The Fermilab Fixed Target "Quark Flavor" Program

B. Cox
2005 FNAL
Users Meeting

Results from 2004-05

Number of participants	In analysis	Number of papers* 2004-05
~60	• KTeV	6
~100	• Focus	6
~110	• Selex	4
~ 37	• HyperCP	6
307		22

Proposed (for CERN?)

Kplus??

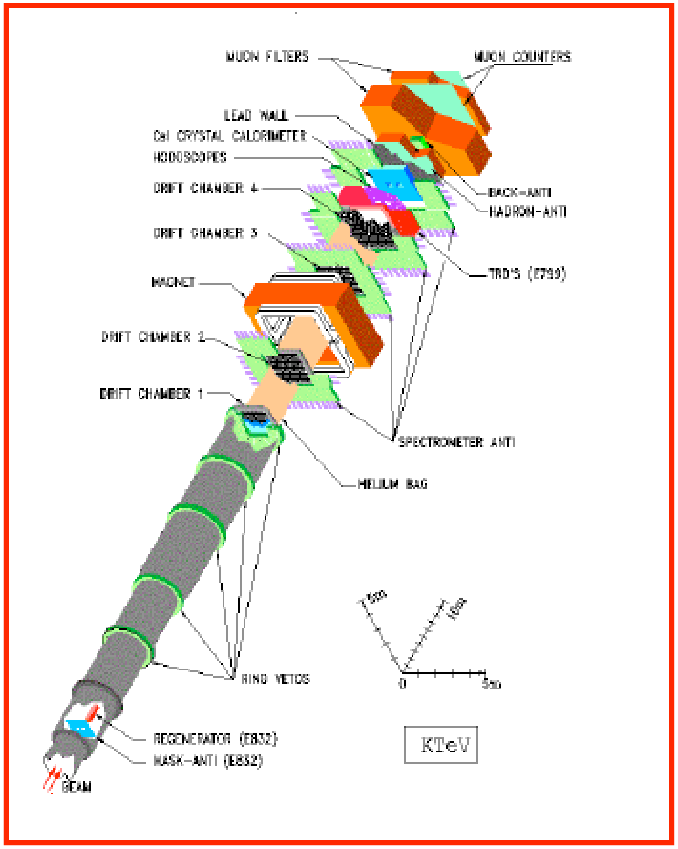
* PRL, PRD, Phys. Letters.

Unique, clever, very different experiments to study s, c quarks

KTeV

6 papers in 2004-05

KTEV Kaons at the Tevatron



I. Unitarity of the CKM matrix and V_{us}
- *a) branching ratios*
- *b) form factors*

II. Decays of K_L with real and virtual γ's
- *a) charge radius of the kaon*
- *b) kaon form factors*
- *c) CP violation*

IIa. Real γ	**IIb. Virtual γ**	
$K_L \to \pi^+\pi^-\gamma$	$K_L \to \pi^+\pi^- e^+e^-$	
$K_L \to \pi^0\pi^0\gamma$	$K_L \to \pi^0\pi^0 e^+e^-$	*First obser-vations*
$K_L \to \pi^+\pi^-\pi^0\gamma$	$K_L \to \pi^+\pi^-\pi^0 e^+e^-$	
$K_L \to \pi^0\pi^0\pi^0\gamma$	$K_L \to \pi^0\pi^0\pi^0 e^+e^-$	

III. *$K_L \to ee\gamma$*
- *a) Branching Ratios*
- *b) Form Factors*

With NA48 and KTeV an epoch is closing

The KTeV Resolution of the CKM unitarity problem

KTEV Kaons at the Tevatron

Charged Weak Interaction

$$(\bar{u} \quad \bar{c} \quad \bar{t})\overbrace{\gamma_\mu(1-\gamma_5)}^{V-A}V_{qq'}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity Problem → V_{us}

$V_{qq'}$ Mixing matrix

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

"first row"

$V_{ud}V^*_{ud} + V_{us}V^*_{us} + V_{ub}V^*_{ub} \neq 1.0$
is 2σ different from 1 according to the PDG

BNL E865 K^+_{l3} measurements indicate a value of Vus that agrees with unitarity but disagrees with V_{us} from K_L

Determination of V_{us} by KTeV by measurement of K_{l3}

KTEV Kaons at the Tevatron

V_{us} is determined by

KTeV measurements of rates

KTeV measurements of form factors

$$\Gamma_{K_{l3}} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^l) |V_{us}|^2 |f_+^2(0)| I_K^l$$

I^e decreased by 1.7%

I^μ decreased by 4.2%

Γ_{Ke3} increased by 5%

$\Gamma_{K\mu3}$ did not change

Short dist.
1.022

New Long dist.
1.013

Form factors at t=0 (theory)
$f_+(0) = 0.961(8)$ Leutwyler-Roos

Radiative corrections (theory)

Components of the V_{us} Calculation

To determine the BR(K_{l3}) accurately enough, must remeasure six main branching ratios representing 99.93% of the K_L decays by measurement of the ratios

$$\Gamma_{K\mu 3}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{\pm}\mu^{\mp}\nu)/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{+-0}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{+}\pi^{-}\pi^{0})/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{000}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

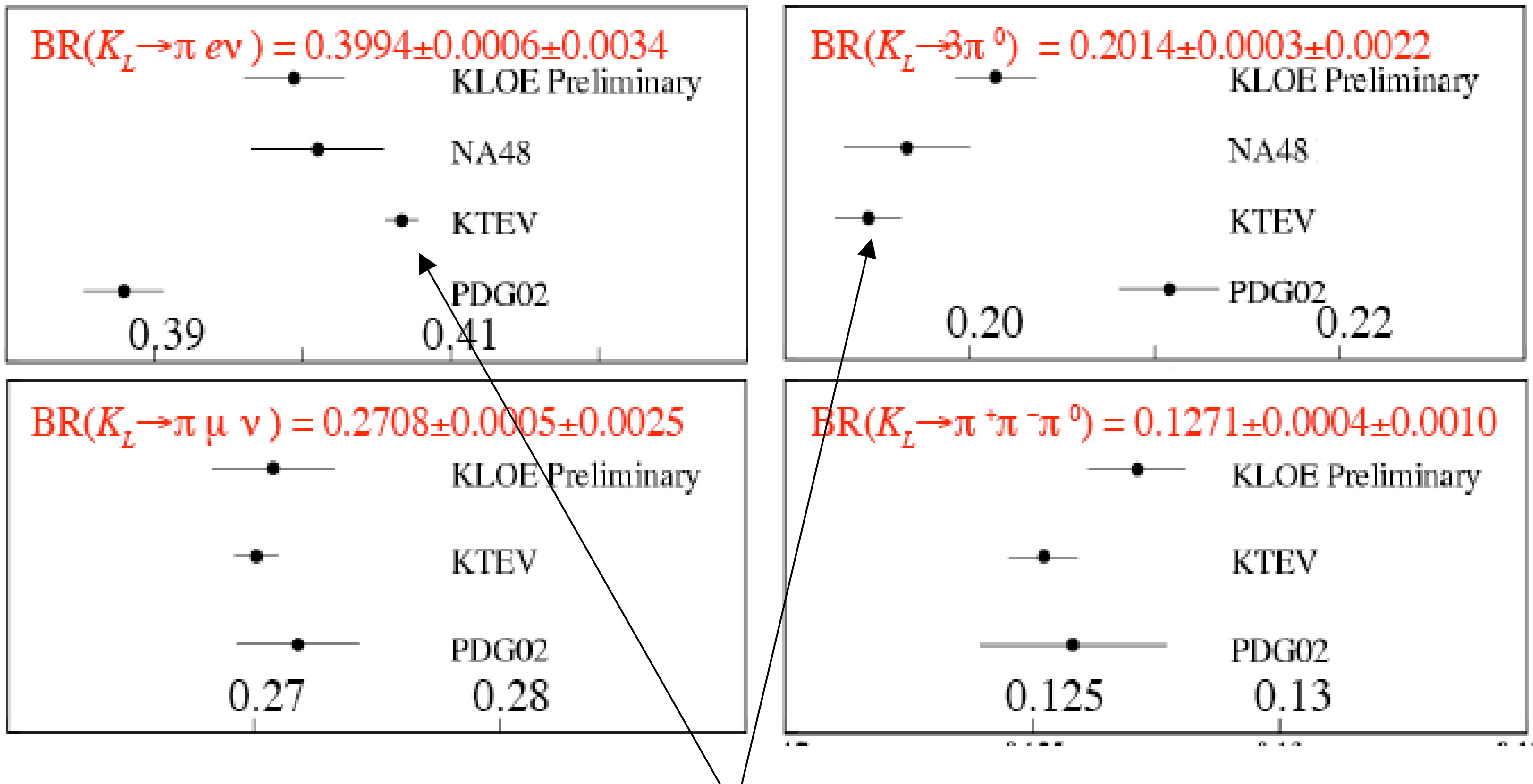
$$\Gamma_{+-}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{+}\pi^{-})/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{00}/\Gamma_{000} = \Gamma(K_L \to \pi^{0}\pi^{0})/\Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})$$

Then $\Gamma_{l3} = BR(K_{l3})/\tau_L$ where τ_L is taken from the PDG

Note: made radiative corrections to K_{l3} using KLOR program (developed by T. Andre (U of Chicago)

KTeV Branching Ratio Disagreement with the PDG



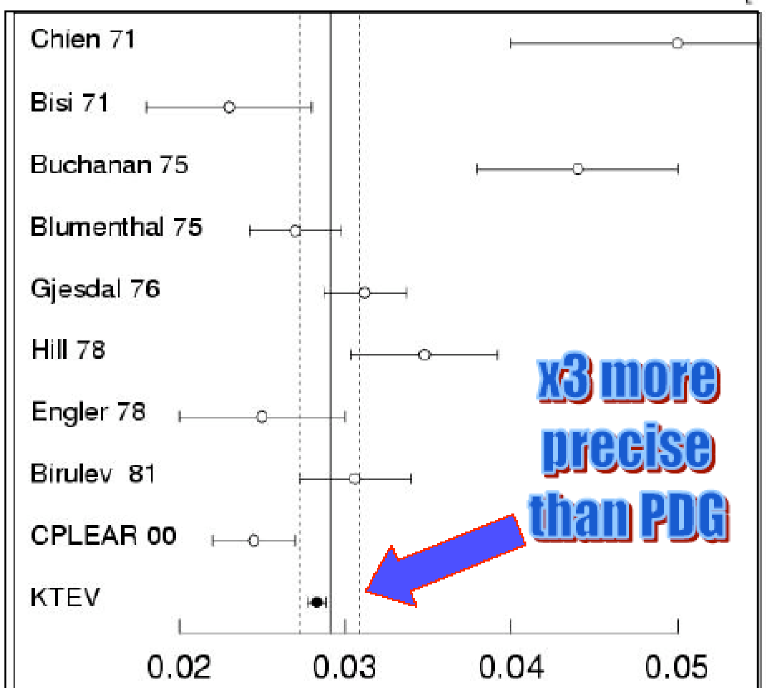
K_{e3} BR's changed significantly from PDG but later corroborated by Kloe/NA48

KTeV Measurement of Semileptonic Form Factors

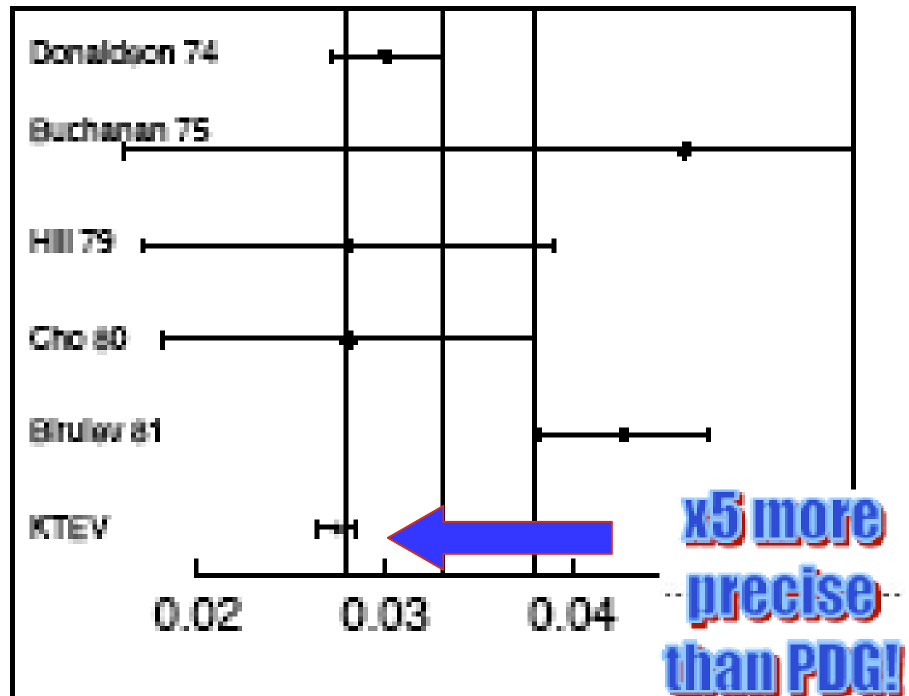
$$f_+(t) = f_+(0)\left[1 + \lambda'_+ \frac{t}{M_\pi^2} + \frac{1}{2}\lambda''_+ \frac{t^2}{M_\pi^4}\right]$$

$$f_0(t) = f_+(0)\left[1 + \lambda_0 \frac{t}{M_\pi^2}\right]$$

where $t = (P_K - P_\pi)^2$



K_{e3} λ_+ *Form Factor*



$K_{\mu 3}$ λ_+ *Form Factor*

V_{us} from KTeV

$V_{us}|f_+(0)| = 0.2165 \pm 0.0012$

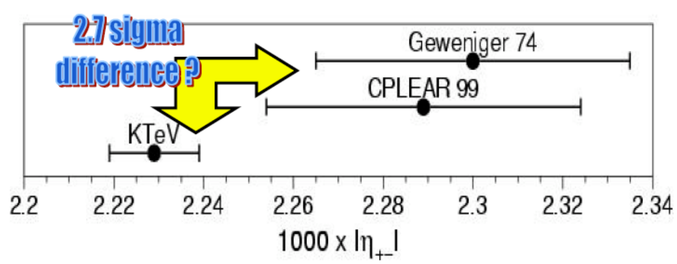
In particular, $f_+(0)$

$V_{us} = 0.2252 \pm 0.0008$ (KTeV exp) ± 0.0021 (other parameters)

$1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0.0018 \pm 0.0019$

Best Fermilab Measurement of 2004!

In addition η_{+-} is changed by the new KTeV branching ratios



Still Competitive!

KTeV Comparison of Real and Virtual Photon Emission in $K_L \rightarrow n\pi\gamma$ and $K_L \rightarrow n\pi\gamma^*$

No result yet	Real γ	Virtual γ	
	$K_L \rightarrow \pi^+\pi^-\gamma$	$K_L \rightarrow \pi^+\pi^- e^+e^-$	First observations
	$K_L \rightarrow \pi^0\pi^0\gamma$	$K_L \rightarrow \pi^0\pi^0 e^+e^-$	
	$K_L \rightarrow \pi^+\pi^-\pi^0\gamma$	$K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-$	Upper limits
No result yet	$K_L \rightarrow \pi^0\pi^0\pi^0\gamma$	$K_L \rightarrow \pi^0\pi^0\pi^0 e^+e^-$	

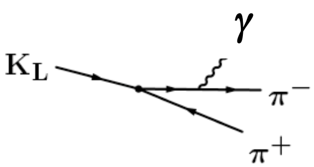
Motivations/observations

- *Real photon emission processes do not include the charge radius process*
- *Both real and virtual direct photon emission processes accompanying neutral pions are greatly suppressed relative to those with charged pions*

Comparison of $K_L \to \pi^+\pi^-\gamma$ and $K_L \to \pi^+\pi^- e^+ e^-$ Decay Processes*

KTEV
Kaons at the Tevatron

Processes contributing to $K_L \to \pi\pi\gamma$ decay (real photons)



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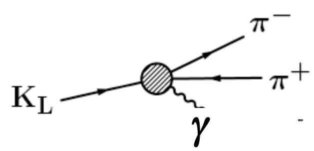


Internal Bremsstrahlung [IB]
Indirect CPV
CP-even

Direct Emission [DE]

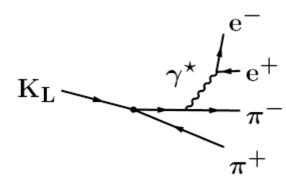
M1 — CP Conserving
CP-odd

E1 — Indirect CPV
CP-even
Even smaller

Two independent variables in $K_L \to \pi\pi\gamma$

$(\cos\theta_\gamma)_{\pi\pi\ CMS}$, $(E_\gamma)_{K\ CMS}$

Processes contributing to $K_L \to \pi\pi ee$ decay (virtual photons)



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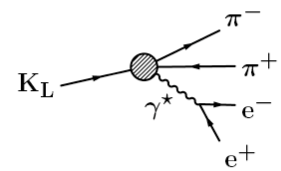

Internal Bremsstrahlung [IB]
Indirect CPV
CP-even

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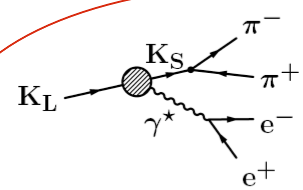


Small, only few %

K^0 Charge Radius [CR]
CP Conserving
CP-odd

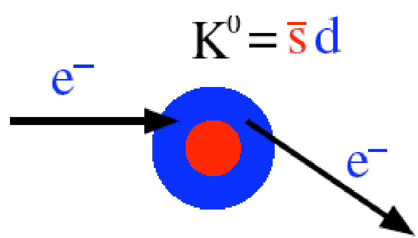
Five independent variables in $K_L \to \pi\pi\gamma^*$

M_{ee}, $M_{\pi\pi}$, $\phi_{K\ CMS}$,
$(\cos\theta_{e+})_{\pi\pi\ CMS}$, $(\cos\theta_{\pi+})_{ee\ CMS}$,

**Phenomenological model due to L.M Sehgal et al*

Kaon charge radius from $K_L \rightarrow \pi^+\pi^- e^+ e^-$ Decay

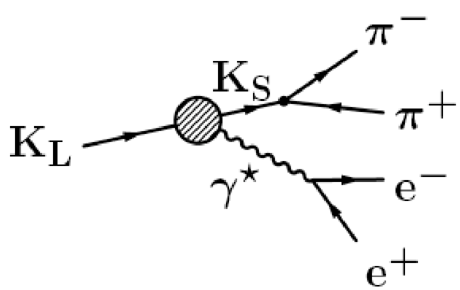
Kaon charge structure can be measured from FF



$$\left\langle r^2_{K^0} \right\rangle \equiv \frac{1}{e} \int_V r^2 \rho\,(V)\, dV < 0$$

was measured before

in K^0+e^- scattering



FF $g_{CR} \sim \left\langle r^2_{K^0} \right\rangle$

$\Rightarrow$ alternative measurement
can not measure sign

$\left\langle r^2_{K^0} \right\rangle$ is related to $m_s - m_d$

Amplitudes for Processes Contributing to $K_L \to \pi^+\pi^-\gamma\ (\gamma^*)$

Phenomenological model used for signal MC

Inner Bremsstrahlung: $g_{BR} = |\eta_{+-}| e^{i(\delta_0(M_K)+\Phi_{+-})}$ ← *Only present with charged π's*

M1 direct emission: $g_{M1} = i|g_{M1}|e^{i\delta_1(M_{\pi\pi})}$

E1 direct emission: $g_{E1} = -i\frac{|g_{E1}|}{|g_{M1}|} g_{M1} e^{i\Phi_{+-}}$

Charge radius amplitude: $g_{CR} = |g_{CR}|e^{i\delta_0(M_{\pi\pi})}$ ← *Only in virtual γ emission*

δ_0 and δ_1 are phases of s- and p-wave $\pi\pi$ scattering. We used recent fits from G.Colangelo et al, Nucl. Phys. B603, 125 (2001)

$|g_{M1}|$ is energy dependent:

$$|g_{M1}| = \tilde{g}_{m1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 + M_K^2) + 2M_K E_\gamma^*}\right]$$

Interference between inner brem and M1 direct photon emission yields a large CPV effect

Determination of
$|g_{M1}|$
$|g_{E1}/g_{M1}|$, a_1/a_2

from fits of the
$K_L \to \pi^+\pi^- e^+e^-$ and
$K_L \to \pi^+\pi^-\gamma$ data

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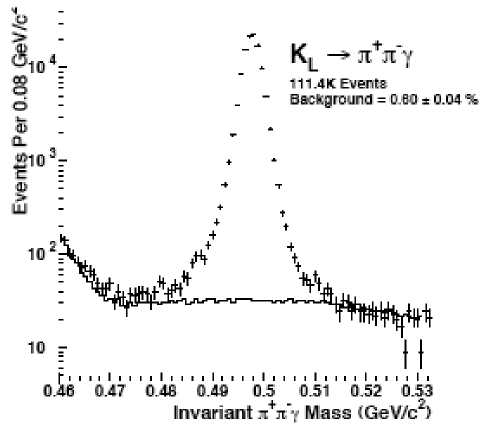
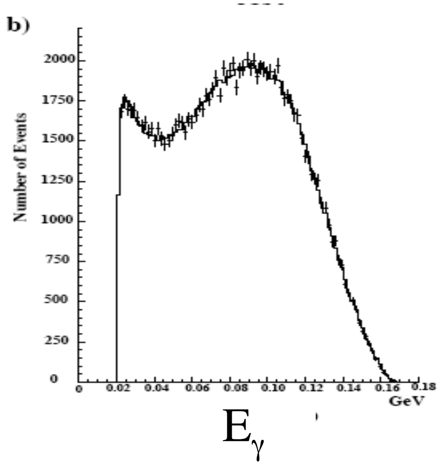
and, in addition, determination from
$K_L \to \pi^+\pi^- e^+e^-$
$|g_{CR}|$ charge radius
and a CP violating asymmetry in the ϕ angle

KTeV Comparison of $K_L \to \pi^+\pi^-\gamma$ vs. $K_L \to \pi^+\pi^- e^+ e^-$ $M_{\pi\pi\ \gamma(\gamma^*)}$ and $E_\gamma (E_{\gamma^*})$

$K_L \to \pi^+\pi^-\gamma$

111.4K candidates (background 671±41 events)

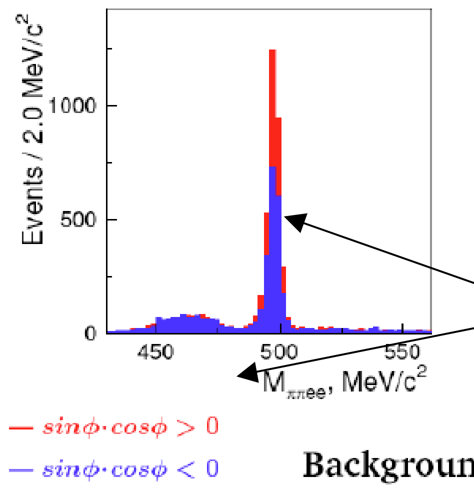




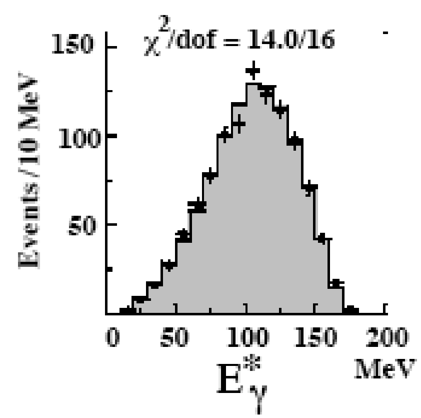
$K_L \to \pi^+\pi^- e^+ e^-$

First observation

5241 candidates (background 185±14 events)



CP violation



Results from the KTeV Measurements of $K_L \to \pi^+\pi^-\gamma$ vs. $K_L \to \pi^+\pi^- e^+e^-$

KTEV Kaons at the Tevatron

Results from $K_L \to \pi^+\pi^-\gamma$

g_{M1} =

Not quite ready for prime time

a_1/a_2 =

g_{CR} = ------------

$<|g_{E1}|>$ **Not quite ready for prime time**

$<r^2_K>$ = -----------

$<|g_{M1}|>$ **Not quite ready for prime time**

Results from $K_L \to \pi^+\pi^- e^+e^-$

$g_{M1} = 1.11 \pm 0.12(stat) \pm 0.08(syst)$

$a_1/a_2 = -0.744 \pm 0.027(stat) \pm 0.032(syst)\ GeV^2$

$g_{CR} = 0.163 \pm 0.14(stat) \pm 0.023(syst)$

$|g_{E1}|/|g_{M1}| < 0.04$ (90%CL)

$<|g_{E1}|> < 0.03$ (90% CL)

$<r^2_K> = -0.077 \pm 0.0079(stat) \pm 0.011(syst)\ fm^2$

$<|g_{M1}|> = 0.74 \pm 0.04$

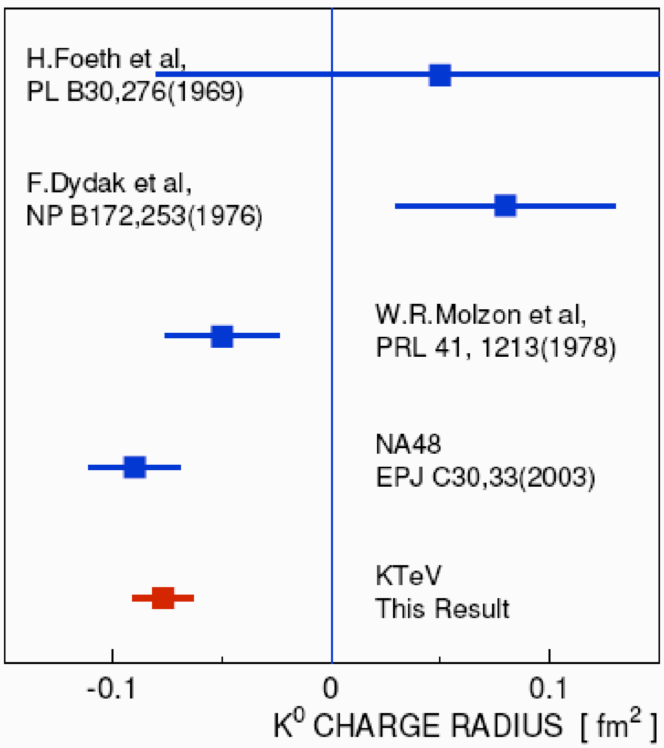
Radius of the kaon

Charge Radius of the Neutral Kaon from $K_L \rightarrow \pi^+\pi^- e^+e^-$

KTEV Kaons at the Tevatron

Charge radius FF and $\left\langle r^2_{K^0} \right\rangle$ calculation

$$|g_{CR}| = 0.163 \pm 0.017(\mathrm{stat}) \pm 0.023(\mathrm{syst})$$



$|g_{CR}| = -\frac{1}{3}\langle R_K^2 \rangle M_K^2$
$\langle R_K^2 \rangle$ is K^0 charge radius

Previous published measurements of $\langle R_K^2 \rangle$ are based on kaon regeneration on free electrons.

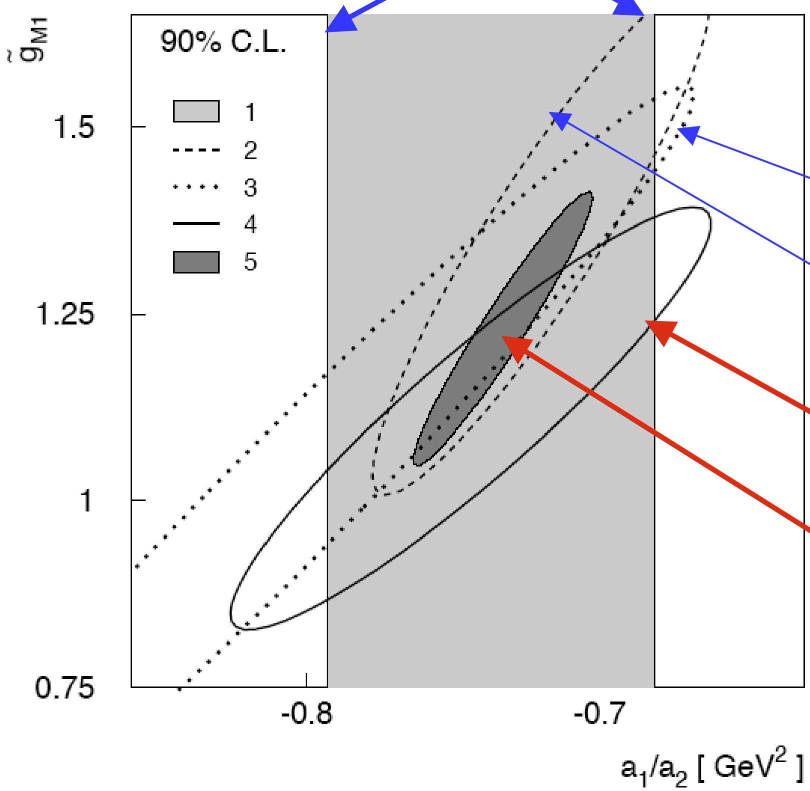
NA48 and KTeV measurements are based on $K_L \rightarrow \pi^+\pi^- e^+e^-$

KTeV Result 97+99 data
$<r^2_K> = -0.077 \pm 0.014\ fm^2$

$K_L \to \pi^+\pi^-\gamma(\gamma^*)$ Measurements of $a1/a2$ and g_{M1} M1 Form Factors

KTeV 96 data: $K_L \to \pi^+\pi^-\gamma$
No correlations

$$F = \tilde{g}_{M1}\left[1 + \frac{a1/a2}{(M_\rho^2 - M_K^2) + 2M_K(E_{e^+} + E_{e^-})}\right]$$



NA48 $K_L \to \pi^+\pi^- e^+e^-$

KTeV 97 data: $K_L \to \pi^+\pi^- e^+e^-$

KTeV 97+99 data: $K_L \to \pi^+\pi^- e^+e^-$

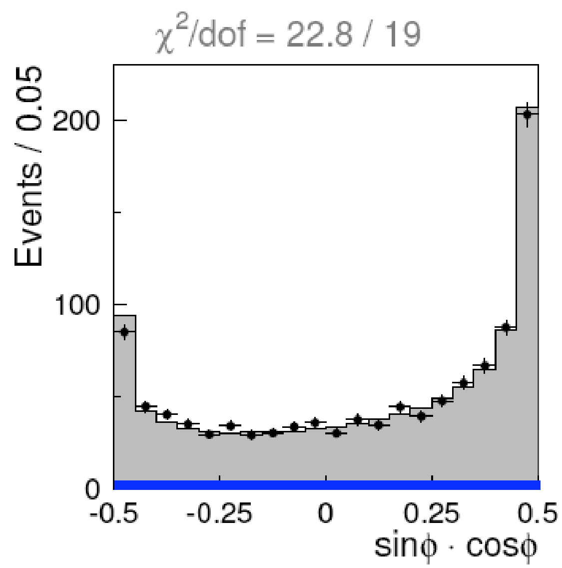
KTeV 97 data: $K_L \to \pi^+\pi^-\gamma$

The ellipses are 90% CL

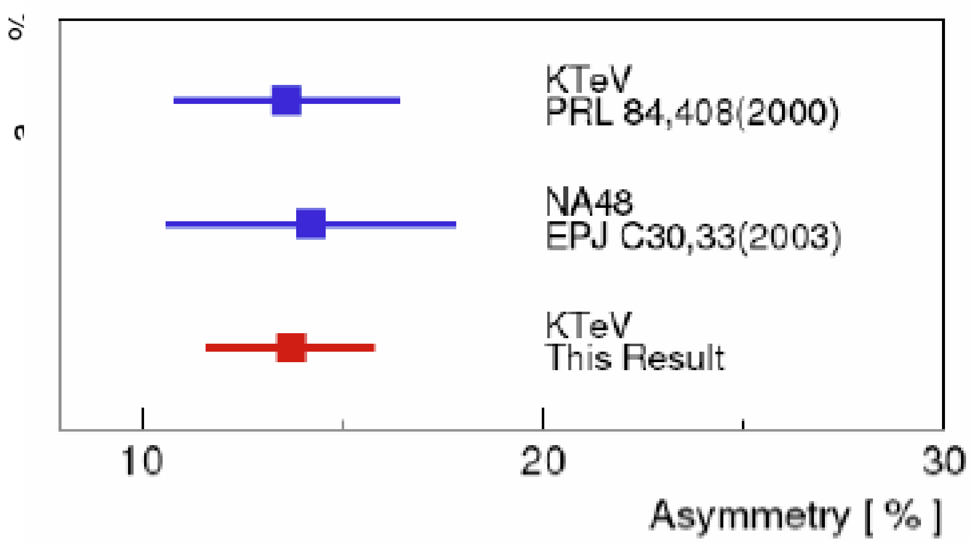
CP Violating Asymmetry in the ϕ Angle

$$\mathcal{A} = \frac{N_{sin\phi cos\phi>0} - r \cdot N_{sin\phi cos\phi<0} - n\frac{1-r}{2}}{N_{sin\phi cos\phi>0} + r \cdot N_{sin\phi cos\phi<0} - n\frac{1+r}{2}}$$

CP violation asymmetry = 13.6±1.4(stat)±1.5(syst)%



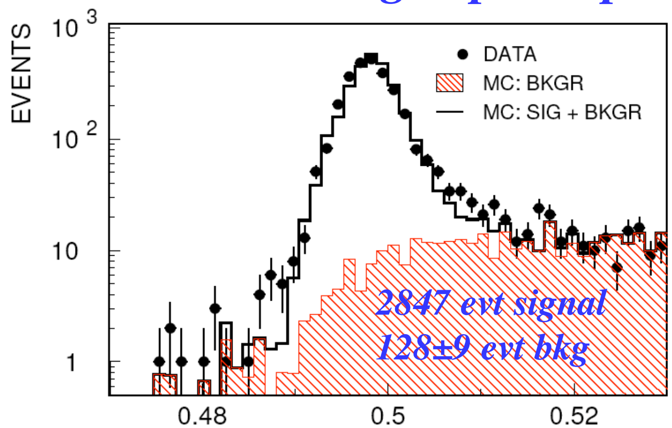
symmetric background n



Second Most Cited Work from KTeV

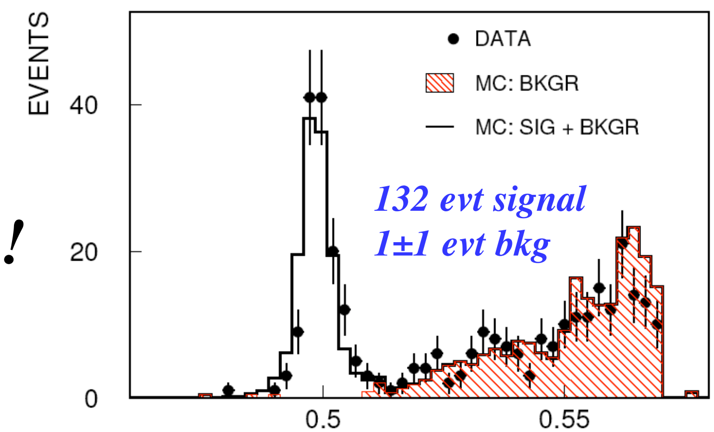
KTeV Comparison
$K_L \to \pi^+\pi^-\pi^0\gamma$ vs. $K_L \to \pi^+\pi^-\pi^0 e^+e^-$
$M_{\pi\pi\,\gamma(\gamma^*)}$ and $E_\gamma (E_{\gamma^*})$

For photon emission in states which containing two charged pions plus a neutral pion there is little theory

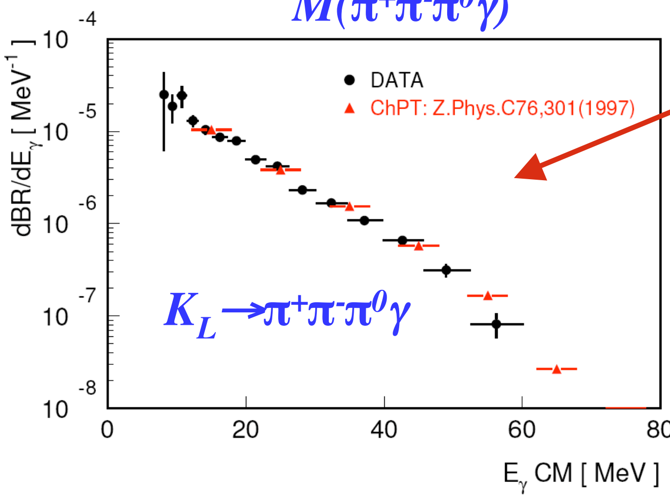


$M(\pi^+\pi^-\pi^0\gamma)$

First Observations!

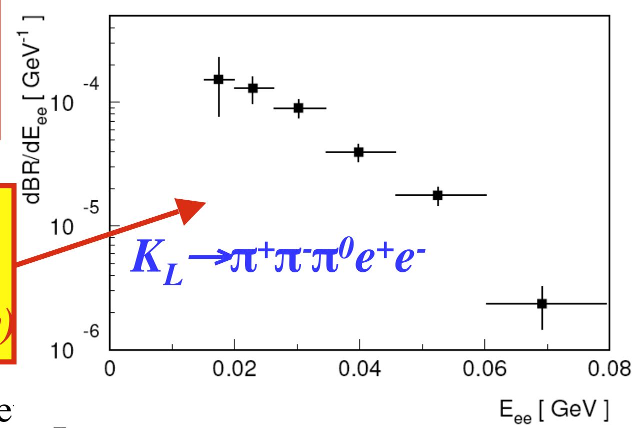


$M(\pi^+\pi^-\pi^0 ee)$ GeV]



$BR(E_\gamma > 10\ \mathrm{MeV})$
$1.56 \pm 0.07 \times 10^{-4}$
Preliminary (stat only)

$BR(E_{\gamma^*} > 20\ \mathrm{MeV})$
$1.60 \pm 0.18 \times 10^{-7}$
Preliminary (stat only)



KTeV Search for And Comparison of $K_L \rightarrow \pi^0\pi^0\gamma$ vs. $K_L \rightarrow \pi^0\pi^0 e^+e^-$

KTEV Kaons at the Tevatron

P. Heilinger and L.M Sehgal have investigated this modes theoretically

They find that the decay $K_L \rightarrow \pi^0\pi^0\gamma$ that, due to gauge invariance and bose statistics, that the pion pair must have at least two units of angular momentum, thereby requiring the lowest multipole for direct photon emission (assuming CP invariance) to be E2

$K_L \rightarrow \pi^0\pi^0\gamma$

$BR(K_L \rightarrow \pi^0\pi^0\gamma) < 4.7\text{x}10^{-7}$ (90% CL)
(preliminary; statistics only)

$K_L \rightarrow \pi^0\pi^0 e^+e^-$

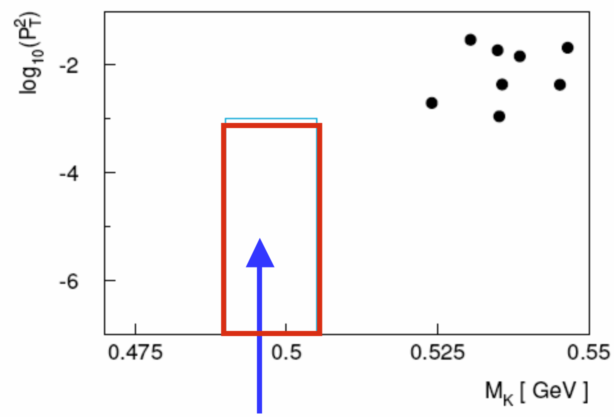
$BR(K_L \rightarrow \pi^0\pi^0 e^+e^-) < 5.4\text{x}10^{-9}$ (90% CL)

Photon emission in K_L decays accompanying two neutral pions is dramatically suppressed relative to that in events with $\pi^+\pi^-$ even if a charge radius amplitude contributes to the virtual photon decay

KTeV search for
$K_L \to \pi^0\pi^0\pi^0\gamma$ vs. $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

For photon emission in states which containing three neutral pions there is no theory

???



No events in the signal box

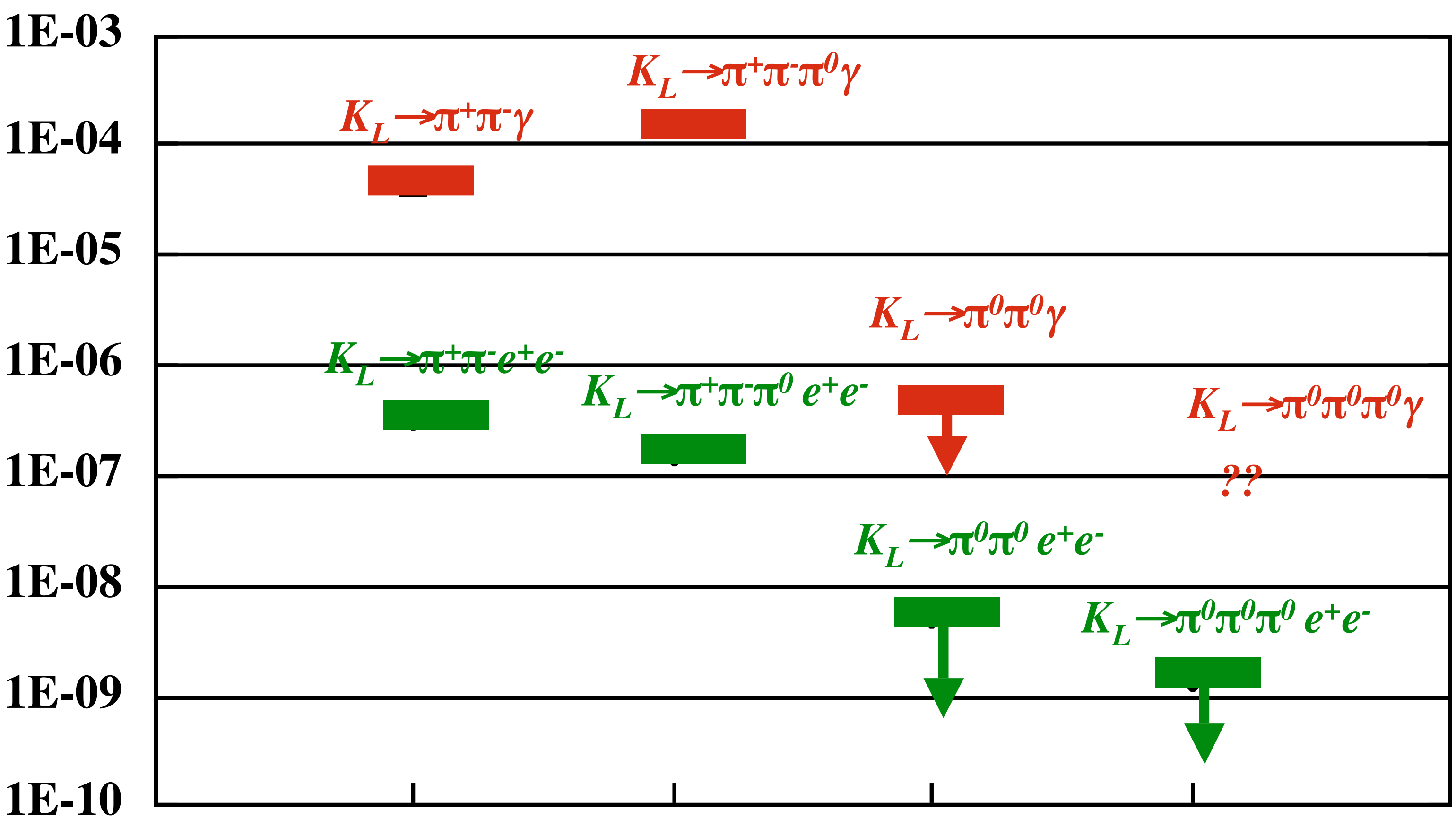
$K_L \to \pi^0\pi^0\pi^0\gamma$

$BR(K_L \to \pi^0\pi^0\pi^0\gamma) < ??$
(no result yet)

$K_L \to \pi^0\pi^0\pi^0\ e^+e^-$

$BR(K_L \to \pi^0\pi^0\pi^0\ e^+e^-) < ??$
(under study)

Summary of KTeV
$K_L \to n\pi + \gamma(\gamma^*)$



Caveat not all photon E cutoffs are the same for these BR

- *The direct γ emission of in states with neutral π's is greatly suppressed wrst states with charged pions*
- *The emission of a virtual γ's is suppressed wrst real γ's*

KTeV

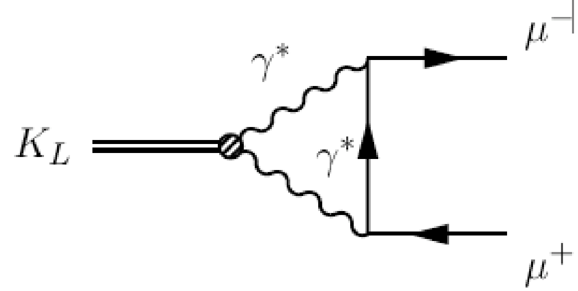
Motivation for the Measurement of the $K_L \rightarrow e^+e^-\gamma$ Branching Ratios and Form Factors

- *The decay $K_L \rightarrow \mu^+\mu^-$ has both short and long range contributions*

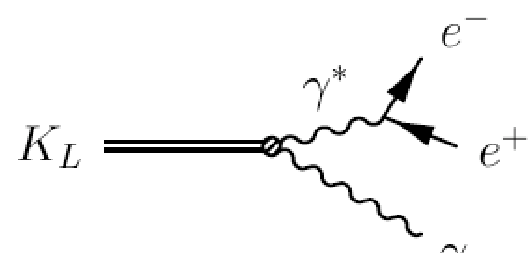
- *The short range contributions can be used to extract $|V_{td}|$*

- *However, the long range contributions from the $K_L \rightarrow \gamma^*\gamma^*$ vertex must be subtracted. A precise understanding of this vertex is necessary*

- *The $K_L \rightarrow \gamma^*\gamma^*$ vertex can be studied via measurements of $K_L \rightarrow e^+e^-\gamma$ and $K_L \rightarrow e^+e^-e^+e^-$*



$K_L \rightarrow \mu^+\mu^-$ QED diagram



$K_L \rightarrow e^+e^-\gamma$ diagram

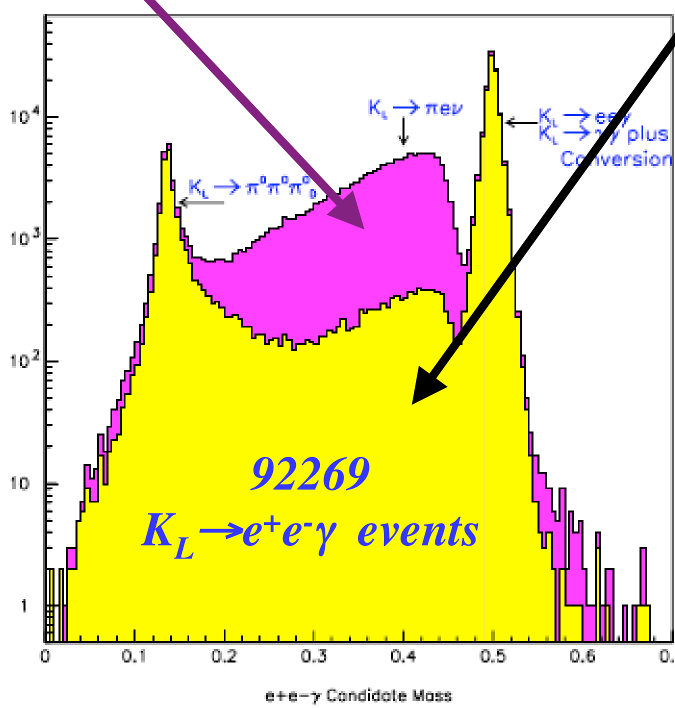
KTeV

KTEV Kaons at the Tevatron

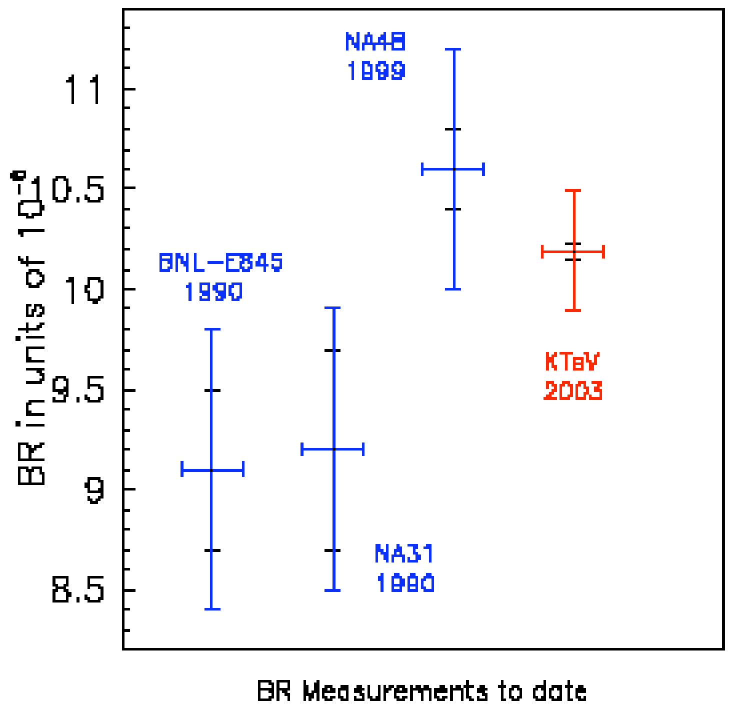
$K_L \rightarrow e^+e^-\gamma$ Branching Ratio

No Transition Radiator cut

With TRD cut



Previous BR($K_L \rightarrow e^+e^-\gamma$) Results



$BR = 9.42 \pm 0.03(stat) \pm 0.07(syst) \pm 0.27(ext.\ syst) \times 10^{-6}$
(preliminary)

KTeV

$K_L \to e^+e^-\gamma$ Form Factors
Very sensitive to shape of $q^2 = M_{ee}$

DIP version vector ff (D'Ambrosio-Isidori-Portoles

$$f_{DIP}(q_1^2,q_2^2) = 1 + \alpha_{DIP}\left(\frac{q_1^2}{q_1^2 - M_\rho^2} + \frac{q_2^2}{q_2^2 - M_\rho^2}\right)$$

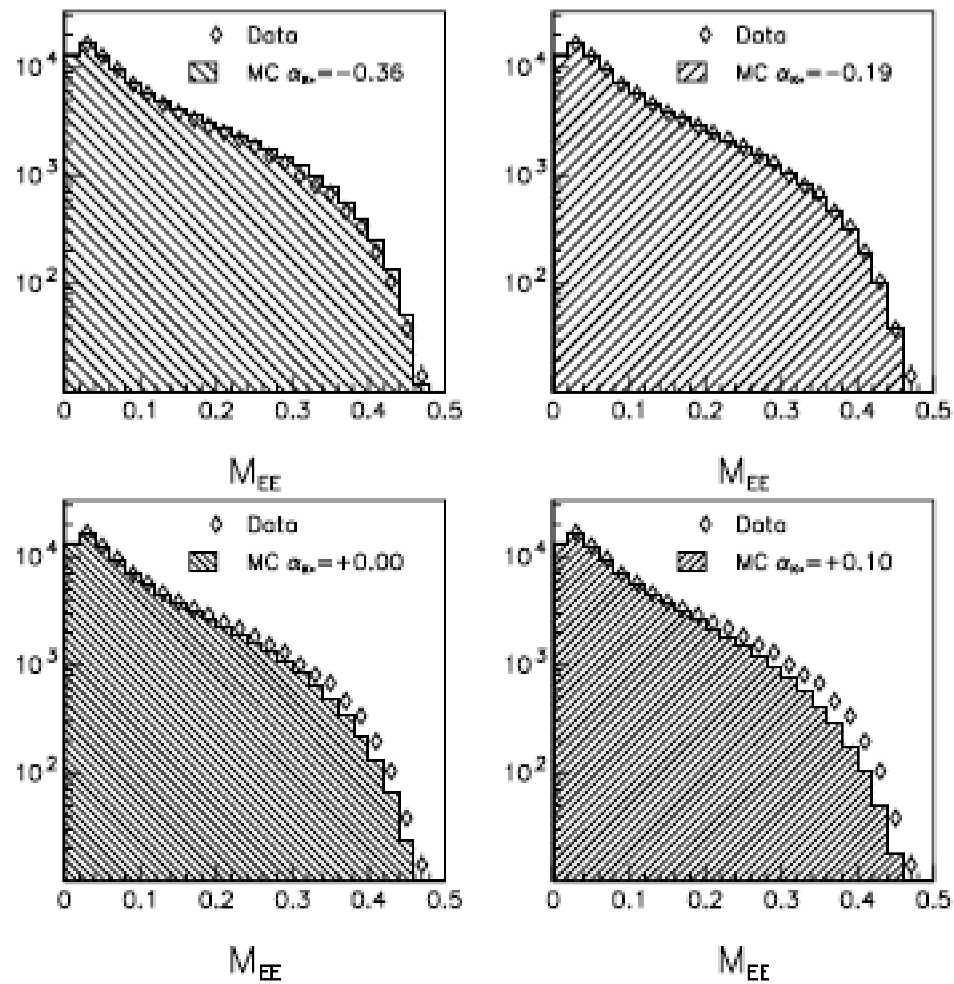
$$+\beta_{DIP}\left(\frac{q_1^2 q_2^2}{(q_1^2 - M_\rho^2)(q_2^2 - M_\rho^2)}\right)$$

α_{K*} version vector ff (Bergstrom-Masso-Singer)

$$f(x) = \frac{1}{1-0.418x} + \frac{2.3\alpha_{K*}}{1-0.311x}$$

$$\left(\frac{4}{3} - \frac{1}{1-0.418x} - \frac{1}{9(1-0.405x)} - \frac{2}{9(1-0.238x)}\right)$$

where $x=M^2_{ee}/M^2_K$

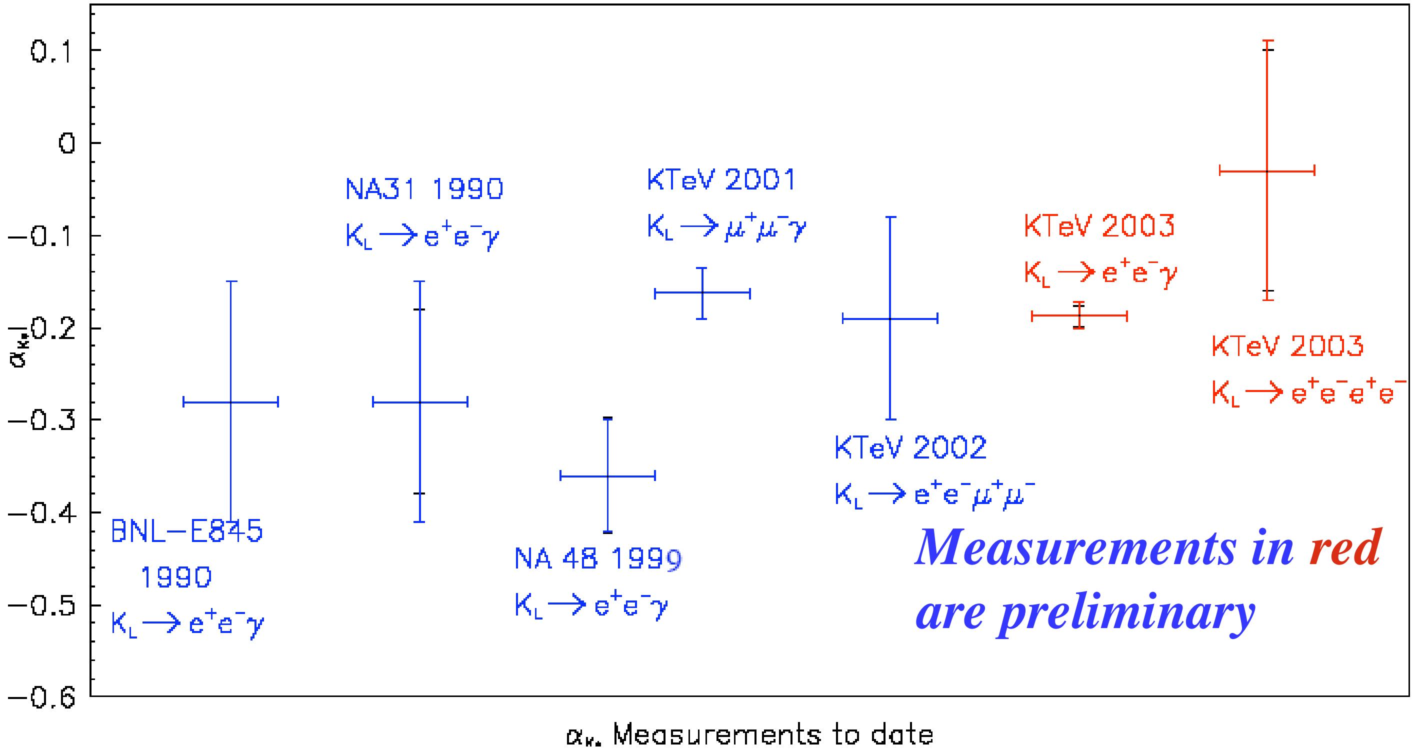


KTeV

Form Factor Results

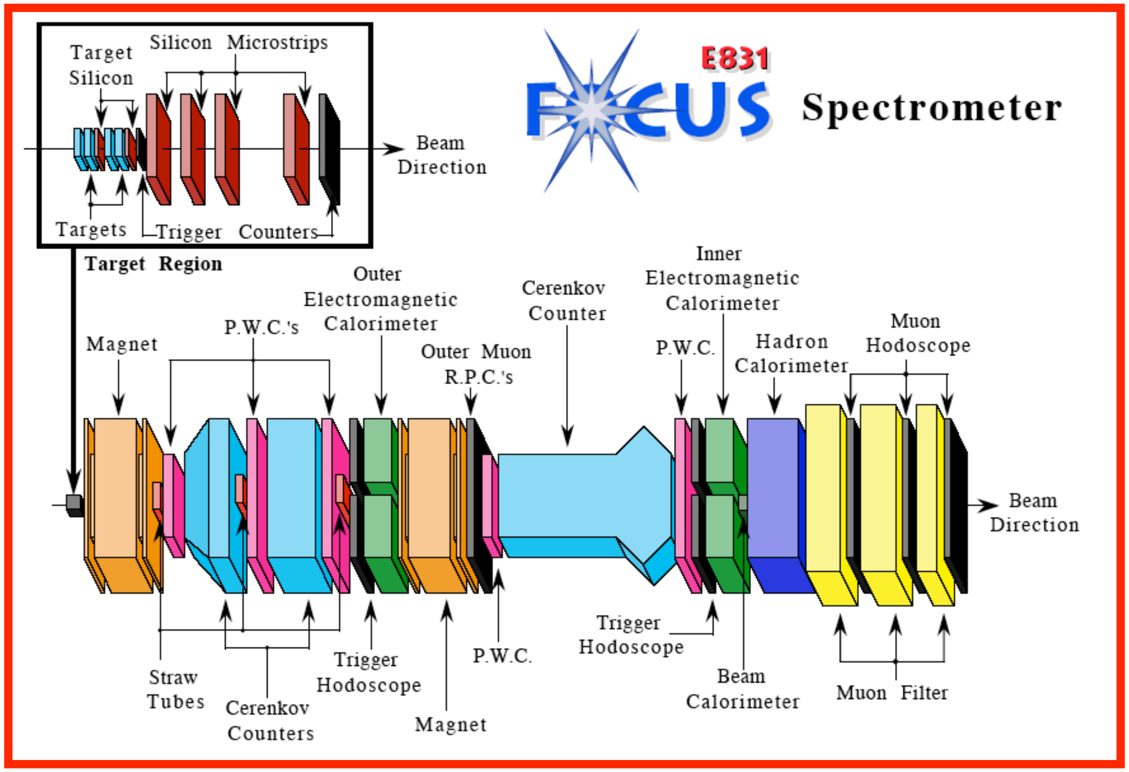
$\alpha_{K^*} = -0.186 \pm 0.011(stat) \pm 0.009(syst)$

$\alpha_{DIP} = -1.630 \pm 0.04(stat) \pm 0.03(syst)$



Focus

6 papers in 2004-05



I. Semileptonic form factor q^2 dependences

II. D_s lifetime measurement

III. Search for mixing and T violation in D hadron decay

IV. Discovery of new Cabbibo favored D decay channels $D^0 \rightarrow K_S K_S X$

V. Search for the pentaquark

The quintessential charm experiment

I.I.Bigi 'Charm physics - Like Botticelli in the Sistine Chapel'

Focus

Semileptonic Form Factors

The matrix element including the f_+ and f_- form factors

$$M = G_F V_{cs}\left[f_+(q^2)(P_D + P_K)_\sigma + f_-(q^2)(P_D - P_K)\right]\overline{u}_\mu \gamma^\sigma (1-\gamma_5)u_\upsilon$$

resulting in a differential cross section for the decays

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{8\pi^3 m_D}|V_{cs}|^2|f_+(q^2)|^2 P_K\left(\frac{W_0 - E_K}{F_0}\right)^2$$

$$\left[\frac{1}{3}m_D P_K^2 + \frac{m_\mu^2}{8m_D}(m_D^2 + m_K^2 + 2m_D E_K) + \frac{1}{3}m_\mu^2\frac{P_K^2}{F_0} + \frac{1}{4}m_\mu^2\frac{m_D^2 - m_K^2}{m_D}\mathrm{Re}\left(\frac{f_-(q^2)}{f_+(q^2)}\right) + \frac{1}{4}m_\mu^2 F_0\left|\frac{f_-(q^2)}{f_+(q^2)}\right|^2\right]$$

$q^2=(P_D-P_K)^2$

where $W_0(m_D^2 + m_K^2 - m_\mu^2)/(2m_D)$ $\quad F_0 = W_0 - E_K + m_\mu^2/(2m_D)$

The form factors are taken to have the following forms

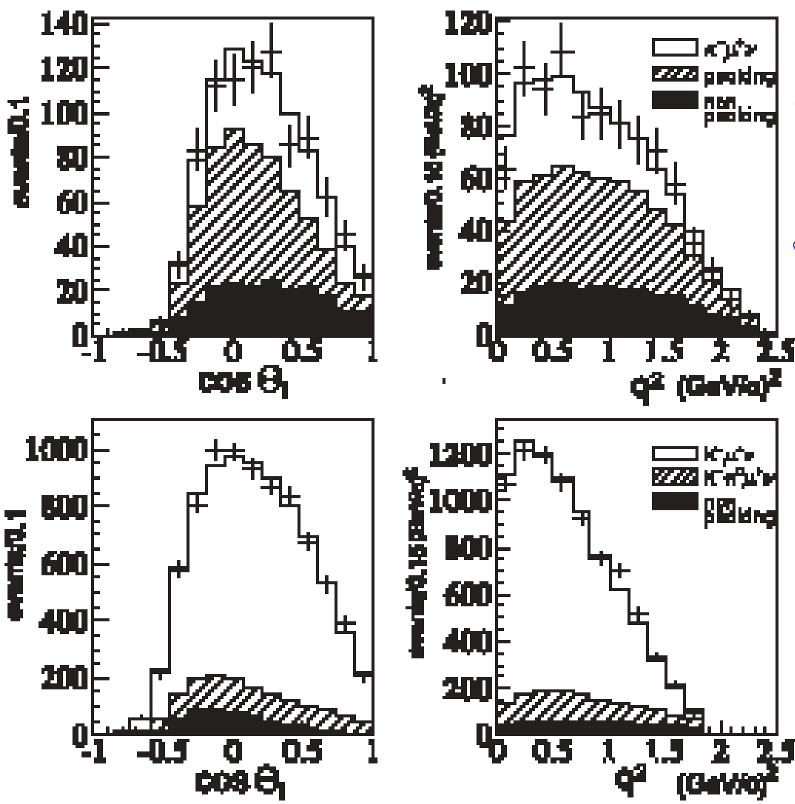
Pole form: $f_+(q^2) = \frac{f_+(0)}{1 - q^2/m_{pole}^2}$

Modified pole form: $f_+(q^2) = \frac{f_+}{(1 - q^2/m_{D^*}^2)(1 - \alpha q^2/m_{D^*}^2)}$

Focus

Semileptonic Form Factors

Focus data



$D^0 \rightarrow \pi^- \mu^+ \upsilon$

$D^0 \rightarrow K^- \mu^+ \upsilon$

Cos Θ *q²*

Extraction of m_{pole} *from* $D^0 \rightarrow \pi^- \mu^+ \upsilon$

$m_{pole} = 1.91 \ ^{+0.30}_{-0.15} \ \pm 0.07 \ GeV/c^2$

Extraction of $\frac{f_+(0)}{f_-(0)}$ m_{pole} *and* α *from* $D^0 \rightarrow K^- \mu^+ \upsilon$

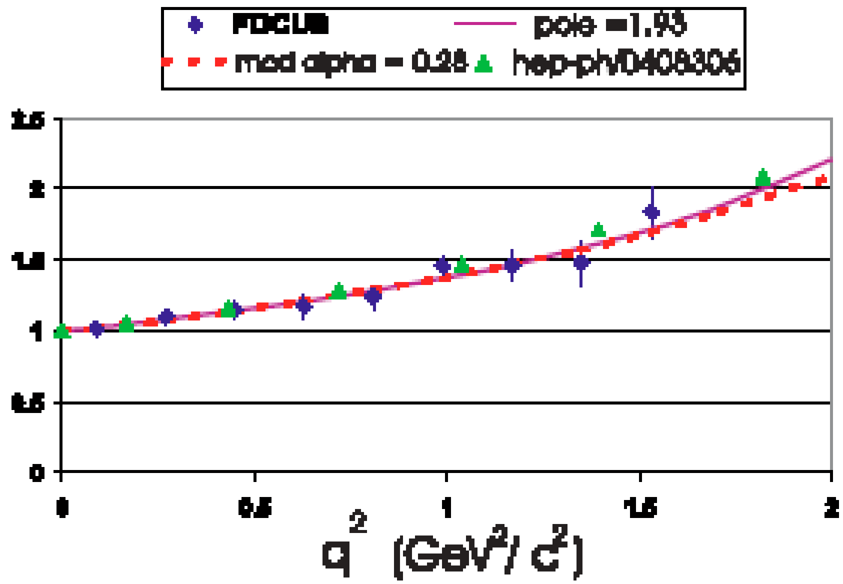
$m_{pole} = 1.93 \pm 0.05 \pm 0.03 \ GeV/c^2$

$\alpha = 0.36 \pm 0.10 ^{+0.03}_{-0.07}$

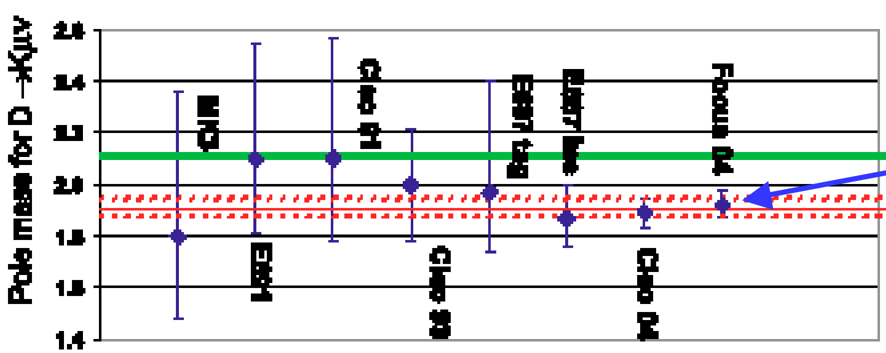
$f_-(0)/f_+(0) = -1.7 \ ^{+1.5}_{-1.4} \ \pm 0.3$

Focus

Semileptonic Form Factors



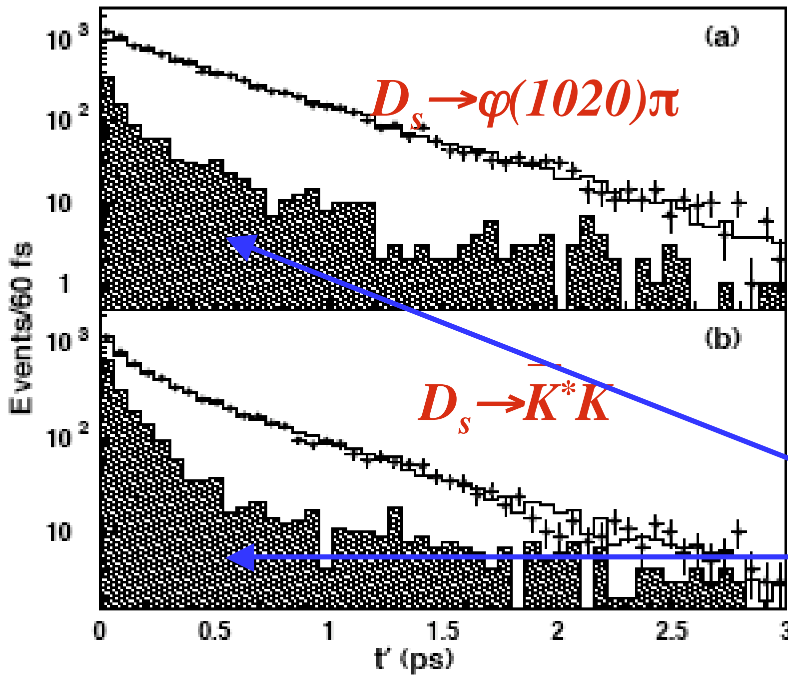
Comparison of $f_+(q^2)$ behavior with Lattice gauge prediction



Comparison of pole mass For $D^0 \rightarrow K^- \mu^+ \upsilon$ with previous exp.

Focus

D^+_s Lifetime



$\tau = 507.4 \pm 5.5(stat) \pm 5.1(syst.)fs$

from a combined
8961 ± 105 events $D_s \to \varphi(1020)\pi$
4680 ± 90 events $D_s \to K^*K$

backgrounds

$\tau(D^+_s) / \tau(D^0) = 1.239 \pm 0.014(stat) \pm 0.009(syst.)$

Focus

Search for Mixing in Charm in $D^0 \rightarrow K^+\pi^-$ Decay

- Use the $D^{*+} \rightarrow D^0\pi^+_s$ decays to tag the produced D^0
- Determine the D^0 flavor by using the Cabibbo favored decay $D^0 \rightarrow K^-\pi^+$

- RS = right sign decay is when the K has the opposite charge from the slow π
- WS = wrong sign decay is when the K has the same charge as the slow π
  (the D^0 can also decay into a WS $K^+\pi^-$ state in a doubly Cabibbo suppressed - DSCD)

- 3D fit of R_{WS} = wrong sign decay rate $[(M(D^0), Q(D^*)=M(D^*)-M(D^0)-m_\pi]$

CP conserving →

$$R_{WS}(t) = e^{-\Gamma t}\left(R_D + \sqrt{R_D}\, y'\Gamma t + \frac{1}{4}\left(x'^2 + y'^2\right)\Gamma^2 t^2\right)$$

DCSD

Interference between DCSD and mixing

Mixing

R_D = ratio of DCSD rate to Cabibbo favored mode

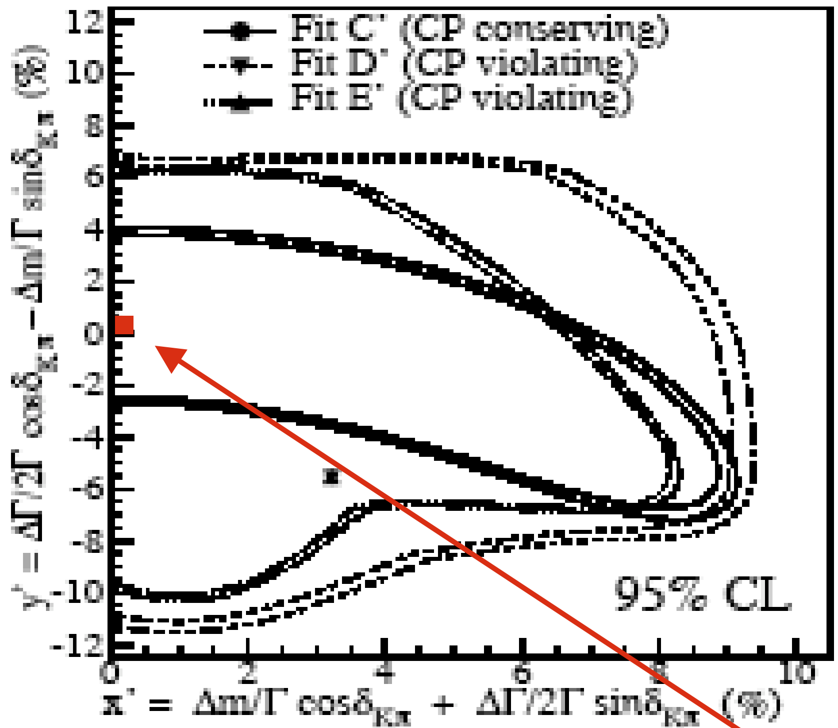
$$x' = \frac{\Delta M}{\Gamma}\cos\delta_{K\pi} + \frac{\Delta\Gamma}{2\Gamma}\sin\delta_{K\pi}$$
$$y' = \frac{\Delta\Gamma}{2\Gamma}\cos\delta_{K\pi} - \frac{\Delta M}{\Gamma}\sin\delta_{K\pi}$$

$\delta_{K\pi}$ = strong phase between DSCD and CF

Focus

Results for Mixing in Charm in $D^0 \to K^+\pi^-$ Decay

Fit C/C'
CP conserving



no $x'^2 > 0$ constraint

$R_D = (0.381^{+0.167}_{-0.163} \pm 0.092)\%$

$x'^2 = -0.6\%$ $y'^2 = 1.0\%$

$x'^2 > 0$ constraint

$R_D = (0.395^{+0.154}_{-0.098} \pm 0.069)\%$

$x'^2 = 0\%$ $y'^2 = 0.5\%$

Focus

T-violation in Charm Decays

In the $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ decays a T-odd triple produce of momenta can be formed

$$C_T = \left\langle \vec{p}_{K^+} \bullet (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \right\rangle$$

Under time reversal T one has $C_T \rightarrow -C_T$

But $C_T \neq -C_T$ does not necessarily establishes T violation.

Time reversal (T) is an antiunitary operator (no eigenstates of T) so the D^0 is not an eigenstate of T and $C_T \neq -C_T$ can be caused by FSI. In contrast to partial width differences, FSI can produce a T-odd correlation with T-invariant dynamics.

This ambiguity can unequivocally be resolved by measuring in $\overline{D^0} \rightarrow K^- K^+ \pi^- \pi^+$.

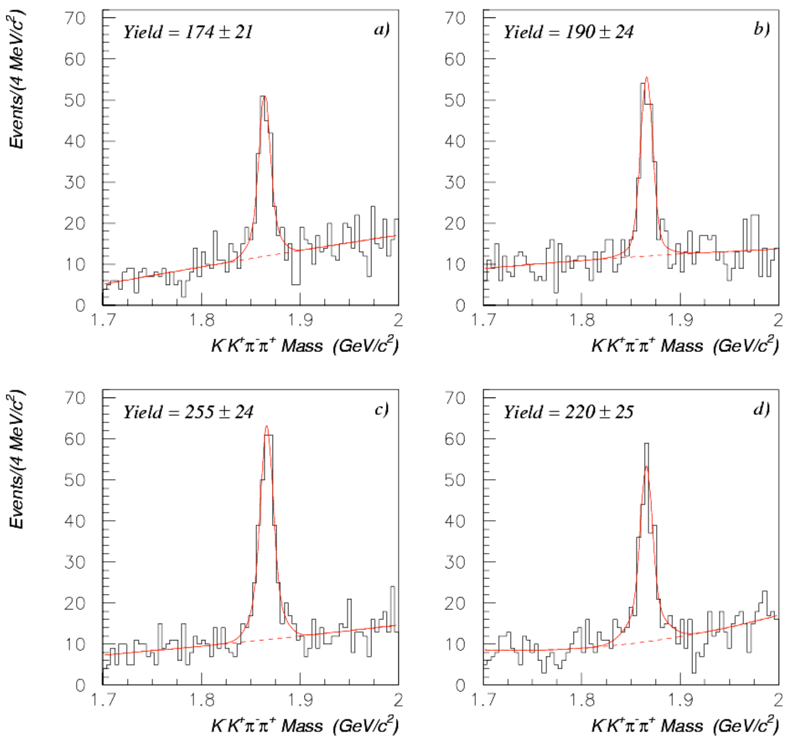
$$\overline{C}_T = \left\langle \vec{p}_{K^-} \bullet (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \right\rangle$$

Finding $C_T \neq -\overline{C}_T$ establishes CP violation

Focus

Preliminary results on T Violation
In three charm decay modes

Use $D^{*+} \rightarrow D^0 \pi^+$ to distinguish D^0 from $\overline{D}^0$



$D^0 \rightarrow K^- K^+ \pi^+ \pi^-$,

$D^+(D_s) \rightarrow K^0 K^+ \pi^+ \pi^-$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

$$\bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

$$A_{Tviol} = 1/2(A_T - \bar{A}_T)$$

$A_{Tviol}(D^0) = 0.010 \pm 0.057(stat) \pm 0.037(syst)$

$A_{Tviol}(D^+) = 0.023 \pm 0.062(stat) \pm 0.022(syst)$

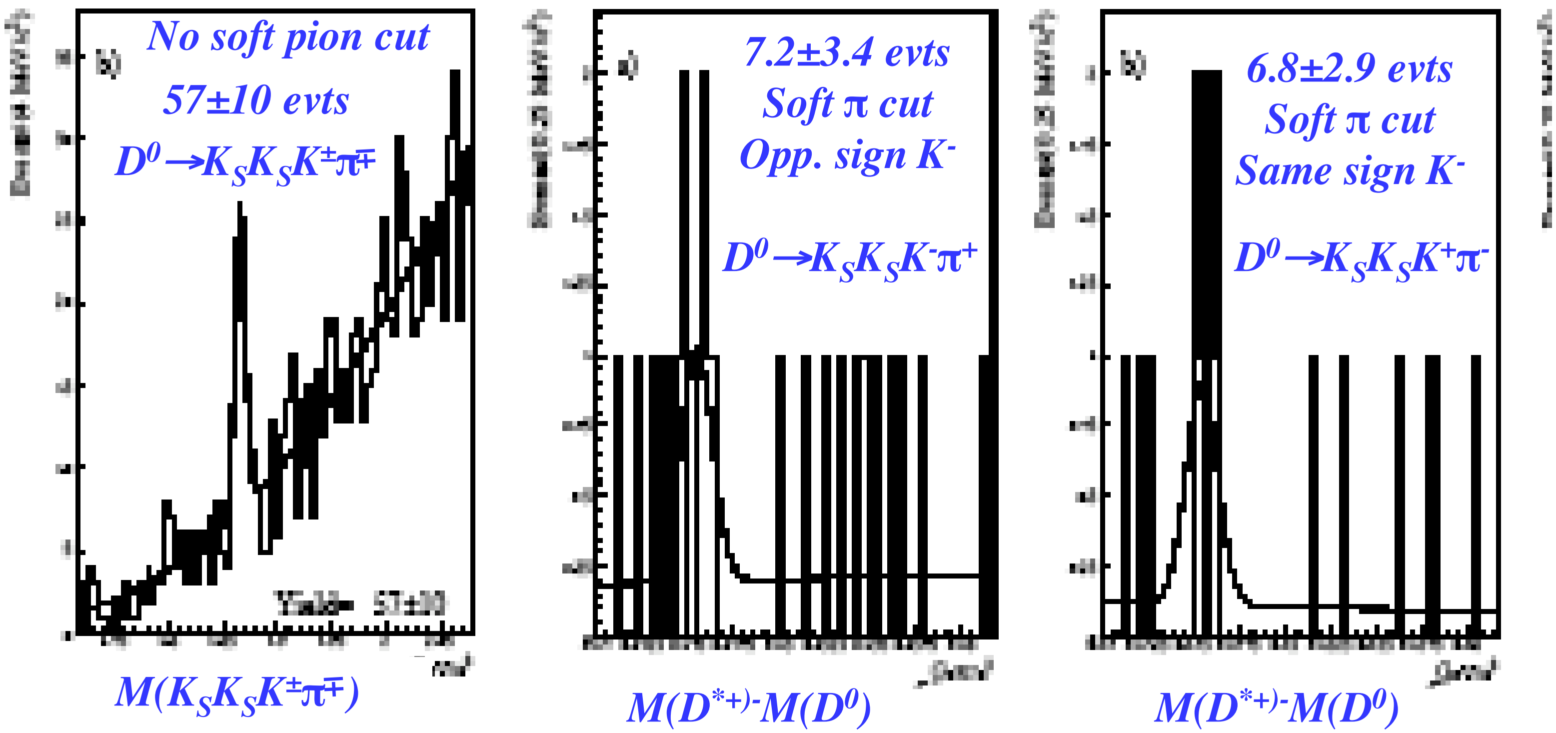
$A_{Tviol}(D_s) = -0.036 \pm 0.067(stat) \pm 0.023(syst)$

No evidence of T violation

Focus

Observation of $D_0 \to K_S K_S X$ decay channels

First Observation of $D^0 \to K_S K_S K^{\pm}\pi^{\mp}$

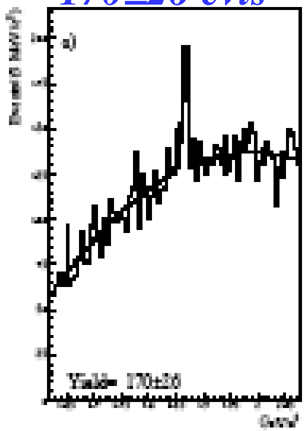


Separation of $D^0 \to K^0_S K^0_S K^+\pi^-$ and $D^0 \to K^0_S K^0_S K^-\pi^+$
By use of the charge of the soft pion from $D^+ \to D^0\pi$ decay

Focus

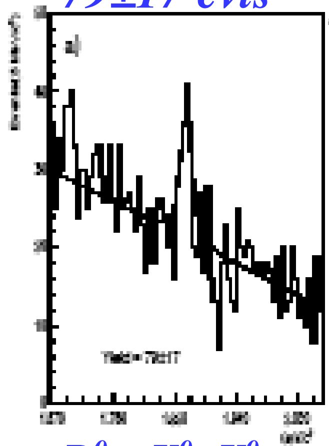
Other $D^0 \rightarrow K_s K_s X$ modes

170±26 evts



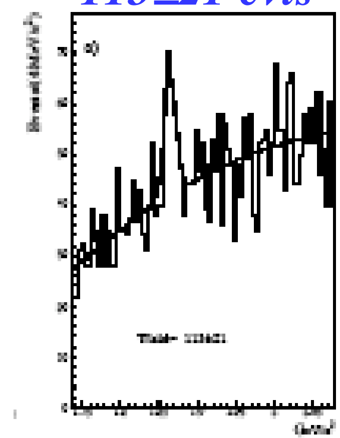
$D^0 \rightarrow K^0_S K^0_S K^0_S$

79±17 evts



$D^0 \rightarrow K^0_S K^0_S$

113±21 evts

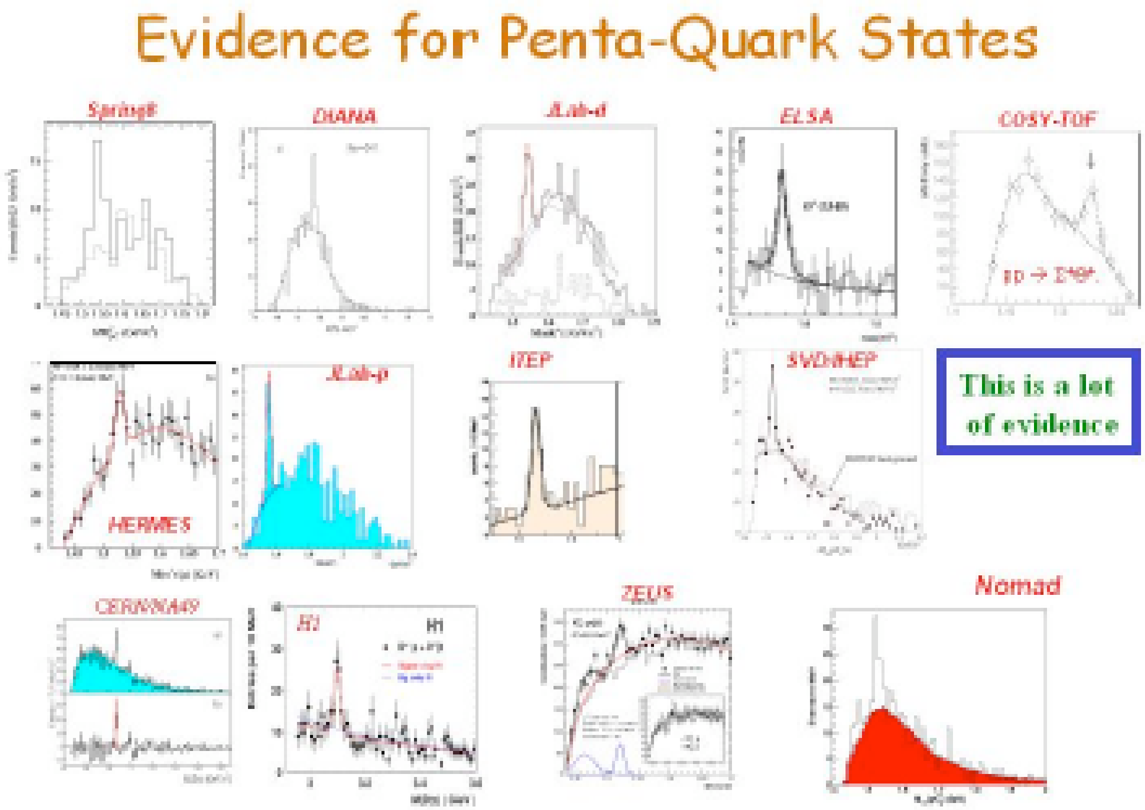


$D^0 \rightarrow K_S K_S \pi^+ \pi^-$

Decay Mode	This experiment	PDG 2004
$\frac{\Gamma(D^0 \rightarrow K^0_s K^0_S K^\pm \pi^\mp)}{\Gamma(D^0 \rightarrow \overline{K}^0 \pi^+ \pi^-)}$	0.0106±0.0019±0.0010	
$\frac{\Gamma(D^0 \rightarrow K^0_s K^0_S K^0_S)}{\Gamma(D^0 \rightarrow \overline{K}^0 \pi^+ \pi^-)}$	0.0179±0.0027±0.0026	0.0154±0.0025
$\frac{\Gamma(D^0 \rightarrow K^0 \overline{K}^0)}{\Gamma(D^0 \rightarrow \overline{K}^0 \pi^+ \pi^-)}$	0.0144±0.0032±0.0016	0.0119±0.0033
$\frac{\Gamma(D^0 \rightarrow K^0_s K^0_S \pi^\pm \pi^\mp)}{\Gamma(D^0 \rightarrow \overline{K}^0 \pi^+ \pi^-)}$	0.0208±0.0035±0.0021	0.031±0.010±0.008

Focus

Search for the Pentaquark



Focus

Search for the Pentaquark

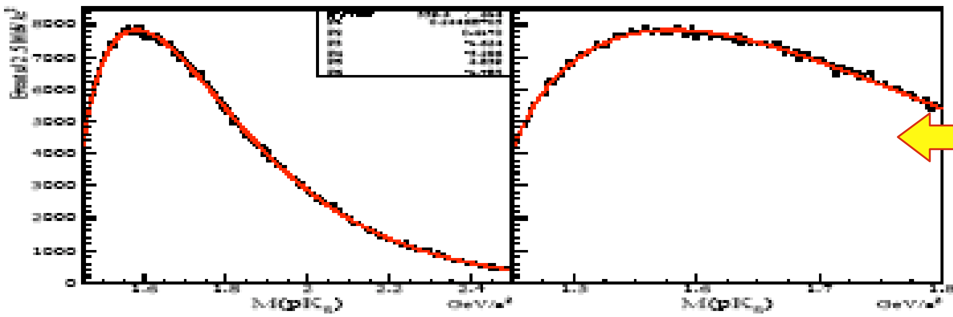
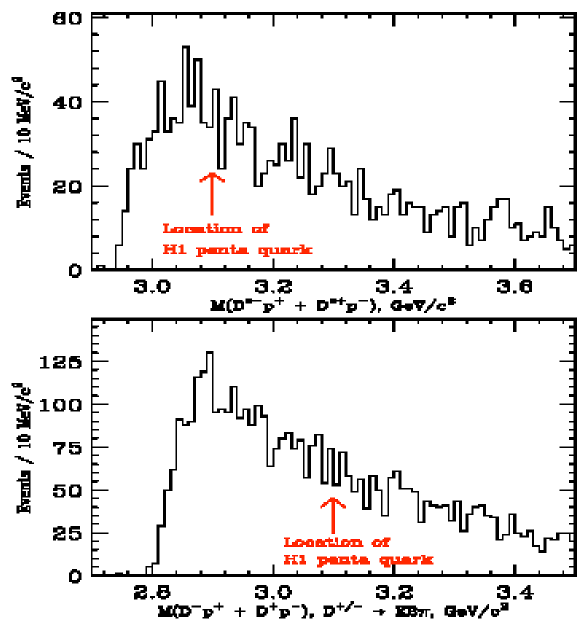
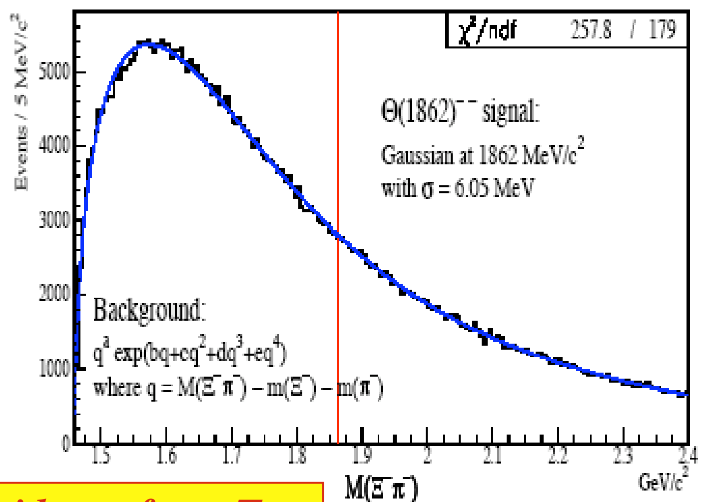


Fig. 1. Fit to $M(pK^0_S)$ in search for $\Theta(1540)^+ \to pK^0_S$.

No evidence for a pK^0_S state at 1540 MeV/c^2



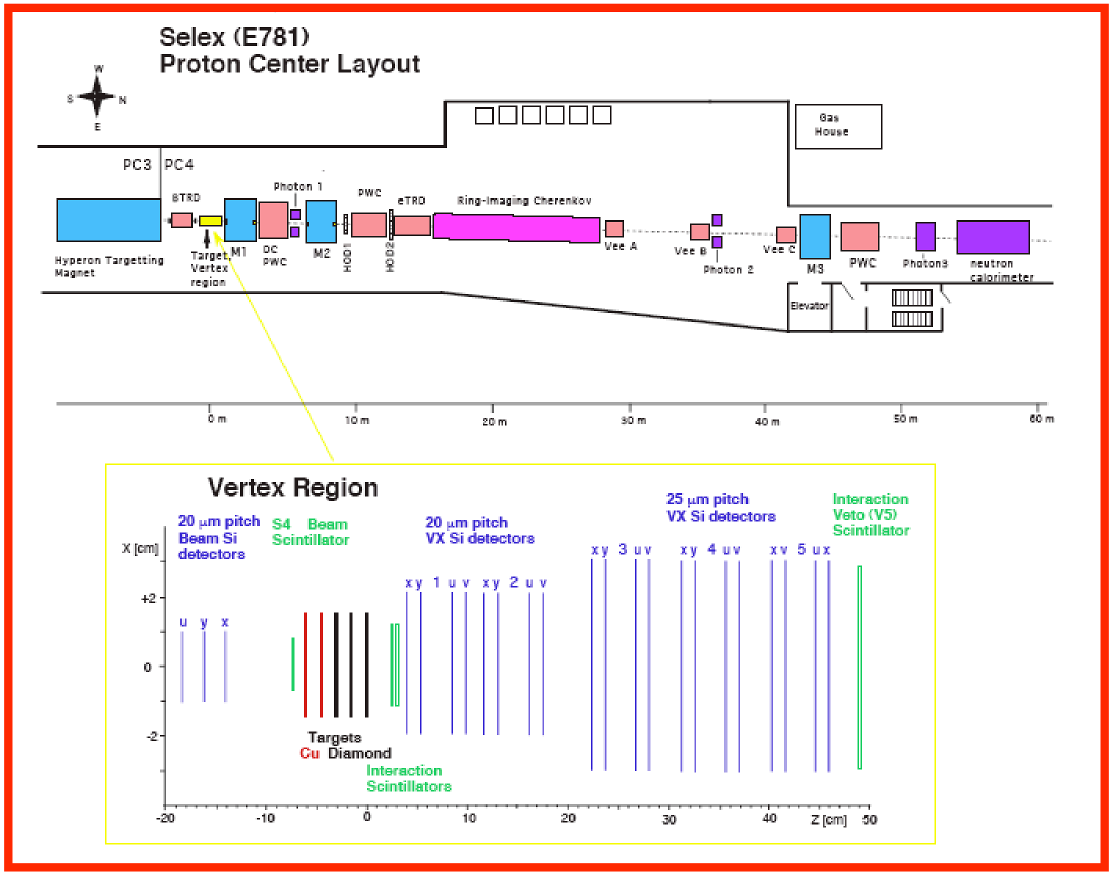


No evidence for a $\Xi^-\pi^-$ state at 1862 MeV/c^2

No evidence for a $D^{\pm}p^{\mp}$ or $D^{*\pm}\,p^{\mp}$ state at 3.1 GeV/c^2

Selex

4 papers in 2004-05



I. Observation of the Ξ^+_{cc} Double Charm Baryon

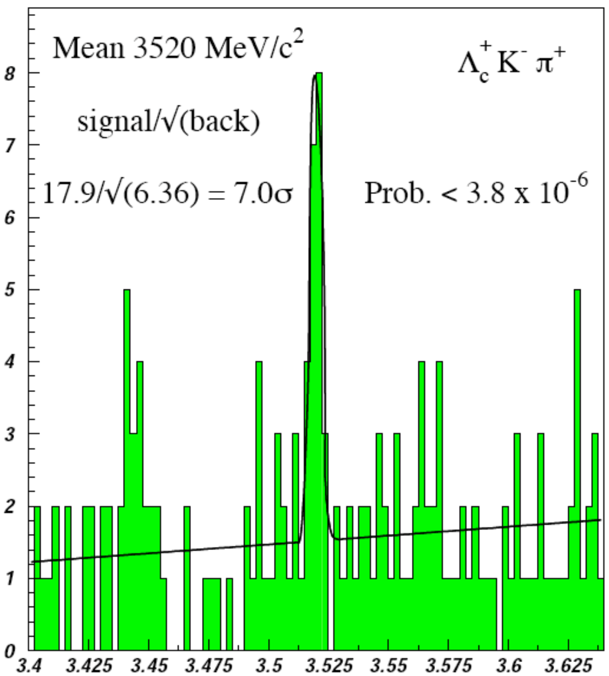
II. Observation of $D_s(2632)$

III. Ω_c lifetime

An original experiment using an original Σ^- and π^- and proton beam

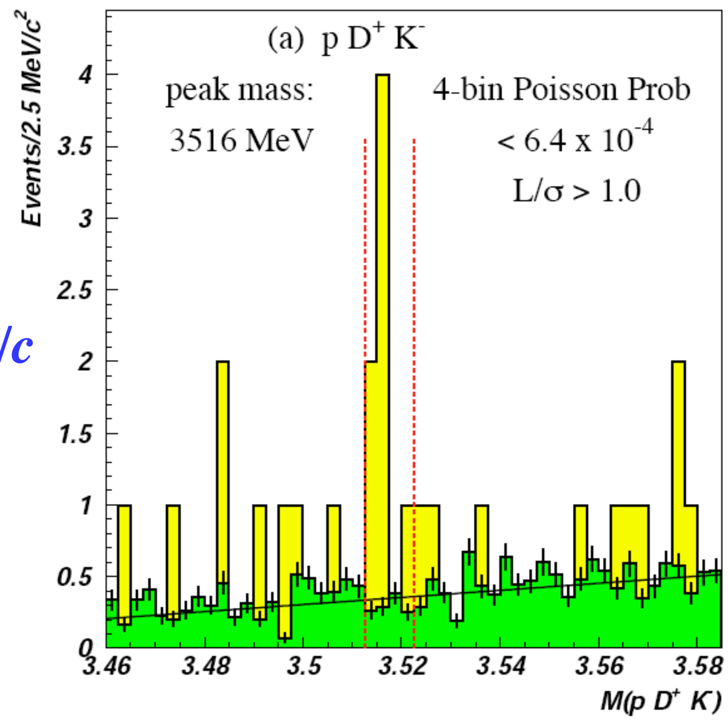
Selex

Observation of the Doubly Charm Ξ^{+}_{cc} baryon



$\Xi^{+}_{cc} \rightarrow \Lambda K^{-}\pi^{+}$

Using the 600 GeV/c Hyperon Beam

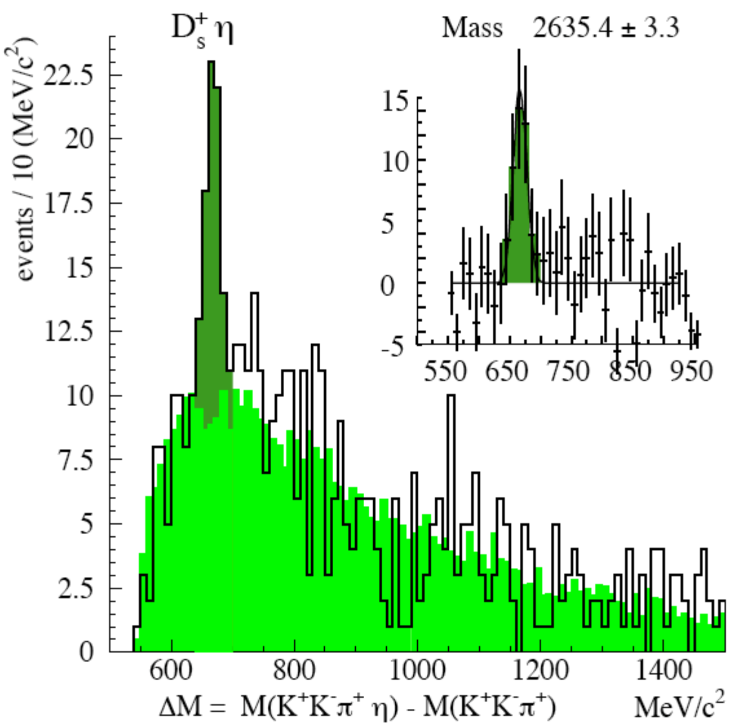


$\Xi^{+}_{cc} \rightarrow pD^{+}K^{-}$

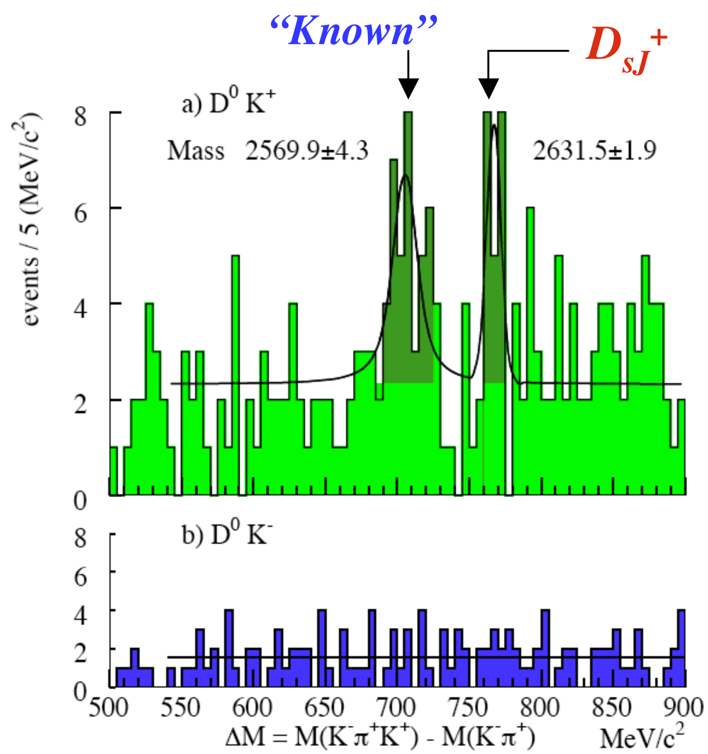
Mass Ξ^{+}_{cc} = 3518±1.7 MeV/c²

Selex

Observation of the Narrow Charm-Strange Meson $D_{sJ}^{+}(2632)$



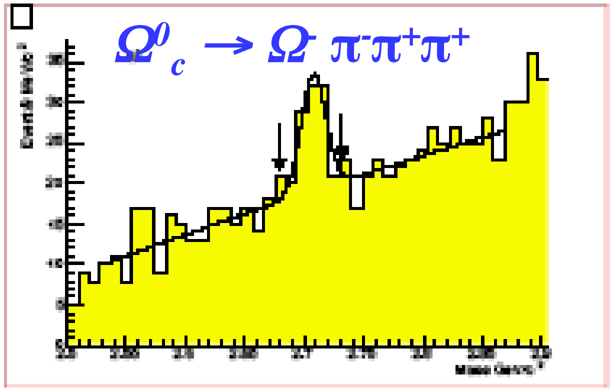
$D_{sJ}^{+} \rightarrow D^{+}_{s}\eta$

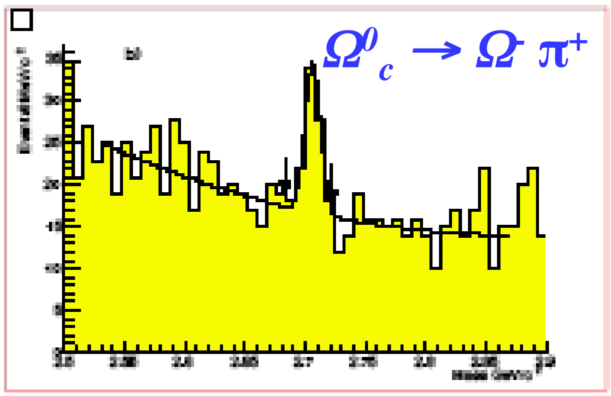


$D_{sJ}^{+} \rightarrow D^{0}K^{+}$

Selex

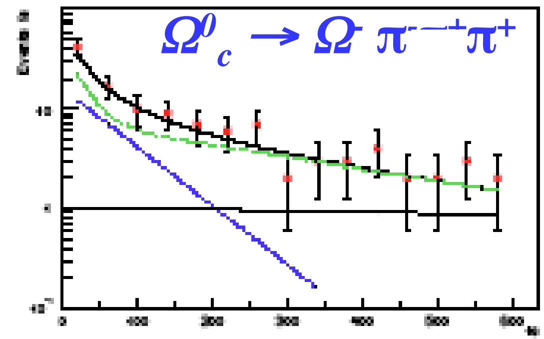
The Ω^0_c *lifetime*

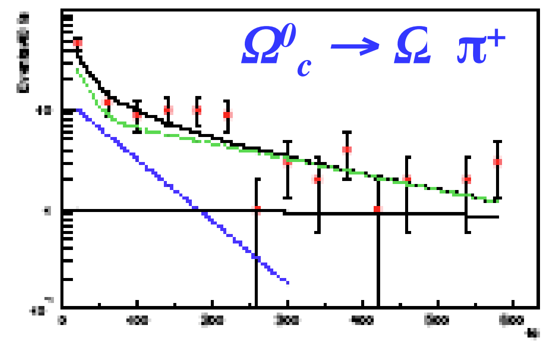




Using
83±19 events from

$\Omega^0_c \to \Omega^- \pi^-\pi^+\pi^+$
$\Omega^0_c \to \Omega^- \pi^+$

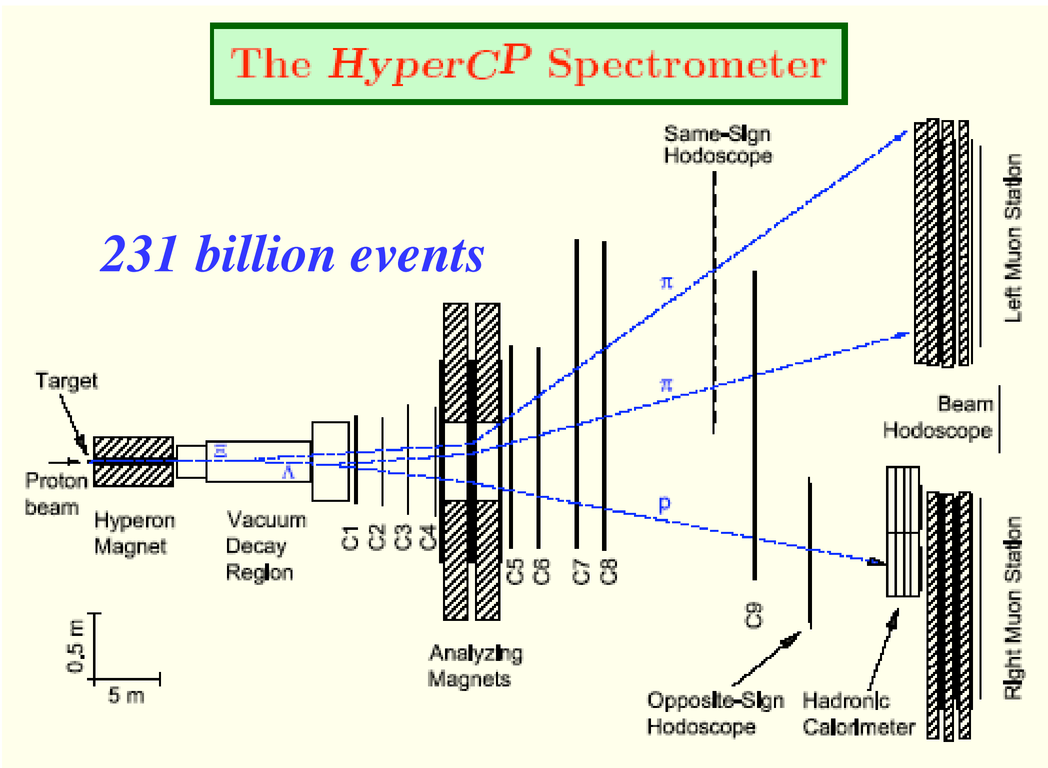




$\tau(\Omega^0_c) = 69.3 \pm 14.4(stat) \pm 8.69 syst.)\ fs$

HyperCP

6 papers in 2004-05



231 billion events

I. Search for novel CP violation in Ξ^- and Λ decay

II. Evidence for the decay $\Sigma^+ \rightarrow p\mu^+\mu^-$

III. Search for the pentaquark

IV. First Observation of parity violation in $\Omega^- \rightarrow \Lambda K^-$ decays

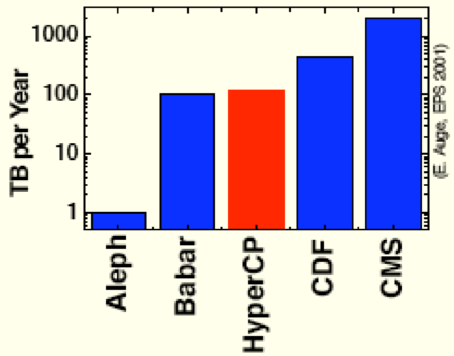
V. Measurement of the parameter α for the $\Omega^- \rightarrow \Lambda K^-$ decay

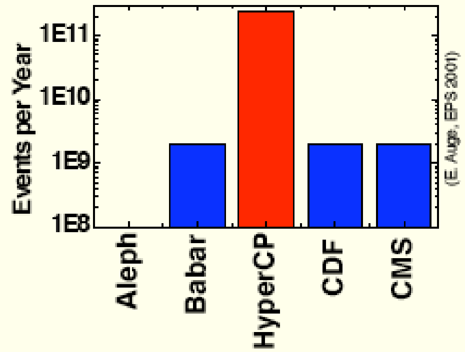
An original, unique and very high rate hyperon experiment

HyperCP

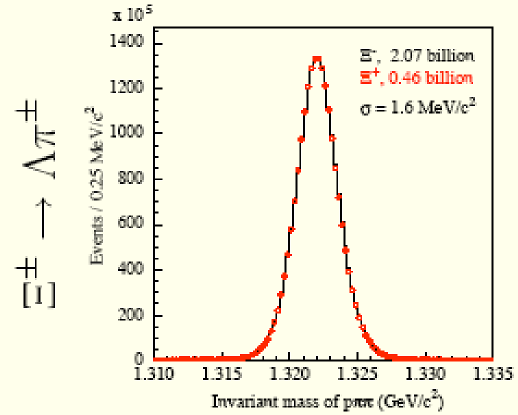
A very high rate experiment

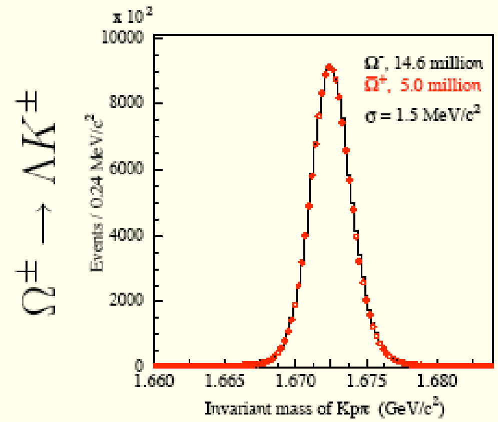
- In 12 months of data taking *HyperCP* recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data





Entire WWW on 9/11/01 was 5 TB!





Reconstructed Events

Type	Channeled beam polarity +	Channeled beam polarity −	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

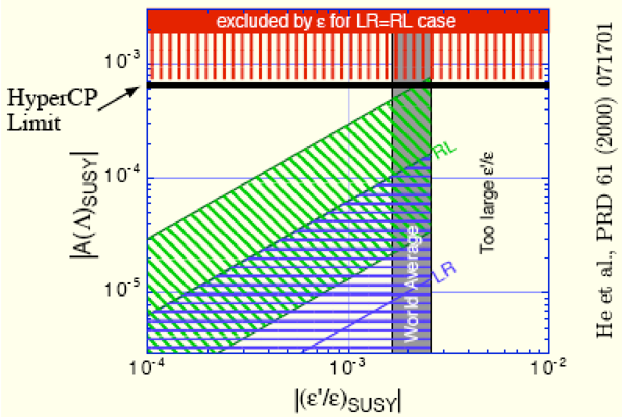
Think back to the discovery of the Ω⁻ in the 80" bubble chamber

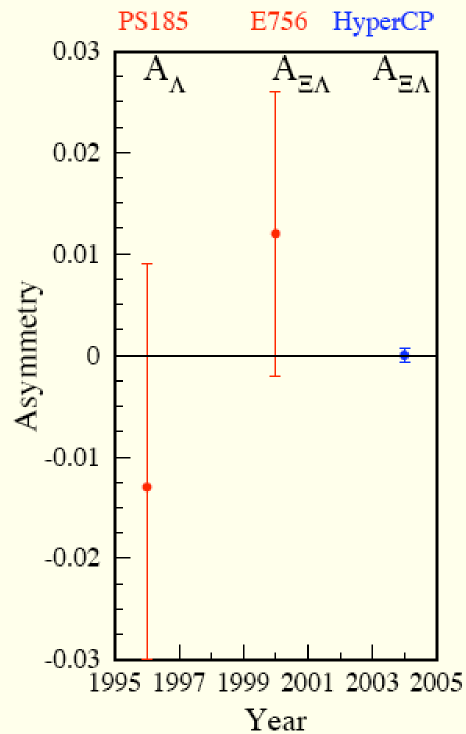
HyperCP

CP violation Search in charged Ξ⁻ Decay

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda} = [0.0\pm5.1(\text{stat})\pm4.4(\text{syst})]\times10^{-4}$$

- ~10% total data sample.
- 118.6 million Ξ^-, 41.9 million Ξ^+.
- Expect 3× improvement with full dataset.
- Constraining beyond-the-standard-model predictions which are not well constrained by kaon *CP* measurements as hyperons probe both parity conserving and parity violating amplitudes.



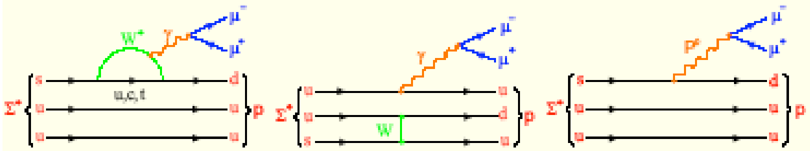


PRL **93**, 262001 (2004).

Most sensitive search for CP violation in hyperon decays by a factor of 20

HyperCP

Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$



- Three events represent the rarest decay of a baryon ever observed:

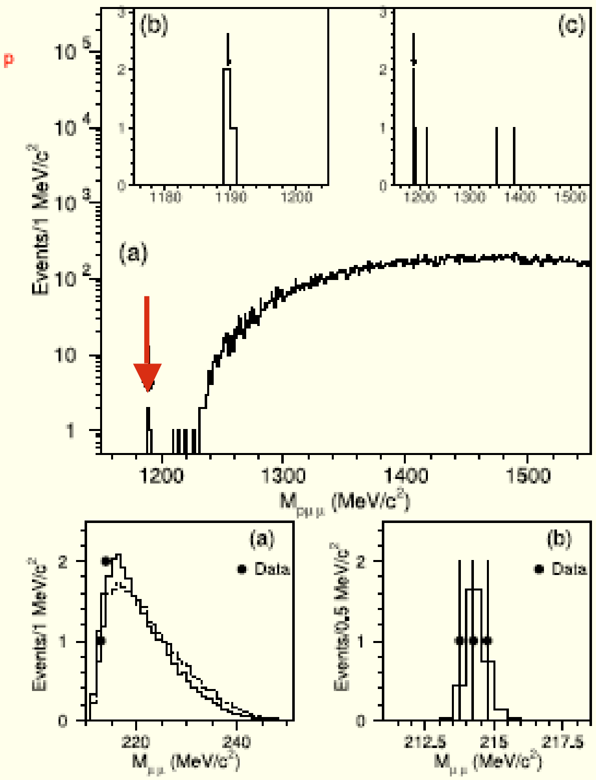
$$\frac{B(\Sigma^+ \to p\mu^+\mu^-)}{B(\Sigma^+ \to \text{all})} = [8.6^{+6.6}_{-5.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}$$

- Narrow dimuon mass, $m = 214.3 \pm 0.5$ MeV, suggests decay procedes via hitherto unknown particle: could it be the pseudoscalar sgoldstino of Gorbunov and Rubakov?

$$\Sigma^+ \to pP^0 \to p\mu^+\mu^-$$

- PRL **94**, 021801 (2005)

→ This needs to be confirmed!

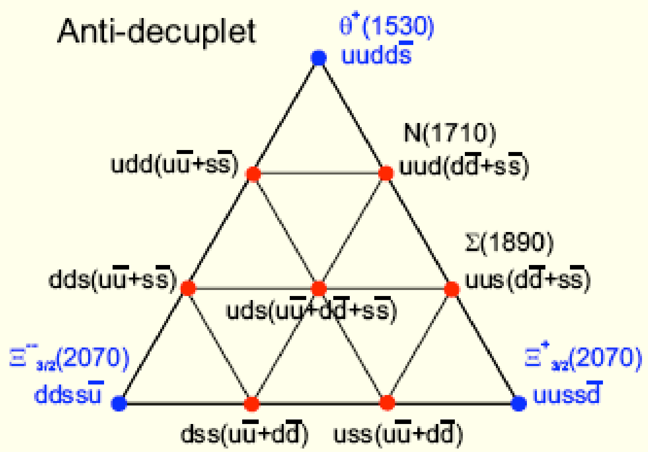


Observation of rarest baryon decay to date

HyperCP

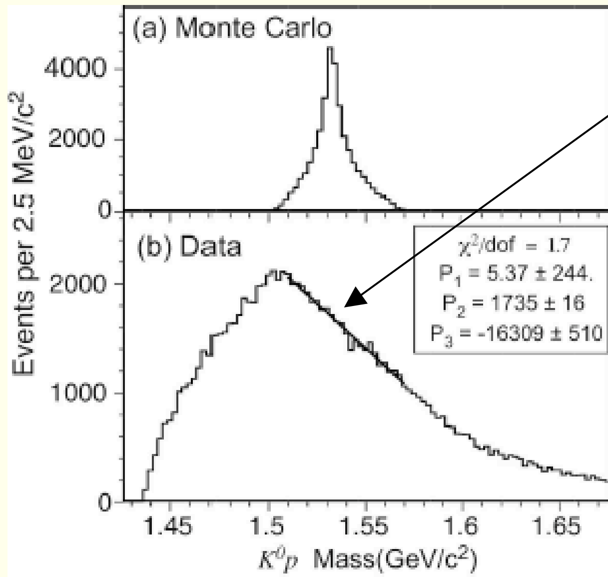
Search for the $\theta^+(1.54)$ pentaquark

- Pentaquark: exotic five-quark particle predicted by Diakonov et al. in 1997.



- Three states in Anti-decuplet have exotic quantum numbers: $\theta^+(1530)$, $\Xi^+_{3/2}(2070)$, $\Xi^-_{3/2}(2070)$
- Many reports of pentaquark states in 2003–2004.

- Search mode: $pN \to \theta^+\Lambda$, $\theta^+ \to K_S p$, $\Lambda \to p\pi^-$, $K_S \to \pi^+\pi^-$
- *HyperCP*: excellent mass resolution largest K_S sample ever taken.
- One of the first of many null results.
- PRD **70**, 111101(R) (2004).

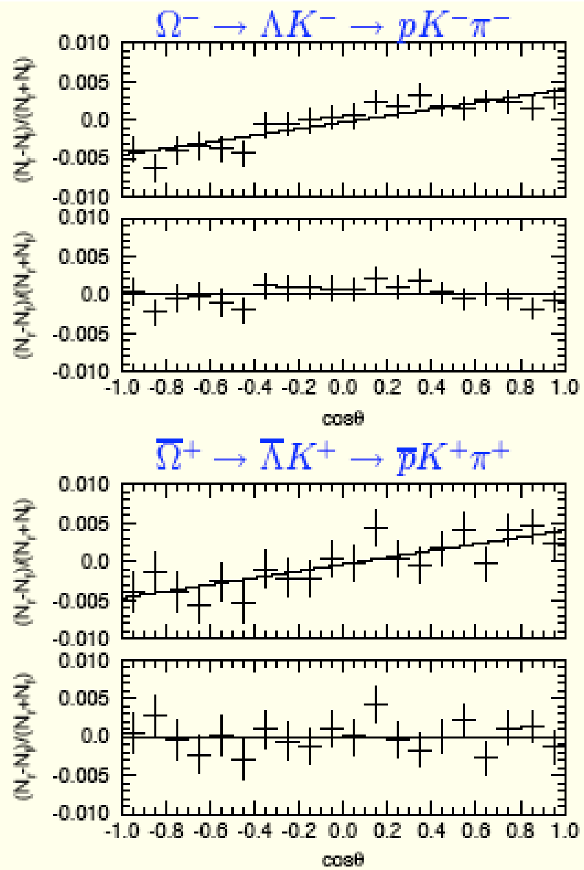


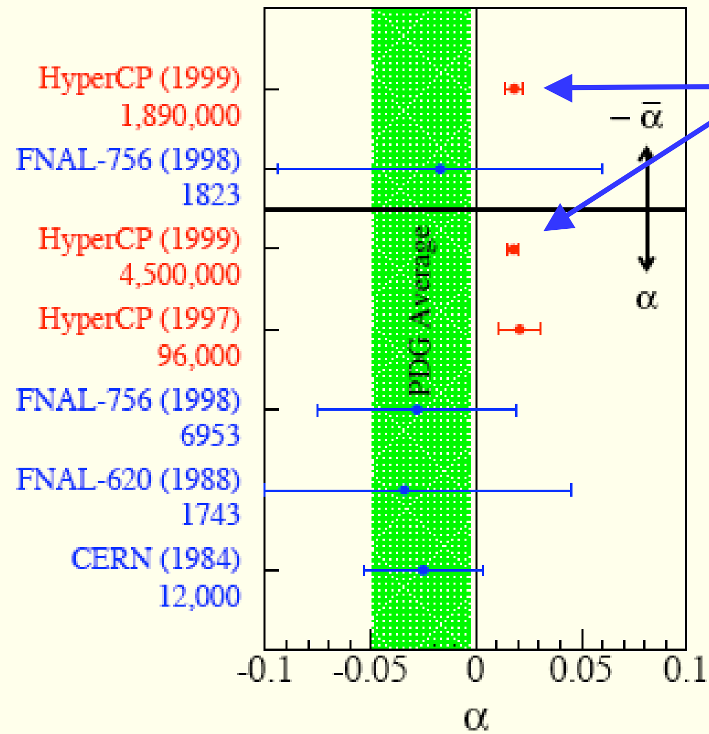
No evidence for the pentaquark $\theta^+(1530) \to K^0{}_s p$

Very high statistics pentaquark search and one of the early null results

HyperCP

First Observation of Parity Violation in $\Omega^- \to \Lambda K^-$ decays



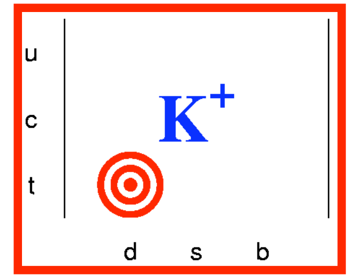


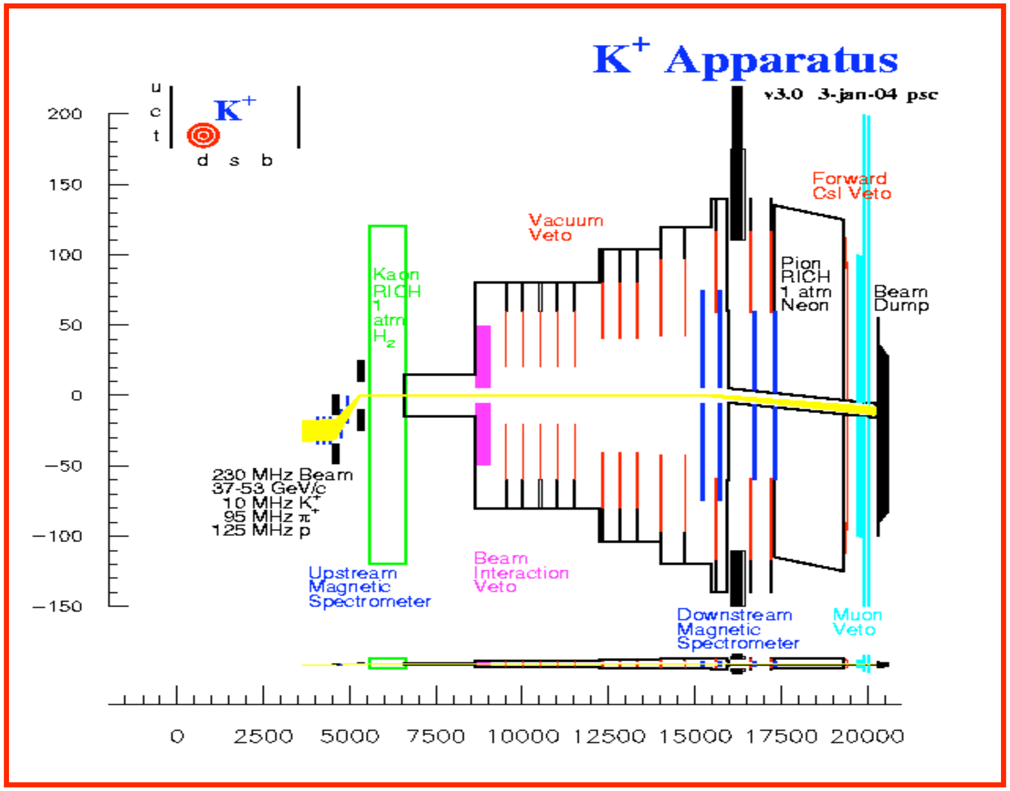
Note the very precise measurement of α and $\overline{\alpha}$ for the Ω^- and $\overline{\Omega}^+$

- No evidence of *CP* violation in $\Omega^-/\overline{\Omega}^+$ decays.
- Most precisely know alpha parameter.
- 97: PRD **71**, 051102(R) (2005)
- 99: to appear in PLB

Kplus

The future???





Objective: A measurement of $K^+ \to \pi^+ \nu\nu$

Will NOT be done at Fermilab

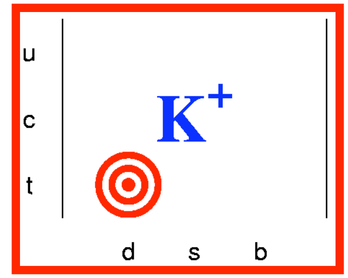
Outsourced to Europe??
CERN (NA48)

Will the US be allowed to participate??

$BR(K^+ \to \pi^+ \nu\nu) \sim 10^{-10}$

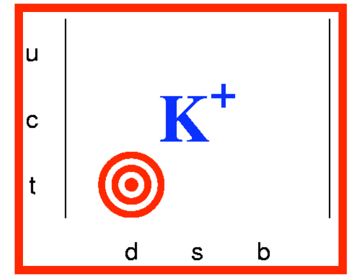
Unseparated beam

Kplus



"The Physics is Compelling…"
Fermilab PAC
April 2005

- ***B physics has been probed at the scale of λ^2 and λ^3 and there is no clear evidence today for new physics.***
- ***$K \rightarrow \pi\nu\nu$ decays are highly suppressed (λ^5) and represent an unexplored window for new physics that could be relatively large in $s \rightarrow d$ transitions.***
- ***New physics at the LHC will unfold like the top-quark discovery…evidence for new states but little information about the new flavor structure.***



Kplus

Pro's/Con's for FNAL

***Pro**: # of weeks per yr of neutrino Running allows longer running time for parallel fixed target running*

***Con**: neutrino running permits no time for parallel fixed target running*

***Pro**: 230 Mhz unseparated beam rate And longer running time allows much lower rate on beam ID/tracking*

***Con**: 35-50 GeV/c beam has 4% K^+*

Pro's/Con's for CERN

***Con**: fewer # of weeks per yr of running*

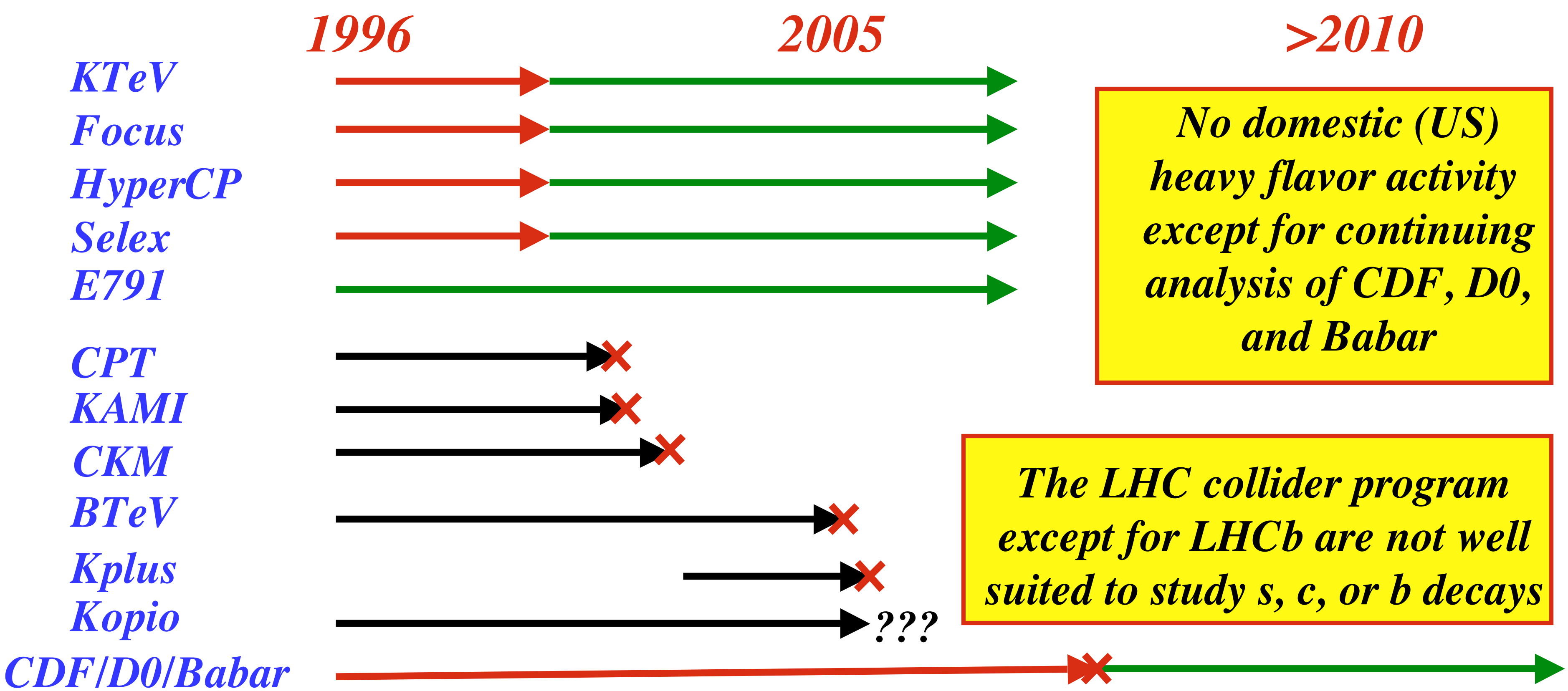
***Pro**: support of CERN and the European community*

***Con**: 800 Mhz unseparated beam rate and shorter running time results in much higher rate on beam ID/tracking*

***Pro**: 75 GeV/c beam has 6% K^+*

Overview of the evolution (intelligent design?) of the "domestic" flavor program

In preparation — black
Running — red
In analysis — green



No domestic (US) heavy flavor activity except for continuing analysis of CDF, D0, and Babar

The LHC collider program except for LHCb are not well suited to study s, c, or b decays

Only LHCb, BES-III, JPARC $K_L \rightarrow \pi^0 \nu\nu$ (and perhaps NA48 $K^+ \rightarrow \pi^+ \nu\nu$??) left standing

Summary

- *The Fermilab (and US) fixed target flavor program has had a long and fruitful history with many outstanding discoveries such as the b quark.*
- *The latest iteration of that program has continued that tradition with the CPV and other kaon decay measurements of KTeV, the charm discoveries and measurements of Focus and E791, the intriguing states observed for the first time by HyperCP and Selex, work that will not be confirmed.*
- *An important observation is that all of these experiments are still vigorously analyzing data and will be for some number of years as evidenced by the 22 PRL's, PRD's and Phys Letters produced this year alone*
- *The future participation of US physicists in strange, charm and beauty flavor physics seems problematic with the demise of Kami, CKM, and BTeV and the outsourcing of Kplus to CERN, the truncated running of Babar, uncertainty of KOPIO's future and the limits on US participation in LHCb*

If full participation in off shore experiments. is supported, then there can be a future for US physicists in strange, charm and beauty physics!