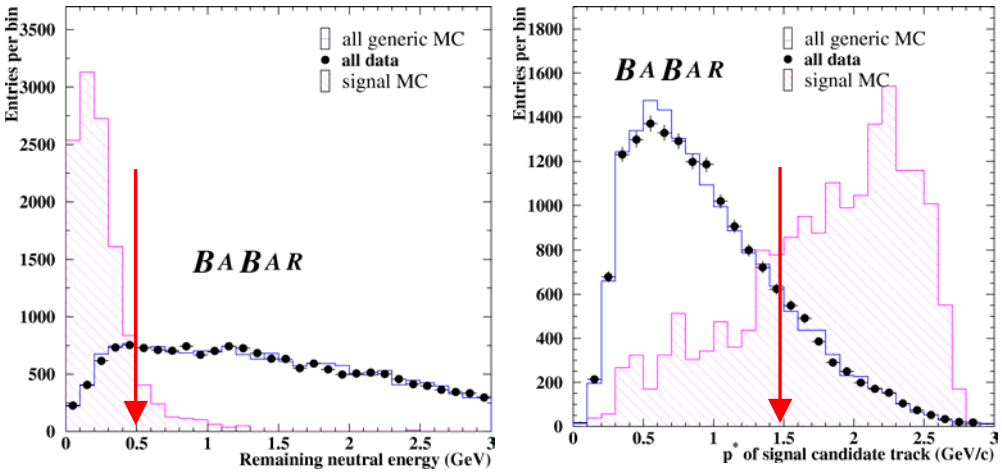
Time-dependent CP analysis: sin2β in the SM

See R.Faccini's talk

EW penguin

Search for $B^+ \to K^+ \nu \bar{\nu}$

L=50.7 fb^{-1}



2 neutrinos: no kinematic constraints !

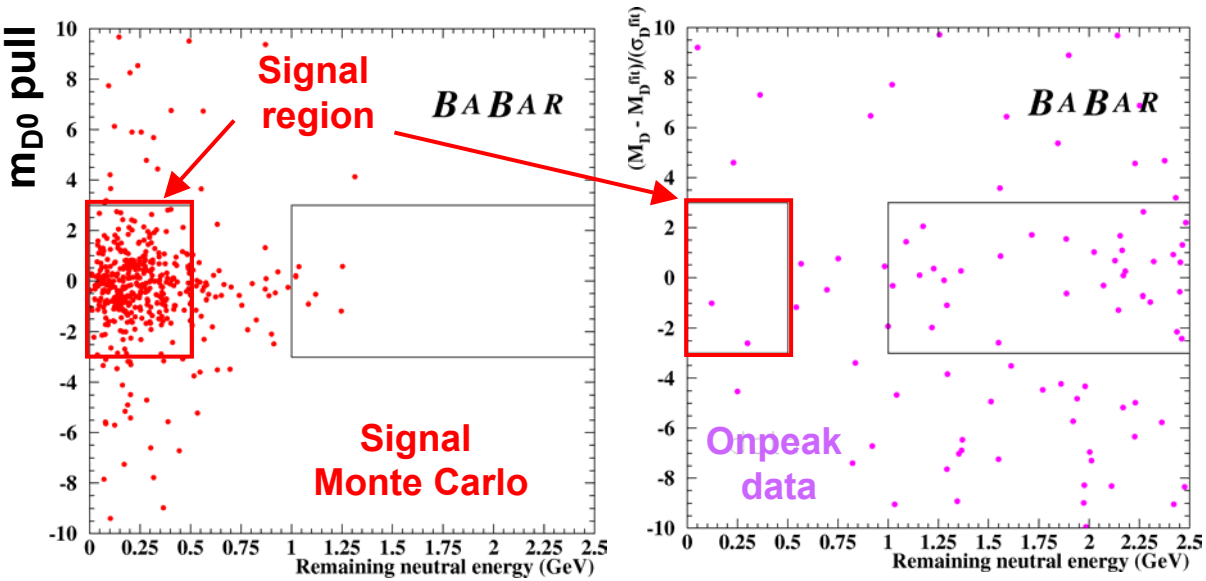
Reconstruct the other B into

$B^- \to D^0(K^-\pi^+, K^-\pi^+\pi^-\pi^+, K^-\pi^+\pi^0)l^-\nu X$

where X=nothing or low momentum π,γ

0.5% efficiency

+ cuts on signal side

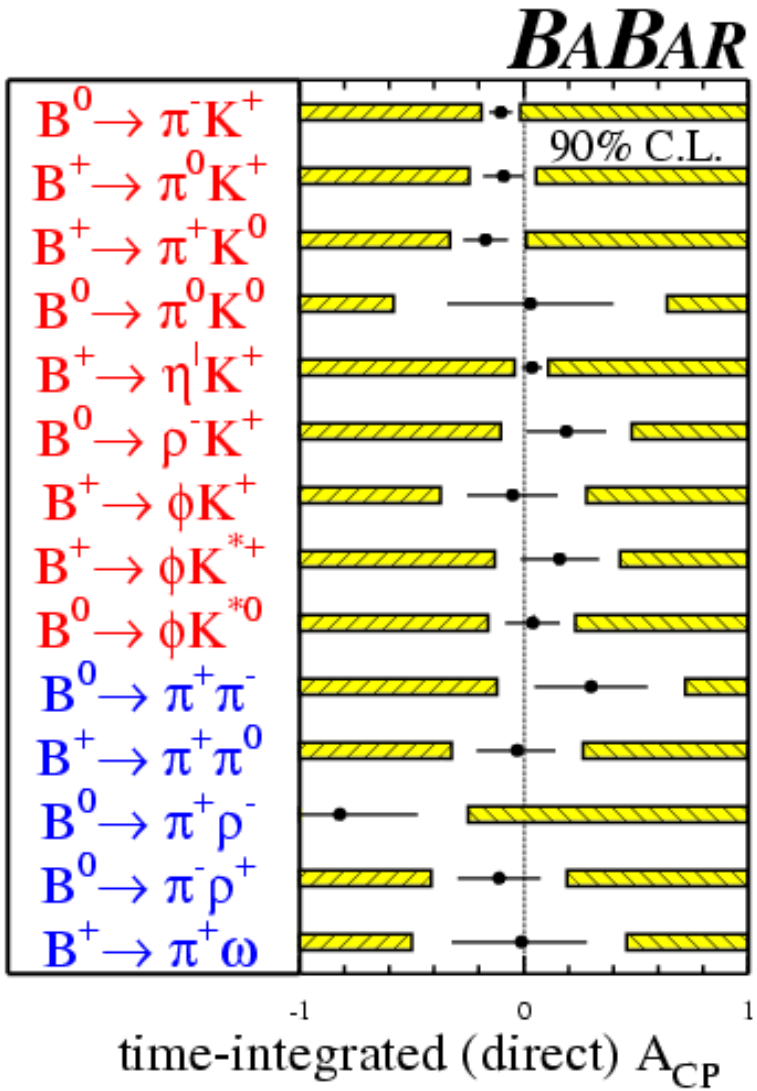


2 events in signal region

Br($B^+ \to K^+\nu\nu$) < 9.4 × 10^{-5} @ 90%CL

SM prediction: $(4 \pm 1).10^{-6}$

Summary of direct CP violation measurements



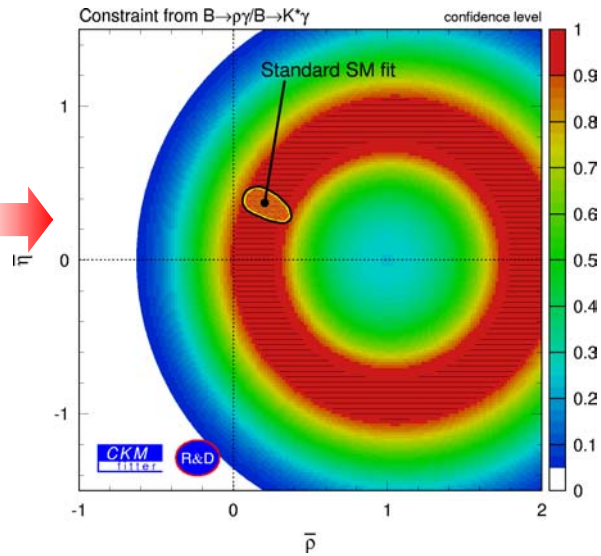
A_{CP}
$-0.102 \pm 0.050 \pm 0.016$
$-0.09 \pm 0.09 \pm 0.01$
$-0.17 \pm 0.10 \pm 0.02$
$+0.03 \pm 0.36 \pm 0.09$
$+0.037 \pm 0.045 \pm 0.011$
$+0.19 \pm 0.14 \pm 0.11$
$-0.05 \pm 0.20 \pm 0.03$
$+0.16 \pm 0.17 \pm 0.04$
$+0.04 \pm 0.12 \pm 0.02$
$+0.30 \pm 0.25 \pm 0.04$
$-0.03 \pm 0.18 \pm 0.02$
$-0.82 \pm 0.31 \pm 0.16$
$-0.11 \pm 0.16 \pm 0.09$
$+0.04 \pm 0.17 \pm 0.01$

See R.Faccini's talk

direct CPV in time-dependent analysis

Conclusions

- **New Physics:** no smoking gun yet (watch η'K…)
- **SM contraints:**
  - ✓ **Theory of B decays**: Determination of HQET parameters
  - ✓**CKM matrix**:
    - $B \to \rho\,\gamma$/ $B \to K^*\gamma$: sensitive to $|V_{td}/V_{ts}|$, complementary to B_d/B_s mixing → $|V_{td}/V_{ts}| < 0.36$ @ 90%CL
    - $B \to \pi\pi$ isospin analysis: → $|\alpha - \alpha_{eff}| < 51°$



- **The near future (500 fb^{-1}):**

Mode	N_{events}	Physics case
$B \to X_s\gamma$	11 K	$\|V_{ts}\|$, HQET
$B \to K^*\gamma$	6 K	$\|V_{ts}\|$
$B \to \tau\nu$	17	$f_B\|V_{ub}\|$
$B \to \mu\nu$	8	$f_B\|V_{ub}\|$
$B \to K^{(*)}l^+l^-$	200	A_{FB}

Projected luminosity:

500 fb^{-1} in 2006
> 1 ab^{-1} by the end of the decade