CLEO Phase IV

- A bit about the CLEO Collaboration
- Rare decays at CLEO II/II.5
- B physics with high luminosity:
  CKM, CP violation, rare decays/new physics
- $B\bar{B}$ datasets, and CESR Phase IV
- Rare decays in Phase IV
- CLEO Detector upgrades
- competition: asymmetric colliders, hadron machines
- Conclusions

THE CLEO COLLABORATION

- CLEO = $\sim$ 200 physicists, 25 institutions (roughly 2:1 DoE:NSF supported). There is much room for growth!

- CLEO II has been taking data since 1989: 5 fb^{-1} analyzed, over 3 million $B\bar{B}$

- CLEO II.V added SVD and 2.2 cm beampipe in 1995: 4.0 fb^{-1} in the can, being analyzed. Typical peak luminosity: $\mathrm{L} \sim 4 \times 10^{32}/\mathrm{cm}^2/\mathrm{s}$

- CLEO III in preparation for 1999:
  - upgraded CESR: $\mathrm{L} \rightarrow 1.7 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$ ($4\times$ current)
  - new SVD, DR, Fast RICH, DAQ, software

- As you can imagine, the collaboration is BUSY with physics (II), commissioning (II.V), upgrading (III), and thinking about the future (Phase IV). We need your help and support!

Physics at CLEO

- CLEO submitted 32 papers to summer 1997 conferences; a typical year.
- Broad range of topical subjects:
  - $B \to X_c$ hadronic decays (tree, color suppressed, $c\bar{c}s$, baryons)
  - $B \to D/D^*/D^{**}\ell\nu$ semileptonic decays, form factors, HQET
  - charmless hadronic decays: $b \to u\bar{u}d$, $b \to sg$, *etc.*
  - charmless $B \to X_u\ell\nu$ semileptonic decays
  - EW penguins: $b \to s\gamma$, $b \to s\ell^+\ell^-$
  - charmed meson spectroscopy and decays (D, D^*, D^{**}, D_s, D_s^*, D_s^{**}, *etc.*)
  - charmed meson semileptonic decay form factors
  - charmed baryon spectroscopy and decays
  - Tau decays: branching fractions, spectral functions, Michel Parameters, rare decays
  - Upsilon physics: transitions, $\Upsilon(1S)$ decays

- QCD: $R(e^+e^-)$, $\alpha_S(10.5\text{ GeV})$, fragmentation, multiplicities
- two photon physics: meson pairs, baryon pairs, form factors, glueballs
- high luminosity collider physics

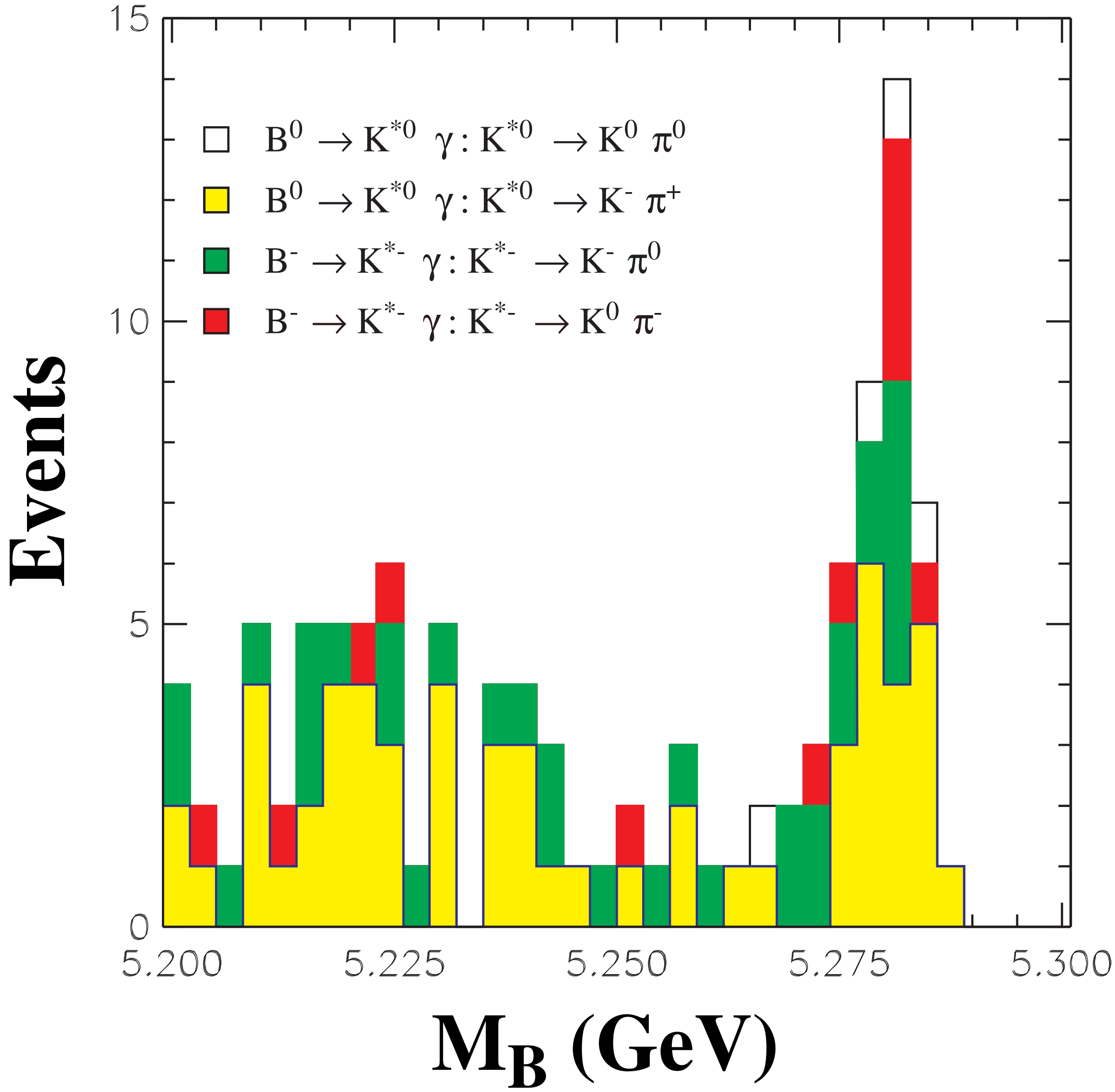
But the physics of CLEO III and Phase IV is *rare decays!*

The rare B years

In the last few years, CLEO has discovered several classes of rare decays:

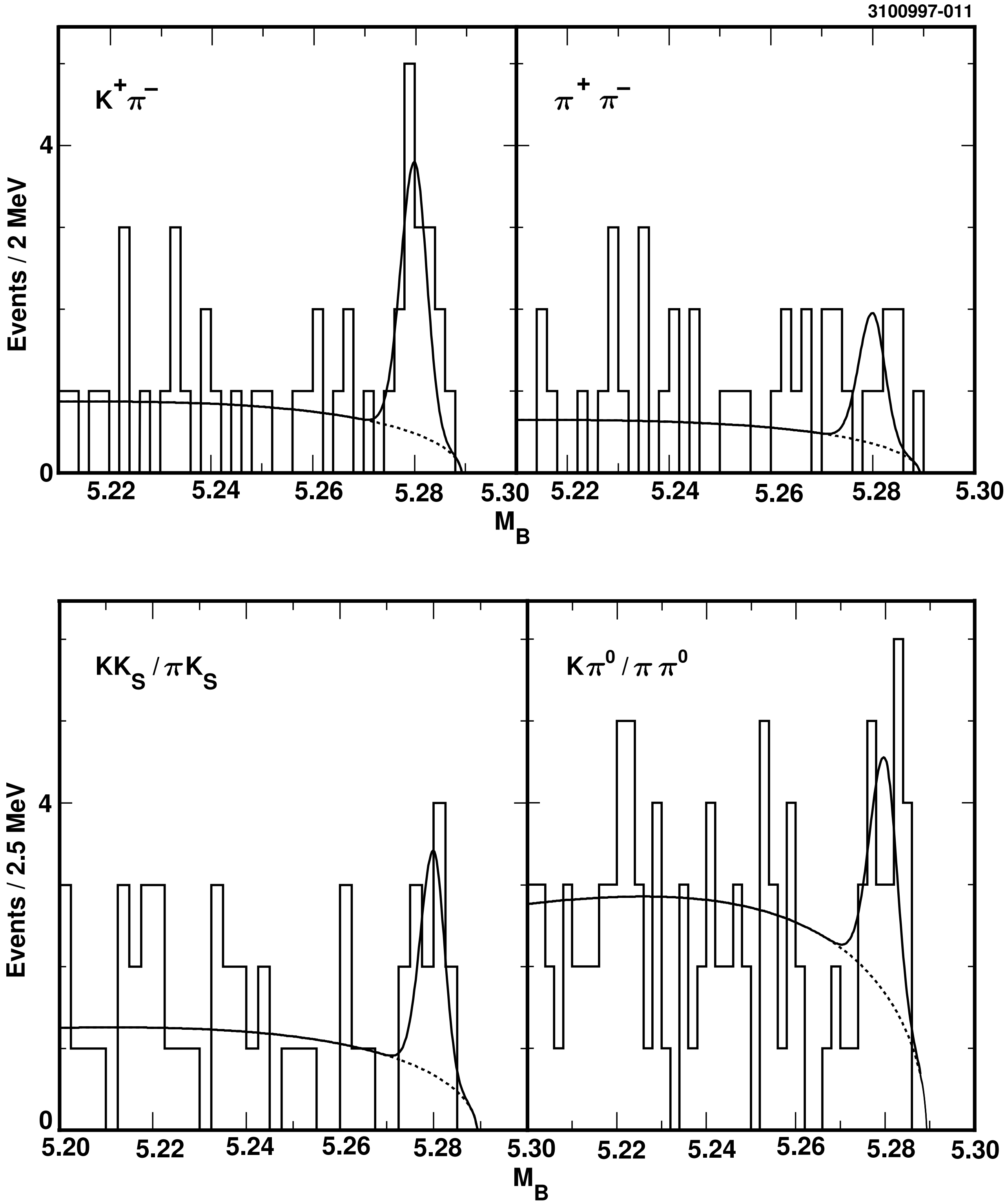
- 1993: First observation of unambiguous penguin decays: $B \to K^*\gamma$
- 1994: Observation of inclusive $b \to s\gamma$ (at $\sim$ SM level)
- 1995: charmless hadronic decay: h^+h^- (mixture of $\pi^+\pi^-$ from $b \to u\bar{u}d$, and $K^+\pi^-$ from $b \to sg$)
- 1996: Exclusive $b \to u\ell\nu$ ($\pi\ell\nu$, $\rho\ell\nu$) and significant $K^+\pi^-$ signal
- 1997: MANY more modes discovered: ($K_s^0\pi^+$, $K^+\pi^0$, ωK^+, ωK_s^0, ϕK^*, $\eta' K^+$, $\eta'\pi^+$, $\eta' K_s^0$, η' inclusive)
  - typical branching fraction: (few)$\times 10^{-5}$
  - typical efficiency: 2–25%
  - typical backgrounds: same order as signal. And: $\pi \leftrightarrow K$ mis-id.

$B \to K^{*\pm}\gamma,\ K^{*0}\gamma$
CLEO 1993-1996



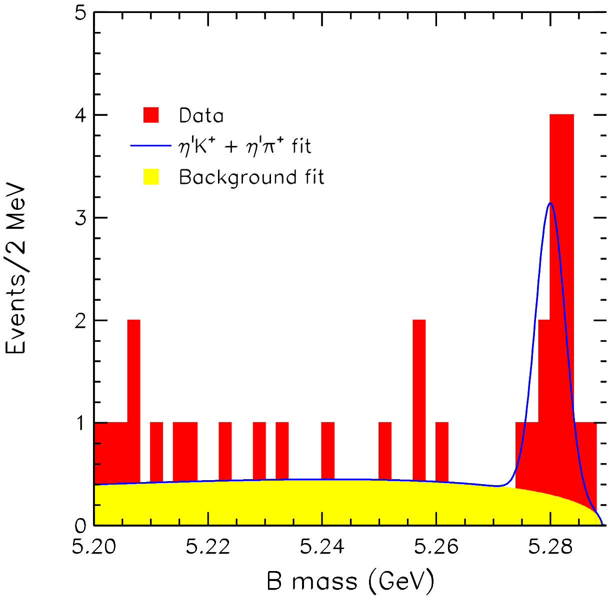
Also inclusive $b \to s\gamma$, $2.2 > E_\gamma > 2.7$ GeV

$B \to \pi\pi,\ K\pi,\ KK$
CLEO 1995-1997

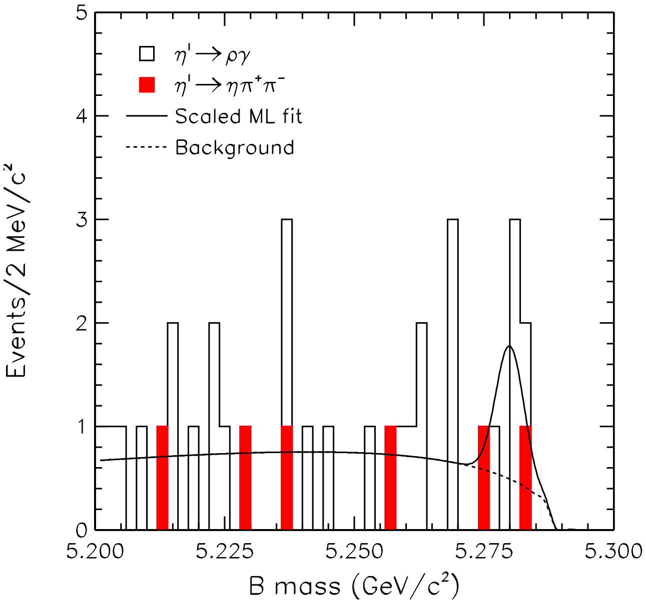


Charmless hadronic B decays
CLEO 1997

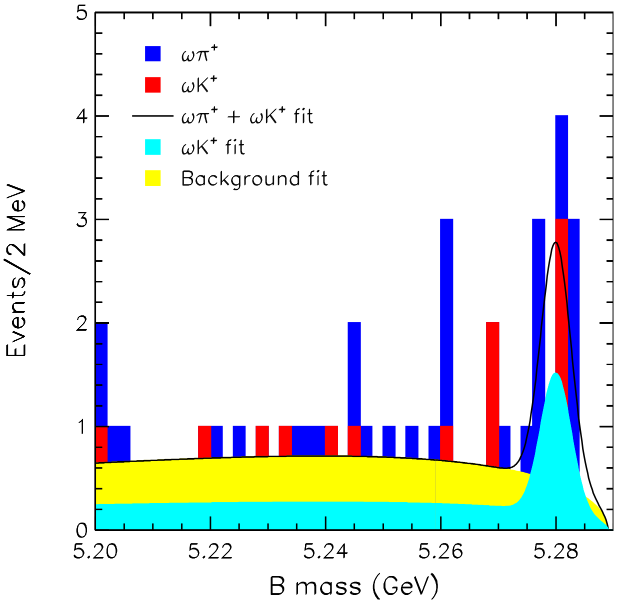
$B^+ \to \eta' h^+$



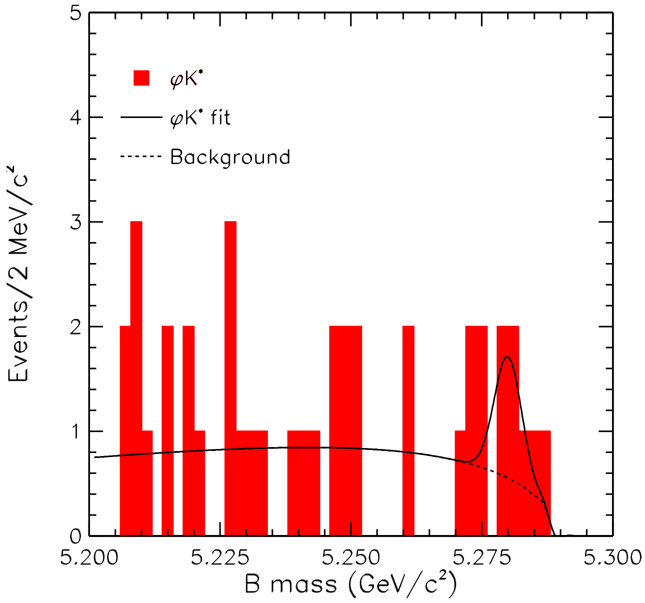
$B^0 \to \eta' K^0_S$



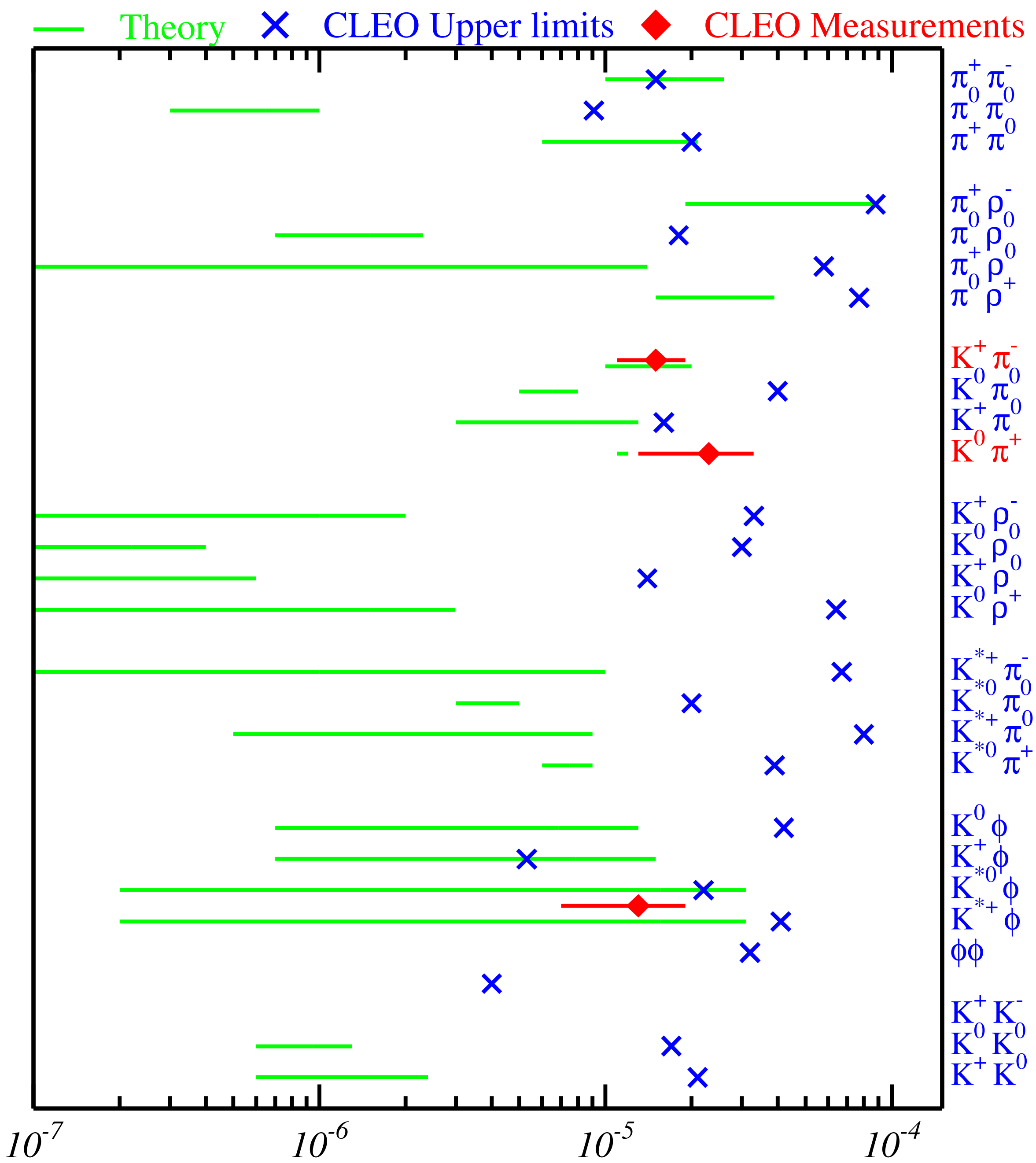
$B^+ \to \omega h^+$



$B \to \phi K^*$

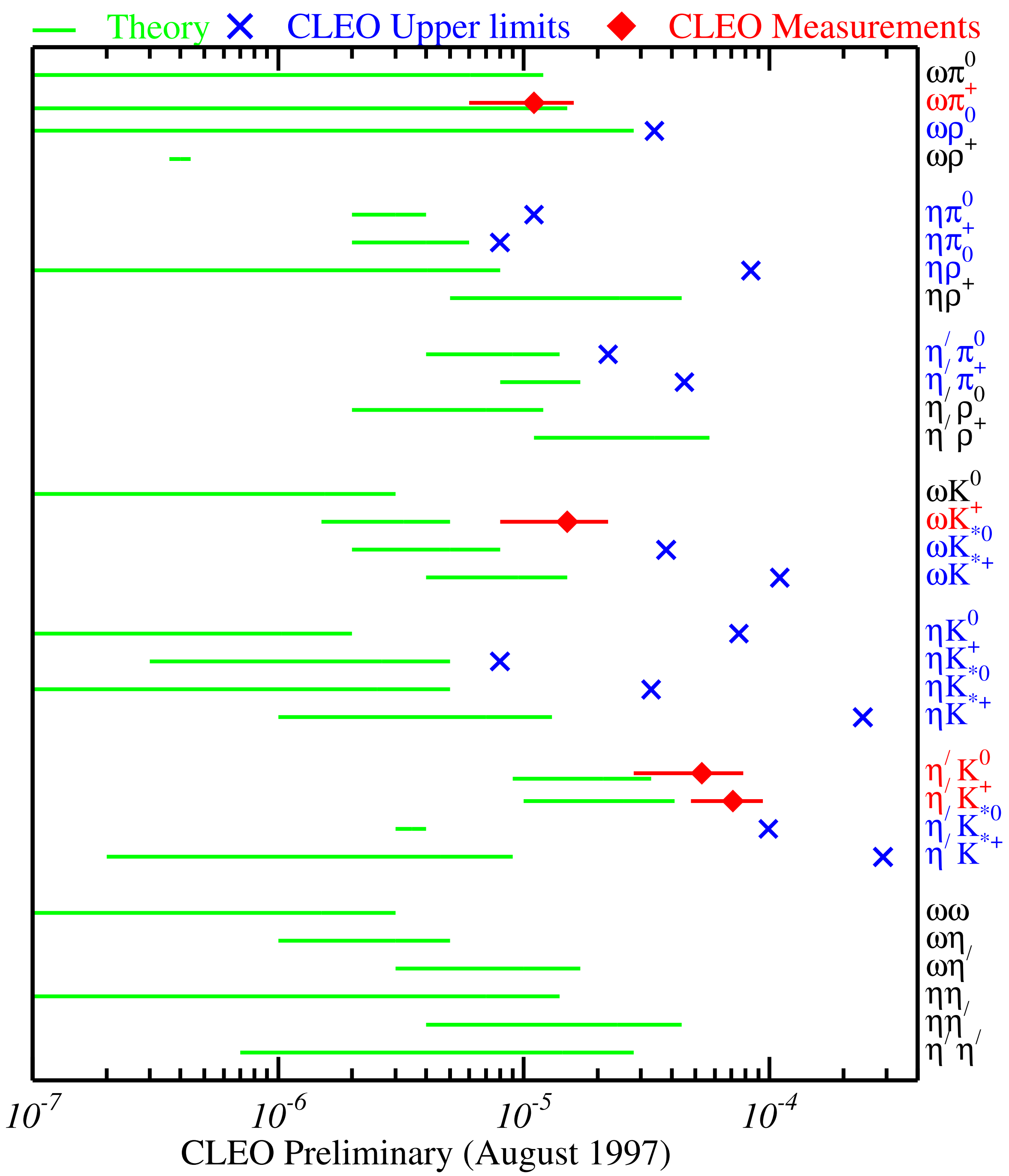


Predictions, Limits, Measurements for rare B Decays



CLEO Preliminary (August 1997)

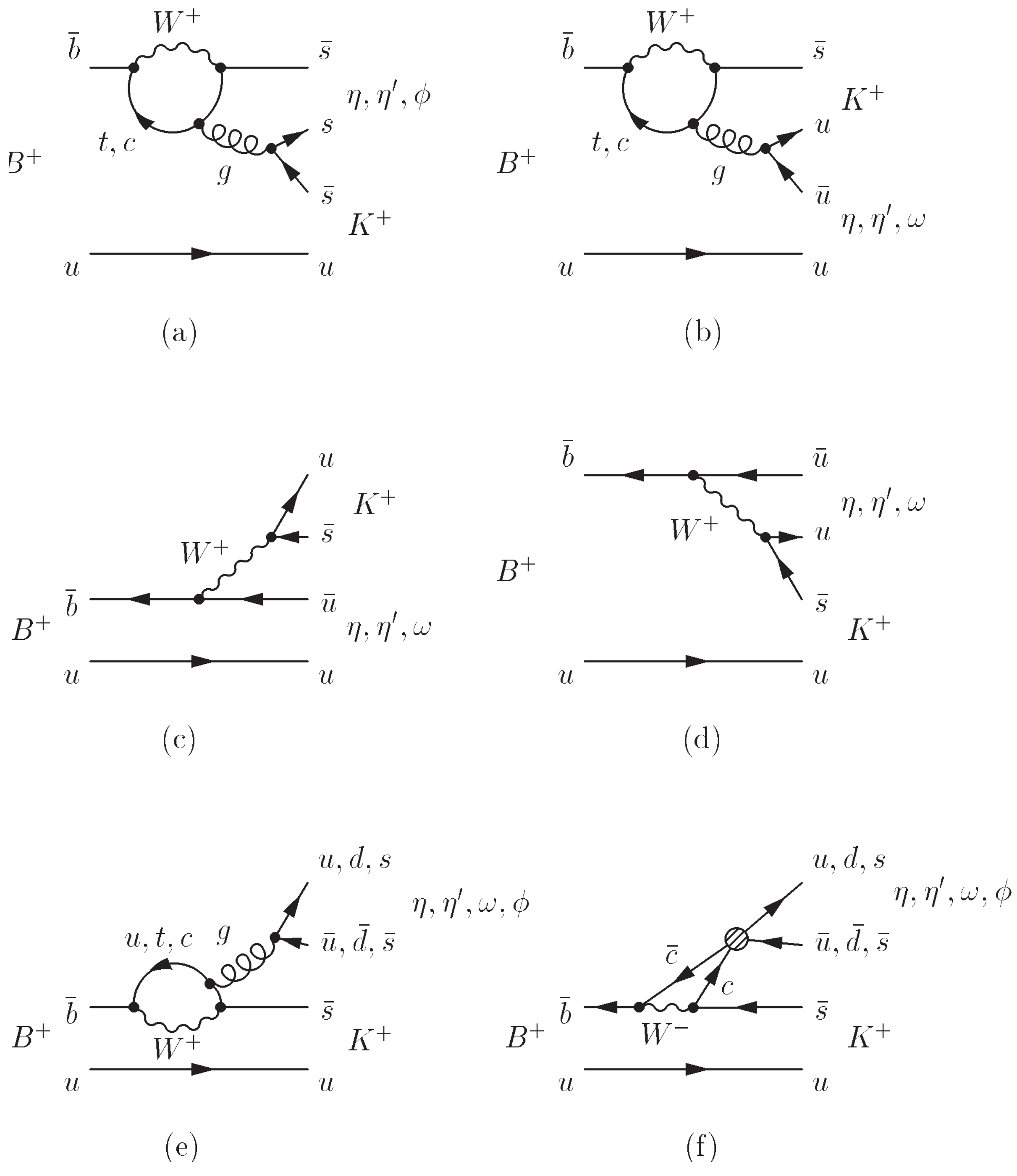
PREDICTIONS, LIMITS, MEASUREMENTS FOR RARE B DECAYS



Branching ratios for rare B decays

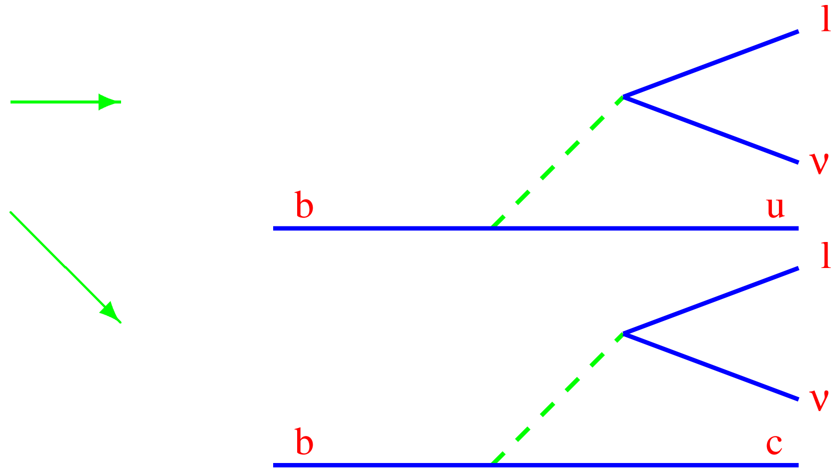
$$
\begin{aligned}
\omega K &= (1.5^{+0.7}_{-0.6} \pm 0.3) \times 10^{-5} \\
\omega \pi &= (1.1^{+0.6}_{-0.5} \pm 0.2) \times 10^{-5} \\
\eta' K &= (7.1^{+2.5}_{-2.1} \pm 0.9) \times 10^{-5} \\
\eta' K^0 &= (5.3^{+2.8}_{-2.2} \pm 1.2) \times 10^{-5} \\
\phi K^* &= (1.3^{+0.7}_{-0.6} \pm 0.2) \times 10^{-5} \\
K^+ \pi^- &= (1.5^{+0.5}_{-0.4} \pm 0.1) \times 10^{-5} \\
K^0 \pi^+ &= (2.3^{+1.1}_{-1.0} \pm 0.2) \times 10^{-5} \\
\eta' X_s &= (62 \pm 16 \pm 13) \times 10^{-5}
\end{aligned}
$$

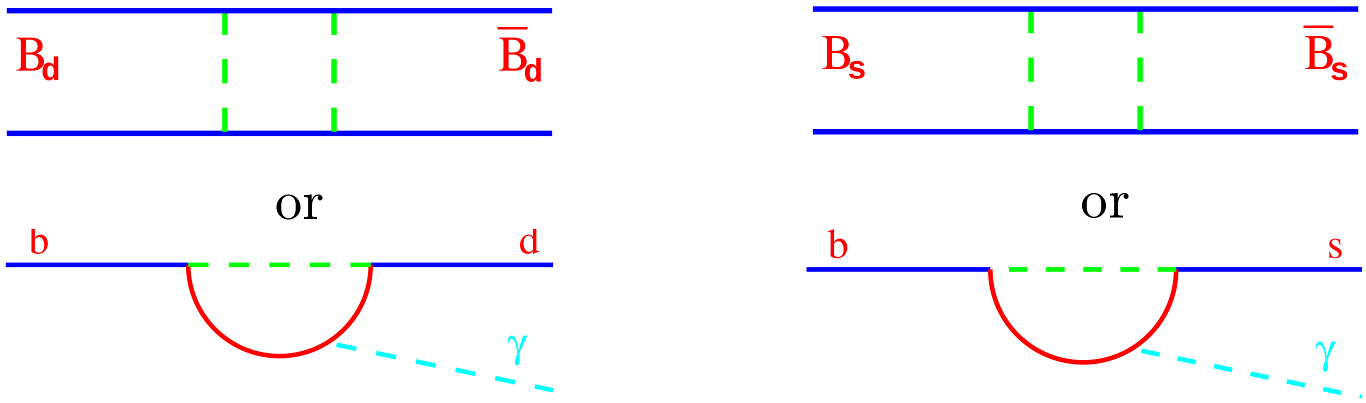
$b \to u$ AND PENGUIN DIAGRAMS



CKM Primer

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



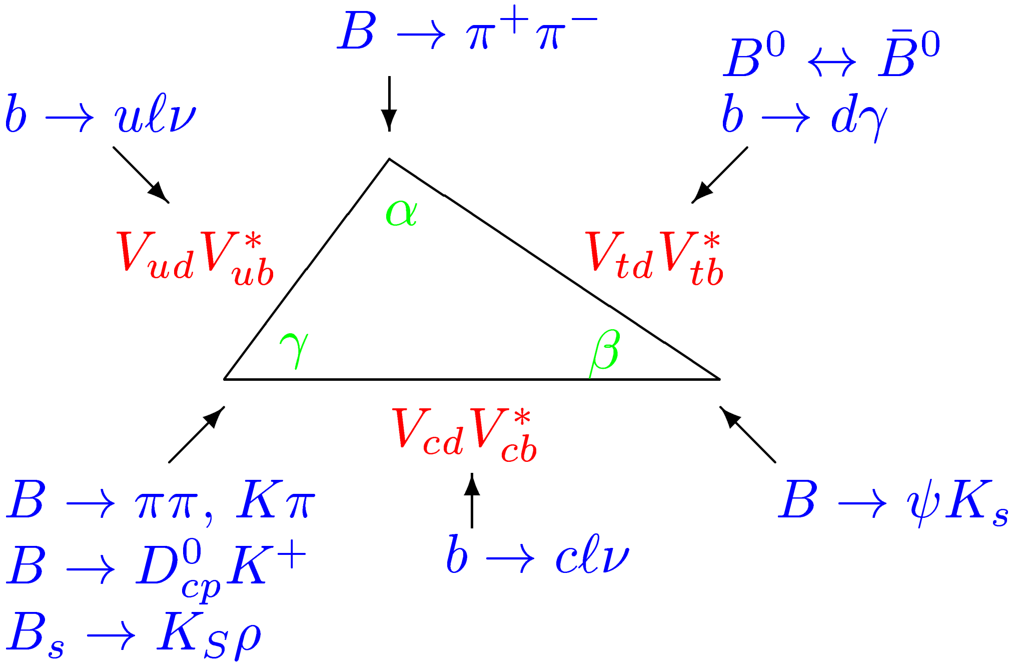


- Unitarity $\Rightarrow$ $\underbrace{V_{ub}^* + V_{td}}_{\text{poorly measured}} = \underbrace{\sin\theta_C V_{cb}^*}_{\text{well known}}$

- Rates $\Rightarrow$ sides of triangle

- $\not{C}P$ asymmetries $\Rightarrow$ angles of triangle

Testing CKM unitarity and CP violation in B decays



- To test unitarity:
  measure all the sides and angles

- $\not{C}\!P$ asymmetries:

  – β: $B\bar{B}$ mixing (phase of V_{td})

  – γ: direct $\not{C}\!P$ in $b \to u$ (phase of V_{ub})

  – α: *both* mixing and direct $\not{C}\!P$

How Could New Physics Appear?

- Lincoln Wolfenstein:

  "The goal of studying CP violation in B decays is *not* the accurate determination of the angles β and γ. . . . The goal is to combine different experiments to constrain the standard model in the hope of uncovering new physics."

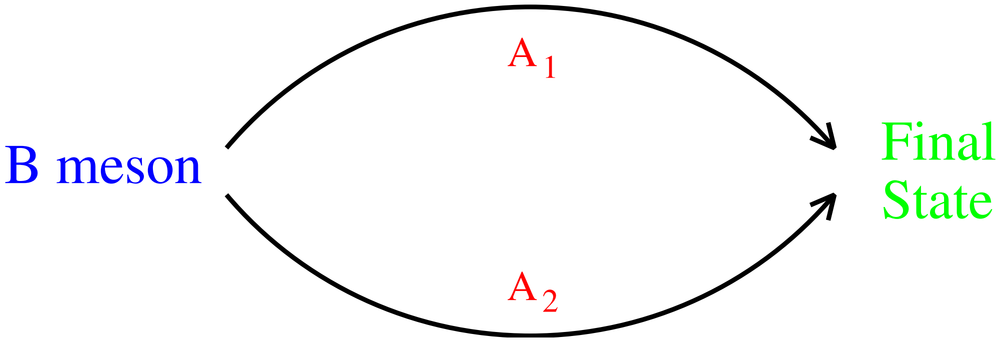
- CKM an $N \times N$ matrix, $N > 3$
  - No unitarity triangle
  - V_{ub}, V_{cb}, V_{ts}, V_{td} could have independent complex phases

- "New Physics" (SUSY, extra Higgs, . . .)
  - New diagrams $\Rightarrow$ extra terms in amplitude

- Strategies to probe CKM
  - measure phases of many amplitudes independently and check consistency $\Rightarrow$ lots of data!
  - measure rates of highly suppressed processes to probe physics of high mass scales $\Rightarrow$ lots of data!

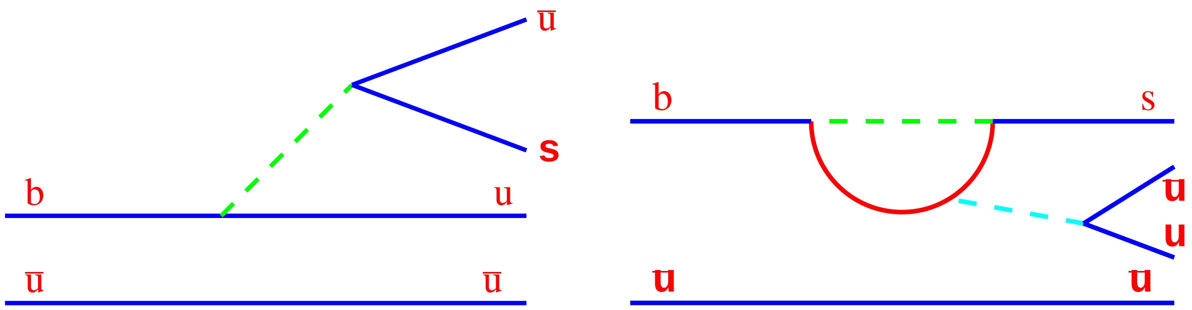
$\not{C}\!P$ Asymmetries as a Probe of New Physics

- $\not{C}\!P$ results from interference of two amplitudes



$$\mathrm{Im}(A_1) \neq \mathrm{Im}(A_2) \Rightarrow \not{C}\!P$$

- Example: $B \to K\pi$



$$\mathcal{A}(B \to K\pi) \propto \arg(V_{ts}^* V_{ub}) \propto \sin\tilde{\gamma}$$

Time independent

- More detail:
  - $\mathcal{A}_t(B \to \psi K_S) \propto \arg(V_{td}^* V_{cb})$

    Phase of B_d mixing (β)
  - $\mathcal{A}_t(B \to \pi\pi) \propto \arg(V_{td}^* V_{ub})$

    Phase of B_d mixing and phase of V_{ub} (α)
  - $\mathcal{A}(B \to DK) \propto \arg(V_{ub}^* V_{cb})$

    Phase of V_{ub} (γ)
  - $\mathcal{A}(B \to K\pi) \propto \arg(V_{ub}^* V_{ts})$

    Phase of V_{ub} and phase of $b \to s$ penguin ($\tilde{\gamma}$)
- NOTE: NEW PHYSICS $\Rightarrow \gamma \neq \tilde{\gamma}$

  $$\Rightarrow \alpha + \beta + \gamma \neq \pi$$

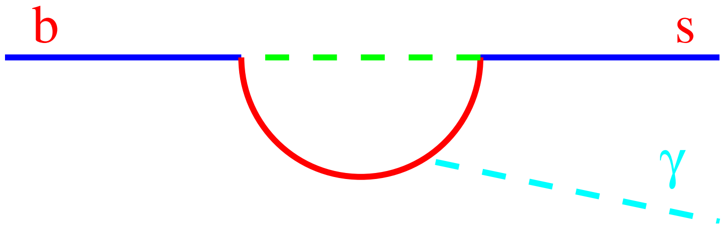
  non-unitarity, 4th gen, new particles in loops, $\cdots$
- TO EXTRACT γ, $\tilde{\gamma}$ NEED:

  $\Rightarrow$ LOTS OF DATA

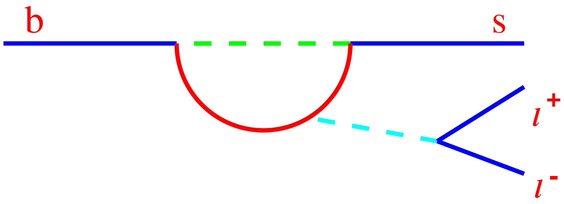
  $\Rightarrow$ ASYMMETRIC ENERGY BEAMS <u>NOT NEEDED</u>

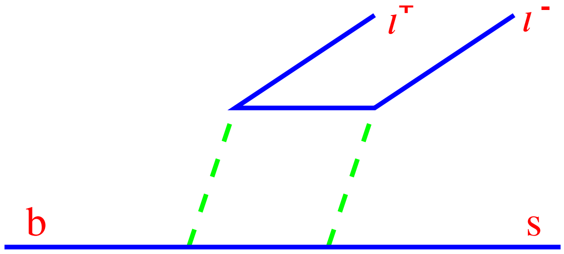
Rare Decay Rates as a Probe of New Physics

- $\Gamma(b \to s\gamma)$

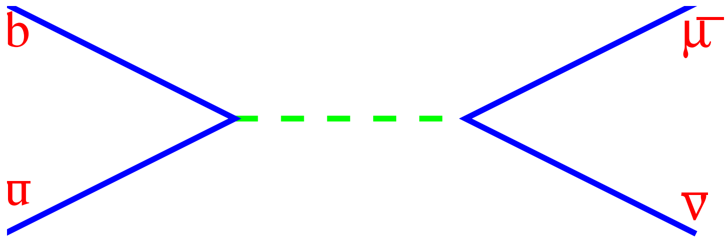


- $\Gamma(b \to s\ell^+\ell^-)$ and $\Gamma(B \to K^{(*)}\ell^+\ell^-)$





- $\Gamma(B \to \mu\bar{\nu})$



- SM processes suppressed

  $\Rightarrow$ new physics can compete

- Loops offer good opportunities for new particles to reveal themselves

From rare decays to CKM

- it is a big step from
  observing a rare decay mode $\rightarrow$
  measuring a CP-violating asymmetry $\rightarrow$
  extracting a CKM phase.

- For example, charge-symmetric backgrounds
  (from continuum, B decays, π/K mis-id)
  dilute significance of non-zero asymmetries
  beyond naive binomial statistics.

- In presence of such backgrounds,
  CLEO II needs considerably more data
  to measure statistically significant asymmetries

- Excellent π/K separation of CLEO III RICH
  will reduce this problem considerably!

- Moral #1: Even in the easiest modes,
  need LOTS of statistics,
  control over backgrounds and mis-id.

From rare decays to CKM

- Once we have observed a $\not{C}P$ asymmetry in a $b \to u$ decay, have we measured a CKM phase?
- NO! Virtually all decay modes proceed by some mixture of $b \to u$ tree (or color suppressed), $b \to sg$ or $b \to dg$ penguins, and $b \to (s/d)(\gamma/Z^0)$ EW penguins
- Disentangling the contributions *is* possible if enough modes (related by isospin or SU(3)) can be measured. This is an old trick in kaon physics!
- MORAL #2: IT ISN'T ENOUGH TO MEASURE THE *easy* MODES; *many* RELATED MODES, ESP. THOSE WITH π^0'S, ARE NEEDED.

Moral Conclusion:

A factor ~10 beyond CLEO II luminosity *is not enough!*
We do real CKM physics only with ~100× the luminosity!

$B\bar{B}$ Datasets

CLEO datasets

CESR	$\mathcal{L}_{\rm peak}$ $({\rm cm}^{-2}{\rm s}^{-1})$	$\int \mathcal{L}dt$ $({\rm fb}^{-1}/{\rm yr})$	$B\bar{B}/{\rm yr}$ $\times 10^6$
Phase 2 (Now)	4×10^{32}	3.6	2.4
Phase 3 (1999 $\rightarrow$ 2003)	1.7×10^{33}	15	10
Phase 4 (2003 $\rightarrow$?)	3×10^{34}	270	200

B Factories in 1999

Machine	$\mathcal{L}_{\rm peak}$
CESR Phase III	1.7×10^{33}
PEP-II	3×10^{33}
KEK-B	10×10^{33}

Phase IV Physics Reach

- Assume Asymm. B Factories will measure time-dependent asymmetries in ψK (β) and maybe also $\pi\pi$ (α)
- Insufficient statistics for $\not{C}P$ asymmetries from $b \to u$ like $DK^{(*)}$ (γ) and $K\pi$ $(\tilde{\gamma})$ or for measurement of rare decays like $b \to s\ell^+\ell^-$
- Assume 600M $B\bar{B}$ events (3 years at design L)
- Backgrounds and efficiencies from current data
  Upgraded for CLEO III particle ID

$B \to \pi\pi/K\pi$ AND $\tilde{\gamma}$

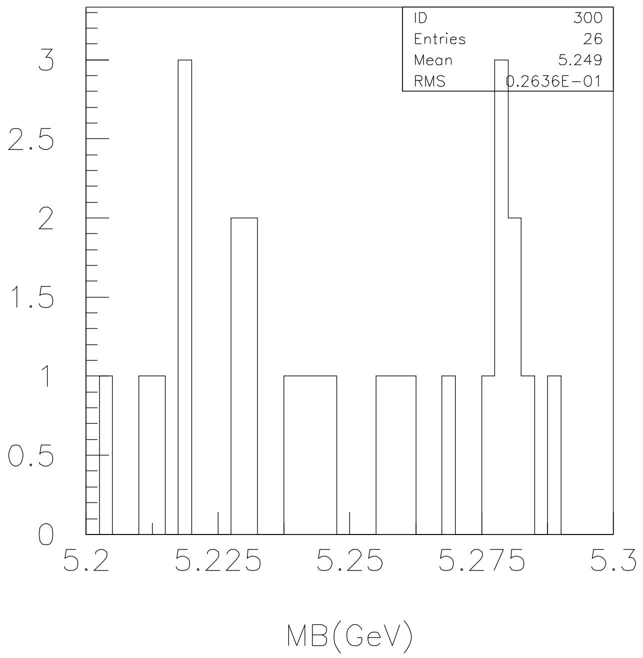
Mode	Number of events (now) 3M $B\bar{B}$ events	Projected Number of Events in 600M $B\bar{B}$ events
$B^0 \to K^+\pi^-$	22	4400
$B^0 \to \pi^+\pi^-$	10	2000
$B^+ \to K^+/\pi^+\pi^0$	20	4000
$B^+ \to K_S\pi^+$	9	1800

$$\begin{aligned}\mathcal{A}_{\rm CP} &= \frac{\Gamma(B^+ \to K^+\pi^0) - \Gamma(B^- \to K^-\pi^0)}{\Gamma(B^+ \to K^+\pi^0) + \Gamma(B^- \to K^-\pi^0)} \\ &\simeq \text{const} \times \sin\tilde{\gamma}\end{aligned}$$

- MUST MEASURE FAMILY OF $B \to K\pi/\pi\pi$ RATES TO EXTRACT $\tilde{\gamma}$ (Gronau, Wyler, and many others)
- Phase IV (600M $B\bar{B}$ events): $\Delta\tilde{\gamma} \approx 6^\circ$ (exptl.)
- Many other measurements, more theor. work required to reduce uncertainty due to EWP

$B \to DK^{(*)}$ AND γ

- Current status (3M $B\bar{B}$ events):
  We have hints of signals in $B^- \to D^0 K^-$, $D^0 K^{*-}$
  $\Rightarrow$ backgrounds and efficiencies are known



- Measure family of $B \to \overset{(-)}{D^0} K^{(*)}$ modes
  with D decays to
  Cabibbo-allowed ($D^0 \to K^-(n\pi)^+$),
  CP-eigenstates ($\pi^+\pi^-$, K^+K^-),
  and DCSD ($D^0 \to K^+(n\pi)^-$)

- Phase IV (600M $B\bar{B}$ events) $\Rightarrow$ $\Delta\gamma \approx 10^\circ$

- These methods are theoretically rather clean!

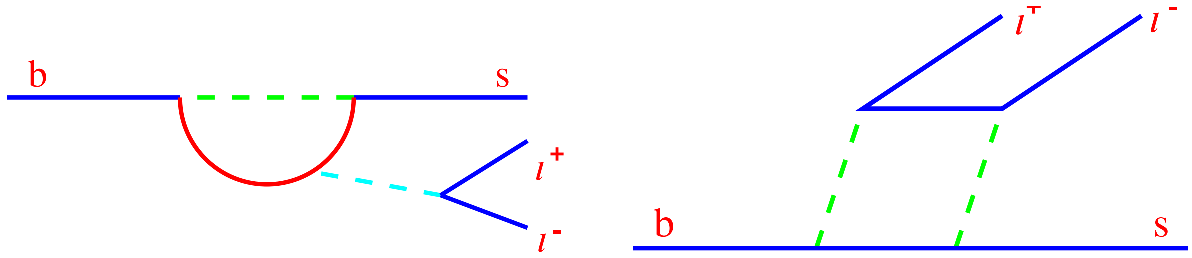
More ways to get CKM phases

- Many other channels to explore:
  - $B \to \eta' K$
  - $B \to \pi\pi/K\pi$ variants
  - $B \to \chi_c \pi$
  - $B \to K^{*0}\gamma$
  - ...
- David London:

  "There are many ways to cleanly extract CKM phase information from CP-violating rate asymmetries in B decay."

Rare Decays in Phase IV

- CLEO measures $\Gamma(b \to s\gamma)$ and puts model dependent limits on charged Higgs: $M(H^+) > 600$ GeV$/c^2$
- $\Gamma(b \to s\ell^+\ell^-)$ and $\Gamma(B \to K^{(*)}\ell^+\ell^-)$



  - Currently (3M $B\bar{B}$ events) CLEO limits
    $\mathcal{B}(b \to s\ell^+\ell^-) < 4 \times 10^{-5}$;
    $\mathcal{B}(B \to K^{(*)}\ell^+\ell^-) \lesssim 1 \times 10^{-5}$
  - Phase IV (600M $B\bar{B}$ events):

$$\frac{\delta\mathcal{B}}{\mathcal{B}}(b \to s\ell^+\ell^-) \approx 15\%$$

$$\frac{\delta\mathcal{B}}{\mathcal{B}}(B \to K^{(*)}\ell^+\ell^-) \approx 8 - 15\%$$

$\Rightarrow$ Help LHC distinguish between different SUSY models (Hewett *et al.*)

$\Rightarrow$ Sensitive to existence of strong symmetry breaking to 2 TeV scale! (Burdman)

Tau and charm physics in Phase III → IV, beyond SM

- $e^+e^- \to \tau^+\tau^-$ and $c\bar{c}$ at 10 GeV is a clean environment to do high precision studies and searches for very rare physics beyond SM.
- Tau physics:
  - rare decays: $7\pi\nu$, $b_1\nu$ (2nd class currents), scalars
  - $\not{C}\!P$ in $a_1\nu$, $\rho\nu$, $K^*\nu$
  - neutrinoless decays: γe, $\gamma\mu$, 3ℓ
  - neutrinoless decays: $X^0_{hadron}\ell$, $X^0_s\ell$, $X^{--}_{hadron}\ell^+$
  - $B-L$ decays: $\bar{p}\gamma$, $\bar{p}X^0_{hadron}$
  - m_{ν_τ} to < 10 MeV??
- Charm physics: mixing, $\not{C}\!P$, much more!
- B_s physics, $\not{C}\!P$, much more!
  (but running on $\Upsilon(5S)$ may entail a big reduction in luminosity; and we'll need all the $B\bar{B}$ we can get.
  We do not envision such a run in the first few years.)

Upgrades to CLEO III

- Working groups organized within CLEO
  to investigate detector issues and physics potential

- Machine backgrounds are biggest concern:
  spurious triggers, detector occupancy, damage

- CLEO III trigger and DAQ designed for:
  < 1000 Hz, 25 MB/s data rate.
  Straightforward to tighten trigger to eliminate spurious triggers (and some $\tau^+\tau^-$!), with no loss of $B\bar{B}$ events, bringing rate below 1000 Hz. But event size must be kept below 25 KB – control occupancy.

- SVD's have finite lifetime. May have to replace inner detectors. Control occupancy $\rightarrow$ faster signal shaping $\rightarrow$ new FE electronics.

- CsI: we are searching for evidence of radiation damage in endcap crystals near beam.

- Beam-related noise showers/occupancy?
  Under study. (Worse in ABFs).

- DR, RICH, magnet, muon chambers OK.

Muon system

- CLEO's muon system is much coarser than B Factories' finely-segmented IFR.
  CLEO: $p_\mu > 1.0 - 1.4$ GeV/c. $P(K_L, n) \sim 25\%$.
  IFR: $p_\mu > 0.8 - 1.2$ GeV/c. $P(K_L, n) \gg 25\%$.
  (K_L, n detection provide hermeticity to aid in reconstruction of $b \to (c/u)\ell\nu$, $B^+ \to \ell^+\nu$, $b \to (s/d)\nu\bar{\nu}$, *etc.*)
- Upgrading muon system will be a major effort, in
  - cost
  - manpower
  - down-time between CLEO III and Phase IV
- physics justifications and cost/benefit analysis are under study.

The Competition: ABF's

PEP-II	$\mathcal{L}_{\text{peak}} \approx 3 \times 10^{33}$	3.1×9 GeV
KEK-B	$\mathcal{L}_{\text{peak}} \approx 1 \times 10^{34}$	3.5×8 GeV

- 600M $B\bar{B}$ events (Phase IV)

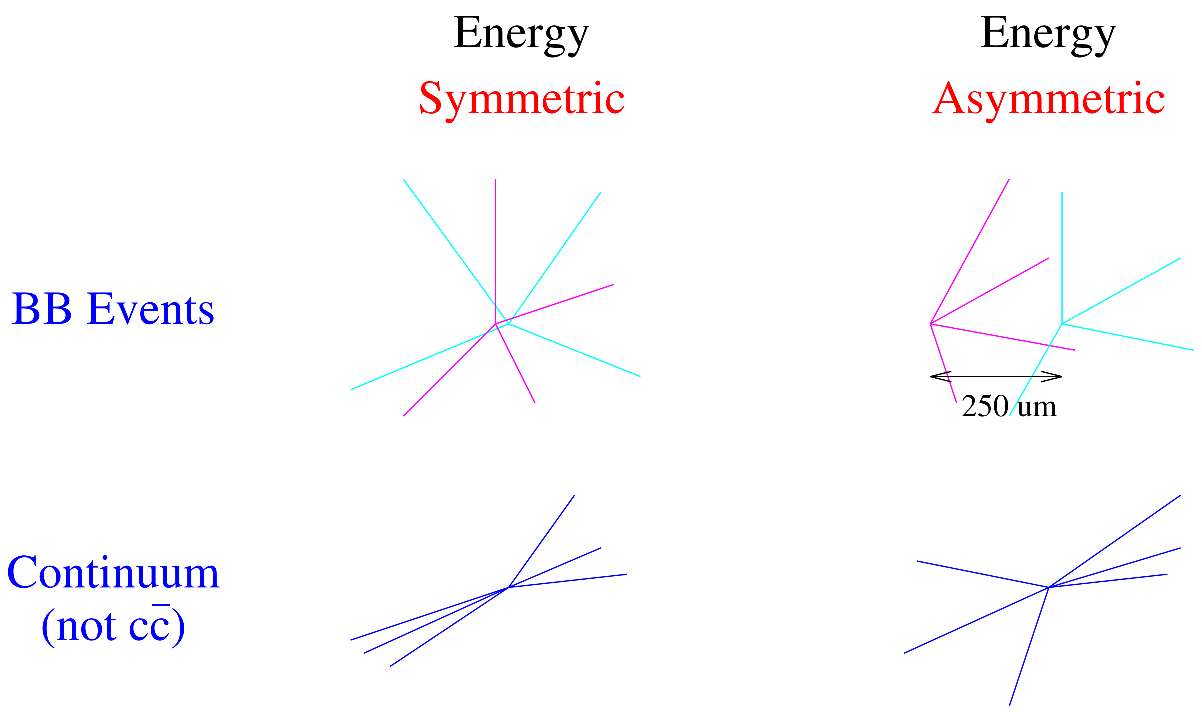
  $\Rightarrow$ 30 design years at PEP-II

  $\Rightarrow$ 10 design years at KEK-B

- For these time-integrated measurements, Does energy asymmetry offer PEP-II or KEK-B any advantages?

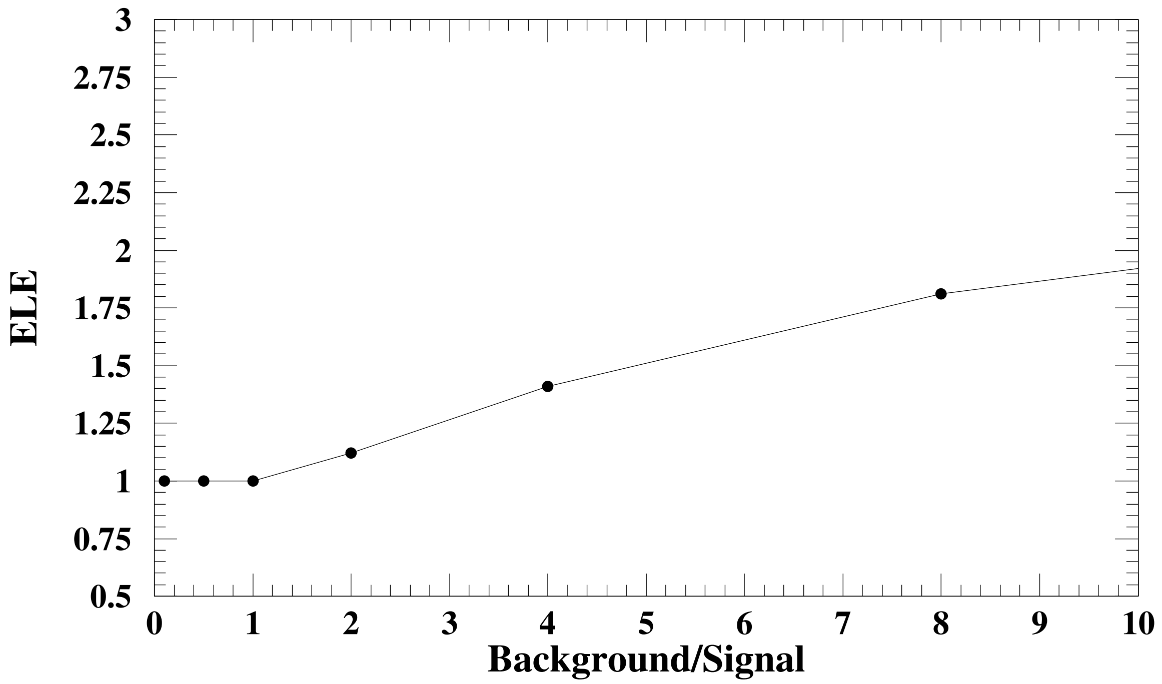
Symmetric vs Asymmetric energies

- Potential advantage of asymmetric machines: topological background suppression using separated B vertices



- Studied in simple Monte Carlo
  - Used vertex resolutions from BaBar TDR
  - Results discussed with many BaBar physicists

- EFFECTIVE LUMINOSITY ENHANCEMENT (ELE) $\equiv \frac{\int \mathcal{L}_{\rm SYM}}{\int \mathcal{L}_{\rm ASYM}}$ to have same statistical significance



- ELE ≈ 1 for "clean" modes ($B \to \pi\pi/K\pi$)

- ELE ≈ 1.5 for "dirty" modes ($B \to DK$)

- CONCLUSION: ENERGY ASYMMETRY IS AT BEST ONLY A SMALL ADVANTAGE

- FOR TIME-INTEGRATED ASYMMETRIES, WHAT COUNTS IS $\int \mathcal{L} dt$!

THE COMPETITION: HADRON MACHINES

- LHC-B, BTEV
  - + B_s physics (without a special run)
  - − Can't trigger on or reconstruct π^0, η
  - + Production of large numbers of B mesons
  - − Tremendous challenge to extract signals in difficult hadronic environment

⇒ HADRON MACHINES OFFER COMPLEMENTARY APPROACH TO THE PHYSICS

Conclusions

- e^+e^- machine with $\mathcal{L}_{\rm peak} \geq 3 \times 10^{34}{\rm cm}^{-2}{\rm s}^{-1}$ needed
  - to explore $\not{C}\!P$
  - to probe new physics in quark mixing sector
- Large $\int \mathcal{L}dt$ needed to do physics
  - Energy asymmetry NOT a substantial advantage
- PHASE IV HAS UNIQUE PHYSICS REACH WELL BEYOND CAPABILITY OF CESR PHASE 3, PEP-II AND KEK-B, AND COMPLEMENTARY TO BTEV/LHC-B