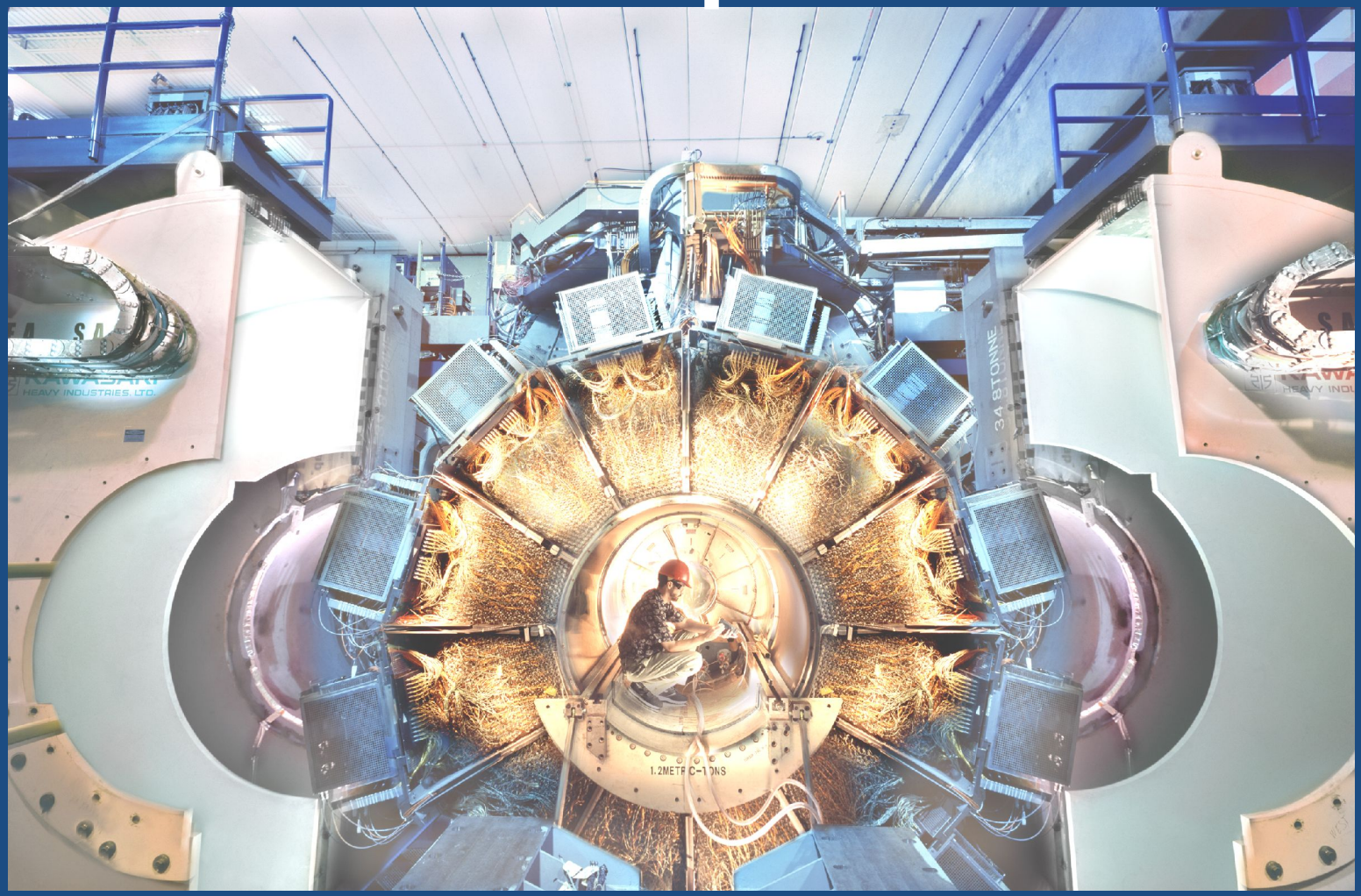
Search for CP Violation in $D^+ \to K^+ K^- \pi^+$
BABAR Experiment



Francisco Yumiceva

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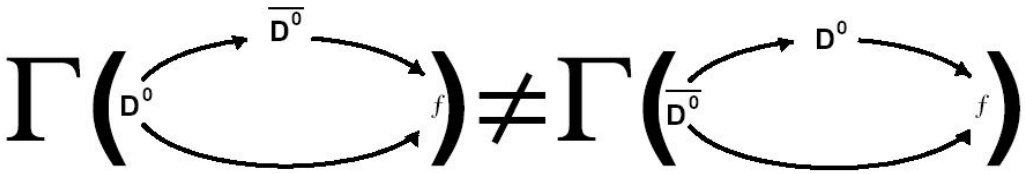
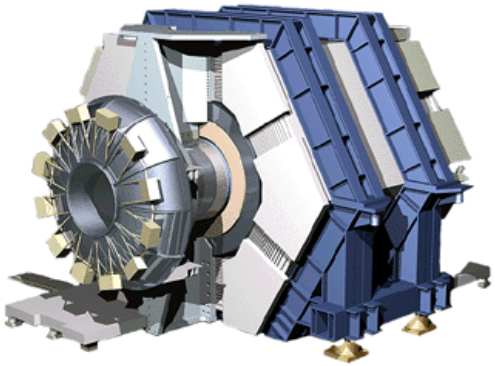
Outline

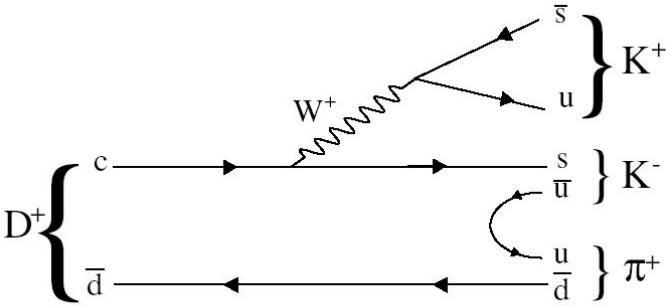
- **Introduction**
  - CP Violation
  - Motivation



- **The BABAR Experiment**
  - Detector



- **Analysis**
  - Selection Criteria
  - Systematics Studies
  - Results



- **Contributions to**
  - BABAR
  - MINOS

CP Violation

- In the standard model via a complex phase the CKM matrix (V):

weak eigenstates

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

mass eigenstates

  - V is 3x3 unitary matrix: $VV^{\dagger}$
  - V_{ij} strength of the i-j quark coupling
  - V can be parametrized with 4 parameters:

$$V \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda & 1 \end{pmatrix} + O(\lambda^4)$$

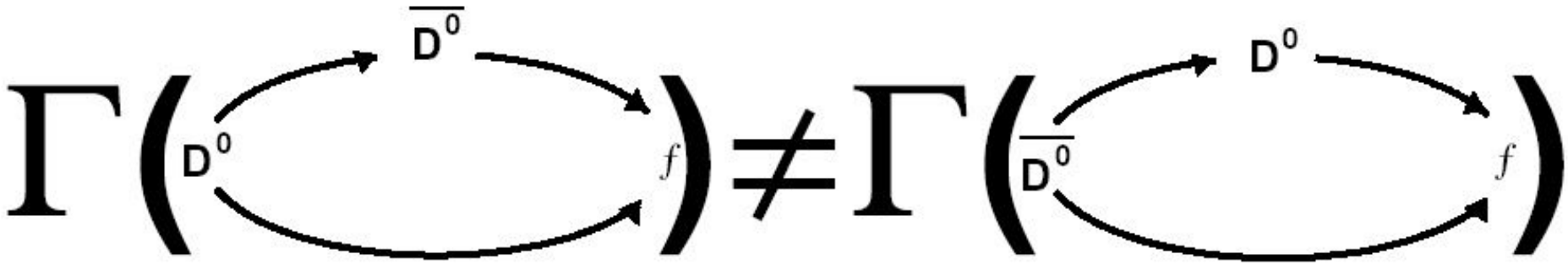
Wolfenstein parametrization: A~ 1, λ ~ 0.22

- **Why is important CP Violation:**
  - Distinguish between matter and antimatter
  - Is the Universe only made out of matter? (CPV is a condition in Sakharov's model)
  - Very sensitive to new physics models

Types of CP Violation

- Three types of CP Violation:

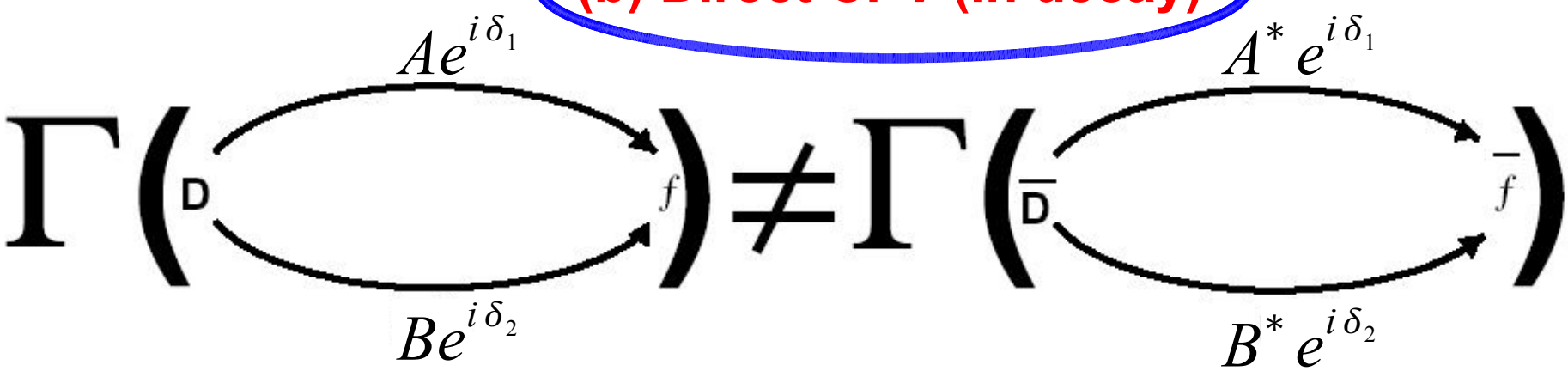
(a) Indirect CPV (in mixing)



In D decays mixing is suppressed ($<10^{-2}$)

(b) Direct CPV (in decay)

this talk



(c) Interference (between mixing and decay)

Experimental Observations of CP Violation

- **In K mesons:**
  - CPV in mixing (1964 using $K_L^0 \to \pi^+\pi^-$): $\epsilon = 2.3 \times 10^{-3}$
  - CPV in decay (1999): $\Re(\epsilon'/\epsilon) = (1.8 \pm 0.4) \times 10^{-3}$
- **In B mesons:**
  - CPV in mixing (2002 charmonium modes): $\sin(2\beta) = 0.72 \pm 0.04 \pm 0.02$
  - CPV in decay (2004 $B^0 \to K^+\pi^-$): $A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$
- **In D mesons:**
  - No CPV observed. No even mixing.

New physics could be hidden in the Charm sector!

Direct CP Violation

Considering a decay amplitude and its conjugate given by

$$A = |\mathrm{A}|e^{i(\delta_1+\phi_1)} + |\mathrm{B}|e^{i(\delta_2+\phi_2)}$$

strong phases (CP even)

$$\bar{A} = |\mathrm{A}|e^{i(\delta_1-\phi_1)} + |\mathrm{B}|e^{i(\delta_2-\phi_2)}$$

weak phases (CP odd)

The CP Asymmetry is

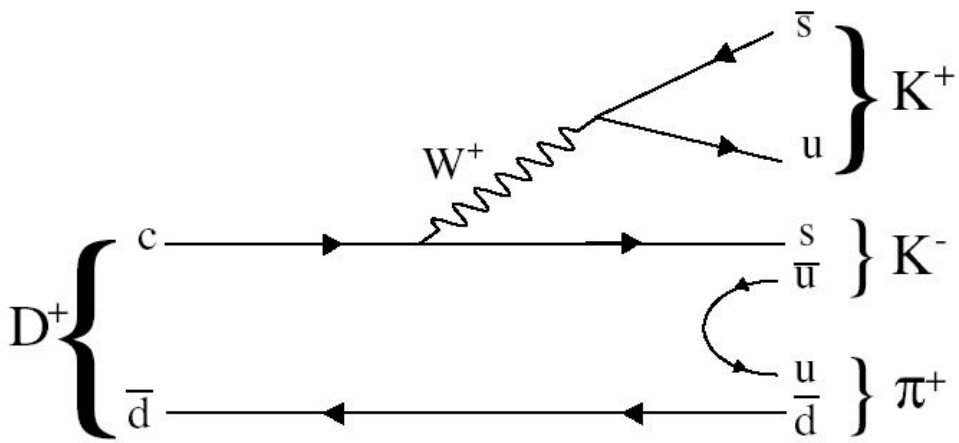
$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2|\mathrm{A}||\mathrm{B}|\sin(\phi_1-\phi_2)\sin(\delta_1-\delta_2)}{|\mathrm{A}|^2 + |\mathrm{B}|^2 + 2|\mathrm{A}||\mathrm{B}|\cos(\phi_1-\phi_2)\cos(\delta_1-\delta_2)}$$

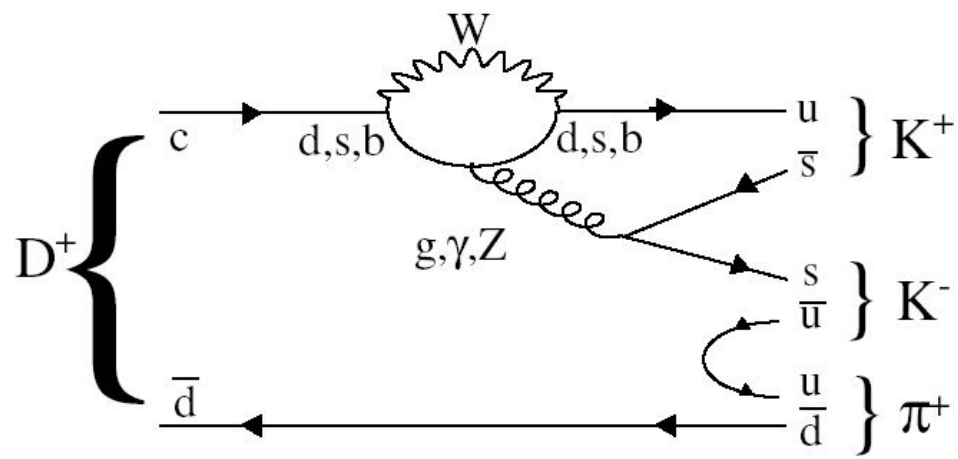
where $A_{CP} \neq 0$ only if $\mathrm{A} \neq \mathrm{B}$ and $(\phi_1-\phi_2) \neq (\delta_1-\delta_2) \neq 0$

CP Asymmetries in the Standard Model

Decay	Example	A_{CP}
Cabibbo-Favored (CF)	$D^+ \to K^- \pi^+ \pi^+$	0
Doubly Cabibbo-Suppressed (DCS)	$D^+ \to K^- K^+ K^+$	0
Singly Cabibbo-Suppressed (SCS)	$D^+ \to K^- K^+ \pi^+$	$< 10^{-3}$

Possible asymmetry in SCS decays in the interference of **tree-level** and **penguin process**





$V^*_{cs} \cdot V_{us}$ ← different weak phases → $V^*_{cd} \cdot V_{ud}$

$\Delta I = 1/2, 3/2$ ← different strong phases → $\Delta I = 1/2$

$$A_{CP} \propto \Im\left(V_{cd} V^*_{ud} V_{cs} V^*_{us}\right) \sin\delta \propto A^2 \eta \lambda^4 \sin\delta < 10^{-3}$$

Direct CP Asymmetry in D decays

The time-integrated CP asymmetries can be written as

$$A_{CP}=\frac{\Gamma(D\to f)-\Gamma(\bar{D}\to\bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to\bar{f})}$$

where $\Gamma(D\to f)$ is the decay rate.

Using $\Gamma_{tot}(D)=\Gamma_{tot}(\bar{D})$, from CPT conservation

$$A_{CP}=\frac{B(D\to f)-B(\bar{D}\to\bar{f})}{B(D\to f)+B(\bar{D}\to\bar{f})}$$

where $B(D\to f)$ is the branching fraction.

Note that A_{CP} can be normalized by a CP invariant branching fraction to reduce systematic errors. In the SM, Cabibbo-Favored decays are CP invariant:

$$B(D\to f_{CF})=B(\bar{D}\to\bar{f}_{CF})$$

Search for New Physics in Charm CP Asymmetries

- CPV in charm is expected to first manifest in **Singly Cabibbo Suppress**.
- In the **standard model**, CPV in SCS decays **~10^{-3}**.
- **New Physics** can give CPV asymmetries **~10^{-2}**.
- Experiments reaching limit of 10^{-2} providing a window for new discoveries

We search for the CP asymmetry in SCS decays $D^+ \to K^+ K^- \pi^+$

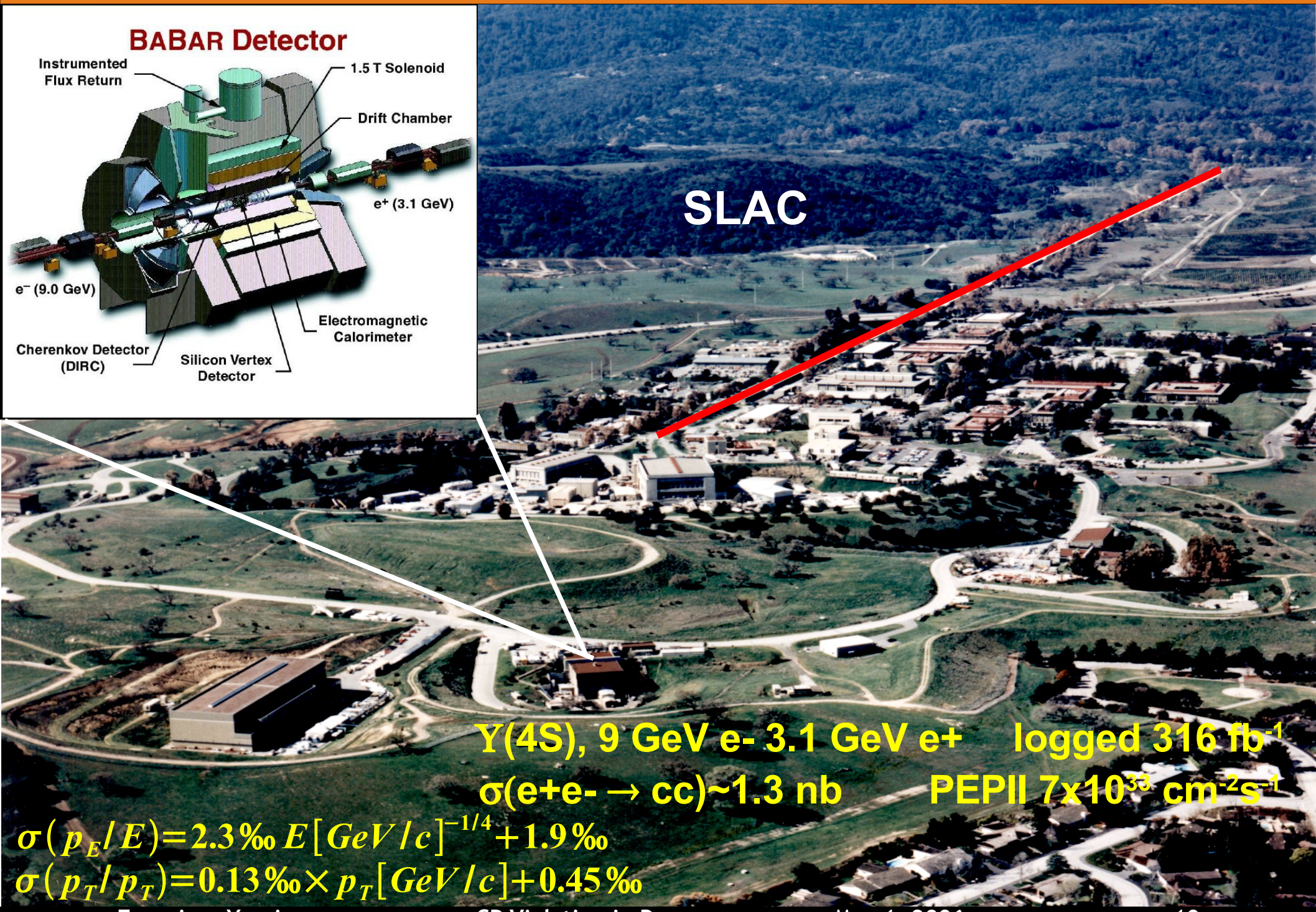
and in the resonant decays $D^+ \to \phi \pi^+$ **and** $D^+ \to \bar{K}^{*0} K^+$

high statistic analysis (stat. error at 1%) → challenge: tiny systematic errors (sub-% syst. errors)

Use **D^+s** Cabibbo-Favored as normalization to reduce systematics due to PID and tracking

$$A_{CP} = \frac{\dfrac{B(D^+ \to K^+ K^- \pi^+)}{B(D_s^+ \to K^+ K^- \pi^+)} - \dfrac{B(D^- \to K^+ K^- \pi^-)}{B(D_s^- \to K^+ K^- \pi^-)}}{\dfrac{B(D^+ \to K^+ K^- \pi^+)}{B(D_s^+ \to K^+ K^- \pi^+)} + \dfrac{B(D^- \to K^+ K^- \pi^-)}{B(D_s^- \to K^+ K^- \pi^-)}}$$

The BABAR Detector



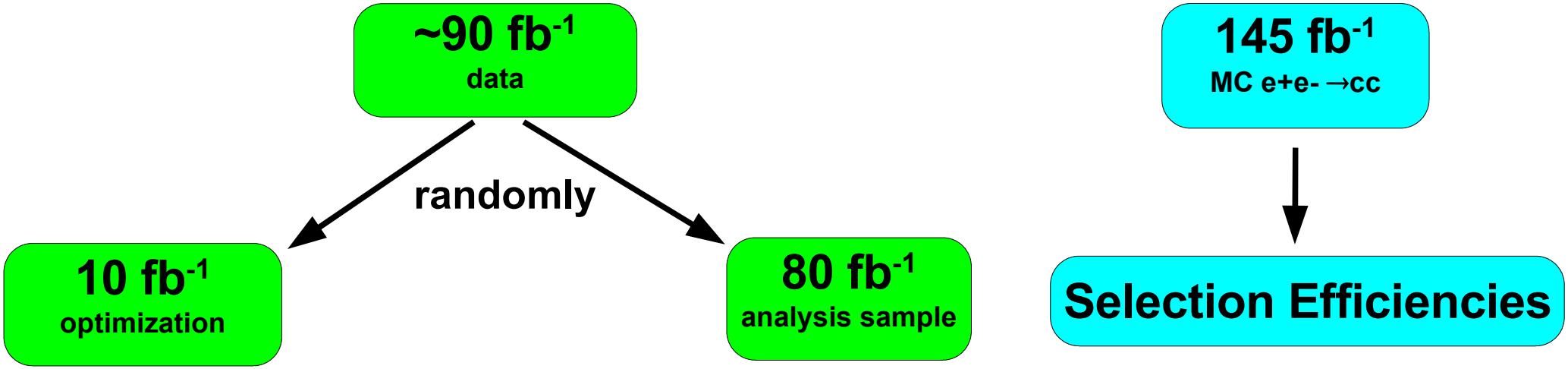
Υ(4S), 9 GeV e- 3.1 GeV e+ logged 316 fb^{-1}

σ(e+e- → cc)~1.3 nb PEPII $7x10^{33}$ $cm^{-2}s^{-1}$

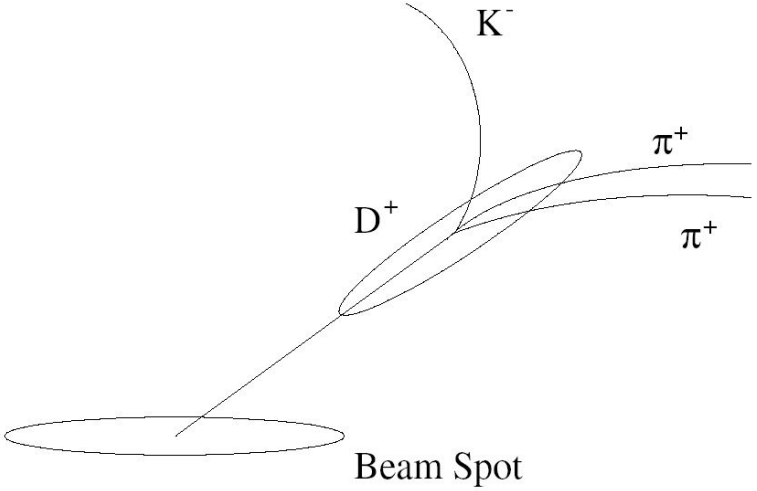
$$\sigma(p_E/E) = 2.3‰\, E[GeV/c]^{-1/4} + 1.9‰$$

$$\sigma(p_T/p_T) = 0.13‰ \times p_T[GeV/c] + 0.45‰$$

Data Sample and Selection



- Same selection criteria applied to CF and SCS modes whenever possible
- Reconstruct decays: $D^{\pm} \to K^{-} K^{+} \pi^{\pm}$ $D_s^{\pm} \to K^{-} K^{+} \pi^{\pm}$ $D^{\pm} \to K^{\mp} \pi^{\pm} \pi^{\pm}$ (for branching fraction)
  - At least three charged tracks
  - Particle identification for kaons
  - Pions are tracks that fail a loose kaon PID
  - Common vertex. Probability $\chi^2 > 1\%$
  - Reject D from B decays (background) by $p_{CM}(D^+)>2.4$ GeV/c
  - Remaining combinatorial background reduced with a likelihood ratio technique

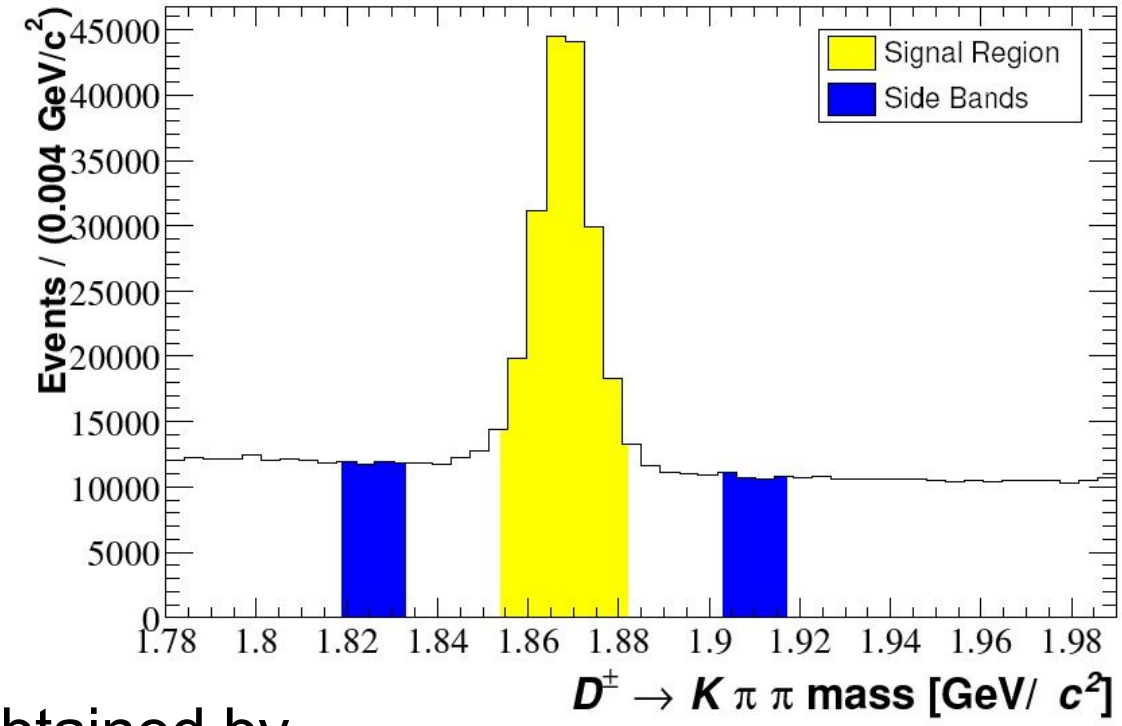


Discriminating Variables

Construct Probability Density Functions (PDF) for signal and background:

Variables for D^+ and D_s^+ decays:

- cm momentum ($p_{c.m.}$)
- Vertex-fit probability with beam-spot constraint ($P_{BS}(\chi^2)$)
- Vertex separation (from interaction point) in the X-Y plane (d_{xy})



Signal PDF obtained by

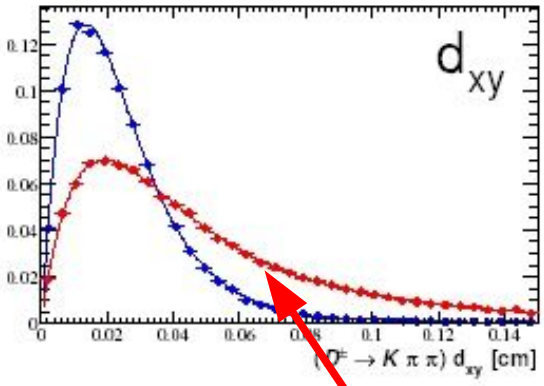
$$F(signal)=\frac{1}{\alpha}F(signal\,region)-\frac{1-\alpha}{\alpha}F(side\,bands),\ \alpha=\frac{N_D}{N_{signal\,region}}$$

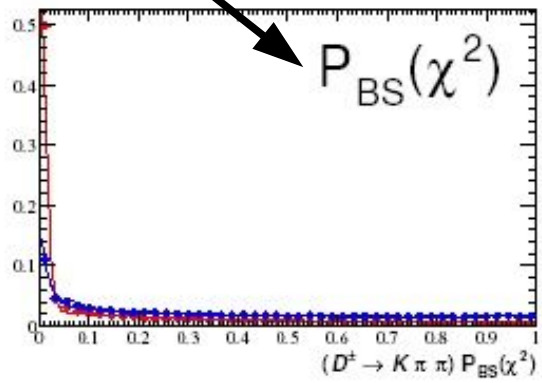
Signal and Background PDFs

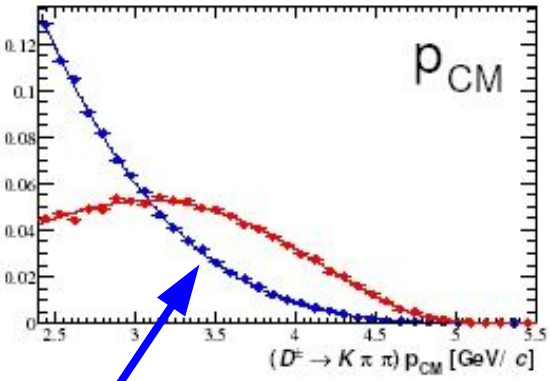
$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ DECAYS:

Probability to form a vertex within the beam-spot region

DATA





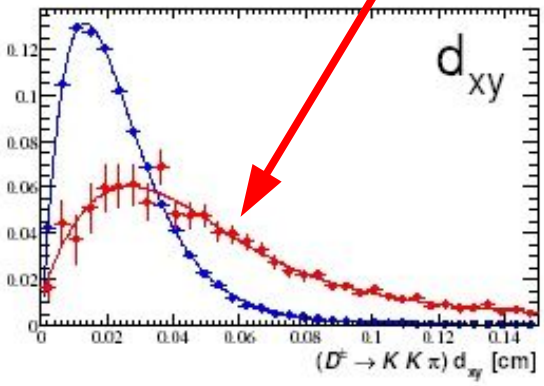


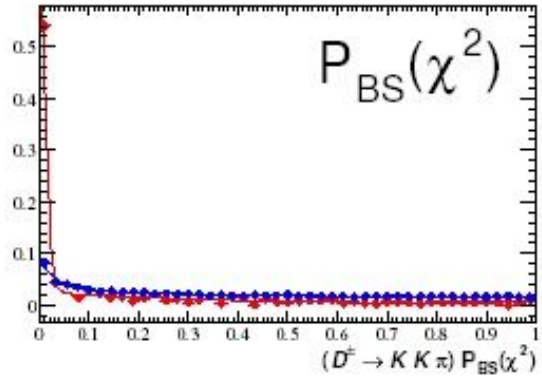
$D^{\pm} \to K^{-}K^{+}\pi^{\pm}$ DECAYS:

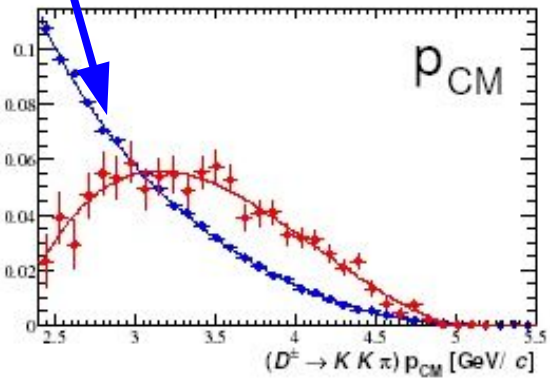
Signal

Background

DATA







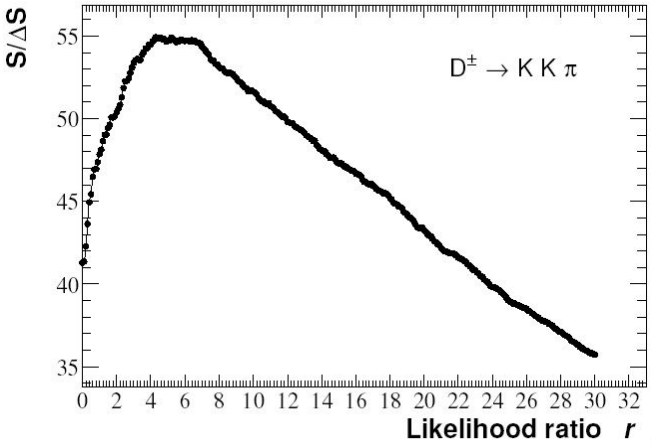
small probability for D+ signal

Likelihood Ratios

Construct a likelihood for signal and background:

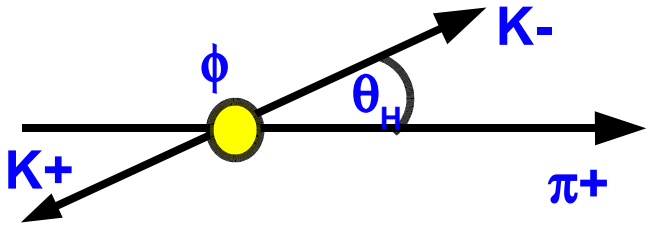
$$L_{signal} = \prod_i L^i_{signal}(x_i) \qquad L_{bkg} = \prod_i L^i_{bkg}(x_i)$$

then, the likelihood ratio is $$r \equiv \frac{L_{signal}}{L_{bkg}}$$



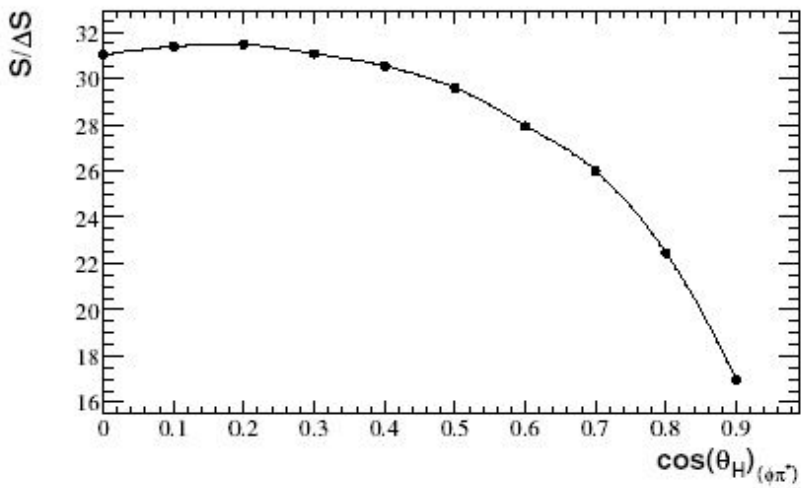
- About 16% of the events have more than one D+:
  - Select event with highest likelihood ratio.
  - Most of these events are combinatorics
- Ratio (r) formed using only $\mathbf{p_{c.m.}}$ and $\mathbf{P_{BS}(\chi^2)}$
- Sensitivity (S/ΔS) optimized as a function of ratio:
  - Maximum at $r \geqslant 4.3$
  - Same criteria applied to both CF and SCS decays
- Define ratio (r_1) by including $\mathbf{d_{xy}}$ PDF in the likelihoods
  - Sensitivity is nearly as good as ratio "r" [d_{xy} correlated with $P_{BS}(\chi^2)$]
  - Used to measure a systematic uncertainty

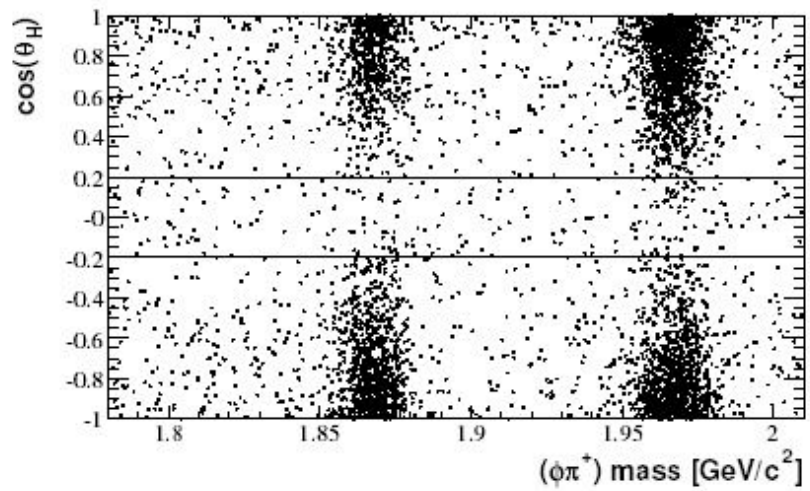
Selection of Resonant Decays



$D^+ \to \phi \pi^+$ reconstruction:

- Invariant mass within 10 MeV/c^2 of nominal ϕ mass
- Helicity angle cut at maximum sensitivity: $|\cos(\theta_H)| \geqslant 0.2$





$D^+ \to \bar{K}^{*0} K^+$ reconstruction:

- Invariant mass within 50 MeV/c^2 of nominal K^{*0} mass
- Helicity angle cut at maximum sensitivity: $|\cos(\theta_H)| \geqslant 0.3$

Remove Additional Background

$D_s^{\pm} \to K^- K^+ \pi^{\pm}$ selection:

- Selected by a procedure identical to that of SCS D^+ decays
- Remove contamination from $D^{\pm} \to K^{\mp} \pi^{\pm} \pi^{\pm}$
  - For all (KKπ), the K with same charge as pion is treated as pion and then the (Kππ) invariant mass is calculated.
  - D+ peak in mass region is removed.
- Contamination from $D^{*+} \to D^0 (\to K^- \pi^+, K^- K^+) \pi^+$
  - Remove events which $m_{K^- \pi^+} \geqslant 1.84\, GeV/c^2$

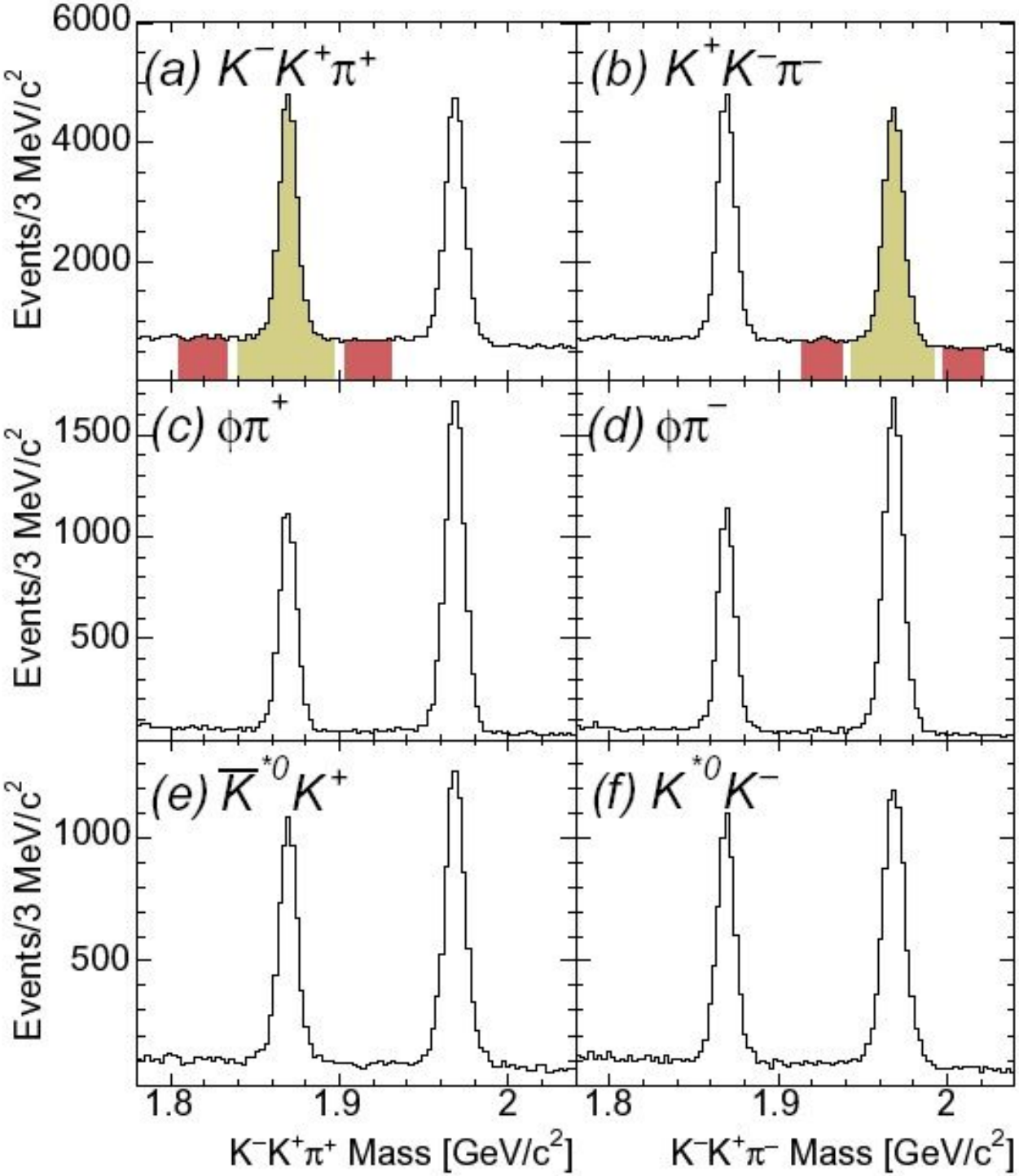
$D^{\pm} \to K^{\mp} \pi^{\pm} \pi^{\pm}$ selection:

- Events removed if either (Kπ) combination satisfies $m_{K^- \pi^+} \geqslant 1.84\, GeV/c^2$

$D^{\pm} \to K^- K^+ \pi^{\pm}$ selection:

- Partially reconstructed $D^{*+} \to D^0 (\to K^- \pi^+ \pi^0) \pi^+$ misidentify as (KKπ), if π^0 missed and pion misidentify as a kaon: Events removed if K track treated as π and $0.139 < (m_{K^- \pi^+ \pi^+} - m_{K^- \pi^+}) < 1.84 [GeV/c^2]$

Mass Distributions After Selection – Full Sample



Total 43k

Total 11k

Total 10k

Parent Charge	+	−
$D^\pm \to K^-K^+\pi^\pm$	21632 ± 228	20940 ± 226
$D^\pm \to \phi\pi^\pm$	5452 ± 87	5327 ± 86
$D^\pm \to K^{*0}K^\pm$	5247 ± 96	5113 ± 96
$D_s^\pm \to K^-K^+\pi^\pm$	23066 ± 217	22928 ± 214

Decay Efficiencies

Decay	ε^+	ε^-
$D^\pm \to K^- K^+ \pi^\pm$	8.20 ± 0.04	8.26 ± 0.04
$D^\pm \to \phi \pi^\pm$	7.67 ± 0.07	7.63 ± 0.07
$D^\pm \to K^{*0} K^\pm$	5.88 ± 0.07	5.90 ± 0.07
$D_s^\pm \to K^- K^+ \pi^\pm$	3.77 ± 0.02	3.79 ± 0.02

- Obtained from a sample of MC generated $c\bar{c}$ events.
- Same selection criteria is applied.
- Efficiency = signal MC events / generated events.
- Monte Carlo includes corrections to Particle ID and Tracking.

Cross – Check of CP Asymmetries

(1) Measure CP Asymmetry in Cabibbo-Favored Ds+ decays as a **cross-check** using full sample (80 fb^{-1})

$$A_{CP}(D_s^+ \to KK\pi) = (+0.64 \pm 0.75) \times 10^{-2}$$

asymmetry consistent with zero

(2)
Alternative $A_{CP}^{(2)}$ measure of CP asymmetry **without** using Ds+ decays

Decay	A_{CP} $[10^{-2}]$	$A_{CP}^{(2)}$ $[10^{-2}]$
$K^-K^+\pi^\pm$	$+1.36 \pm 1.01$	$+2.07 \pm 0.84$
$\phi\pi^\pm$	$+0.24 \pm 1.45$	$+0.94 \pm 1.33$
$\overline{K}^{*0}K^\pm$	$+0.88 \pm 1.67$	$+1.58 \pm 1.57$

(statistic errors only)

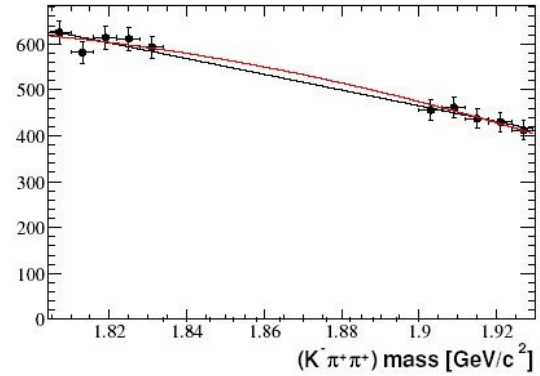
(both A_{CP} consistent)

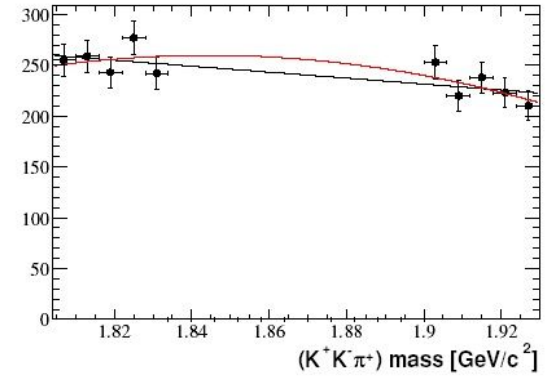
Additional Cross - Checks

Line shape background

Linearity of the background bands checked with a linear and quadratic functions. Best Probability χ^2 obtained with linear function.

(no contribution)

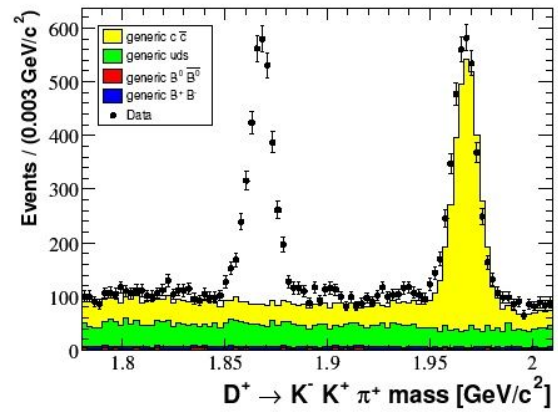


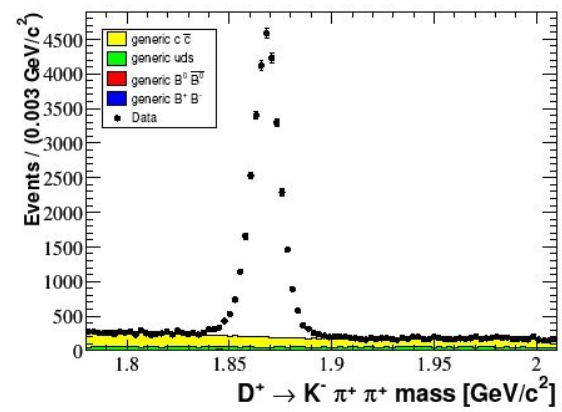


Peaking backgrounds

Selection criteria run over generic MC samples: B+B-, $B^0\bar{B}^0$, $c\bar{c}$, uds.

(no contribution)

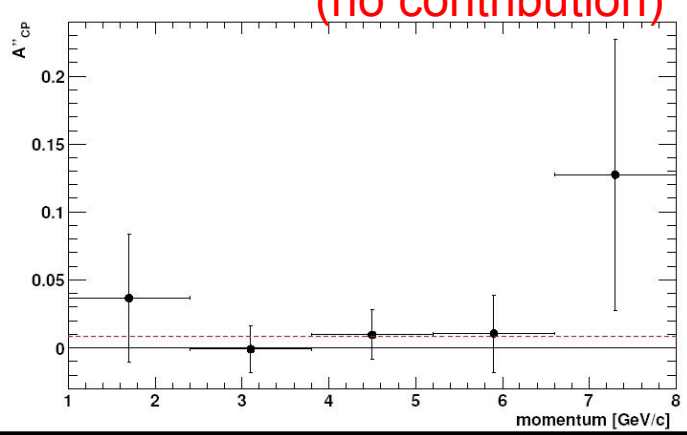




Momentum dependency

Probability χ^2 to be constant 32%

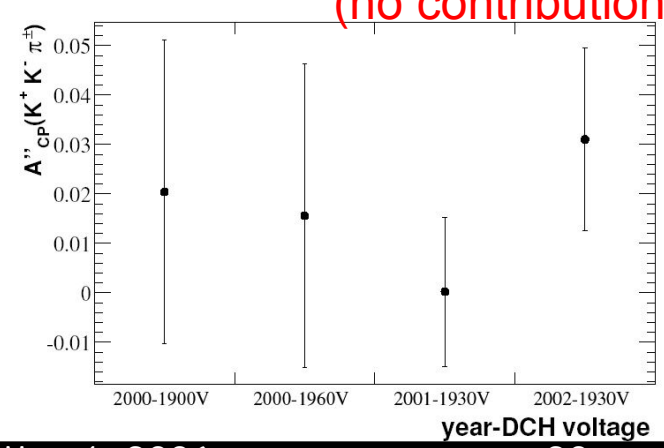
(no contribution)



Temporal dependency

Probability χ^2 to be constant 63%

(no contribution)



Systematic Uncertainties

Source	$K^-K^+\pi^\pm$ A_{CP} $[10^{-2}]$	$\phi\pi^\pm$ A_{CP} $[10^{-2}]$	$\overline{K}^{*0}K^\pm$ A_{CP} $[10^{-2}]$
MC simulation	0.06	0.06	0.06
Background estimate	0.63	0.32	0.49
Selection criteria	0.46	0.54	0.54
Total	0.78	0.63	0.73

MC simulation

Slightly harder momentum spectrum for Ds+ decay products.(Conservatively) estimated as three times the maximum difference in π, K asymmetries in the efficiencies from D+ vs Ds+

Background estimate

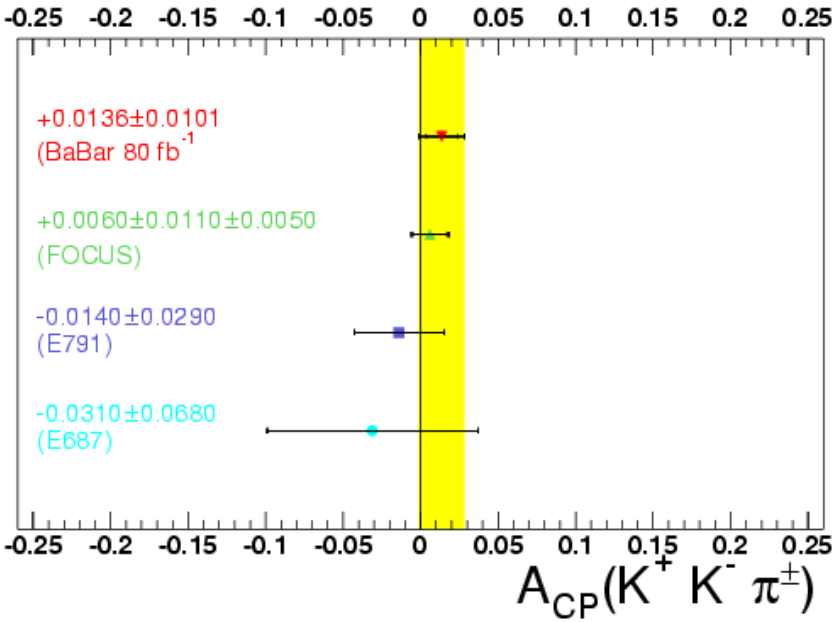
Increase by 50% the widths of the sideband mass regions. Uncertainty is taken to be the resulting difference in the central value of A_{CP}.

Selection criteria

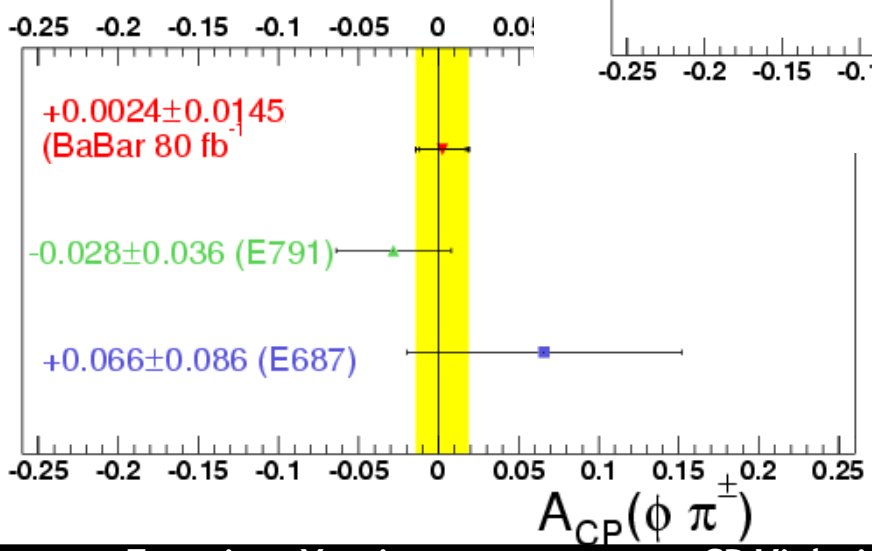
Estimated with two variants: (1) tightening the LH ratio to produce a 10% change in the yields, and (2) using the LH ratio (r_1) in place of r. The uncertainty is chosen to be the larger of the two.

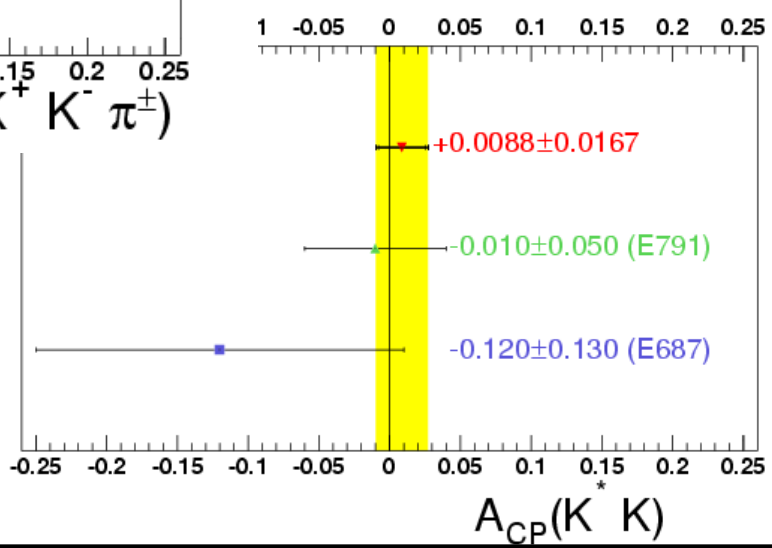
CP Asymmetry Results

Decay	A_{CP} $[10^{-2}]$
$K^-K^+\pi^\pm$	$+1.4 \pm 1.0(\text{stat.}) \pm 0.8(\text{syst.})$
$\phi\pi^\pm$	$+0.2 \pm 1.5(\text{stat.}) \pm 0.6(\text{syst.})$
$\overline{K}^{*0}K^\pm$	$+0.9 \pm 1.7(\text{stat.}) \pm 0.7(\text{syst.})$



Significant improvement in resonant modes

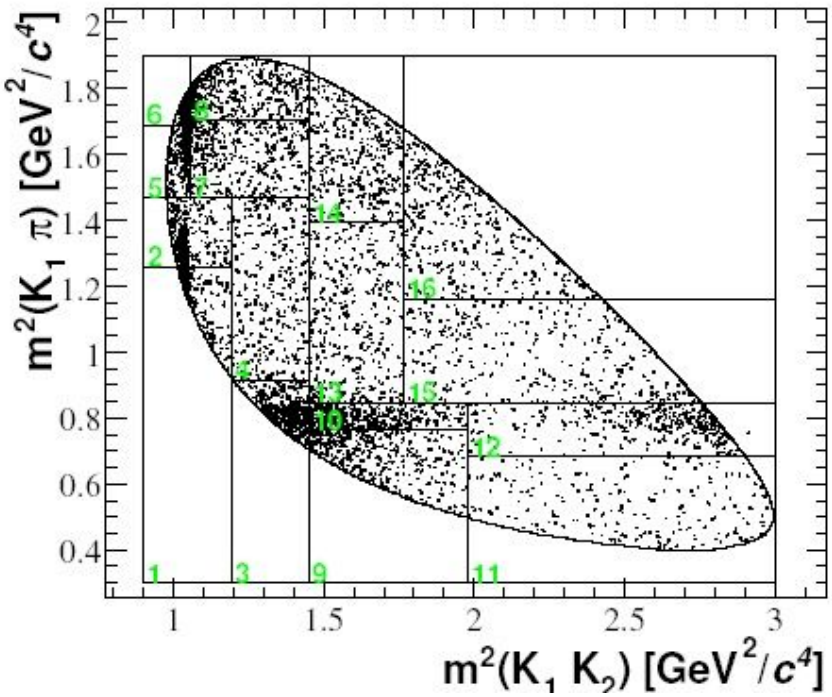


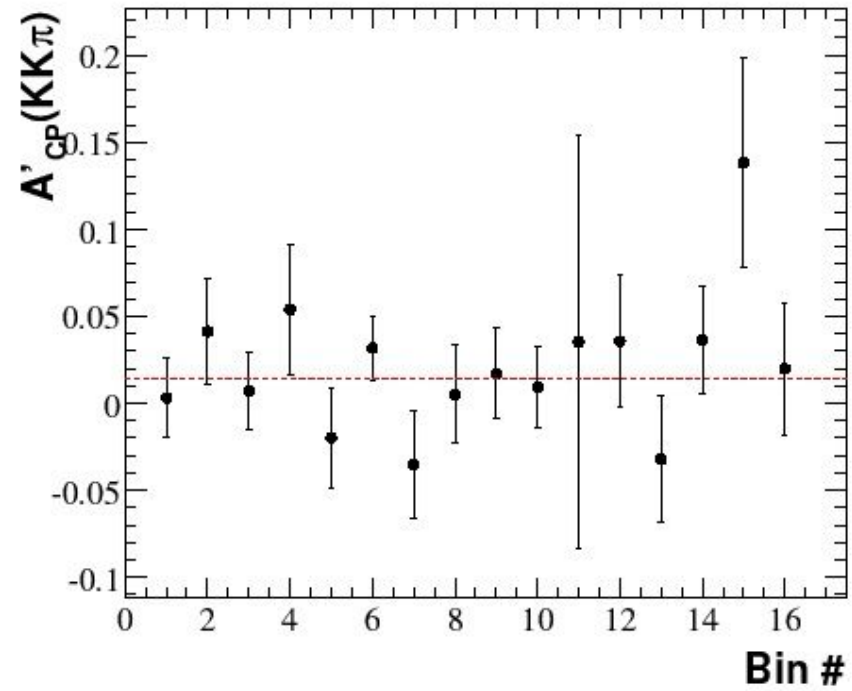


Exploration of CP Asymmetry in the Dalitz Plot

- Construct an adaptive binned Dalitz plot and study the asymmetry in each bin.
- For the ith-bin:

$$A^i_{CP} = \frac{S^+_i/\epsilon^+_i - S^-_i/\epsilon^-_i}{S^+_i/\epsilon^+_i + S^-_i/\epsilon^-_i}$$

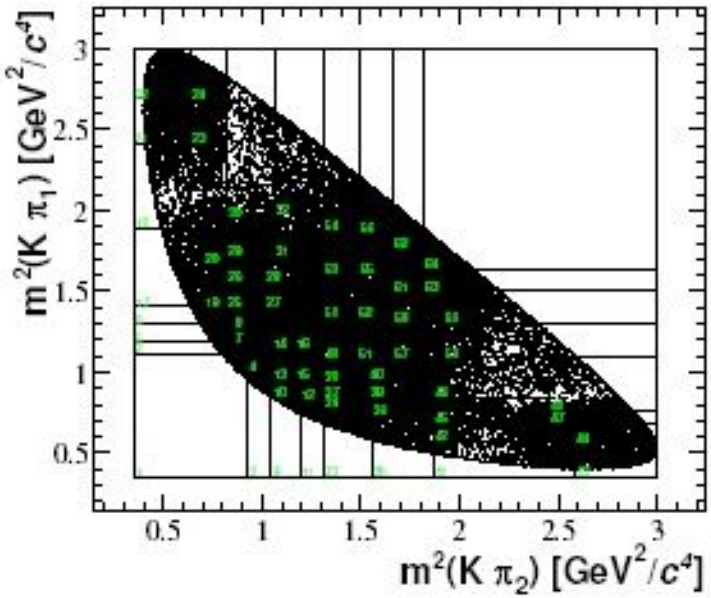


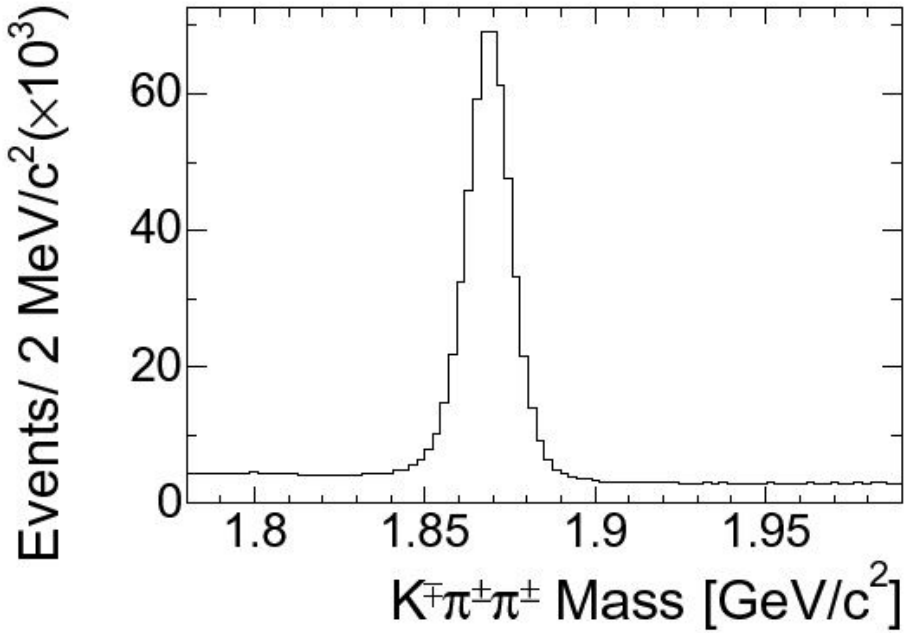


- Asymmetry consistent with being constant (with a probability of 51%) and zero

Relative Branching Fraction

- Same selection criteria for CF D+ decays
- Equally populated bins
- Average efficiency = 10.03 ± 0.01 %



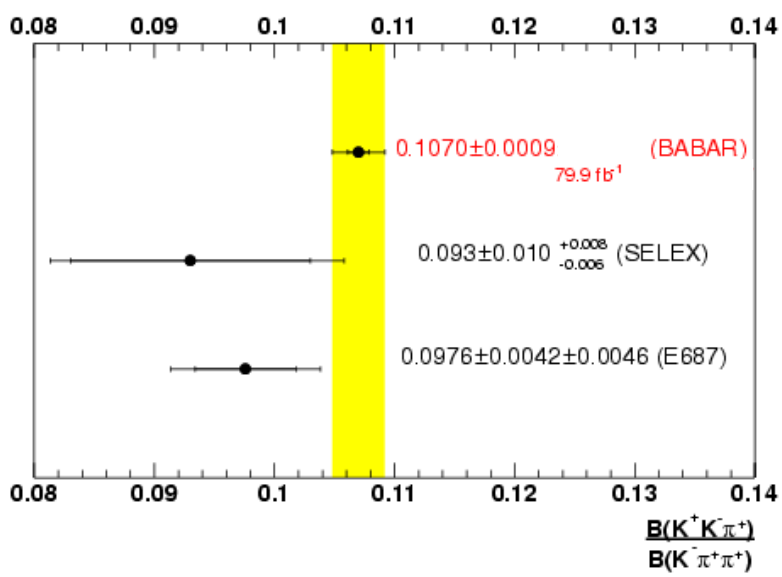


$$\frac{\Gamma(D^+ \to K^+ K^- \pi^+)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)} = \frac{\sum_i S^i_{KK\pi} / \epsilon^i_{KK\pi}}{\sum_j S^j_{K\pi\pi} / \epsilon^j_{K\pi\pi}}$$

Relative Branching Fraction

Source	Uncertainty $[10^{-2}]$
PID + tracking	0.22
Background estimate	0.05
Selection criteria	0.02
Total	0.23

$$\frac{\Gamma(D^+ \to K^+ K^- \pi^+)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)} = (10.7 \pm 0.1(stat) \pm 0.2(syst)) \times 10^{-2}$$



Significant improvement

Other Contributions to BABAR

- Search for rare $D^0 \rightarrow l^+l^-$ decay
- Particle Identification:
  - Electron control sample
  - Data/MC corrections
  - User support

Search for Rare Dilepton D^0 Decays

In the standard model, **Flavor Changing Neutral currents** (FCNC) are very rare (BR ~ 10^{-13}) and **Lepton Number Violations** (LNV) are strictly forbidden.

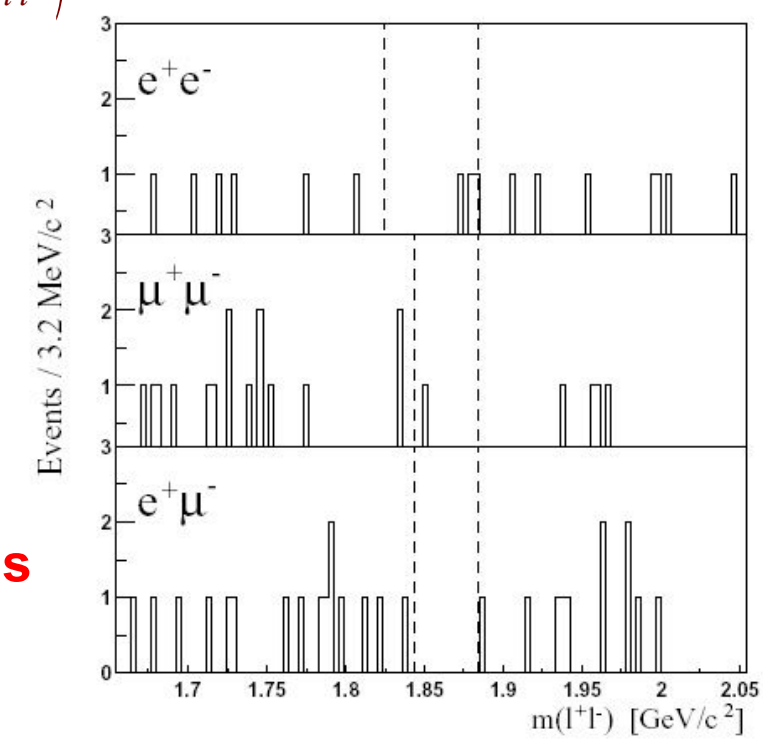
Observation of such decays would be sign of physics beyond the SM, for example R-parity violating SUSY can increase BR by

$$B(D^0 \to e^+ e^-) \sim 10^{-10}$$
$$B(D^0 \to \mu^+ \mu^-) \sim 10^{-6}$$

Branching ratio:

$$B(D^0 \to l^+ l^-) = \left(B(D^0 \to \pi^+ \pi -) \cdot \frac{1}{N_{\pi\pi}} \cdot \frac{\epsilon_{\pi\pi}}{\epsilon_{ll}} \right) \cdot (N_{obs} - N_{bkg})$$

	$D^0 \to e^+e^-$	$D^0 \to \mu^+\mu^-$	$D^0 \to e^\pm\mu^\mp$
$N_{\rm bg}^{hh}$	0.02	3.34 ± 0.31	0.21
$N_{\rm bg}^{\rm comb}$	2.21 ± 0.38	1.28 ± 0.32	1.93 ± 0.36
$N_{\rm bg}$	2.23 ± 0.38	4.63 ± 0.45	2.14 ± 0.36
S $[10^{-7}]$	2.25 ± 0.12	4.53 ± 0.30	3.27 ± 0.20
$N_{\rm obs}$	3	1	0
UL obtained	1.2×10^{-6}	1.3×10^{-6}	8.1×10^{-7}



Limits improved by 5 2 10 times

Phys.Rev.Lett. 93 (2004) 191801

BABAR Particle Identification

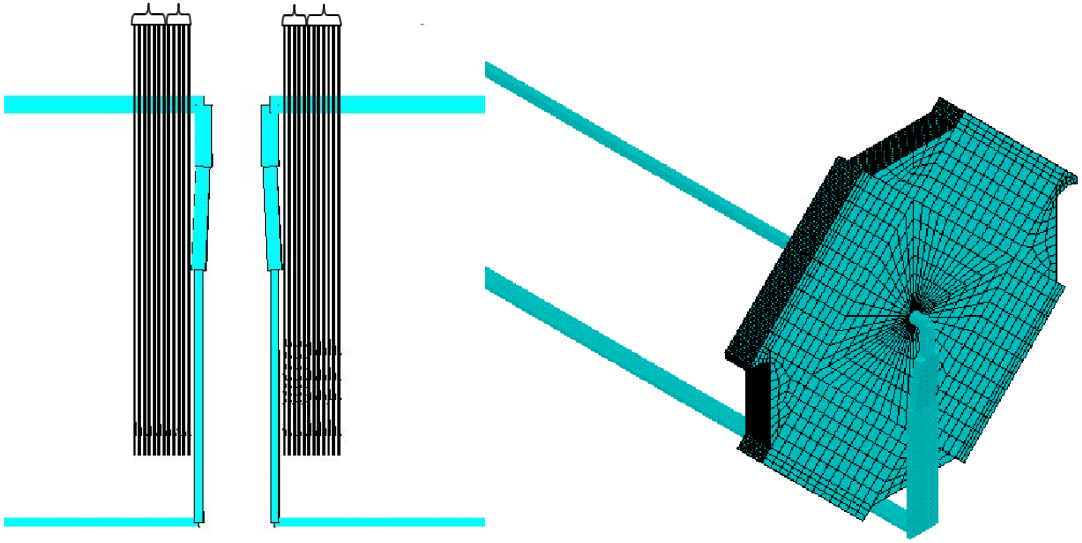
- Production of pure particle control samples
  - optimize particle selectors
  - calculate efficiencies and misidentification of PID selection
- Develop of pure electron control sample
- Develop and maintain of tools for reducing data/MC PID discrepancies
- Analysis software

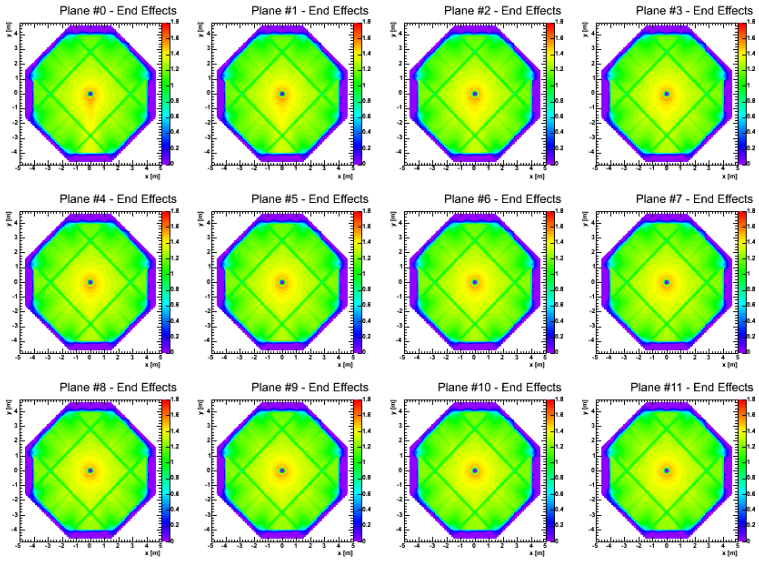
Contributions to MINOS

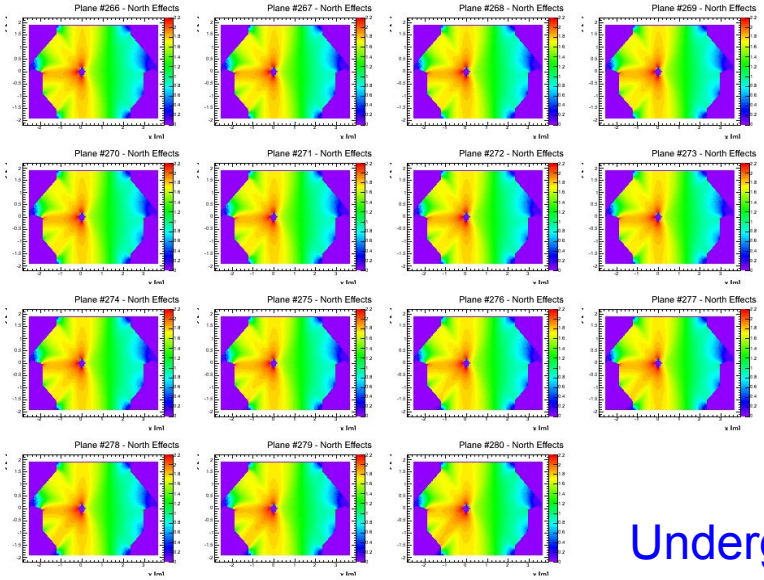
- Magnetic Field Simulation and Calibration
- Neutrino Beam simulation
- Off-axis far detector cross-check
- MC neutrino beam and detector generation

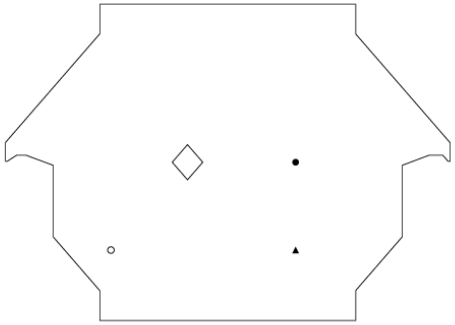
Current Projects – *Modeling of Magnetic Fields*

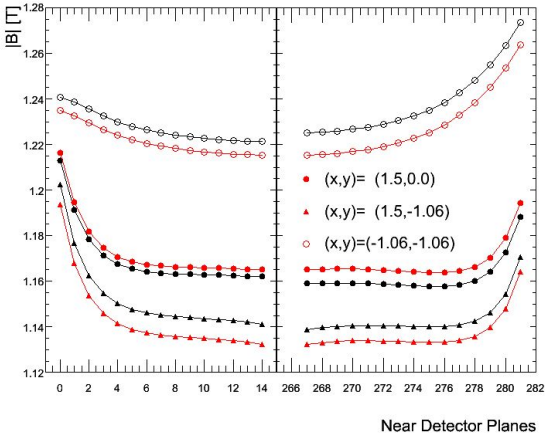
- Modeling of end-of-toroid effects for near and far coils.
- Implementation of maps in the reconstruction code.







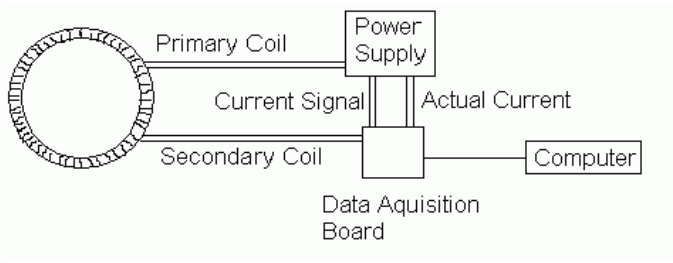


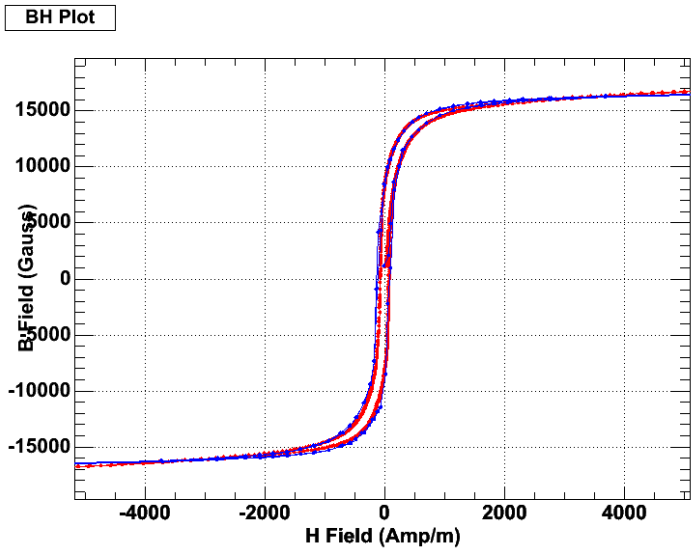


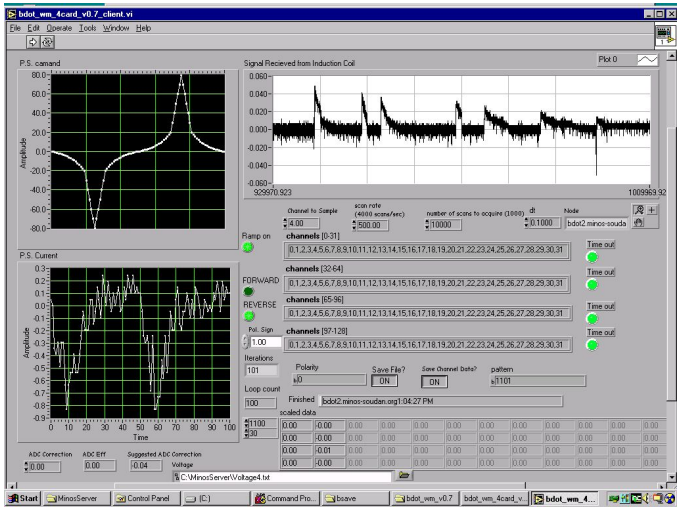
Undergraduate students involved in this work

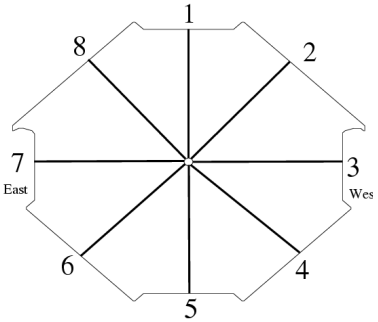
Current Projects – *Magnetic Field Calibration*

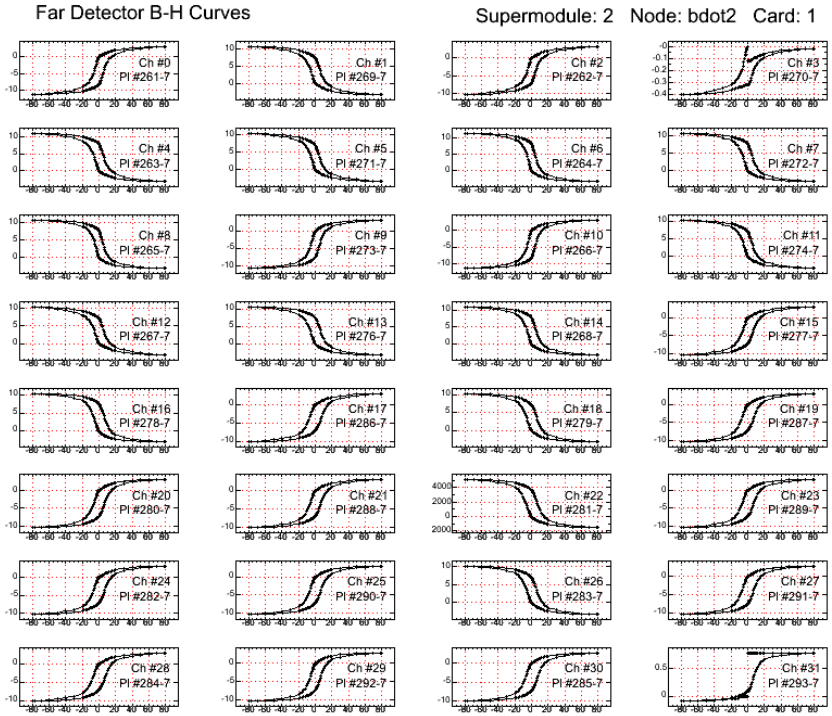
- BH curve of steel samples.
- BH curves from steel planes.











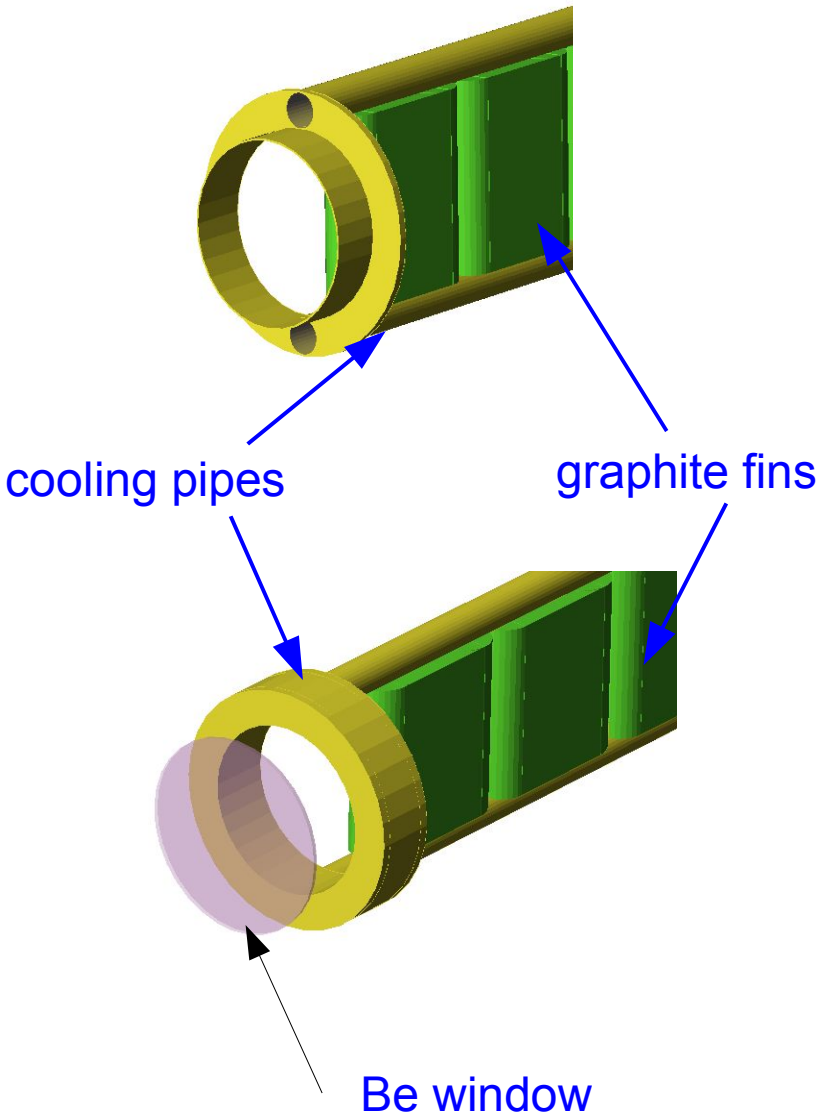
students involved in this work

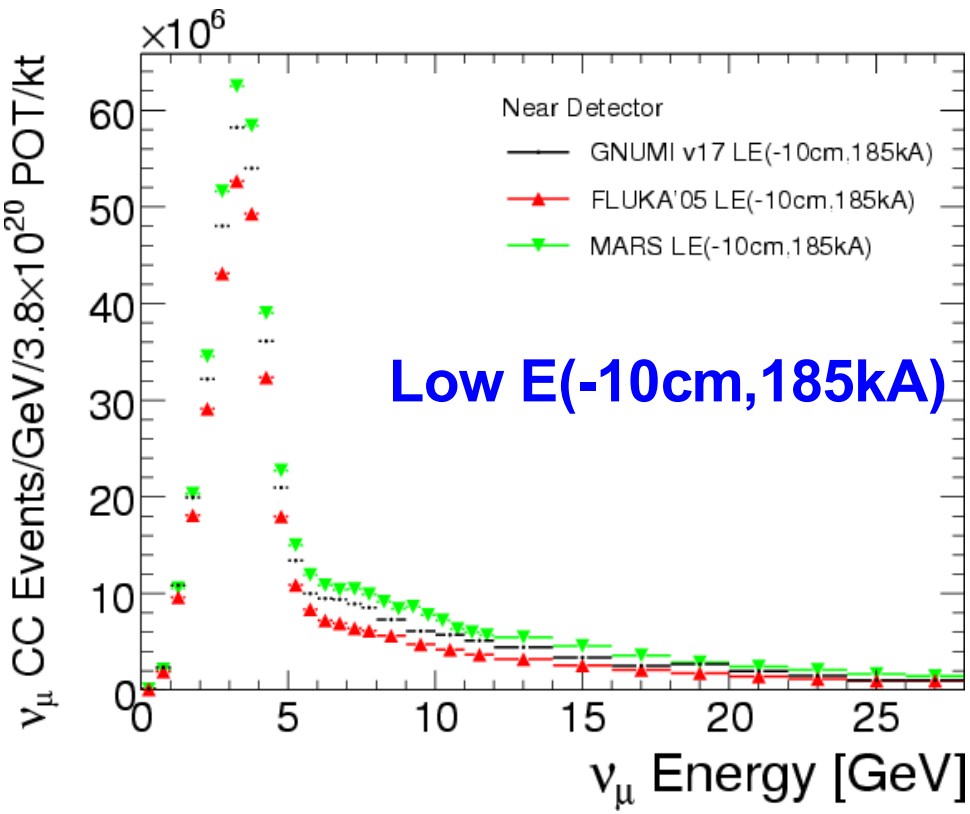
Simulation of the Beam Flux

Hadronic production simulated with a detailed target model in FLUKA'05

+

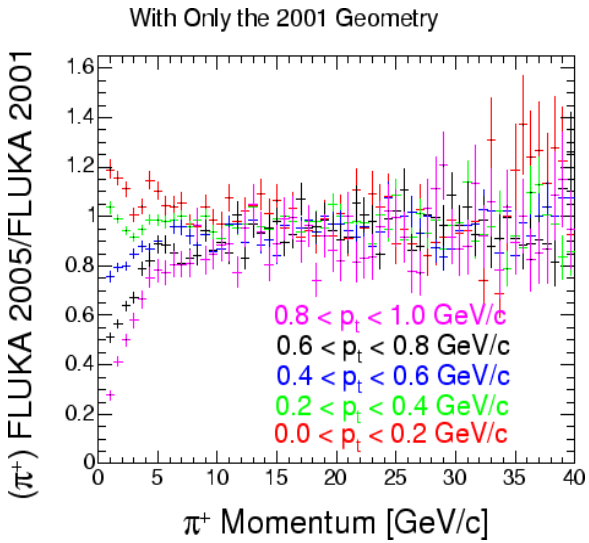
Particle Transport and decays with GEANT3

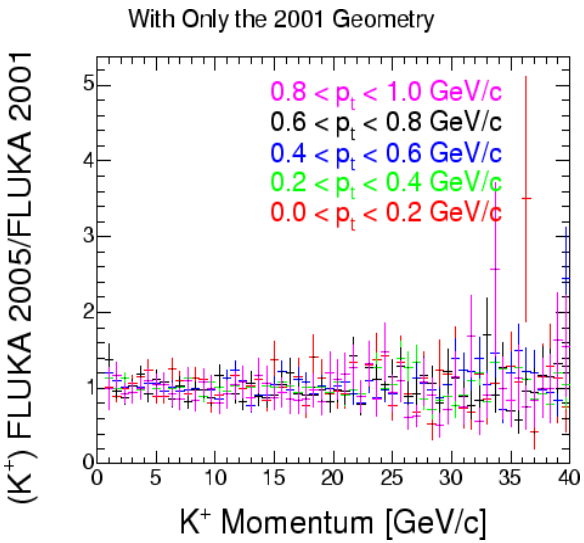


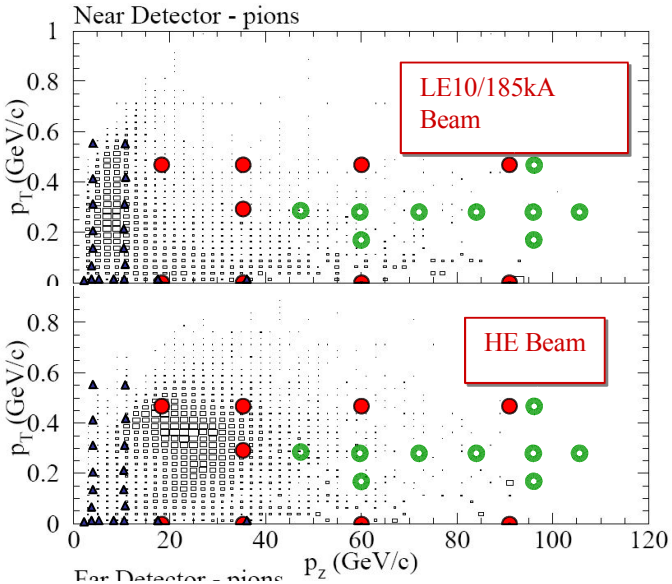


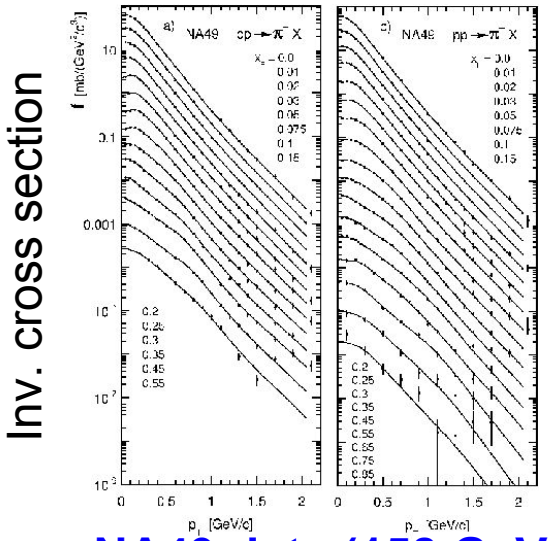
Current Projects – *Hadron Production*

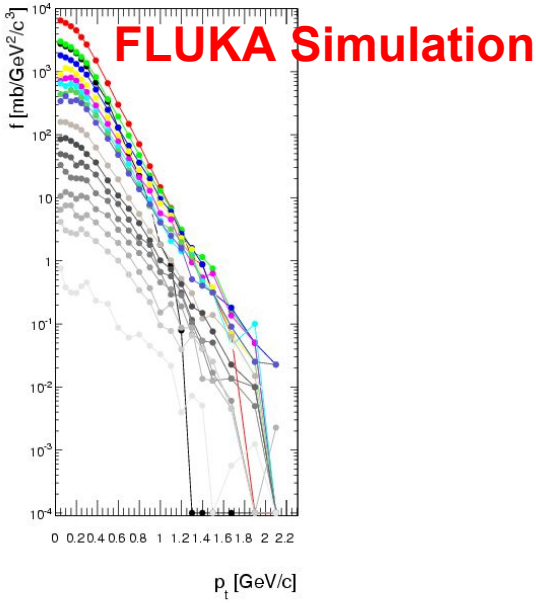
- Improving modeling of hadron production:
  - Accurate target geometry in the simulation
  - Checking models in the simulation





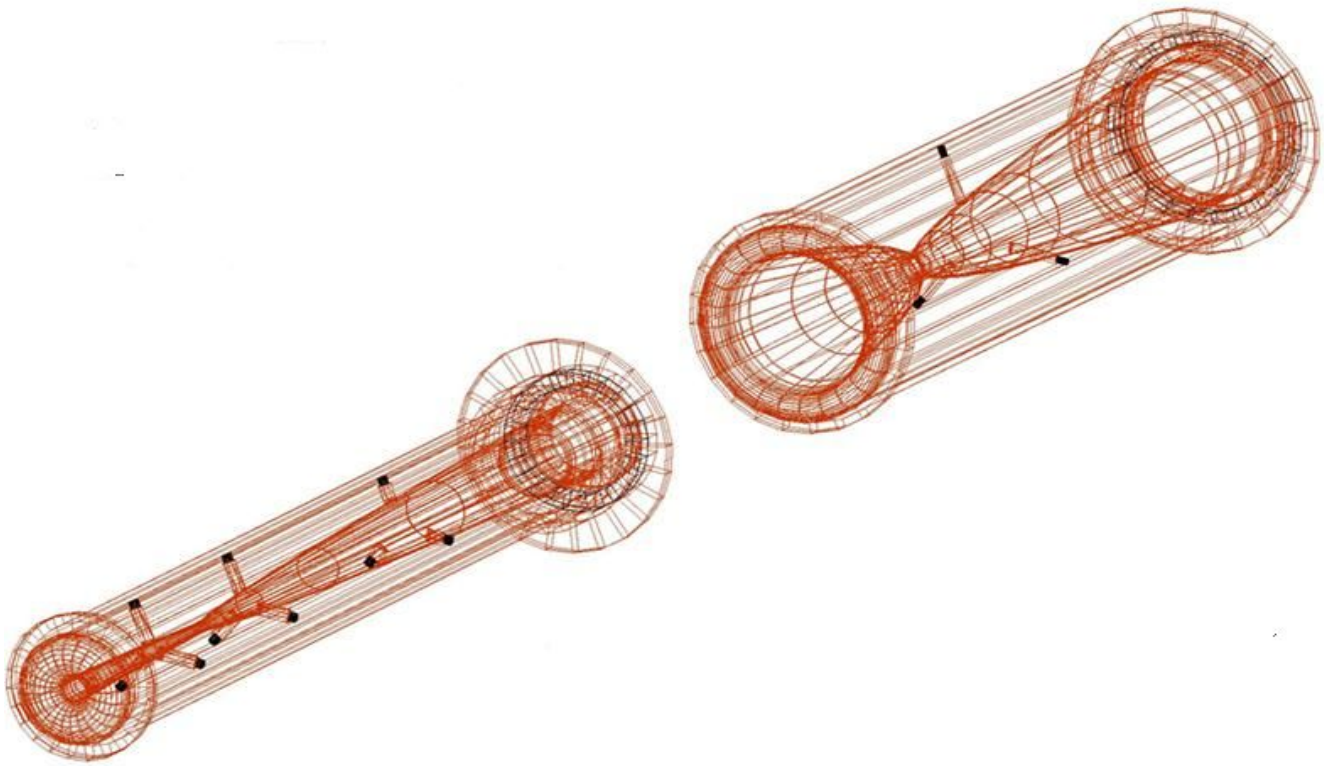






Current Projects – *Beam Simulation*

- Improving the beam simulation:
  - Detailed modeling of the beam line in GEANT4
  - Validation and implementation

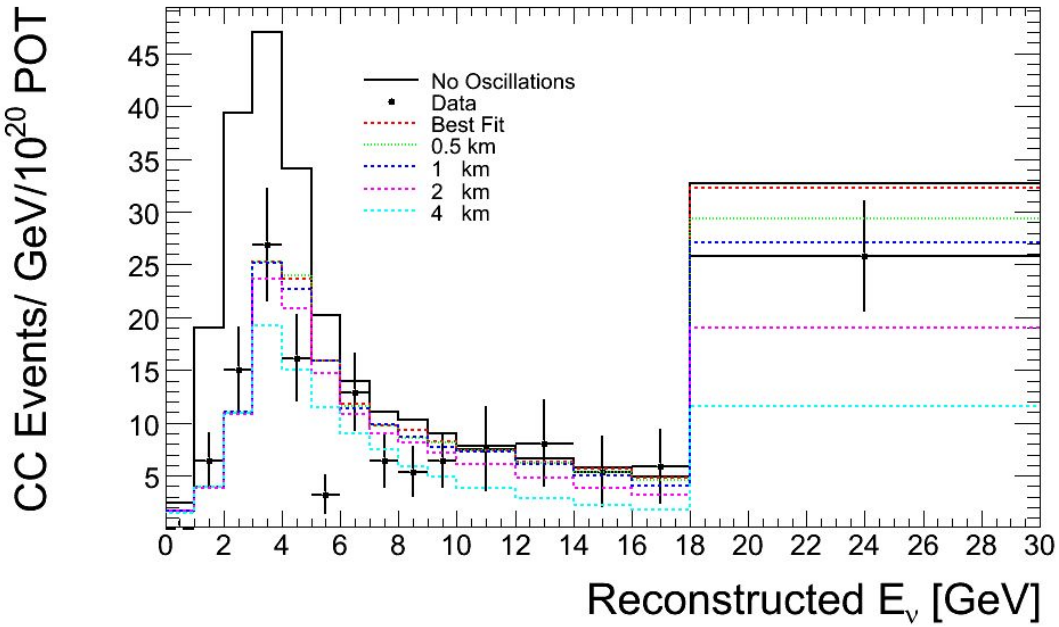


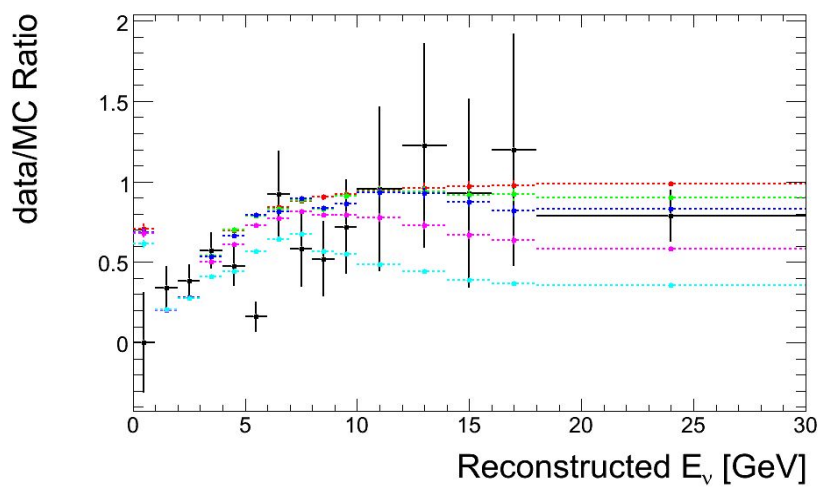
students involved in this work

Current Projects – *Off-Axis Analysis*

VERY PRELIMIRARY

- Cross-check of an off-axis detector analysis





best fit: 1.5 ± 1.3 km

Current Projects – *Monte Carlo Generation*

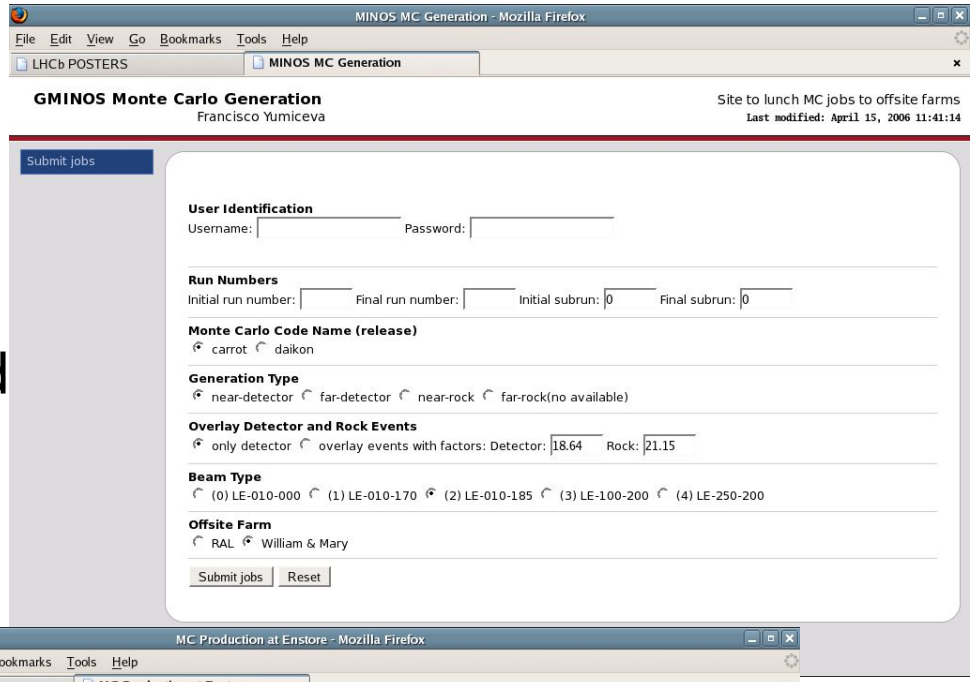
Produced more than 50% of the MINOS MC samples

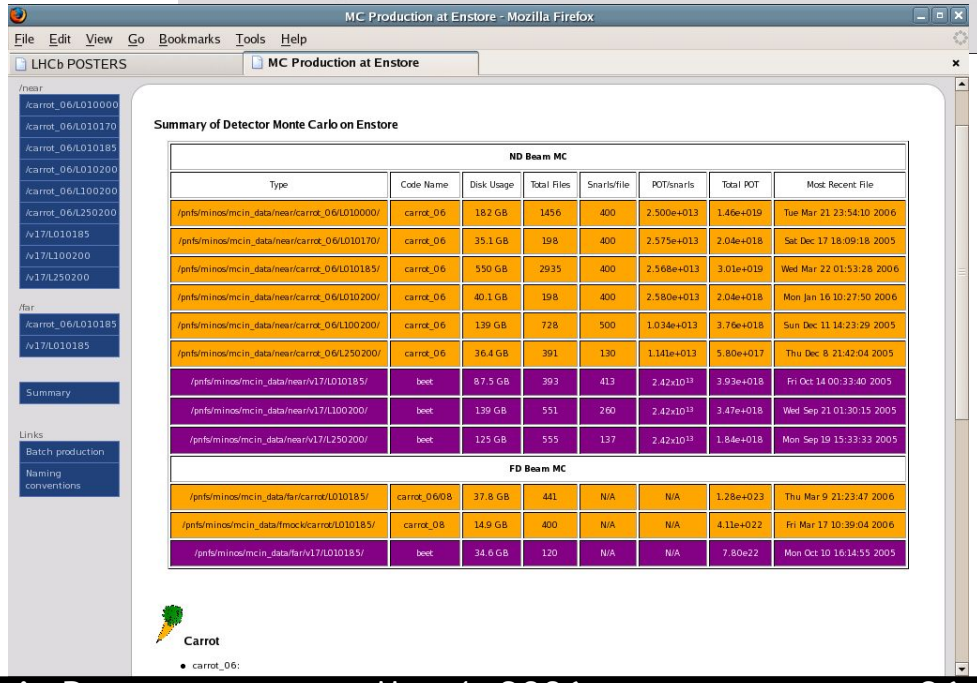
Steps:

- (FLUKA) Hadron production
- (Particle transport) Neutrino flux
- (near detector) Rock events
- Detector events
- (near) Rock and detector event overlaid

Tools:

- Submitting jobs
- Monitoring jobs
- MC samples status





ND Beam MC							
Type	Code Name	Disk Usage	Total Files	Snarls/file	POT/snarls	Total POT	Most Recent File
/pnfs/minos/mcin_data/near/carrot_06/L010000/	carrot_06	182 GB	1456	400	2.500e+013	1.46e+019	Tue Mar 21 23:54:10 2006
/pnfs/minos/mcin_data/near/carrot_06/L010170/	carrot_06	35.1 GB	198	400	2.575e+013	2.04e+018	Sat Dec 17 18:09:18 2005
/pnfs/minos/mcin_data/near/carrot_06/L010185/	carrot_06	550 GB	2935	400	2.568e+013	3.01e+019	Wed Mar 22 01:53:28 2006
/pnfs/minos/mcin_data/near/carrot_06/L010200/	carrot_06	40.1 GB	198	400	2.580e+013	2.04e+018	Mon Jan 16 10:27:50 2006
/pnfs/minos/mcin_data/near/carrot_06/L100200/	carrot_06	139 GB	728	500	1.034e+013	3.76e+018	Sun Dec 11 14:23:29 2005
/pnfs/minos/mcin_data/near/carrot_06/L250200/	carrot_06	36.4 GB	391	130	1.141e+013	5.80e+017	Thu Dec 8 21:42:04 2005
/pnfs/minos/mcin_data/near/v17/L010185/	beet	87.5 GB	393	413	2.42×10^{13}	3.93e+018	Fri Oct 14 00:33:40 2005
/pnfs/minos/mcin_data/near/v17/L100200/	beet	139 GB	551	260	2.42×10^{13}	3.47e+018	Wed Sep 21 01:30:15 2005
/pnfs/minos/mcin_data/near/v17/L250200/	beet	125 GB	555	137	2.42×10^{13}	1.84e+018	Mon Sep 19 15:33:33 2005
FD Beam MC							
/pnfs/minos/mcin_data/far/carrot/L010185/	carrot_06/08	37.8 GB	441	N/A	N/A	1.28e+023	Thu Mar 9 21:23:47 2006
/pnfs/minos/mcin_data/fmock/carrot/L010185/	carrot_08	14.9 GB	400	N/A	N/A	4.11e+022	Fri Mar 17 10:39:04 2006
/pnfs/minos/mcin_data/far/v17/L010185/	beet	34.6 GB	120	N/A	N/A	7.80e22	Mon Oct 10 16:14:55 2005

Summary and Conclusions

- Detector asymmetries understood at the sub-percent level

- CP Asymmetries consistent with zero observed for

$$D^{\pm} \rightarrow K^{-} K^{+} \pi^{\pm} \qquad D^{\pm} \rightarrow \phi \pi^{\pm} \qquad D^{\pm} \rightarrow \bar{K}^{*0} K^{\pm}$$

- CP Asymmetry across the phase space of D+ Dalitz plot is consistent with zero

- Significant improvement in the asymmetries has been achieved reducing errors at 1%

- Relative branching fraction improved by more than 4 times

- Published Phys. Rev. D 71, 091101 (2005)

FIN

Backup slides

Fundamental Symmetries

- **Charge Conjugation (C):** Transform particle into its antiparticle

$$C\psi(t,x)C=-i\left(\bar{\psi}\gamma^0\gamma^2\right)^T$$

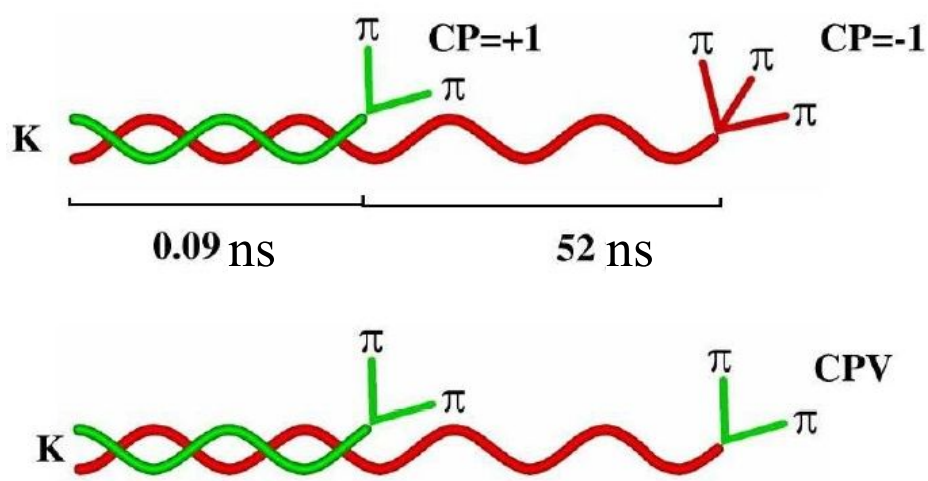
No conserved in weak interactions (no observed left-handed antineutrinos)

- **Parity (P):** Space mirror operation

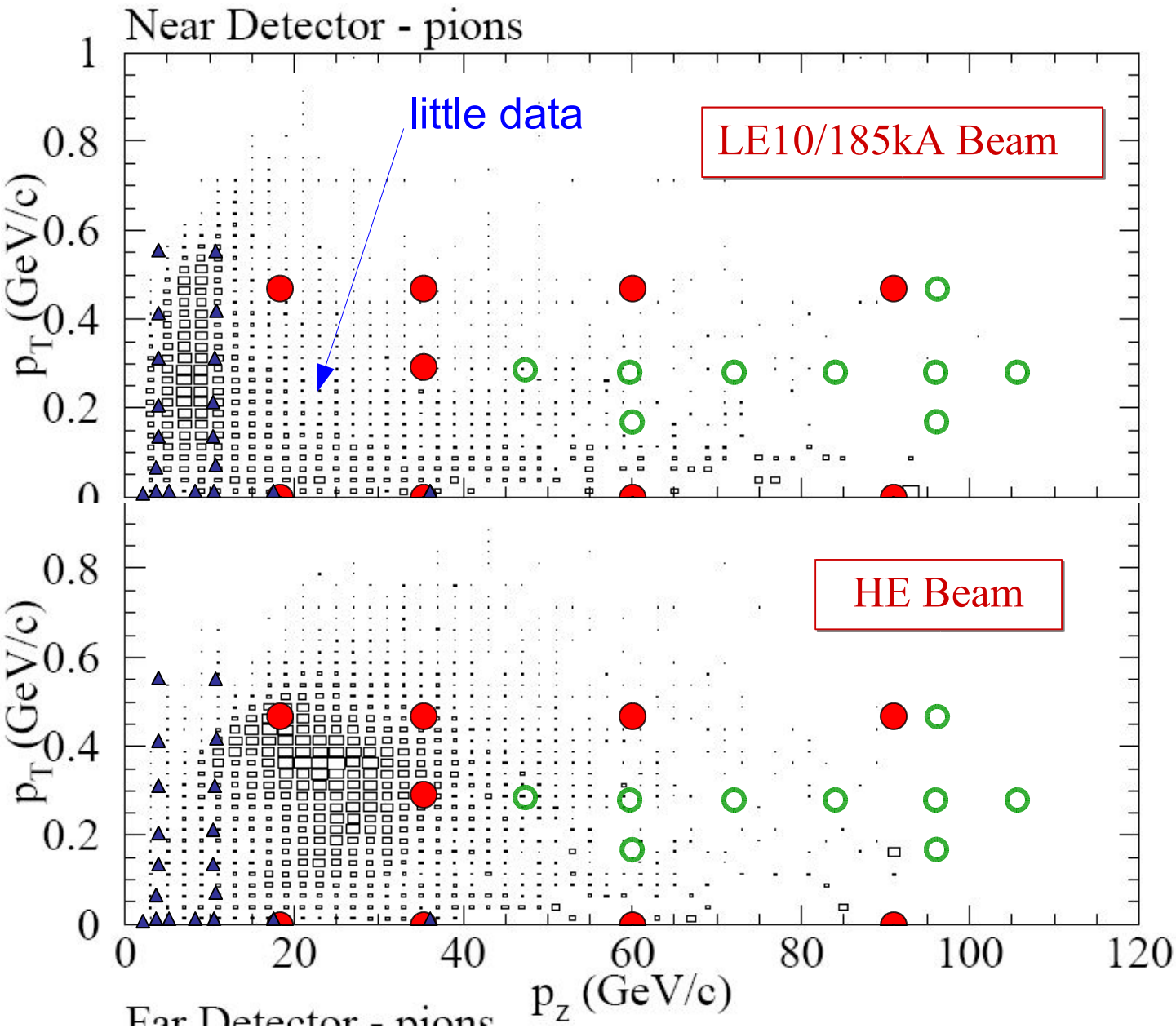
$$P\psi(t,x)P=\gamma^0\psi(t,-x)$$

No conserved in weak interactions observed in beta decays (Co^{60})

- **Charge – Parity (CP):** **No conserved in weak interactions**
  - CP Violation discovered in neutral kaon decays (1964)
  - CP Violation: Decay rate of particle ≠ rate of antiparticle



Previous Hadron Production Data



Atherton
400 GeV/*c* p-Be

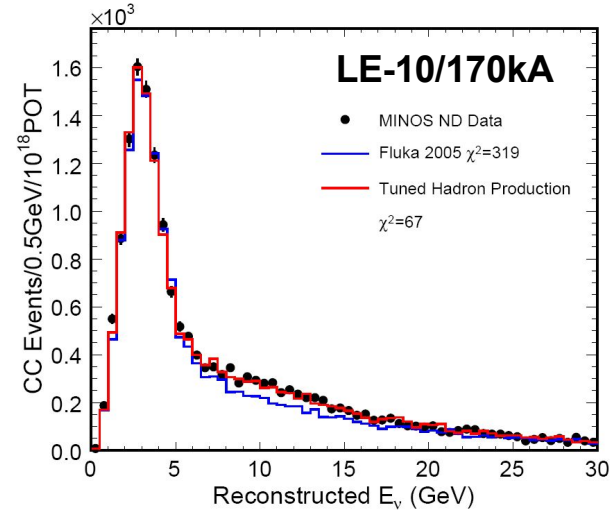
Barton
100 GeV/*c* p-C

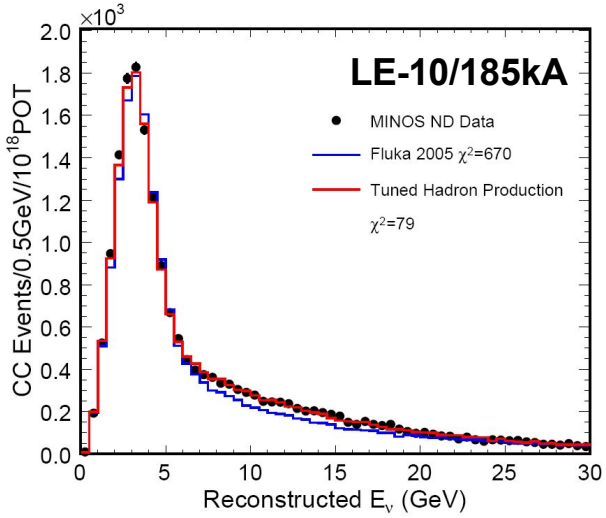
SPY
450 GeV/*c* p-Be

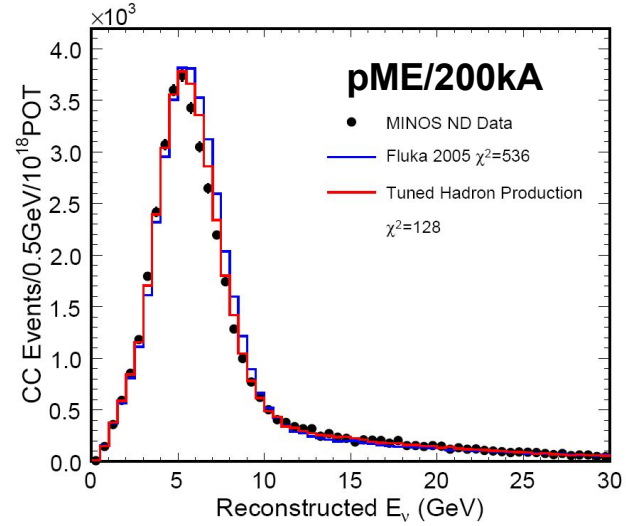
- Never been measured for a thick C-target (MIPP)
- Little data to constraint high energy tail

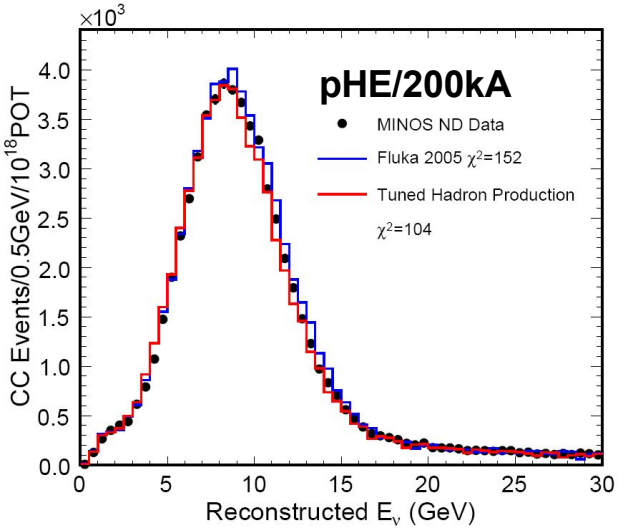
Hadron Production Tuning

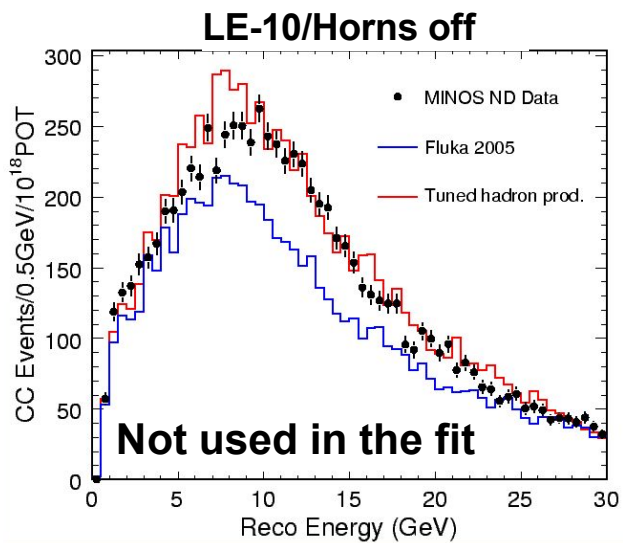
Improvements between data and beam MC were obtained by tuning MC by fitting to hadronic x_F and p_T distributions.

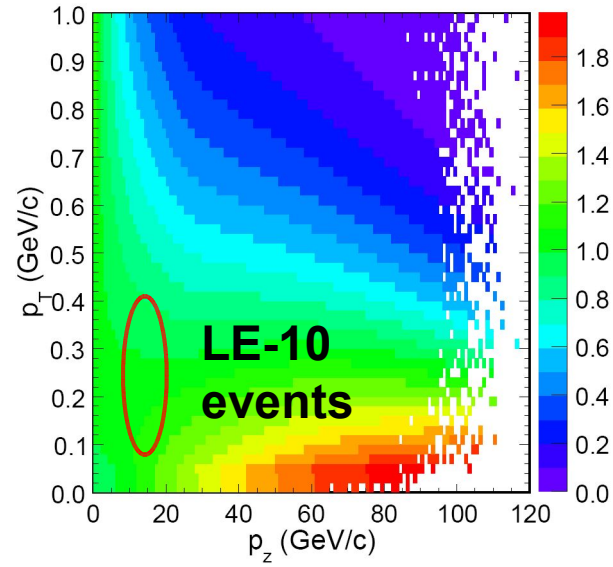












Weights applied as a f(x_F , p_T)

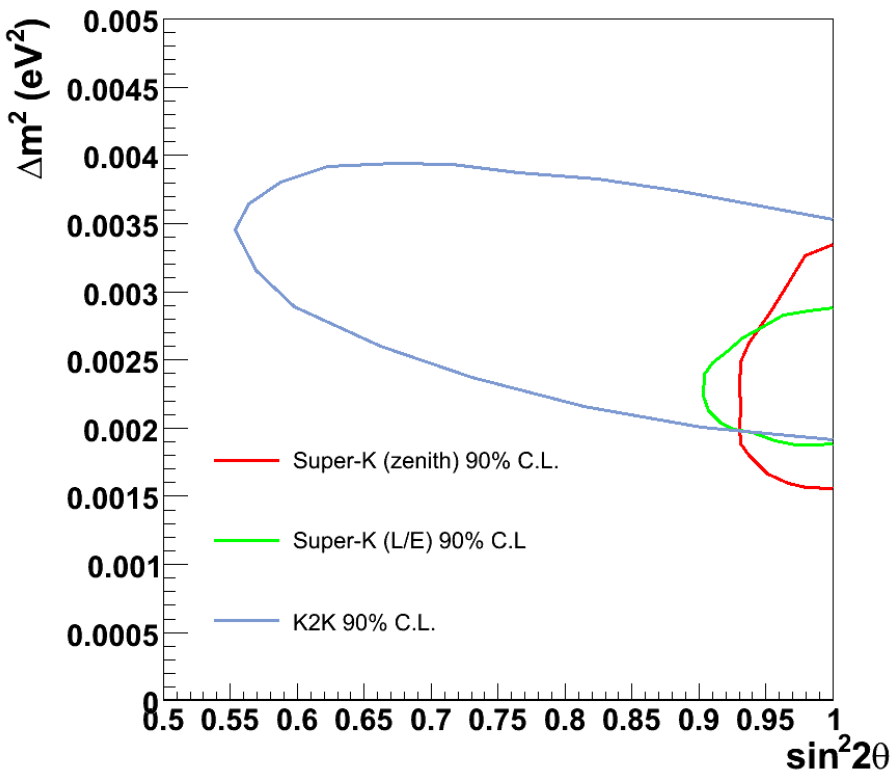
Current knowledge of 2-3 Mixing

- Current best measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$ are provided by Super-Kamiokande (atmospheric neutrino analysis) and K2K (9×10^{19} pot)

- The limits (at 90% C.L.) are:
  - $\sin^2 2\theta > 0.9$
  - $1.9 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

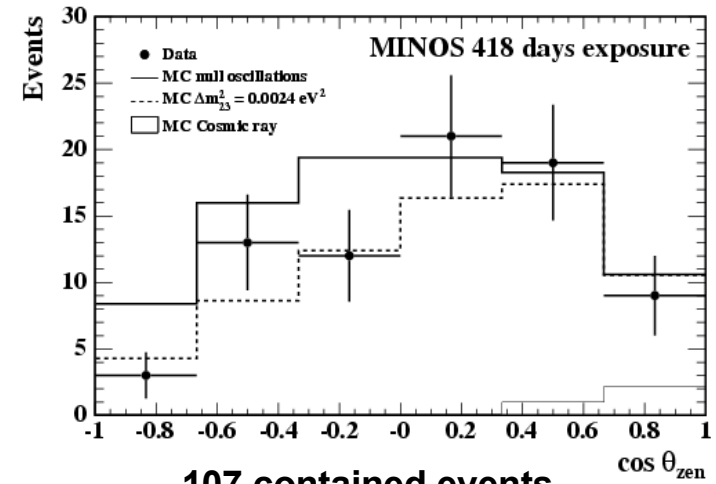
- The analysis presented in this talk, which is for 9.3×10^{19} pot, should provide a measurement of the mixing parameters that is competitive with these results

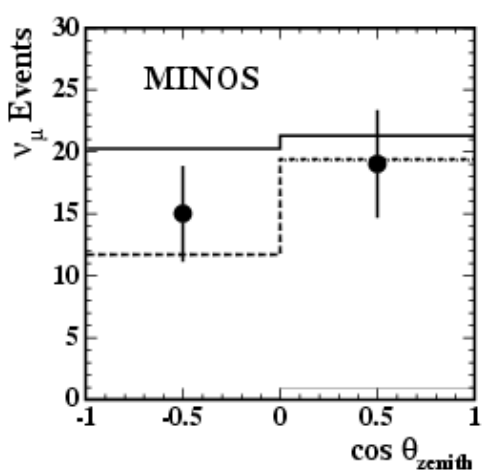
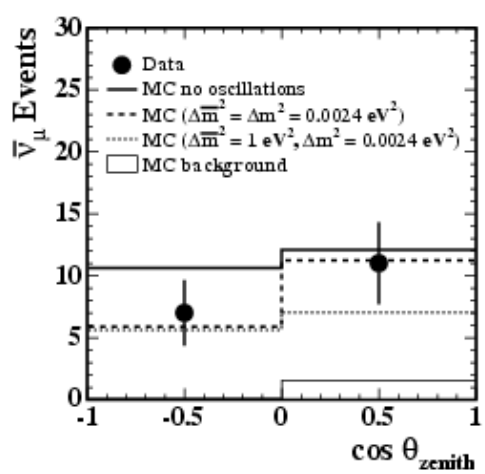
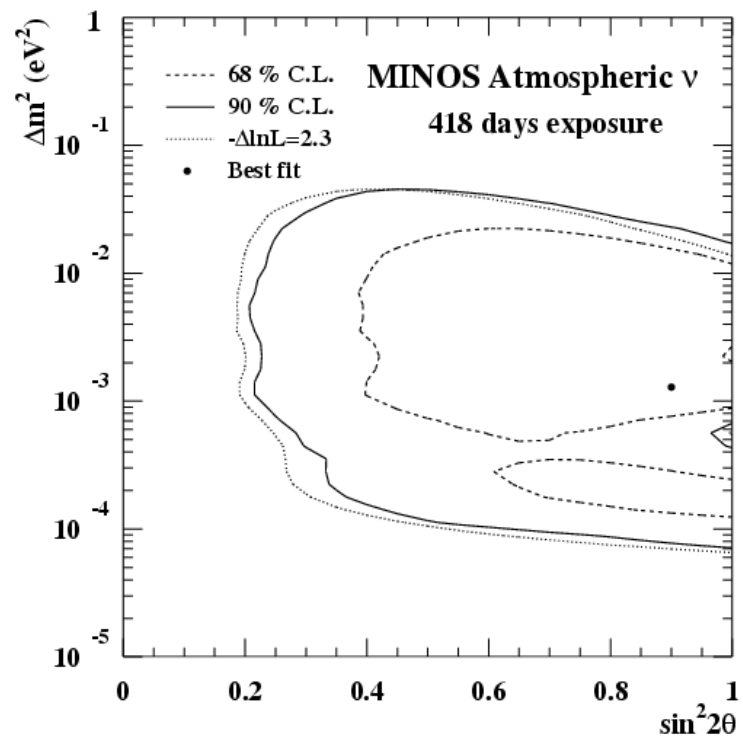
Allowed regions from Super-K and K2K



Atmospheric Neutrino Analysis

First direct results on neutrino/anti-neutrino oscillations using atmospheric neutrinos



107 contained events

Selection	Data	Expected no oscillations	Expected $\Delta m^2_{23} = 0.0024\,eV^2$
Low Res.	30	37 ± 4	28 ± 3
Ambig. $\nu_\mu/\overline{\nu}_\mu$	25	26 ± 3	20 ± 2
ν_μ	34	42 ± 4	31 ± 3
$\overline{\nu}_\mu$	18	23 ± 2	17 ± 2