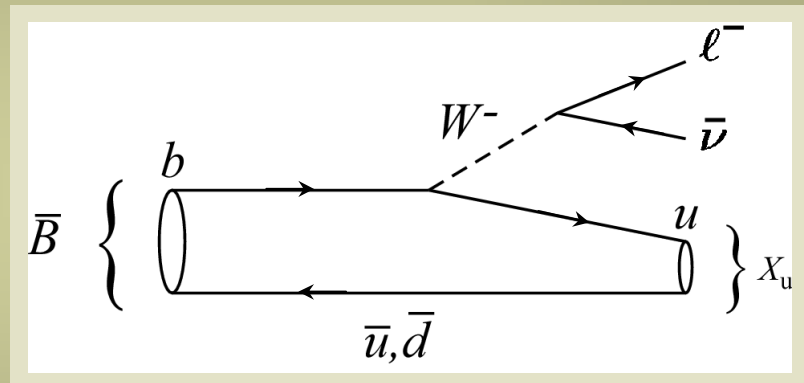


Limits on Weak Annihilation in Inclusive $B \rightarrow X_u l \nu$ Decays

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20 Dec 2004 – Thesis Defense

- The Standard Model
- $|V_{ub}|$ and Weak annihilation
- Creating B 's in the lab
- Reconstructing $B \rightarrow X l \nu$
- Modeling the data
- Fitting the data
- Results
- Systematic errors
- Future



Features of the Standard Model

The Standard Model

- Matter is composed of quarks and leptons
- Interactions are mediated by the exchange of force-carrying bosons

FERMIONS					
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	-1	d down	0.006	-1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	-1	b bottom	4.3	-1/3

PROPERTIES OF THE INTERACTIONS					
Property \ Interaction	Gravitational	Weak (Electroweak)		Strong	
		Flavor	Electric Charge	Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W⁺ W⁻ Z⁰	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at:	10^{-41}	0.8	1	25	Not applicable to quarks
for two protons in nucleus	10^{-41}	10^{-4}	1	60	
	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Quark Mixing

- Charged weak interaction couples up- and down-type quarks

$$t \rightarrow bW$$

$$c \rightarrow sW$$

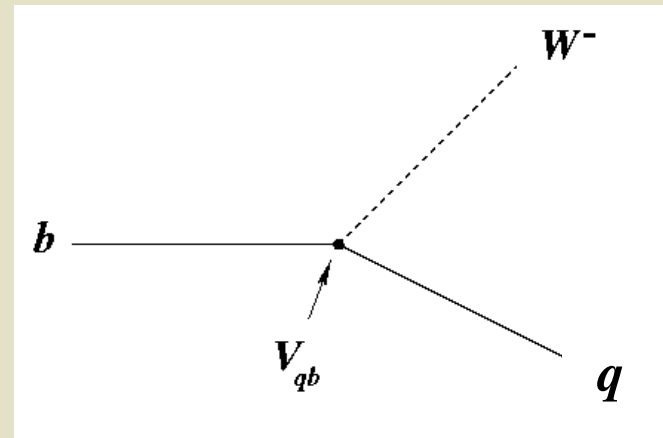
$$u \rightarrow dW$$

- But also **between** families

$$u_i \rightarrow d'_i W = \left(\sum_j V_{ij} d_j \right) W$$

- Mixing very generally described by CKM matrix

$$\S V_{ij} : u_i \leftrightarrow d_j \text{ coupling}$$



$$\mathcal{A}(b \rightarrow q W) \sim V_{qb}$$

CKM Matrix

- 3×3 unitary matrix – 9 complex elements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

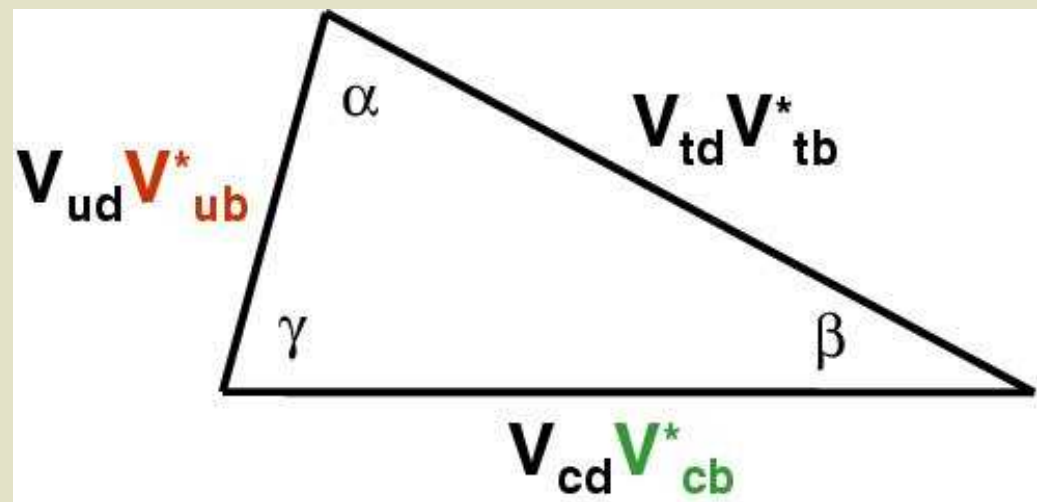
- Only 4 indep. real parameters (3 angles, 1 phase)
- Phase is integral to SM explanation of CP violation
 - § Essential ingredient in explaining “Where did all the antimatter go?”
- Ubiquitous in description of weak decays

A Window to New Physics

- Numerous experimental avenues for measuring V_{ij}
- Test consistency of measurements by checking unitarity

$$(V)_i^T \cdot (V)_j = \delta_{ij}$$

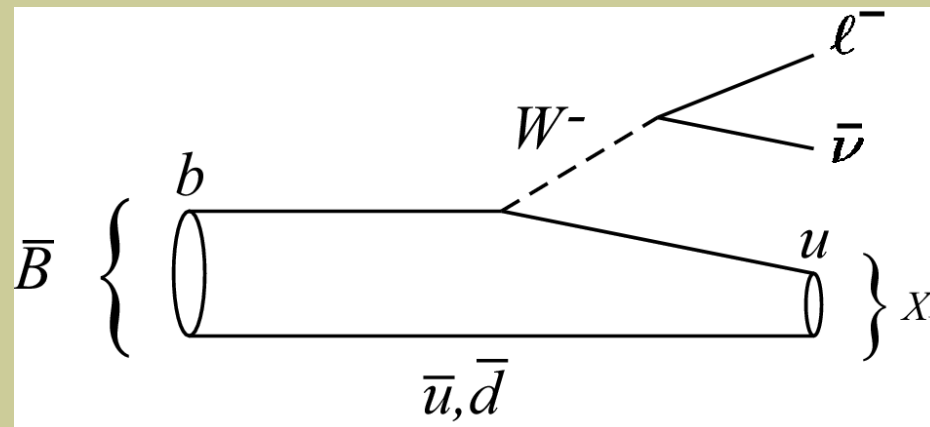
- § Orthog. relns are zero-sum triangles in complex plane
- § For d, b columns, sides are of same scale



- Ultimately tests Standard Model against itself
 - § Inconsistencies \Rightarrow **New Physics?**

Semileptonic B Decay

- Decay of b the quark is an excellent laboratory for studying the $b \rightarrow u$ transition and measuring $|V_{ub}|$
- Leptonic decay of W is convenient
 - § Clean experimental signature; define $q^2 = (p_l + p_\nu)^2$
 - § Eliminates complications from final-state interactions

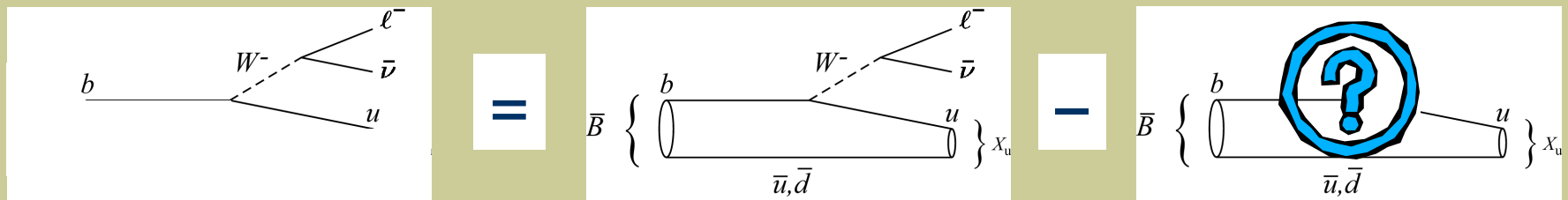


- But quarks are not found alone in nature!
- \Rightarrow Bound by strong force into hadrons

$$\bar{B}_q \equiv (b\bar{q})$$

Strong Interactions

- Measuring $|V_{ub}|$ requires disentangling weak $b \rightarrow u$ decay from background strong dynamics



- Difficult because strong interaction is **non-perturbative** in this regime—usual tools of perturbation theory don't apply
 - § Bad news for $|V_{ub}|$
 - § For that matter, how do we do *any* quark physics?!

Theory

Inclusive $b \rightarrow u l \nu$

- **Inclusive** measurements sum over a set of final states, *e.g.*

“all B decays yielding $X_u + l + \nu$, any X_u ”

§ Effectively “averages” over hadronic details of final state

- Non-perturbative physics of initial-state meson handled with **heavy quark expansion**

§ Rigorous framework for systematics corrections to heavy quark limit

▶ In $m_Q \rightarrow \infty$ limit, light degrees of freedom in the meson are insensitive to flavor, spin of Q

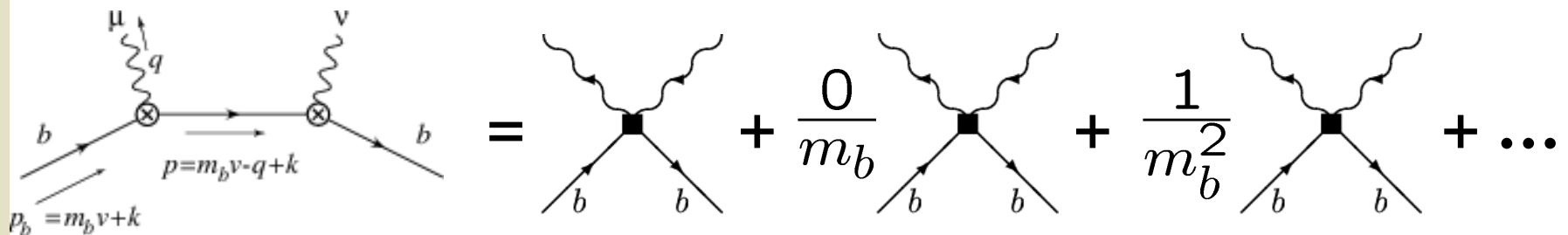
§ Exploits separation in scales between heavy quark mass m_Q and hadronic binding Λ_{QCD}

$$m_b \sim 5 \text{ GeV} \gg \Lambda_{\text{QCD}} \sim 250 \text{ MeV}$$

Inclusive $b \rightarrow u l \nu$

- Resulting **Heavy Quark Effective Theory** provides a framework for calculating decay rates
 - § An operator-product expansion in powers of Λ/m_b
 - § Non-perturbative parameters are introduced at every order that wrap up the long-distance hadronic physics of **initial** state
 - § Parameters are to some extent universal across B decays

$$\Gamma(b \rightarrow ul\nu) = \Gamma_0 \left(1 + \frac{f(\lambda_1, \lambda_2)}{m_b^2} + \dots \right)$$



$|V_{ub}|$ from $b \rightarrow u l \nu$

- Ignorance of strong physics is organized—not eliminated
- Nonetheless, possible to relate $|V_{ub}|^2$ to experimental measurements of $\Gamma(b \rightarrow u l \nu)$
 - ... using a truncation of the infinite expansion
- Neglected terms constitute corrections
 - § Subject to ability to determine incalculable non-pert. parameters
- Extracted values of $|V_{ub}|$ suffer from large theoretical uncertainties as a result

Weak Annihilation

- Four-quark operator at order $(\Lambda/M_B)^3$ in HQE

$$\mathcal{A}_{\text{WA}} = \frac{1}{2M_B} \langle B | \bar{b}_L \gamma_\alpha \underline{u}_L \bar{u}_L \gamma_\beta b_L | B \rangle (\delta_{\alpha\beta} - v_\alpha v_\beta)$$

- § One of several “spectator-dependent” terms
 - § Associated with presence of a $q\bar{q}$ pair of the same flavor
 - § Simplest diagram is analagous to parton annihilation in $B \rightarrow l \nu$
 - § ... But subtle dynamical effects arise at higher-orders
- Impact on rate can be parameterized as

$$\delta\Gamma_{\text{WA}} \doteq \langle B | \mathcal{A}_{\text{WA}} | B \rangle = \frac{G_F^2 |V_{ub}|^2 f_B^2 m_b^2 M_B}{12\pi} (B_2 - B_1)$$

- QCD factorization: Expect $B_2 = B_1 = 0$

Weak Annihilation

- Little is known beyond a few basic properties

- § Contribution relative to total rate is expected to be small

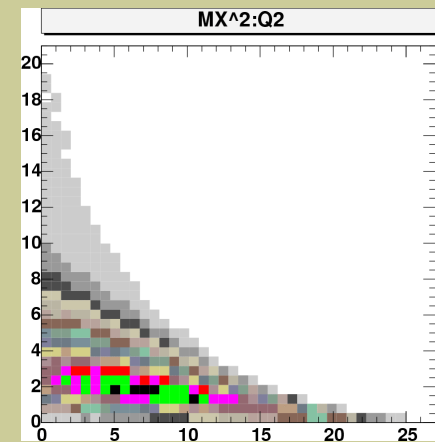
$$\Gamma_{\text{WA}} / \Gamma_{b \rightarrow u l \nu} \sim 2\text{-}5\%$$

Set by scale of violation of factorization ($\sim 10\%$ est.)

- § **Non-trivial** distribution across phase space

$$d\Gamma_{\text{WA}}/dq^2 \propto \delta(q^2 - m_b^2)$$

⇒ Potential impact on $|V_{ub}|$ extraction depends on what part of phase space is sampled by the experimental measurement

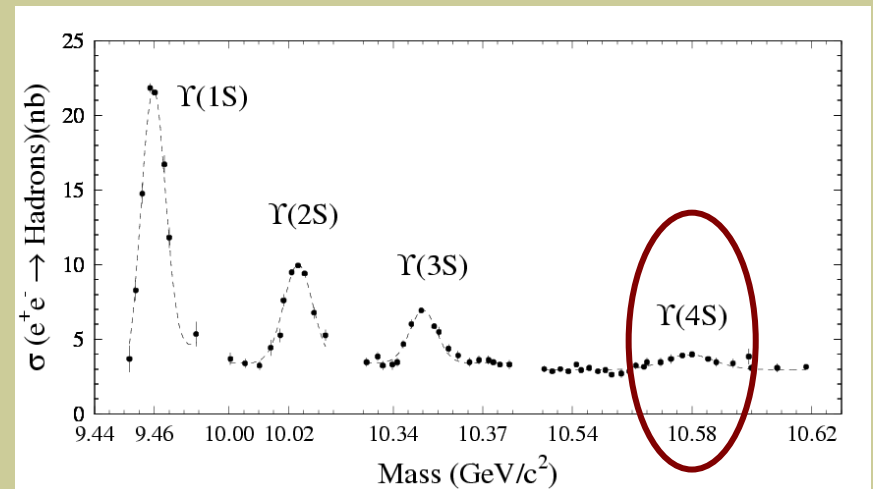
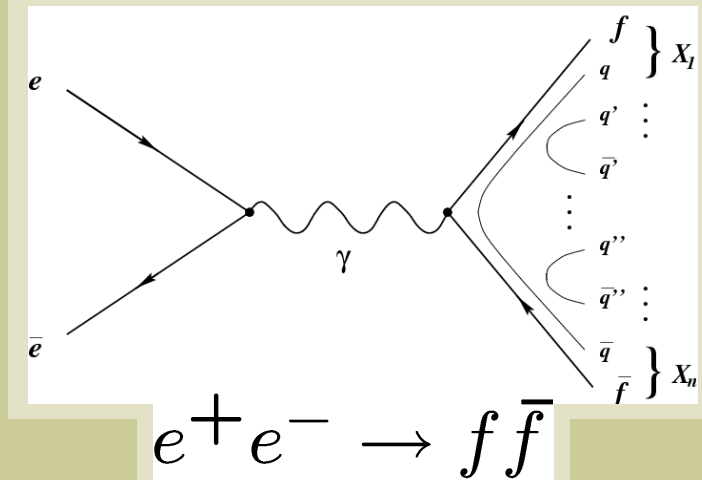


We try to constrain WA using CLEO data

Experiment

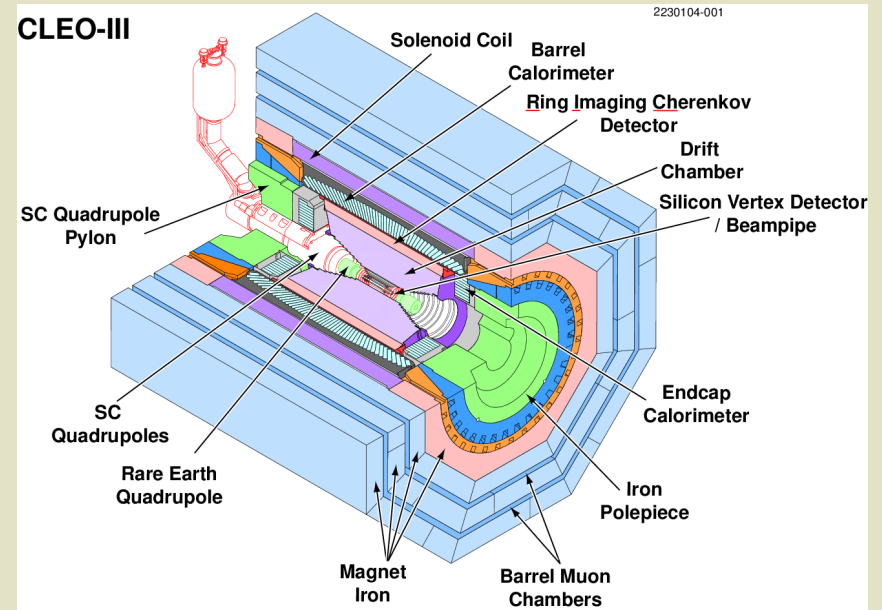
Making Big B 's

- Collide electrons and positrons at high-energy in CESR accelerator
 - § Annihilation produces fermion pair $f\bar{f}$, with $f = u, d, c, s, b, \ell$
 - § For $E_{\text{cm}} \sim 10.6$ GeV, enough energy is available to turn a pair of b quarks into a pair of B mesons
 - § Not every $e^+ e^-$ collision results in $\Upsilon(4S) \rightarrow B\bar{B}$



CLEO Detector

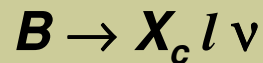
- Measure properties of particles produced in the $e^+ e^-$ collision
 - § Trajectories
 - § Kinematics
 - § Identity
- Cylindrical geometry
- Different subdetectors target different particles or different properties of the same particle
 - § **Drift chamber** records paths of charged particles \Rightarrow “**Tracks**”
 - § **Calorimeter** measures energy deposited by charged and neutral particles \Rightarrow “**Showers**”



- 10 M $B\bar{B}$ events collected with CLEO II, II.V detectors

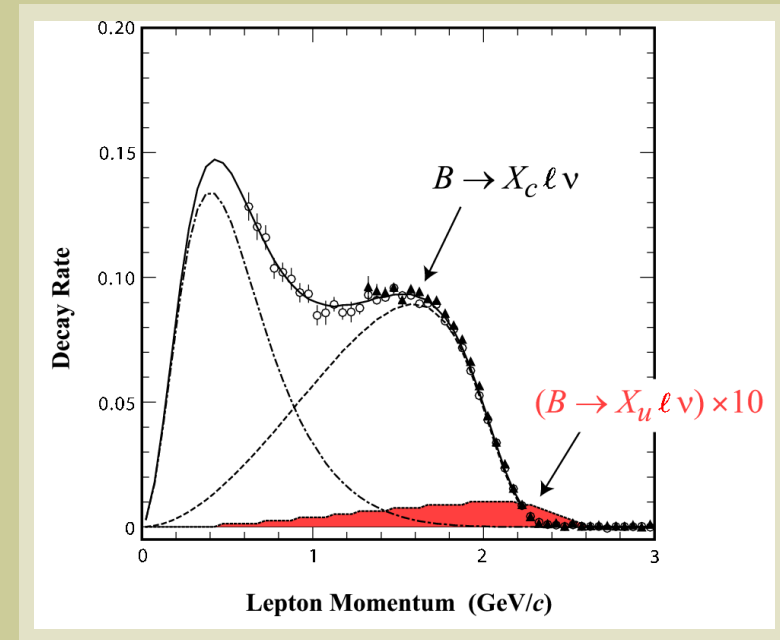
$B \rightarrow X_u l \nu$ at CLEO

- Inclusive analysis
 - § Identify lepton (e, μ)
 - § “Reconstruct” neutrino
- Must discriminate against
 - § Non- BB events
 - § Other B decays that look like our signal
- Chief background is from



- § Experimental fact that

$$\frac{|V_{ub}|}{|V_{cb}|} \approx 0.08$$



⇒ Signal decay is swamped by a much larger background

Neutrino Reconstruction

- Neutrinos leave no visible trace
- But apply (E, p) conservation to the event

$$\begin{aligned}
 p_{\text{initial}} &= p_{\text{final}} \\
 &= \sum_i p_i \\
 &= \sum_{\text{charged}} p_i + \sum_{\text{neutral}} p_i \\
 &\simeq \underbrace{\sum_{\text{charged tracks}} p_i + \sum_{\text{neutral showers}} p_i}_{\text{detector signatures}} + p_\nu
 \end{aligned}$$

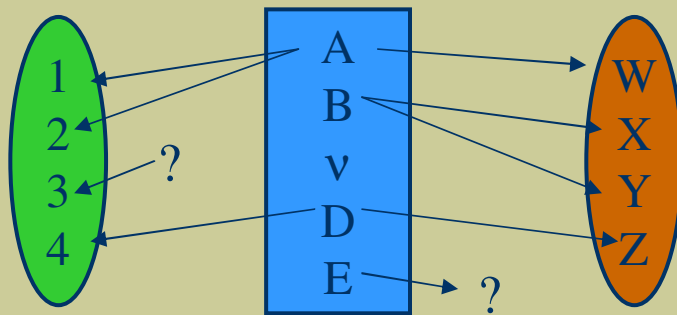
beam
conditions

detector
signatures

- **Infer** neutrino kinematics, assuming
 - § We saw everything else in the event
 - § What we saw has been measured accurately

If You Start out Right . . .

- Veto events with features that suggest anything, anywhere might have gone wrong
 - § Additional missing particles
 - ▶ $N_{lep} > 1 \Rightarrow N_\nu > 1$ (likely)
 - ▶ Missing momentum points down beampipe
 - § $E_{miss} < 0$ (unphysical)
 - § Expect $\sum_i Q_i = 0$
- Identify reconstruction mistakes to avoid double-counting



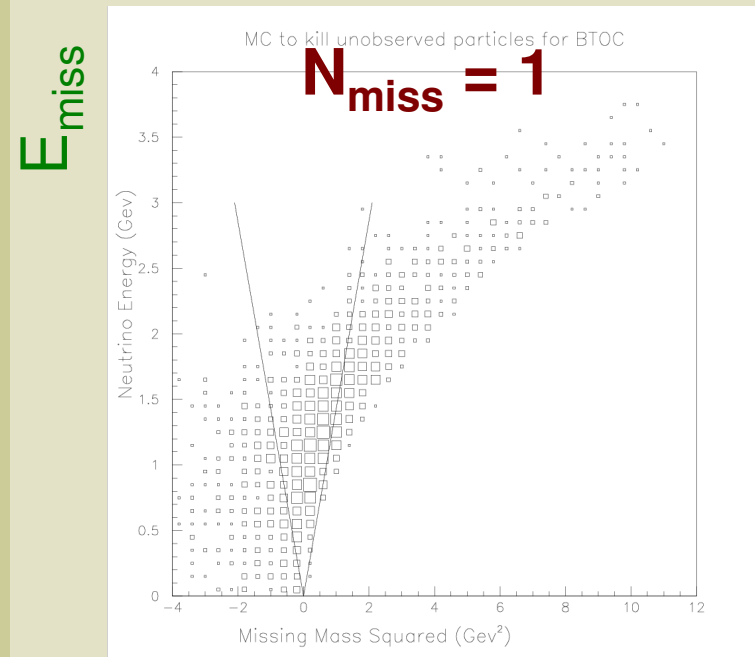
Tracks

(Cor

Particles

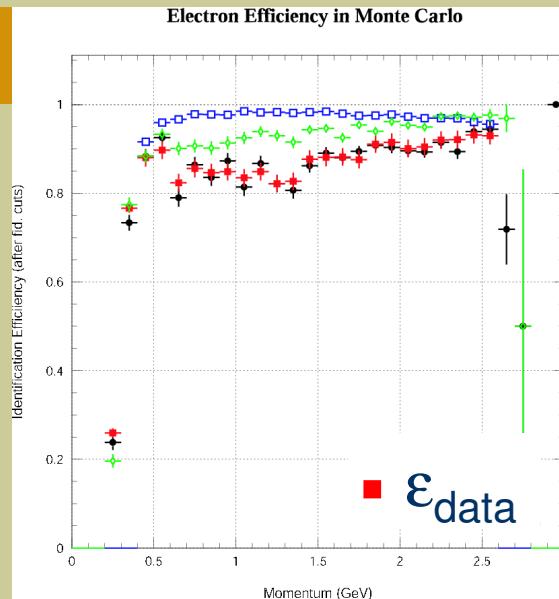
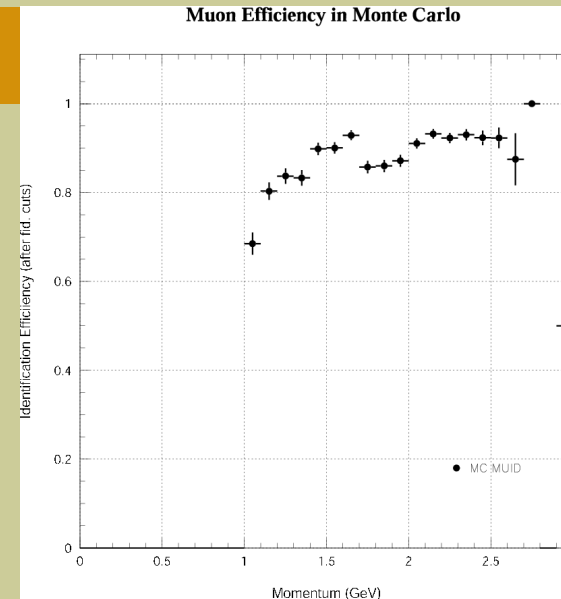
Showers

- Confirm consistency of indep. measured E_{miss} and p_{miss}



$$MM^2 = E_{miss}^2 - p_{miss}^2$$

Lepton Identification

 e  μ 

- e -likelihood combines
 - § $E_{\text{CC}}/p_{\text{trk}}$ (≈ 1 for e)
 - § Shower shape variables
 - § dE/dx information
- Good eff'y down to low momentum

- Muons must penetrate at least $3 X_0$ of iron absorber and reach instrumented layers of muon chambers

Expectations

What We Expect in the Data

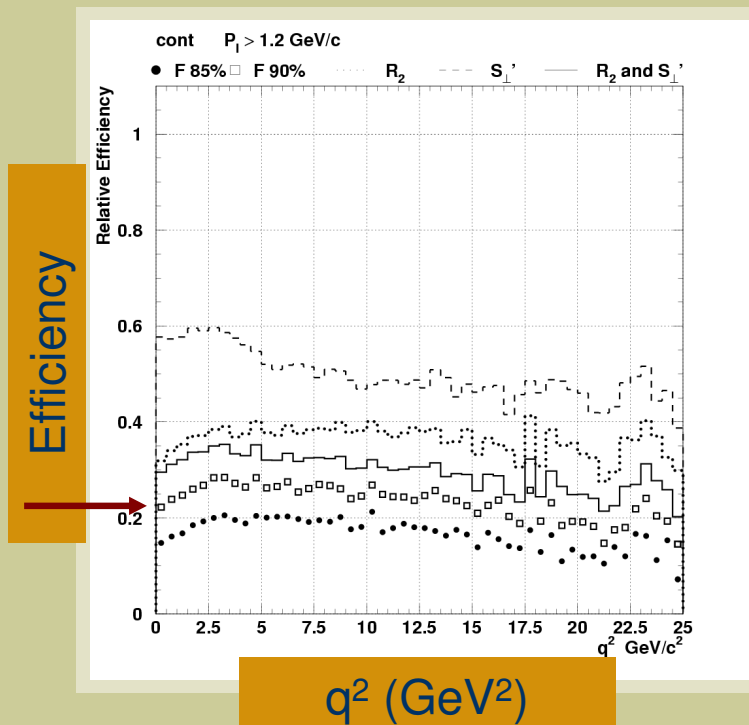
- Signal sample is based on
 - § Identifying a high-momentum lepton, $|p_{lep}| > 1.5 \text{ GeV}$
 - § Successfully reconstructing a neutrino
- But inevitably also include
 - § Continuum events $e^+e^- \rightarrow q\bar{q}$, $q \neq b$
 - § Events with “fake” signal leptons
 - § $B \rightarrow X_c l \nu$ events
- To extract $b \rightarrow u l \nu$ signal
 - § Reduce backgrounds as much as possible
 - § Model surviving background with **data**, when possible
 - § Use simulated event samples to stand in for what can't be measured directly

Continuum Background

- Suppress with cuts based on event “shape”

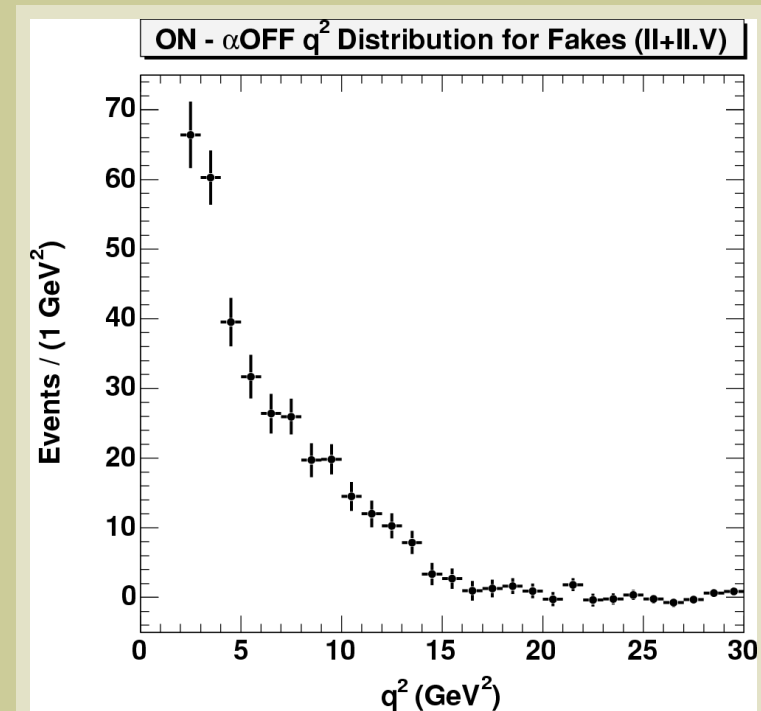
- Account for remainder with data collected below $Y(4S)$
- In the sense of distributions,

$$B\bar{B} \doteq \text{ON} - \alpha \text{OFF}$$



Fake Lepton Background

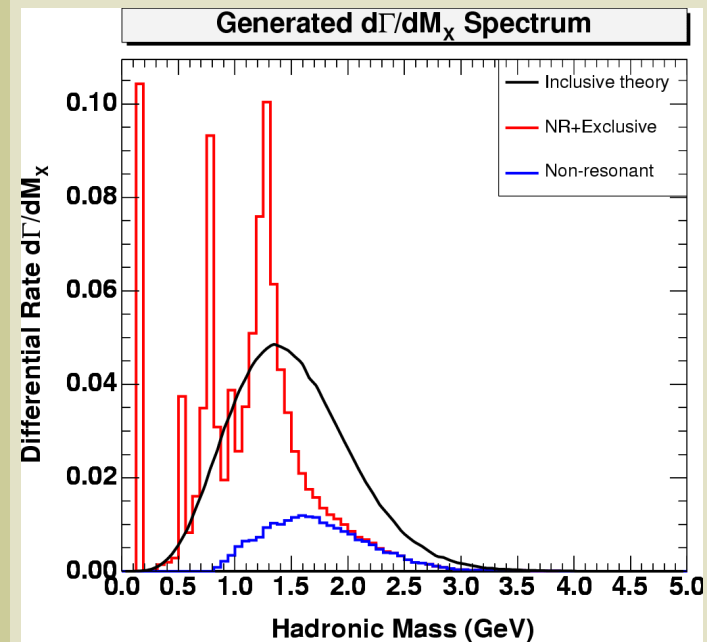
- Hadrons are occasionally mis-identified as leptons
 - § Allows random events into signal sample
- Model contribution using non-leptonic events
 - § Analyze each event in the sample as if a selected track had been identified as the signal lepton
 - § Weight result by fake rate for chosen track
- Entirely based on data



q^2 distribution of fake lepton events

$b \rightarrow u l \nu$ Signal

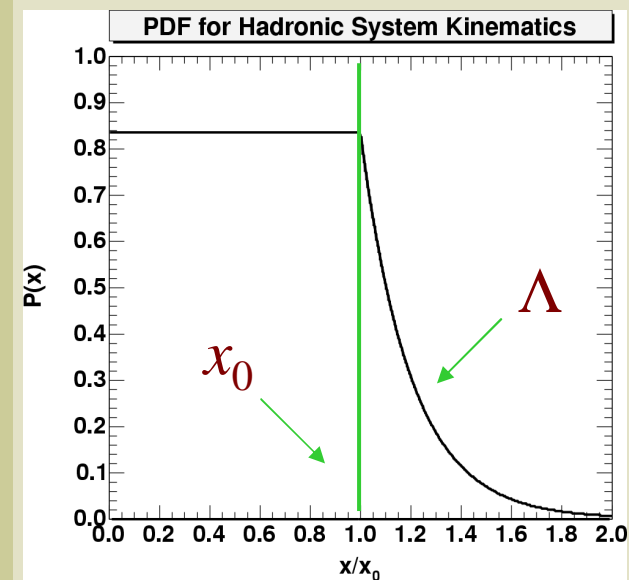
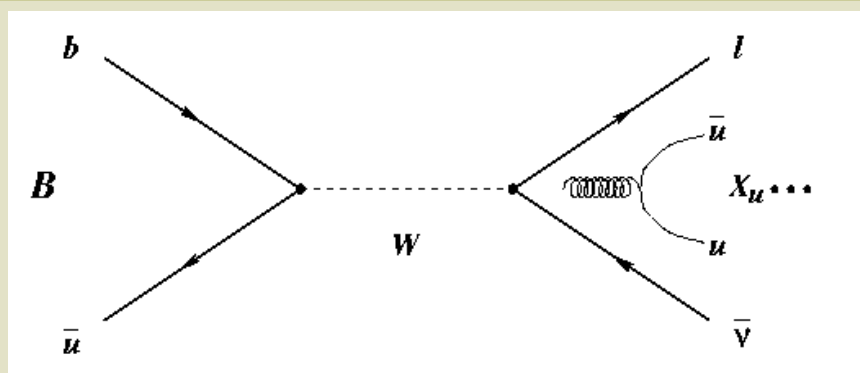
- True spectrum contains contributions of two types
 - § X_u resonances: π, ρ, \dots
 - ▶ Few predictions cover all resonances
 - ▶ Often model-based
 - § Non-resonant n -body states
- Theory prediction
 - § HQET-based, tied to QCD
 - § Inclusive – finer hadronic details are averaged over
- Simulation must blend measurement with prediction . . .



- New event generator (“**InclGen**”) assigns rate according to inclusive mass spectrum, to
 - § Known resonances (ISGW2)
 - § Non-resonant decays

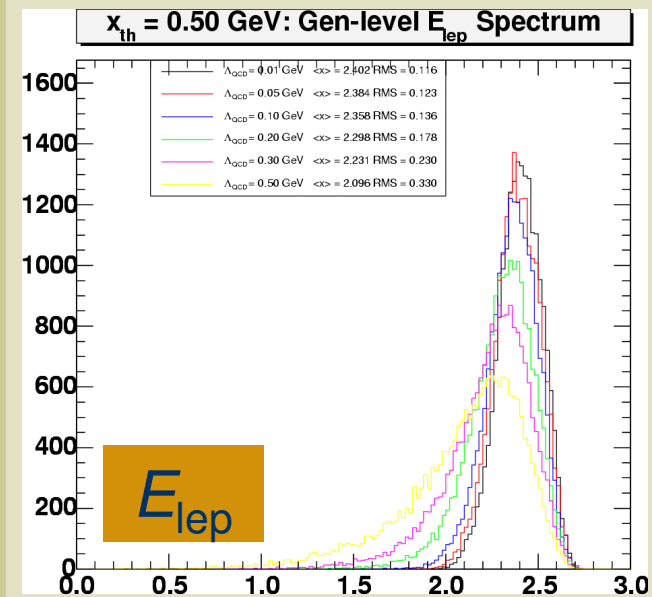
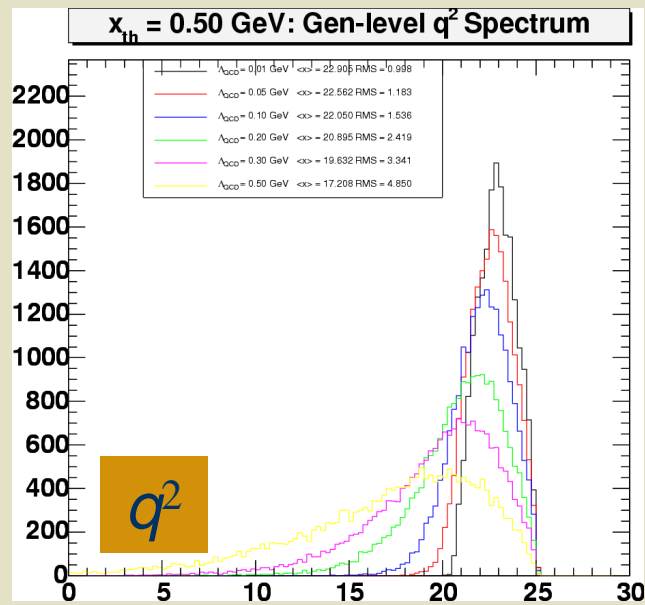
Model for WA

- Model based on leading-order annihilation graph
 - § Lepton and neutrino carry most of the energy
 - § “Soft” hadronic system appears in the debris
 - ▶ All kinematics $\sim \Lambda_{\text{QCD}}$



- M_X, p_X pulled from soft pdf
 - § Box of width x_0
 - § Exponential rolloff $\propto e^{-(x-x_0)/\Lambda}$
- X_u decayed non-resonantly
- $(l\nu)$ system V-A, $s_X = 0$

Ali Baba and the Thirty Samples



- Parameters of model varied through $5 \times 6 = 30$ different values

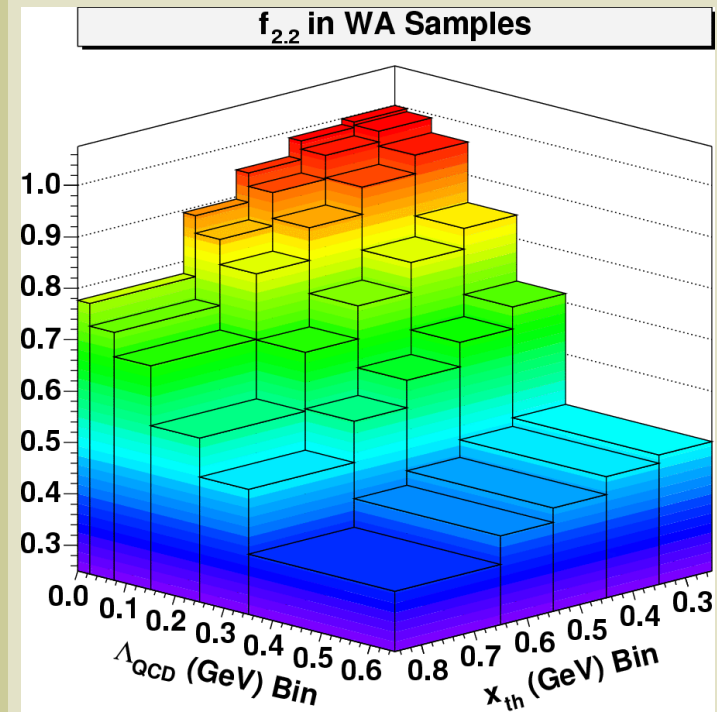
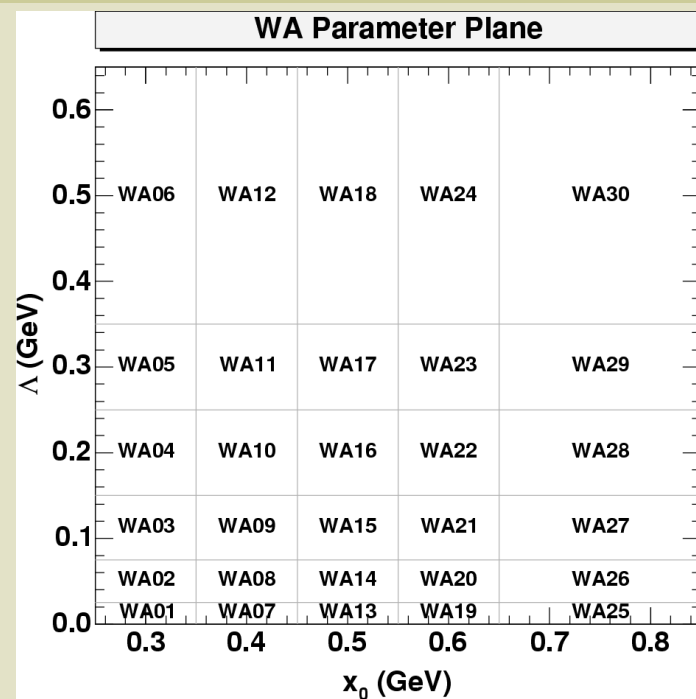
$$x_0 = 0.30 \dots 0.75 \text{ GeV}$$

$$\Lambda = 0.01 \dots 0.50 \text{ GeV}$$

- Each 100 K event sample represents a possible “realization” of WA

WA Sample Characteristics

- View parameter space a 2-D plane, Λ vs. x_0
- 1 bin/sample, center at $(x_0^{(i)}, \Lambda^{(i)})$

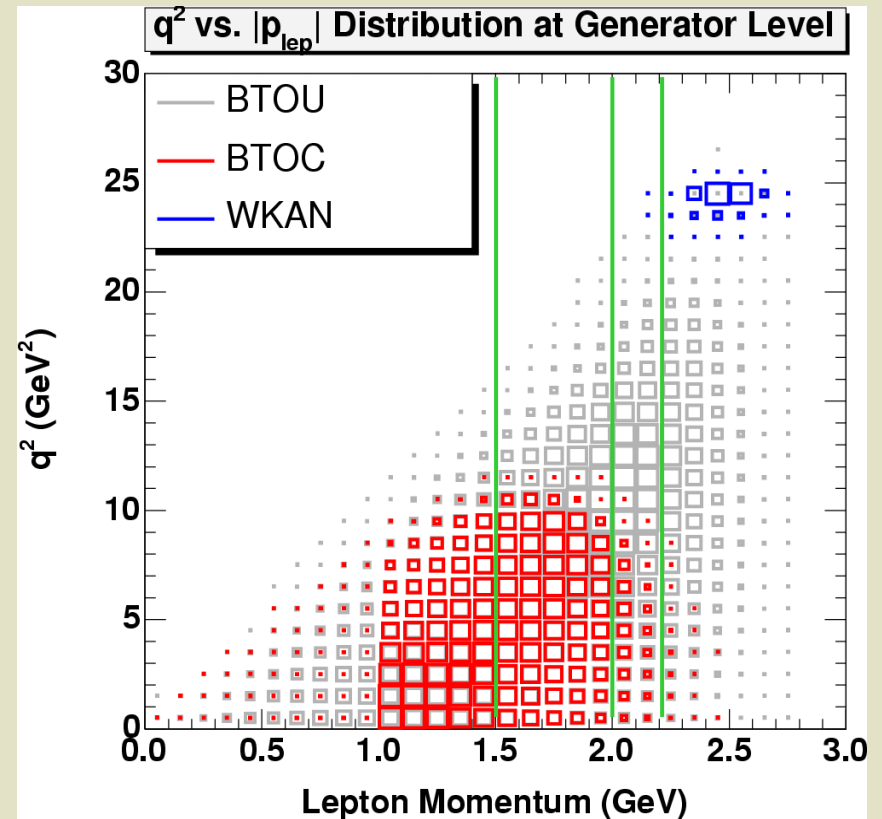


Fraction of rate with
 $E_{lep} > 2.2 \text{ GeV}$

Fit

Fit Strategy

- Two kinematic variables available
 - ⇒ q^2
 - ⇒ Lepton momentum
- Separation available in each
- Use a **binned fit** in both variables



q^2 bins: 1 GeV² each

$|p_{lep}|$ bins: 1.5-2.0, 2.0-2.2, 2.2+ GeV

Fit

- Minimize χ^2 fit statistic
- Fix ctm and fake contributions
- **Float** other normalizations
 - § $f_i N_i^{\text{source}}$
- **Run fit with each WA sample in turn**

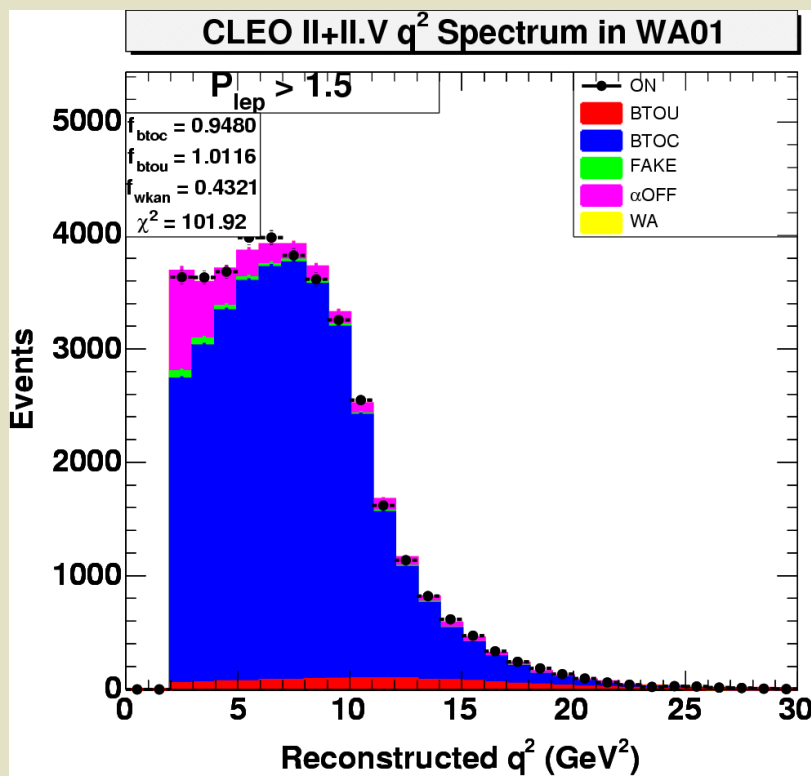
Sum gives total $b \rightarrow u l \nu$ rate

$$\chi^2 = \sum_{p_\ell \text{ bins}} \sum_{q^2 \text{ bins}} \left(\frac{N_i^{\text{data}} - N_i^{\text{pred}}}{\sigma_i} \right)^2$$

- N_{data} is from on-resonance data
- N_{pred} includes sum over all contributing sources
 - § Scaled off-resonance data (ctm)
 - § Scaled fake lepton data (fakes)
 - § $b \rightarrow c l \nu$ Monte Carlo
 - § InclGen $b \rightarrow u l \nu$ Monte Carlo
 - § WA Monte Carlo

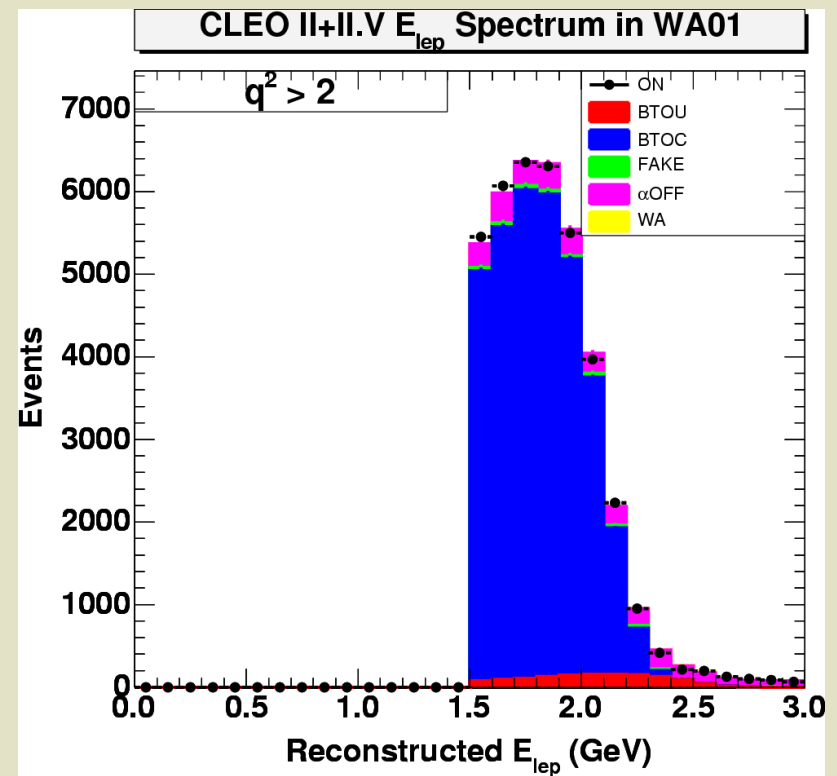
Sample Fit Results Fit Projections

- From fit to WA01 – most “compact” version of WA



q^2

$\chi^2 = 101.9/81$

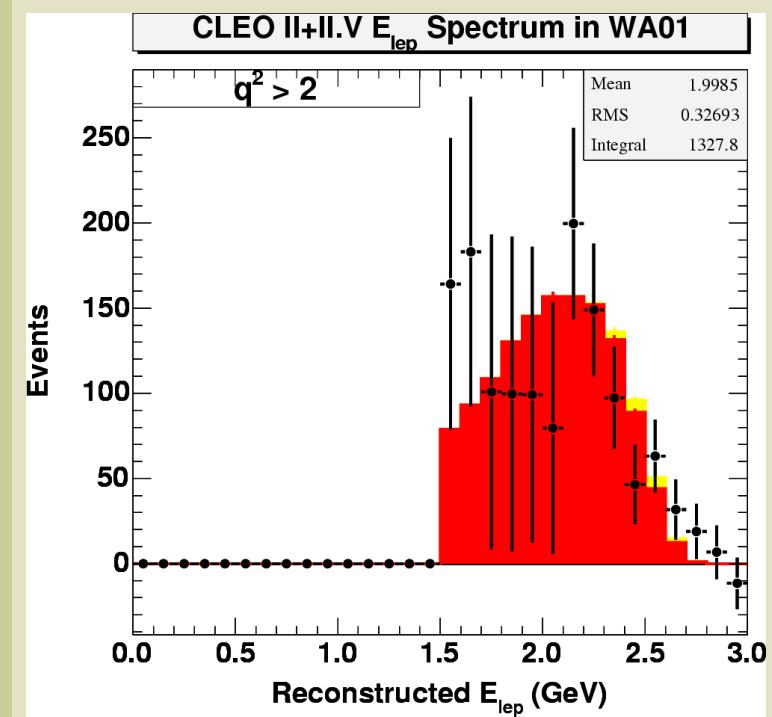
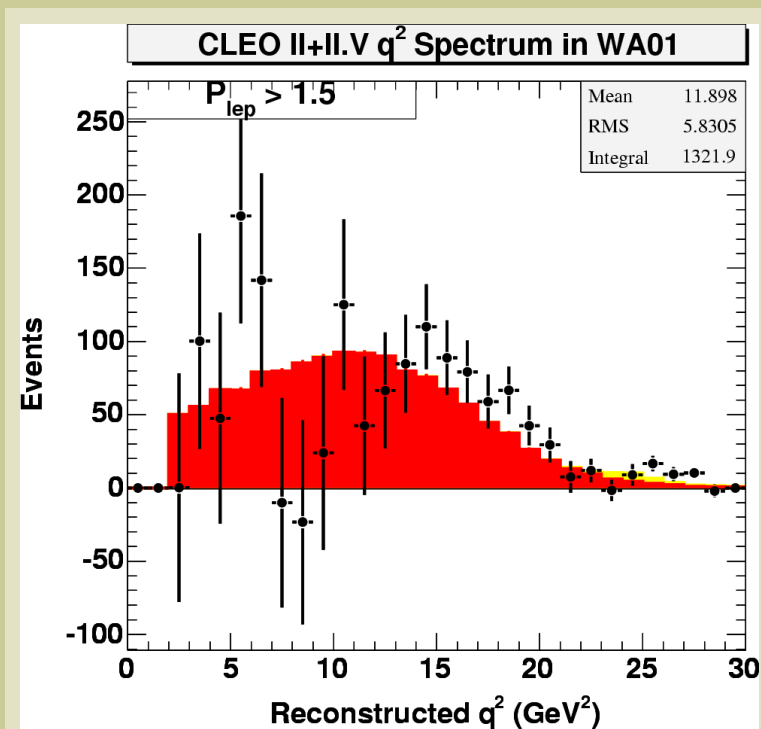


E_{lep}

Sample Fit Results

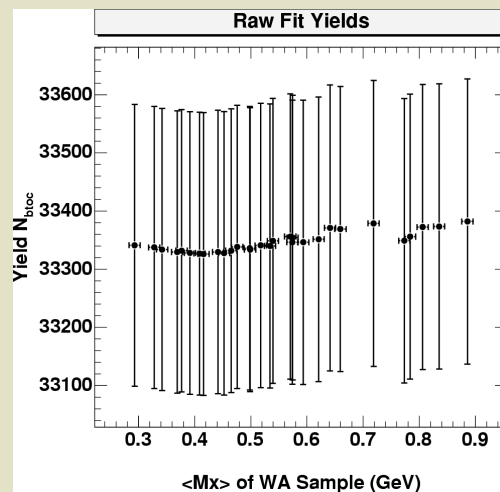
Bkg Subtracted

- Subtract off $b \rightarrow c l \nu$, continuum, and fakes to see $b \rightarrow u l \nu$ signal (including WA contribution)

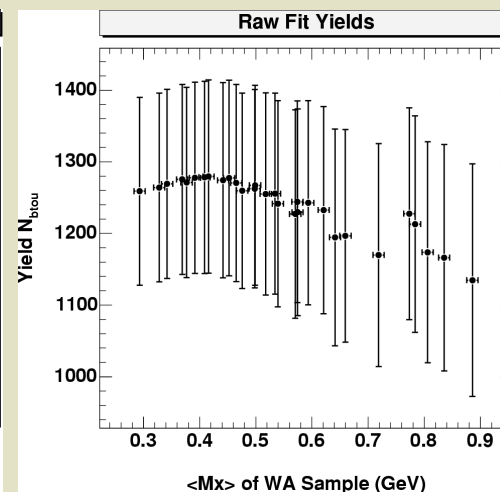


Fit Yields

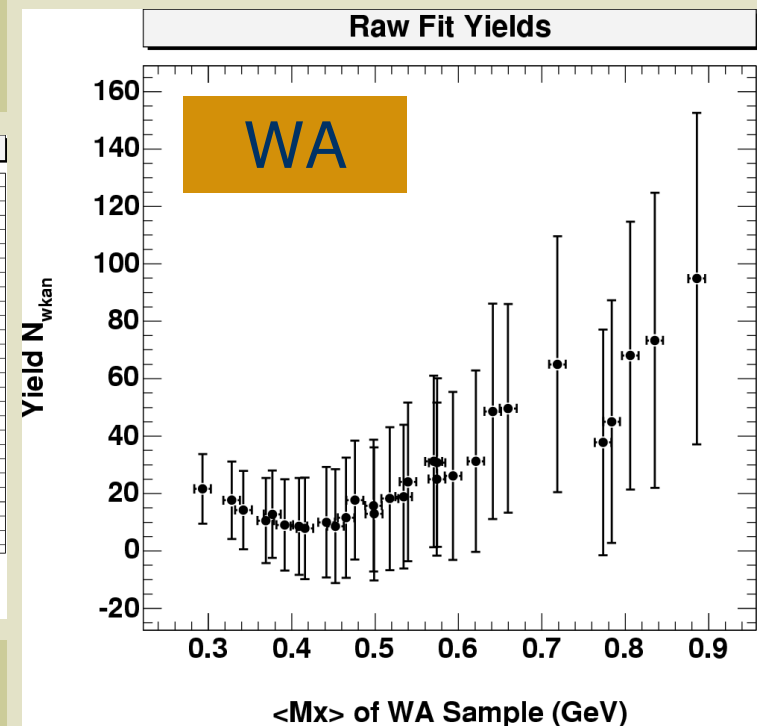
- Visualize all 30 fits by plotting results against other physical properties of the WA samples, *e.g.*
 - § Mean hadronic mass



btoc

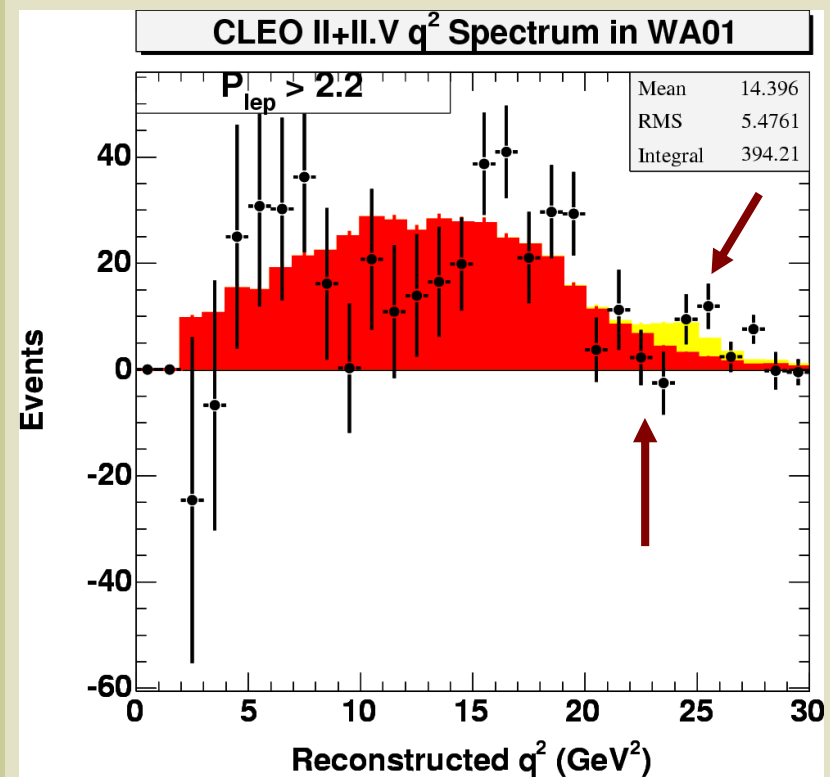


btou



Understanding the Yield Curve

- Shape of WA yield reflects shape of data spectrum at high q^2 and lepton energy
- Fluctuation happens to be consistent with “compact” WA samples
- For suff. broad WA, it can take rate from $btou$ instead



Relevance for $|V_{ub}|^2$

- Neglect of WA can impact extraction of $|V_{ub}|$
- For an analysis that applies cuts $\{a\}$ on $btou$ phase space, define correction factor or “impact ratio”

$$R_a = \frac{\Gamma_{WA}}{\Gamma_{btou}} = \frac{f_{wkan} N_{wkan}^a}{f_{wkan} N_{wkan}^a + f_{btou} N_{btou}^a}$$

Relevance of WA for analysis $\{a\}$, as a fn. of WA model, with input from data!

norml'zn result from fit

Evts passing cuts $\{a\}$

- Model-dependent
- Cut-dependent

Impact Ratios

Endpoint

$$\S E_{\text{lep}} > 2.2 \text{ GeV}$$

Belle-style

$$\S |p_{\text{lep}}| > 1.0 \text{ GeV}$$

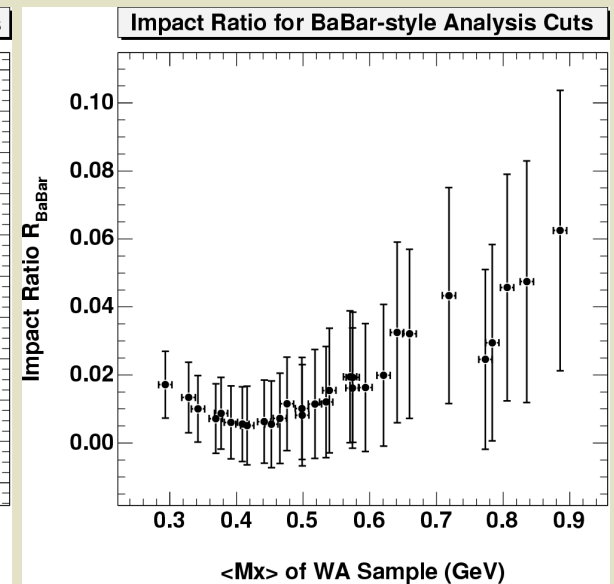
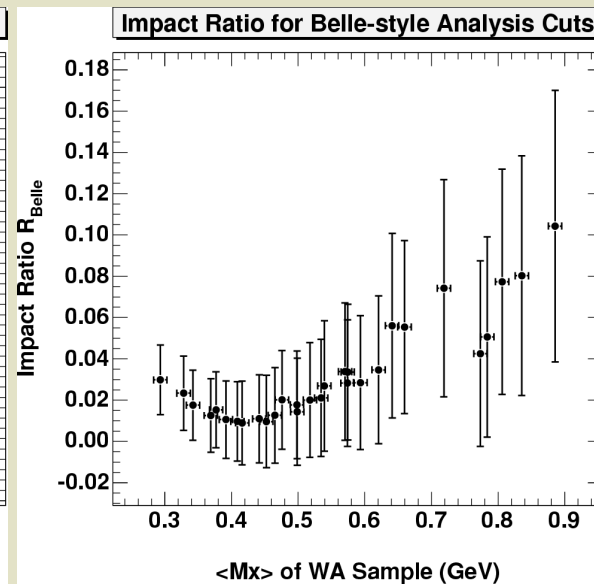
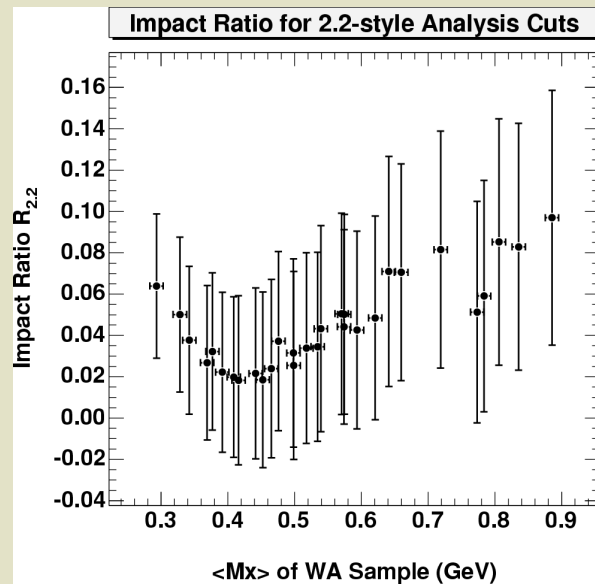
$$\S q^2 > 8.0 \text{ GeV}^2$$

$$\S M_X < 1.7 \text{ GeV}$$

BaBar-style

$$\S |p_{\text{lep}}| > 1.0 \text{ GeV}$$

$$\S M_X < 1.55 \text{ GeV}$$



Shape determined by WA yields

Stat. errors only

Systematics

Experimental Systematics

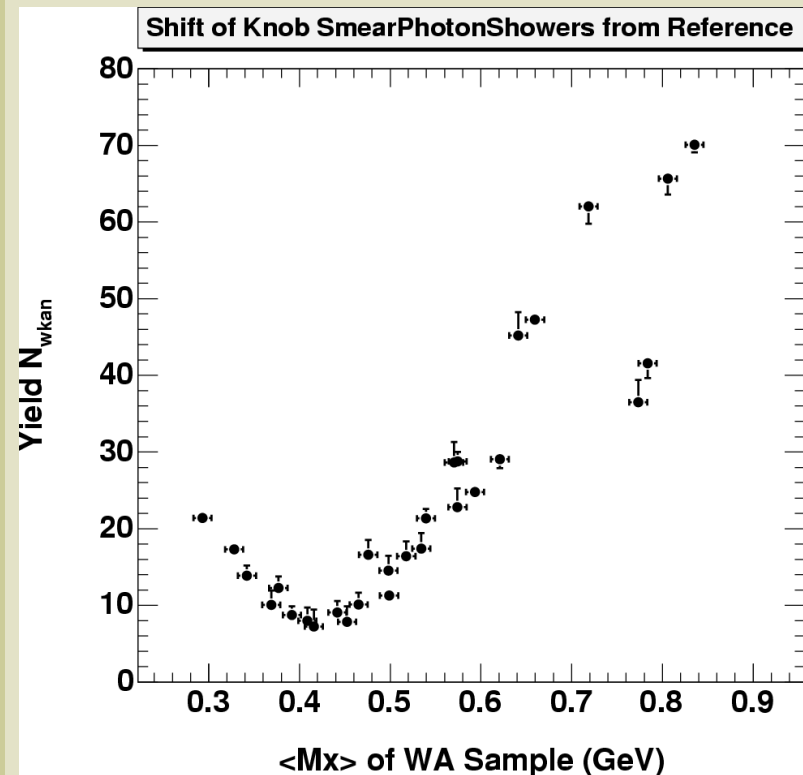
- Neutrino reconstruction depends on entire reconstructed event
- Fit to data relies on having simulated all details correctly
 - § Calorimetry
 - § Tracking
 - § Particle identification
 - § Generic B decay
- Study sensitivity of analysis to data-MC discrepancies with individual “knob turns”
 - § Modify some feature of the simulation, repeat analysis
 - § Resulting shift in central values measures dependence on selected feature

btoc
btou
WA

Calorimetry

- Shower reconstruction
 - § Shower-finding efficiency
 - § Shower energy resolution
 - § Splitoff showers per hadron
 - § Splitoff rejection algorithm

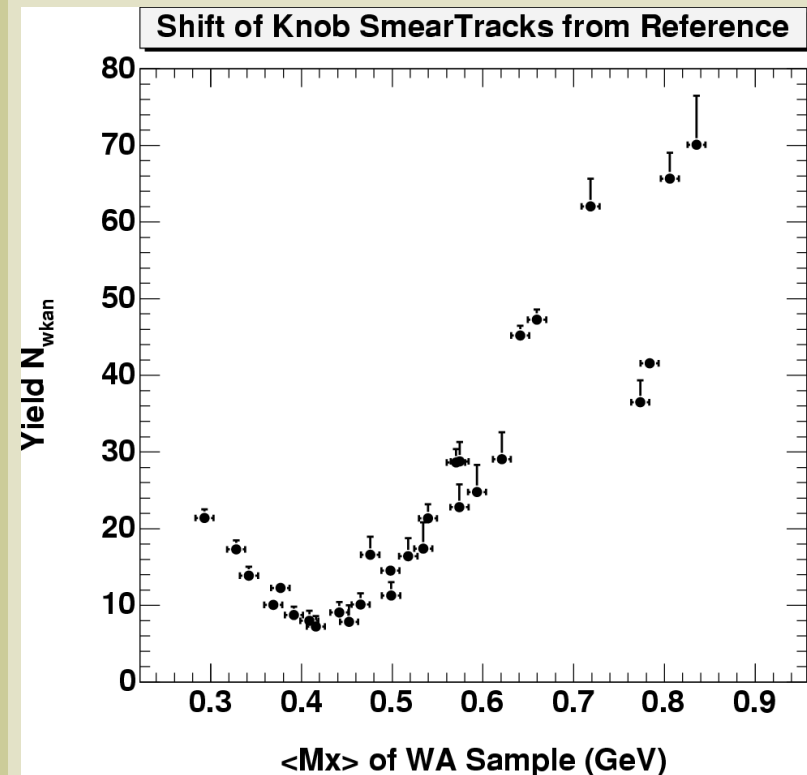
- K_L energy deposition



Error bars: Shift in WA yield when shower energy resolution is worsened by 10%

Tracking

- Tracking-finding efficiency
- Track momentum resolution



Error bars: Shift in WA yield when track momentum resolution is worsened by 10%

Physics of Generic B Decay

- K_L multiplicity has been compared between data and simulation

$$\frac{\langle N(K_L) \rangle_{\text{DATA}}}{\langle N(K_L) \rangle_{\text{MC}}} = 1.072 \pm 0.010$$

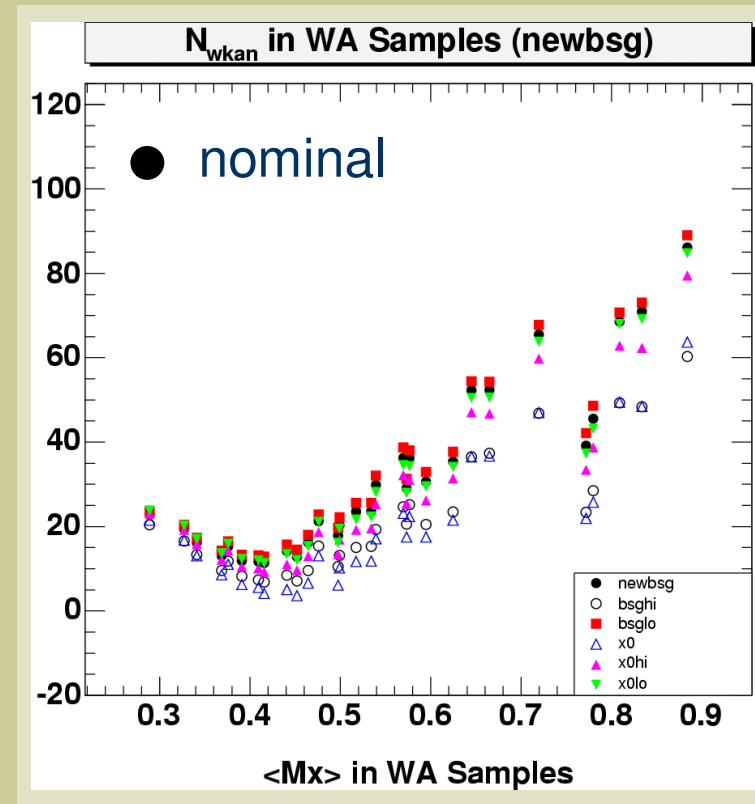
- § We already correct the simulation for the nominal deficit
- § Use **errors** as scale for variation of this re-weighting
- Secondary leptons can signal additional neutrinos

$$b \rightarrow c (\ell \nu), \text{ with } c \rightarrow s, d \ell \nu$$

- § Momentum spectrum critical to modeling lepton ID
- § Vary shape of spectrum within errors obtained from CLEO and CLEO-c component spectra

$b \rightarrow u l \nu$ Model Dependence

- Inclusive spectrum depends on parameters extracted from CLEO's $b \rightarrow s \gamma$ photon energy spectrum
 - § Vary “shape fn” parameters within uncertainties
- Turn off all resonances
 - § Purely non-resonant spectrum, matching theoretical prediction



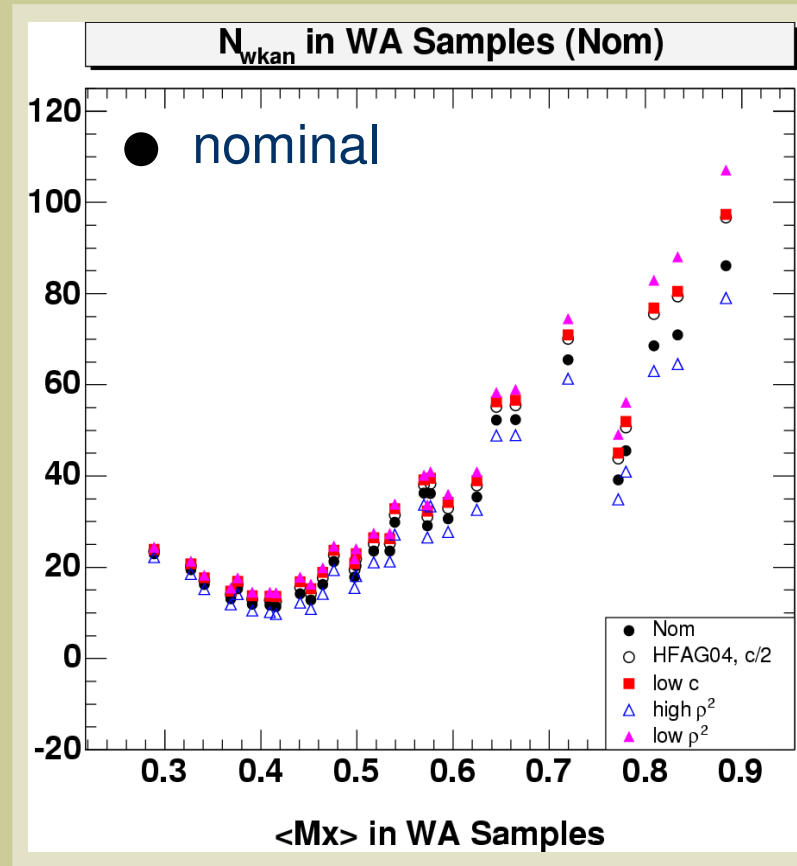
WA yields for different $btou$ models

$b \rightarrow c l \nu$ Model Dependence

- $B \rightarrow D^* l \nu$ dominates the $b \rightarrow c l \nu$ branching fraction

§ Vary form factor parameterization for this mode

$$\xi(w) = \xi(1) - \rho^2(w - 1) + c(w - 1)^2$$

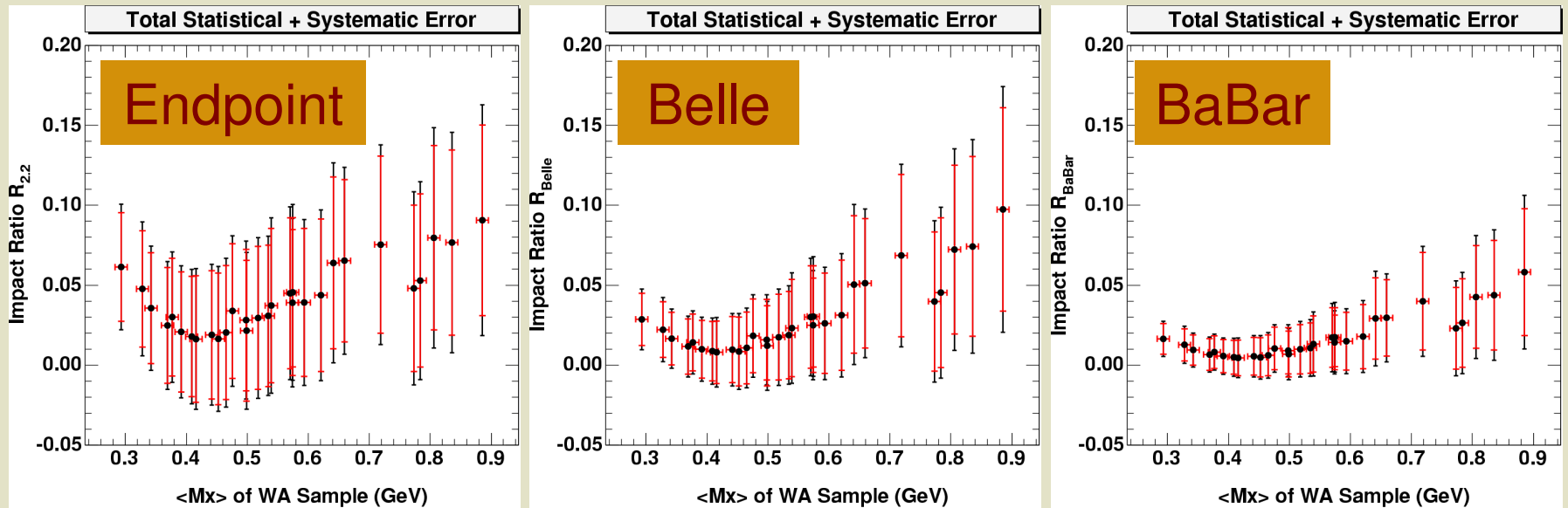
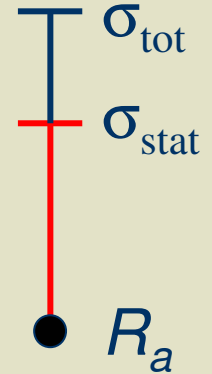


WA yields for different $btoc$ models

Summary of Systematics

- Combine all errors in quadrature

$$\sigma_{\text{tot}} = \sigma_{\text{stat}} \oplus \sigma_{\text{expt}} \oplus \sigma_{\text{btoc}} \oplus \sigma_{\text{btou}}$$



Conclusion

Take-Home Message about WA

- Statistically-limited measurement, so we place an upper limit
- Averaging (unweighted) across all 30 WA samples

Endpoint analysis

- ▶ $E_{\text{lep}} > 2.2 \text{ GeV}$

Belle-style analysis

- ▶ $|\rho_{\text{lep}}| > 1.0 \text{ GeV}$
- ▶ $q^2 > 8.0 \text{ GeV}^2$
- ▶ $M_X < 1.7 \text{ GeV}$

BaBar-style analysis

- ▶ $|\rho_{\text{lep}}| > 1.0 \text{ GeV}$
- ▶ $M_X < 1.55 \text{ GeV}$

$$\langle R_{2.2} \rangle \sim 10\%$$

$$\text{RMS } R_{2.2} \sim 2.8\%$$

$$\langle R_{q^2, M_X} \rangle \sim 6.5\%$$

$$\text{RMS } R_{q^2, M_X} \sim 3.8\%$$

$$\langle R_{M_X} \rangle \sim 3.8\%$$

$$\text{RMS } R_{M_X} \sim 2.3\%$$

Impact for $|V_{ub}|$ is $R_d/2$

At worst, a 5% effect

Further Work

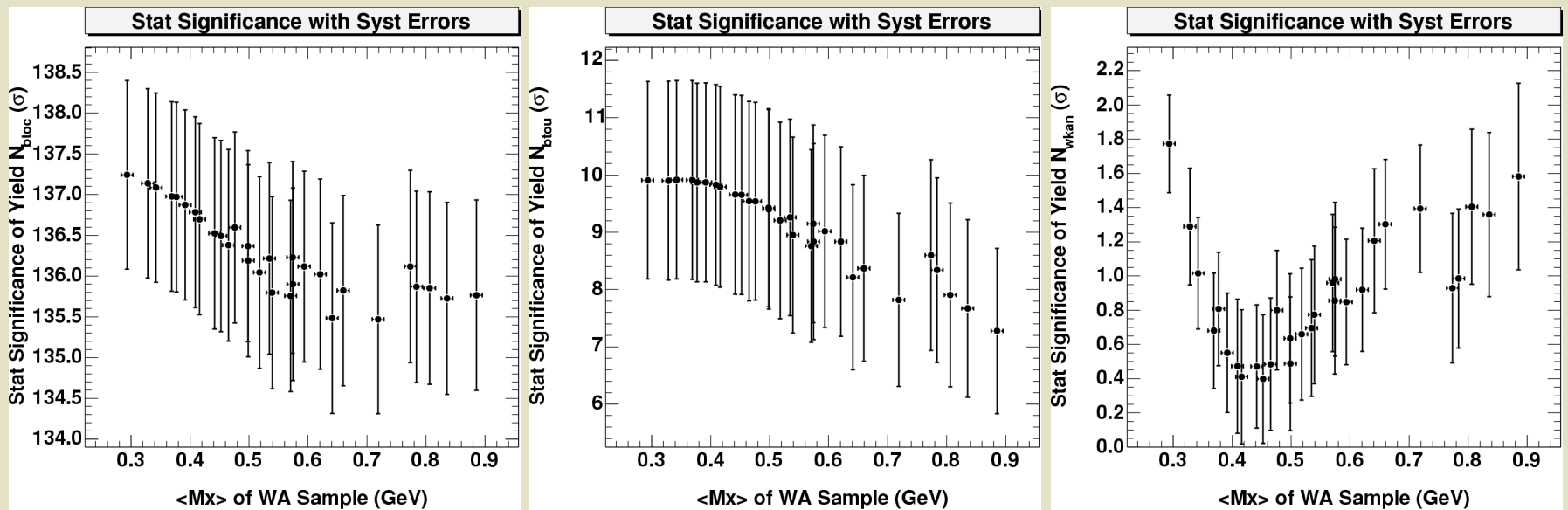
- CLEO III dataset – another 6 fb^{-1}
- B Factories
 - § Compare $\Gamma_{\text{SL}}(B^\pm)$ to $\Gamma_{\text{SL}}(B^0)$
 - ▶ Requires reconstruction of X_u or other B
- Other avenues for exploring WA and/or violation of factorization
 - § D semileptonic width
 - § D_s - D lifetime difference

Statistical Significance

- Statistics-limited analysis

$$S = \frac{N}{\sigma_{\text{stat}}}$$

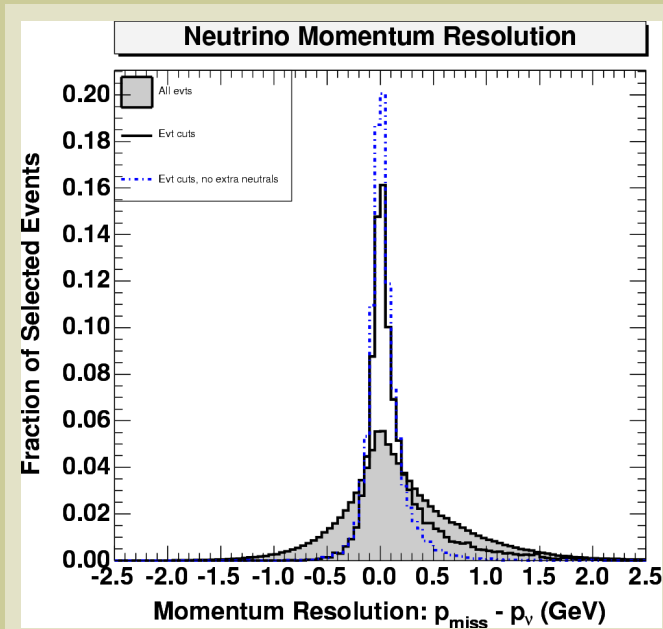
Error bars indicate proportional systematic error in units of σ_{stat}



Neutrino Reconstruction Performance

Resolution

- Dominated by additional undetected particles
 - § Chiefly ν and K_L
- After all analysis cuts (MC)
 - § $\sigma(p_{\text{miss}}) \sim 150 \text{ MeV}$

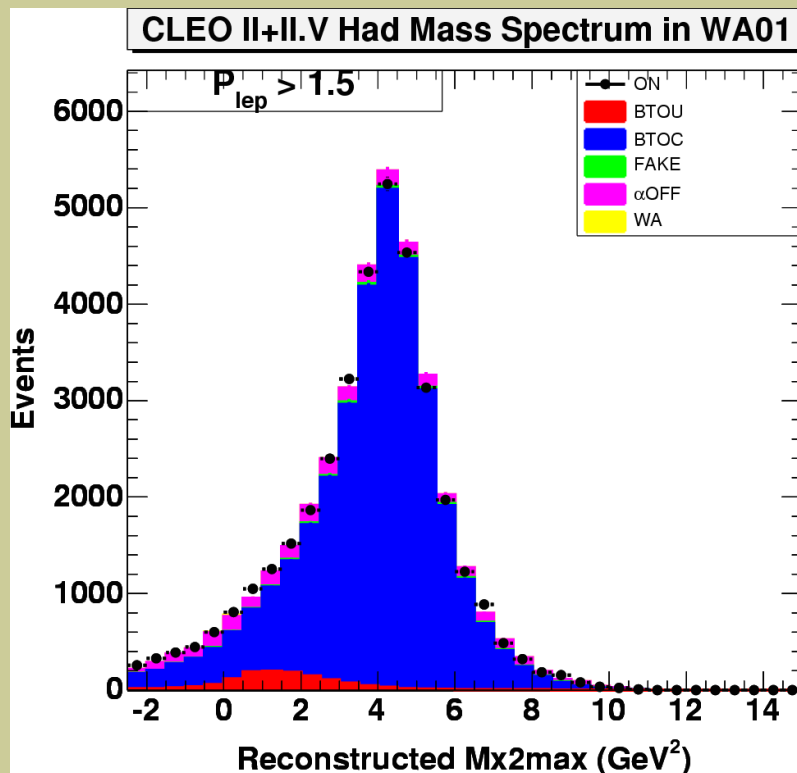


Efficiency

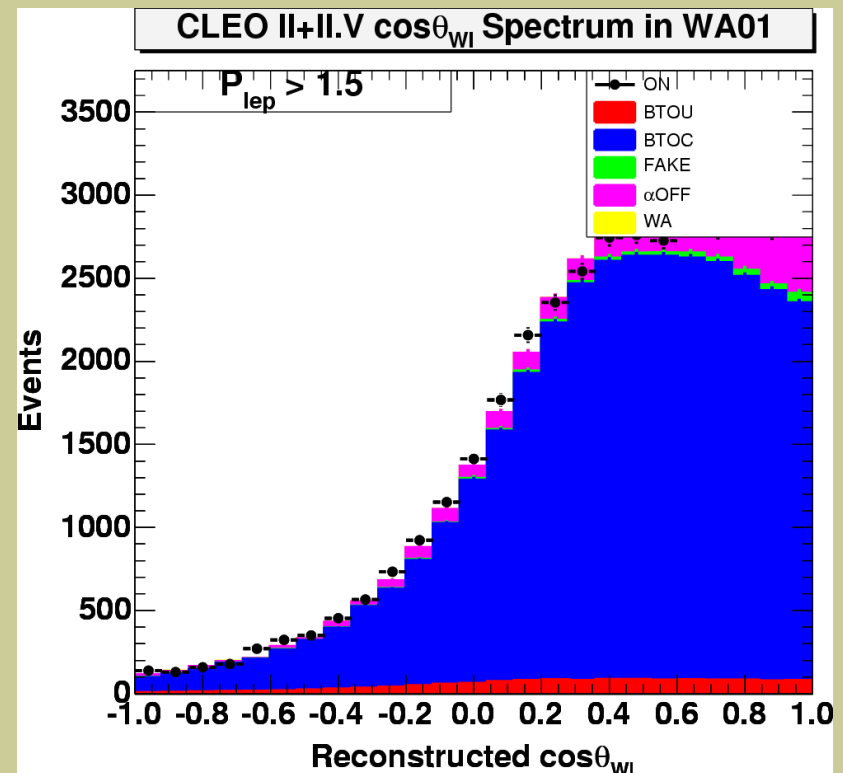
- Neutrino selection cuts disfavor $b \rightarrow c l \nu$ because X_c decays to K_L tend to trigger $MM^{\#}$ veto

Sample	ϵ
$b \rightarrow u l \nu$	2.68%
$b \rightarrow c l \nu$	1.12%
DATA	0.36%

Sample Fit Results Fit Projections

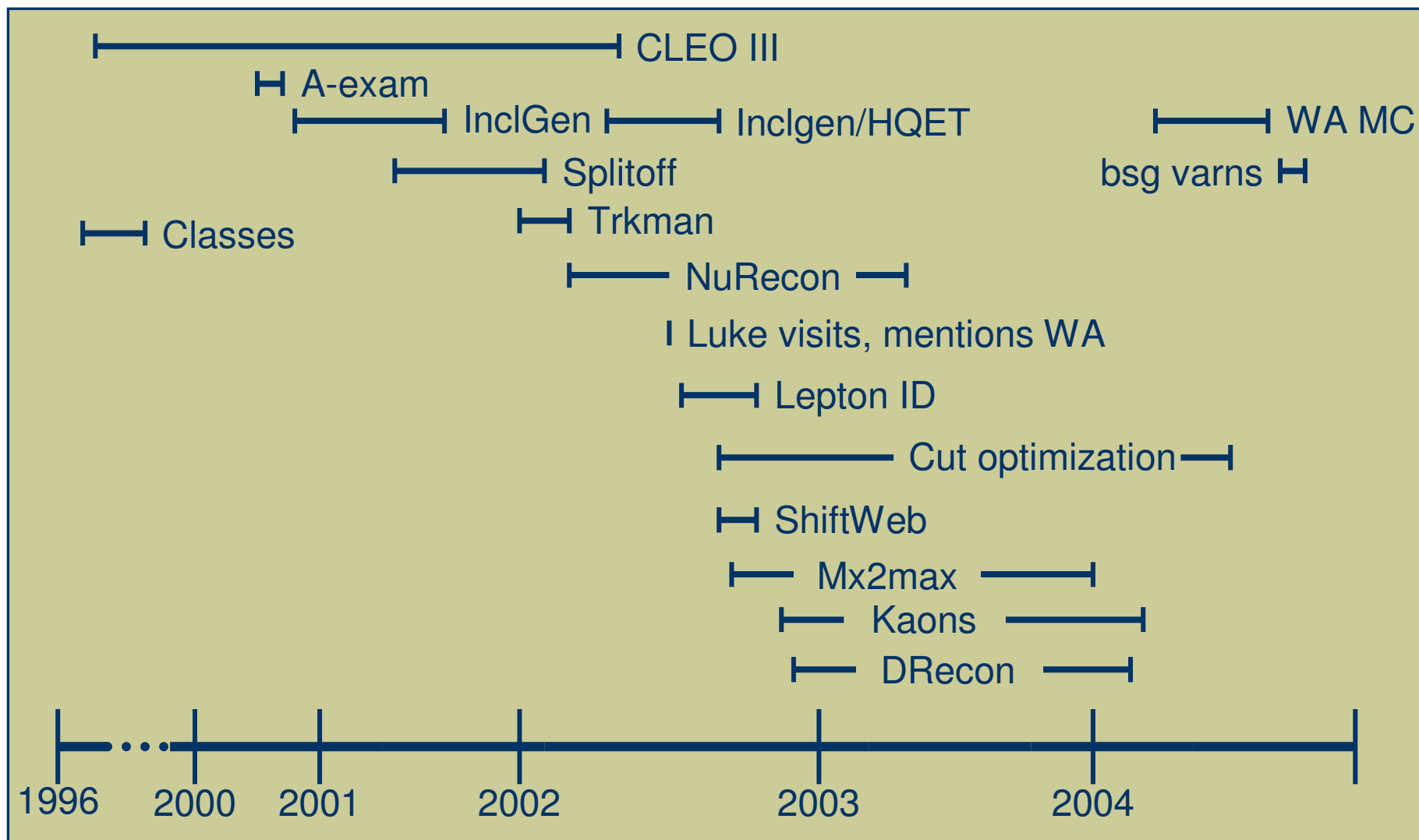


M_{x2max}

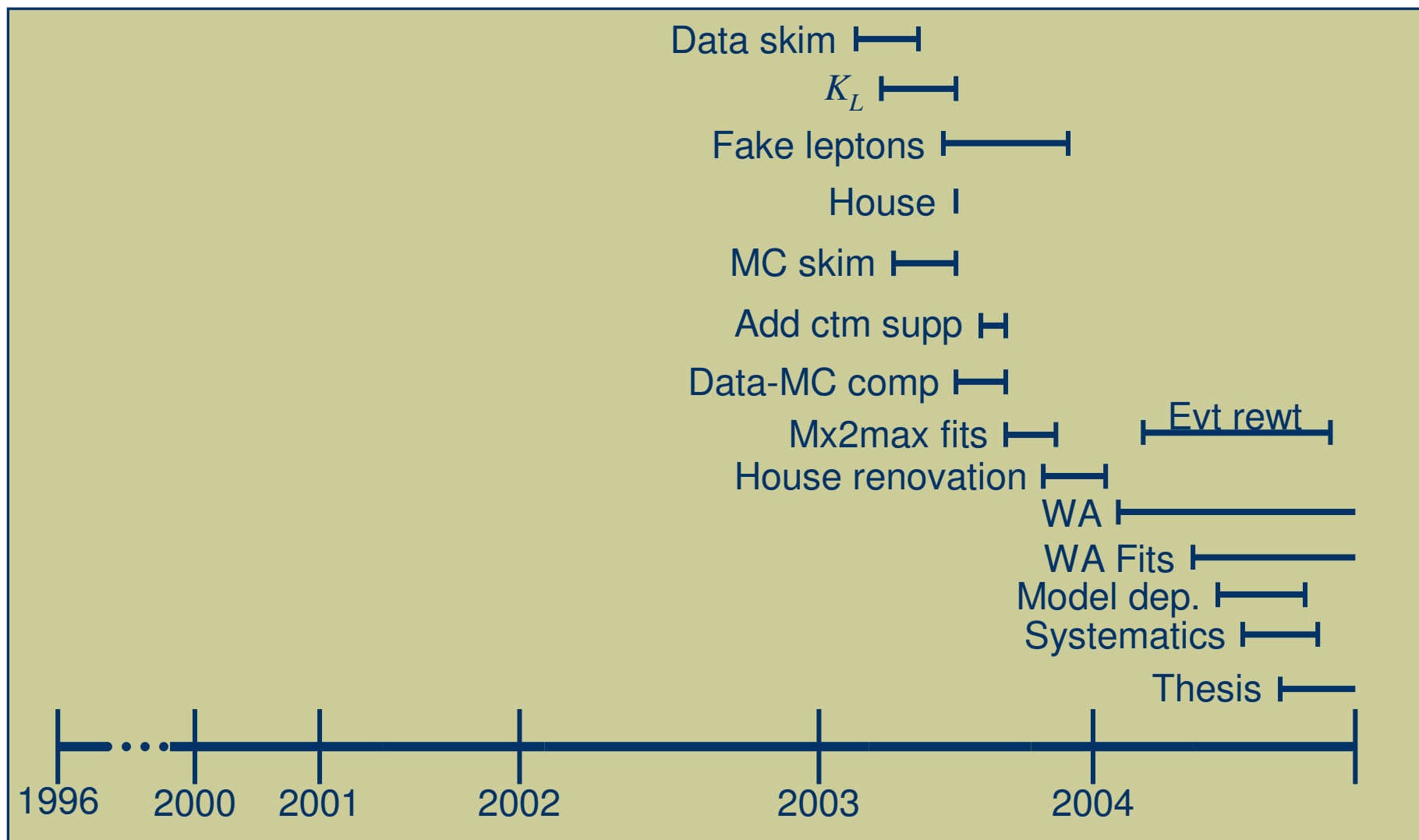


$\cos\theta_{Wl}$

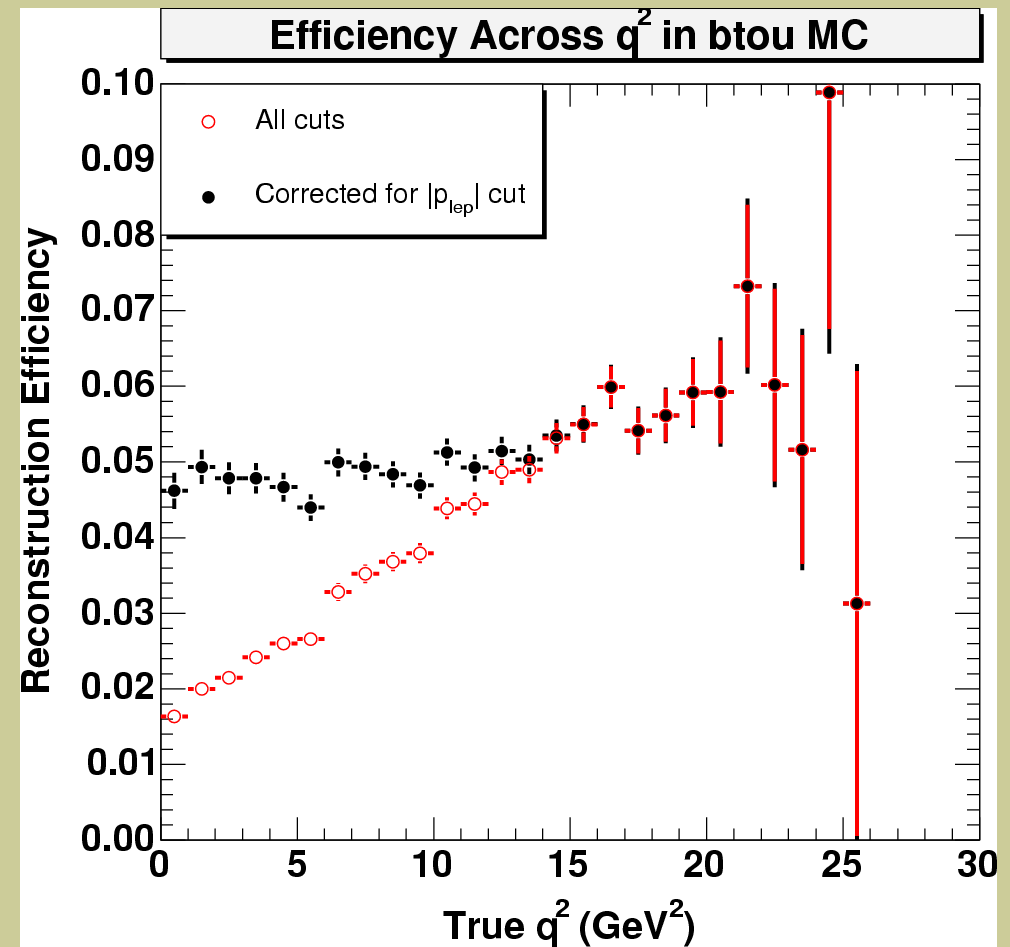
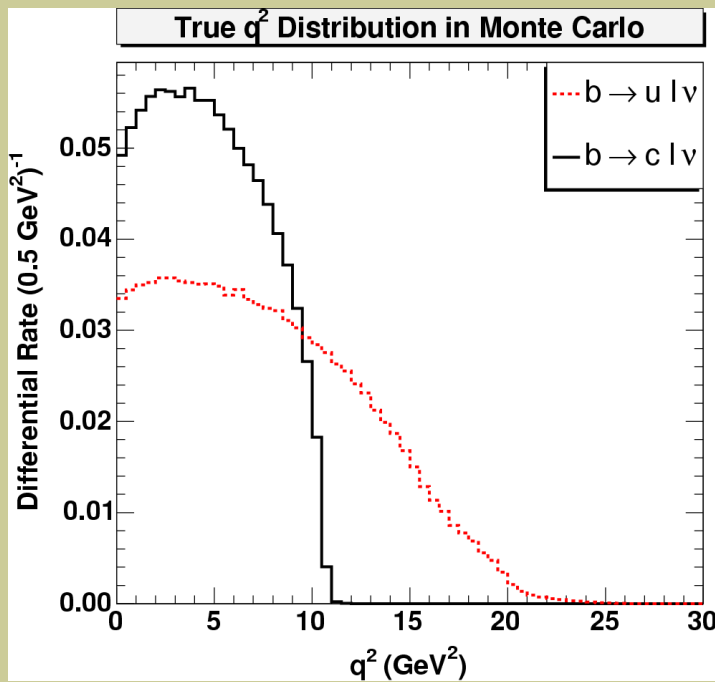
Where Did All The Time Go?



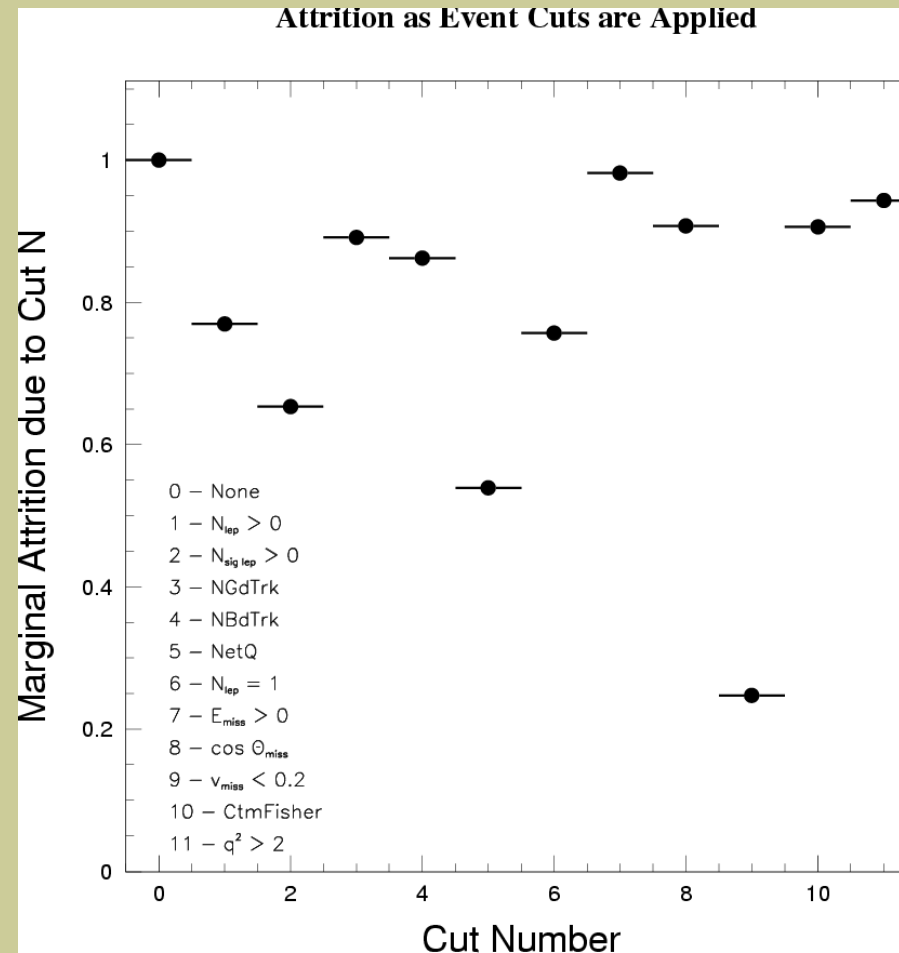
Where Did All The Time Go?



Reconstruction of q^2



Neutrino Reconstruction Cuts

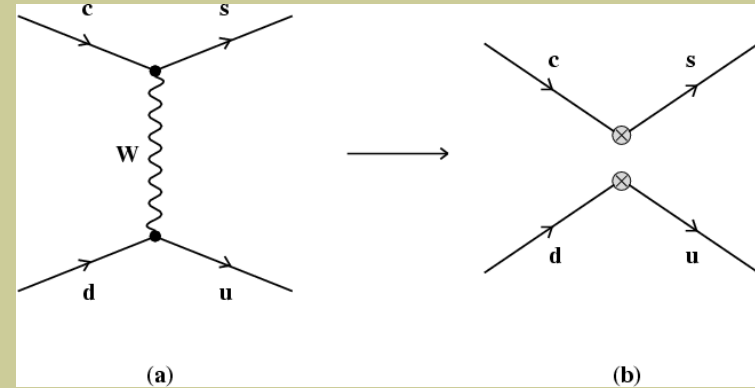


Operator-Product Expansion

- A rigorous framework for handling natural separation in scales between weak and hadronic physics

$$(M_W \sim 100 \text{ GeV}) \gg (\Lambda_{\text{QCD}} \sim 250 \text{ MeV})$$

- § Short-distance physics can be handled perturbatively
- § Long-distance physics is swept into hadronic matrix elements of local operators



$$\frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} \frac{M_W^2}{k^2 - M_W^2} (\bar{s} \gamma^\mu P_L c) (\bar{u} \gamma_\mu P_L d)$$



$$\frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} (\bar{s} \gamma^\mu P_L c) (\bar{u} \gamma_\mu P_L d) + \mathcal{O}\left(\frac{k^2}{M_W^2}\right)$$

Heavy Quark Expansion

- Intuitive notion of a “heavy quark symmetry”
 - § In $\lim m_Q \rightarrow \infty$, light degrees of freedom in a hadron H_Q are insensitive to the actual mass and spin of the heavy quark Q
- For finite m_Q , there is still a natural separation between the heavy quark mass scale and typical hadronic energy scales

$$m_b \sim 5 \text{ GeV} \gg \Lambda_{\text{QCD}} \sim 250 \text{ MeV}$$

- HQE provides rigorous framework for systematic corrections to this limit