Searching for New Physics in the Rare Decay $B \rightarrow K^* l^+ l^-$ at the B-Factories

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Fermilab Postdoc Seminar

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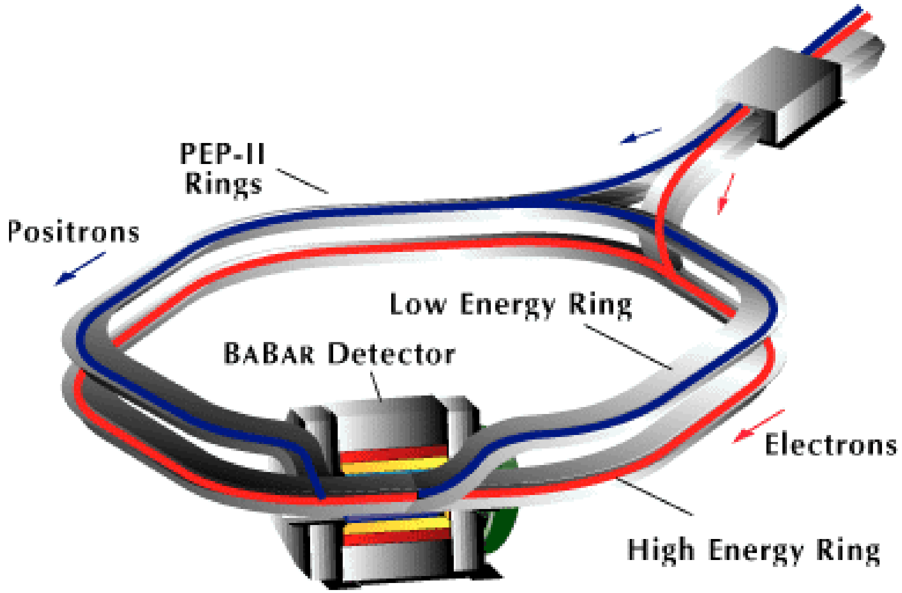
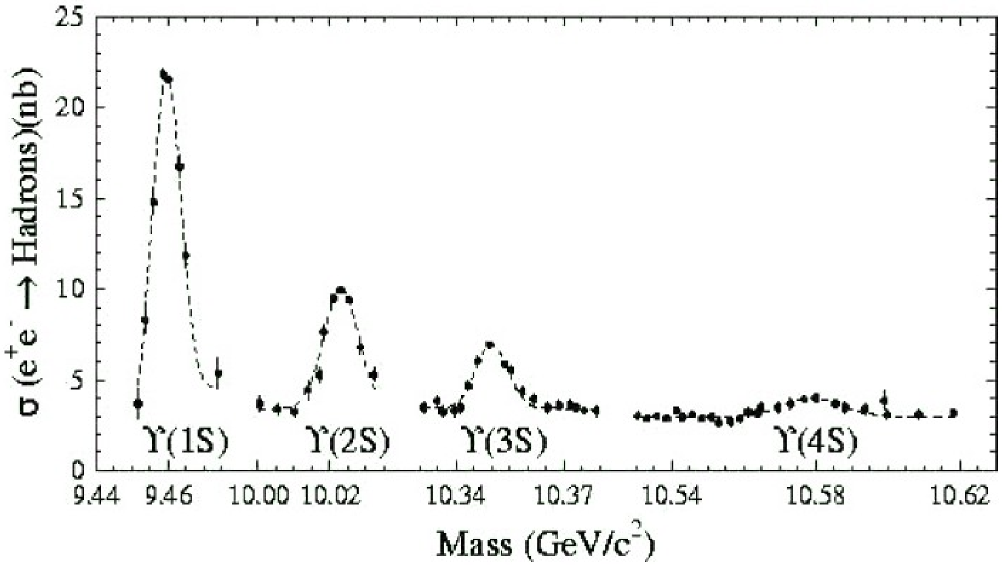
Outline

- The B-Factories and the BaBar and BELLE Experiments
- Goals of the B-Factories
- The $b \to s$ Transition and Flavor Changing Neutral Currents
- Analysis Methodology
  - Event Selection
  - Background Sources
  - Event Classification Using Neural Networks
  - Cut Optimization
  - Fit Model
- Results
- Systematic Errors
- Conclusions

The B-Factories





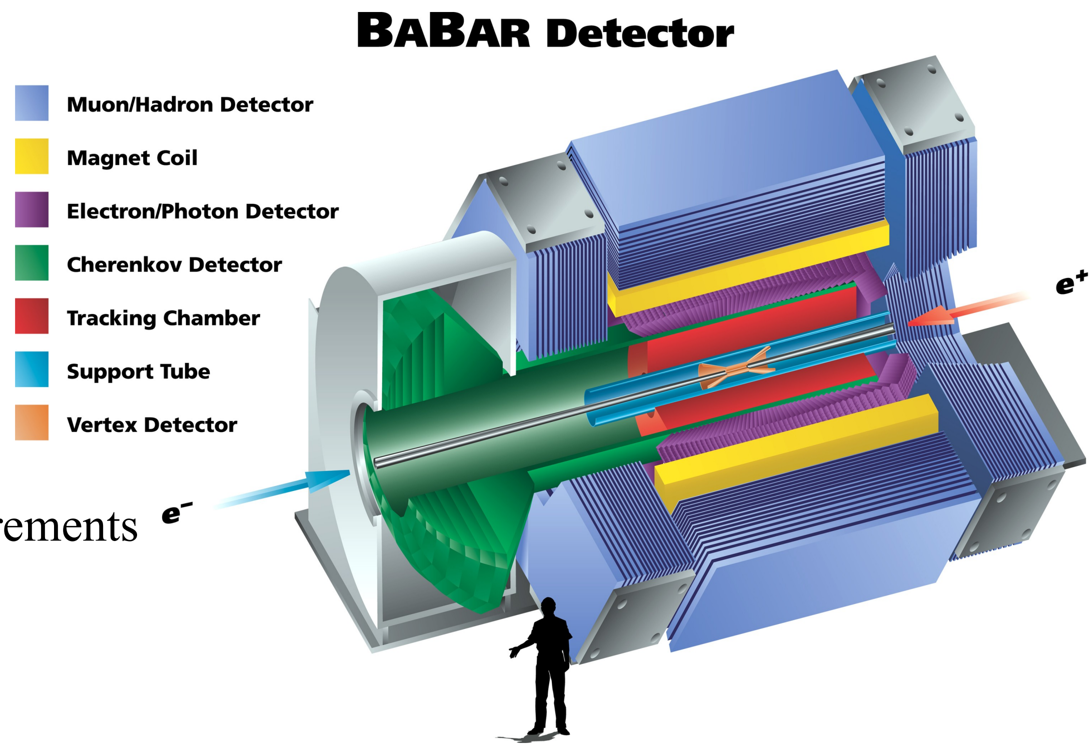
- Asymmetric $e^+ e^-$ colliders
- PEP-II
  - Electrons 9.0 GeV, Positrons 3.1 GeV
  - $\beta\gamma = 0.56$ at $\Upsilon(4S) \to B\bar{B}$ (10.58 GeV CM energy)
- KEKB
  - Electrons 8.0 GeV, Positrons 3.5 GeV
  - $\beta\gamma = 0.45$ at $\Upsilon(4S) \to B\bar{B}$ (10.58 GeV CM energy)

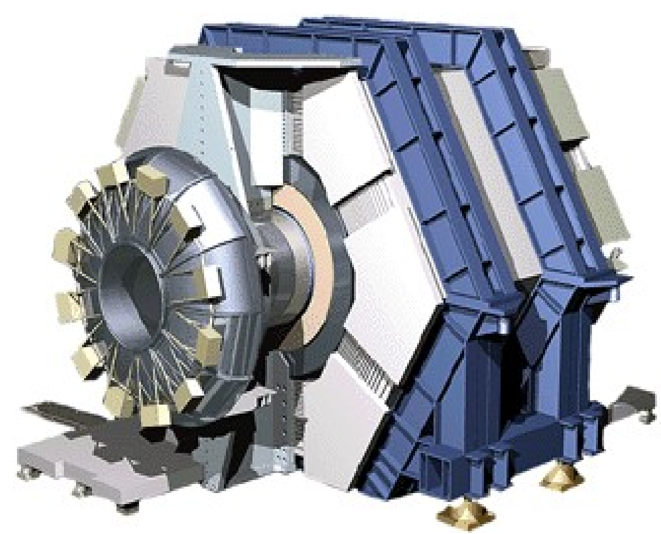
The BaBar Detector

- **<u>Consists of 5 subsystems</u>**

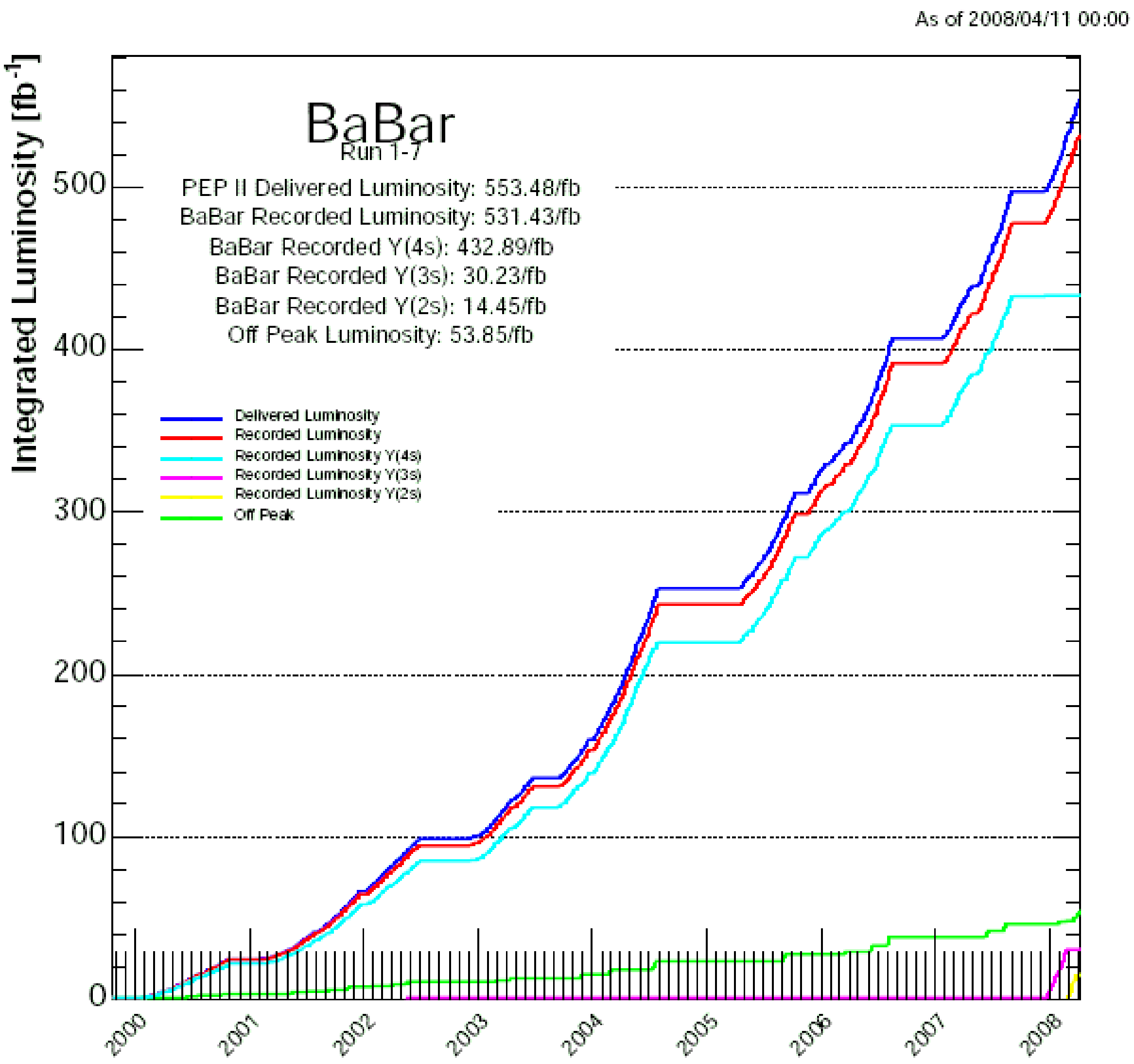
  (Increasing distance from beamline)

- **Silicon Vertex Tracker (SVT)**
  - Used for tracking and vertexing
- **Drift Chamber (DCH)**
  - Charged particle tracking and **p** measurements
- **Detector of Internally Reflected Cerenkov Light (DIRC)**
  - π/K separation
- **Electromagnetic Calorimeter (EMC)**
  - γ and $e^+ e^-$ energies
- **Instrumented Flux Return (IFR)**
  - μ and neutral hadron ID
- **Superconducting Magnet**
  - Longitudinal **B** ~ 1.5 T



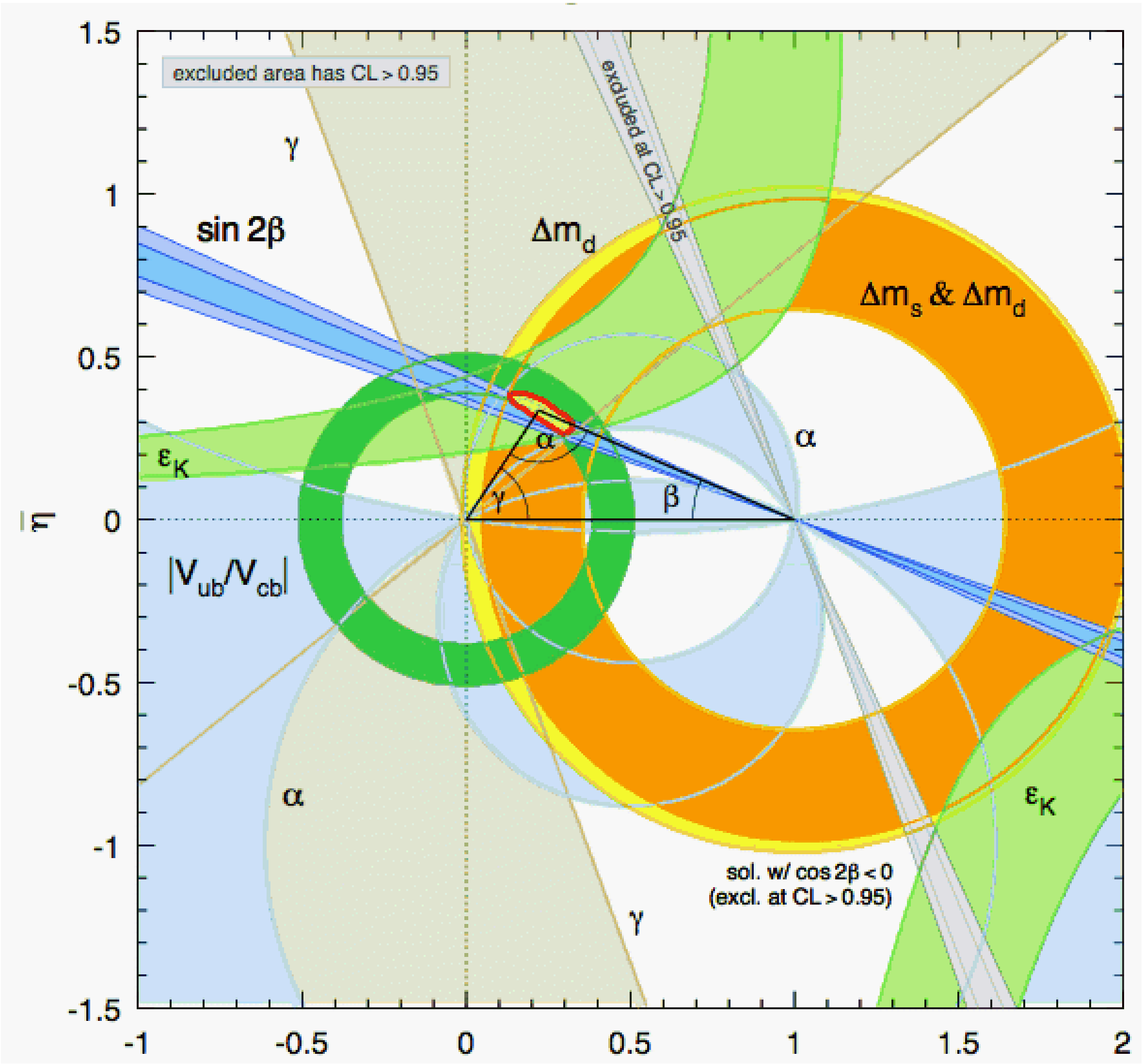


Luminosity: BaBar



- BaBar began taking data in 2000.
- Data taking ended earlier this year.
- This analysis uses 349 fb^{-1} (= ~ 384 million BB pairs) collected at the ϒ(4S)
- BELLE analysis uses ~600 fb^{-1} =~ 650 million BB pairs

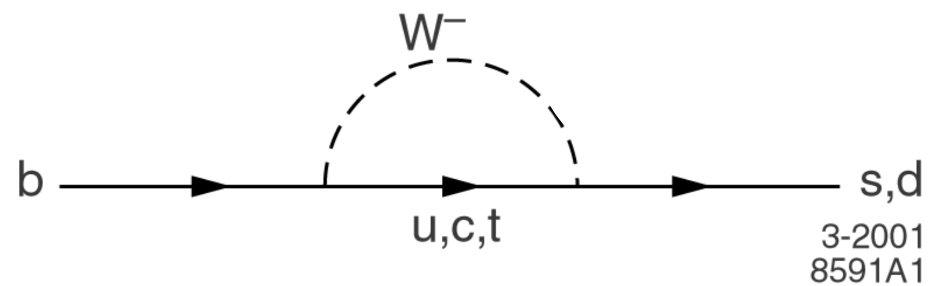
Goal of the B-Factories



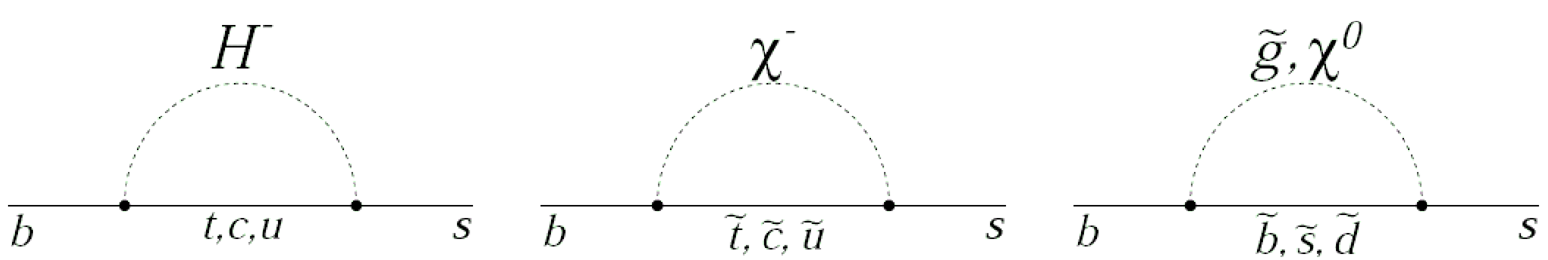
- Overconstrain the CKM triangle through redundant measurements of angles and sides of the Unitarity Triangle.
- We have found no source(s) of CP-violation beyond the SM CKM mechanism.

New Physics in FCNC

- b $\rightarrow$ s is a loop-level FCNC process
  - Disallowed at tree level
  - BF(b $\rightarrow$ sγ) = $(3.56 \pm 0.25) * 10^{-4}$



- Sensitive to new physics
  - Higgs or SUSY particles could enter the loop at the same level as the SM bosons.



B→sll Theory

- Effective Hamiltonian factorizes short-distance from long-distance effects.

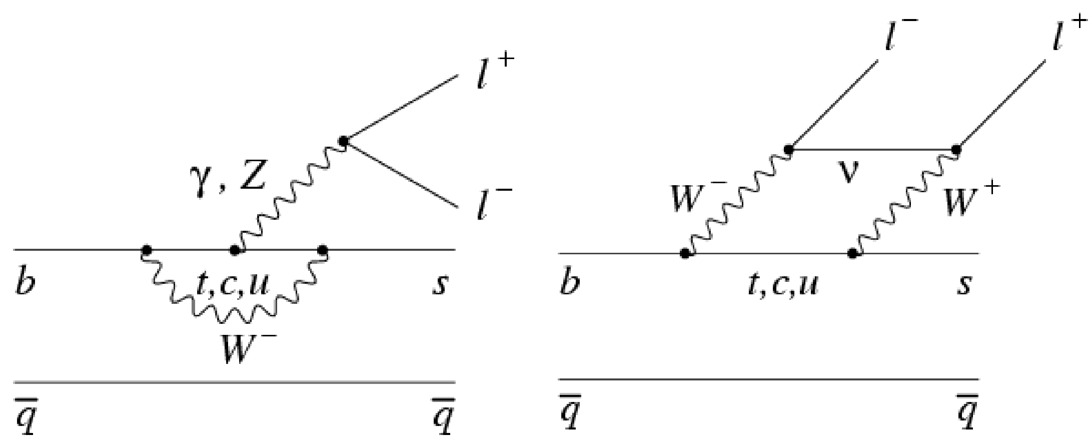
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} \left(V_{tb} V_{ts}^{*}\right) \sum_{i=1}^{10} C_i \, O_i$$

CKM factors

Wilson coefficients

operators

- Three short-distant Wilson coefficients:
  - C_7^{eff} from photon penguin Magnitude constrained by $b \to s\gamma$ BF measurement: $|C_7^{eff}| \cong 0.33$ (arXiv:0704.3575)
  - C_9^{eff}(C_{10}^{eff}) from vector (axial-vector) parts of the Z,W box



- New physics may modify C_i's or introduce additional scalar or pseudoscalar terms

Theoretical Concerns

- Exclusive $B \to K^*ll$ branching fraction (BF) predictions suffer from large theoretical uncertainties (~35%) due to uncertainty in form factors (~15%)
- Inclusive $B \to X_s ll$ BF predictions do not suffer the same uncertainty, however the exclusive decays are easier to study experimentally
- The three-body nature of the $B \to K^*ll$ provides angular distributions which have very precise SM predictions. Form factor uncertainties do not enter!
- One such observable is the forward-backward asymmetry A_{FB}: in the rest-frame of the di-lepton system, the B meson has a preferred direction.

Effects of New Particles

- New physics can effect many observables as functions of q^2
- Decay Rate

$$\Gamma(B \to K^{(*)} l^+ l^-)$$

- CP Asymmetry

$$A_{CP}^{K^{(*)}} \equiv \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)} \ell^+ \ell^-) - \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)} \ell^+ \ell^-) + \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}$$

- Isospin Asymmetry

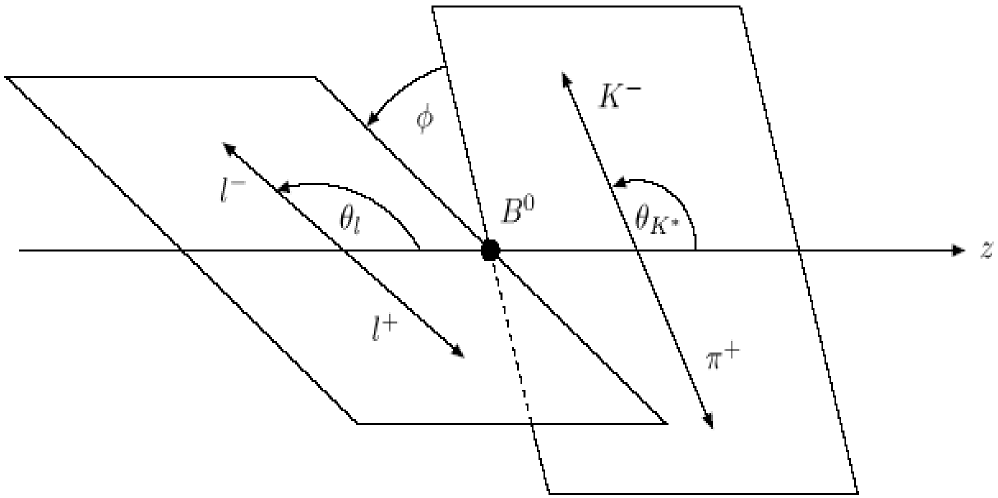
$$A_I \equiv \frac{\mathrm{B}(B^0 \to K^{(*)0} \ell^+ \ell^-) - (\frac{\tau_0}{\tau_+})\mathrm{B}(B^\pm \to K^{(*)\pm} \ell^+ \ell^-)}{\mathrm{B}(B^0 \to K^{(*)0} \ell^+ \ell^-) + (\frac{\tau_0}{\tau_+})\mathrm{B}(B^\pm \to K^{(*)\pm} \ell^+ \ell^-)}$$

- Lepton Flavor Asymmetry

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$

- Angular Asymmetries

Angular Variables in $B \rightarrow K^*ll$



$$A_{\text{FB}} = \frac{N_{forward} - N_{backward}}{N_{forward} + N_{backward}}$$

- θ_l - lepton angle in di-lepton rest frame. Forward-backward asymmetric due to V-A nature of the weak decay.
  - A_{FB} from *b* tagged $\cos(\theta_l)$: If we have a b flavored quark, define the angle with respect to the positive lepton.
  - Define forward s.t. $\cos(\theta_l) > 0$
  - Define backward s.t. $\cos(\theta_l) < 0$
- θ_k - kaon angle in K* rest frame: longitudinal K* polarization. The fraction of longitudinal polarization is F_L
- A_{FB} and F_L have a strong s dependence

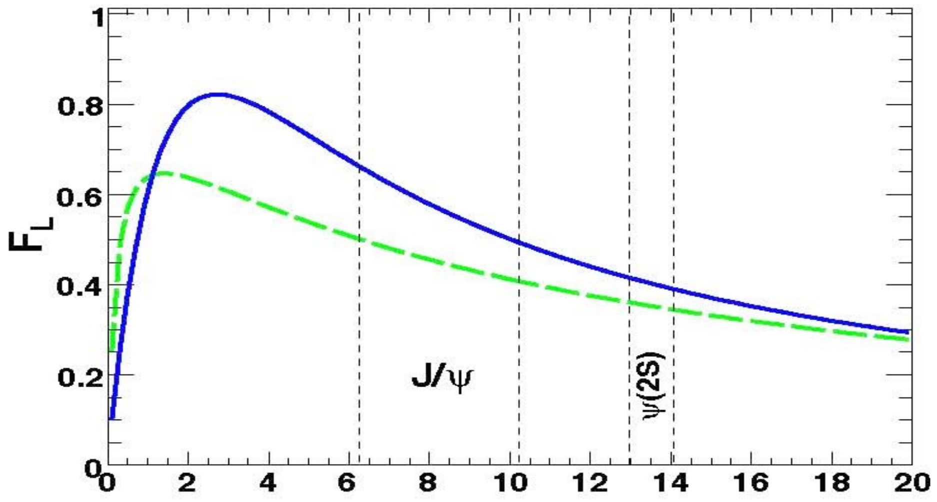
Angular Distributions

Angular distributions as functions of q^2 are particularly sensitive to possible new physics.

K* longitudinal polarization F_L

From distribution of the angle θ_K between the K and B in the K* rest frame

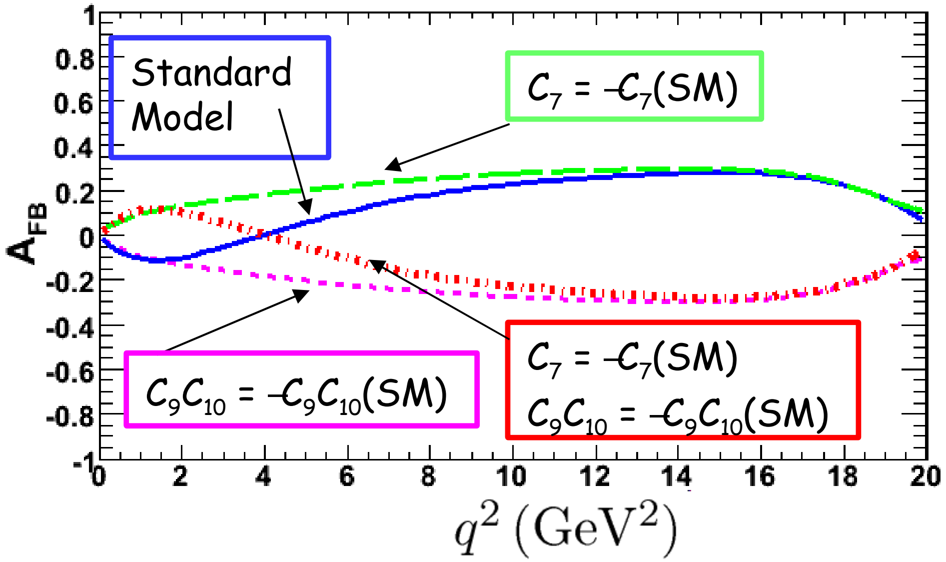
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$



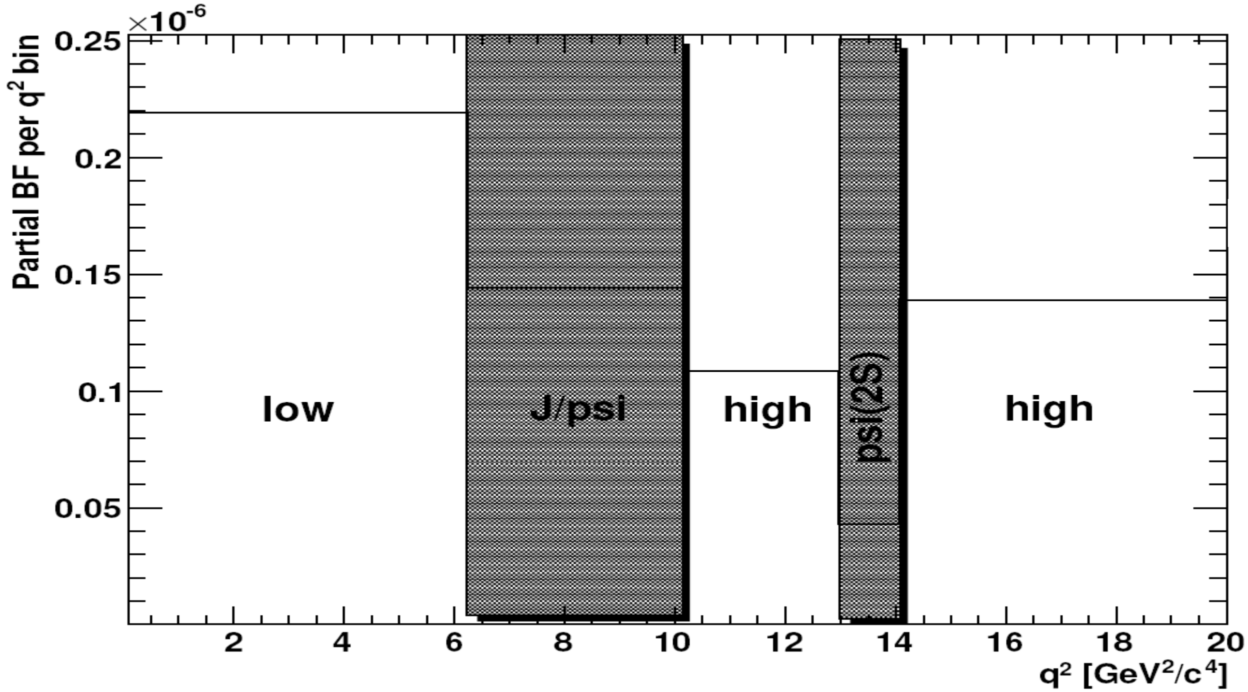
Lepton forward-backward asymmetry A_{FB}

From distribution of the angle θ_l between the l^+ and B in the l^+l^- rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$



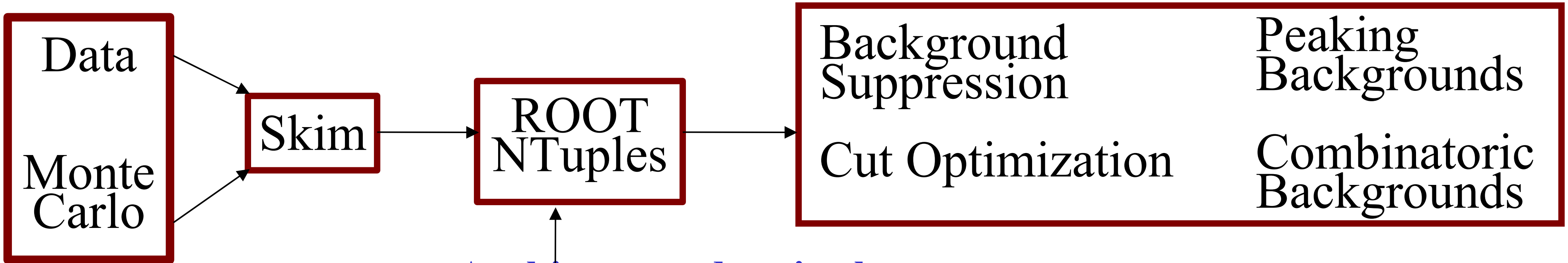
Analysis Goals



- **Extract signal in bins of s with an unbinned maximum likelihood fit.**
- **Veto the large B → J/ψ(→ l^+l^-) K* region by cutting on the di-lepton mass.**
- **Initially tried 4 s bins. We found that statistics were too limited to make this measurement.**
- **Decided on 2 s bins: 1 above and 1 below J/ψ invariant mass.**
- **BELLE uses 6 s bins: 3 below J/ψ, 1 between J/ψ and ψ(2S), 2 above ψ(2S)**

Analysis Outline

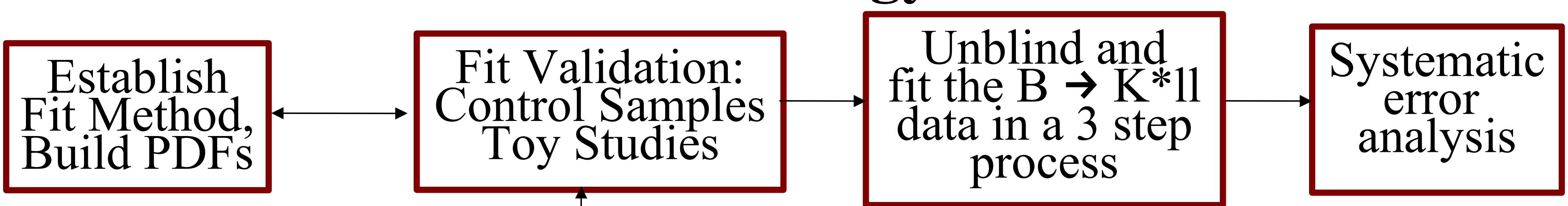
Event Selection



Data collected by BaBar detector.
MC generated using GEANT detector model

At this stage, data in the signal region is blinded. Studies performed using MC or data control samples similar to the B → K*ll final state.

Fit Strategy



PDFs built using functional forms or fixed shapes from the data or MC

This stage is also used to establish unblinding criteria.

Event Selection

- Reconstruct B $\rightarrow$K*ll for 10 K(*) decays, ll=e^+e^- or $\mu^+\mu^-$

$$\left\{ K^{\pm},\, K_S^0,\, K^{\pm}\pi^{\mp},\, K^{\pm}\pi^0, K_S^0\pi^{\pm} \right\} \times \left[e^+ e^-, \mu^+ \mu^- \right]$$

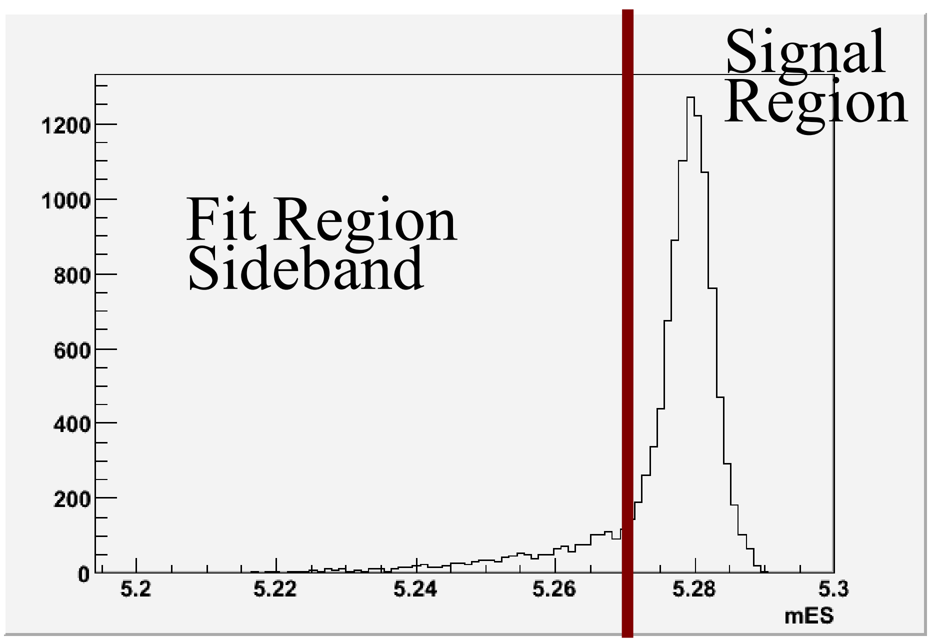
- Tight particle Identification on the e,μ,K to reduce backgrounds
  - electrons include Bremsstrahlung recovered photons (select one low energy photon that lies within a small cone around the electron track)
- Multivariate (Neural Network) suppression of combinatoric background (qq and BB)
- Veto most peaking (backgrounds that peak in m_{ES} and ΔE) background (J/ψ, ψ(2S)), estimate the rest.
- Validate technique using large (vetoed) charmonium control sample

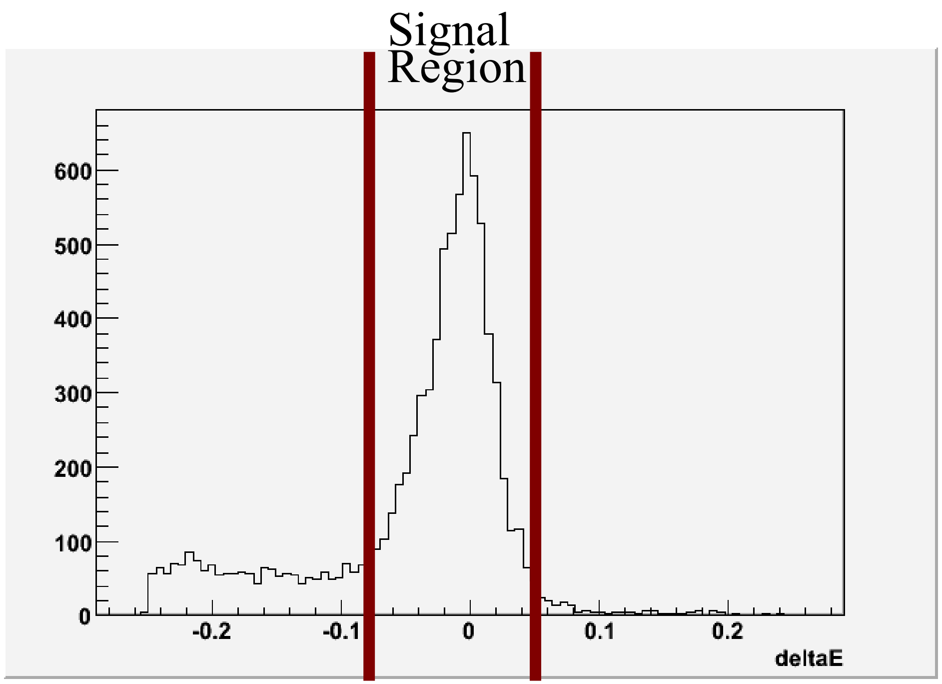
Event Selection

- Use uncorrelated variables m_{ES} (beam energy substituted mass), ΔE to define the signal region. Using the known beam energy improves mass resolution.

$$m_{ES} = \sqrt{E_{beam}^{*2} - \mathbf{p}_B^{*2}} \qquad \Delta E = E_B^* - E_{beam}^*$$

Sample Distributions from B → K*ll Signal MC

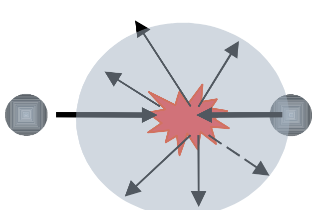




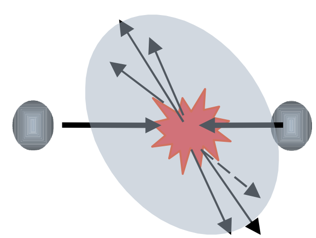
Background Suppression

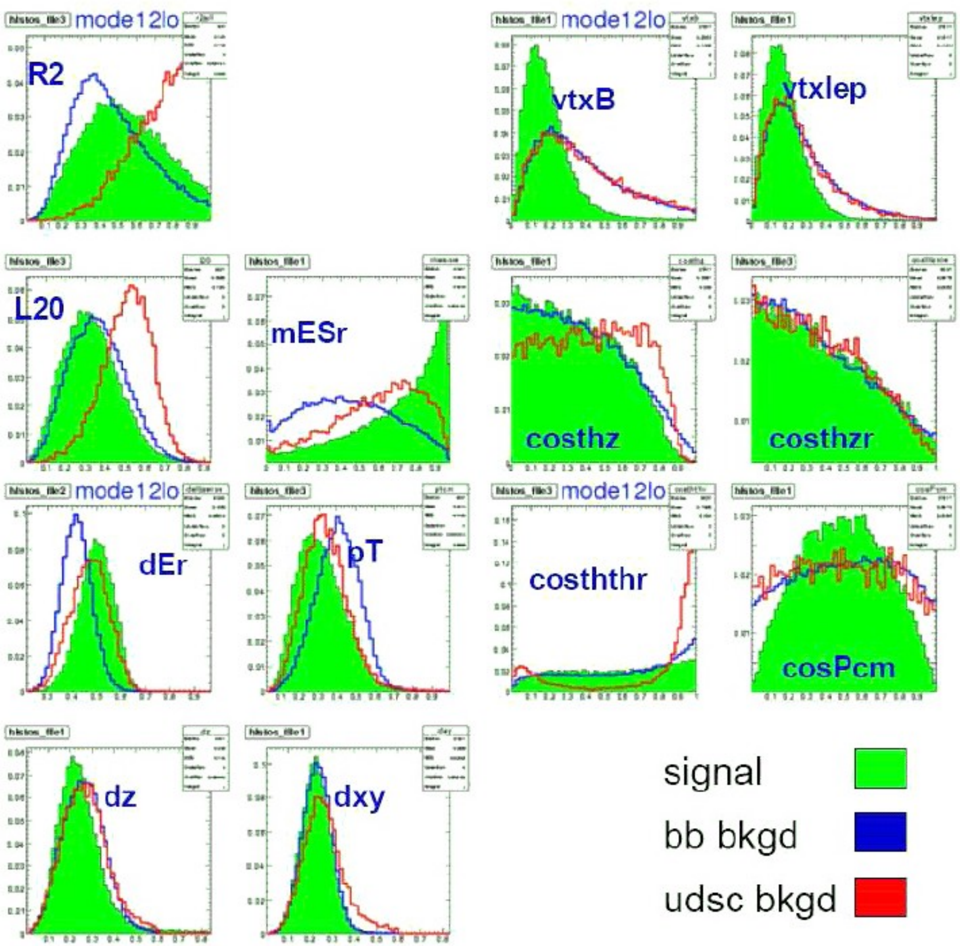
- Reject combinatoric backgrounds using Neural Networks with event shape variables as input
- B mesons decay isotropically whereas continuum processes $e^+e^- \rightarrow$ qq (q=udsc) are jet-like: thrust variables are useful for distinguishing:

BB



continuum

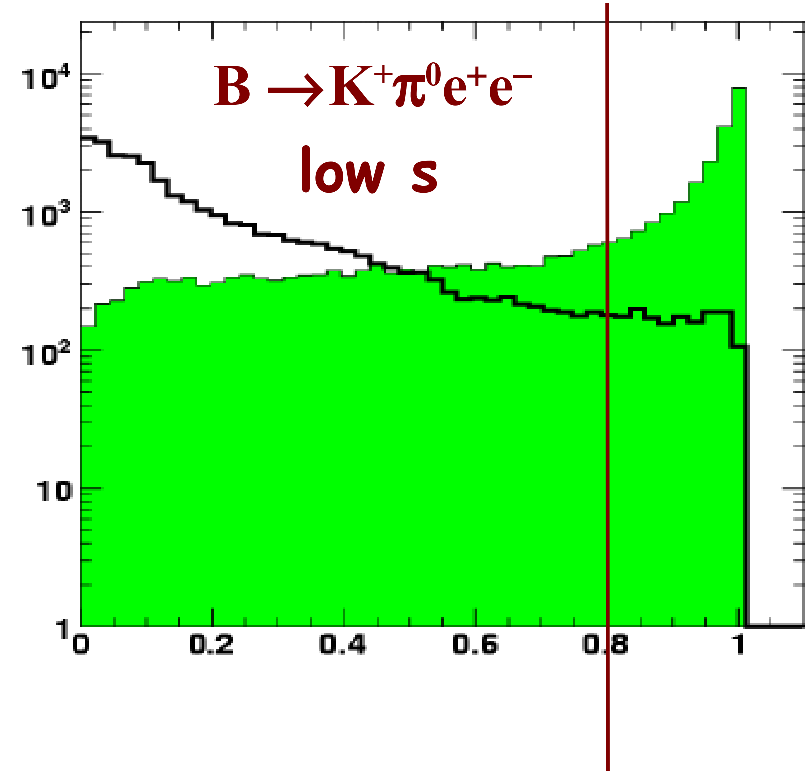




Event Selection Optimization

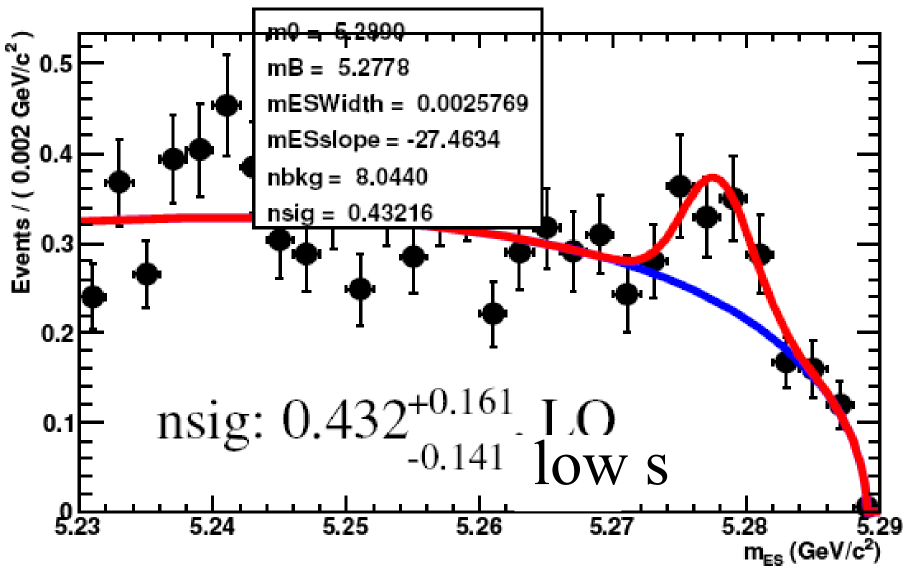
- Use NNs to reduce qq and BB backgrounds
  - 24 NNs: two (BB,qq) trained for each mode and each s bin
- Mode dependent cut optimization of ΔE, K* mass, and NN output
  - In each q^2 bin, simultaneously optimize all cuts by mode
  - Fix optimal ΔE, K* mass
    - **ΔE =~ -0.08 to 0.05 GeV**
    - **K* mass = 0.82 to 0.97 GeV**
  - Optimize NN cuts across all modes for $S/(S+B)^{1/2}$ such that $m_{ES} > 5.27$

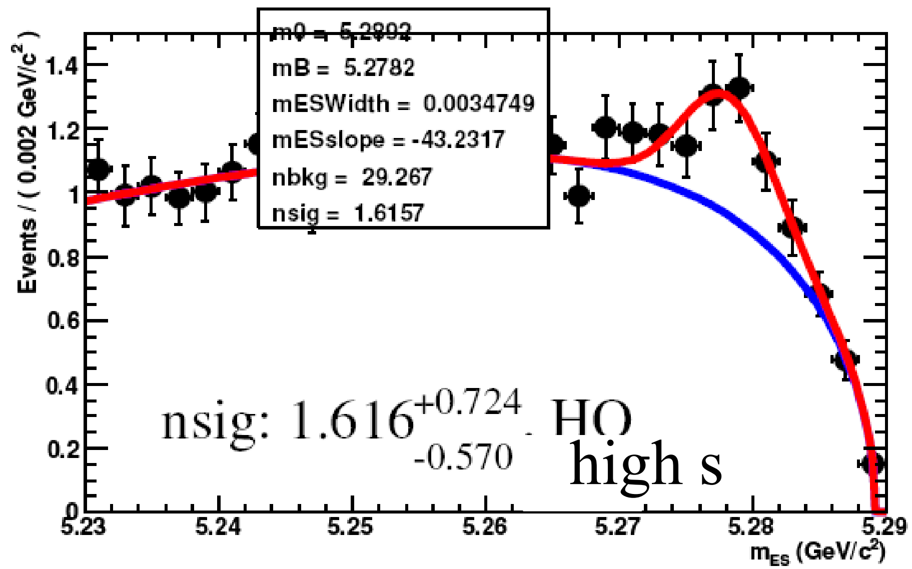
Example: BB NN Output



Peaking Backgrounds

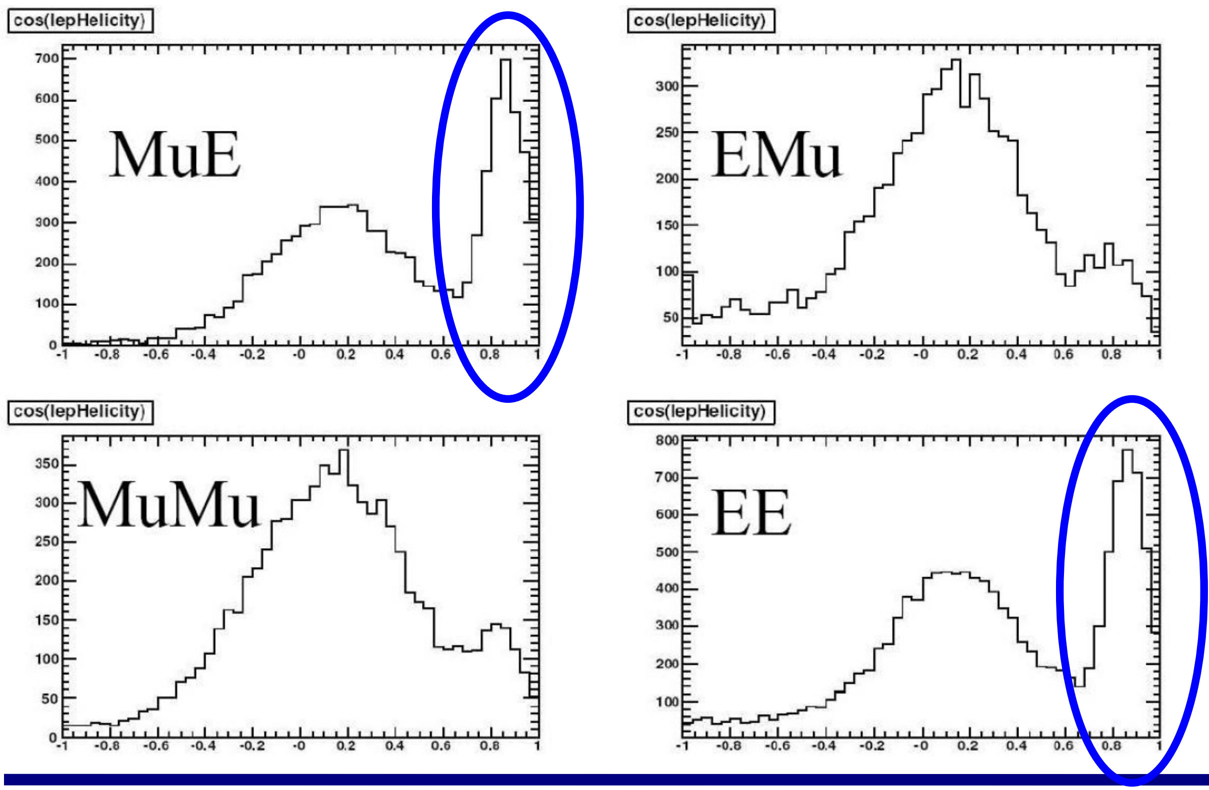
- We expect peaking backgrounds from:
  - Crossfeed (mis-reconstructed signal events)
  - J/ψ and ψ(2S) events where events escape our veto
  - B →Dπ where one or both muons are faked by pions
  - B → K*μh events in which a pion fakes a muon and peaks in our signal region
    - Modelled using the data by removing the PID requirements of one muon





Combinatoric Backgrounds

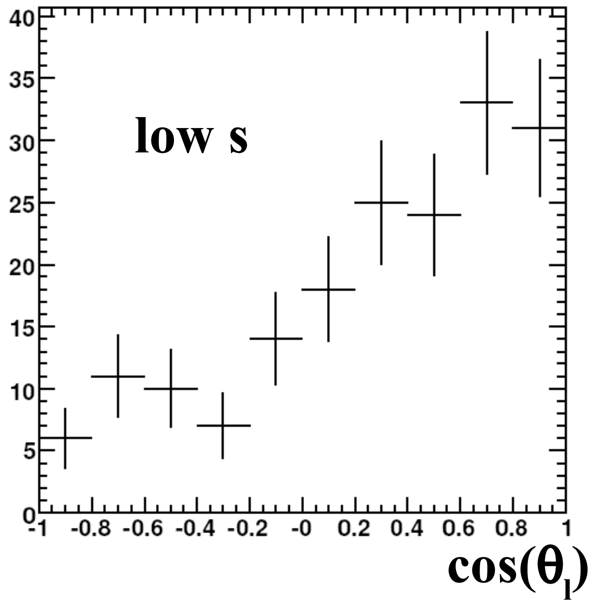
- Large asymmetries in the combinatoric backgrounds
- Would like to model using the data
- In the wrong lepton flavor control sample, the same hadronic final states are reconstructed but now $K^*l^+l^- = K^*e^+\mu^-$ or $K^*\mu^+e^-$

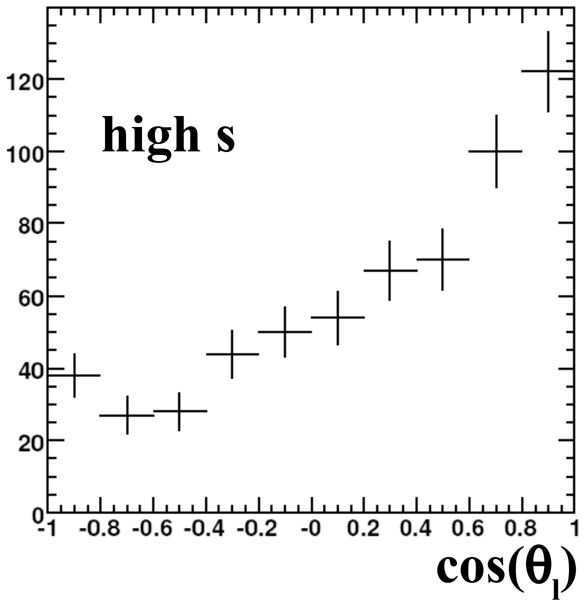


- This peak at high $\cos(\theta_l)$ is from events in which the B decays semi-leptonically to a D + lepton + ν, and the D also decays semi-leptonically
- We see the cascades in MuE and EE and less in MuMu and EMu. **This is a result of differing momentum cuts on electrons (300 MeV/c) and muons (700 MeV/c).**

Final Combinatoric PDF Shape

- The size of the peak changes as a function of where you are in m_{ES}. It is larger the closer you are to the signal region.
- Due to the m_{ES} dependence on the shape we choose our combinatoric model in the **FitRegion Sideband** fit $\cos(\theta_l)$ and $\cos(\theta_k)$ only in the **Signal Region.**
- **Simultaneously fit the data and the sideband model (below) using a binned pdf.**





Fit Strategy

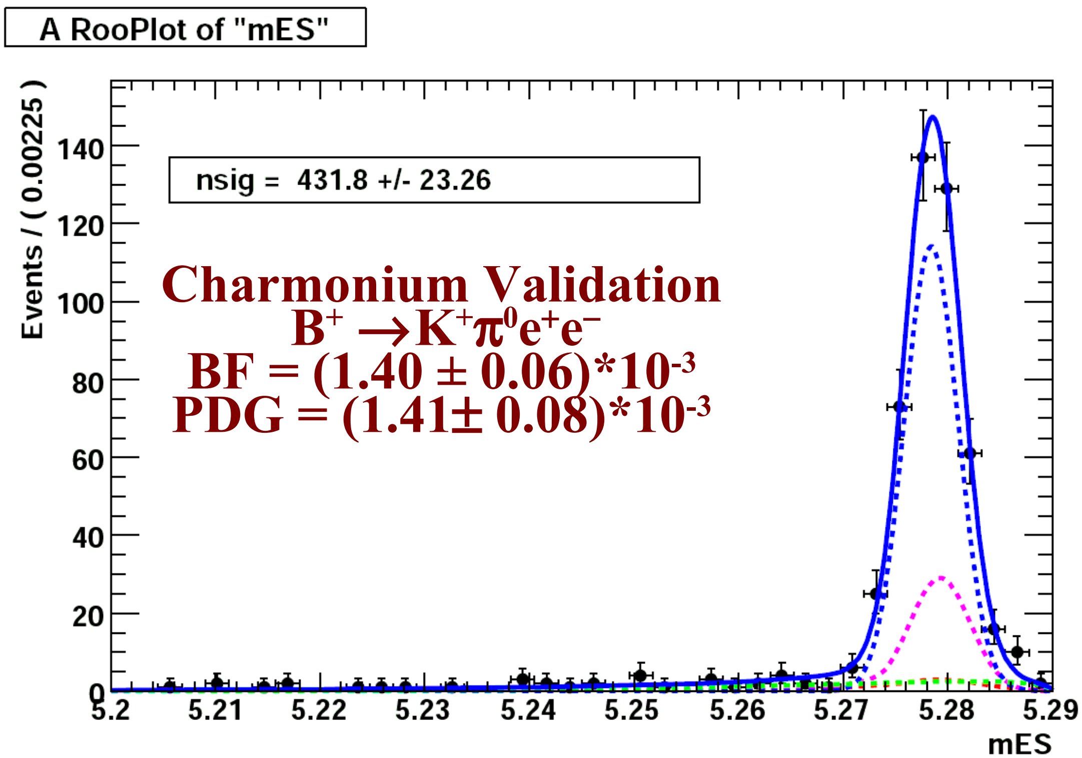
- Combine the datasets for the 6 B $\rightarrow$K*ll modes in each s bin and fit.
- Three step fit in m_{ES}, cos θ_k, cos θ_l
  - Signal, combinatoric and peaking background components modelled in the fit
  - Fit is validated using charmonium and toy studies. Once validated, the data is unblinded at each step.

    1) Fit m_{ES} to extract the signal and background yields

    2) Fit cos θ_k in the m_{ES} signal region to extract F_L

    3) Fit cos θ_l in the m_{ES} signal region to extract A_{FB}
- RooFit/ROOT used to build PDFs, MINUIT used to perform minimization

m_{ES} Fits - Charmonium Validation

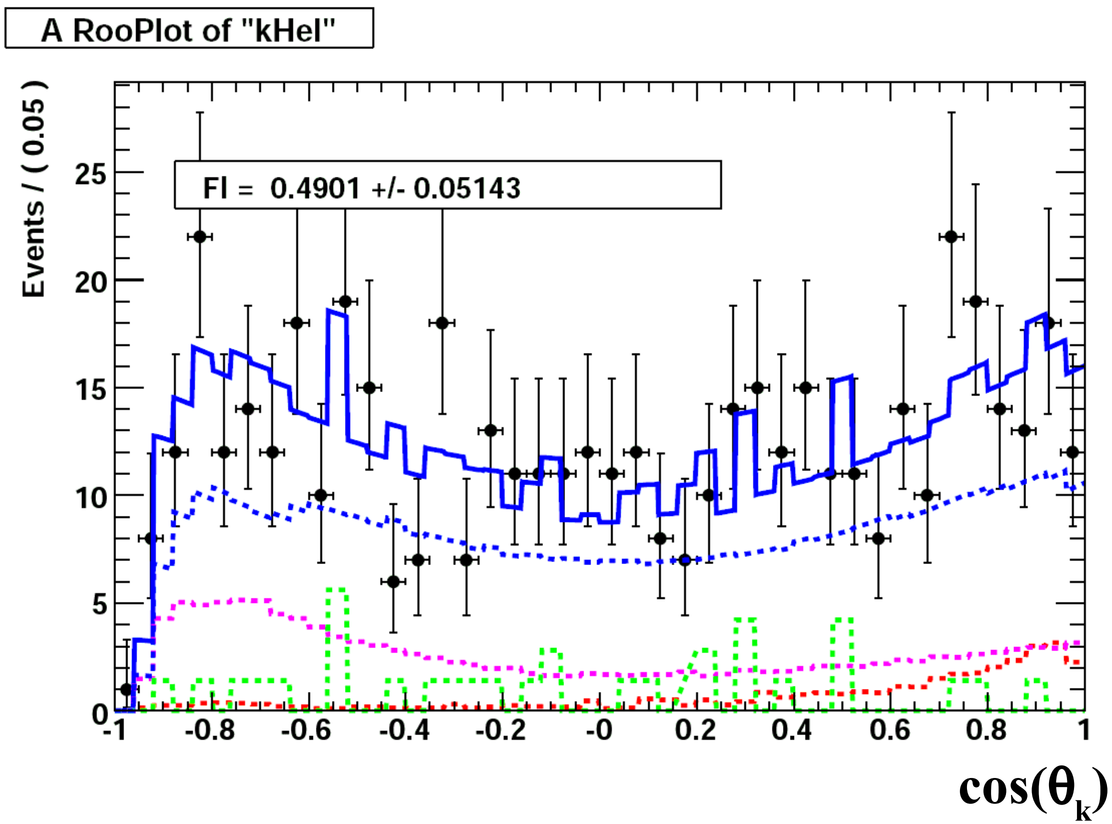


- m_{ES} Components
  - Gaussian signal
  - ARGUS shape models combinatoric background
  - Gaussian with a power law tail (Crystal Ball function) to fit self-crossfeed (shape fixed from signal MC)
  - Crystal Ball feed-across crossfeed

- BF(B → J/ψK*) ≈ 1000*BF(B → K*ll)
- Validate on the vetoed charmonium dataset
- Run the fit on each of the 6 charmonium modes separately
- Excellent agreement across the modes

F_L Fits - Charmonium Validation

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos(\theta_K)} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$



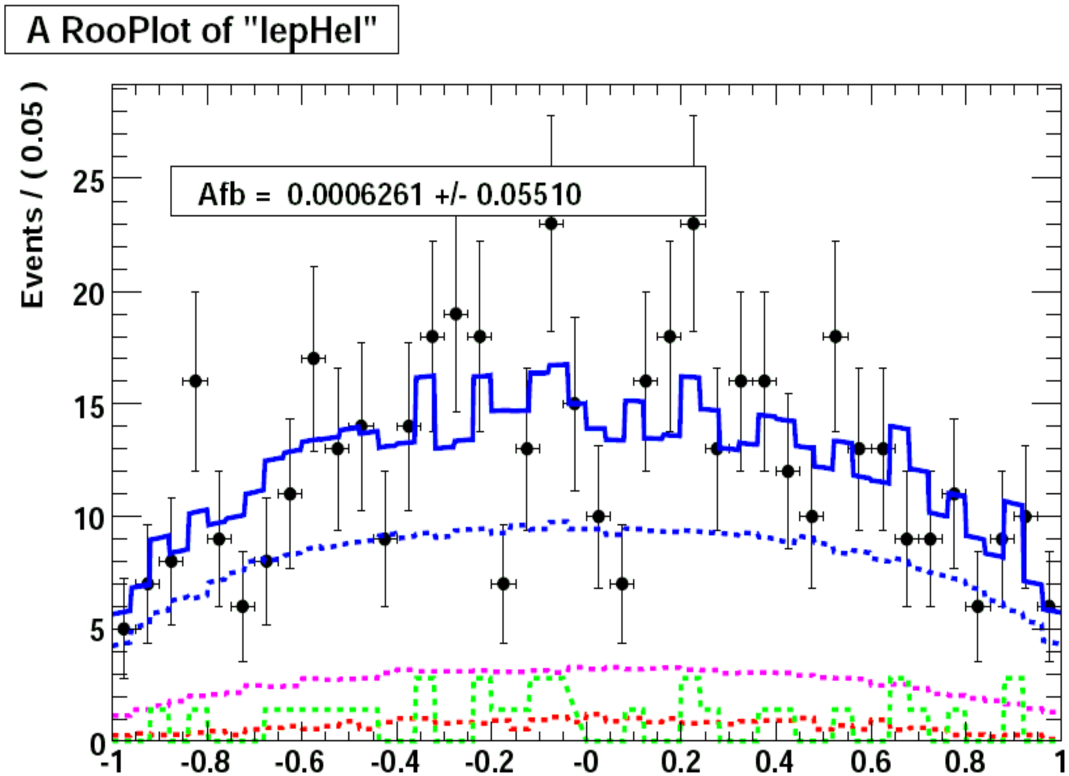
Charmonium Validation
$B^+ \rightarrow J/\psi K^+\pi^0$ ($J/\psi \rightarrow e^+e^-$)
Expected F_L = 0.56 +/- 0.03

– $\cos(\theta_k)$ Components

- Signal (given above), modified by efficiency
- Binned pdf models combinatoric background
- Self Crossfeed – fixed pdf shape from MC
- Feed-across Crossfeed – fixed pdf from MC

A_{FB} Fits - Charmonium Validation

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos(\theta_l)} = \frac{3}{4}F_L\left(1-\cos^2\theta_l\right)+\frac{3}{8}\left(1-F_L\right)\left(1+\cos^2\theta_l\right)+A_{FB}\cos\theta_l$$



$\cos(\theta_l)$

Charmonium Validation
$B^+ \rightarrow K^+\pi^0e^+e^-$
Consistent w/ null AFB

– $\cos(\theta_l)$ Components
- Signal (given above), modified by efficiency
- Binned pdf models combinatoric background
- Self Crossfeed – fixed pdf from MC
- Feed-across Crossfeed – fixed pdf from MC

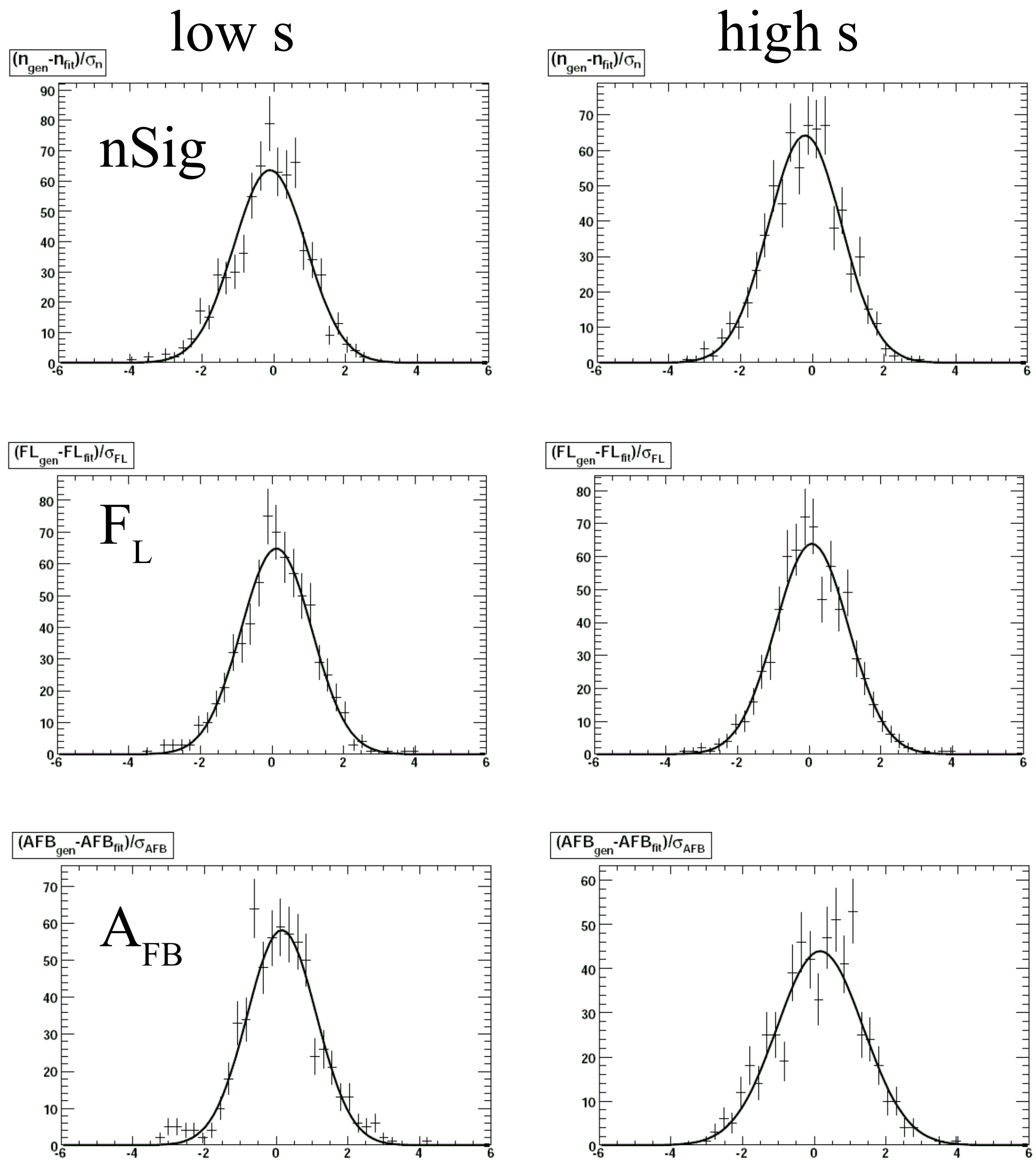
Validation using Toy Datasets

- Datasets are created to represent what we might expect in the data:
  - signal events come from generated signal MC
  - crossfeed events also from generated signal MC
  - combinatoric backgrounds are generated from PDFs fit to the combined generic MC (BB, udsc) sample.
  - peaking backgrounds when possible come from the data, otherwise a corresponding MC sample
- Full likelihood function is fit to an ensemble of 700 of these so-called "toy" datasets.
- Define the pull of a floating parameter as:

$$\text{Pull} = \frac{par_{\text{exp}} - par_{\text{fit}}}{par_{\sigma}}$$

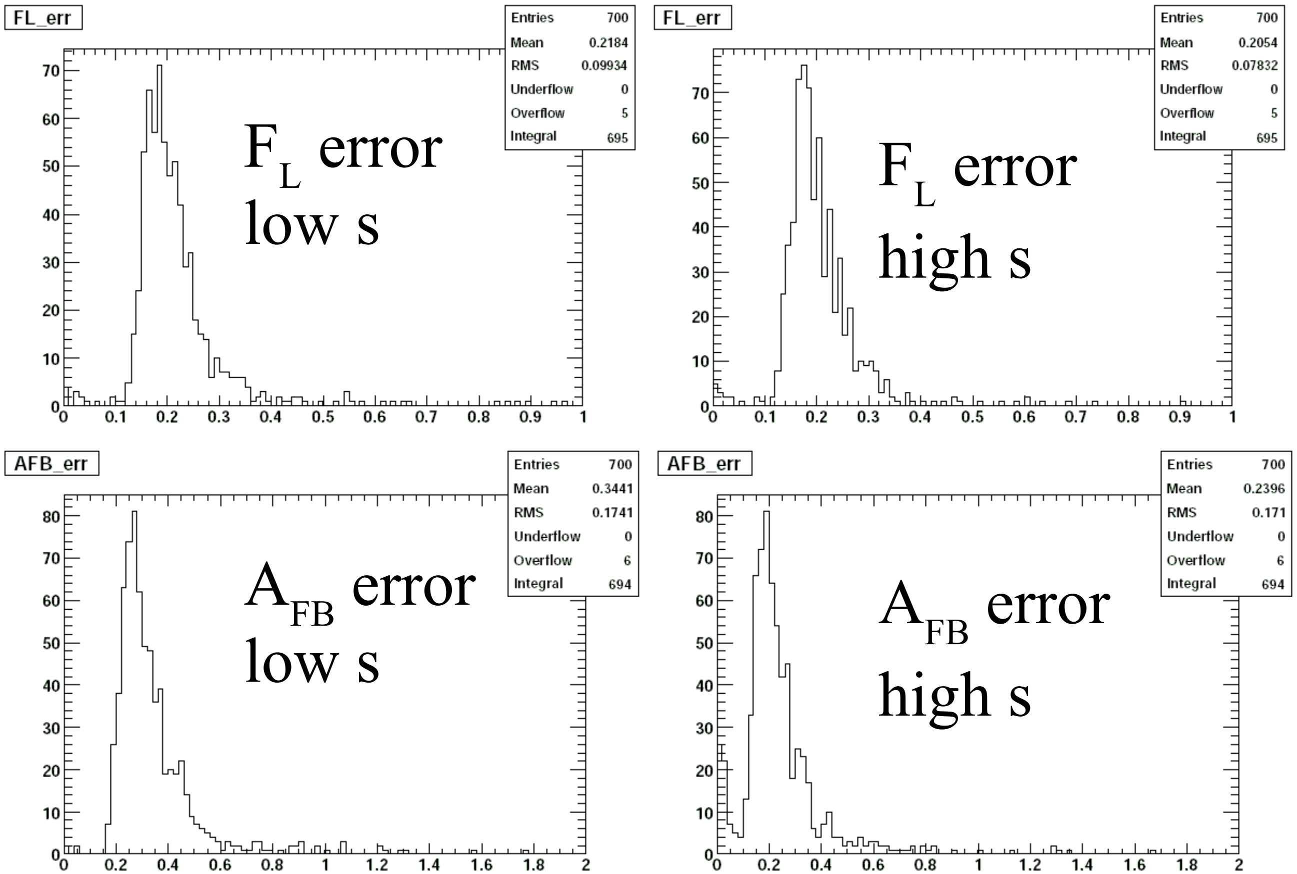
- Gaussian distribution
- Mean at 0 and $\sigma = 1$

Pull Distributions



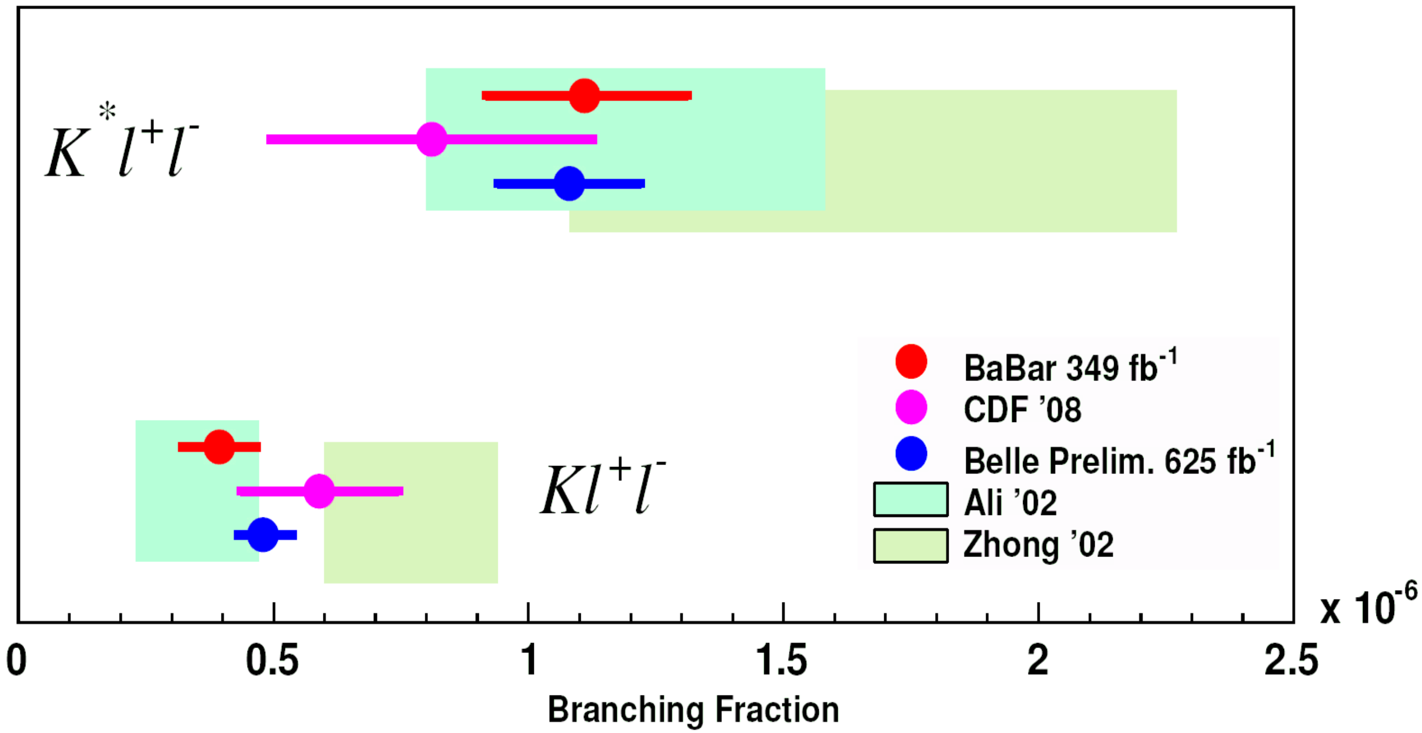
Good Fit Criteria

- Define a good fit based on the error distributions from the previous toy studies



- the error on F_L be $0.05 < \sigma(F_L) < 1.00$;
- the error on A_{FB} be $0.05 < \sigma(A_{FB}) < 2.00$

B→K(*)ll Branching Fractions



BaBar preliminary – ICHEP '08

$$\mathrm{B}(B \to K^{*}\ell^{+}\ell^{-}) = (11.1^{+1.9}_{-1.8} \pm 0.7) \times 10^{-7}$$

$$\mathrm{B}(B \to K\ell^{+}\ell^{-}) = (3.9 \pm 0.7 \pm 0.2) \times 10^{-7}$$

BELLE preliminary – ICHEP '08

$$\mathcal{B}(B \to K^{*}\ell^{+}\ell^{-}) = (10.8^{+1.0}_{-1.0} \pm 0.9) \times 10^{-7}$$

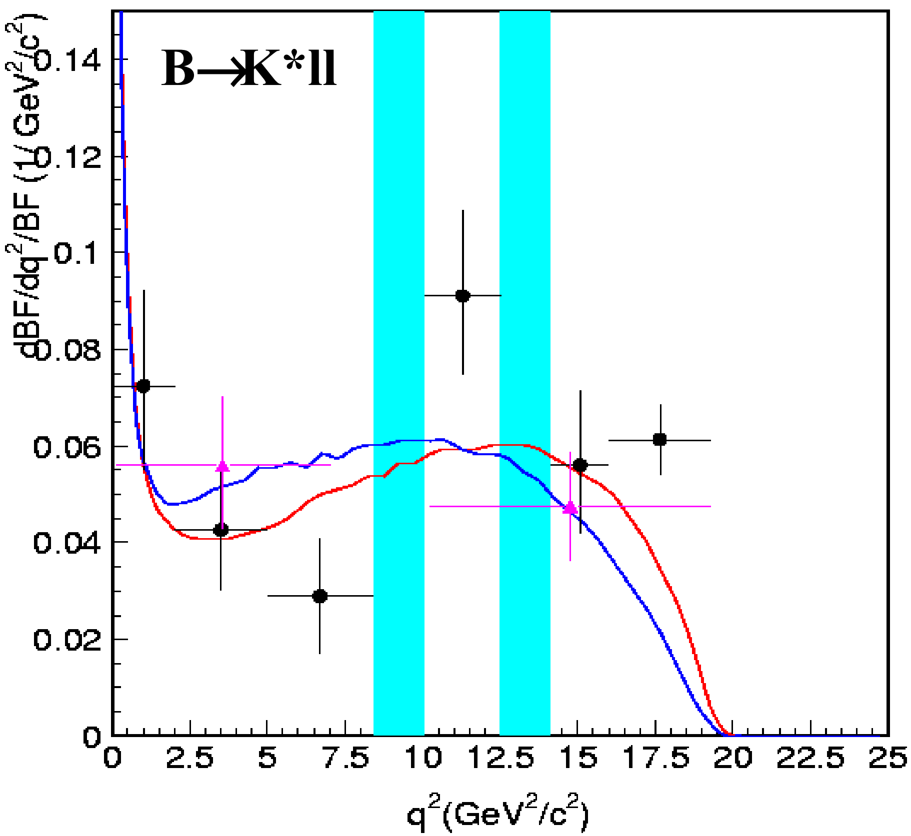
$$\mathcal{B}(B \to K\ell^{+}\ell^{-}) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$$

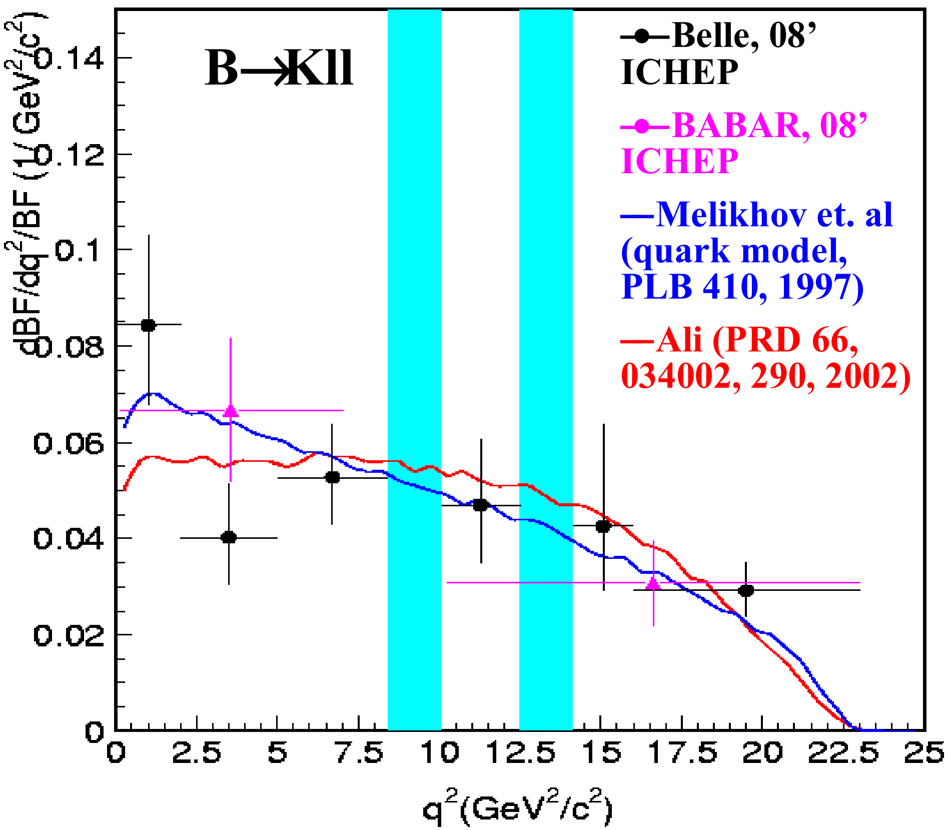
Consistent with theory.
Next level of SM tests from rate asymmetries and angular information (as functions of $q^2 = s = m_{ll}^{\ 2}$)

B→K(*)ll q^2 Distributions

BaBar Result:
arXiv: 0807.4119
submitted to PRL

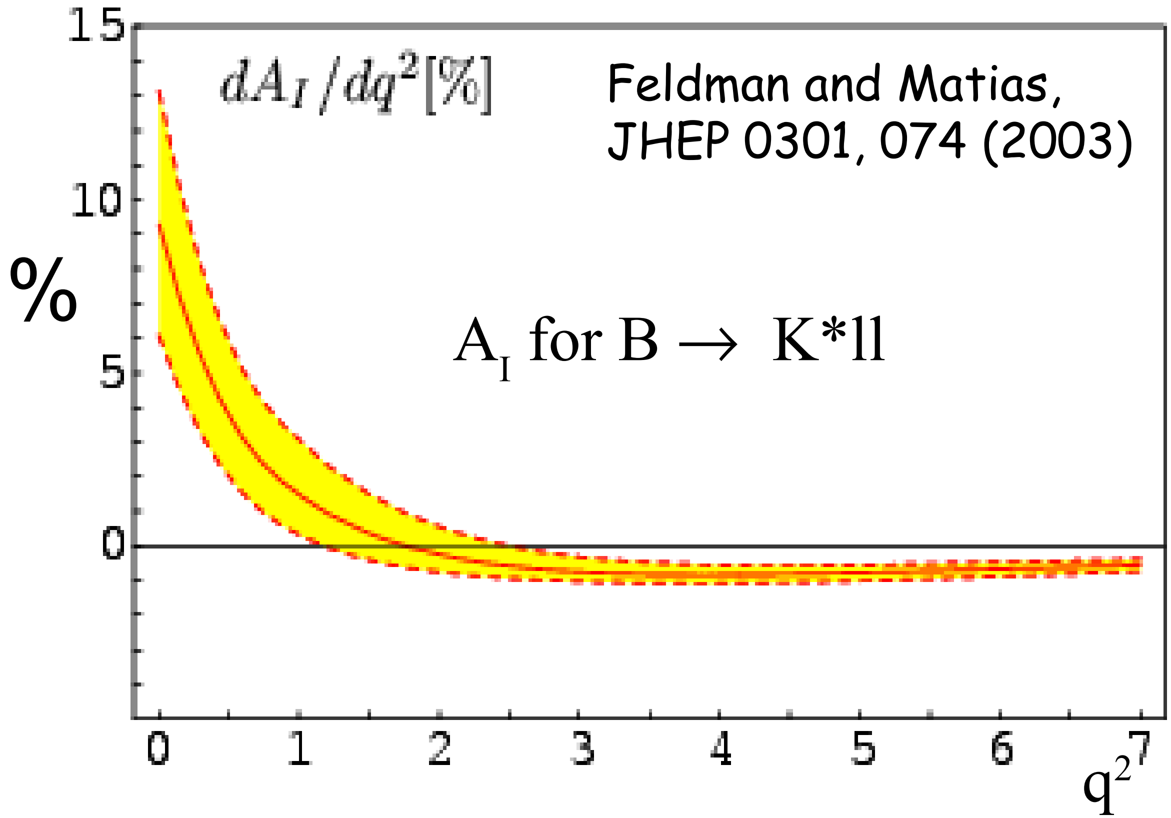
$$q^2 = m_{\ell\ell}^2$$





$B \to K(^*)ll$ Isospin Asymmetries

$$A_I \equiv \frac{\mathrm{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - (\frac{\tau_0}{\tau_+})\mathrm{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}{\mathrm{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + (\frac{\tau_0}{\tau_+})\mathrm{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}$$



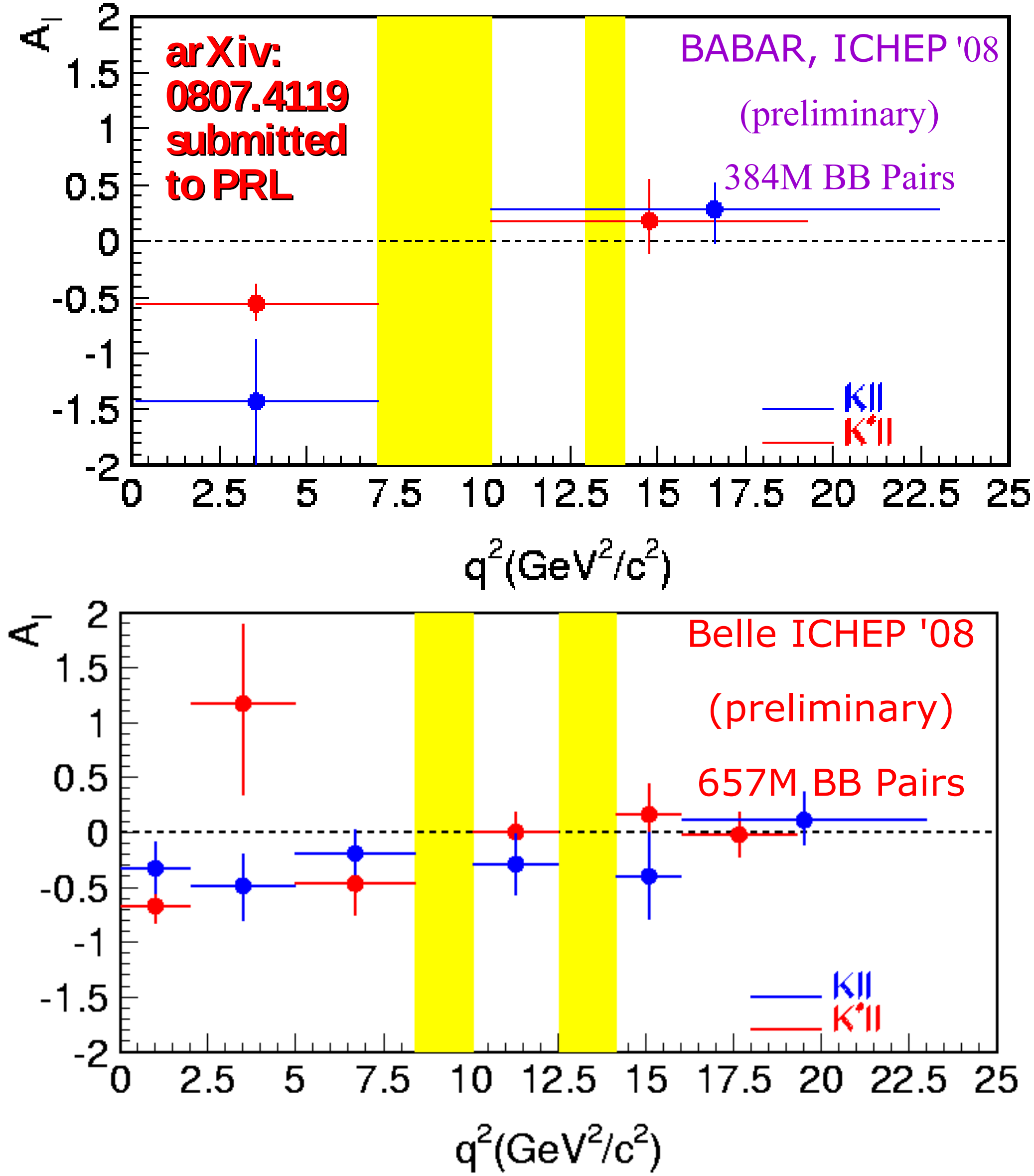
Isospin asymmetry is expected to be 0 for $B \to Kll$

For $B \to K^*ll$: Small in Standard Model, with some variation at low- q^2, near 0 for high-q^2

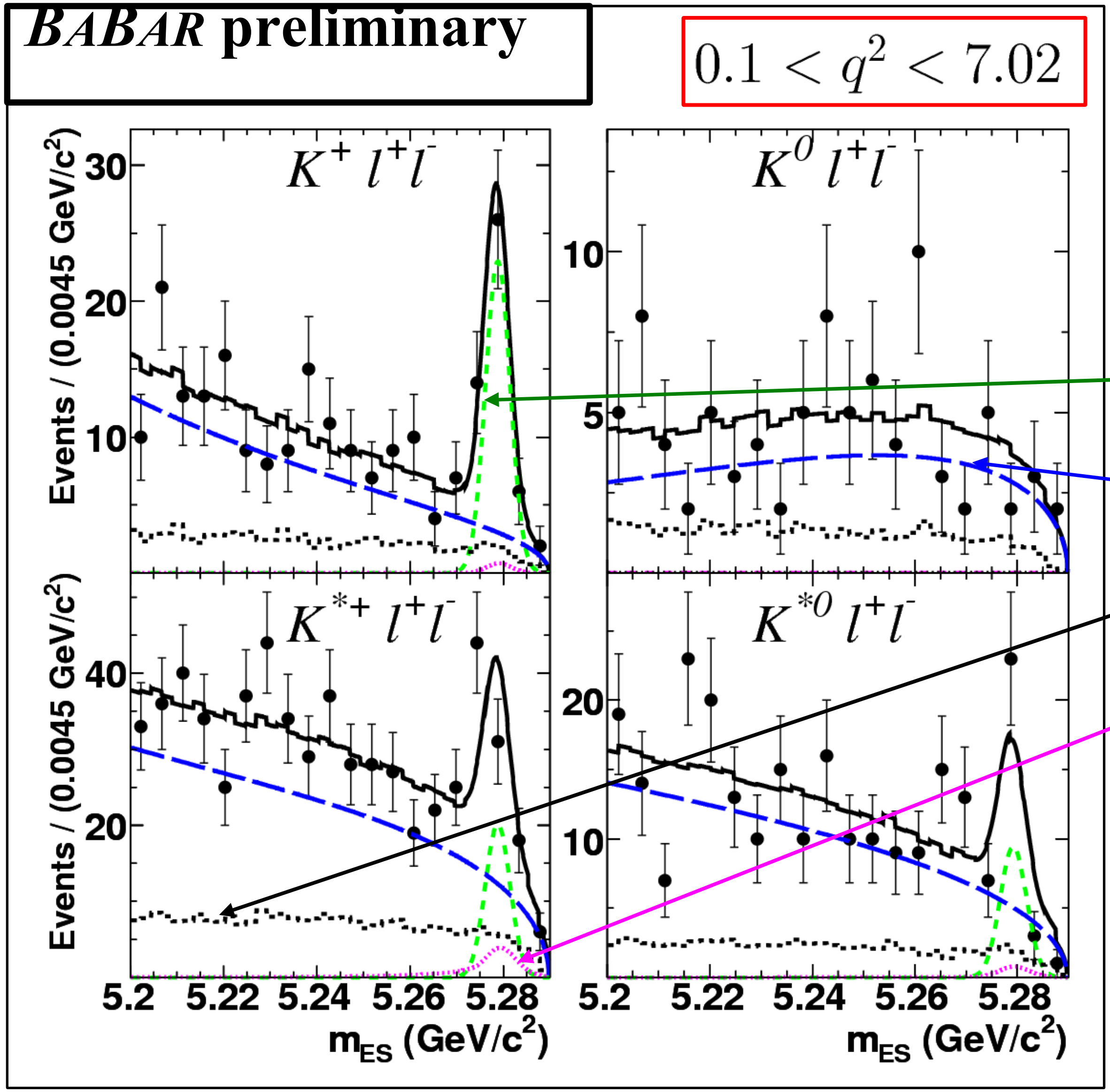
Some sensitivity to the sign of C_7

$B \to K^{(*)} ll$ Isospin Asymmetries

- No significant asymmetry in the high q^2 region
- BaBar sees significant negative isospin asymmetries in the low q^2 region
- Belle and BaBar's results are consistent.



B^0 vs. $B^+ \to K(*)ll$ Comparison (BaBar)



$$B(B^\pm \to K^\pm \ell^+ \ell^-) = (2.5^{+0.52}_{-0.47} \pm 0.1) \times 10^{-7}$$

$$B(B^0 \to K^0 \ell^+ \ell^-) < 0.9 \times 10^{-7} \text{ (90\% CL)}$$

- Signal
- Combinatoric BG
- Fake Muons
- Crossfeed/peaking

$$B(B^0 \to K^{*0} \ell^+ \ell^-) = (2.6^{+1.1}_{-1.0} \pm 0.2) \times 10^{-7}$$

$$B(B^\pm \to K^{*\pm} \ell^+ \ell^-) = (9.8^{+2.6}_{-2.4} \pm 0.6) \times 10^{-7}$$

Lepton Flavor and CP Asymmetries

- The ratio of electron BF to muon BF ($R_{K(*)}$) should be R_{K*}=1.33 for K* modes (contribution from the pole region) and R_K=1.0 for K modes in the SM.
- R_K is predicted to be larger than 1.0 in the two Higgs doublet model with large tan(β)
- Results:

Lepton Asy.	Belle (657M)	BABAR (384M)
$K^*\ell\ell$	1.21±0.25±0.07	$1.37^{+0.53}_{-0.40}$
$K\ell\ell$	0.97±0.18±0.05	$0.96^{+0.44}_{-0.34}$

- CP Asymmetry:

$$A_{CP} = \frac{N_{\overline{B}} - N_B}{N_{\overline{B}} + N_B}$$

CP Asy.	Belle (657M)	BABAR (384M)
$K^*\ell\ell$	-0.10±0.10±0.03	-0.02±0.16
$K\ell\ell$	0.04±0.10±0.02	-0.18±0.18

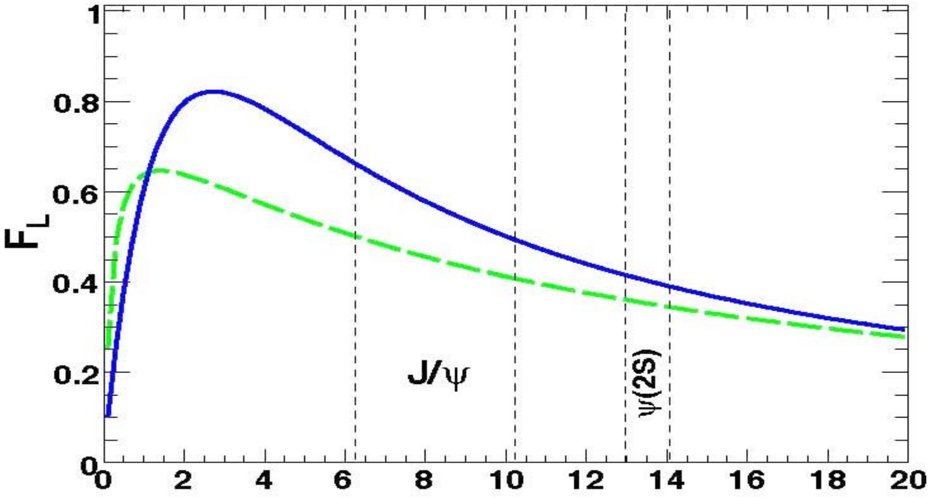
Angular Distributions

Angular distributions as functions of q^2 are particularly sensitive to possible new physics.

K* longitudinal polarization F_L

From distribution of the angle θ_K between the K and B in the K* rest frame

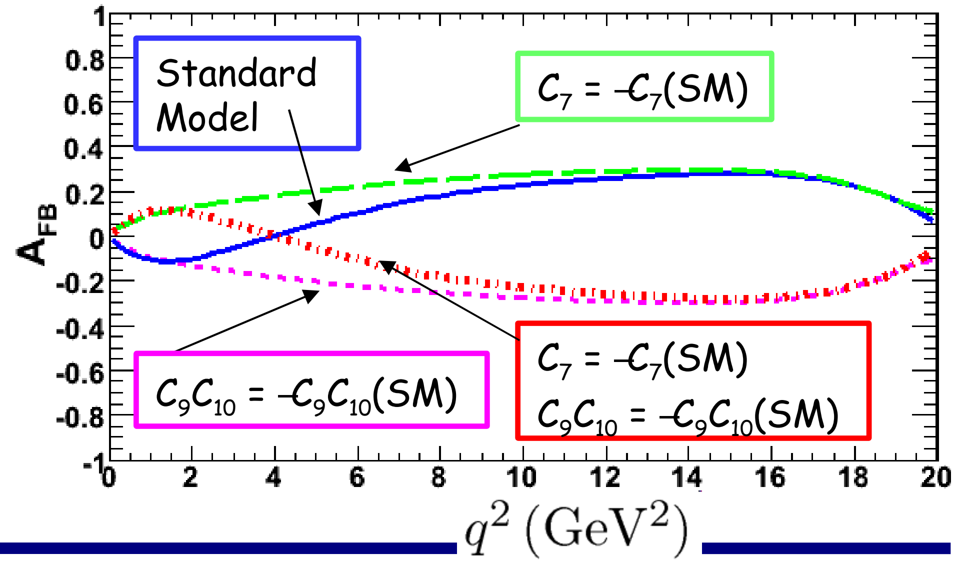
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$



Lepton forward-backward asymmetry A_{FB}

From distribution of the angle θ_l between the l^+ and B in the l^+l^- rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$



BaBar Angular Fits

Two q^2 bins:

low – $0.1 < q^2 < 6.25\ GeV^2$

high - $q^2 > 10.24\ GeV^2$

except $12.96 < q^2 < 14.06$

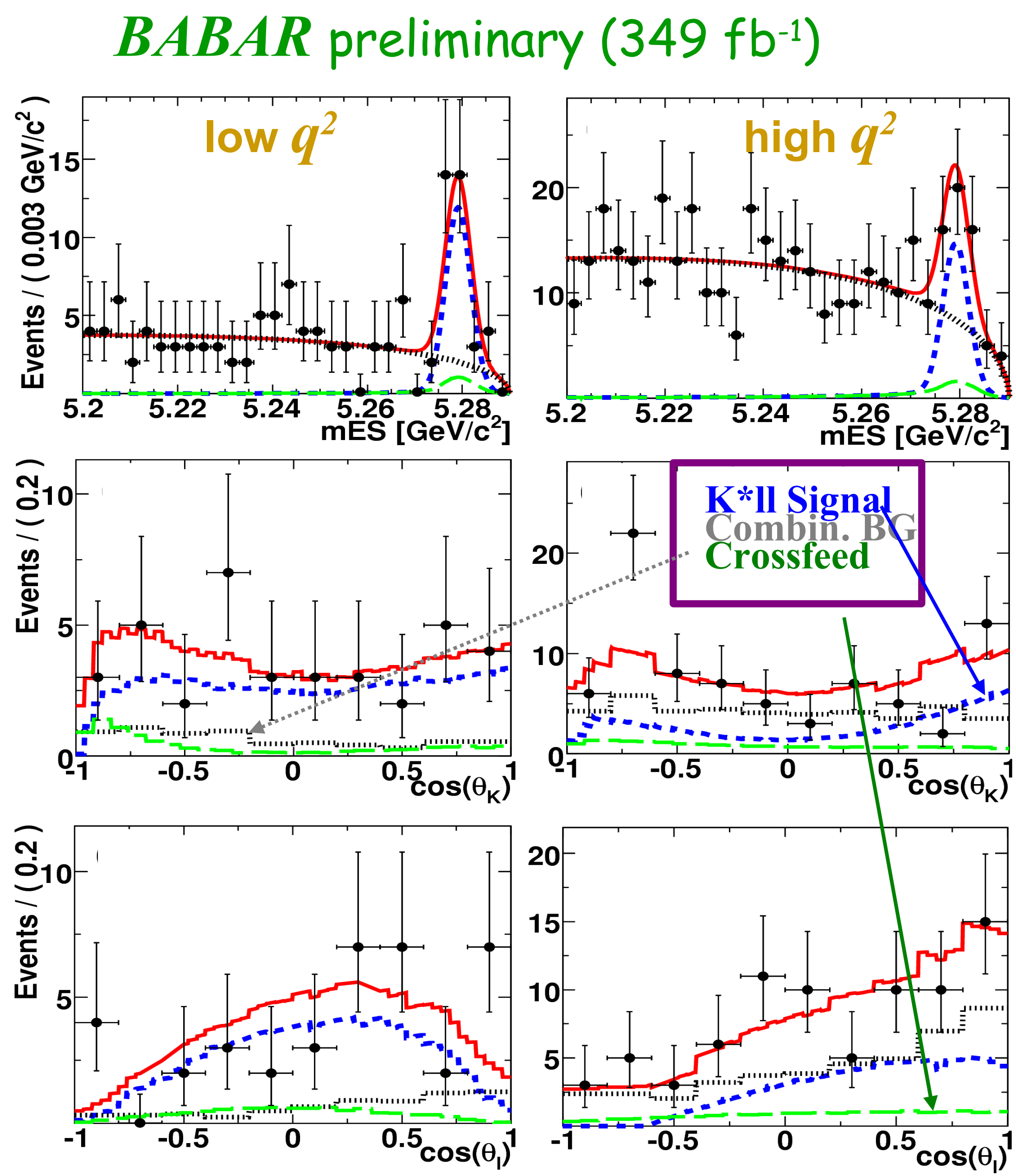
Three Step Fit Procedure:

- Combine $K^* l^+ l^-$ modes, fit for yields.
- Fix yields. For $m_{ES} > 5.27$, fit $\cos(\theta_K)$ for F_L
- Fix F_L, fit $\cos(\theta_l)$ for A_{FB}

Angular PDFs:

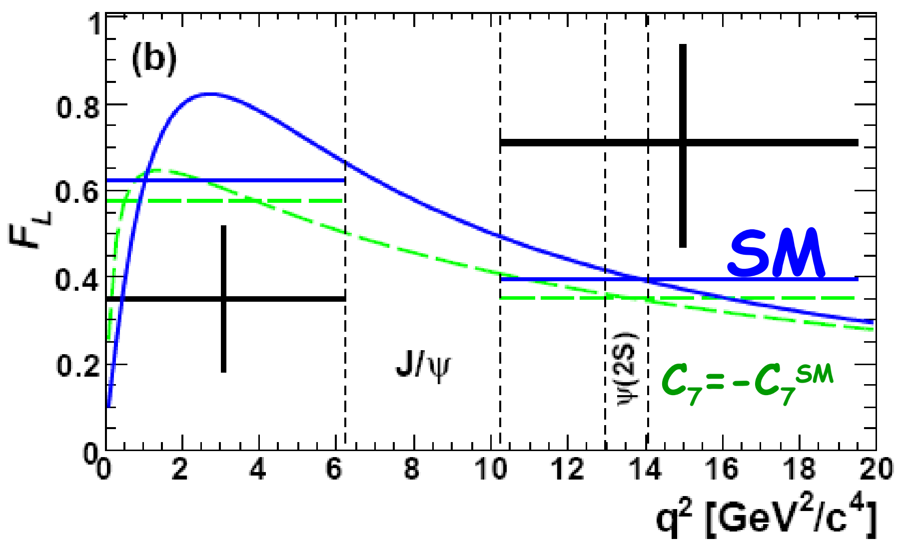
- Signal weighted by detector efficiency from MC

- Combinatorial background from m_{ES} sidebands in data

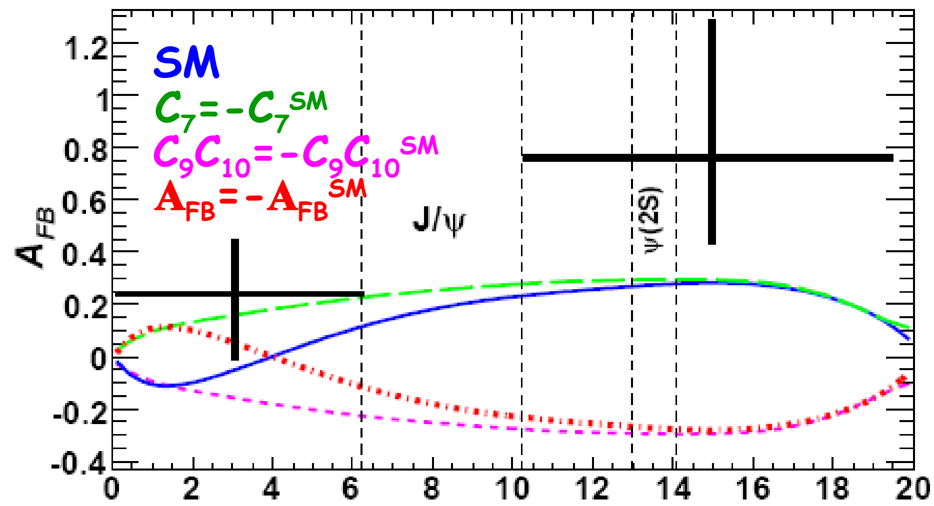


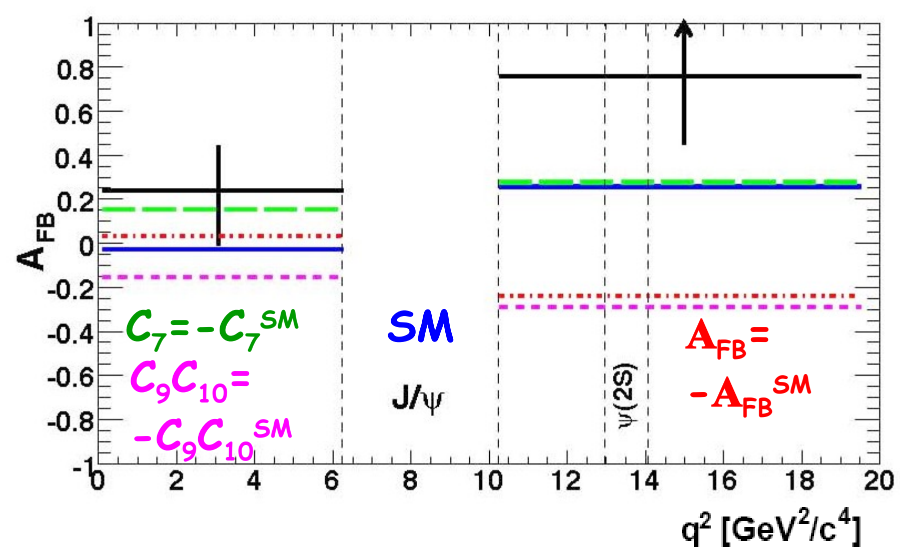
BaBar F_L, A_{FB} (Preliminary) Results

Longitudinal K* polarization



Forward- backward Asymmetry





$$F_L^{\text{low } s} = 0.35 \pm 0.16 \pm 0.04$$

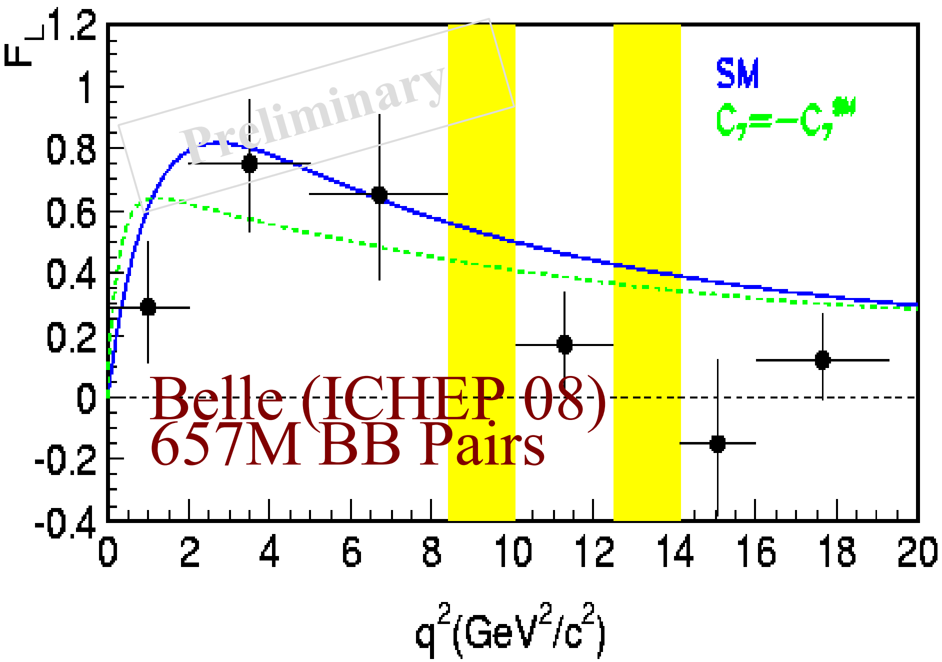
$$F_L^{\text{high } s} = 0.71^{+0.20}_{-0.22} \pm 0.05$$

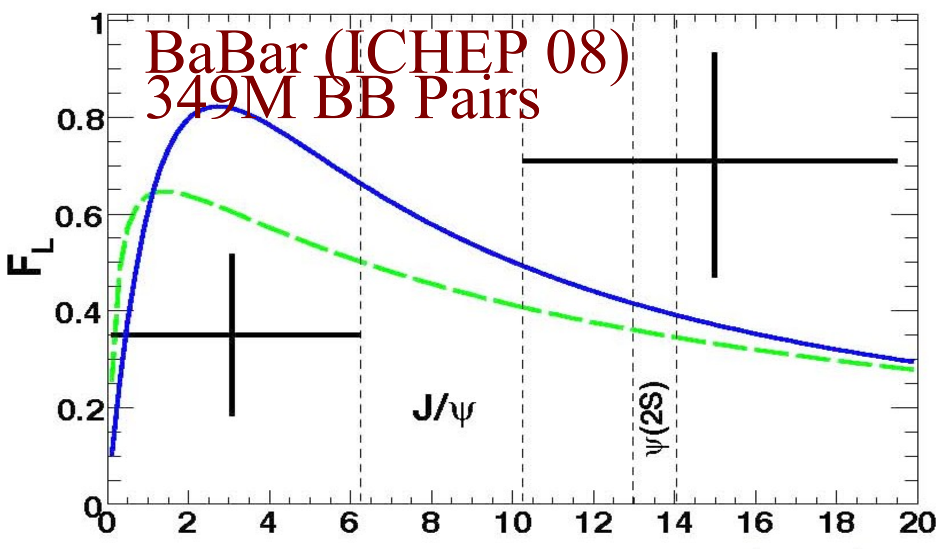
$$A_{FB}^{\text{low } s} = 0.24^{+0.18}_{-0.23} \pm 0.06$$

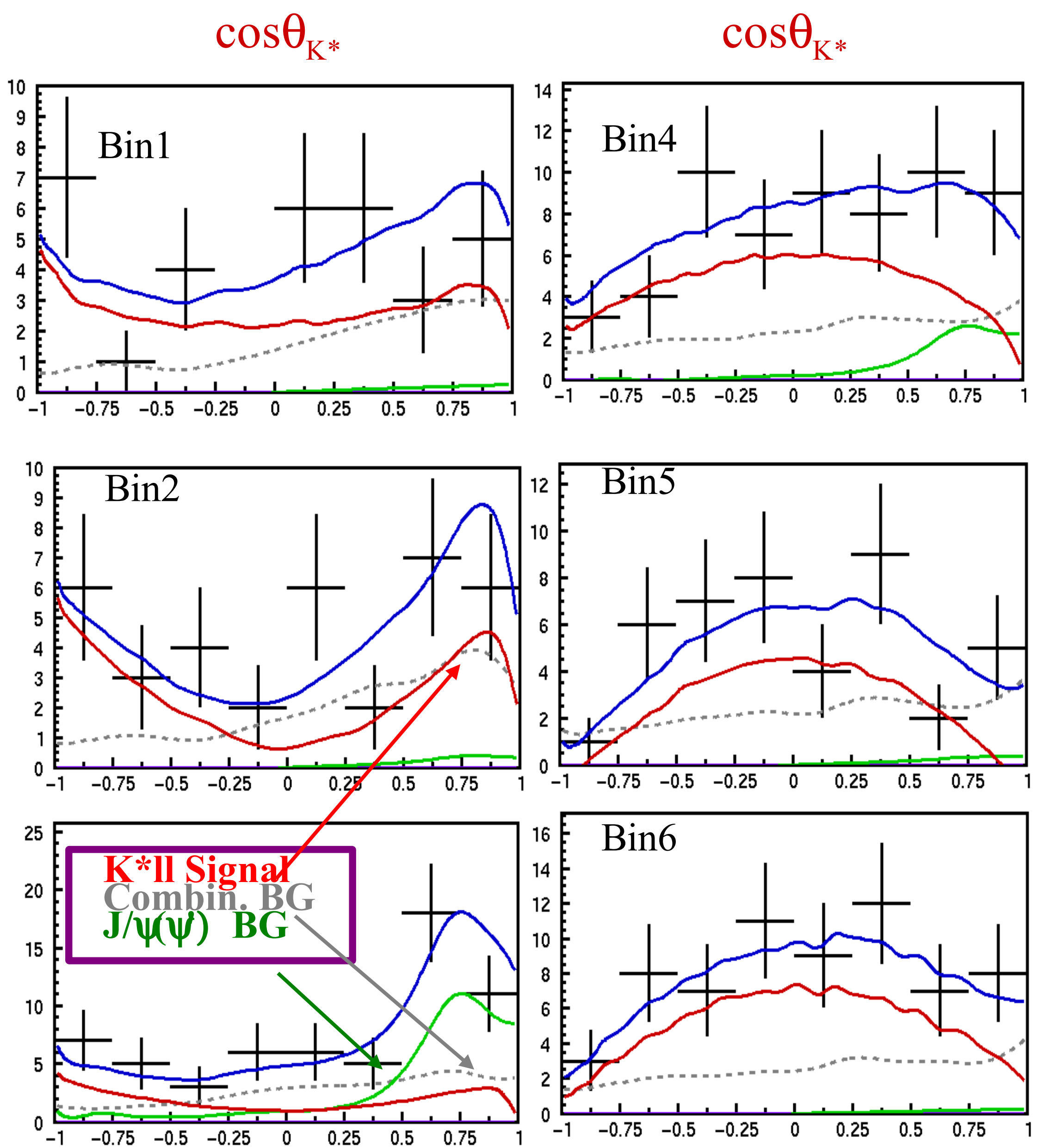
$$A_{FB}^{\text{high } s} = 0.76^{+0.52}_{-0.32} \pm 0.07$$

arXiv: 0804.4412 submitted to PRL

Belle Angular Fits (Preliminary): F_L

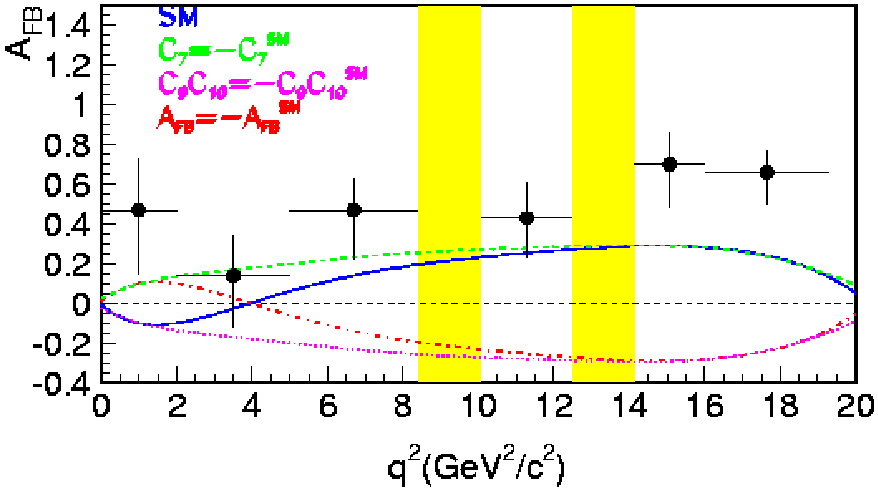




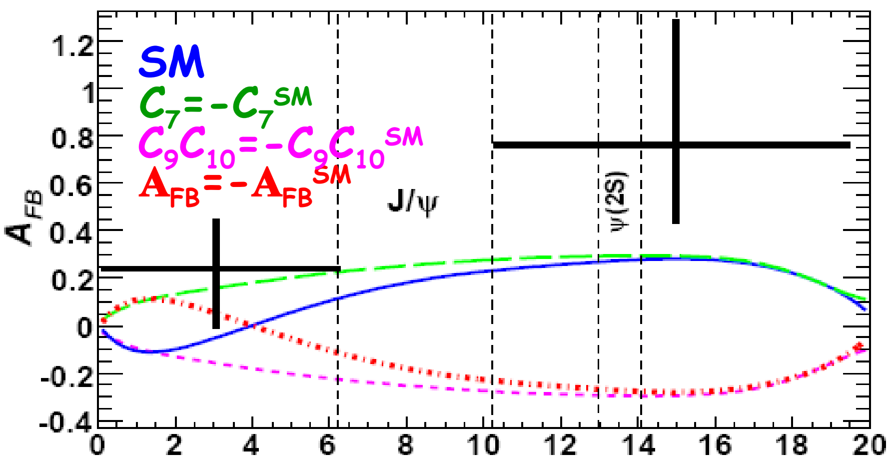


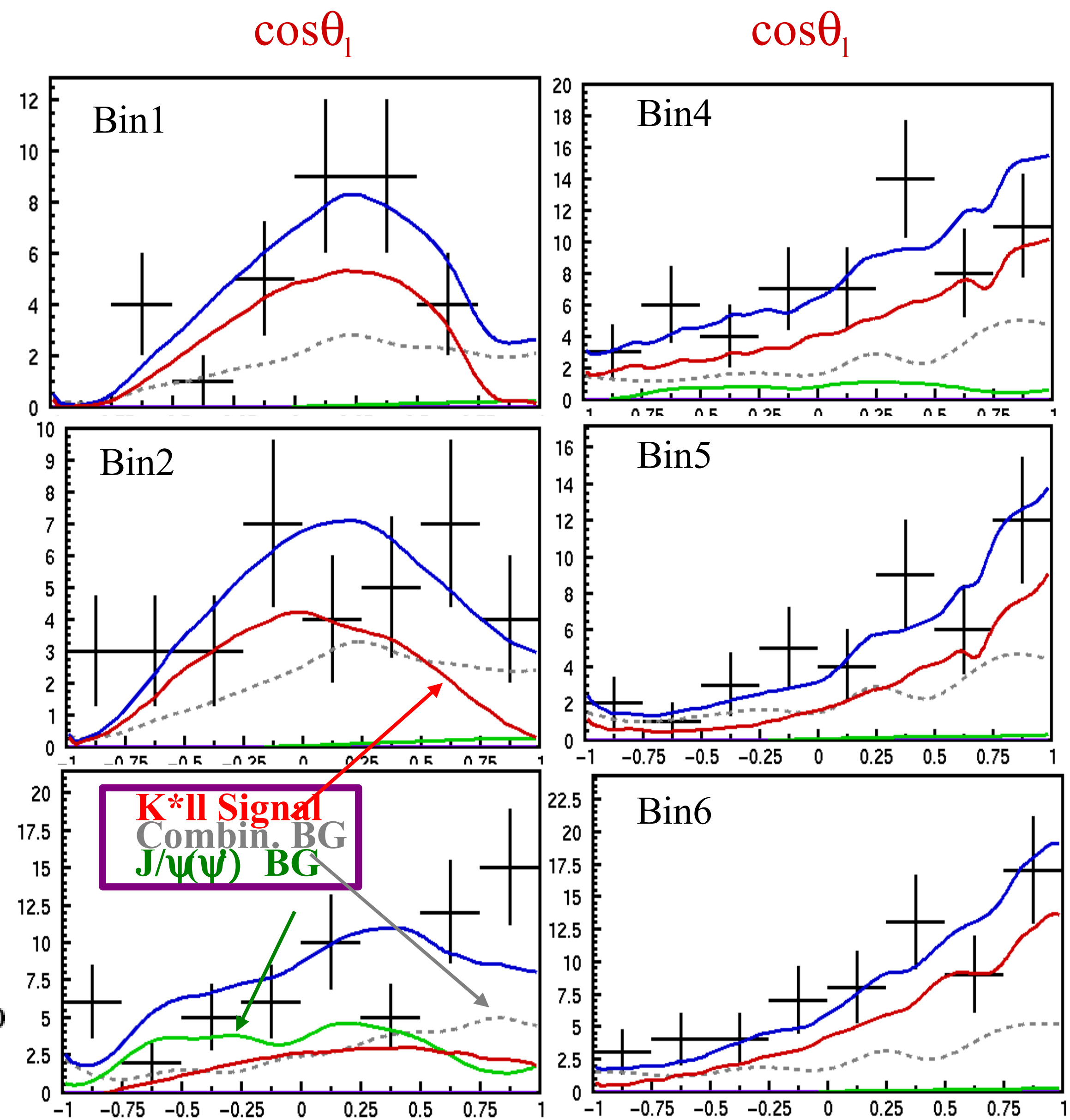
Belle Angular Fits (Preliminary): A_{FB}

Belle (ICHEP '08)



BaBar (ICHEP '08)





Conclusion/Outlook

- The B $\rightarrow$ K*ll transition is one of the rarest decays accessible to the B-factories: provides a very promising avenue to search for new physics.
- I have presented current measurements the rate and angular asymmetries from BaBar and BELLE. The B-factories are nearing SM sensitivity to these observables.
- Significant isospin asymmetries observed by BaBar are unexpected. BELLE's results are consistent.
- A_{FB} measurements from both Belle and BaBar show no sign of a 0-crossing point and strongly disfavor a flipped-sign C_9C_{10} scenario. New physics possible???
- A measurement using the final dataset is underway. I plan on finishing an analysis of the B $\rightarrow X_s$ll final state using the final BaBar dataset.
- LHCb and SuperB (Lumi. = 10^{36}) should precisely measure the A_{FB} including the 0-crossing.

Backup Slides

Systematic Error Sources

- m_{ES} Fit Yields
  - from ARGUS shape parameter: vary by $\pm 1\sigma$
- F_L Fit Error
  - vary by $\pm 1\sigma$ to measure the effect on A_{FB}
- Background shape
  - see next slide
- Signal Model
  - Generate signal MC with different values of the Wilson coefficients to see the affect on signal shape. Toy MC studies used to measure the fit bias.
- Efficiency/Crossfeed
  - Varied Wilson coefficient MC used to study efficiency
  - Crossfeed systematic from the charmonium control sample

Systematic Errors

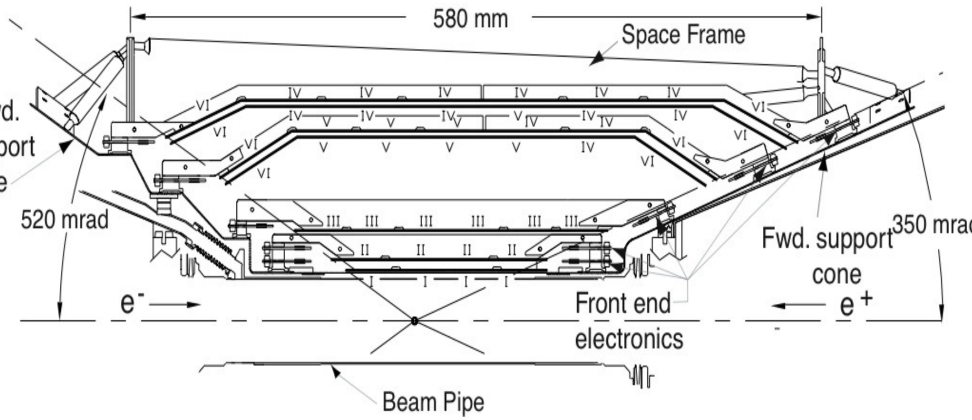
Source of Error	F_L systematic		$\mathcal{A}_{FB}$ systematic	
	low s	high s	low s	high s
m_{ES} fit yields	0.001	0.016	0.003	0.002
F_L fit error	N/A	N/A	0.025	0.022
Background shape	0.006	0.020	0.027	0.006
Signal model	0.036	0.034	0.030	0.038
Fit bias	0.012	0.020	0.023	0.052
Efficiency/cross-feed	0.010	0.010	0.020	0.020
Total	0.04	0.09	0.10	0.08

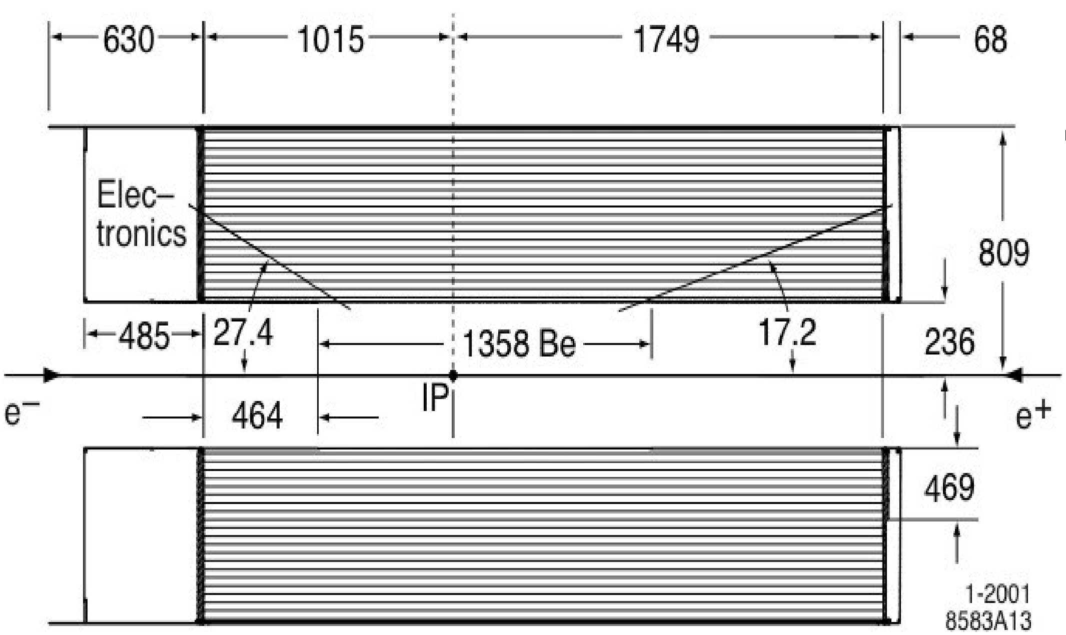
Combinatoric Background Systematic

Variation	F_L systematic		$\mathcal{A}_{FB}$ systematic	
	low s	high s	low s	high s
$5.20 < m_{\text{ES}} < 5.23$	$+0.011$	-0.008	-0.002	$+0.001$
$5.23 < m_{\text{ES}} < 5.27$	-0.004	$+0.007$	-0.017	-0.021
$\Delta E > 0$	$+0.002$	-0.031	-0.037	$+0.003$
$\Delta E < 0$	$+0.001$	$+0.017$	unconverged fit	-0.002
LFC	$+0.011$	-0.026	-0.037	unconverged fit
wrong flavor	-0.008	$+0.023$	$+0.024$	-0.003
Error	0.006	0.020	0.027	0.006

SVT and DCH

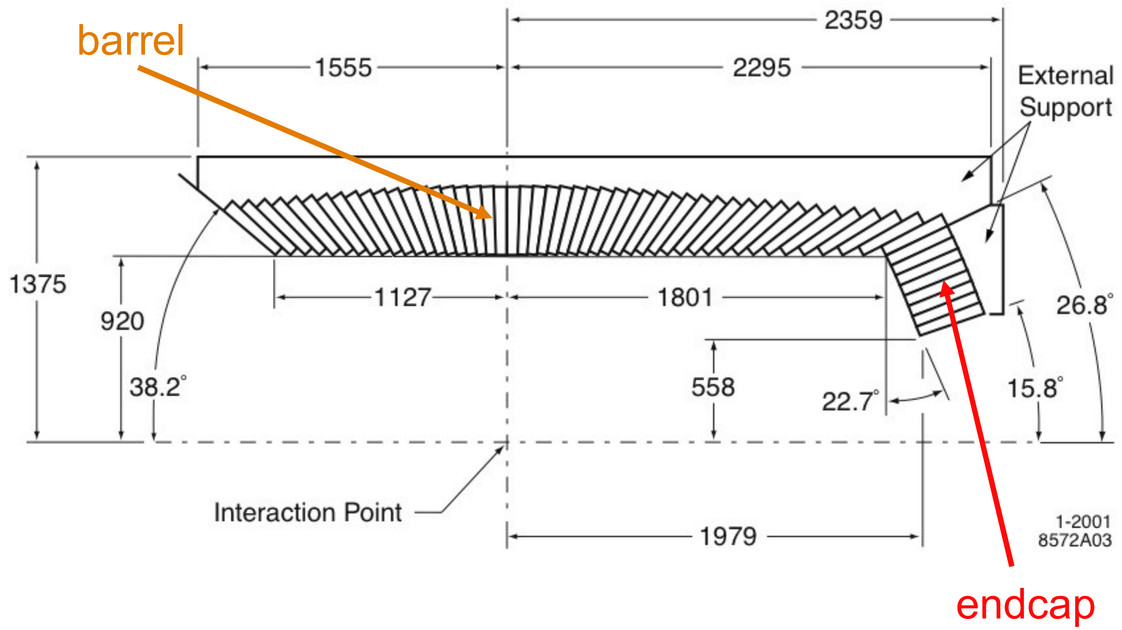
- <u>**Silicon Vertex Tracker**</u>:
  - Efficient detection/measurement of charged particle momentum and track angle near the IP .
  - 5 layers of double-sided silicon strip detectors arranged for **z** and **ϕ** measurement
  - Particles traverse ~0.04$\mathbf{X_o}$ material





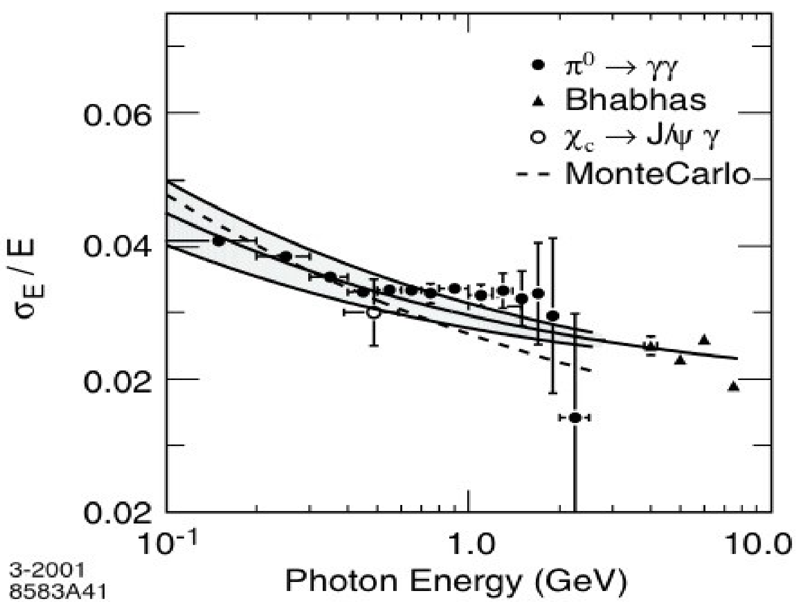
- <u>**Drift Chamber**</u>:
  - Efficient detection/measurement of charged particle momentum and track angle for $\mathbf{p}_T$ > 100 MeV/*c*
  - Good for reconstruction of decays and interactions that occur outside SVT, e.g. K^0_s.
  - Particle ID through ionization (**dE/ dx**) measurements at low momentum

Electromagnetic Calorimeter



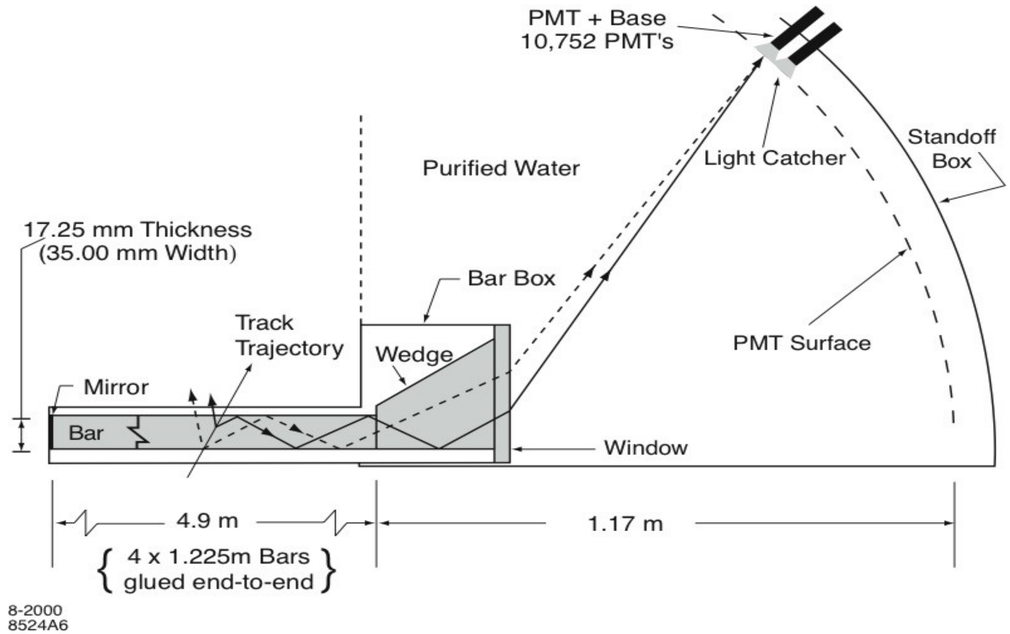
- EMC
  - Provides energy measurements of neutral clusters and electrons
  - Also aids in reconstruction of neutral hadrons (π^0/η)

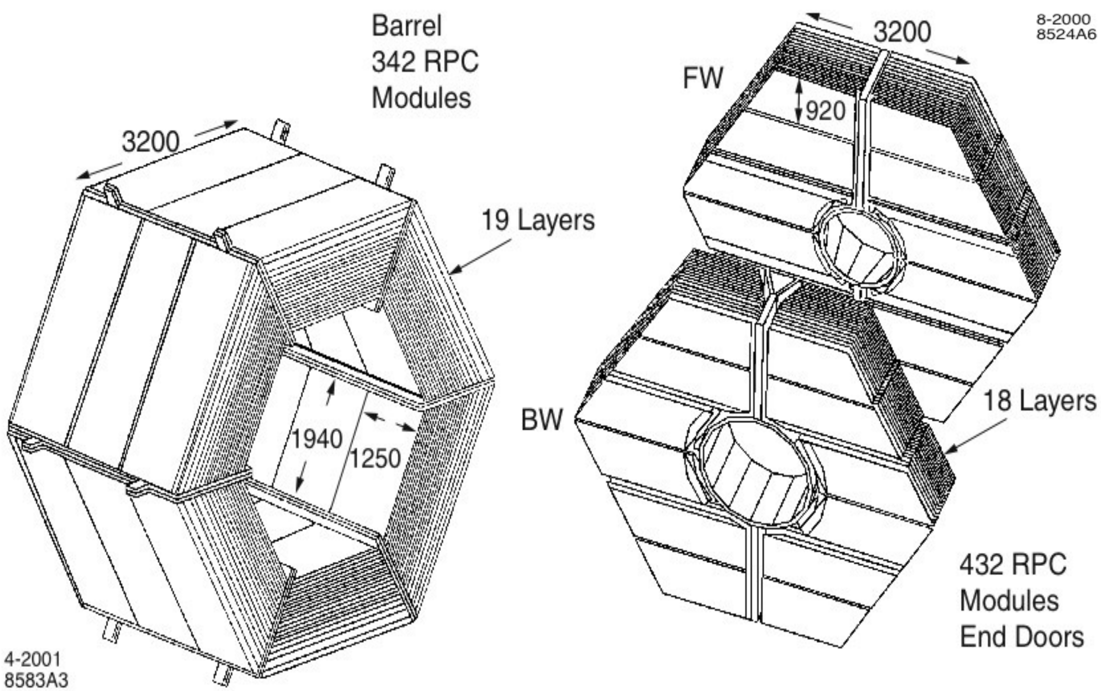
$$\frac{\sigma_E}{E} = \frac{(2.32 \pm 0.30)\%}{\sqrt[4]{E(\,\mathrm{GeV})}} \oplus (1.85 \pm 0.12)\%$$



DIRC and IFR

- **DIRC**:
  - Cerenkov detector
  - Kaon ID for B tagging
  - π/K separation from B meson decays for **p** $\leq$ 4.2 GeV/c





- **IFR**:
  - Used to detect μ's and neutral hadrons (ex. K^0_L)
  - Constructed of iron segmented with resistive plate chambers and limited streamer tubes
  - Thickness of iron increases from 2-10cm in radial direction