New $|V_{ub}|$ results from CLEO

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For the CLEO Collaboration

Joint Experimental-Theoretical Physics Seminar
(Wine and Cheese Seminar)
Fermi National Accelerator Laboratory
Batavia, IL, USA
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Outline

- What is $|V_{ub}|$?
- Ways to attack it
- Making B-meson pairs nearly at rest
- CLEO: the collaboration; the detector
- Exclusive approach to $|V_{ub}|$
- Neutrino reconstruction
- Measuring branching fractions
- Determining $|V_{ub}|$
- Worldwide status: a snapshot
- Future
- Concluding remarks

What is $|V_{ub}|$?

Charged-Current Weak Interaction Lagrangian

$$L_W = -\frac{g}{2\sqrt{2}} V_{ij} \bar{u}_i \gamma^\mu W_\mu^+ (1-\gamma^5) d_j + \text{h.c.}$$

Cabibbo-Kobayashi-Maskawa (CKM) Quark-Mixing Matrix

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

b-to-u Flavour Change

$|V_{ub}|$: A fundamental parameter of Nature ⇒ Interesting!

$|V_{ub}|$ and the CKM Quark-Mixing Matrix

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \boxed{A\lambda^3(\rho - i\eta)} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

(Lincoln Wolfenstein)

Standard Model:

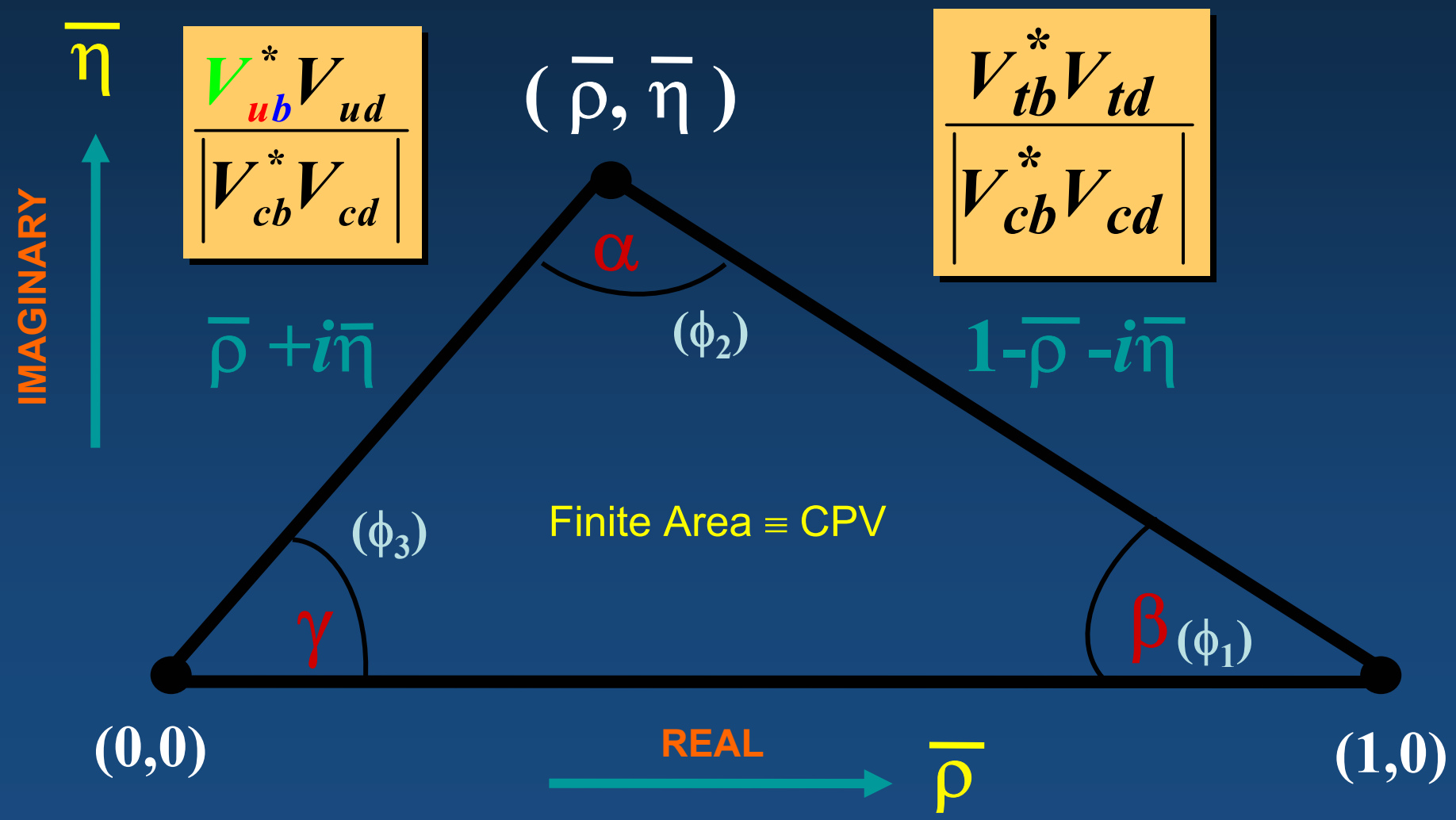
- 3 quark generations
- Charge-Parity (CP) violation possible
- $\eta \neq 0$

CP Violation: experimentally observed in K^0-$\overline{K}^0$ and B^0-$\overline{B}^0$ systems

Open Questions:

- Why can the universe's matter-antimatter asymmetry not be ascribed to η?
- Are the experimentally observed violations described by $\eta \neq 0$ alone?
- New Physics? We must peer at the CKM matrix from all directions!

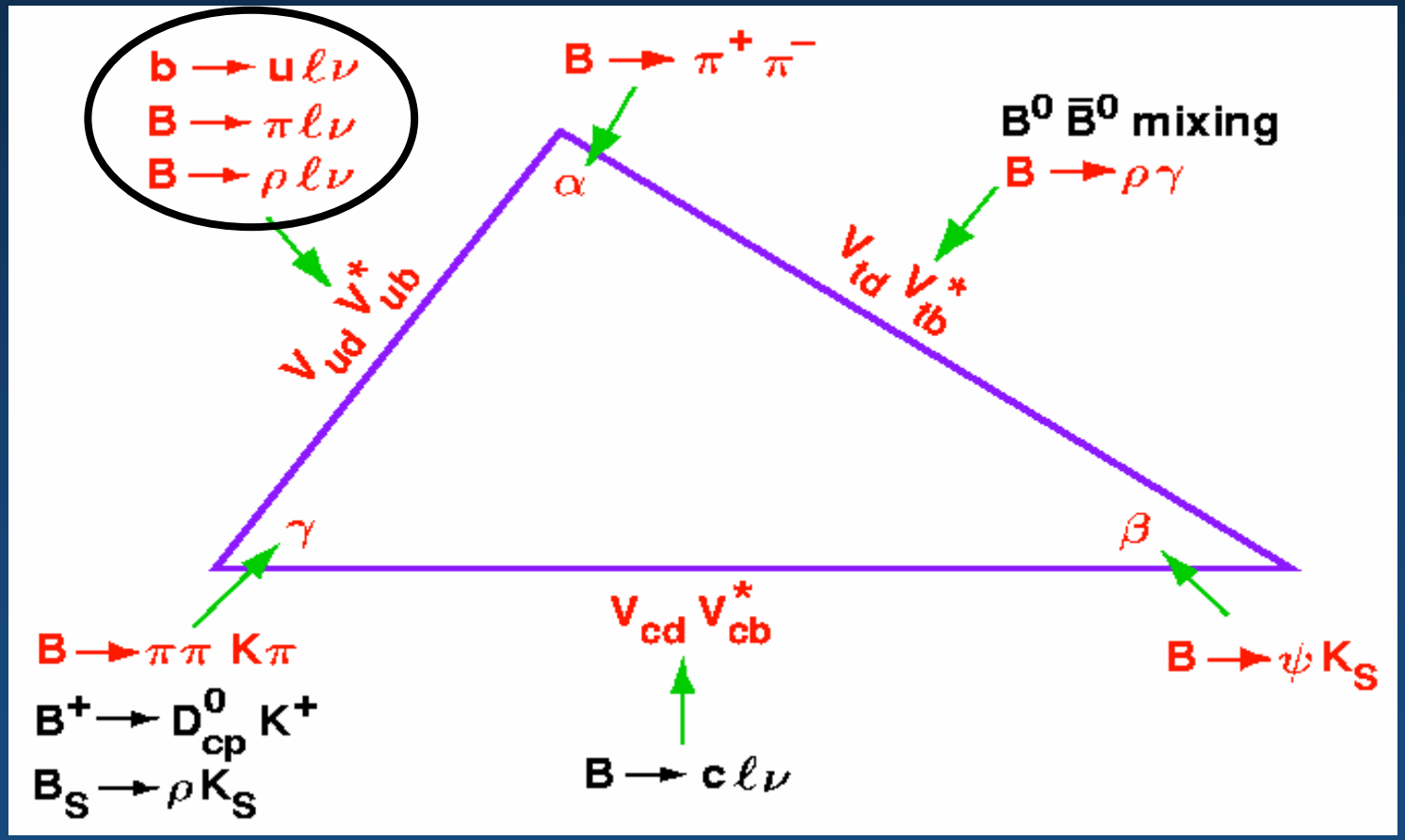
Unitarity: $$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Probing "The" Unitarity Triangle:
A Battery of Modes

b-to-u Flavour Changes

Semileptonic $b \to u$ decays offer best route to measure $|V_{ub}|$



Where we be at?

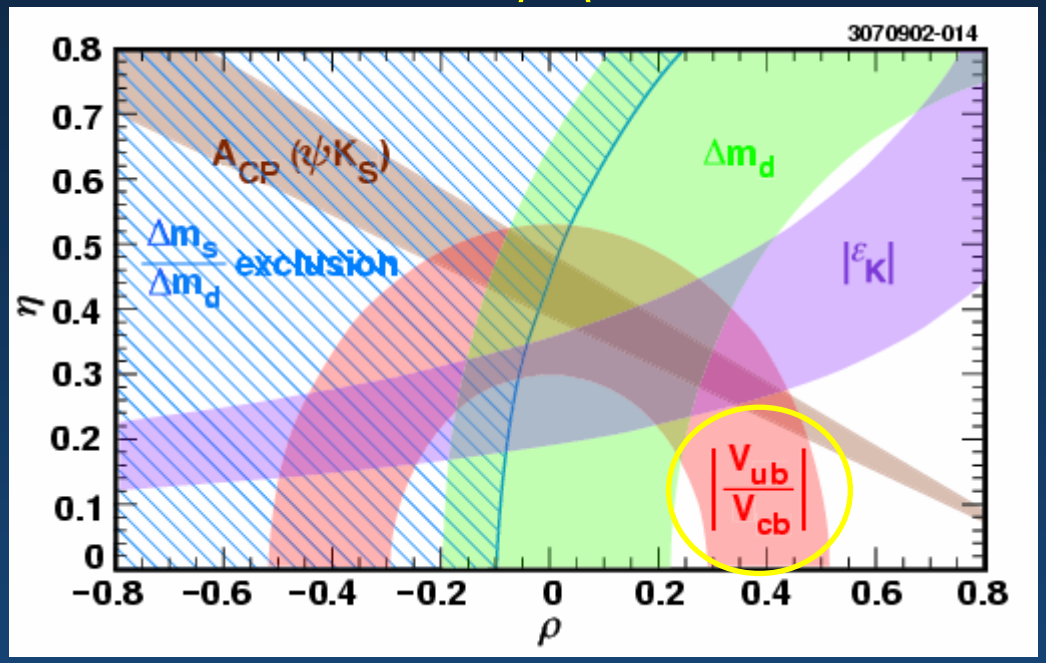
sin 2β: well-measured (BaBar/Belle), theoretically clean

$|V_{cb}|$: known at the few percent level

$|V_{ub}|$ side needs greater precision:

- CLEO is pioneering techniques
- Theoretical advances: recent and ongoing

~ Current ρ-η Plane



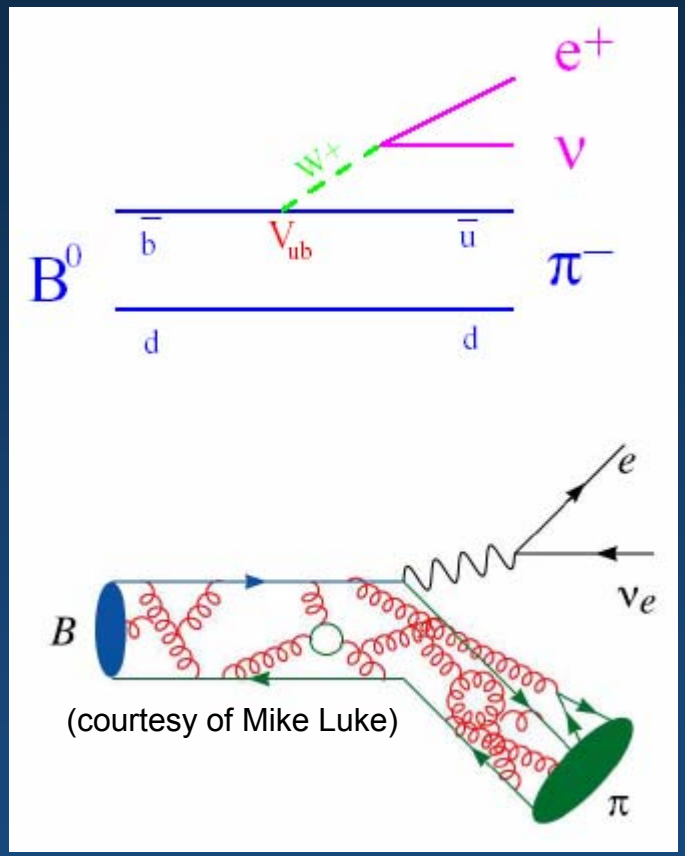
Could be accidental!
More measurements crucial!

Still room for New Physics, ±20%

Yossi Nir: *"Very likely, the KM mechanism is the dominant source of CP violation in flavour changing processes."*

Flavour diagonal CPV can still be dominated by New Physics!

$|V_{ub}|$ in Exclusive Semileptonic B-Meson Decay



(courtesy of Mike Luke)

At the parton level:

Decay rate

$$\Gamma(b \to u \ell \nu) \approx \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2$$

At the hadron level:

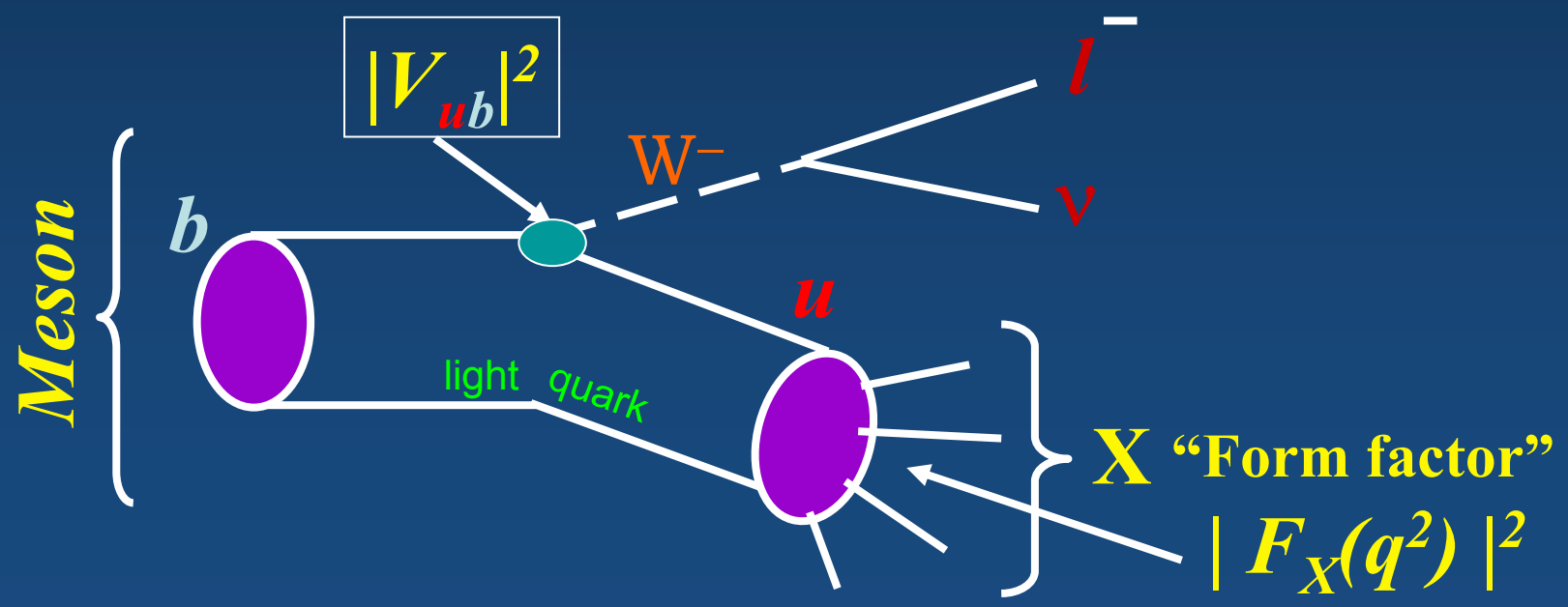
- QCD corrections play a vital rôle
- Theoretical input: form factors (FF)

Experiment Theory

$$\boxed{\frac{d\Gamma}{dq^2}} \approx \frac{G_F^2 p_\pi^3}{24\pi^3} \boxed{|f_i(q^2)|^2} |V_{ub}|^2$$

Realities of the $|V_{ub}|$ Business

- Lepton system can serve as a kinematic "probe" of the quark process
- Predicting the form factors requires long-distance QCD (*i.e.*, it's very difficult)
- Finding $|V_{ub}|$ is as much (more?) about QCD as (than) it is about the CKM matrix
- Understanding the physics of many background sources is crucial



Inclusive Approaches to $|V_{ub}|$

CLEO: *Phys. Rev. Lett.* **88**, 231803 (2002)

Inclusive: blind to the specific brand of meson in the final state

$$B \to X_u \ell \nu$$

Theoretical Tools (mature, reliable):

- Heavy Quark Effective Theory (HQET)
- Operator Product Expansion (OPE)

$$\Gamma(B \to X_u \ell \nu) = \gamma_{\text{theory}} |V_{ub}|^2$$

Parton Level

$$\frac{d^3\Gamma(b \to u \ell \nu)}{dk_1 dk_2 dk_3}$$

Experimental Considerations (severe):

- collossal (~20 dB) backgrounds from favoured b → c processes
- Canonical observables: $d\Gamma/dE_\ell,\ d\Gamma/dm^2_{X_u},\ d\Gamma/dq^2$
- Respective fractions of b → u rate in charm-free phase space: $\sim 10\%,\ \sim 80\%,\ \sim 20\%,\ [\sim 45\%]$
- Cuts on these observables have drastic implications for theoretical expansions and assumptions about quark-hadron duality

C. W. Bauer, Z. Ligeti, M. Luke, *et al.*

Exclusive Approaches to $|V_{ub}|$

Exclusive: treat explicit final states for each decay mode

$$B \to \left[\pi^{\pm}, \pi^{0}, \rho^{\pm}, \rho^{0}, \omega, \eta, \ldots\right] \ell \nu$$

Phenomenological Form-Factor Tools (a jungle!):

- Lattice QCD Techniques (calculations with uncertainties!)
- QCD Sum-Rule Methods
- Quark Models (non-relativistic and relativistic)
- others…
- Bottom Line: the most reliable calculations are only valid in restricted regions of phase space $\Rightarrow$ $|V_{ub}|$ extractions difficult!

Experimental Considerations:

- more kinematic constraints to reject $b \to c$ pollution
- "neutrino reconstruction" methods (poor, but better than nothing!)
- probe more phase space $\Rightarrow$ take form-factor predictions to task!

$|V_{ub}|$ Challenges: Theory and Experiment

- Cabibbo Suppression: Rates are small from the outset, $\sim\Gamma(b \to c)/100$
- Interpretation: Requires both Theory and Experiment
- Mutual Reliability of Theory and Experiment: Only in limited kinematic regions!

Fraction of Full $b \to u$ Decay Rate:	Inclusive	Exclusive
Theory	LARGE (OPE; Duality)	SMALL (LCSR: non-pQCD; LQCD: discretization)
Experiment	SMALL ($b \to c$ background)	LARGE (Kinematic Constraints)

Checkpoint

So Far…

The CKM quark-mixing matrix
Unitarity Triangle, CP violation
Multipronged attack: Theory, Experiment, Inclusive, Exclusive

Next…

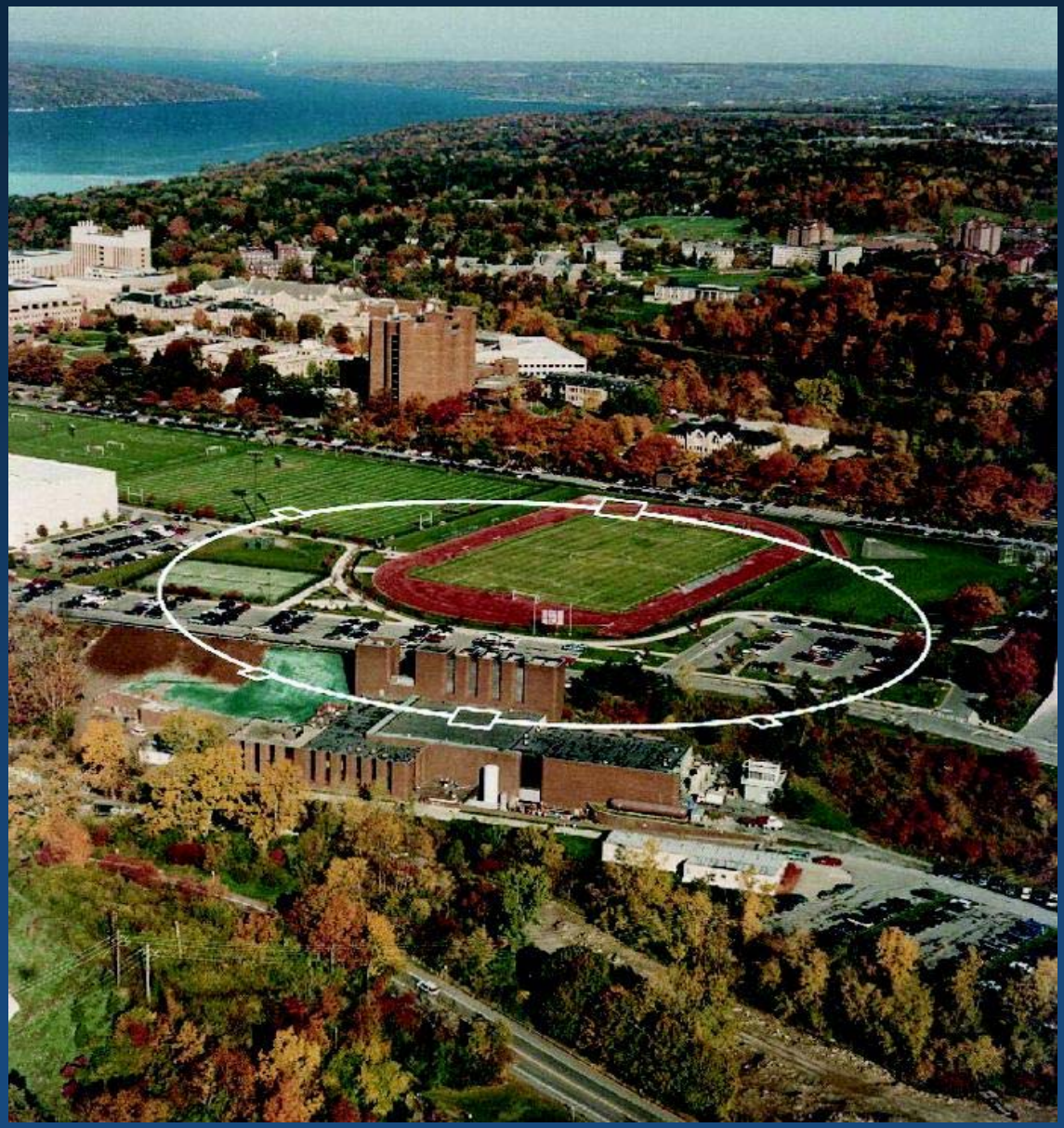
Making Υ(4S) mesons nearly at rest

Wilson Synchrotron Laboratory

LEPP

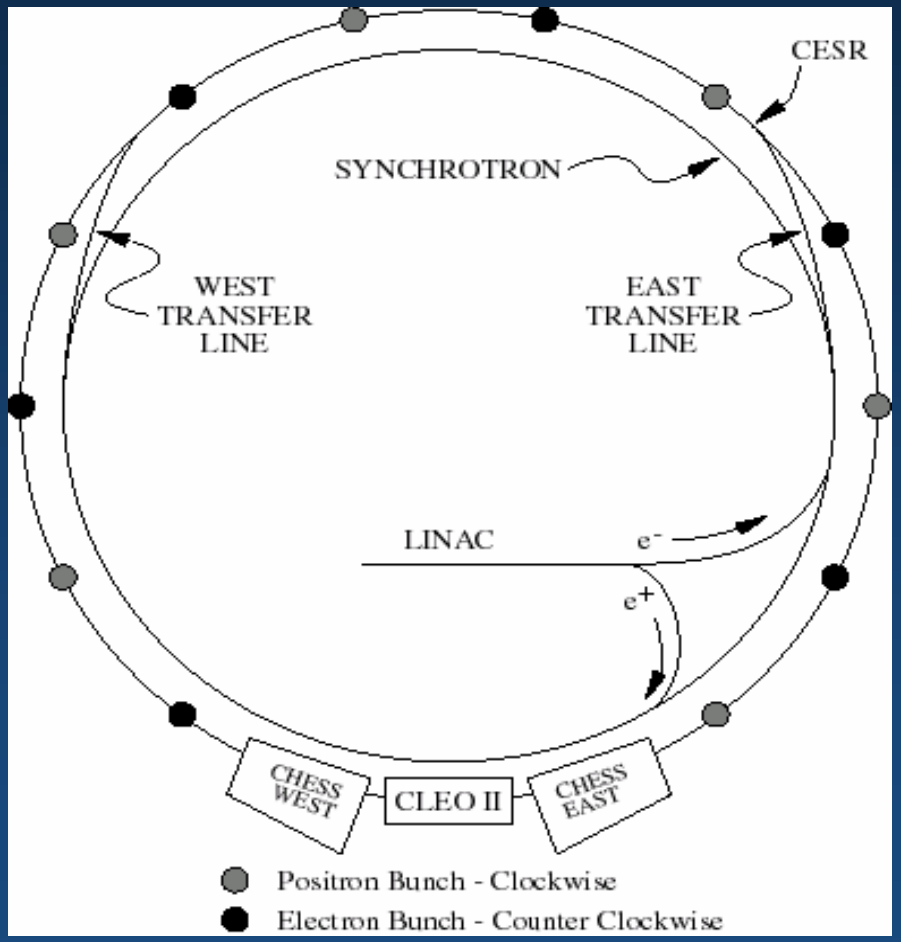
[Laboratory for Elementary-Particle Physics]
(formerly LNS)

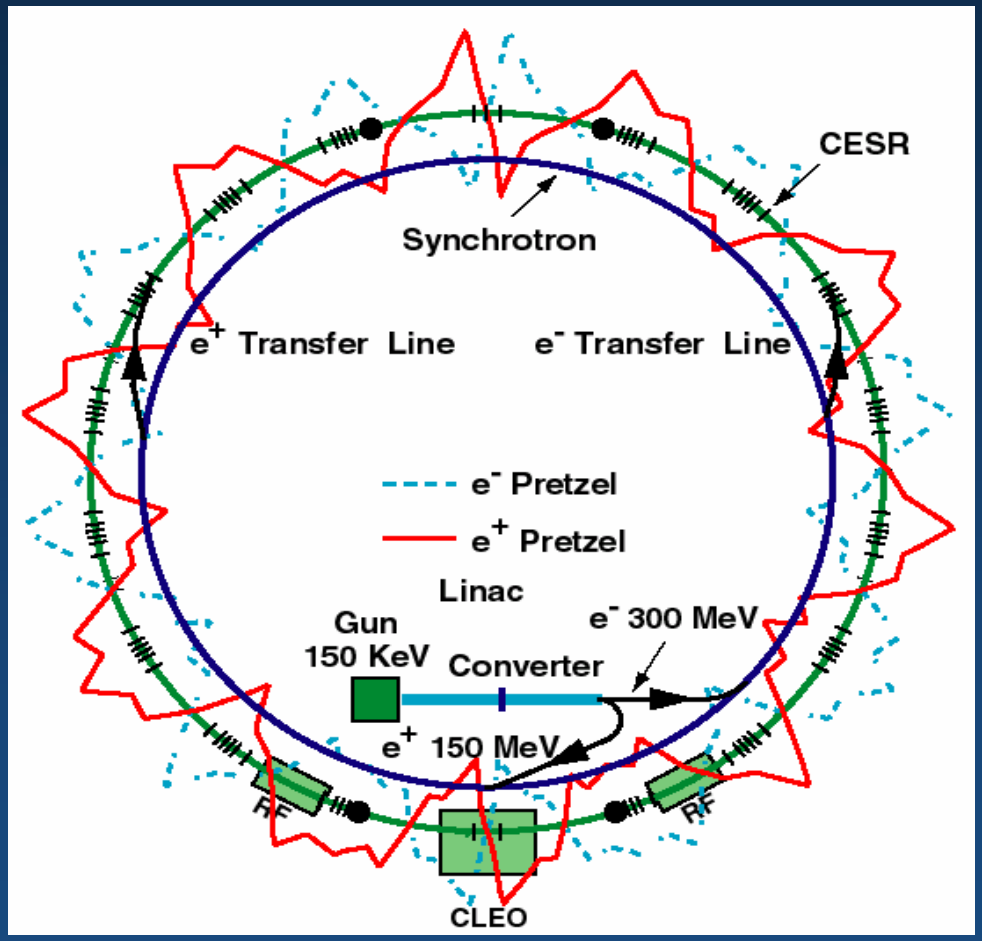
Cornell University



The Accelerator

CESR: Cornell Electron Storage Ring





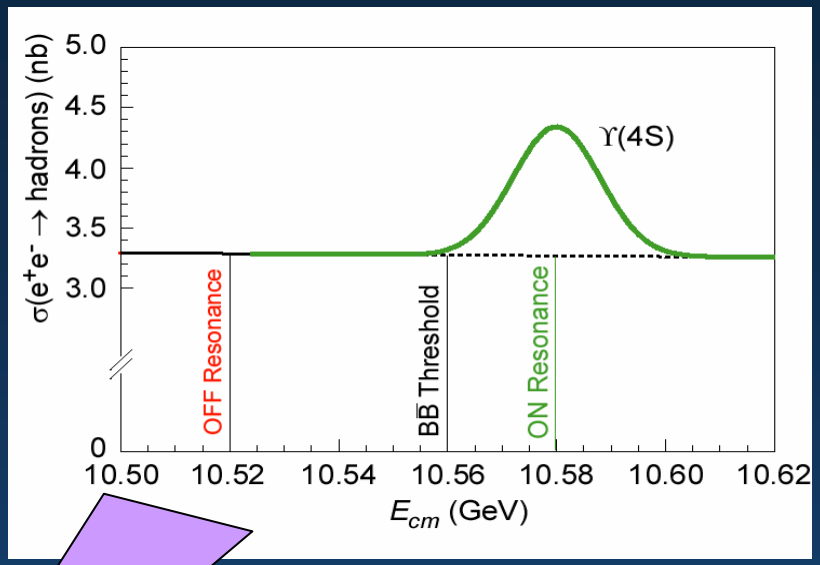
Synchrotron + CESR

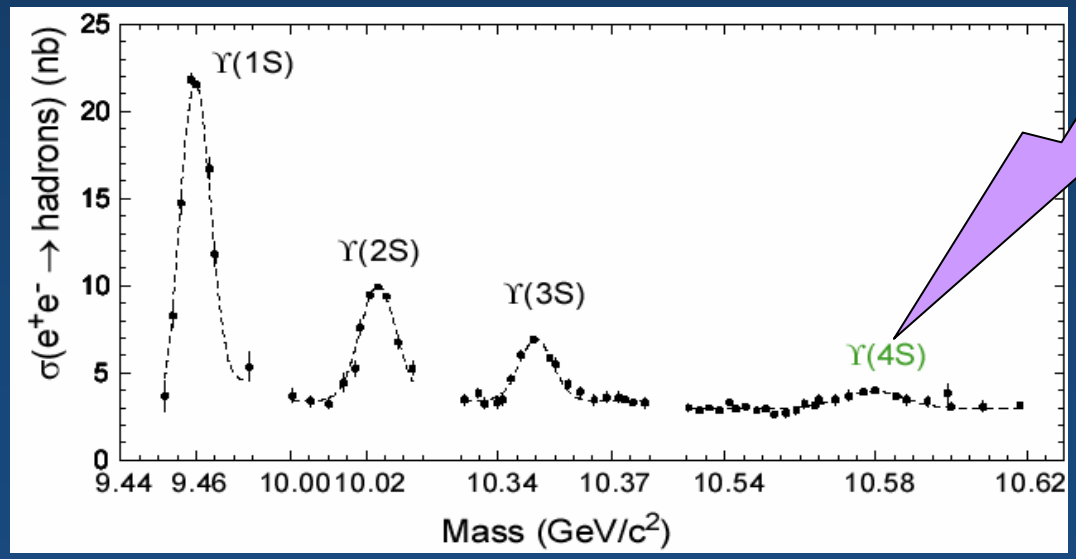
(AIP Archives)

ϒ Resonance Region

symmetric

$$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$





2/3 running **ON** the $\Upsilon(4S)$:

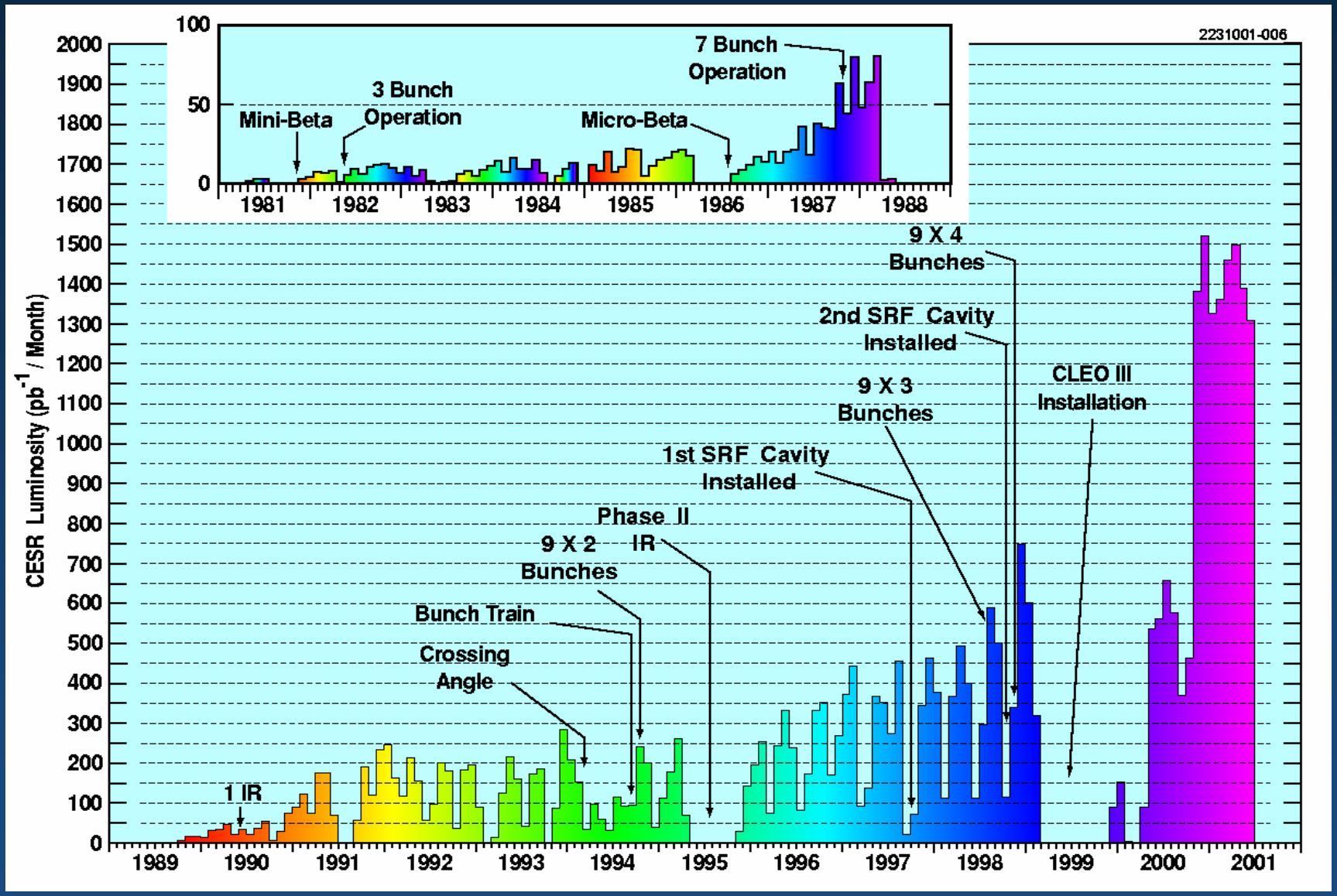
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$ ($\sigma \sim 1$ nb)

$e^+e^- \rightarrow qq$, ($q = u, d, c, s$) ($\sigma \sim 3$ nb)

1/3 running **OFF** the $\Upsilon(4S)$:

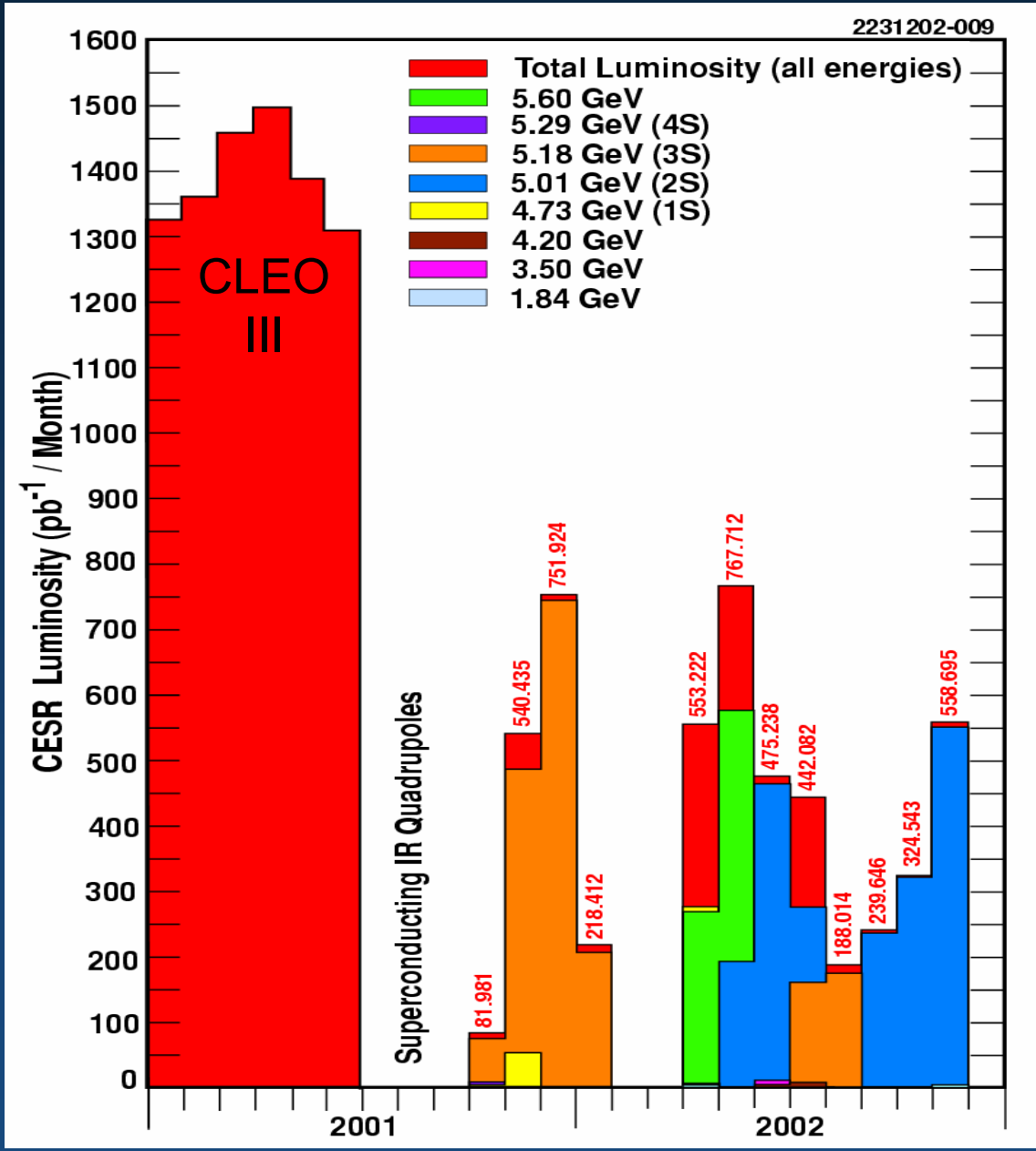
allows subtraction of continuum backgrounds

CESR Luminosity Performance



Recent CESR Performance:

A Change of Focus



Checkpoint

So Far…

CESR and the making of B mesons

Next…

CLEO Collaboration and Detector

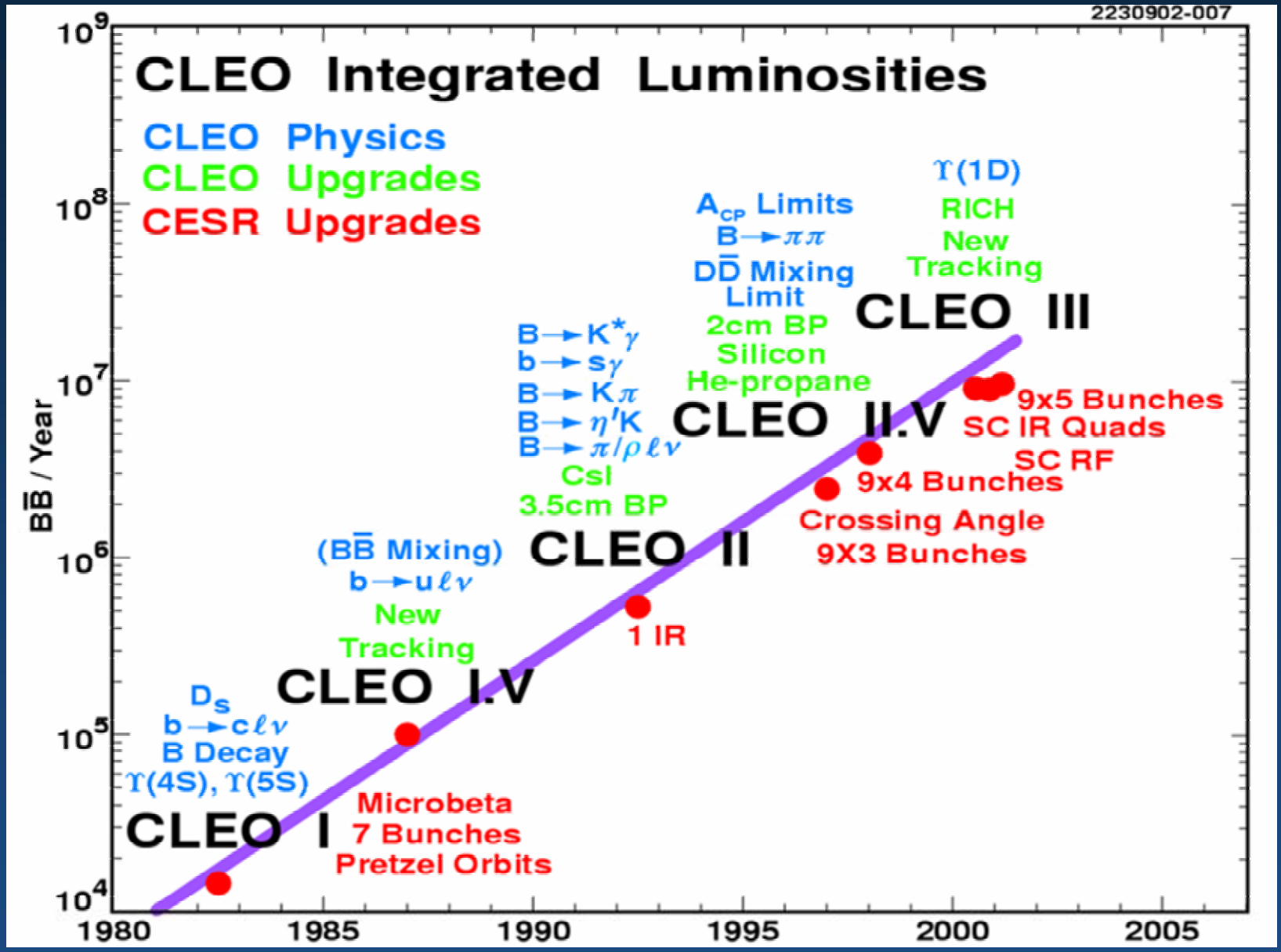
The CLEO Collaboration

Membership:

- ~20 Institutions
- ~120 Physicists
- ~1/2 DOE, 1/2 NSF
- Currently expanding…

Albany
Caltech
Carleton
Carnegie-Mellon
Cornell
Florida
Illinois
Kansas
Minnesota
Northwestern
Ohio State
Oklahoma
Pittsburgh
Purdue
Rochester
SMU
Syracuse
Texas – Pan Am.
Vanderbilt
Wayne State

A Brief History of the CLEO Experiment



CLEOII + II.V

CLEO II (1989 – 1995):

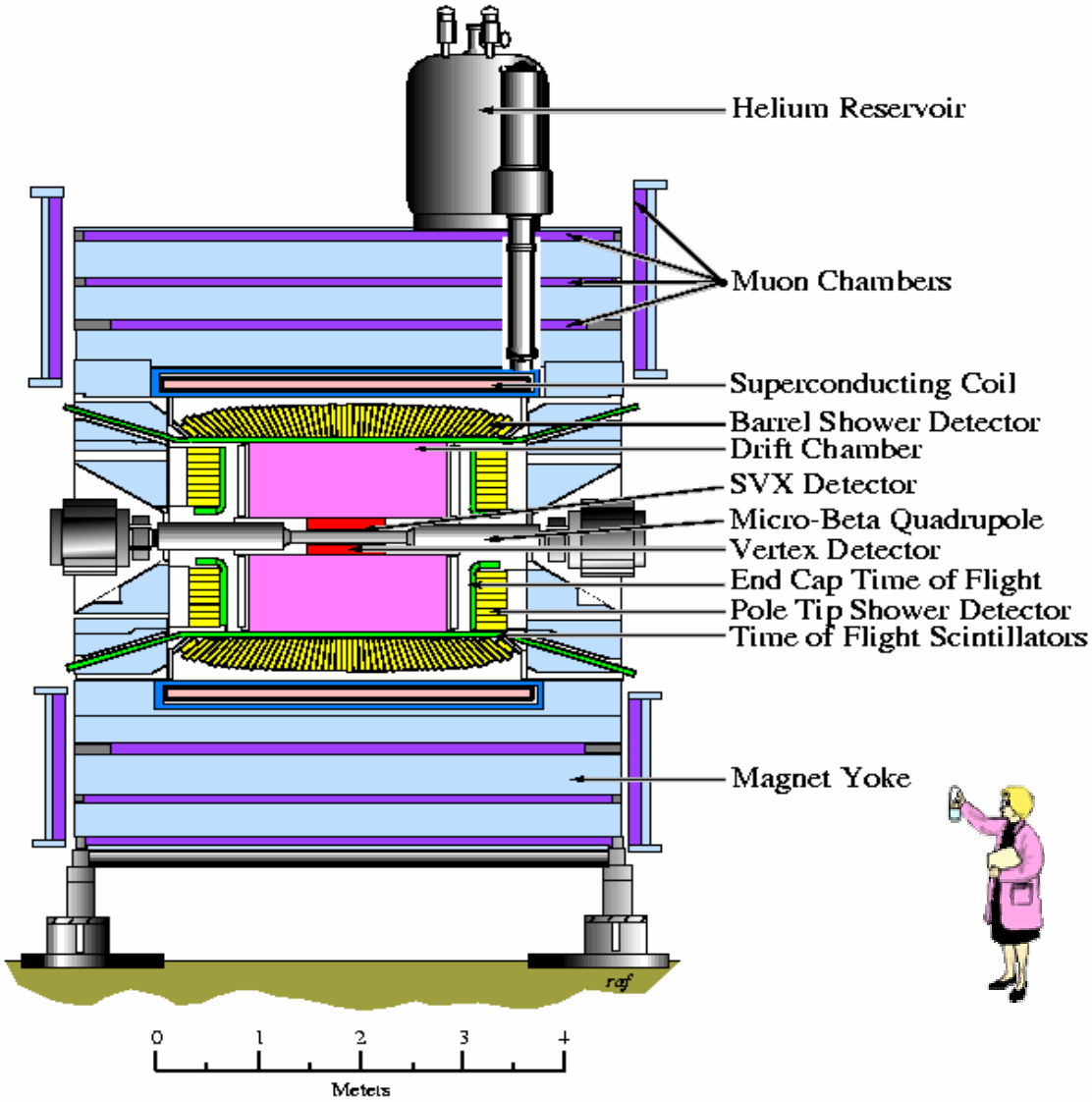
- 1.5 T Solenoid Magnet
- 3 Tracking Chambers
- CsI Calorimeter
- Time-of-Flight System
- Muon Systems
- 3.3×10^6 BB pairs

CLEO II.V (1996 – 1999): →

- 3-layer Silicon Detector replaced inner tracker (a first!)
- Ar-Ethane → He-Propane (a first!)
- 6.4×10^6 BB pairs

Both detectors well-understood with mature Monte Carlo understanding

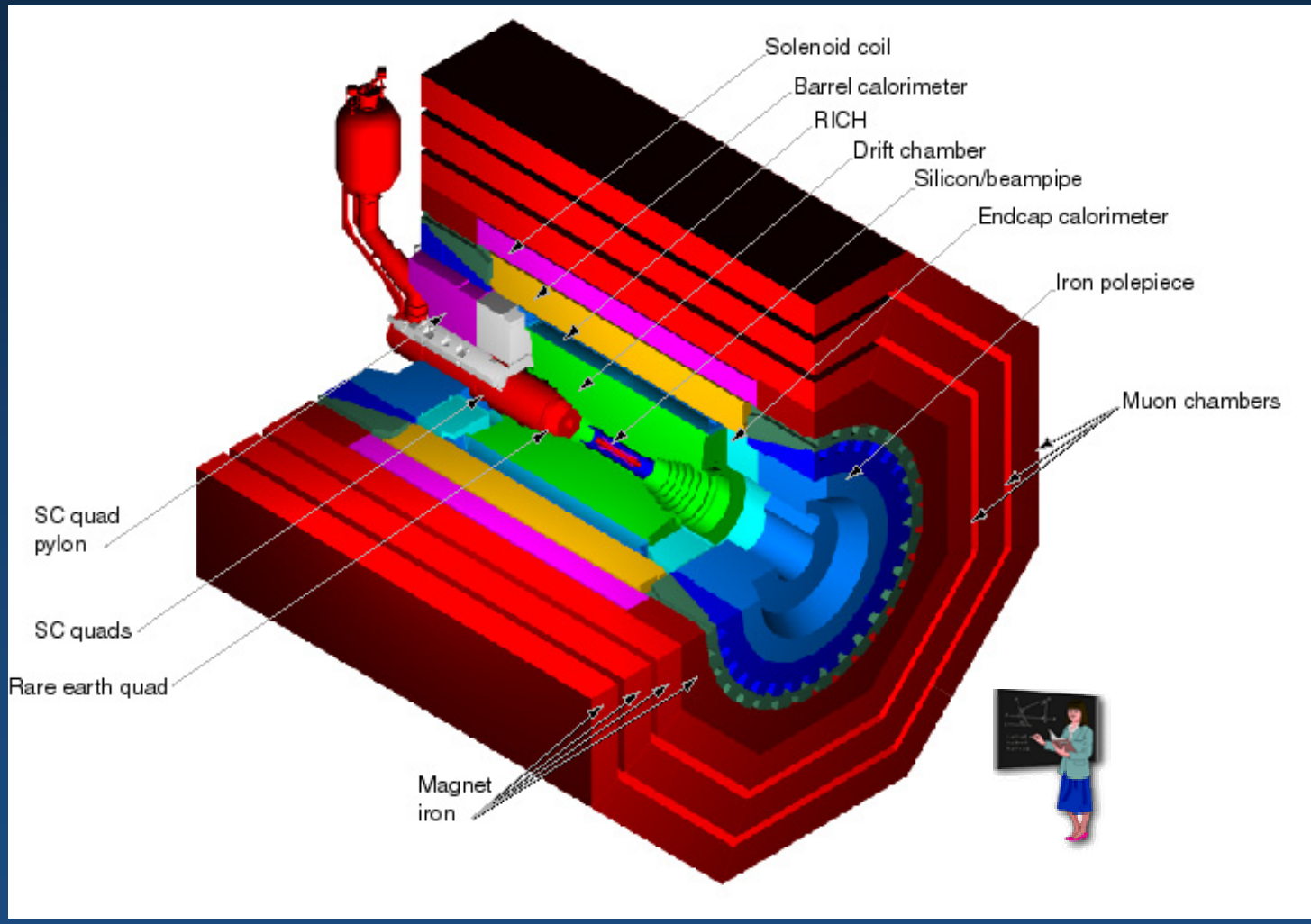
Hermeticity: ≥95%



CLEO III

CLEO III (2000 – 2001):

- Inner Systems all new
  - Si Vertex Detector
  - Drift Chamber
  - RICH Detector
  - Thin Beampipe
  - SC Focussing Quads
- 7.4×10^6 BB pairs



Data Collection and Sample Facts

e+ e- crossing rate	~20 MHz
Max data collection rate	~1 kHz
bb Production Rate	1 Hz
qq Production Rate (q = u,d,s,c)	3 Hz
Lepton-pair Production Rate	40 Hz (~95% e+e-)
Multiple Interactions per Crossing	~0
Trigger efficiency for hadrons	~100%

	Detector	$\Upsilon(4S)$ [fb^{-1}]	Continuum [fb^{-1}]	BB Events (10^6)
This Analysis	CLEO II	3.1	1.6	3.3
	CLEO II.V	6.0	2.8	6.4
	Subtotal	9.1	4.4	9.7
	CLEO III	6.9	2.3	7.4
	Total	16.0	6.7	17.1

Checkpoint

So Far…

CLEO Collaboration and Detector

Next…

Exclusive Approach to $|V_{ub}|$ Measurements
"Neutrino Reconstruction"

CLEO's Exclusive Approach to b → u Decay

Véronique Boisvert, Lawrence Gibbons, a.w.

Tom Meyer | Ed Thorndike

Main Goals:

- Identify specific final states of $B \to X_u l \nu$, where $X_u \in \{\pi^{\pm}, \pi^0, \rho^{\pm}, \rho^0, \omega, \eta\}$
- Use theoretical form-factor calculations to extract signal yields in each mode
- Derive model-dependent $|V_{ub}|$ from measured rates
- Examine rate as a function of momentum transfer (q^2) : exercise the models!

for π:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |\vec{p}_\pi|^3 \left| f_1(q^2) \right|^2 + \ldots$$

(more form factors in the case of vector modes)

Ancient History

model dependence

$$\Gamma = \frac{Br(B \to \pi l \nu)}{\tau_B} = \gamma_u |V_{ub}|^2$$

First Observation

$$Br(B^0 \to \pi^- l^+ \nu) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$$

J. Alexander *et al*. (CLEO), Phys. Rev. Lett. **77**, 5000 (1996)

First Attempt at Partial Rate Measurement (endpoint kinematics only)

$$Br(B^0 \to \rho^- l^+ \nu) = (2.57 \pm 0.29^{+0.33}_{-0.46} \pm 0.41) \times 10^{-4}$$

B.H. Behrens *et al*. (CLEO), Phys. Rev. D **61**, 052001 (2000)

Technique recently re-used by BaBar: B.Aubert *et al*. (BaBar), Phys. Rev. Lett. 90, 181801 (2003)

What's new in the new CLEO analysis?

Help to reduce model dependence!

- Full CLEO II + II.V dataset (size increased by a factor ~3)
- More hadron daughter modes reconstructed
- Improved characterization of backgrounds
- Lowered charged-lepton momentum criteria:
  1.0 (1.5) GeV/*c* for pseudoscalar (vector) modes
- Higher reconstruction efficiencies
- Partial rates in q^2 bins
- Significant theoretical progress, esp.
  - lattice QCD techniques
  - QCD sum rule calculations
  - (more models available…)

Desired Deliverables

- q^2-dependent decay rates
- $|V_{ub}|$ with reduced model dependence

Coarse Analysis Roadmap: Measuring Rates

1. Find a **charged-lepton** candidate

   Apply Cuts

2. Reconstruct **light-hadron** candidates $\left(\pi^{\pm}, \pi^{0}, \rho^{\pm}, \rho^{0}, \omega, \eta\right)$

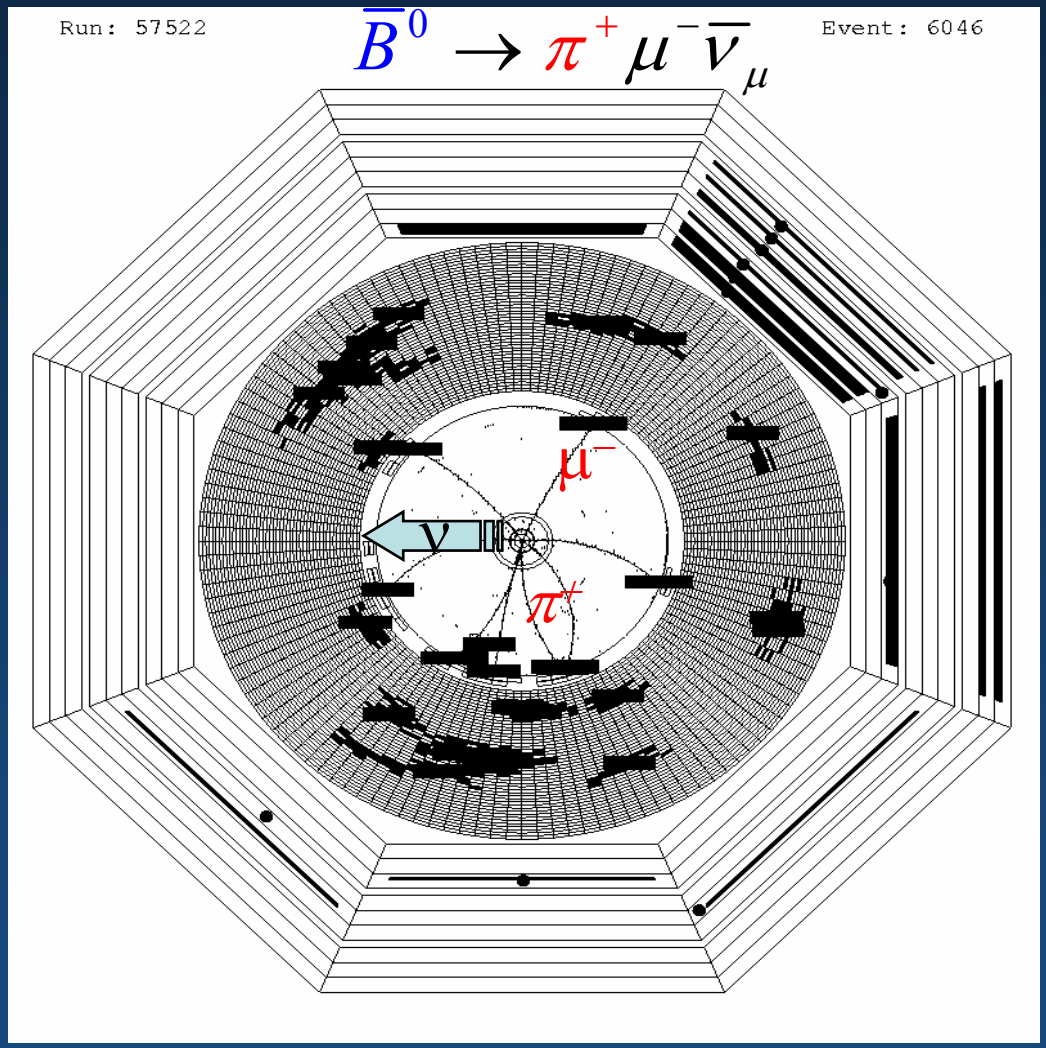
   Apply Cuts

3. Reconstruct **neutrino** candidate

   Apply Cuts

4. **Fit** several observables simultaneously

5. Consider several form-factor **models**



Principles of Neutrino Reconstruction

Reconstruct the entire event!

Exploit CLEO detector hermeticity,
[0.93 to 0.95](4π): $i \in$ {"good" tracks, showers}

$$E_{\text{miss}} = 2E_{\text{beam}} - \Sigma_i E_i$$

$$\vec{p}_{\text{miss}} = -\Sigma_i \vec{p}_i \quad \left[\sigma\left(\left|\vec{p}_{\text{miss}}\right|\right) \approx 85 \text{ MeV}/c\right]$$

$$\left(E_\nu, \vec{p}_\nu\right) \equiv \left(\left|\vec{p}_{\text{miss}}\right|, \vec{p}_{\text{miss}}\right)$$

Employ powerful collider-beam constraints:

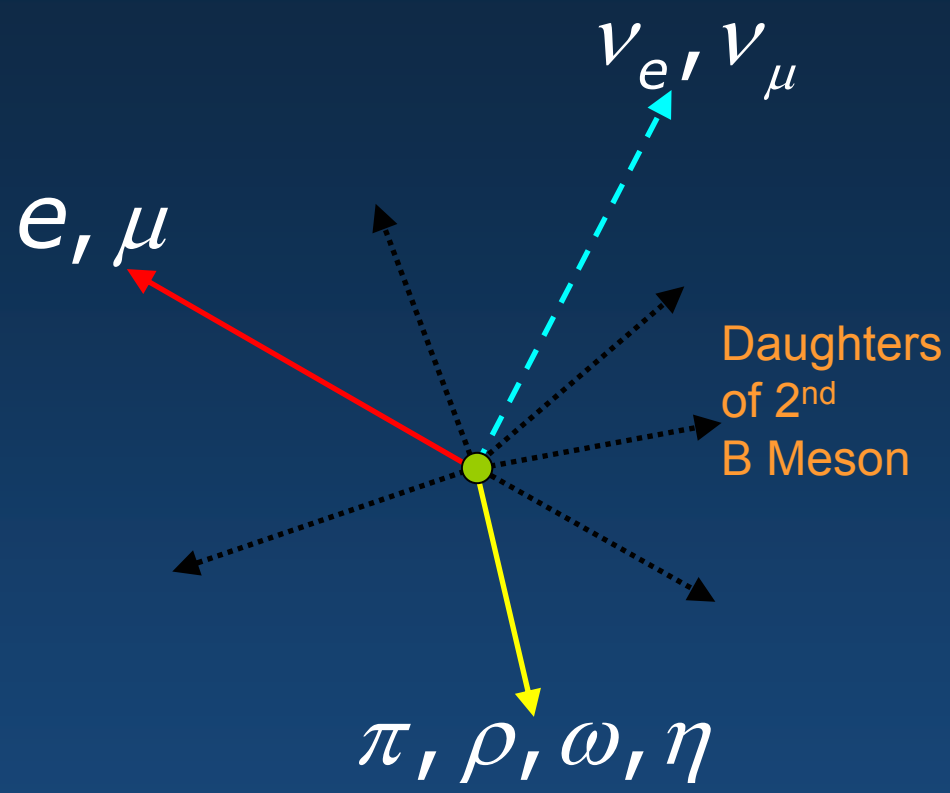
$$M_{m\ell\nu} \equiv \sqrt{E_{\text{beam}}^2 - \left|\alpha\vec{p}_\nu + \vec{p}_\ell + \vec{p}_m\right|^2}$$

$$\Delta E \equiv (E_\nu + E_\ell + E_m) - E_{\text{beam}}$$

Define signal region by energy and momentum conservation:

$$\Delta E \approx 0$$

$$M_{m\ell\nu} \equiv M_B$$



Symmetric interaction regions are advantageous!

Neutrino Reconstruction: The Hard Parts

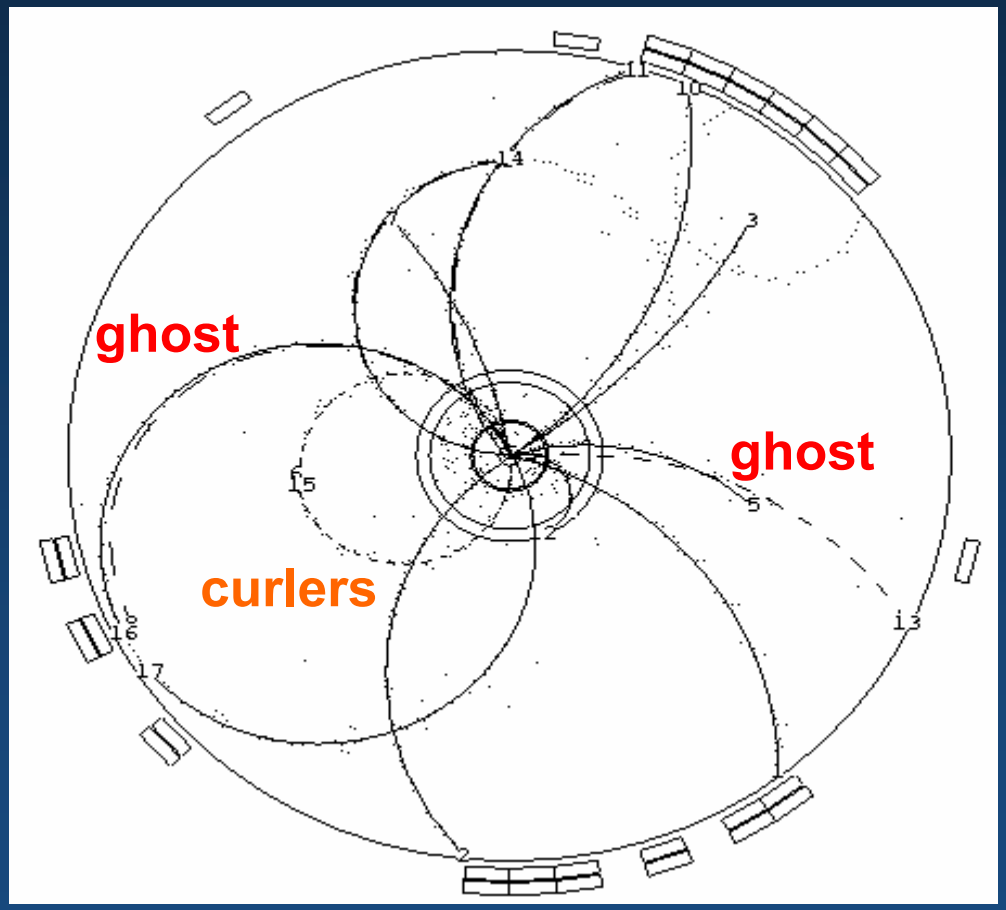
Need to establish a one-to-one correspondence between

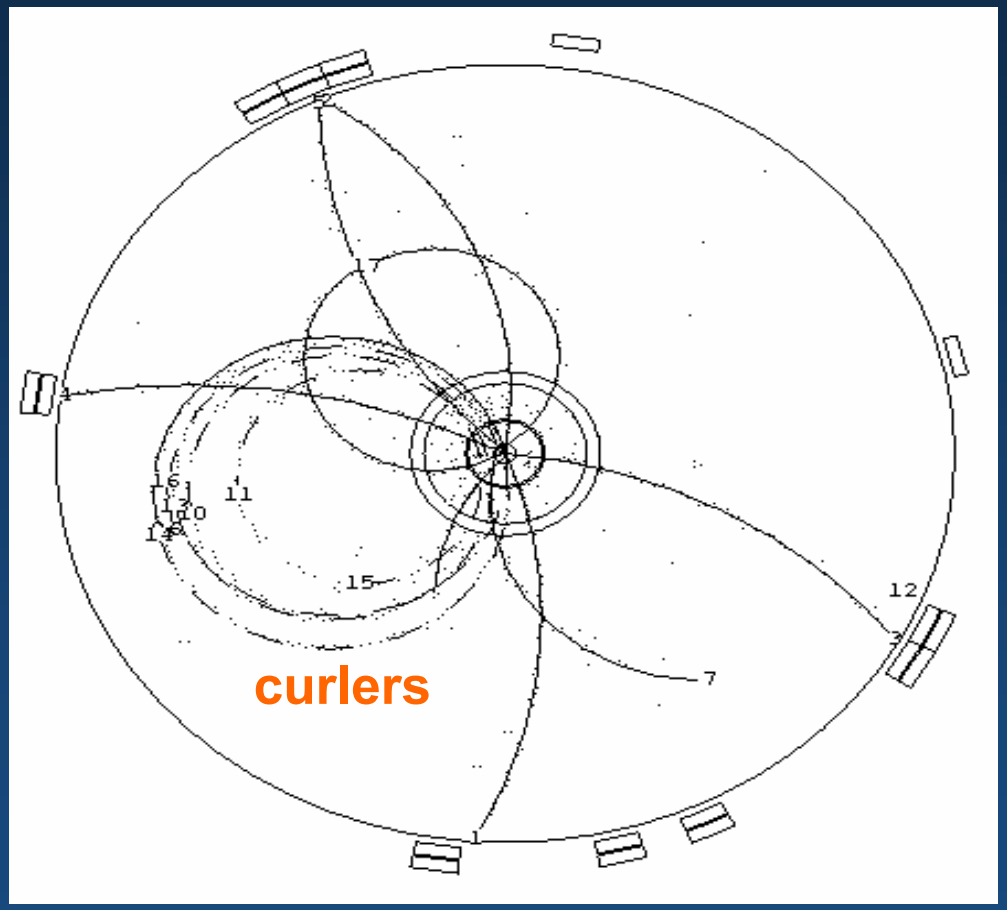
- Tracks → Charged decay products
- Calorimeter Showers → Neutral decay products

Difficulties:

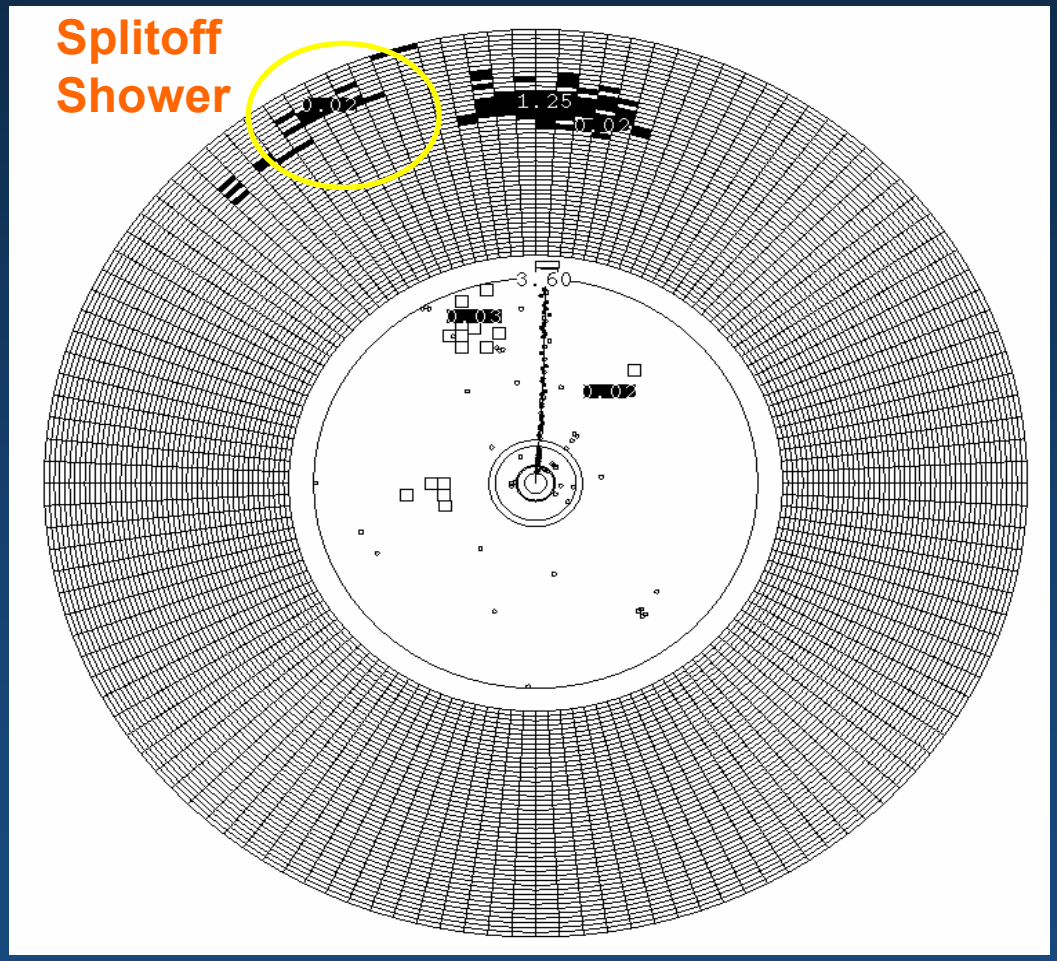
- Extra tracks
  - Ghosts
  - Curlers
- Extra calorimeter showers
  - "splitoff" clusters from charged hadrons
- Lost tracks or showers
- Extra neutrinos
- K_L mesons
- Hermeticity imperfections

Track Reconstruction Errors

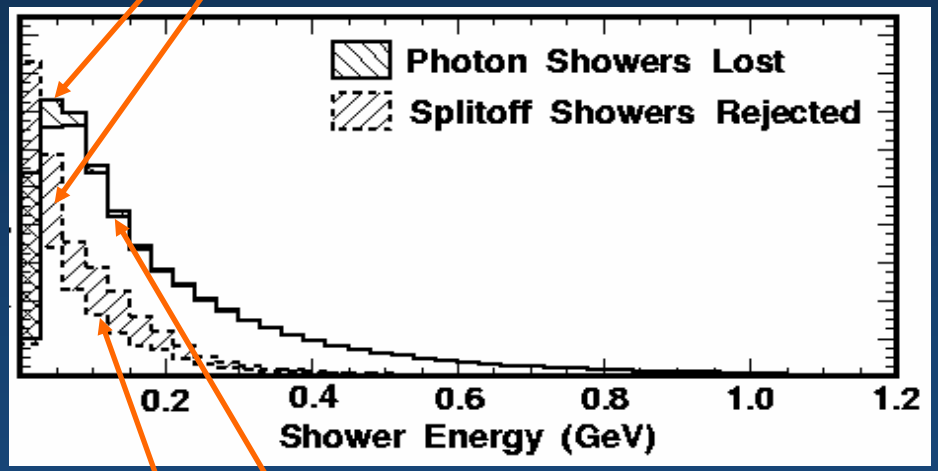




Splitoff Calorimeter Showers



Before Splitoff Rejection



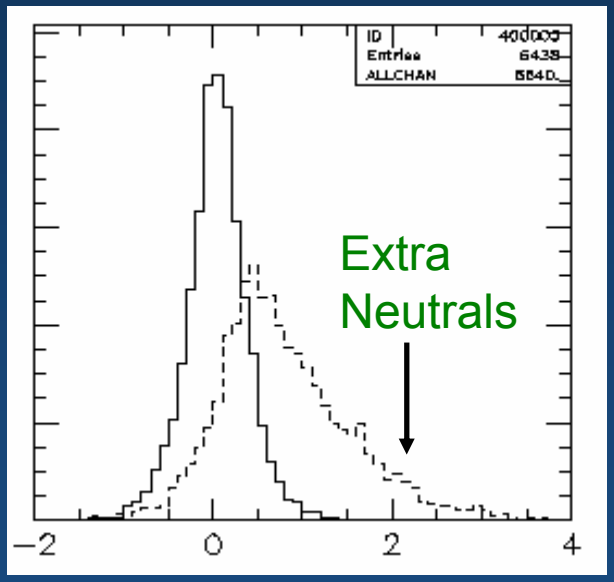
After Splitoff Rejection

Unreconstructed Neutral-Particle Pollutants

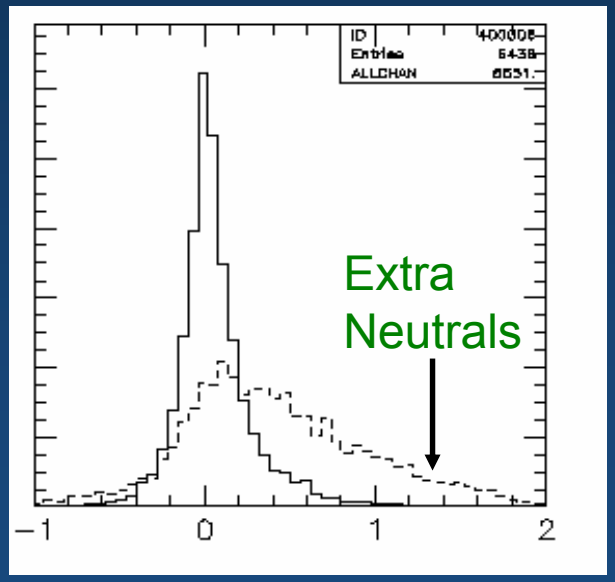
Undesirable Contributions to Missing Energy

- **Extra neutrinos:** require one-and-only-one charged lepton candidate
- **K_{long} mesons:** in every 2nd event; leave showers 50% of the time
- **neutrons**

Monte Carlo



$E_{rec} - E_{gen}$ [GeV]



$|p|_{rec} - |p|_{gen}$ [GeV/c]

$$p_\nu \equiv (|\vec{p}_{miss}|, \vec{p}_{miss})$$

Checkpoint

So Far

Exclusive Approach to $|V_{ub}|$ Measurements
"Neutrino Reconstruction"

Next…

Branching-Fraction Fits

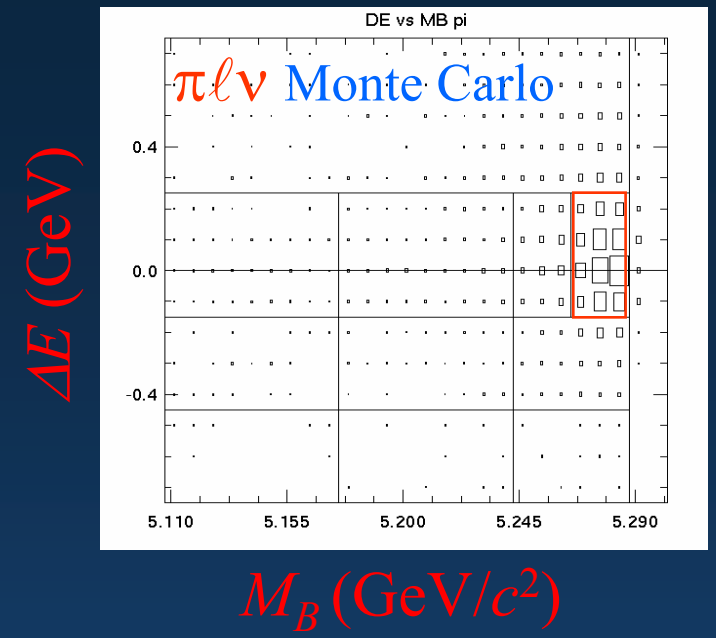
Binned Maximum Likelihood Fit

Use approach of Barlow/Beeston
[Comput. Phys. Commun. **77**, 219 (1993)]

$$\ln \mathcal{L} = \sum_{i=1}^{n} x_i \ln \mu_i - \mu_i + \sum_{i=1}^{n} \sum_{j=1}^{m} a_{ji} \ln A_{ji} - A_{ji}$$

$a_{ji} \equiv$ # of MC events from source j in bin i

$A_{ji} \equiv$ expected # of MC events from source j in bin i



Method accommodates

- **Finite** MC statistics
- Bins with **0 events** from a MC source
- **Weighted** MC events

Bins fit simultaneously:
- 7 in ΔE and M_B
- 3 in q^2 (1 bin for ω, η modes)
- 7 signal-mode topologies
- 2 event net-charge states ($|\Delta Q| = 0,1$)
- 3 vector-meson mass bins

259 (406) bins in total!

Sources: 7 in total
(see projections on next slide)

Exclusive Reconstruction of $B \to [\pi, \rho, \omega, \eta]\ell\nu$ Decays

Points: On-resonance data

Open: Signal MC simulation

Coarsely Hatched: crossfeed among P (V) modes and q^2 bins

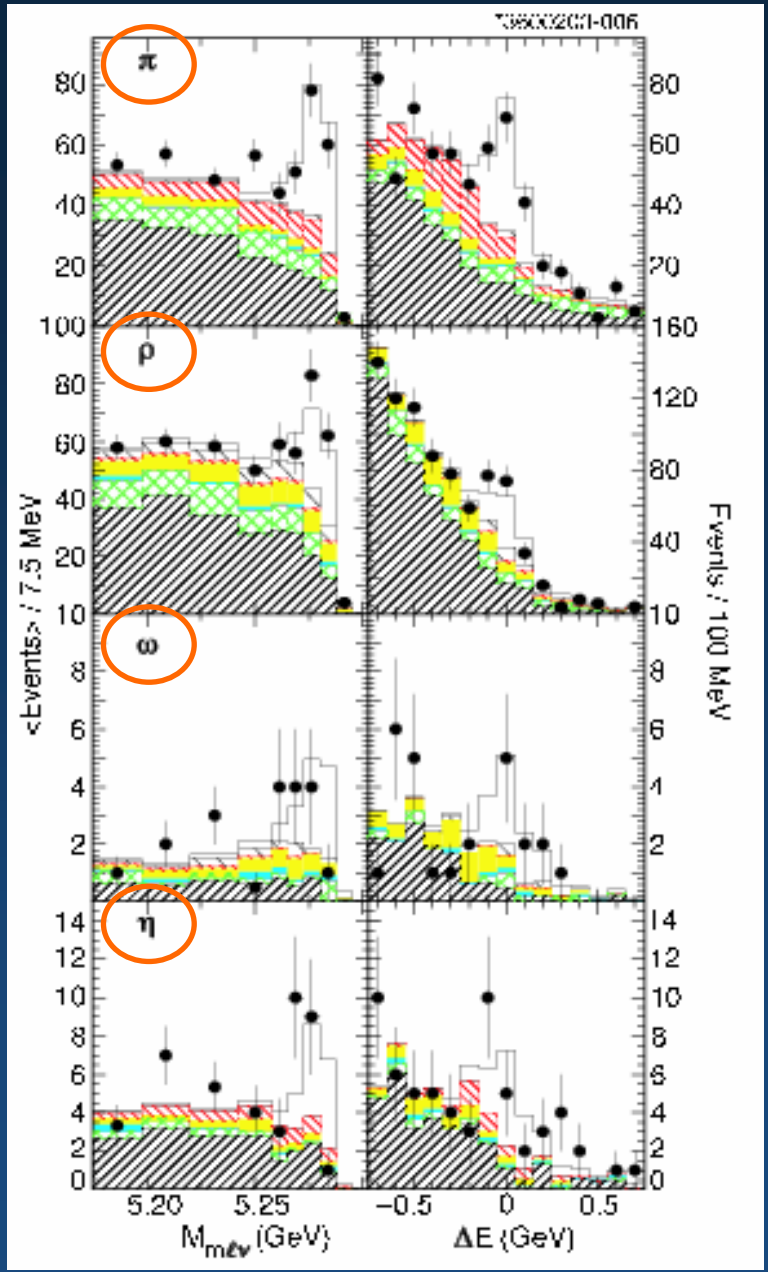
Red: Crossfeed from V (P) modes into P (V) modes

Yellow: $B \to X_u \ell \nu$ non-signal feeddown; floated in fit, subject to constraint from CLEO endpoint analysis

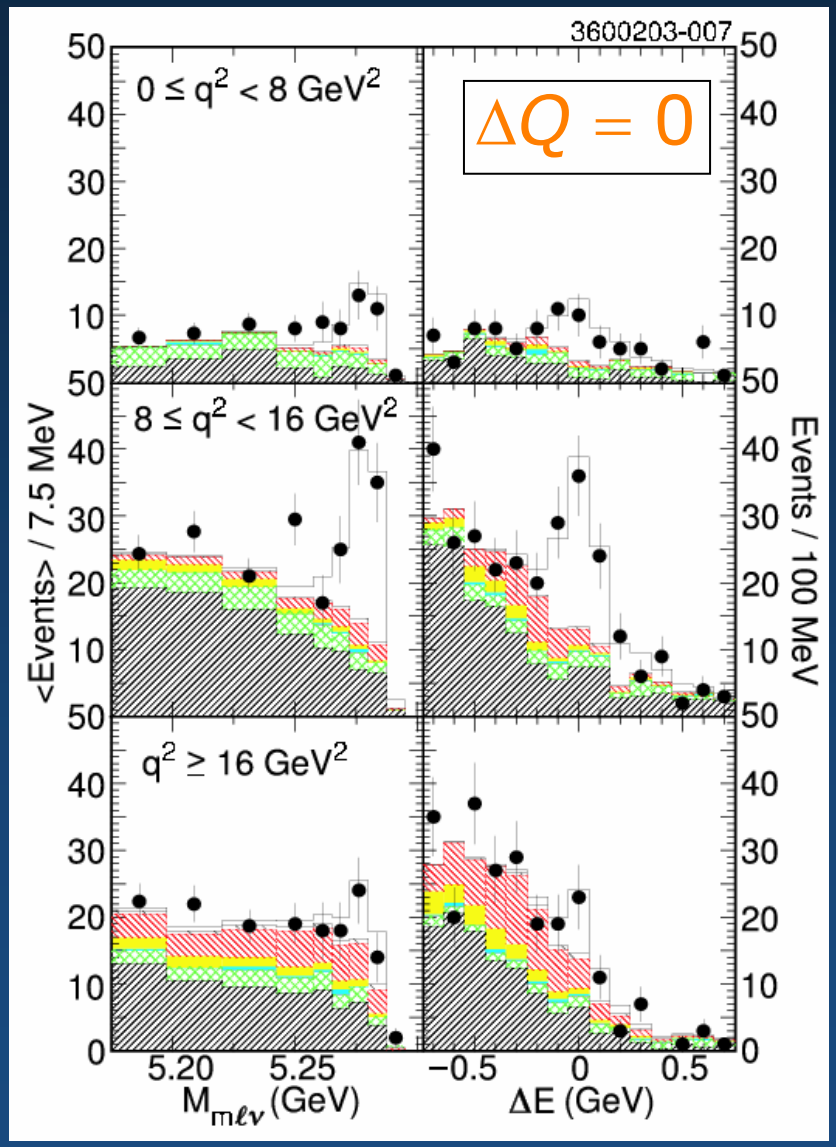
Cyan: Fake leptons

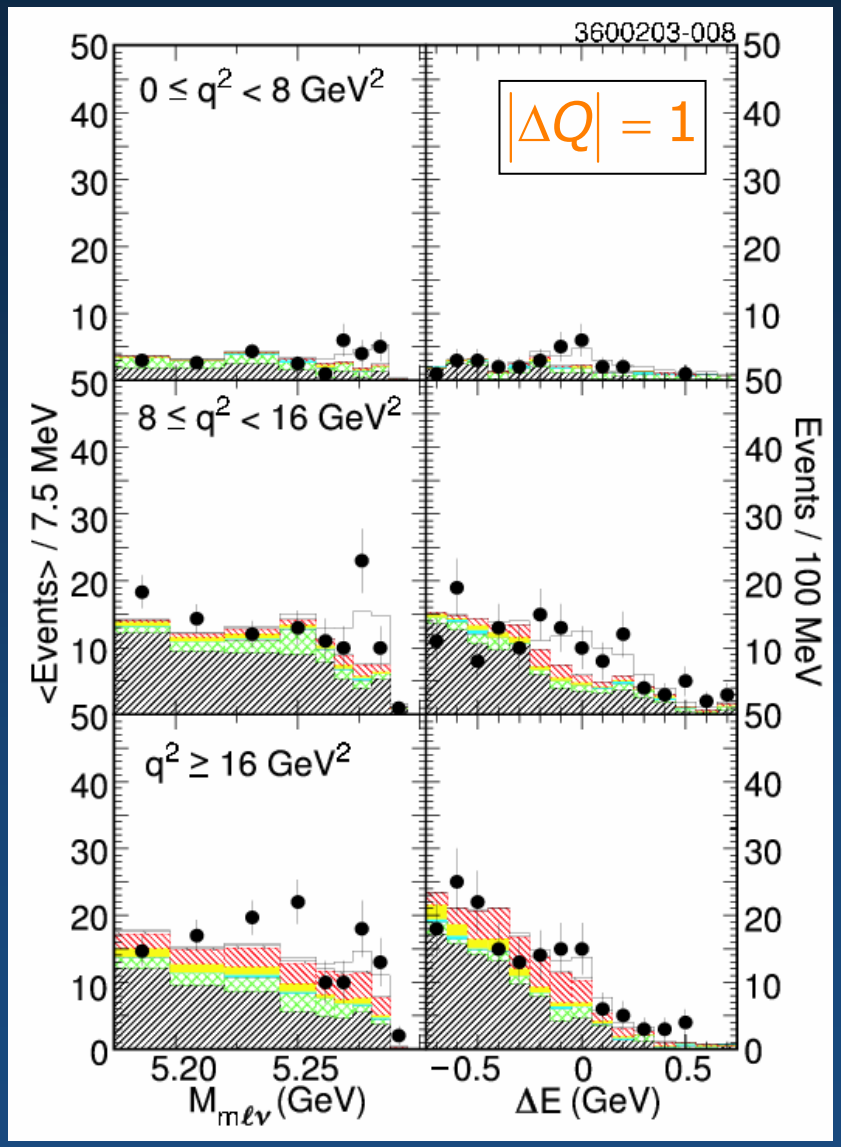
Cross Hatch: Continuum

Finely Hatched: $b \to c$



$B \to \pi \ell \nu$ Partial Rate Fit Projections





Feeddown from other b → u Modes

Impose Internal CLEO Consistency

Home Grown Model (with signal modes excised):

- OPE calculation of inclusive spectrum, differential in X_u mass
  [Kagan, Neubert, EPJ **C7**, 5 (1999)]
- Nonperturbative parameters in the above model obtained from CLEO analysis of b → sγ photon spectrum
  [CLEO, PRL **87**, 251807 (2001)]
- "Folded in" resonances up to ρ(1450), according to the ISGW II model
  [Scora, Isgur, PRD **52**, 2783 (1995)]

Float in fit, subject to constraint from CLEO's inclusive endpoint $|V_{ub}|$ analysis:
[CLEO, PRL **88**, 231803 (2002)]

(2.2 – 2.6 GeV/c)

$$-2\ln L \rightarrow -2\ln L + \frac{(B_{em} - B_{ep})^2}{\sigma_{em}^2}$$

where

$$B_{ep} = B_{u\ell\nu} f_{u\ell\nu} + \sum_m \sum_{i=1}^{N_{q^2}(m)} B_{m,i} f_{m,i}$$

$$m \in \{\pi^+, \pi^0, \rho^+, \rho^0, \omega, \eta\}$$

Blood and Sweat: ν Simulation Systematics

- Modify several attributes of every Monte Carlo event in each signal and background sample
- Refit using full branching-fraction fitting machinery
- Note (%) effects on fit parameters

variation (%)	$\pi^-\ell^+\nu$				$\rho^-\ell^+\nu$				$\eta\ell\nu$
	total	$q^2 < 8$	$8 \le q^2 < 16$	$q^2 \ge 16$	total	$q^2 < 8$	$8 \le q^2 < 16$	$q^2 \ge 16$	total
γ eff.	2.6	7.0	2.7	9.1	11.1	11.9	11.1	10.6	5.7
γ resol.	4.1	2.9	5.4	2.3	2.9	3.7	2.3	4.2	9.6
K_L shower	1.3	1.0	1.4	1.4	6.0	8.4	7.2	1.6	2.7
particle ID	1.9	2.5	3.0	6.3	8.2	27.5	6.9	1.1	0.2
split-off rejection	1.5	2.9	3.0	5.0	1.2	9.4	1.8	2.5	5.5
track eff.	3.7	4.5	4.2	2.6	8.6	13.3	9.5	3.4	9.5
track resol.	1.0	1.8	2.4	11.2	6.2	12.7	6.0	2.7	0.9
split-off sim.	0.4	1.4	0.5	2.3	1.0	10.4	1.0	4.7	6.0
K_L production	0.2	0.1	0.2	0.4	0.1	0.8	0.1	0.3	0.1
ν production	0.5	3.5	2.2	2.0	0.6	15.1	4.1	0.9	2.9
Total	6.8	10.4	9.2	17.2	18.7	41.7	19.4	13.5	17.3

Why the π is as easy as pie…
but the ρ is a tough row to hoe!

(%)	$\pi\ell\nu$				$\rho(\omega)\ell\nu$				
		q^2 interval (GeV^2)				q^2 interval (GeV^2)			
Systematic	$\mathcal{B}_{\mathrm{total}}$	< 8	$8-16$	≥ 16	$\mathcal{B}_{\mathrm{total}}$	< 8	$8-16$	≥ 16	η
ν simulation	6.8	10.5	9.2	17.2	18.7	41.7	19.4	13.5	17.3
$B \to D/D^*/D^{**}/D^{\mathrm{NR}}X\,\ell\nu$	1.7	2.5	1.9	3.2	2.0	21.4	4.7	4.2	5.5
$B \to X_u\ell\nu$ feed down	0.5	3.0	1.8	1.9	8.3	23.8	6.1	5.6	1.6
Continuum smoothing	1.0	2.0	0.2	2.0	3.0	10.0	1.0	2.0	2.0
Fakes	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Lepton ID	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
f_{+-}/f_{00}	2.4	2.6	2.3	2.2	0.0	2.5	1.0	0.1	4.1
τ_{B^+}/τ_{B^0}	0.2	0.1	0.3	0.5	2.1	4.2	1.4	2.1	1.4
Isospin	0.0	0.0	0.0	0.2	2.4	1.9	2.7	2.3	0.1
Luminosity	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Upper	**8.6**	12.4	10.7	18.3	**21.4**	53.9	21.5	16.2	**19.3**
Non Resonant	–	–	–	–	-13	-9	-15	-14	
Lower	**8.6**	12.4	10.7	18.3	**25.1**	54.7	26.2	21.4	**19.3**

Summary of Branching Fractions from Nominal Fit

Form-Factor Models: Ball *et al*. (2001) and Ball *et al*. (1998) for π and ρ, respectively (light-cone sum rules)

Mode	$\mathcal{B}_{q^2\,\text{interval}}$ $\times 10^4$	analysis requirement (vector modes) $p_\ell > 1.5$ GeV/c	$p_\ell > 1.75$ GeV/c	$p_\ell > 2.0$ GeV/c
$B^0 \to \pi^- \ell^+ \nu$	$\mathcal{B}_{\text{total}}$	$1.33 \pm 0.18 \pm 0.11$	$1.31 \pm 0.18 \pm 0.11$	$1.32 \pm 0.18 \pm 0.12$
	$\mathcal{B}_{<8}$	$0.43 \pm 0.11 \pm 0.05$	$0.43 \pm 0.11 \pm 0.05$	$0.42 \pm 0.11 \pm 0.05$
	$\mathcal{B}_{8-16}$	$0.65 \pm 0.11 \pm 0.07$	$0.65 \pm 0.11 \pm 0.07$	$0.66 \pm 0.11 \pm 0.07$
	$\mathcal{B}_{\geq 16}$	$0.25 \pm 0.09 \pm 0.04$	$0.24 \pm 0.09 \pm 0.04$	$0.24 \pm 0.09 \pm 0.05$
$B^0 \to \rho^- \ell^+ \nu$	$\mathcal{B}_{\text{total}}$	$2.17 \pm 0.34\ ^{+0.47}_{-0.54}$	$2.34 \pm 0.34\ ^{+0.43}_{-0.51}$	$2.29 \pm 0.35\ ^{+0.40}_{-0.49}$
	$\mathcal{B}_{<8}$	$0.43 \pm 0.20\ ^{+0.23}_{-0.23}$	$0.50 \pm 0.20\ ^{+0.21}_{-0.22}$	$0.62 \pm 0.22\ ^{+0.22}_{-0.23}$
	$\mathcal{B}_{8-16}$	$1.24 \pm 0.26\ ^{+0.27}_{-0.33}$	$1.32 \pm 0.26\ ^{+0.26}_{-0.29}$	$1.11 \pm 0.25\ ^{+0.23}_{-0.25}$
	$\mathcal{B}_{\geq 16}$	$0.50 \pm 0.10\ ^{+0.08}_{-0.11}$	$0.52 \pm 0.10\ ^{+0.08}_{-0.10}$	$0.56 \pm 0.10\ ^{+0.07}_{-0.09}$
$B^+ \to \eta \ell^+ \nu$	$\mathcal{B}_{\text{total}}$	$0.84 \pm 0.31 \pm 0.16$	$0.84 \pm 0.31 \pm 0.16$	$0.83 \pm 0.31 \pm 0.15$

(theory uncertainties not included in table)

Branching-Fraction Form-Factor Model Dependence

e.g., $\rho\ell\nu$

Study effect of form-factor model variation on signal (ρ) and crossfeed (π) components

π Model	ρ Model	$\mathcal{B}_{\text{total}}$ ($\times 10^4$)	$\mathcal{B}_{<8}$	$\mathcal{B}_{8-16}$	$\mathcal{B}_{\geq 16}$	$-2\ln L$
		q^2 interval (GeV^2)				
Ball'01	Ball'98	2.172 ± 0.338	0.429 ± 0.198	1.244 ± 0.256	0.499 ± 0.097	240.3
ISGW2	Ball'98	2.176 ± 0.338	0.430 ± 0.198	1.248 ± 0.256	0.499 ± 0.098	240.7
SPD	Ball'98	2.169 ± 0.338	0.420 ± 0.198	1.250 ± 0.256	0.499 ± 0.098	239.8
$1.7 \times \text{RMS}_{\pi\text{FF}}$		0.01	0.01	0.004	0.004	
$p_\ell > 1.5$ GeV/c						
Ball'01	Ball'98	2.17 ± 0.34	0.43 ± 0.20	1.24 ± 0.26	0.50 ± 0.10	240.3
Ball'01	ISGW2	1.91 ± 0.28	0.30 ± 0.13	1.14 ± 0.23	0.47 ± 0.10	239.4
Ball'01	Melikhov'00	2.56 ± 0.37	0.33 ± 0.15	1.49 ± 0.31	0.75 ± 0.14	240.2
Ball'01	UKQCD'98	2.08 ± 0.32	0.39 ± 0.17	1.21 ± 0.25	0.49 ± 0.10	239.3
$1.7 \times \text{RMS}_{\rho\text{FF}}$		0.41	0.09	0.22	0.19	
$p_\ell > 1.75$ GeV/c						
Ball'01	Ball'98	2.34 ± 0.34	0.50 ± 0.20	1.32 ± 0.26	0.52 ± 0.10	241.6
Ball'01	ISGW2	2.03 ± 0.28	0.34 ± 0.13	1.20 ± 0.23	0.49 ± 0.10	240.3
Ball'01	Melikhov'00	2.74 ± 0.37	0.38 ± 0.16	1.58 ± 0.31	0.78 ± 0.14	241.4
Ball'01	UKQCD'98	2.23 ± 0.32	0.45 ± 0.18	1.28 ± 0.25	0.51 ± 0.10	240.4
$1.7 \times \text{RMS}_{\rho\text{FF}}$		0.44	0.11	0.24	0.20	
$p_\ell > 2.0$ GeV/c						
Ball'01	Ball'98	2.29 ± 0.35	0.62 ± 0.22	1.11 ± 0.25	0.56 ± 0.10	244.2
Ball'01	ISGW2	1.89 ± 0.27	0.38 ± 0.13	0.98 ± 0.22	0.54 ± 0.09	243.4
Ball'01	Melikhov'00	2.66 ± 0.38	0.48 ± 0.17	1.36 ± 0.31	0.83 ± 0.14	244.6
Ball'01	UKQCD'98	2.15 ± 0.32	0.54 ± 0.19	1.07 ± 0.24	0.55 ± 0.09	243.3
$1.7 \times \text{RMS}_{\rho\text{FF}}$		0.47	0.15	0.24	0.21	

Reduction of Model Dependence: q^2 Binning

Branching Fraction Fit Results

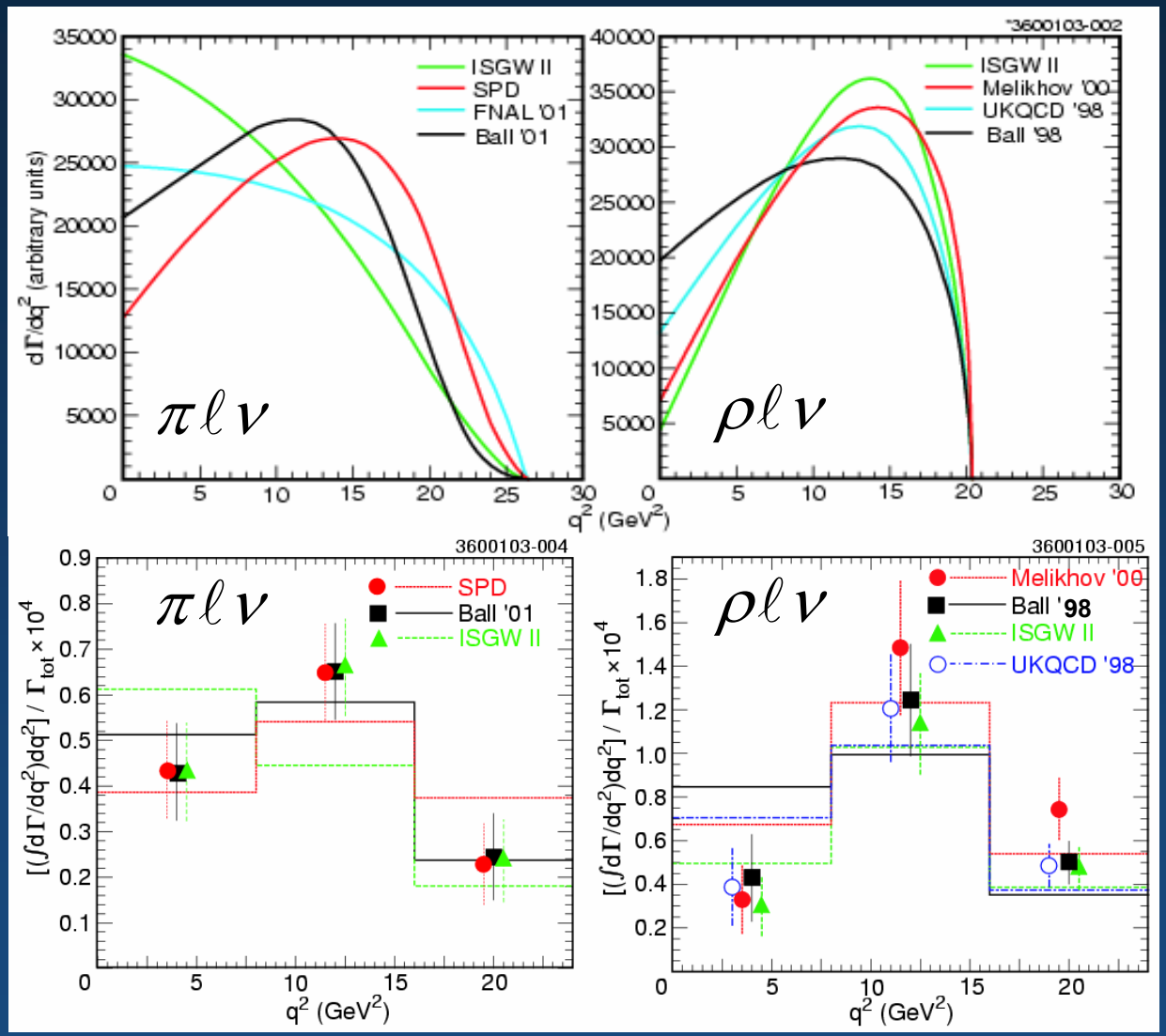
Only sensitive to FF shapes within a given q^2 bin

$|V_{ub}|$ Fits

Can discriminate between FF models

$$\mathrm{Br}(B^0 \to \pi^- \ell^+ \nu) = \left[13.3 \begin{array}{ll} \pm 1.8 & \text{stat} \\ \pm 1.1 & \text{syst} \\ \pm 0.1 & B \to \pi \text{ FF} \\ \pm 0.7 & B \to \rho \text{ FF} \end{array} \right] \times 10^{-5}$$

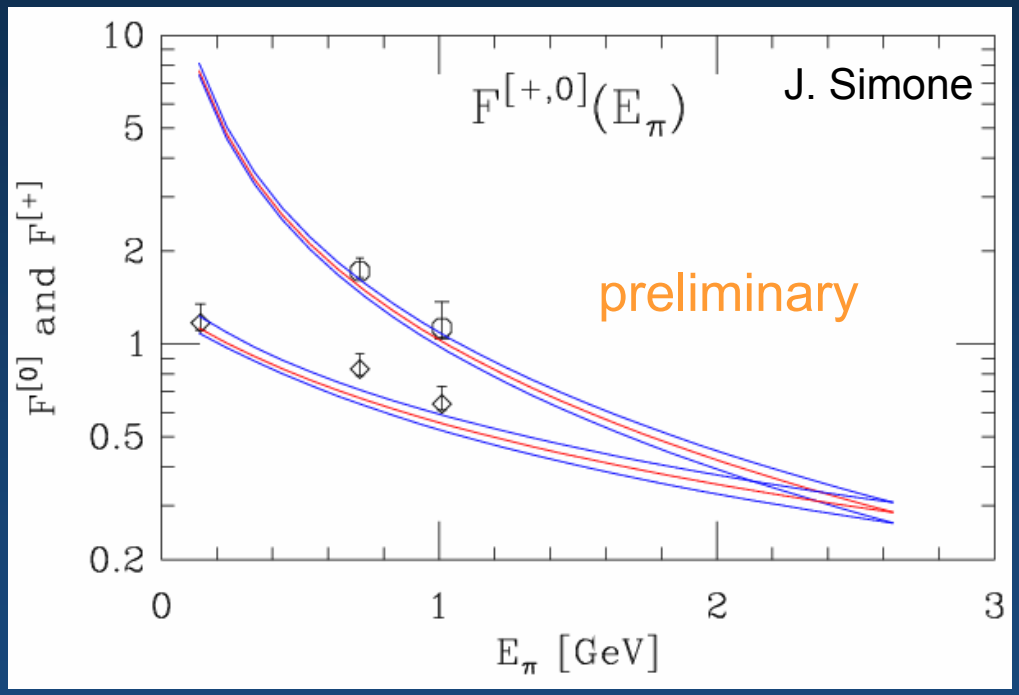
$$\mathrm{Br}(B^0 \to \rho^- \ell^+ \nu) = \left[21.7 \begin{array}{ll} \pm 3.4 & \text{stat} \\ {}^{+4.7}_{-5.4} & \text{syst} \\ \pm 4.1 & B \to \rho \text{ FF} \\ \pm 0.1 & B \to \pi \text{ FF} \end{array} \right] \times 10^{-5}$$

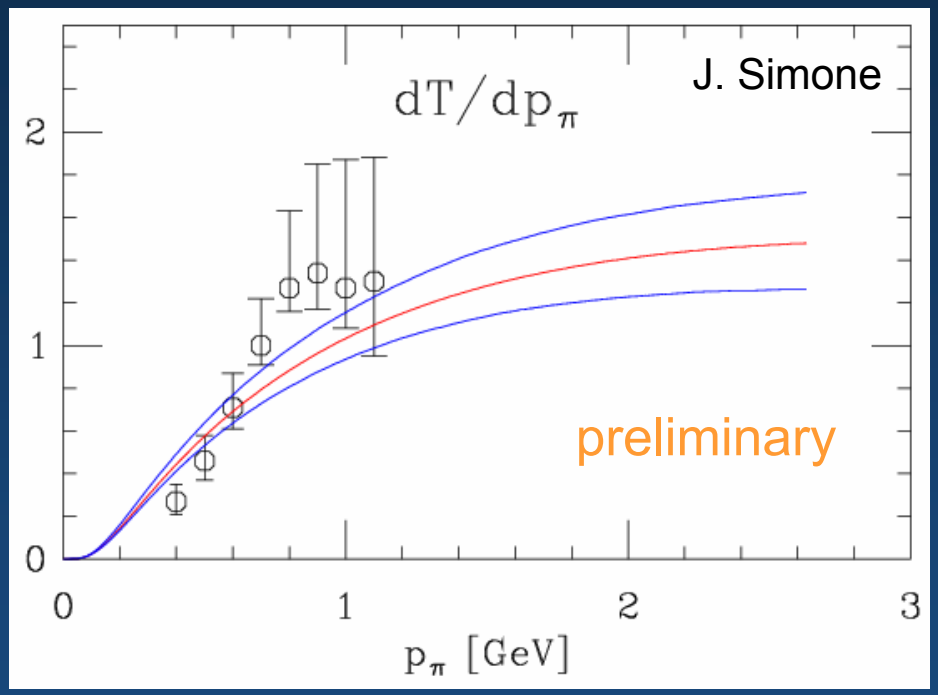


ISGW2 disfavoured in π fits!

Special Thanks to A. Kronfeld and J. Simone

[El-Khadra, Kronfeld, Mackenzie, Ryan, and Simone, PRD 64, 014502 (2001)]





[Becirevic, Kaidalov, PLB 478, 417 (2000)]

Checkpoint

So Far…

Branching-Fraction Fits

Next…

Determining $|V_{ub}|$

Approach to $|V_{ub}|$ Extraction

Use only QCD calculations with reliable uncertainties (skip the quark models)

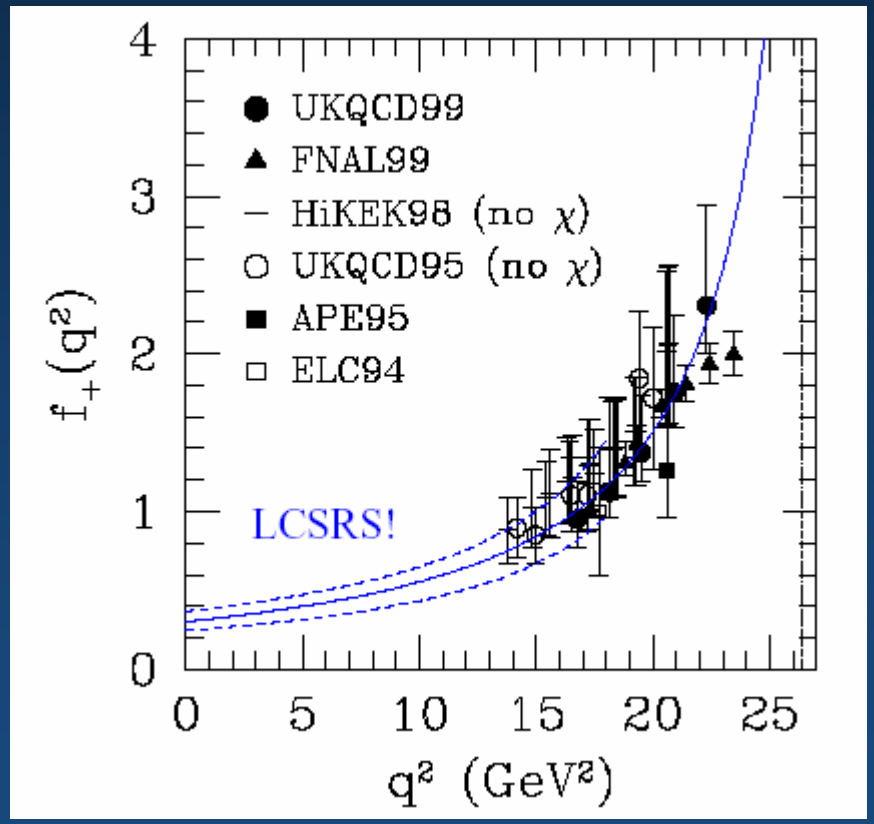
Light-Cone Sum Rules (LCSR)

- Valid for $E_{\pi,\rho} \gg \Lambda_{QCD}$
- Use two q^2 bins below 16 GeV^2

Lattice QCD (LQCD) [presently quenched]

- At low meson energies, uncertainties are under control:
  - discretization
  - statistics
- Use q^2 bin above 16 GeV^2
  - FNAL LQCD (Kronfeld, Simone)
  - Japan LQCD (Onogi)

Assess all experimental systematic uncertainties in $|V_{ub}|$ fits to accommodate correlations



Newly Final! CLEO Exclusive $|V_{ub}|$ Result

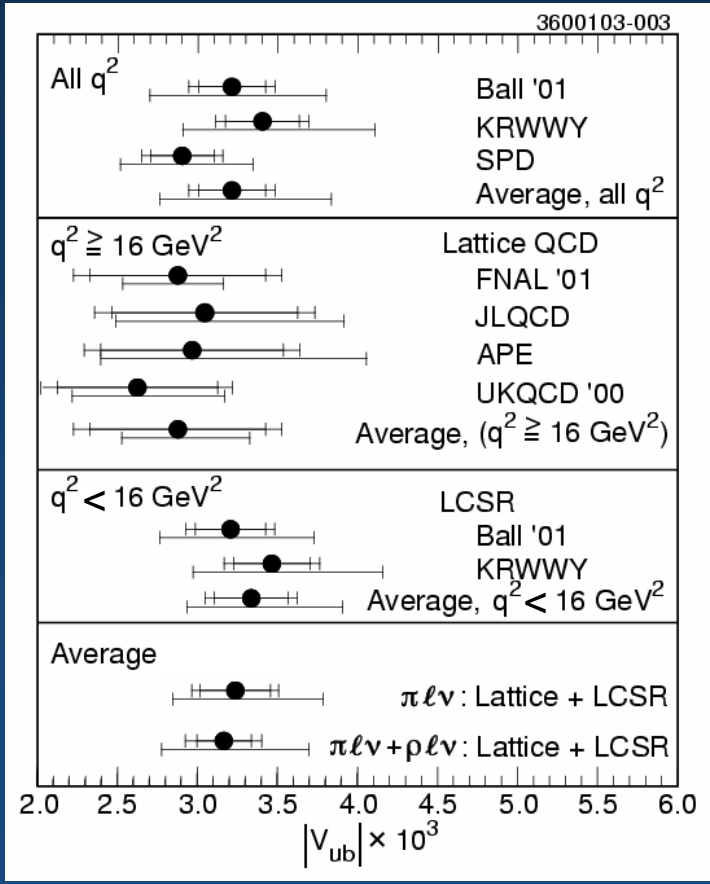
Optimally Combining π, ρ, LQCD, LCSR:

$$|V_{ub}| = \left[31.7 \pm 1.7\big|_{stat} \; {}^{+1.6}_{-1.7}\big|^{expt}_{syst} \; {}^{+5.3}_{-3.9}\big|^{theor}_{LQCD/LCSR} \pm 0.3\big|^{theor}_{\rho\ell\nu\ FF} \right] \times 10^{-4}$$

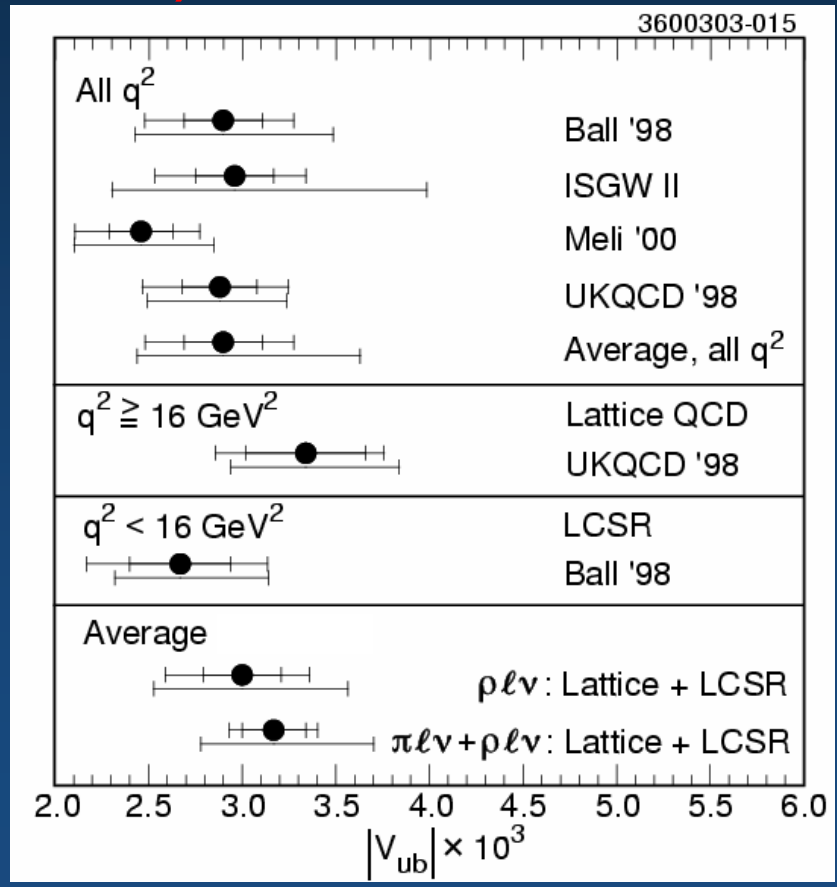
hep-ex/0304019

Accepted by Phys. Rev. D

$B \to \pi \ell \nu$



$B \to \rho \ell \nu$



Error Bars

Upper: Experimental stat ⊕ syst

Lower: Theoretical

Checkpoint

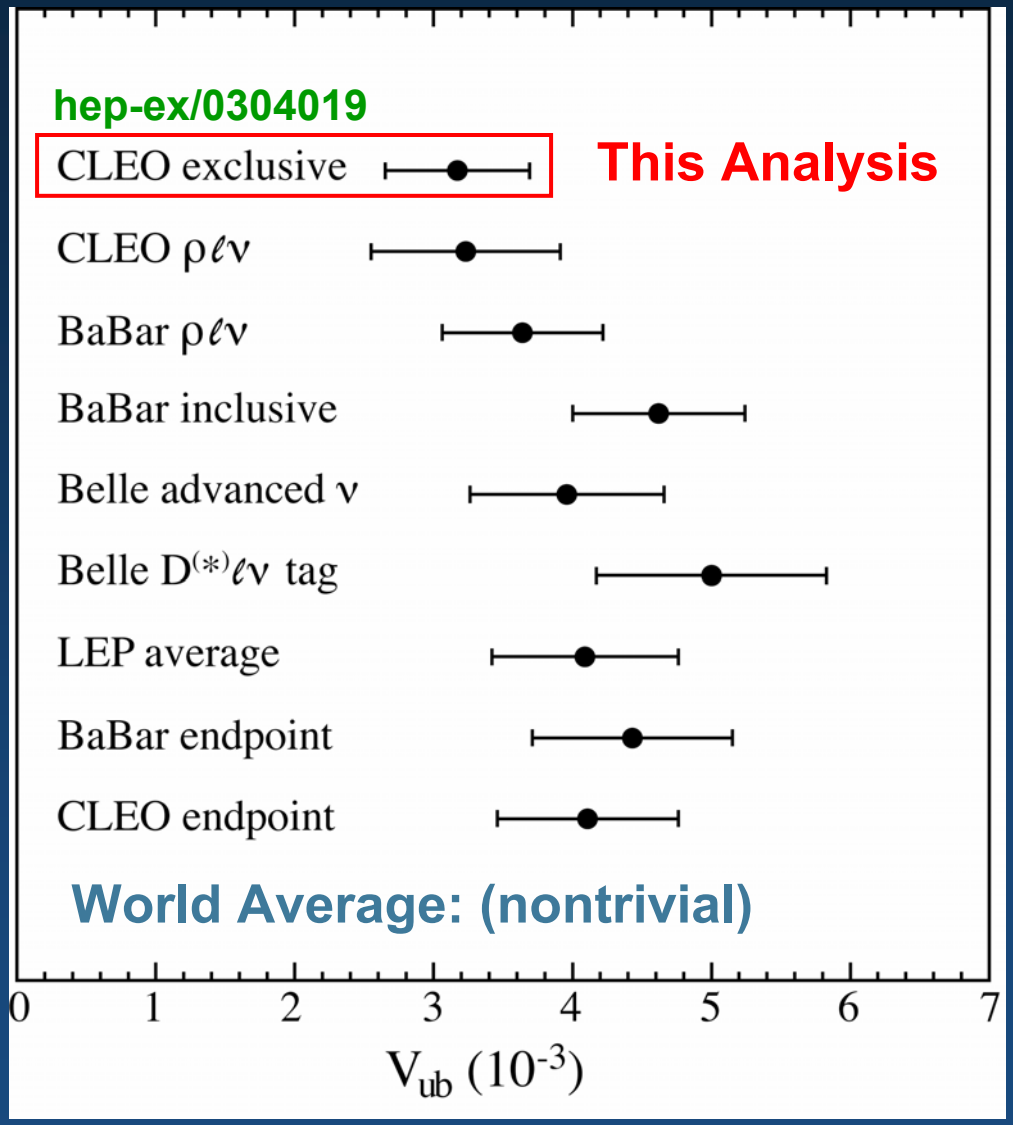
So Far…

Determining $|V_{ub}|$

Next…

Worldwide Status
Future
Conclusion

Status of $|V_{ub}|$ Measurements Worldwide



Weak hint of an Exclusive vs. Inclusive difference?

World Average requires:

- treatment of correlations between $b \to c$ background models
- treatment of correlations between $b \to u$ signal and feeddown models
- consistent use of theoretical FF calculations
- consistent procedures for combining theory uncertainties

The Future

hep-lat/0304004

High-Precision Lattice QCD Confronts Experiment

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(Dated: 31 March 2003)

We argue that high-precision lattice QCD is now possible, for the first time, because of a new improved staggered quark discretization. We compare a wide variety of nonperturbative calculations in QCD with experiment, and find agreement to within statistical and systematic errors of 3% or less. We also present a new determination of $\alpha_{\overline{\rm MS}}^{(5)}(M_Z)$; we obtain 0.121(3). We discuss the implications of this breakthrough for phenomenology and, in particular, for heavy-quark physics.

PACS numbers: 11.15.Ha,12.38.Aw,12.38.Gc

⟺ **CLEO-c**

- Approved
- Detector upgrade done
- On the roll…

Concluding Remarks

- $|V_{ub}|$ is interesting:
  - fundamental
  - intimate with CP violation
  - currently holding up the CKM show (Theor.: QCD; Expt.: difficult, lengthy)
- CLEO measures $|V_{ub}|$ exclusively with total uncertainty +18% / –14% by simultaneously reconstructing 7 signal decay chains
- Analysis uses improved techniques to
  increase kinematic acceptance,
  improve background characterization, &
  improve neutrino resolution
- Demonstration that measuring partial rates can both
  - confront form-factor calculations
  - markedly reduce effects of theoretical uncertainties
- $|V_{ub}|$ measurements are currently limited by theory and systematics
- With unquenched lattice QCD calculations coming soon, exclusive techniques are a promising route to $|V_{ub}|$ to $<\pm 10\%$!