CLEO B Physics

David G. Cassel

Cornell University

CLEO B Physics

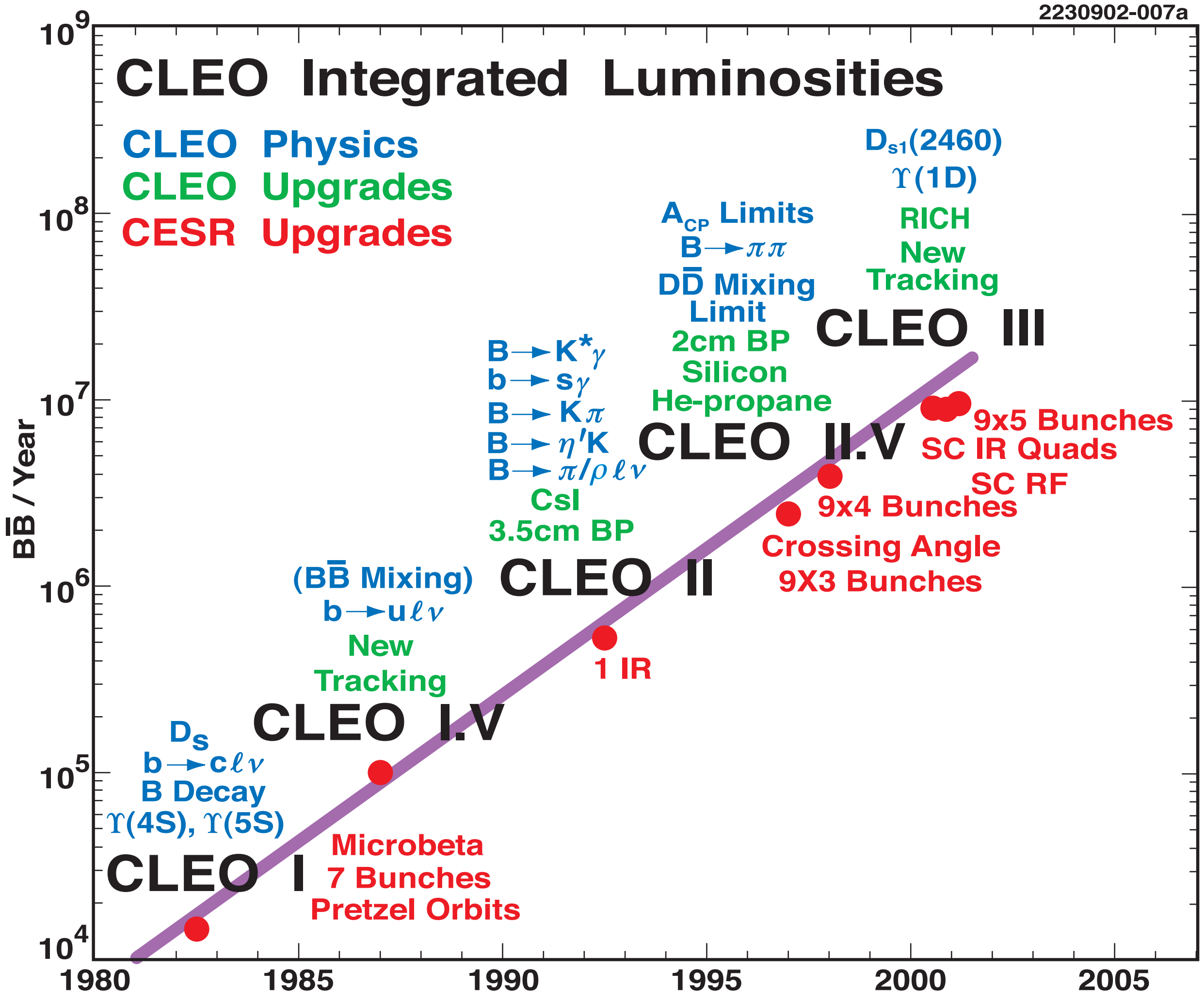
- Before $B^0\bar{B}^0$ Mixing
- Studying $B^0\bar{B}^0$ Mixing
- After $B^0\bar{B}^0$ Mixing
- Concluding Remarks

Emphasis is on

- insights
- turning points
- interactions with ARGUS, and
- measurements that are still competitive.

More information on the CLEO history is available in
A Personal History of CESR and CLEO, by Karl Berkelman
World Scientific (2004)
http://www.lns.cornell.edu/public/CLNS/2002/CLNS02-1784/history.pdf

CLEO History



Some CLEO-c Physics

First Observations:

$h_c(^1P_1)$

f_D

Confirmations:

$\eta_c(2S)$

$Y(4260)$

Precision Measurements:

f_{D_s}

M_{D^0}

Branching Fractions:

Absolute Hadronic: D^0, D^+, D_s

Semileptonic: D^0, D^+

CLEO Physics: Discovery or co-discovery

($B^0\bar{B}^0$ Mixing) Confirmation

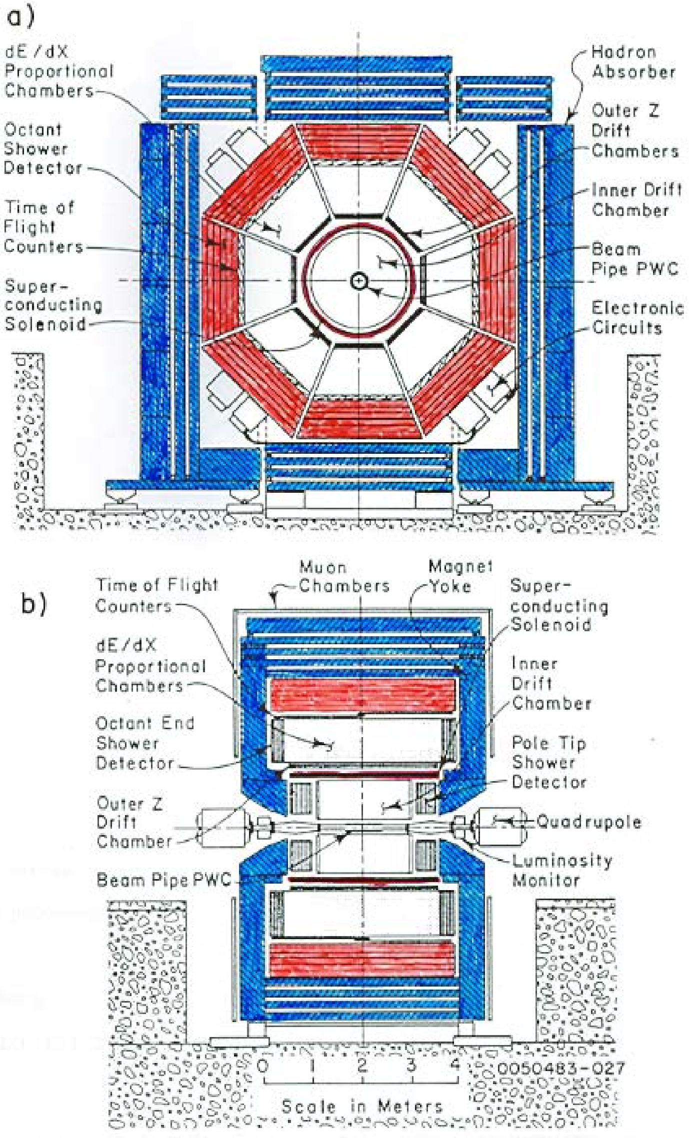
Also: Many other results on Υs, charm, τs, and QCD

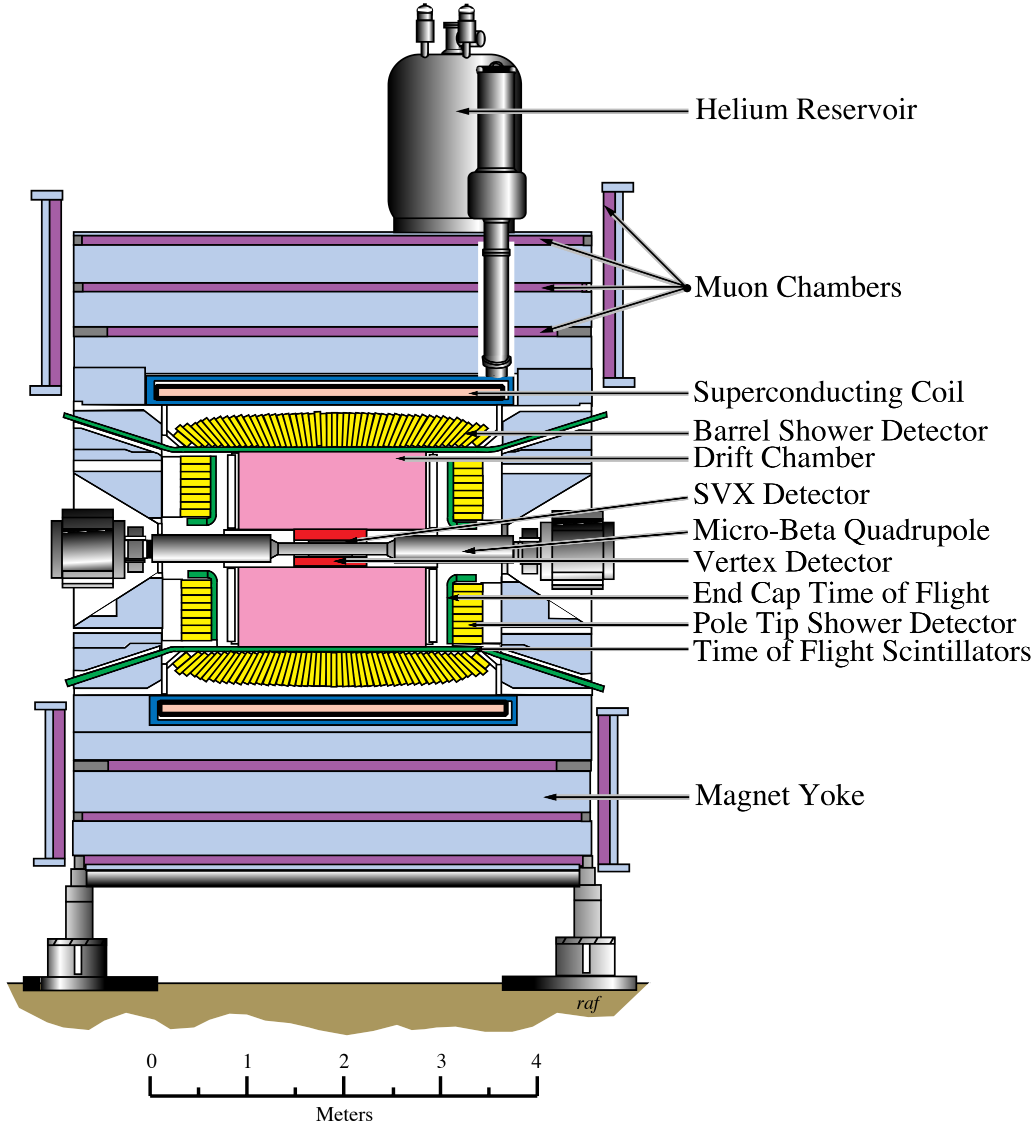
First observation of 2/3 of the charmed baryons

Some statistics:

- 455 refereed publications
- 211 CLEO Ph.D. theses
- 30 CESR Ph.D. theses

CLEO I and CLEO II.V Detectors

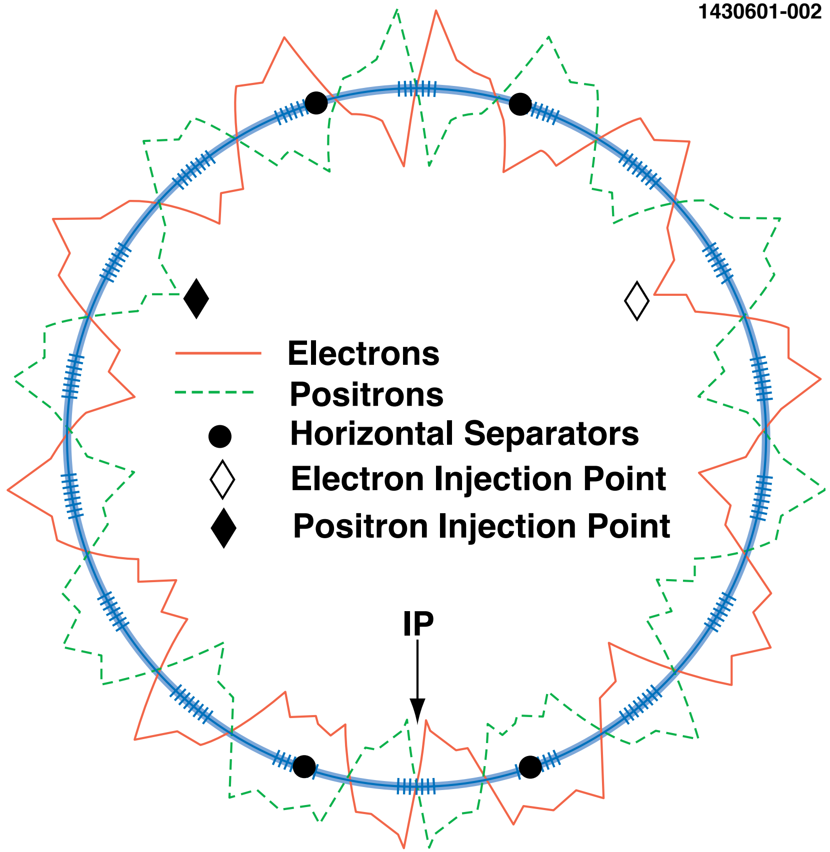




CLEO I & I.V 1979 – 1989

CLEO II and II.V 1989 – 1999

CESR



Two Cornell accelerator innovations

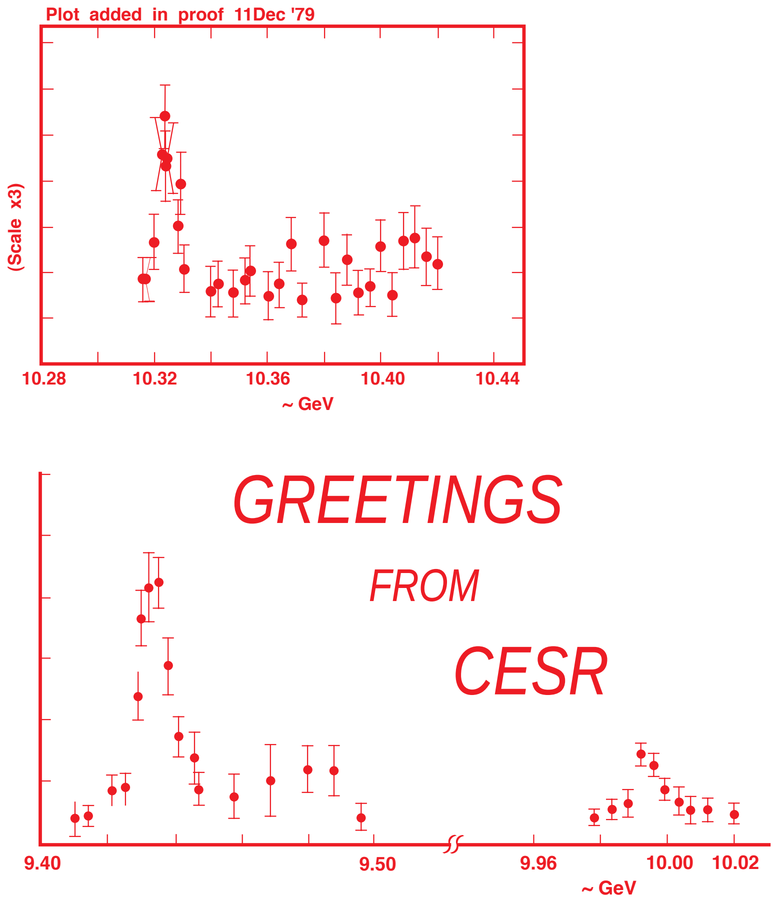
- Pretzel orbits Littauer 1985
- Bunch trains Meller 1990
- Utilized in LEP and LEPII

$\Upsilon(3S)$ and $\Upsilon(4S)$

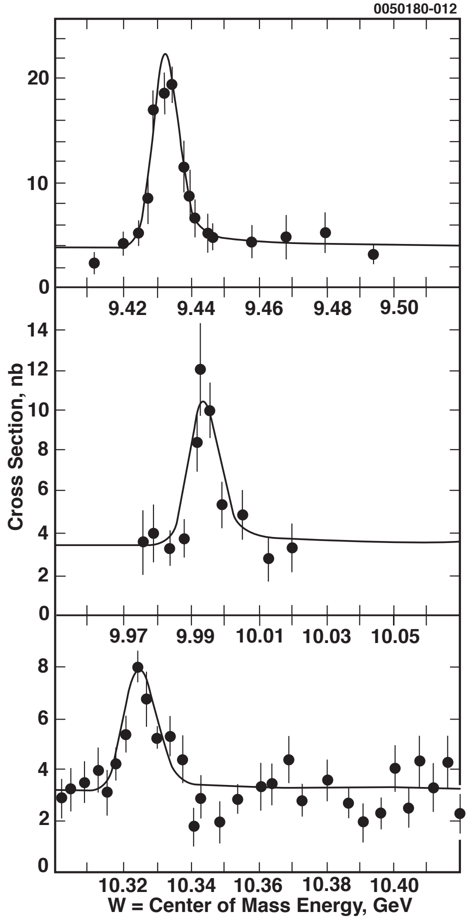
DESY contributed to observations of the Υ states by CLEO and CUSB

- DASP and LENA measured $M_{\Upsilon(2S)} - M_{\Upsilon(1S)}$ accurately
- Once we found the $\Upsilon(1S)$, finding the $\Upsilon(2S)$ was quick and easy
- The $\Upsilon(3S)$ and $\Upsilon(4S)$ required more time and effort

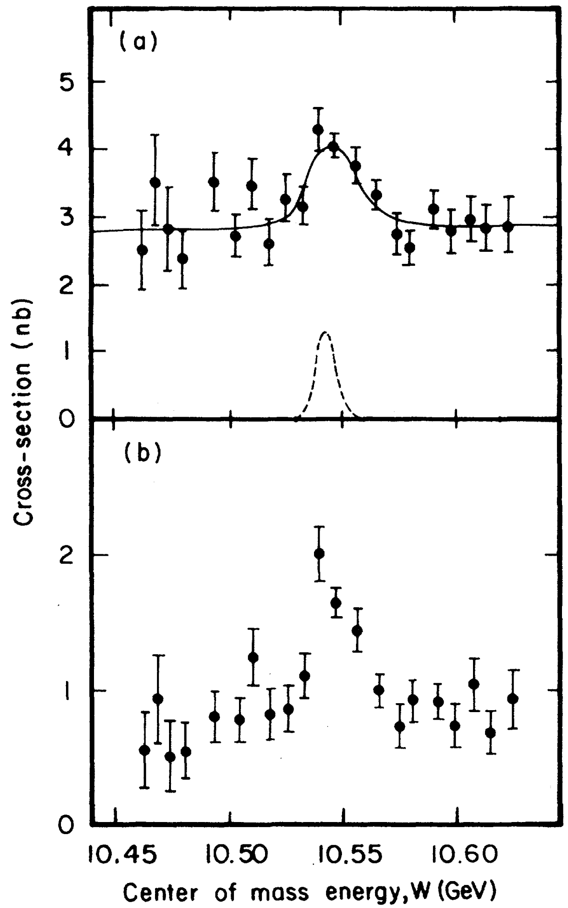
1979 Holiday Card



$\Upsilon(1S)$, $\Upsilon(2S)$ & $\Upsilon(3S)$

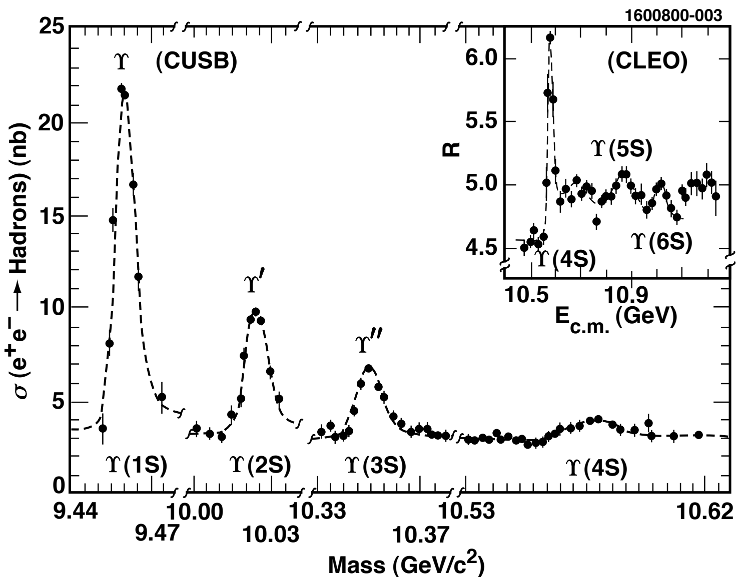


$\Upsilon(4S)$

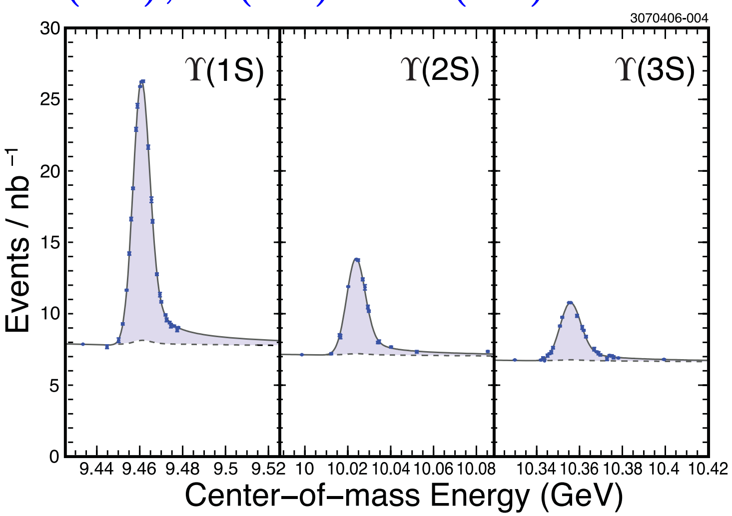


$\Upsilon(5S)$ and $\Upsilon(6S)$ and Evidence of B mesons

Observation of $\Upsilon(5S)$ and $\Upsilon(6S)$



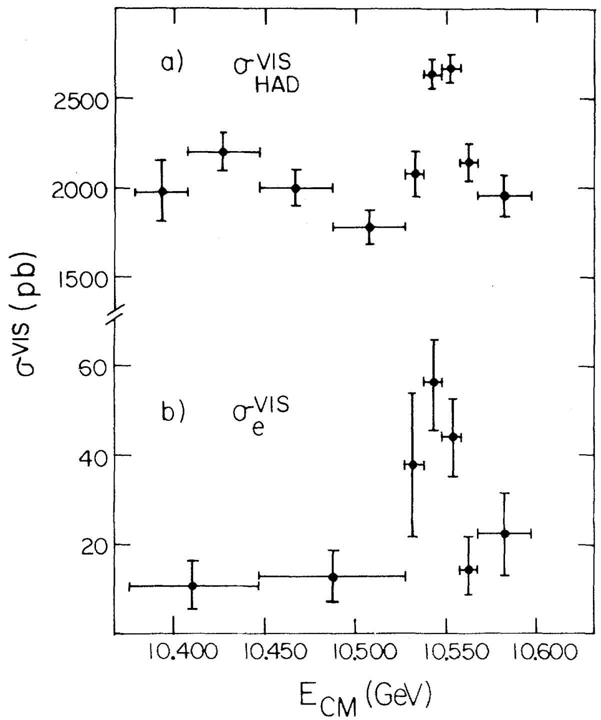
$\Upsilon(1S)$, $\Upsilon(2S)$ & $\Upsilon(3S)$ in 2006



Evidence of B Mesons

- Leptons come from weak decays (thresholds) and e^+e^- annihilation (smooth)
- A new flavor enhances lepton yields
- CLEO saw enhanced lepton yields at the $\Upsilon(4S)$
  - $\mathcal{B}(B \to X e \nu) = (13 \pm 3 \pm 3)\%$
  - $\mathcal{B}(B \to X \mu \nu) = (9.4 \pm 3.6)\%$

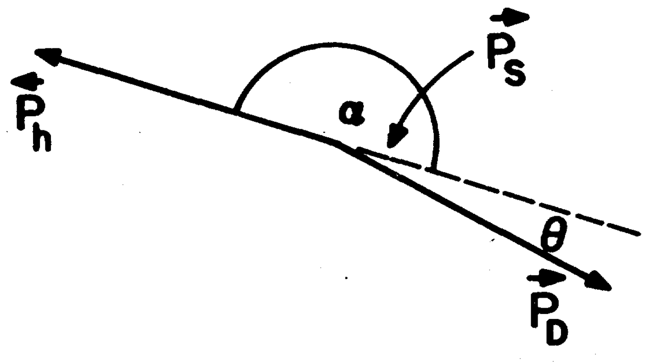
CLEO 1981



Exploring B Physics

The period 1981-1986 was an exciting time in B physics!

- Since nothing about B mesons was know, everything was new
- The the long ($\gtrsim$ 1 ps) lifetime of B mesons was the big surprise
  - Meant that $|V_{cb}|$ was small compared to $\sin(\theta_C)$
  - Led to the Wolfenstein Parameterization of the CKM matrix
- Many B decay modes were discovered and branching fractions were measured
  - PDG 2007 lists 347 B^0 and 300 B^+ modes and submodes (including upper limits)
  - Hard to pick out any one hadronic mode as particularly significant
- In 1984 CLEO used partial reconstruction of D^{*+} to measure $\bar{B}^0 \to D^{*+}\pi^-$
  - Variations on and improvements on the theme are still used in B physics



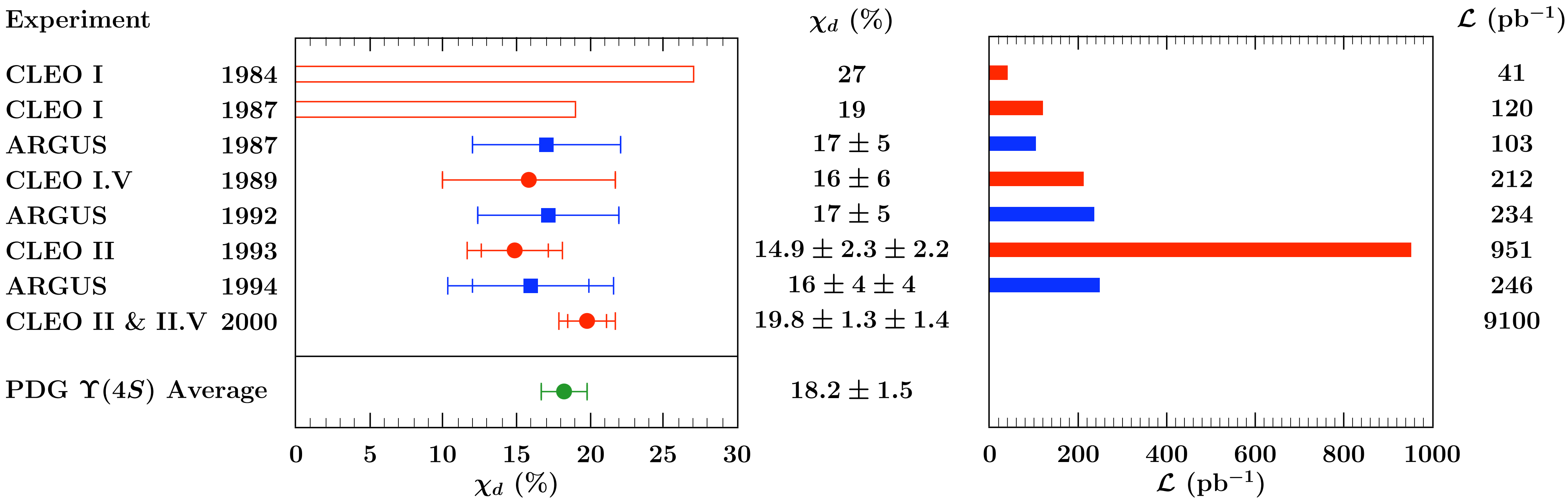
Partially reconstruct $\bar{B}^0 \to D^{*+}\pi^-$ using:

- p_h of the π^-
- p_s of the π^+ from $D^{*+} \to D^0\pi^+$
- Don't need to measure p_D by reconstructing the D^0
  - Small branching fractions for D^0 to few hadrons

CLEO and $B^0\bar{B}^0$ Mixing

ARGUS's discovery of $B^0\bar{B}^0$ mixing came as a surprise to CLEO

- Large $B^0\bar{B}^0$ mixing opened the door to observation of CP violation in B decay.
  - CP violation is the principal *raison d'être* for the high interest in B physics
- CLEO published two upper limits before the ARGUS discovery
- CLEO had slightly more luminosity than ARGUS at that time, but the ARGUS (next generation) detector was much better suited for the measurement
- CLEO required two more years and a new detector to confirm ARGUS.



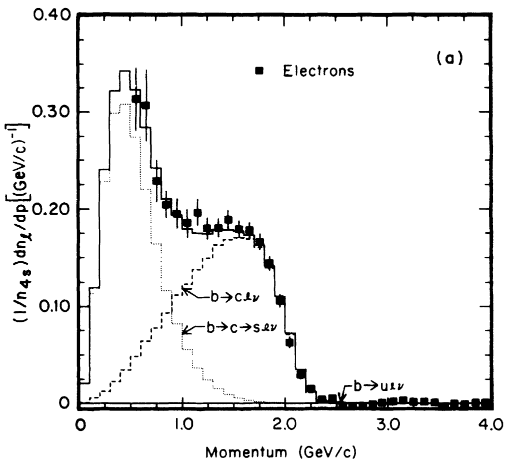
- χ_b values from HFAG reevaluation
- δm_d from these measurements superseded by others, particularly BaBar and Belle

Measuring $|V_{cb}|$ with Inclusive $B \to X_c \ell \nu$ Decay

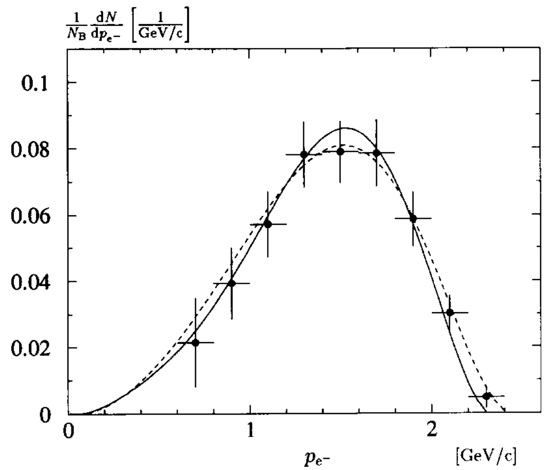
Large background from $D \to X_s \ell \nu$ decays below $p_\ell = 1.2$ GeV$/c$

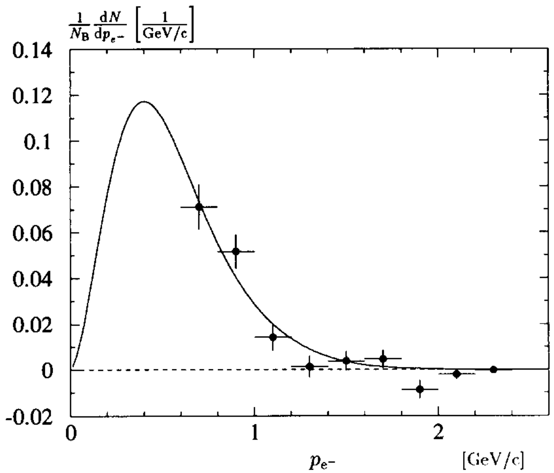
- Model dependent $|V_{cb}|$ from models required to extrapolate to $p_\ell = 0$ GeV$/c$
- ARGUS technique: Tag B events with high p_ℓ leptons and charge correlations
  - Tagging B's down to $p_\ell = 0.6$ GeV$/c$ essentially eliminates model dependence.

CLEO No Tag (1992)

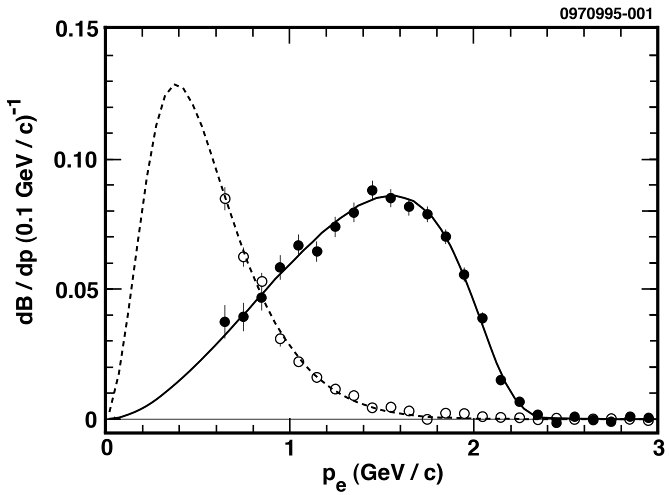


ARGUS Tag (1994)





CLEO Tag (1996)

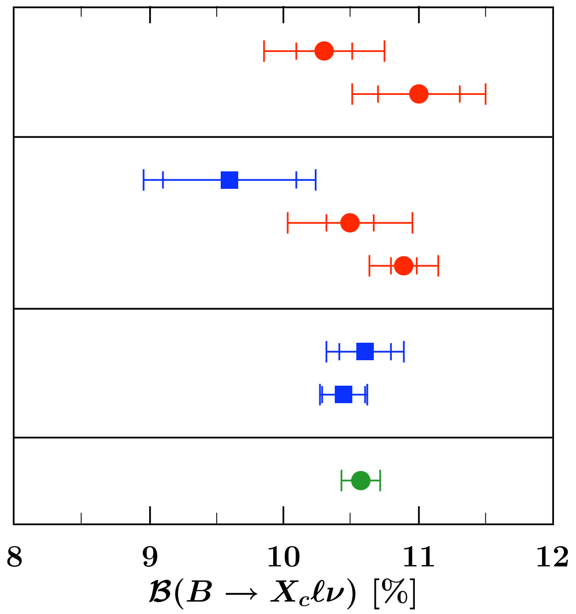


This paper included a measurement tagged with high momentum leptons.

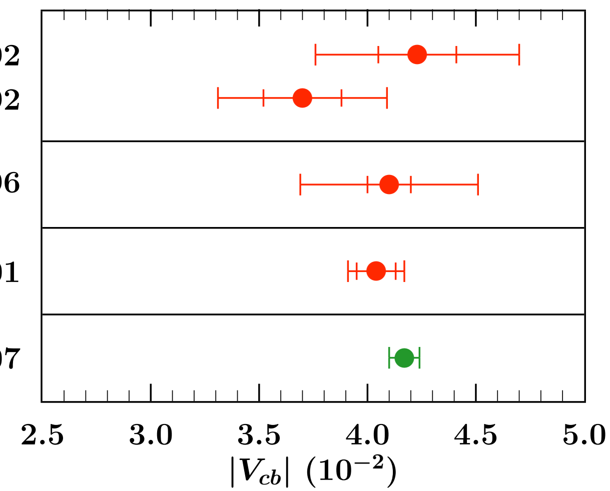
Did not attempt to decrease the minimum momentum for B decays.

Measuring $|V_{cb}|$ with Inclusive $B \to X_c \ell \nu$ Decay

Experiment	Model		$\mathcal{B}(B \to X_c \ell \nu)$ [%]
CLEO I.V	ACCMM	1992	$10.3 \pm 0.2 \pm 0.4$
CLEO II	ISGW**	1992	$11.0 \pm 0.3 \pm 0.4$
ARGUS	Tagged	1993	$9.6 \pm 0.5 \pm 0.4$
CLEO II	Tagged	1996	$10.49 \pm 0.17 \pm 0.43$
CLEO II & II.V	Tagged	2004	$10.90 \pm 0.09 \pm 0.24$
BaBar		2004	$10.61 \pm 0.19 \pm 0.22$
Belle		2006	$10.44 \pm 0.16 \pm 0.06$
PDG Average 2007			10.57 ± 0.15



Experiment	Method		$\lvert V_{cb} \rvert$ (10^{-2})
CLEO I.V	ACCMM	1992	$4.2 \pm 0.2 \pm 0.4$
CLEO II	ISGW**	1992	$3.7 \pm 0.2 \pm 0.4$
CLEO II	Tagged	1996	$4.1 \pm 0.1 \pm 0.4$
CLEO II & II.V	Moments	2001	$4.04 \pm 0.09 \pm 0.09$
PDG		2007	4.17 ± 0.07

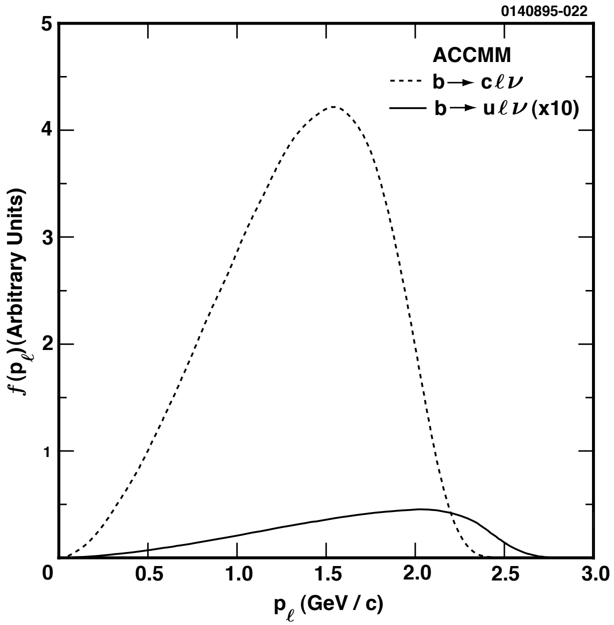


Measuring $|V_{ub}|$ with Inclusive $B \to X_u \ell \nu$ Decay

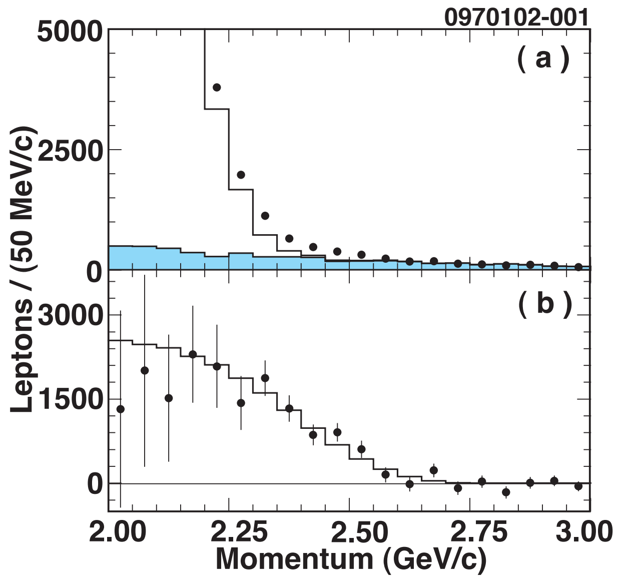
Measuring $B \to X_u \ell \nu$ is even more challenging

- Only a very narrow window in p_ℓ is useful
- Measurable branching fraction is very small $\mathcal{O}(10^{-4})$
- Background from $B \to X_c \ell \nu$ decays is large
- CLEO and ARGUS both reported $B \to X_u \ell \nu$ signals in 1990
- ARGUS fully reconstructed two events with $B \to X_u \ell \nu$ decays

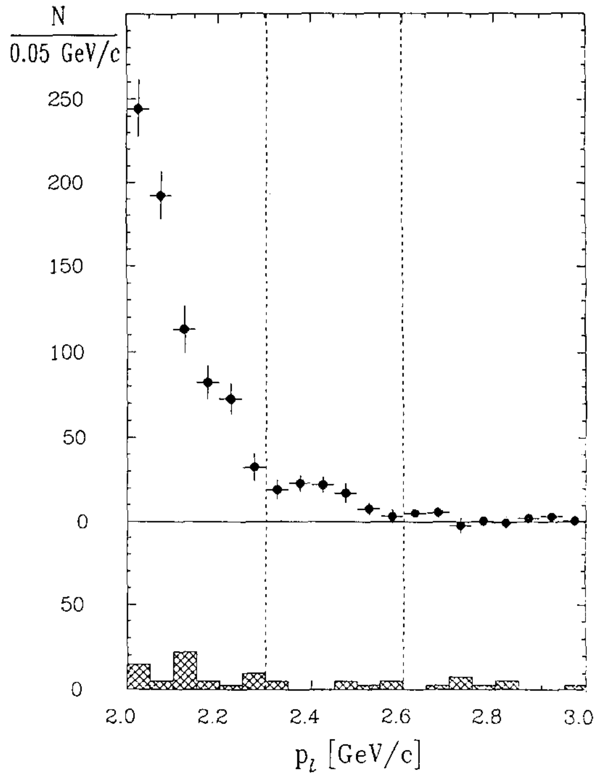
ACCMM Model



CLEO (2002)



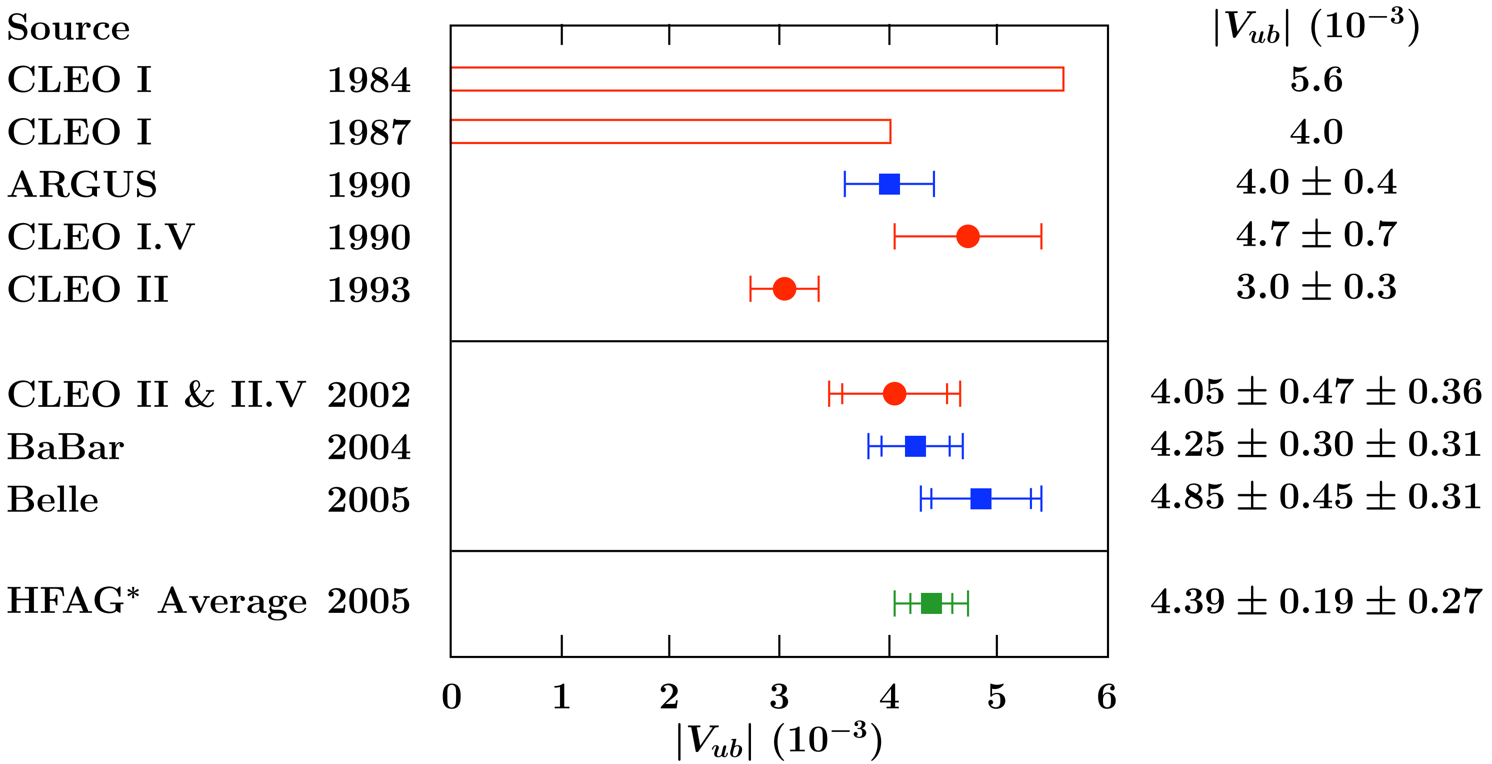
ARGUS (1991)



Measuring $|V_{ub}|$ with Inclusive $B \to X_u \ell \nu$ Decay

Model dependence for $|V_{ub}|$ is much more serious than it is for $|V_{cb}|$

- ACCMM model used for
  CLEO 1984 to CLEO 1993
- CLEO 2000, Babar, and Belle use more recent and rigorous theoretical techniques

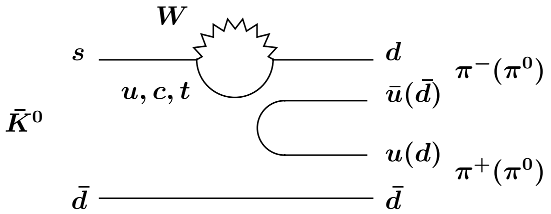


* HFAG Average includes BaBar and Belle measurements using other techniques

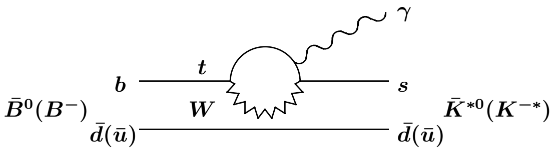
- $|V_{ub}|$ values from HFAG 2007

Discovery of Radiative Penguin Diagrams

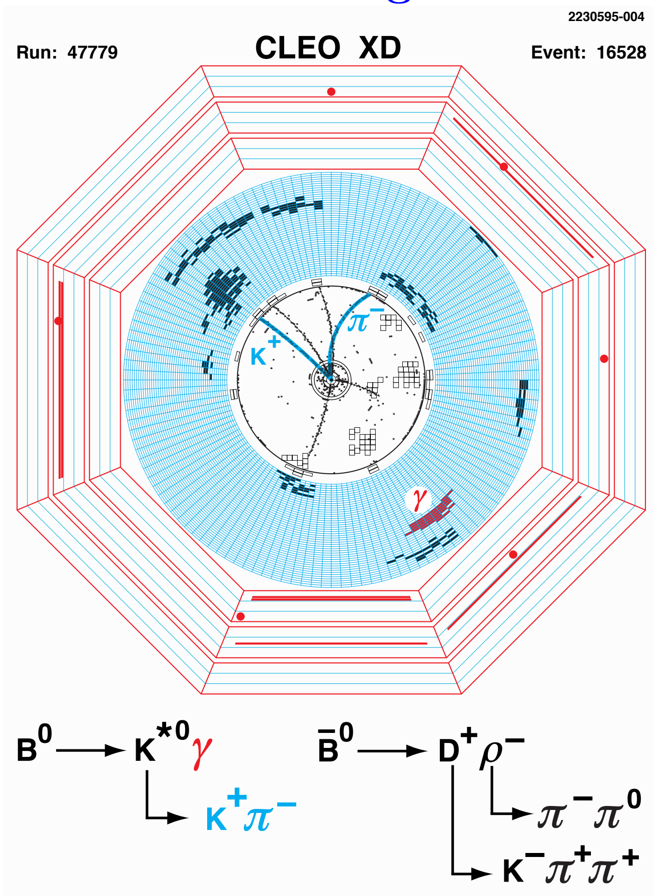
Penguin diagrams were proposed to explain the $\Delta I = \frac{1}{2}$ rule in K decay.



No hard experimental evidence for penguin diagrams for nearly 20 years, until CLEO observed $B \to K^*\gamma$ decays.

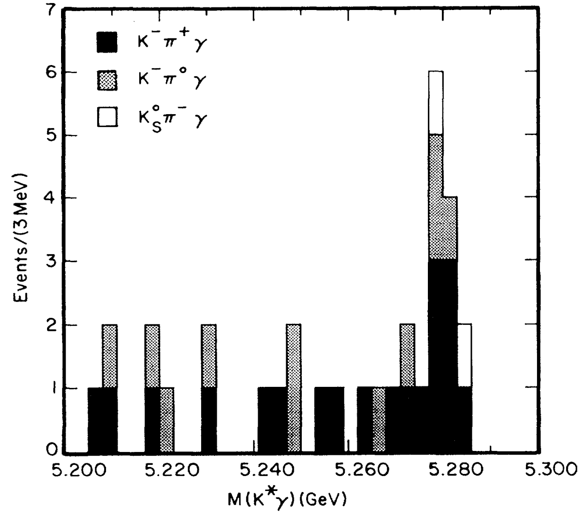


Radiative Penguin Event

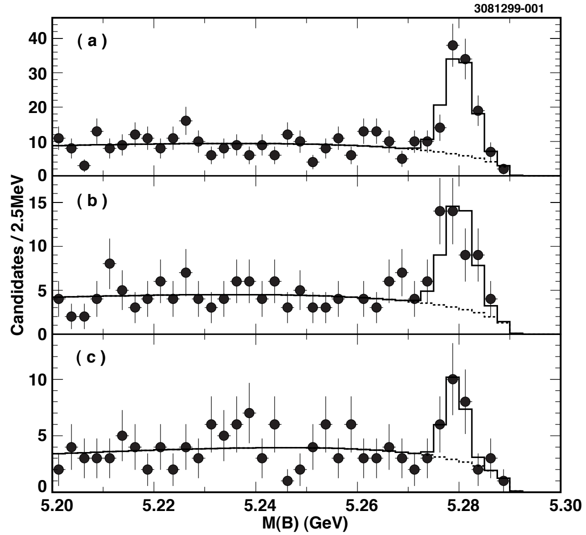


K^* Candidate Masses

CLEO 1993

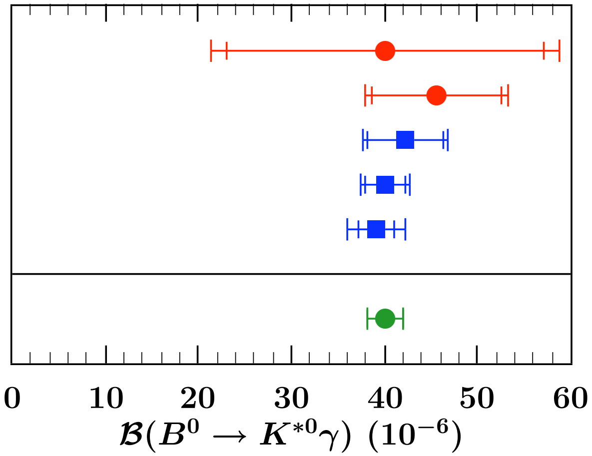


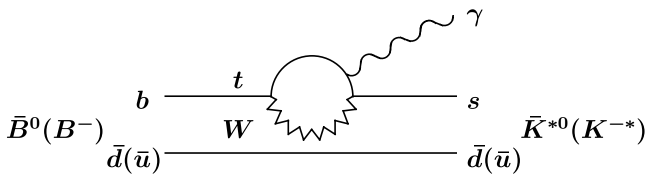
CLEO 2000



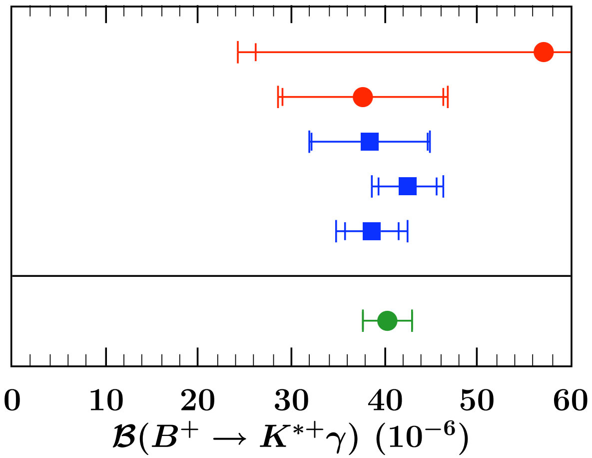
$\mathcal{B}(B^0 \to K^{*0}(890)\gamma)$

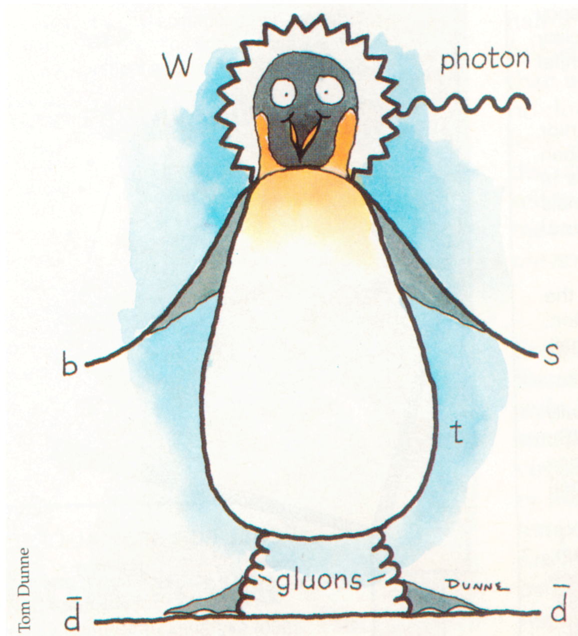
Experiment		$\mathcal{B}(B^0 \to K^{*0}\gamma)$ (10^{-6})
CLEO II	1993	$40 \pm 17 \pm 8$
CLEO II & II.V	2000	$45.5 \pm 7.0 \pm 3.4$
BaBar	2002	$42.3 \pm 4.0 \pm 2.2$
Belle	2004	$40.1 \pm 2.1 \pm 1.7$
BaBar	2005	$39.2 \pm 2.0 \pm 2.4$
PDG Average		40.1 ± 2.0



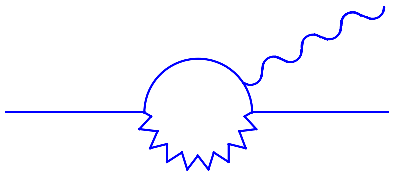


Experiment		$\mathcal{B}(B^+ \to K^{*+}\gamma)$ (10^{-6})
CLEO II	1993	$57 \pm 31 \pm 11$
CLEO II & II.V	2000	$37.6 \pm 8.6 \pm 2.8$
BaBar	2002	$38.3 \pm 6.2 \pm 2.2$
Belle	2004	$42.5 \pm 3.1 \pm 2.4$
BaBar	2005	$38.7 \pm 2.8 \pm 2.6$
PDG Average		40.3 ± 2.6



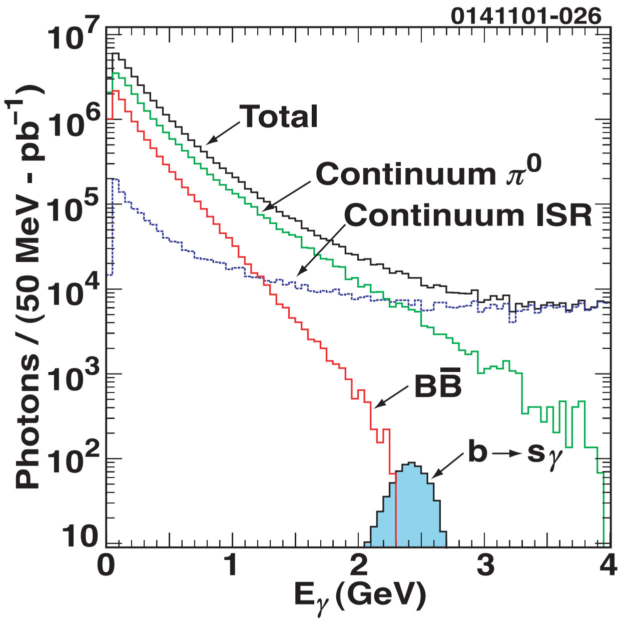


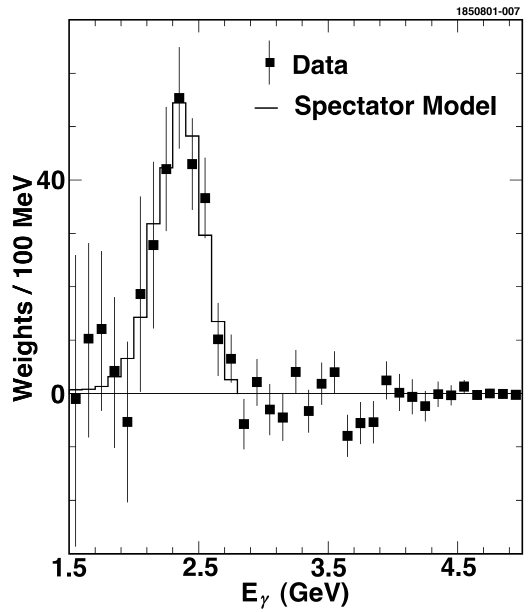
$\mathcal{B}(\bar{B} \to X_s\gamma)$

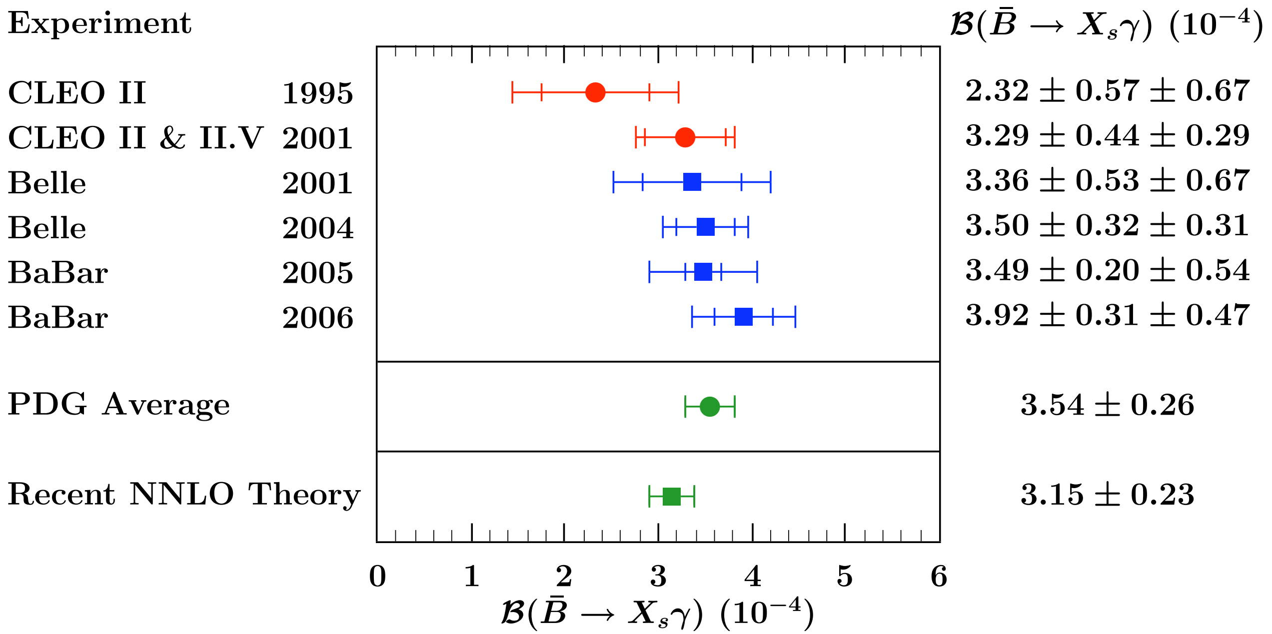


Inclusive $\mathcal{B}(\bar{B} \to X_s\gamma)$ is much more important than $\mathcal{B}(B^0 \to K^*(890)\gamma)$

- SM rate can be calculated
- Rate sensitive to Higgs and Beyond SM effects in the loop







Concluding Remarks

Congratulations to ARGUS for discovering $B^0\bar{B}^0$ Mixing!

Some personal thoughts about ARGUS, CLEO, and my experience in CLEO.

- $B^0\bar{B}^0$ mixing and the promise of CP violation were crucial for mustering the community and agency support necessary for the last 20 years of the CLEO program!
- Competition between ARGUS and CLEO was very healthy for both collaborations.
  - It kept us all on our toes and we learned from each other.
- Discovering something
  - Converging upper limits may indicate that a discovery is near.
- Developing a new field
  - Even experienced physicists have a lot to learn.
  - Understanding how to study a new field takes time and creative effort.
- Sustaining an experiment requires detector and luminosity upgrades
- Heavy quark physics with CLEO
  - It was (and still is) a wonderful experience!
  - Now it's time for CLEO members to finish CLEO-c and move on.

Thanks to ARGUS and DESY for including CLEO in this ARGUS Symposium!