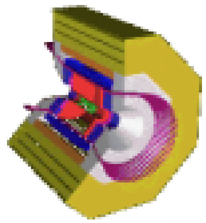


Experimental High Energy Physics (HEP)

Yongsheng Gao
Southern Methodist Univ.
June 12, 2002 at QuarkNet at SMU

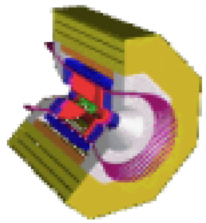
Why is HEP interesting?

What questions HEP addresses?

Current focus of Experimental HEP

CESR/CLEO and selected results

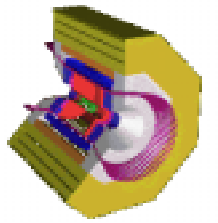
Future Outlook



A Simplified Picture of High Energy Physics

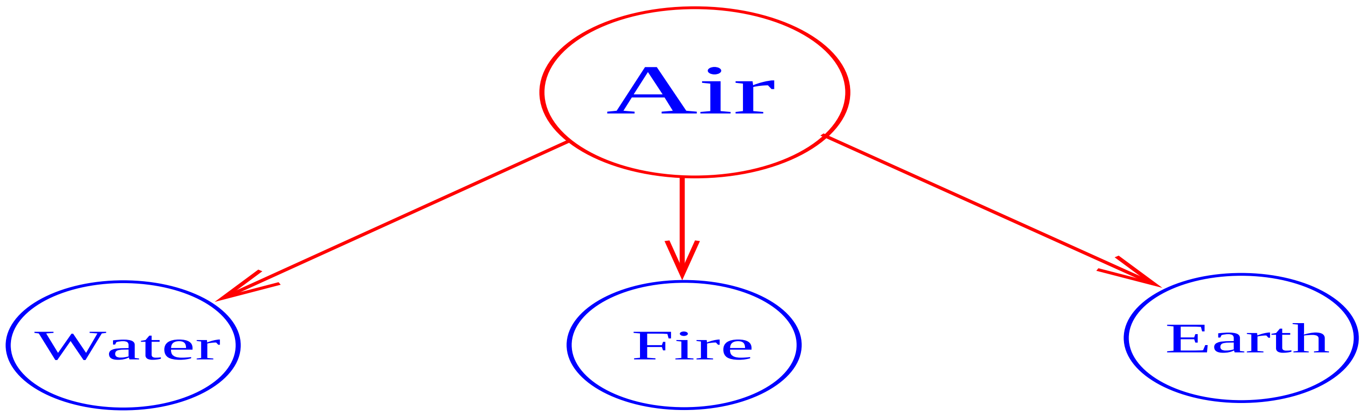
In our endeavor to understand reality we are somewhat like
a man trying to understand the mechanism of a closed watch.
He sees the face and the moving hands, even hears its ticking,
but he has no way of opening the case.
If he is in genius, he may form some picture of a mechanism
which could be responsible for all the things he observes,
but he may never be quite sure his picture is
the only one which could explain his observations.

— Albert Einstein in 1938



Building blocks of matter

Anaximenes (∼ 500 BC):



Mendeleev (∼ 1869): The Periodic Table

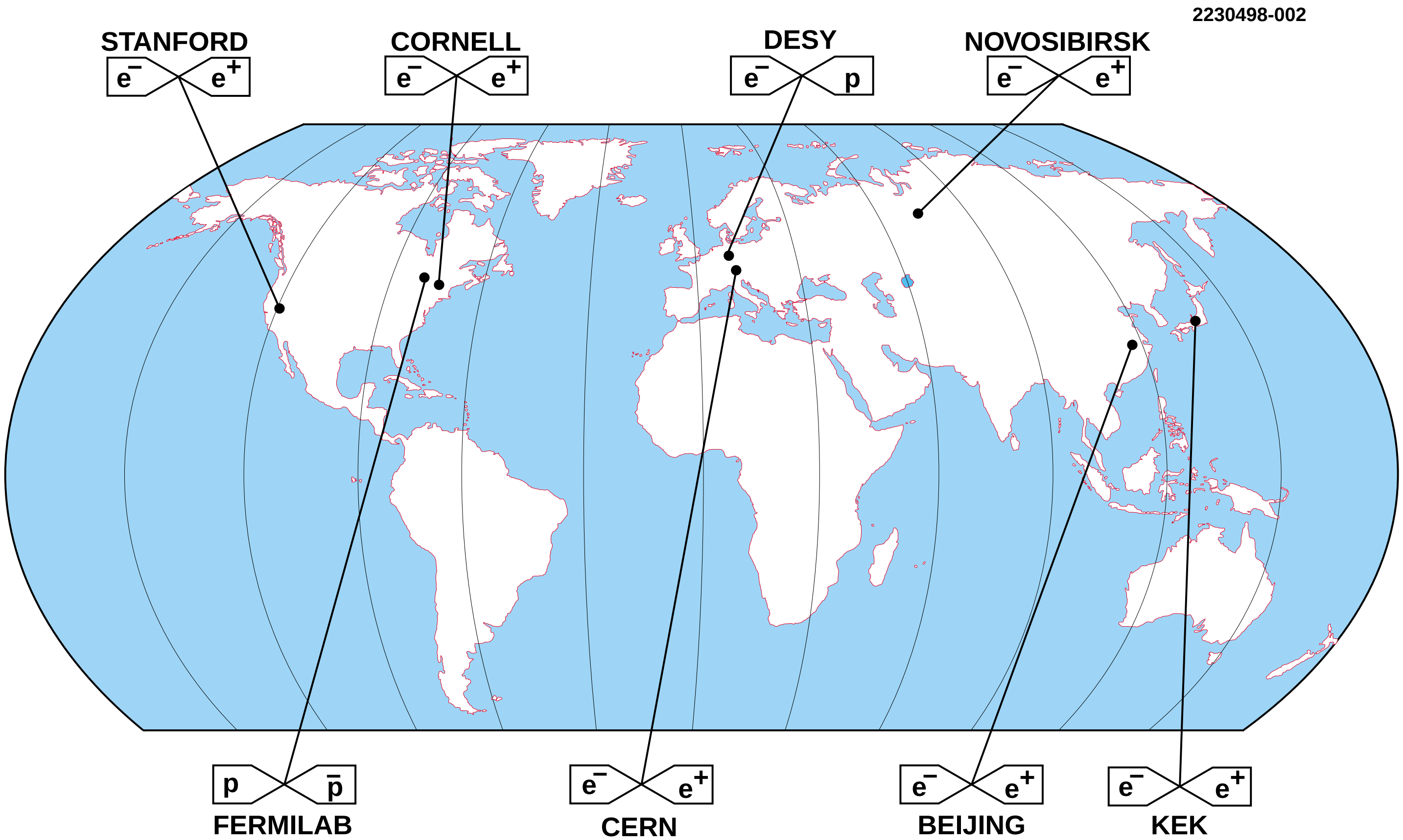
Our current picture: The Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}; \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix};$$

$$g, \ \gamma, \ W^{\pm}, \ Z$$

Success of the Standard Model

- High Energy (Tevatron, LHC)
- High Luminosity (CESR, PEP-II, KEK-B)

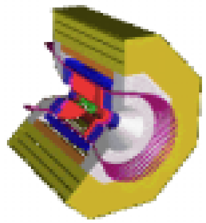


Why SM is not the full story?

- "Replication" problem
- Free parameters
- Matter-antimatter asymmetry

Physics beyond the Standard Model:

- New particles search (LEP, Tevatron, LHC)
- Neutrino physics (Super-K, Minos etc)
- CP violation study (B-factories etc)



What is CP Violation?

- C: Charge conjugation
- P: Parity reflection

CP Violation → difference between:

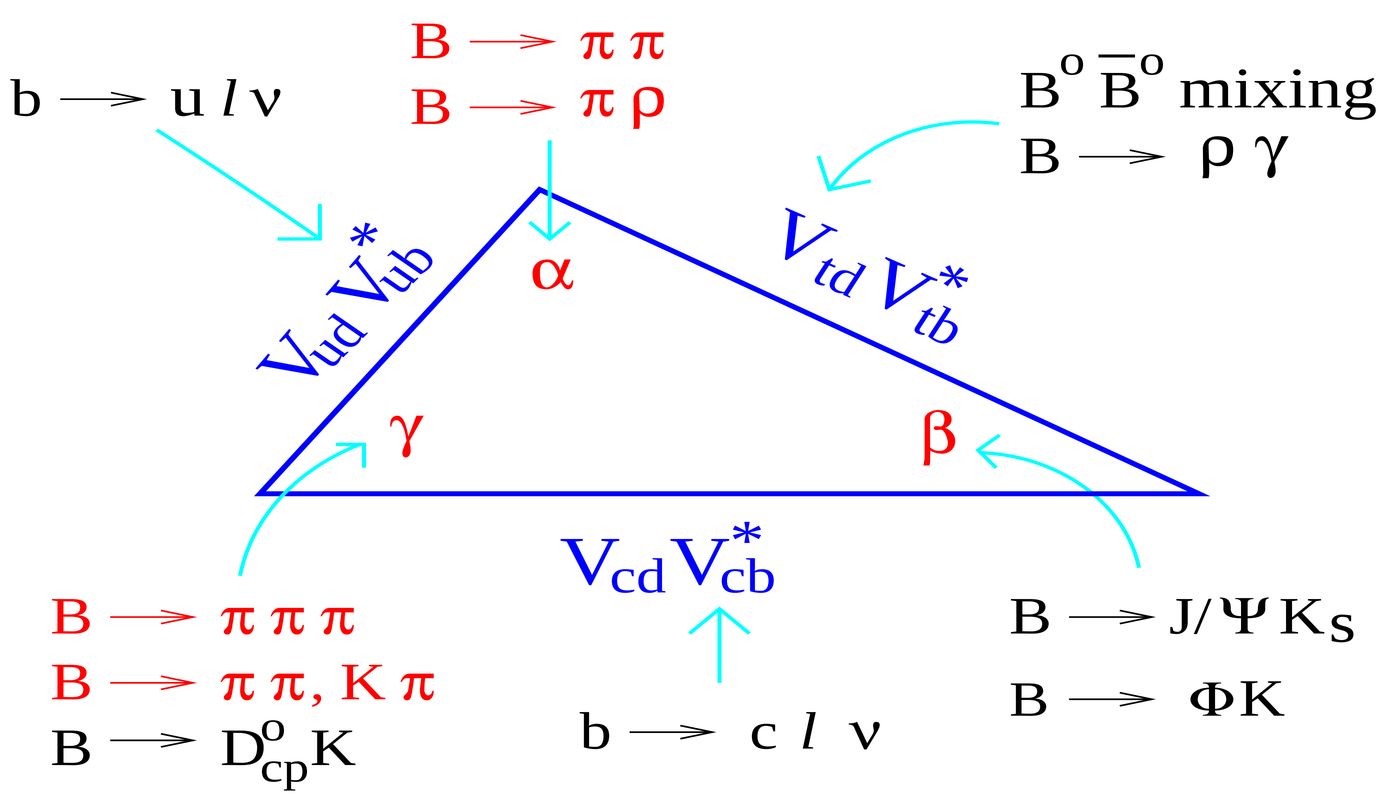
- Matter in universe
- Antimatter, mirror universe
- Matter-Antimatter asymmetry in the Universe

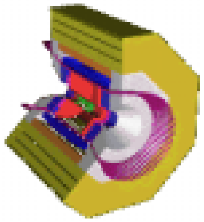
Observation of CP violation:

- Observation of CP violation in Kaon system (1964)
- Observed CP violation in B meson system (2001)

Test the SM and Search for New Physics

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

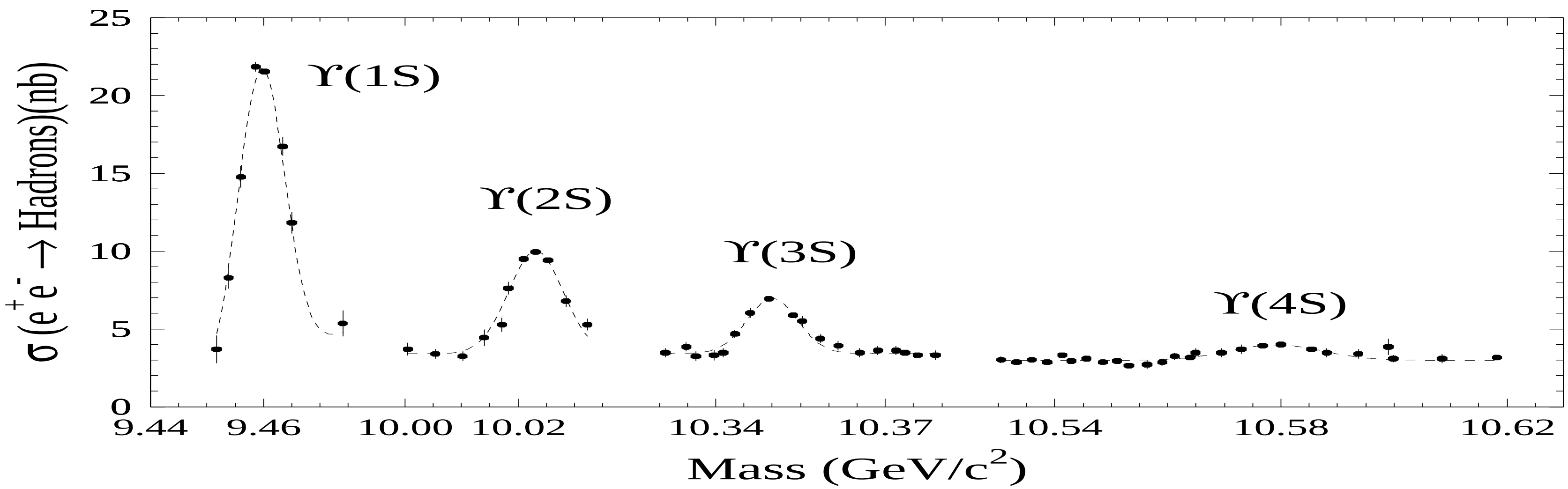




Cornell Electron Storage Ring

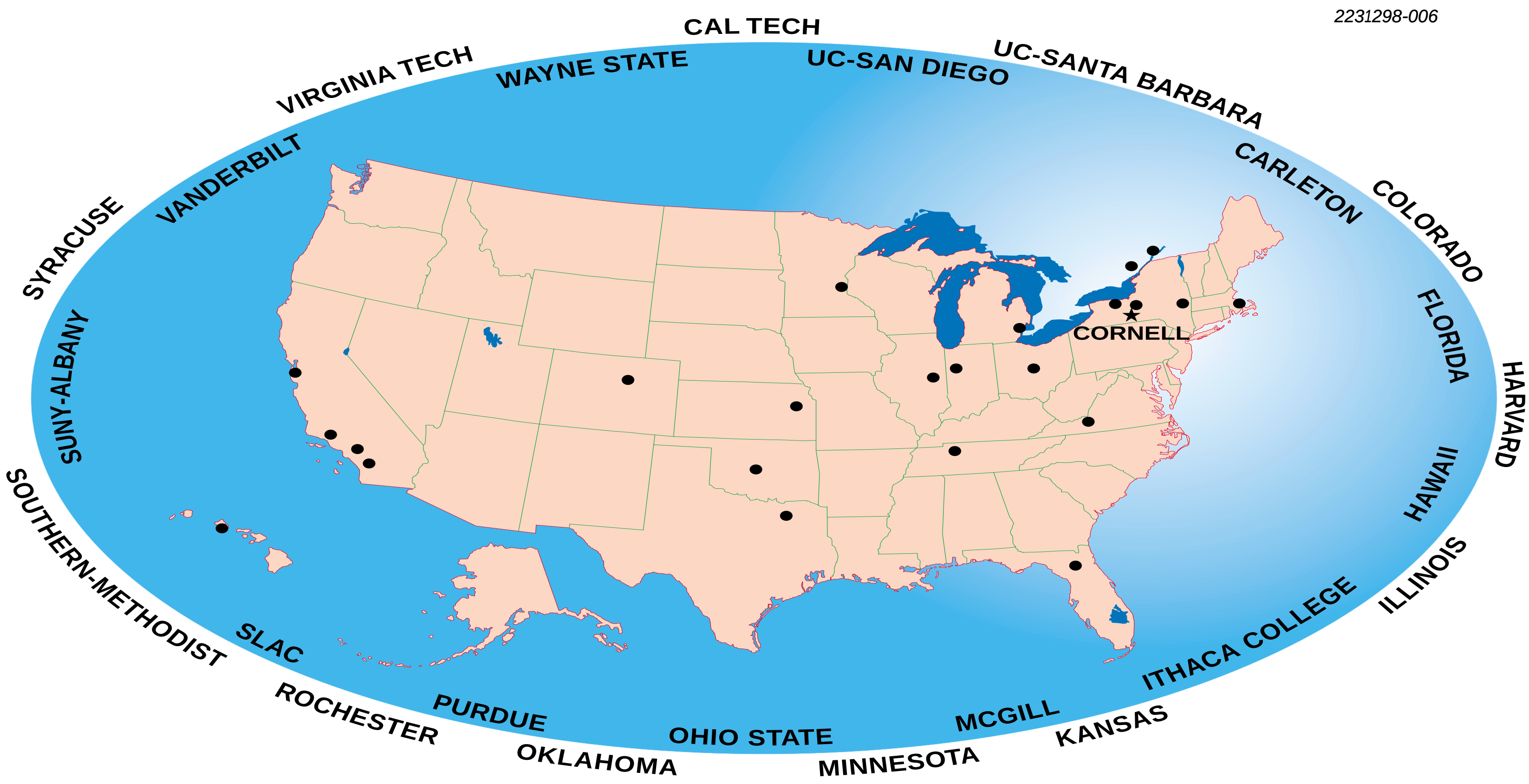
CESR: e^+e^- **at** $\sqrt{s} \simeq 10$ **GeV.**

- On $\Upsilon(4s)$ resonance:
  - $e^+e^- \to \Upsilon(4s) \to B\bar{B}$, $e^+e^- \to$ Continuum
  - $B(\bar{B})$ momentum $\simeq 350$ MeV/c (at rest!)
- Continuum: $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$

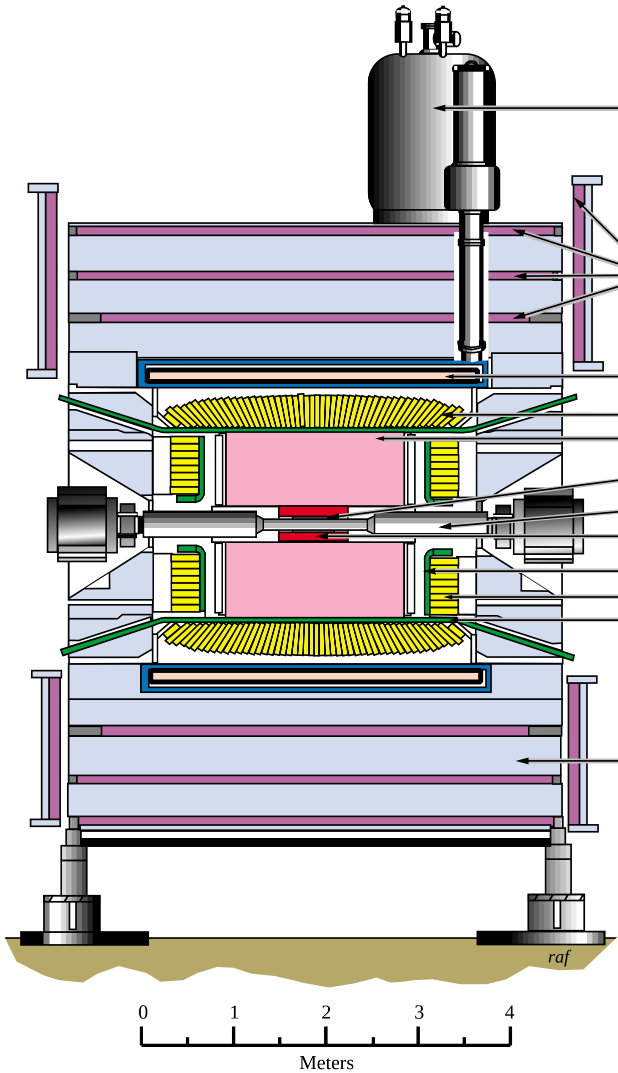


CLEO Collaboration

- ∼ 22 institutions and ∼ 150 physicists



CLEO Detector



CLEO II

- Oct.'89 – Apr.'95
- N($B\overline{B}$)= 3.3×10^6
- 6-layer straw tube

CLEO II.V

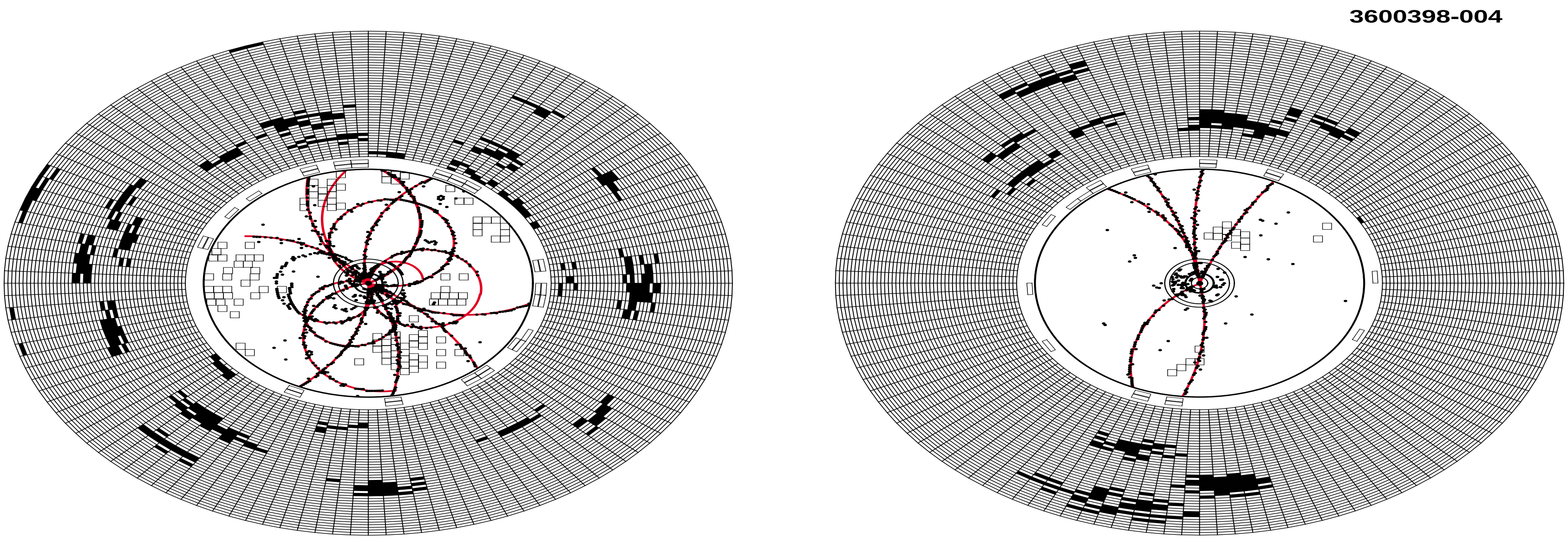
- Nov.'95 – Feb.'99
- N($B\overline{B}$)= 6.4×10^6
- 3-layer Si vertex detector

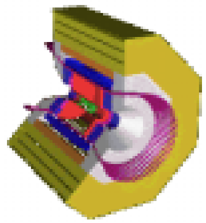
CLEO III

- 2000 – 2001
- New SVX, DR and RICH

Experimental challenges in HEP/CLEO

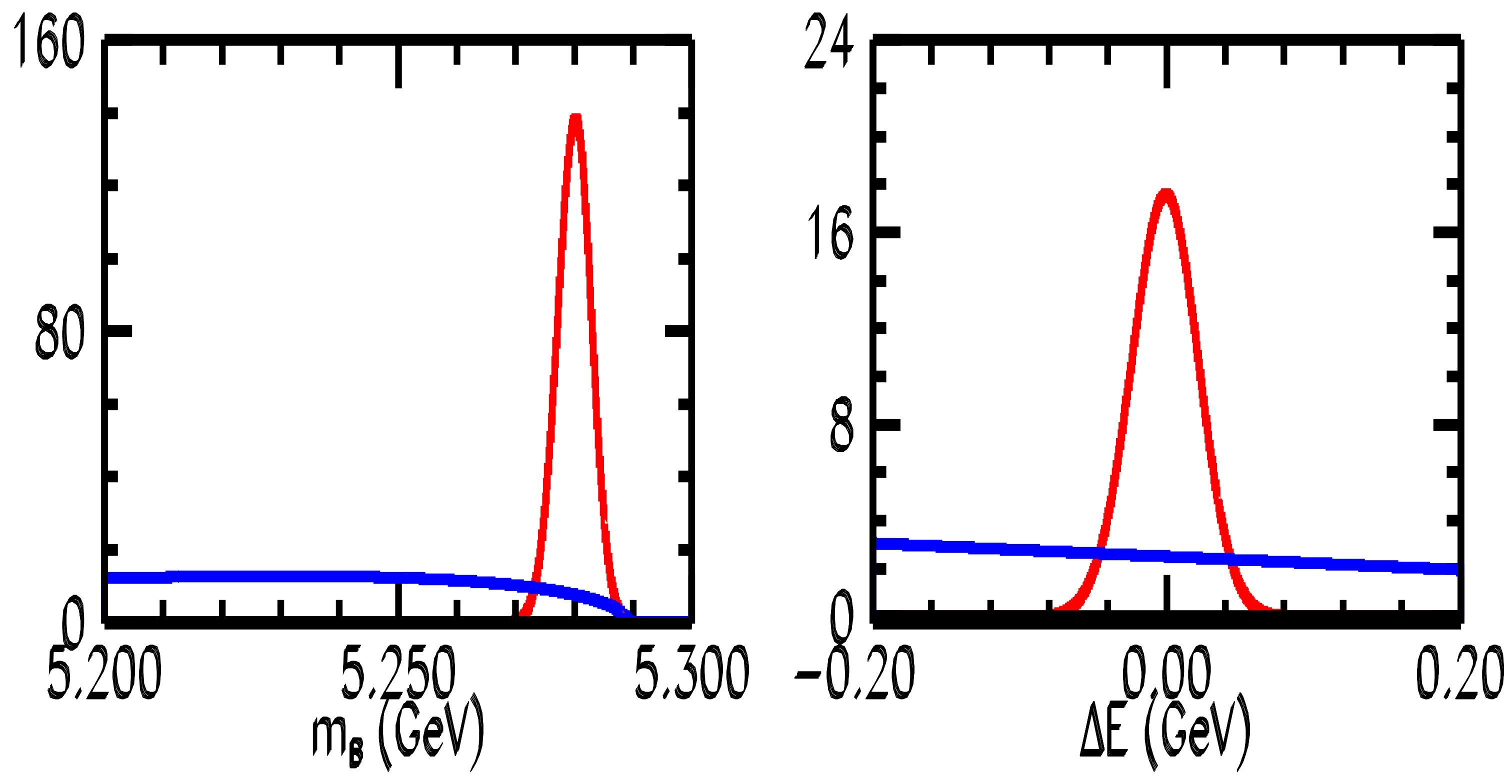
- How to identify $\sim$ 30 signal events from:
  - **40,000,000 continuum events**
  - **10,000,000 generic B events**
  - **Other signal-like events (Physics Backgrounds)**



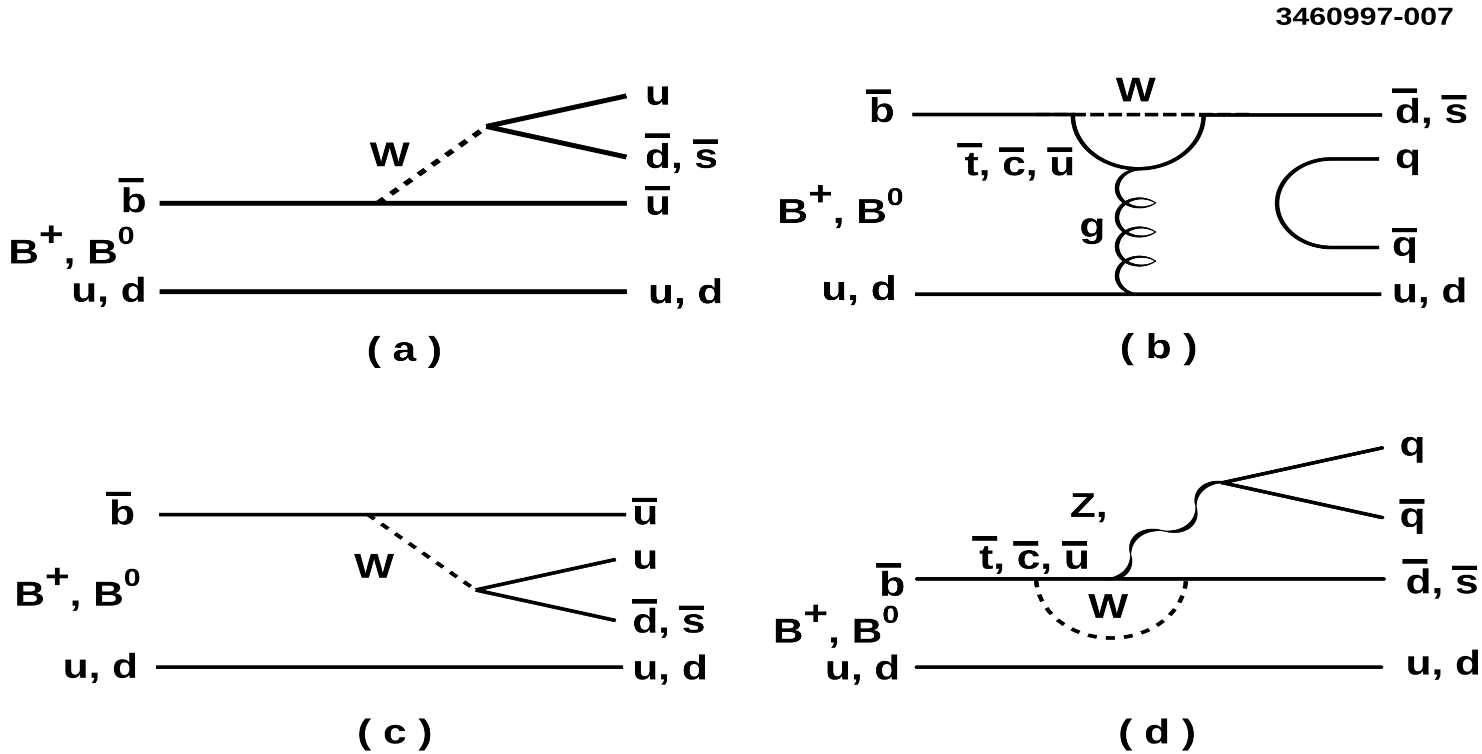


Power of HSP in HEP

- $M_B = \sqrt{E_{beam}^2 - p_{\text{cand}}^2}$ $\quad(\sigma_M \approx 2.5 - 3.4\, MeV/c^2)$
- $\Delta E = E_{\text{cand}} - E_{beam}$ $\quad(\sigma \approx 20 - 60\, MeV)$

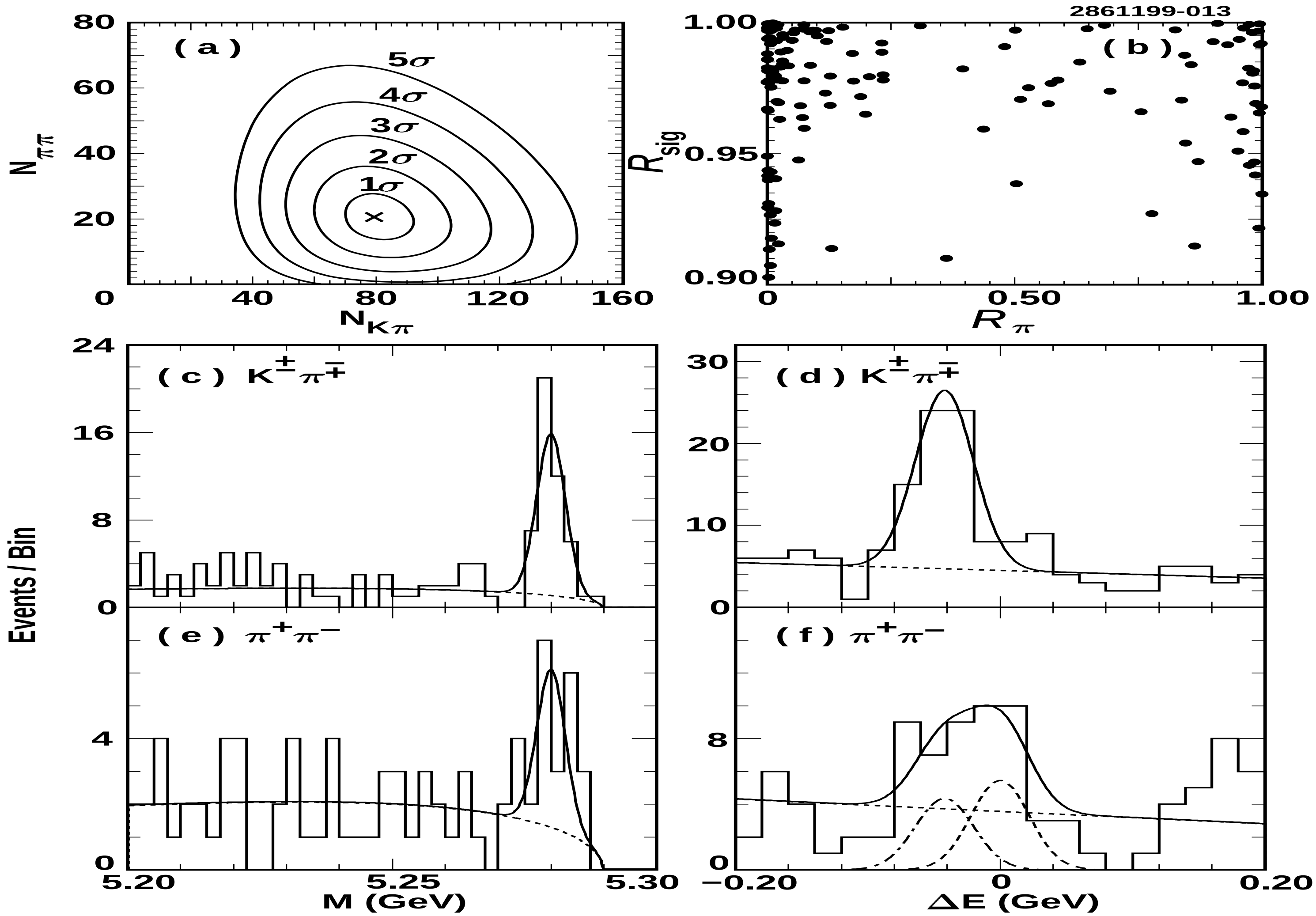


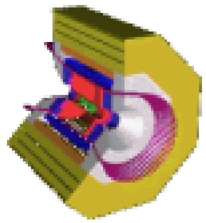
Selected CLEO Results: Rare B Decays



- **Unitarity triangle (angles α and γ, CKM elements V_{ub}, ...)**
- **Sensitive to physics beyond the Standard Model**

$B \to \pi\pi$, $K\pi$ and KK Results





$B \to \pi\pi$, $K\pi$ and KK Results

Mode	N_{sig}	Sig.	Efficiency	$BR \times 10^6$
$\pi^+\pi^-$	$20.0^{+7.6}_{-6.5}$	4.2σ	48%	$4.3^{+1.6}_{-1.4} \pm 0.5$
$\pi^\pm\pi^0$	$21.3^{+9.7}_{-8.5}$	3.2σ	39%	< 12.7 (90%C.L.)
$\pi^0\pi^0$	$6.2^{+4.8}_{-3.7}$	2.0σ	29%	< 5.7 (90%C.L.)
$K^\pm\pi^\mp$	$80.2^{+11.8}_{-11.0}$	11.7σ	48%	$17.2^{+2.5}_{-2.4} \pm 1.2$
$K^\pm\pi^0$	$42.1^{+10.9}_{-9.9}$	6.1σ	38%	$11.6^{+3.0+1.4}_{-2.7-1.3}$
$K^0\pi^\pm$	$25.2^{+6.4}_{-5.6}$	7.6σ	14%	$18.2^{+4.6}_{-4.0} \pm 1.6$
$K^0\pi^0$	$16.1^{+5.9}_{-5.0}$	4.9σ	11%	$14.6^{+5.9+2.4}_{-5.1-3.3}$
K^+K^-	$0.7^{+3.4}_{-0.7}$	0.0σ	48%	< 1.9 (90%C.L.)
$K^\pm K^0$	$1.4^{+2.4}_{-1.3}$	1.1σ	14%	< 5.1 (90%C.L.)
$K^0\bar{K}^0$	0	0.0σ	5%	< 17 (90%C.L.)

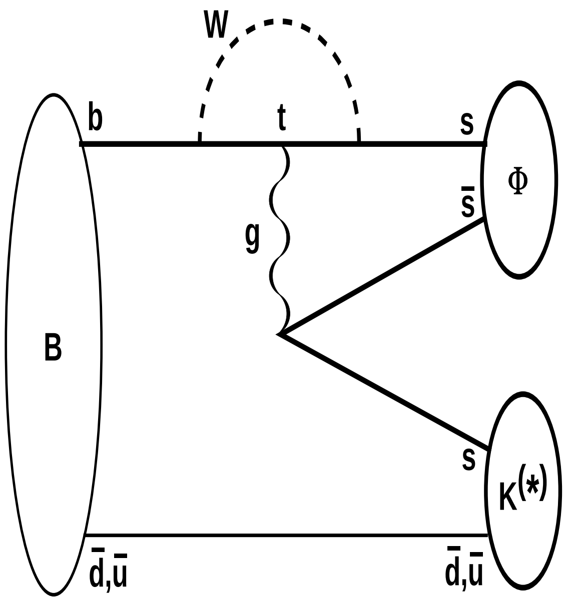
- **Published in Phys. Rev. Lett. 85, 515 (2000)**
- **hep-ex/0103040, CLNS 01/1718, submitted to PRL**

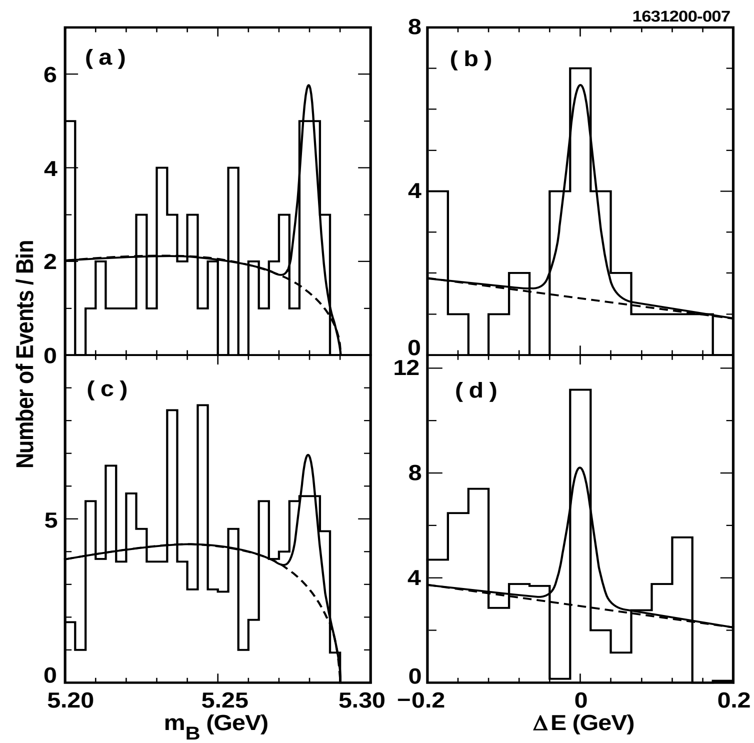
$B \to PV$ and VV Results

Decay Mode	$BR \times 10^6$	Theoretical Prediction $\times 10^6$
$\pi^\pm \rho^0$	$10.4^{+3.3}_{-3.4} \pm 2.1$	$0.4 - 13.0$
$\pi^\pm \rho^\mp$	$27.6^{+8.4}_{-7.4} \pm 4.2$	$12 - 93$
$\pi^0 \rho^0$	< 5.5	$0.0 - 2.5$
$K^\pm \rho^0$	< 17	$0.0 - 6.1$
$\pi^\pm K^{*0}$	< 16	$3.4 - 13.0$
$K^\pm K^{*0}$	< 5.3	$0.2 - 1.0$
$\rho^0 \rho^0$	< 4.6 (5.9)	$0.54 - 2.5$
$K^{*0} \rho^0$	< 13 (19)	$0.7 - 6.2$
$K^{*0} \bar{K}^{*0}$	< 8.7 (10)	$0.28 - 0.96$

- **Published in Phys. Rev. Lett. 85, 2881 (2000)**
- **hep-ex/0101029, CLNS 00/1705, submitted to PRL**

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





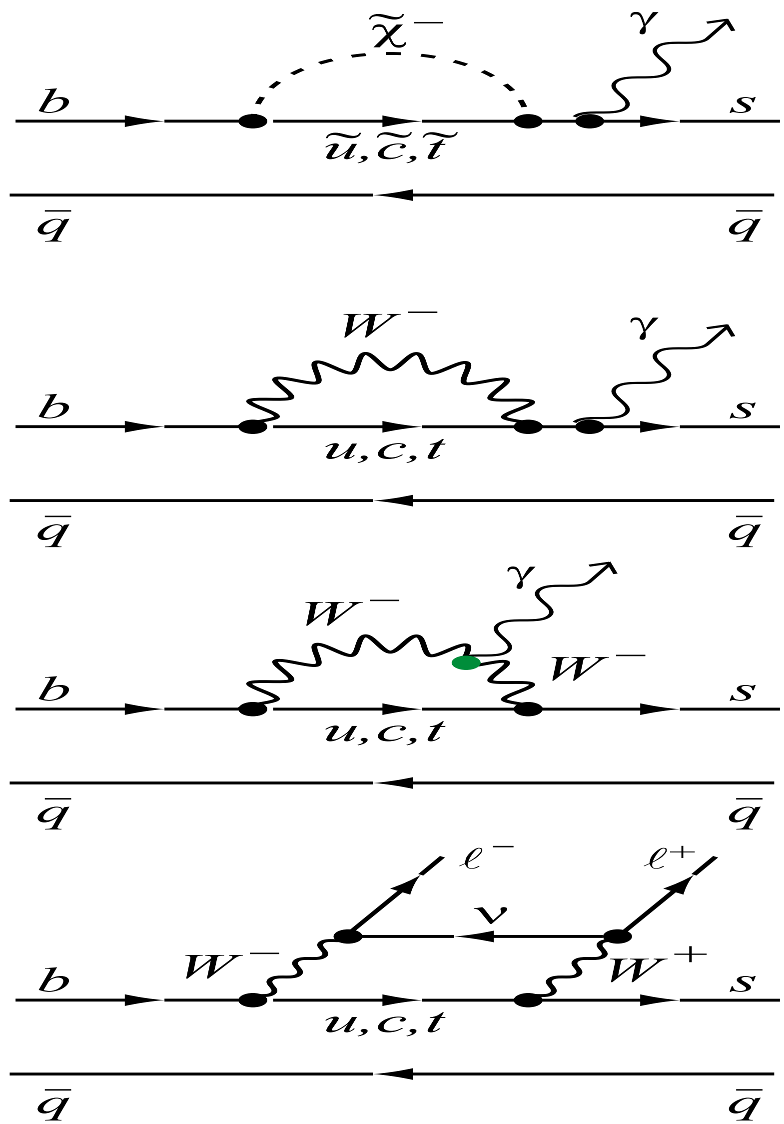
- **Clean signature for gluonic penguin**
- **Sensitive to $\mathbf{V}_{ts}$**

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

Mode	N_{sig}	Sig.	Efficiency	$BR \times 10^6$
$\phi K^{\pm}$	$14.2^{+5.5}_{-4.5}$	5.4σ	54%	$5.5^{+2.1}_{-1.8} \pm 0.6$
ϕK^0	$4.2^{+2.9}_{-2.1}$	2.9σ	48%	< 12.3 (90%C.L.)
ϕK Combined		6.1σ		$5.5^{+1.8}_{-1.5} \pm 0.7$
$\phi K^{*0}(K^-\pi^+)$	$12.1^{+5.3}_{-4.3}$	4.5σ	38%	$9.9^{+4.3}_{-3.5} \pm 1.6$
$\phi K^{*0}(K^0\pi^0)$	$5.1^{+3.9}_{-2.8}$	2.7σ	20%	$46.3^{+35.7+5.9}_{-26.0-6.6}$
ϕK^{*0} Combined		5.1σ		$11.5^{+4.5+1.8}_{-3.7-1.7}$
$\phi K^{*\pm}(K^{\pm}\pi^0)$	$3.8^{+4.1}_{-2.8}$	1.5σ	25%	$9.3^{+10.1+1.7}_{-7.0-1.5}$
$\phi K^{*\pm}(K^0\pi^{\pm})$	$4.0^{+3.1}_{-2.2}$	2.7σ	32%	$11.4^{+9.0}_{-6.3} \pm 1.8$
$\phi K^{*\pm}$ Combined		3.1σ		$10.6^{+6.4+1.8}_{-4.9-1.6}$
ϕK^* Combined		5.9σ		$11.2^{+3.6+1.8}_{-3.1-1.7}$

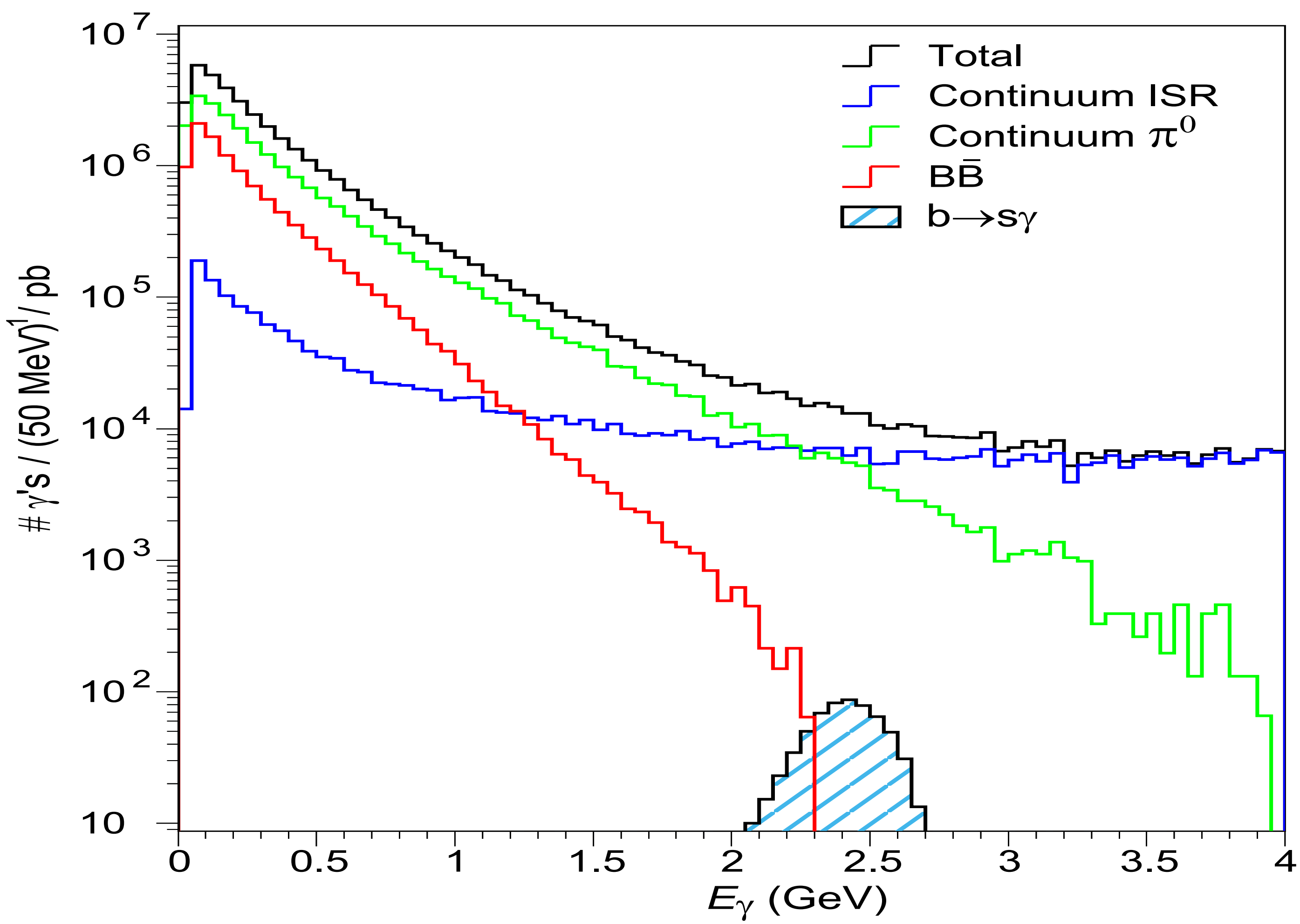
- **hep-ex/0101032, to be published by PRL**

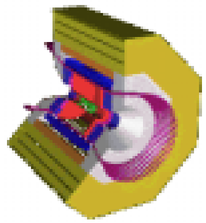
$b \to s\gamma$



- **EW penguin** $\mathbf{V}_{ts}^{*}\mathbf{V}_{tb}$
- **SM prediction:** $\mathcal{B}(b \to s\gamma) = \mathbf{(3.28 \pm 0.33) \times 10^{-4}}$
- **Sensitive to New Physics beyond SM**

Experimental challenge in measuring $b \to s\gamma$

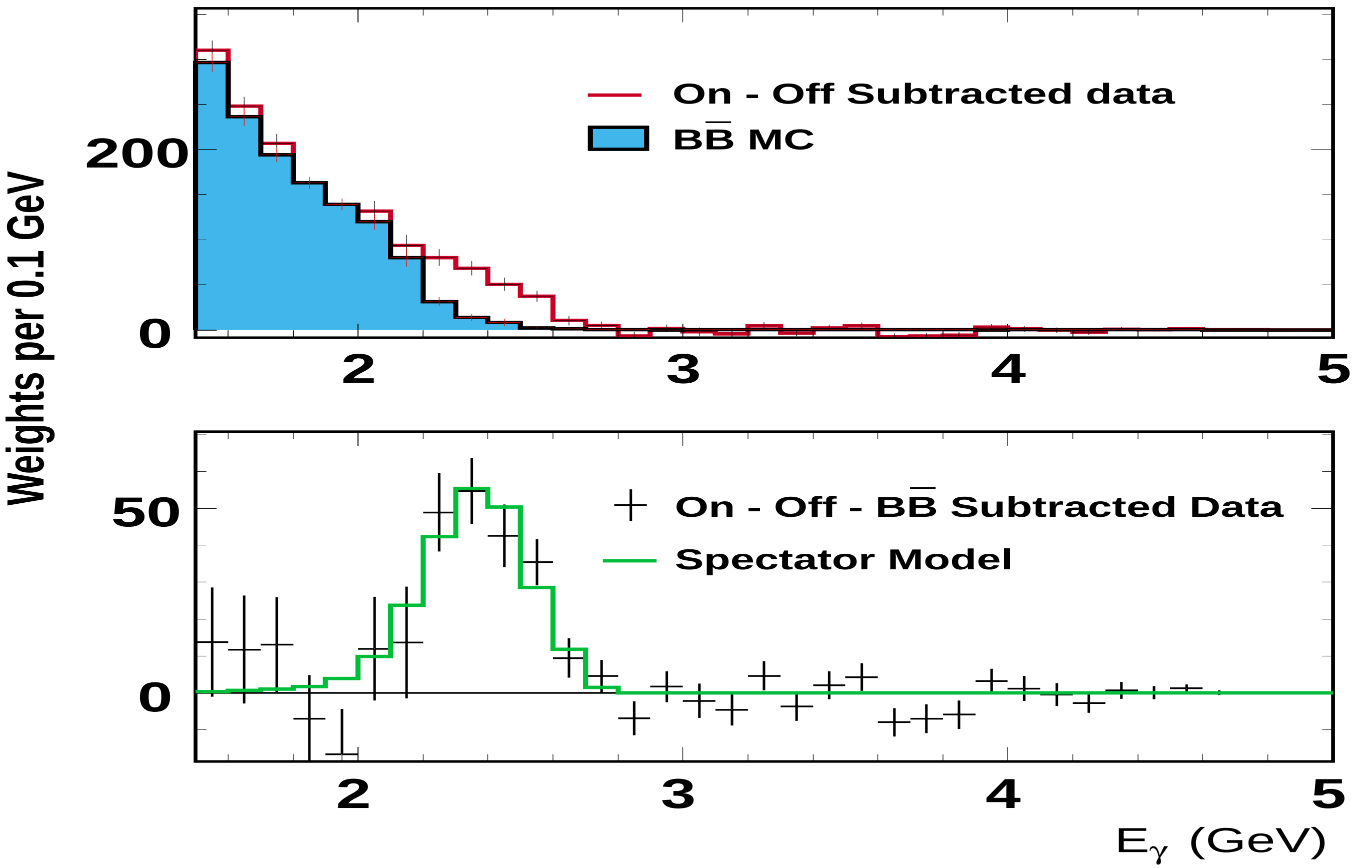




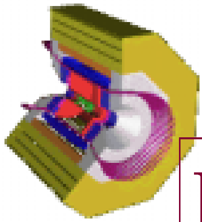
Analysis Strategy in measuring $b \to s\gamma$

- **Select photon candidate:** **2.0GeV < $\mathbf{E}_\gamma$ < 2.7GeV**
- **Suppression of Continuum background:**
  - **"pseudo reconstruction"**
  - **"lepton tag"**
  - **Event shape variables (neural net)**
- **Subtract backgrounds from π^0, η, and other B decays**

$b \to s\gamma$ Results



- $\mathcal{B}(b \to s\gamma) = (3.21 \pm 0.43\ ^{+0.32}_{-0.29}) \times 10^{-4}$
- **SM prediction:** $\mathcal{B}(b \to s\gamma) = (\mathbf{3.28} \pm \mathbf{0.33}) \times \mathbf{10}^{-4}$

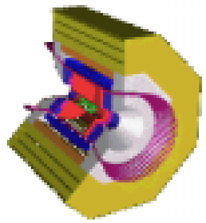


Exclusive FCNC Processes: $B \rightarrow l^+l^-K^{(*)}$

- **Suppressed in SM:** **BR $\sim$ (10^{-6} to 10^{-7})**
- **Sensitive to Physics beyond SM:** **SUSY etc**

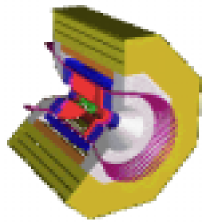
Strategy in Searching for FCNC Processes

- **Select Lepton candidates**
- **Select Kaon candidate from pion backgrounds**
- **Suppress Physics Backgrounds:**
  - $B \rightarrow J/\psi K^{(*)}$ **where** $J/\psi \rightarrow e^+e^-$ **or** $\mu^+\mu^-$
  - $B \rightarrow \psi(2S)K^{(*)}$ **where** $\psi(2S) \rightarrow e^+e^-$ **or** $\mu^+\mu^-$
- **Suppress Continuum and other B backgrounds:**
  - **Event Shape variable, Missing Energy, etc**



CLEO Exclusive FCNC Results

Decay Mode	Efficiency	Evts Obsved	BR UL (90% CL)
$B \to K^0 e^+ e^-$	**4.8%**	**1**	$<$ **8.5**$\times 10^{-6}$
$B \to K^0 \mu^+ \mu^-$	**3.3%**	**0**	$<$ **7.2**$\times 10^{-6}$
$B \to K^\pm e^+ e^-$	**15.6%**	**1**	$<$ **2.4**$\times 10^{-6}$
$B \to K^\pm \mu^+ \mu^-$	**8.4%**	**1**	$<$ **4.5**$\times 10^{-6}$
$B \to K l^+ l^-$	**32.2%**	**3**	$<$ **1.9**$\times 10^{-6}$
$B \to K^{*\pm}(K^0 \pi^\pm) e^+ e^-$	**2.0%**	**0**	$<$ **11.9**$\times 10^{-6}$
$B \to K^{*\pm}(K^0 \pi^\pm) \mu^+ \mu^-$	**1.2%**	**0**	$<$ **20.1**$\times 10^{-6}$
$B \to K^{*\pm}(K^\pm \pi^0) e^+ e^-$	**1.4%**	**3**	$<$ **46.4**$\times 10^{-6}$
$B \to K^{*\pm}(K^\pm \pi^0) \mu^+ \mu^-$	**0.7%**	**0**	$<$ **34.2**$\times 10^{-6}$
$B \to K^{*0}(K^\pm \pi^\mp) e^+ e^-$	**8.0%**	**1**	$<$ **4.8**$\times 10^{-6}$
$B \to K^{*0}(K^\pm \pi^\mp) \mu^+ \mu^-$	**3.9%**	**0**	$<$ **6.2**$\times 10^{-6}$
$B \to K^{*0}(K^0 \pi^0) e^+ e^-$	**0.6%**	**0**	$<$ **43.0**$\times 10^{-6}$
$B \to K^{*0}(K^0 \pi^0) \mu^+ \mu^-$	**0.2%**	**0**	$<$ **145.23**$\times 10^{-6}$
$B \to K^* l^+ l^-$	**18.0%**	**4**	$<$ **3.8**$\times 10^{-6}$



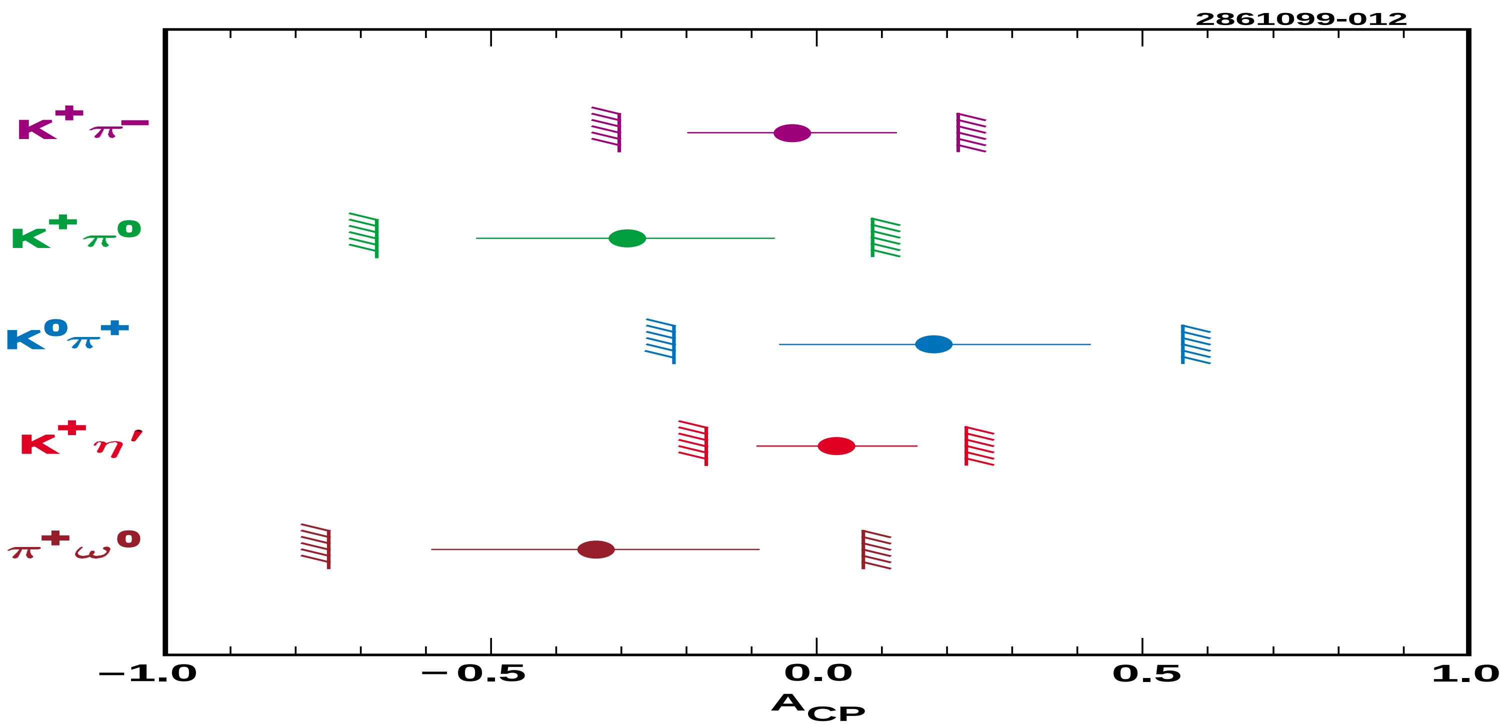
CP Asymmetries in $b \to s\gamma$

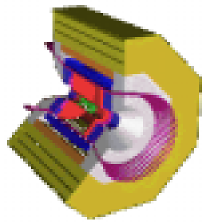
- **Measure the asymmetry:** $\mathcal{A}_{CP} \equiv \frac{\Gamma(b\to s\gamma)-\Gamma(\bar{b}\to\bar{s}\gamma)}{\Gamma(b\to s\gamma)+\Gamma(\bar{b}\to\bar{s}\gamma)}$
- **Standard Model Prediction:** $\mathcal{A}_{CP} < \mathbf{1.0\%}$
- **Non Standard Model Prediction:** $\mathcal{A}_{CP} \approx \mathbf{(10 - 40)\%}$
- **Analysis strategy:**
  - **2.2GeV < E$_\gamma$ < 2.7GeV**
  - **Flavor Tag by "pseudo reconstruction" and "lepton tag"**
  - **Mistake rates, On-off subtraction, particle detection biases**
- $\mathcal{A}_{CP} = \mathbf{(-0.079 \pm 0.108 \pm 0.022)(1.0 \pm 0.030)}$

$$-0.27 < \mathcal{A}_{CP} < +0.10 \quad \text{at } 90\% \text{ C.L.}$$

CP Asymmetries in other B Decays

- **Search for CP violation in self tagging decays**
- **Measure the asymmetry:** $\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B}\to\bar{f})-\mathcal{B}(B\to f)}{\mathcal{B}(\bar{B}\to\bar{f})+\mathcal{B}(B\to f)}$
- **Prediction:** $\mathcal{A}_{CP} \approx \pm\ 0.1\%$ **(Ali, Kramer, Lu, PRD 59, 014005 (1999))**

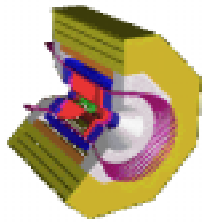




CP Asymmetries in other B Decays

Decay Mode	N_{sig}	$\mathcal{A}_{CP}$	Prediction
$B \to K^{\pm}\pi^{\mp}$	80^{+12}_{-11}	-0.04 ± 0.16	$(+0.037, +0.106)$
$B \to K^{\pm}\pi^{0}$	$42.1^{+10.9}_{-9.9}$	-0.29 ± 0.23	$(+0.026, +0.092)$
$B \to K^{0}_{s}\pi^{\pm}$	$25.2^{+6.4}_{-5.6}$	$+0.18 \pm 0.24$	$+0.015$
$B \to K^{\pm}\eta'$	100^{+13}_{-12}	$+0.03 \pm 0.12$	$(+0.020, +0.061)$
$B \to \omega\pi^{\pm}$	$28.5^{+8.2}_{-7.3}$	-0.34 ± 0.25	$(-0.120, +0.024)$
$B \to J/\psi K^{\pm}$	534	$+0.018 \pm 0.043$	< 0.04
$B \to \psi(2S)K^{\pm}$	120	$+0.020 \pm 0.092$	< 0.04

- **Published in Phys. Rev. Lett. 84, 5940 (2000)**
- **Published in Phys. Rev. Lett. 85, 525 (2000)**



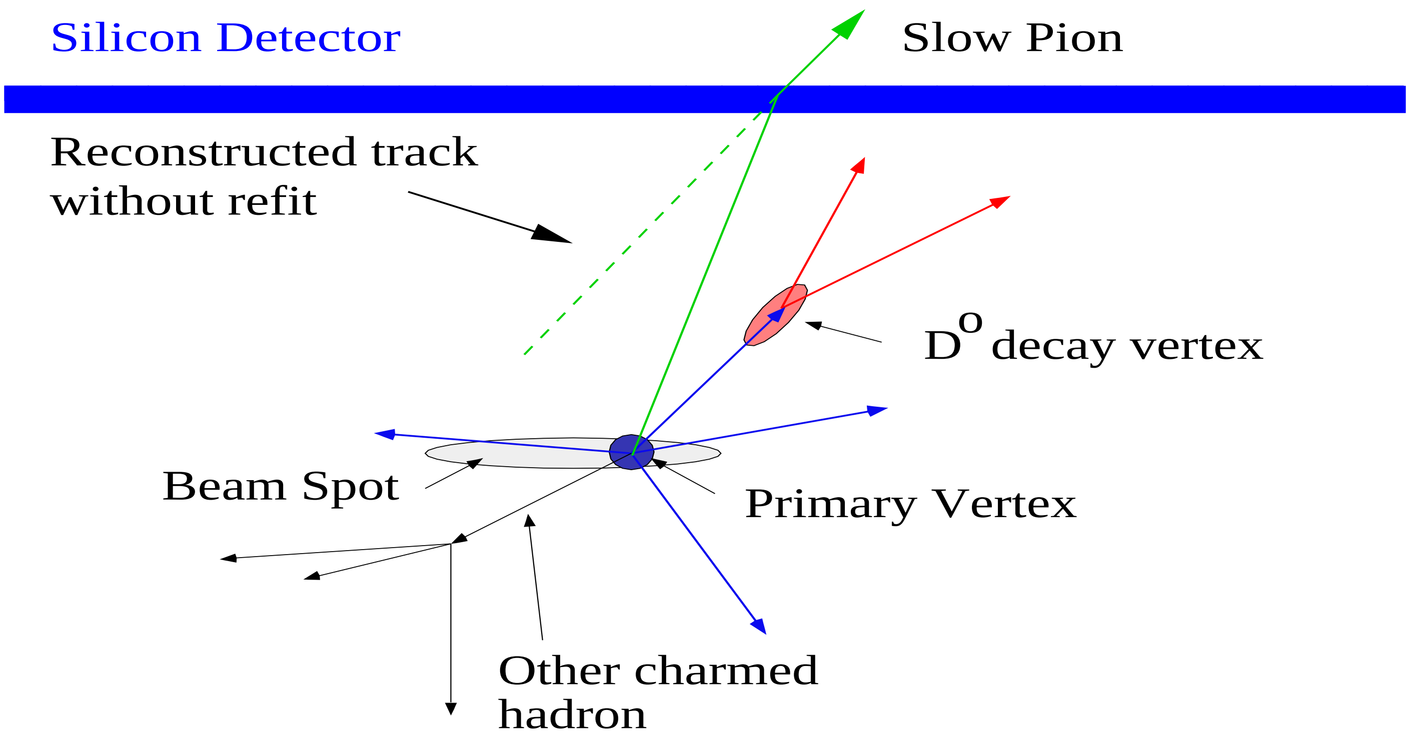
Search for CP Violation in D^0 Decay

Possible CP violation in Cabibbo Suppressed D^0 decays:

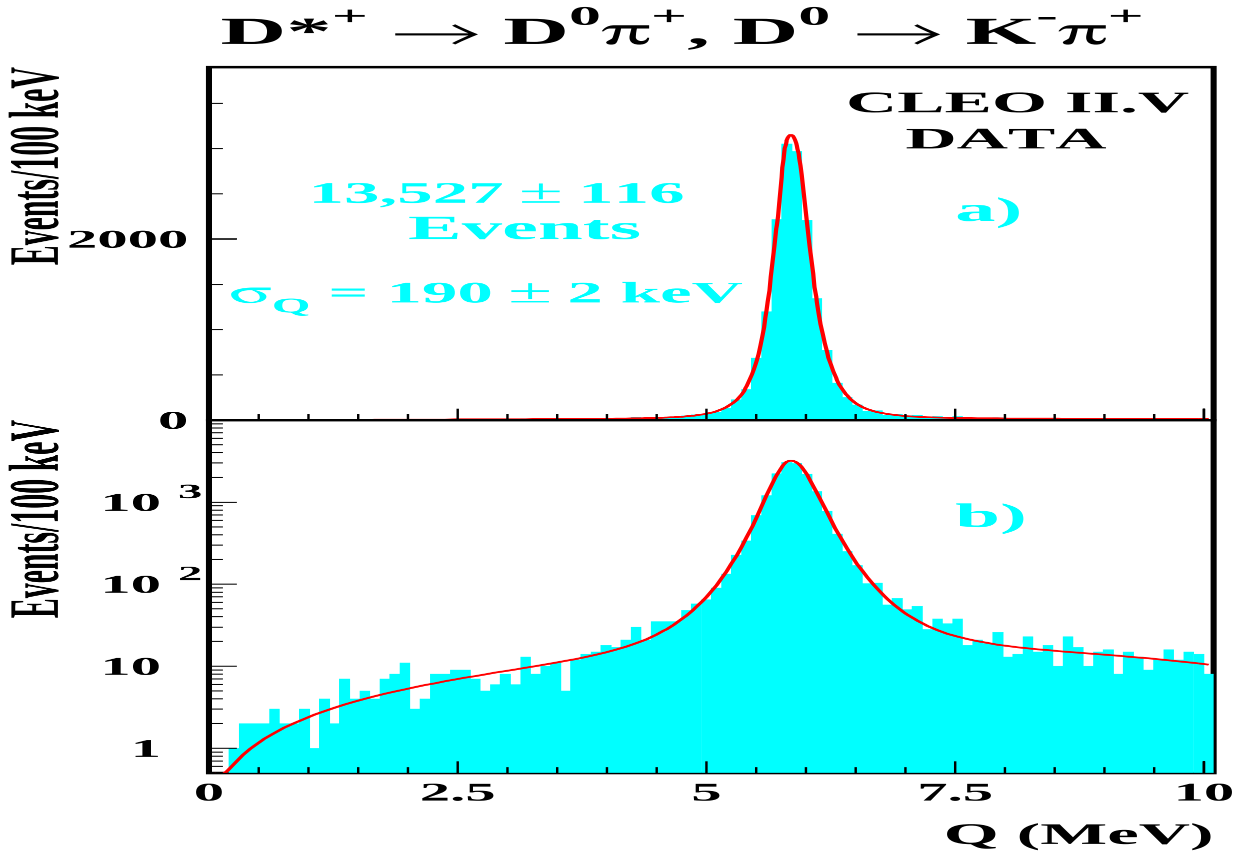
- **At least two paths (tree, exchange, penguin)**
- **Same final state with different CP-odd, CP-even phases**
- **Sensitive to New Physics:**
  - **Standard Model Expection:** $\mathcal{A}_{CP}$ $\mathcal{O}(0.1\%)$
  - **New Physics can enter in the loops**

Experimental Technique

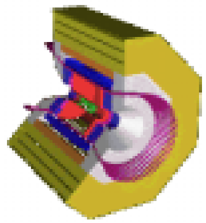
- **Decay chain:** $D^{*+} \to D^0 \pi_s^+$
- **Use SLOW π_s^+ to tag D^0 flavor at production**
- **Refit slow pion:** $Q \equiv M(D^0_{cand}\pi_S^+) - M(D^0_{cand}) - M_\pi$



Q resolution after refit



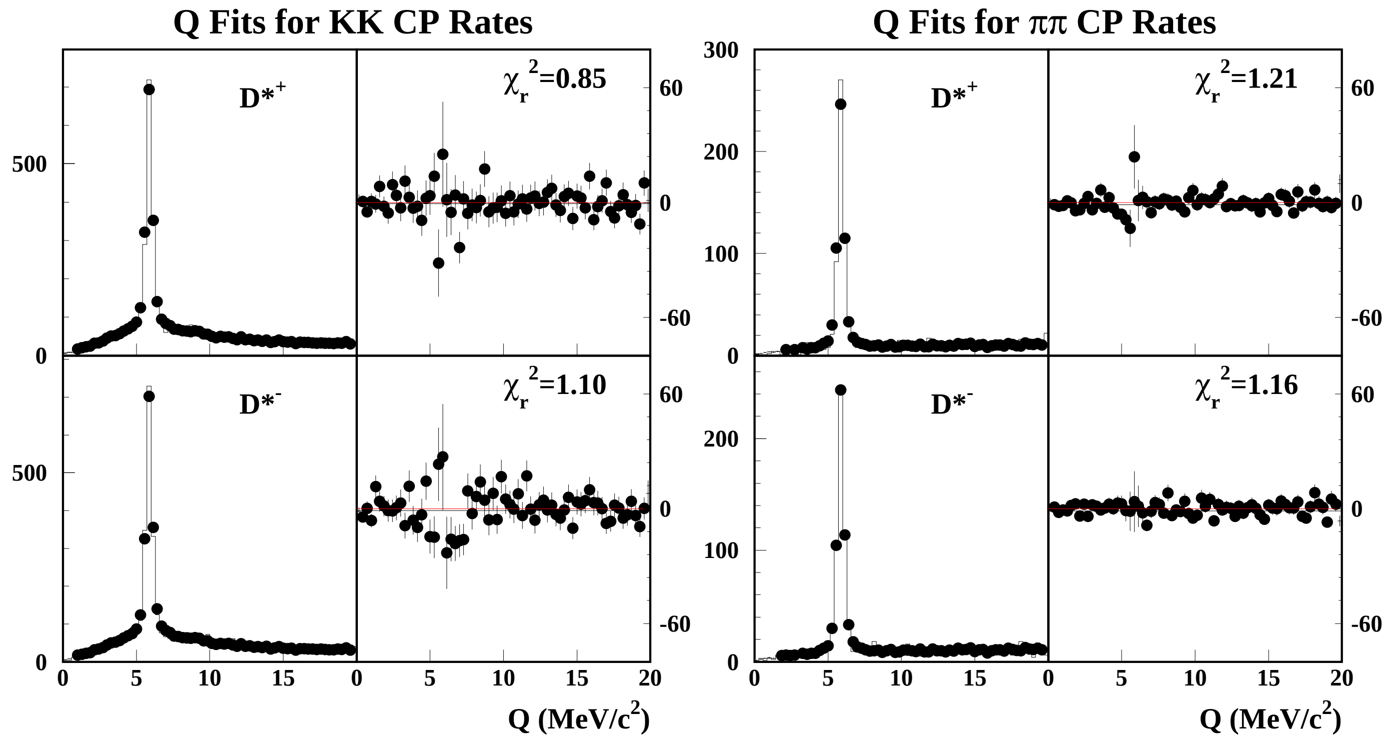
- **Same technique we measured** $\Gamma(D^{\star +}) = 96 \pm 4 \pm 22$ **MeV**



CP Violation in $D^0 \to K^+K^-, \pi^+\pi^-$

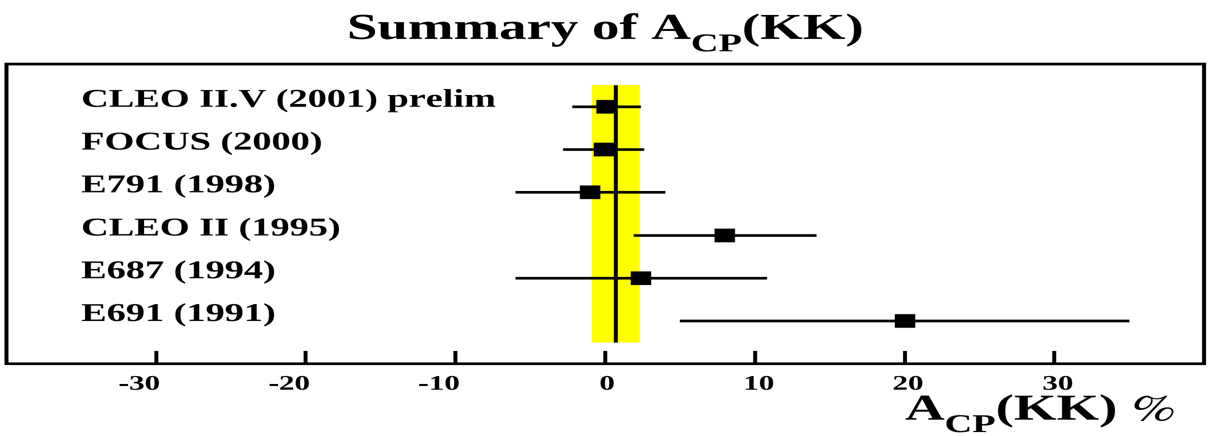
- **Select** $D^0 \to K^+K^-(\pi^+\pi^-)$
- **Use slow pion tag from** $D^{*+} \to D^0\pi_S^+$
- **Fit** Q **distribution to obtain yields**
- **Measure** CP **asymmetry** $A_{CP}(KK)$
- $A_{CP}(KK) = \frac{\Gamma(D^0\to K^+K^-)-\Gamma(\overline{D^0}\to K^+K^-)}{\Gamma(D^0\to K^+K^-)+\Gamma(\overline{D^0}\to K^+K^-)}$

CP Violation in $D^0 \to K^+K^-, \pi^+\pi^-$

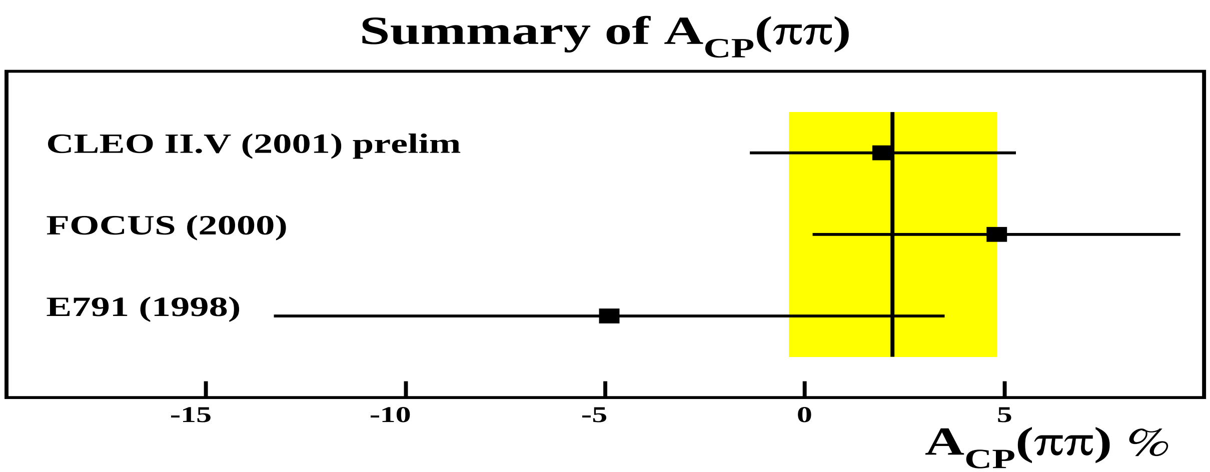


- 1512 ± 47 $D^0 \to K^+K^-$ **events** $\quad$ 579 ± 26 $D^0 \to \pi^+\pi^-$ **events**
- 1511 ± 47 $\overline{D^0} \to K^+K^-$ **events** $\quad$ 557 ± 26 $\overline{D^0} \to \pi^+\pi^-$ **events**

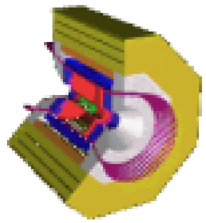
CP Violation in $D^0 \to K^+K^-, \pi^+\pi^-$



CLEO II.V $A_{CP}(K^+K^-) = (0.1 \pm 2.2 \pm 0.8)\%$



CLEO II.V $A_{CP}(\pi^+\pi^-) = (2.0 \pm 3.2 \pm 0.8)\%$



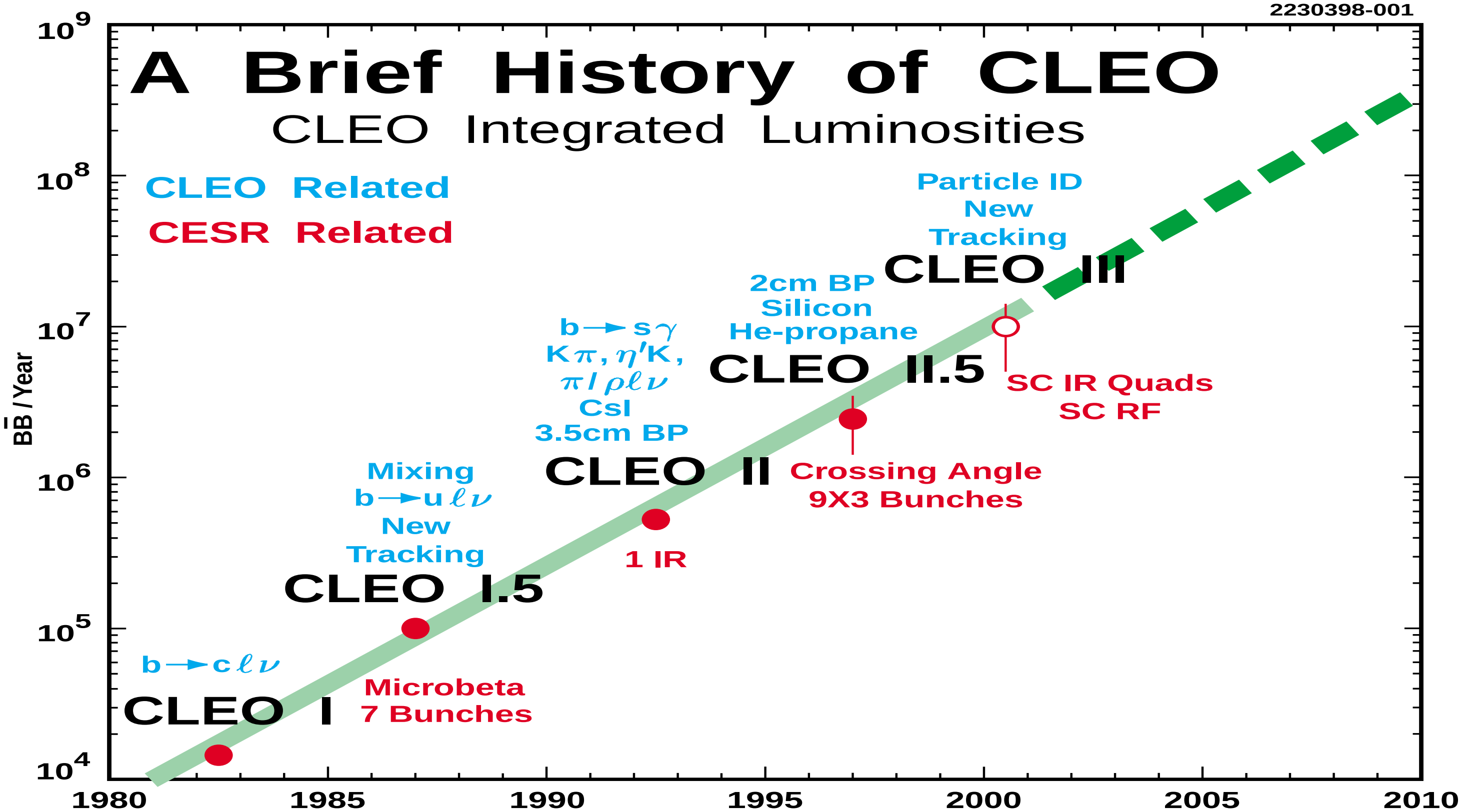
CLEO II + II.V data (13.5 fb^{-1})

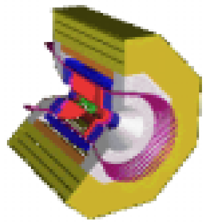
- **Rare B decays:** $B \to PP$, PV, VV, $\phi K^{(*)}$, $l^+l^-K^{(*)}$; $b \to s\gamma$
- CP **Violation in** B **and Charm Decays**
- **First Observation of** $B^0 \to D^{(*)0}\pi^0$ **and** $B \to D^*\pi\pi\pi\pi$
- **First Observation of** $B \to D^{(*)}K^{*-}$
- CP **Violation in Tau Decays**
- **Measurement of CKM Elements** V_{ub} **and** V_{cb}

CLEO III data (9.2 fb^{-1})

- **First preliminary physics results reported at LP01**

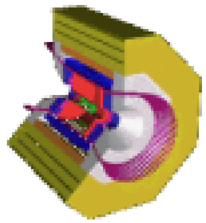
The past/present/future of CESR/CLEO





The CLEO-c Proposal

- **Modify CESR/CLEO for High Lumi. @ 3 – 4 GeV**
- **CLEO-c Workshop, Snowmass, Proposal to NSF**
- **Expected CESR performance:**
  - **Luminosity: (1 – 4) × 10^{32} cm^{-2}s^{-1}**
  - **Intergrated Luminosity: (1 – 4) fb^{-1}/year**
- **Expected data sample (start early 2003):**
  - 2×10^9 J/ψ/fb^{-1}, 10^7 ψ''/fb^{-1}, 5×10^5 $D_s\overline{D_s}$/fb^{-1}
- **Physics can be achieved:**
  - **Precision decay constants, absolute BR ......**
  - **Test of QCD (Glueball, Hybrids) ......**
  - **Mixing, CP violation in charm, τ decays ......**



Future Outlook of Experimental HEP

- **HEP experiments at e^+e^- Colliders:**
  - **B-factories: BABAR at PEP-II and BELLE at KEK-B**
  - **C-factories: CLEO-c at CESR etc**
- **HEP experiments at $p\overline{p}$ and pp Colliders:**
  - $p\overline{p}$**: CDF and D0 at Tevetron**
  - pp**: ATLAS and CMS at LHC**
- **Neutrino Experiments:**
  - **Super-K, Minos, SNO etc**