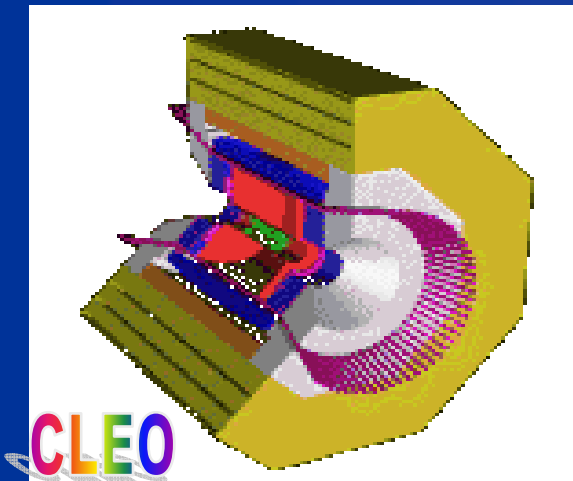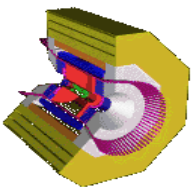# Hadronic decays and cross-sections at Ψ'' from CLEO-c

Yongsheng Gao

Southern Methodist University

(CLEO Collaboration)

HEP2005, Lisbon, Jul. 21 − 27, 2005

Preliminary CLEO results

Absolute D hadronic BR & $\Psi'' \rightarrow$ DD cross-section
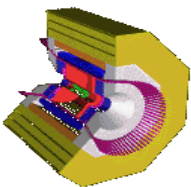(**55.8 pb^{-1}** , **CLNS 05/1904, submitted to PRL**)

Inclusive production of η, η', Φ in D decays
(**281 pb^{-1}**, **CLEO CONF 05-4**)

BF measurement of $D^+ \rightarrow K^0_s/K^0_L \, \pi^+$
(**281 pb^{-1}**)   **Shown for the first time**

$\Psi'' \rightarrow$ non DD final states (VP, multi-body)
(**281 pb^{-1}, 55.8 pb^{-1}**, **CLEO CONF 05-1, CLNS 05/1921**)

p and K time-like form factors at $\sqrt{s}$ = 3.671 GeV
(**20.7 pb^{-1}**, **CLEO CONF 05-9**)

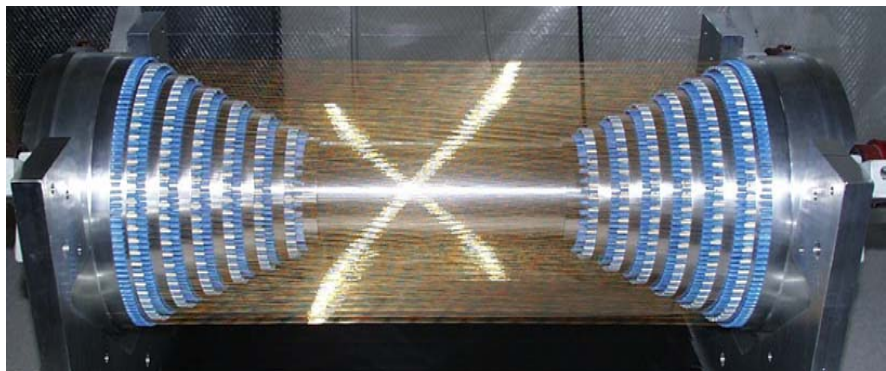# CESR-c
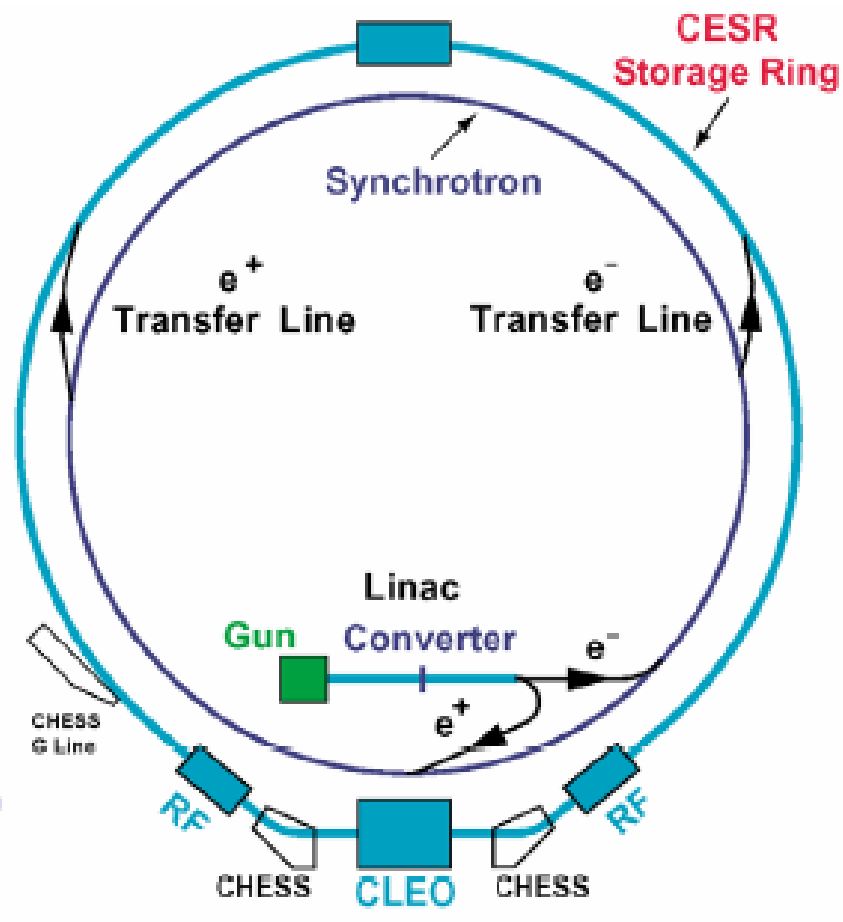
E_{beam} = 1.5 – 5.6 GeV

CLEO-c Detector & Data

CLEO-c

2230104-002

Labels: Solenoid Coil, Barrel Calorimeter, Ring Imaging Cherenkov Detector, Drift Chamber, Inner Drift Chamber, Beampipe, SC Quadrupole Pylon, SC Quadrupoles, Rare Earth Quadrupole, Magnet Iron, Barrel Muon Chambers, Iron Polepiece, Endcap Calorimeter
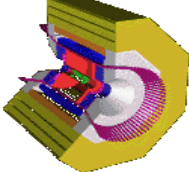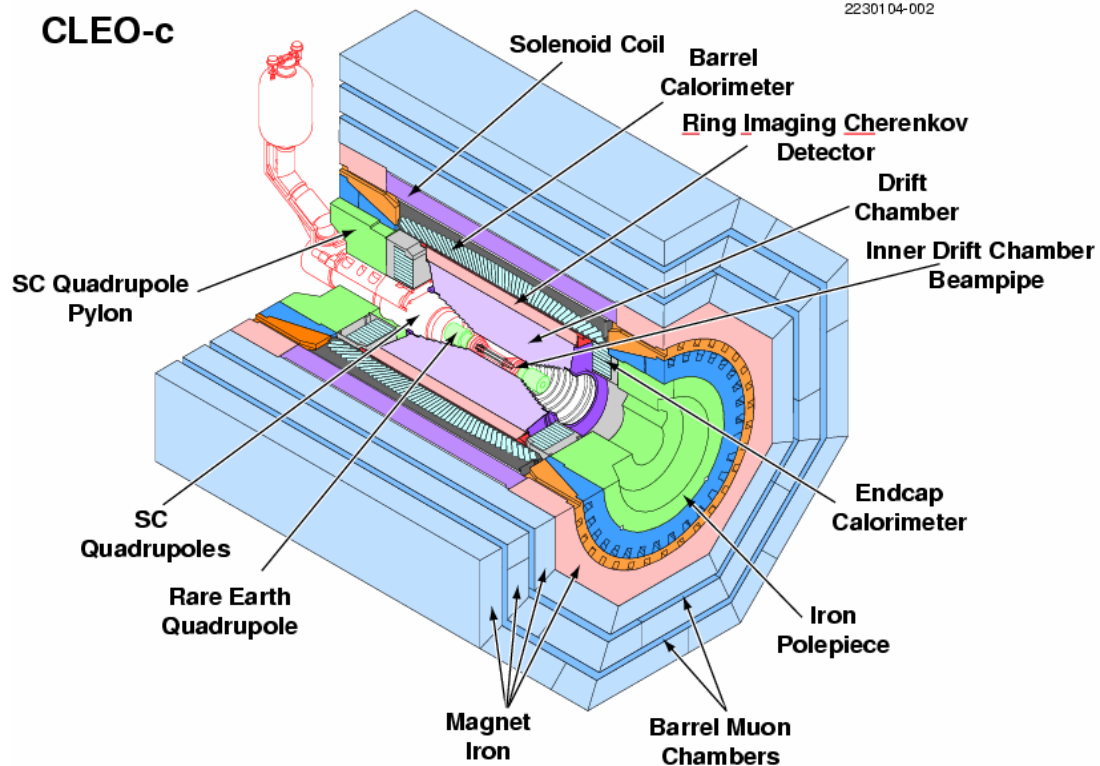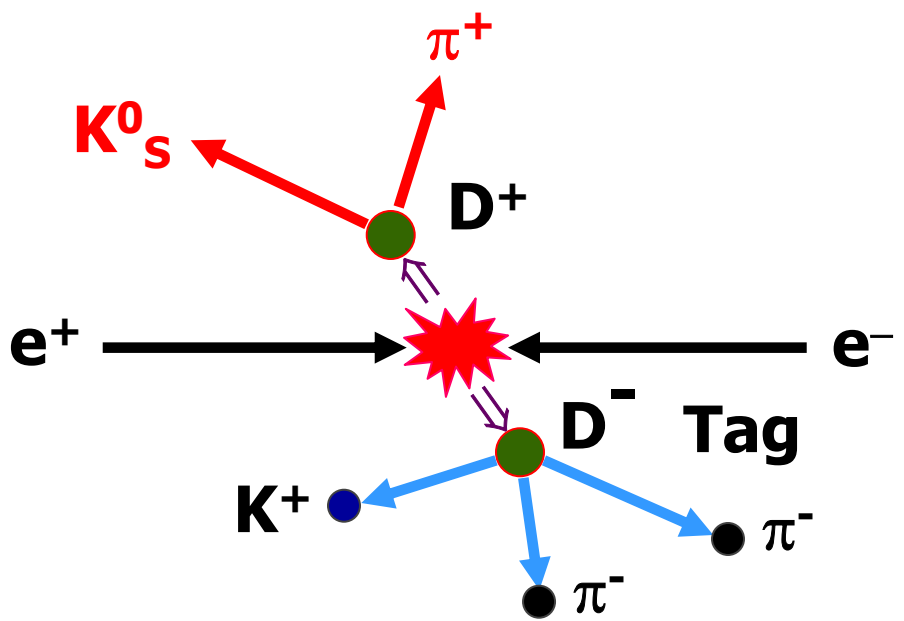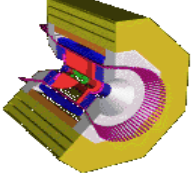
- **New inner drift chamber replaced old silicon vertex**

- **1T B field (old 1.5 T)**

- **Track (93% of 4π): σ = 0.6% @ 1 GeV**

- **PID: Rich (80% of 4π), dE/dx, EM calorimeter, muon (> 1GeV)**

- **E_γ: σ = 2.2% @ 1 GeV, 5% @ 100MeV.**

CLEO-c $\cong$ CLEO III
281 pb^{-1} at ψ(3770)

ψ(3770) Analysis Techniques

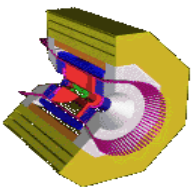## The MARK III Method

Fully reconstruct 1st D "the tag", then analyze decay of 2nd D to extract exclusive or inclusive properties.

$$\Delta E = E(D) - E_{\text{beam}}$$

$$M_{BC} = \sqrt{E_{\text{beam}}^2 - \left| p(D) \right|^2}$$

ψ(3770) ~ DDbar threshold

➔ No extra fragmentation = simpler geometry / combination

➔ Clean neutrino reconstruction

➔ High tagging efficiency at 25% of all D's produced.

Absolute Hadronic D Decay BRs

Many current measurements determined with respect to reference modes: $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$

Input to many measurements (*e.g.* V_{cb} from $B \rightarrow D^* l \nu$)
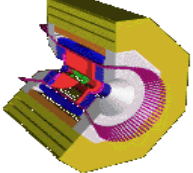
CLEO-c at $\psi(3770)$ provides:

- **Absolute/relative precise measurements**
- **Most precise measurement of D hadronic BRs**

Much easier to do at threshold and in pairs than at 10GeV!

Byproduct: $D\bar{D}$ **production cross sections**
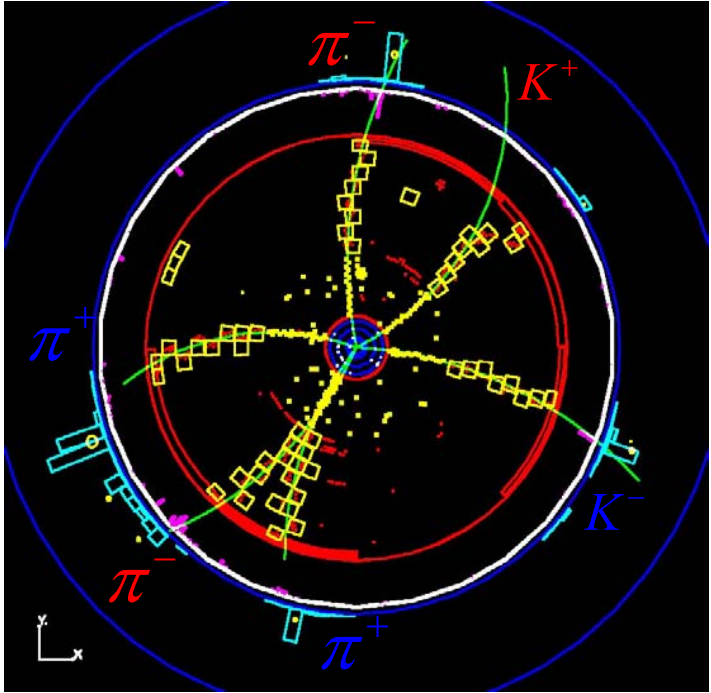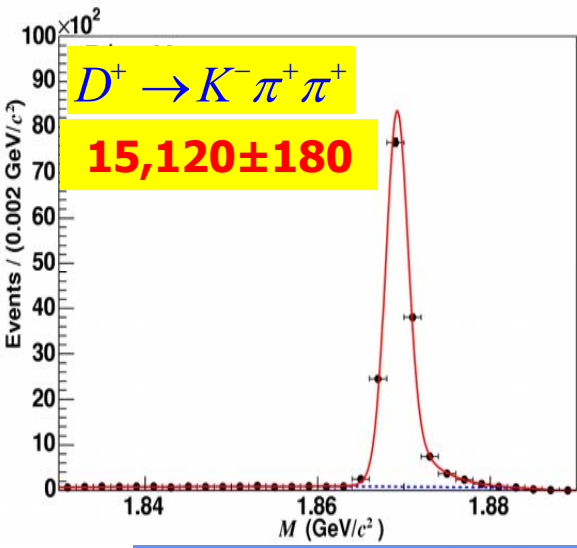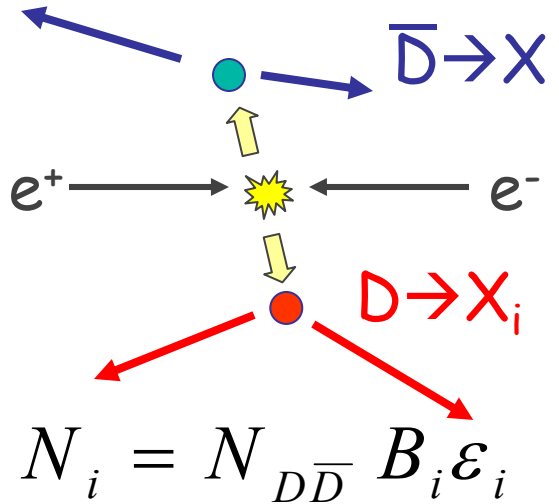
hep-ex/0504003, submitted to PRL (55.8 pb^{-1})

Updated results with 281 pb^{-1} in progress.

Absolute Hadronic D Decay BRs

Single tagged

Double tagged

$\overline{D} \to X$

$D \to X_i$

$\overline{D} \to X_j$

$D \to X_i$

e^+ e^-

e^+ e^-

π^-

K^+

π^+

K^-

π^-

π^+

$$N_i = N_{D\overline{D}} B_i \varepsilon_i$$

$$N_{ij} = N_{D\overline{D}} B_i B_j \varepsilon_{ij}$$

$D^+ \to K^- \pi^+ \pi^+$

15,120±180

$D^+ \to K^- \pi^+ \pi^+,$

$D^- \to K^+ \pi^- \pi^-$

377±20
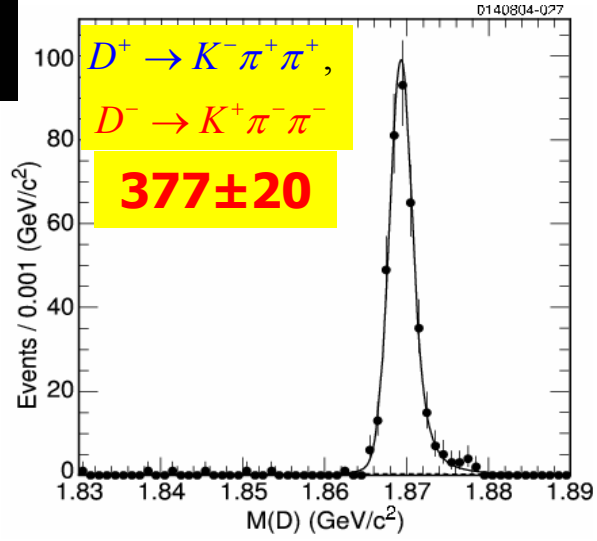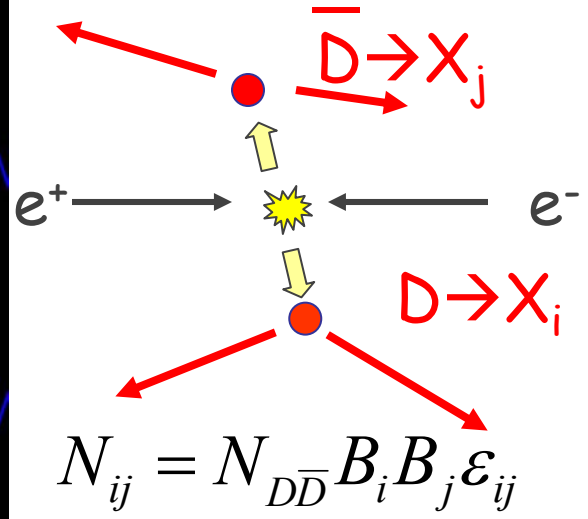
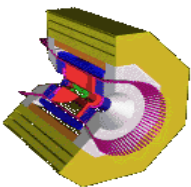$$N_{D\overline{D}} = \frac{N_i N_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

$$B_i = \frac{N_{ij}}{N_j} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

0140804-027

Fitting technique

Simultaneous fit for all BR & cross sections is performed

- **Charged and neutral modes fit simultaneously**

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

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

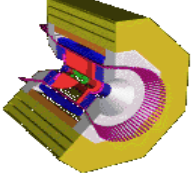$$K_S^0 \pi^+ \pi^0, \ K_S^0 \pi^+ \pi^- \pi^+, \ K^+ K^- \pi^+$$

- **All correlations taken into account**

Efficiencies

- **Denominator of efficiency may be determined using missing mass in data and MC**
  - **Data & MC: 0.7% for charged, 2.0% for π^0, 3.0% for K_S^0**
- **Include effects of final state radiation (FSR)**

W. M. Sun, physics/0503050, CLNS 05/1912, submitted to NIM.

Single/Double Tag Yields

3 D⁰ Modes — $3 \; D^0$ Modes

6 D⁺ Modes — $6 \; D^+$ Modes

$D^0 \to K^- \pi^+$ · $D^+ \to K^- \pi^+ \pi^+$ · $D^+ \to K^0_S \pi^+$

$D^0 \to K^- \pi^+ \pi^0$ · $D^+ \to K^- \pi^+ \pi^+ \pi^0$ · $D^+ \to K^0_S \pi^+ \pi^0$

$D^0 \to K^- \pi^+ \pi^- \pi^+$ · $D^+ \to K^0_S \pi^+ \pi^+ \pi^-$ · $D^+ \to K^- K^+ \pi^+$
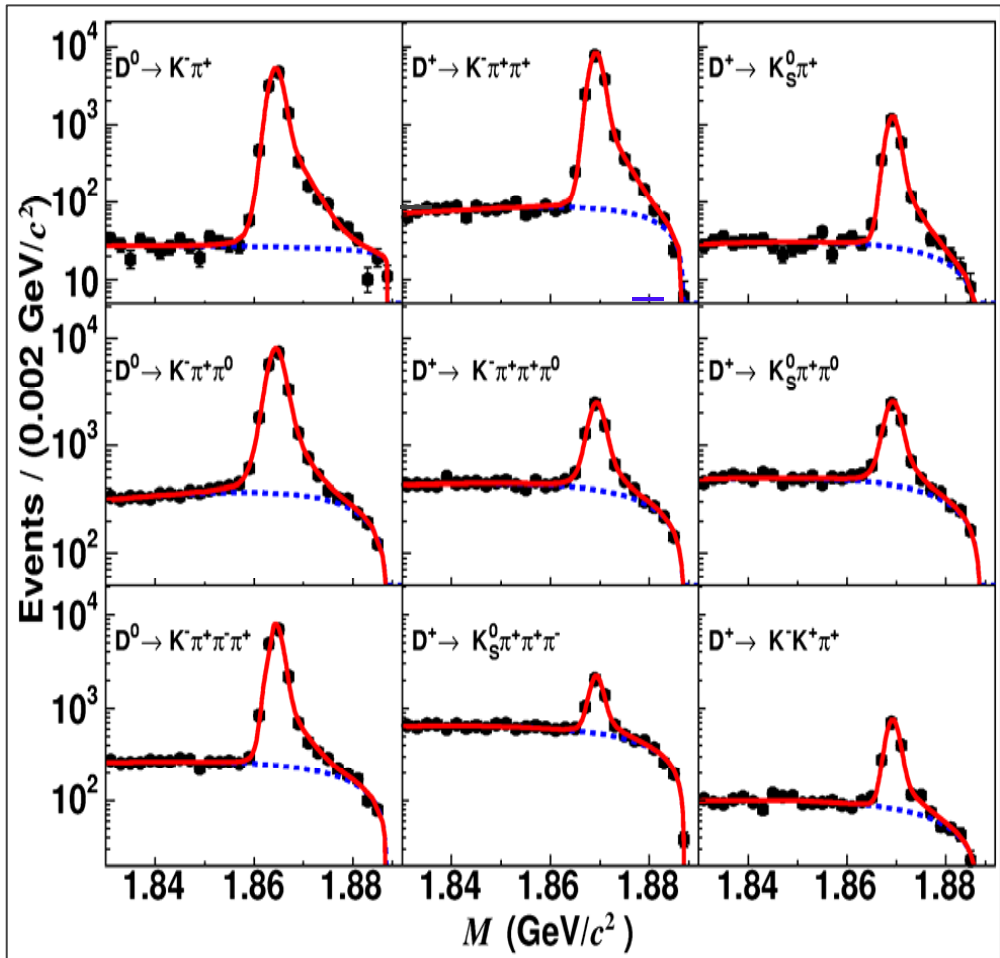
Single Tag (log scale)!

D⁰

2,484±51 (combined)

Double Tag

D⁺

1,650±42 (combined)

Double Tag
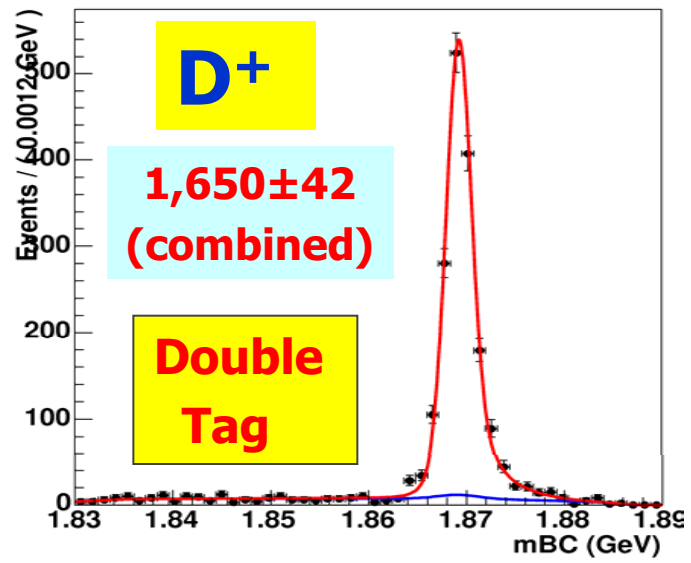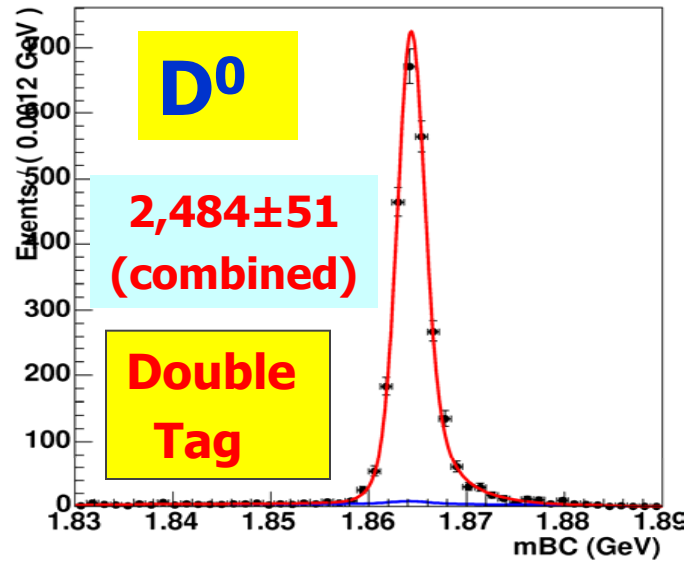
Preliminary, submitted to PRL
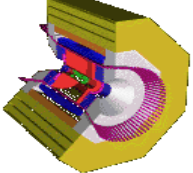
Parameter	Fitted Value (%)
$N(D^0\overline{D^0})$	$(2.006\pm0.038\pm016)\times10^5$
$\mathcal{B}(D^0\to K^-\pi^+)$	$(3.91\pm0.08\pm0.09)$ %
$\mathcal{B}(D^0\to K^-\pi^+\pi^0)$	$(14.94\pm0.30\pm0.47)$ %
$\mathcal{B}(D^0\to K^-\pi^+\pi^+\pi^-)$	$(8.29\pm0.17\pm0.32)$ %

Parameter	Fitted Value (%)
$N(D^+D^-)$	$(1.558\pm0.038\pm012)\times10^5$
$\mathcal{B}(D^+\to K^-\pi^+\pi^+)$	$(9.52\pm0.25\pm0.27)$ %
$\mathcal{B}(D^+\to K^-\pi^+\pi^+\pi^0)$	$(6.04\pm0.18\pm0.22)$ %
$\mathcal{B}(D^+\to K_s\pi^+)$	$(1.55\pm0.05\pm0.06)$ %
$\mathcal{B}(D^+\to K_s\pi^+\pi^0)$	$(7.17\pm0.21\pm0.38)$ %
$\mathcal{B}(D^+\to K_s\pi^+\pi^+\pi^-)$	$(3.20\pm0.11\pm0.16)$ %
$\mathcal{B}(D^+\to K^+K^-\pi^+)$	$(0.97\pm0.04\pm0.04)$ %

$$\frac{\sigma(e^+e^-\to D^+D^-)}{\sigma(e^+e^-\to D^0\overline{D^0})}=0.78\pm0.02\pm0.01$$

$$\sigma(D\bar{D})=6.39\pm0.10^{+0.17}_{-0.08}\ \text{nb}$$
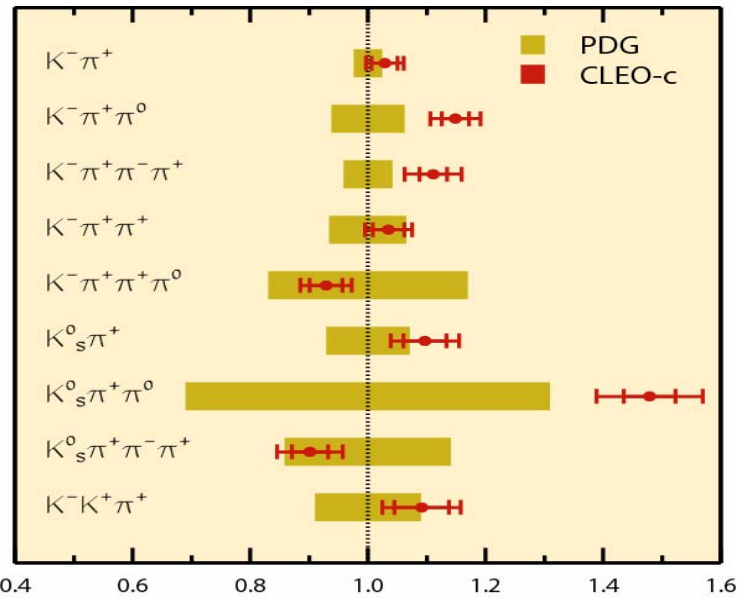
55.8 pb^{-1}

Six modes more precise than PDG.

Normalized to PDG

$\overline{D}^0 \rightarrow K^+ \pi^-$

49,418±246

$\overline{D}^0 \rightarrow K^+ \pi^- \pi^0$

101,960±476

$\overline{D}^0 \rightarrow K^+ \pi^- \pi^- \pi^+$

76,178±306

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

77,387±281

Preliminary

# of events / 0.5MeV

M_{bc}(GeV)

m_{BC} (GeV)
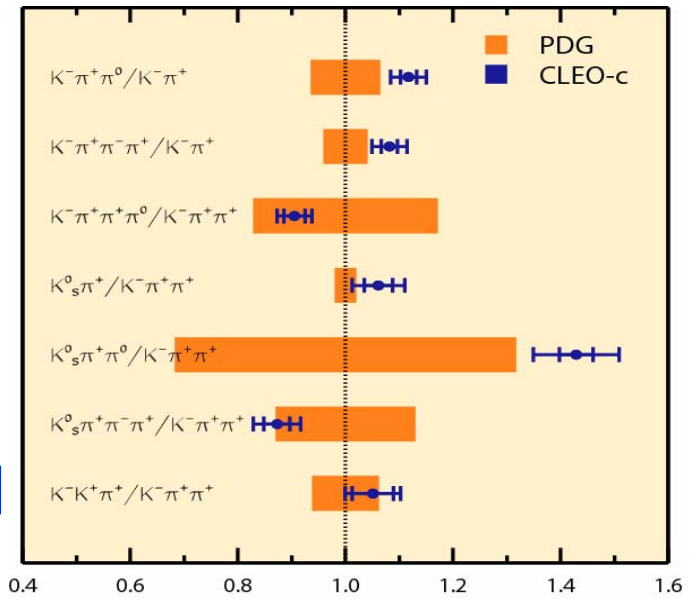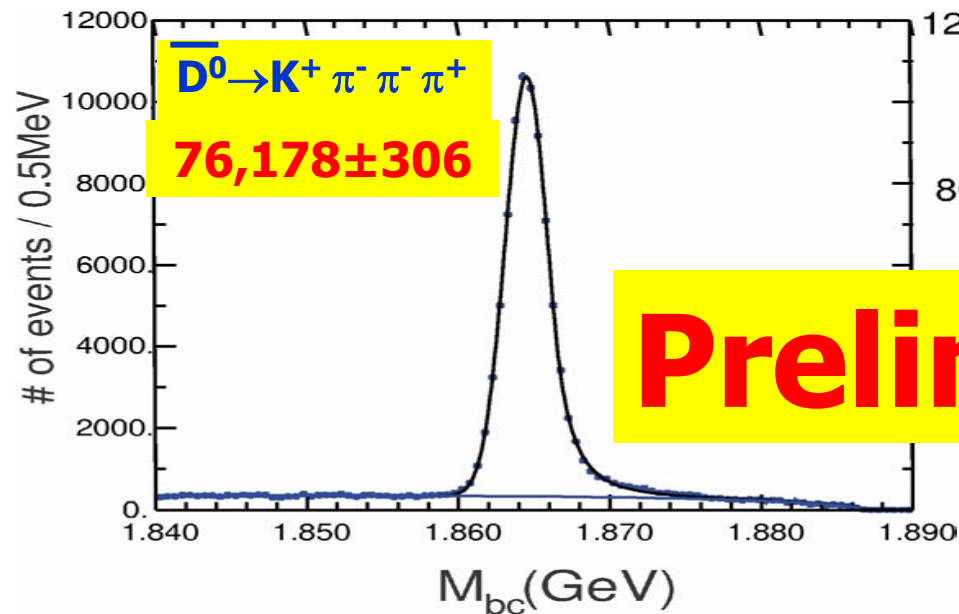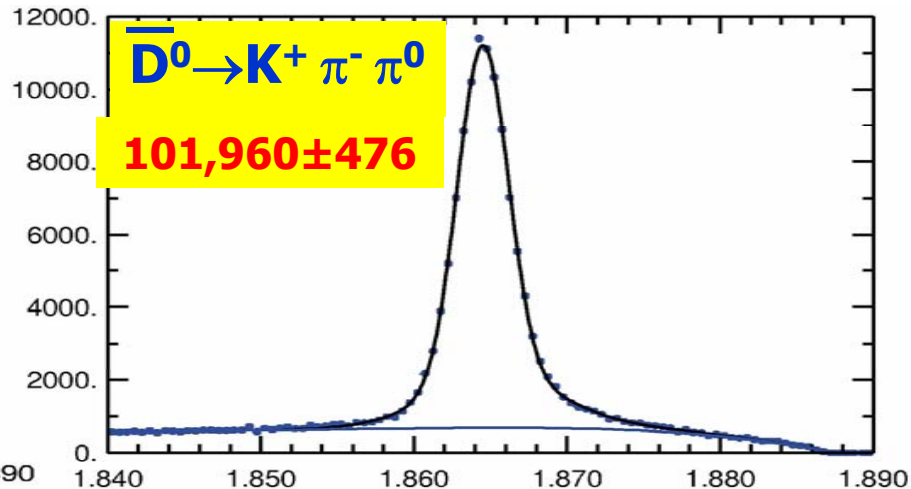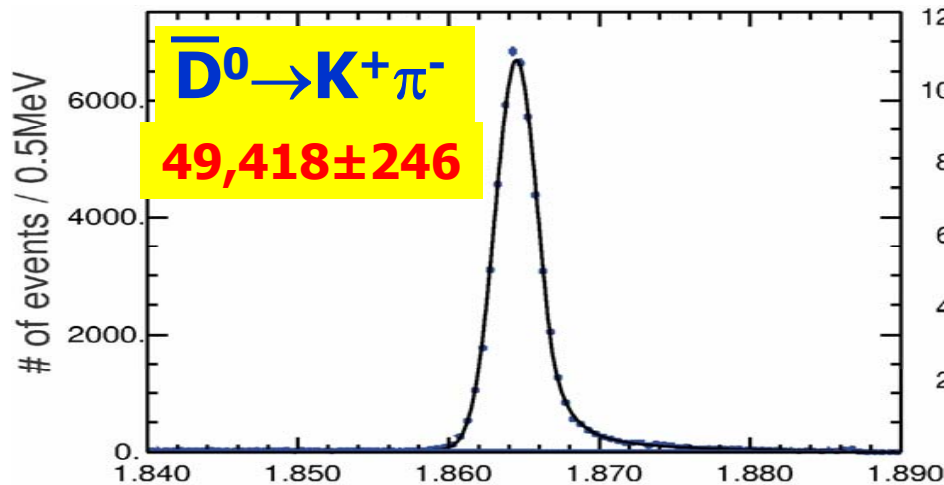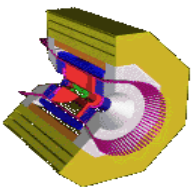
Inclusive η, η', Φ in D decays

Single tag yield from 281 pb⁻¹ at ψ(3770)

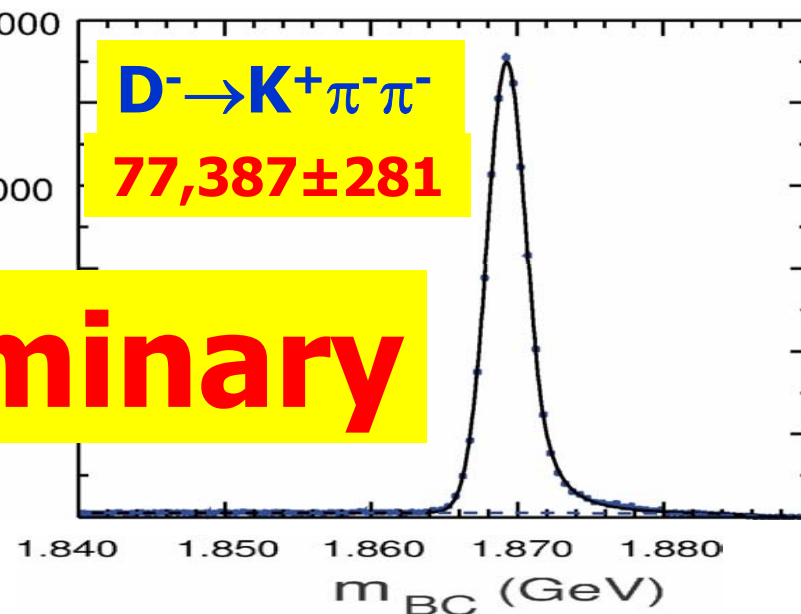| Tag	Mode	Signal	Background
	$K^+\pi^-\pi^-$	77387 ± 281	1868
	$K^+\pi^-\pi^-\pi^o$	24850 ± 214	12825
D^-	$K_s\pi^-$	11162 ± 136	514
	$K_s\pi^-\pi^-\pi^+$	18176 ± 255	8976
	$K_s\pi^-\pi^o$	20244 ± 170	5223
	Sum	151819 ± 487	29406
	$K^+\pi^-$	49418 ± 246	630
$\overline{D^o}$	$K^+\pi^-\pi^o$	101960 ± 476	18307
	$K^+\pi^-\pi^+\pi^-$	76178 ± 306	6421
	Sum	227556 ± 617	25357

Preliminary

Inclusive η, η', Φ in D decays

P_η > 0.3GeV

0.3 < P_η < 1.0GeV

η' in D⁰

η' in D⁺

P_η > 0.3GeV

0.3 < P_η < 1.0GeV

BKG

BKG

BKG   η' in D⁰

BKG   η' in D⁺
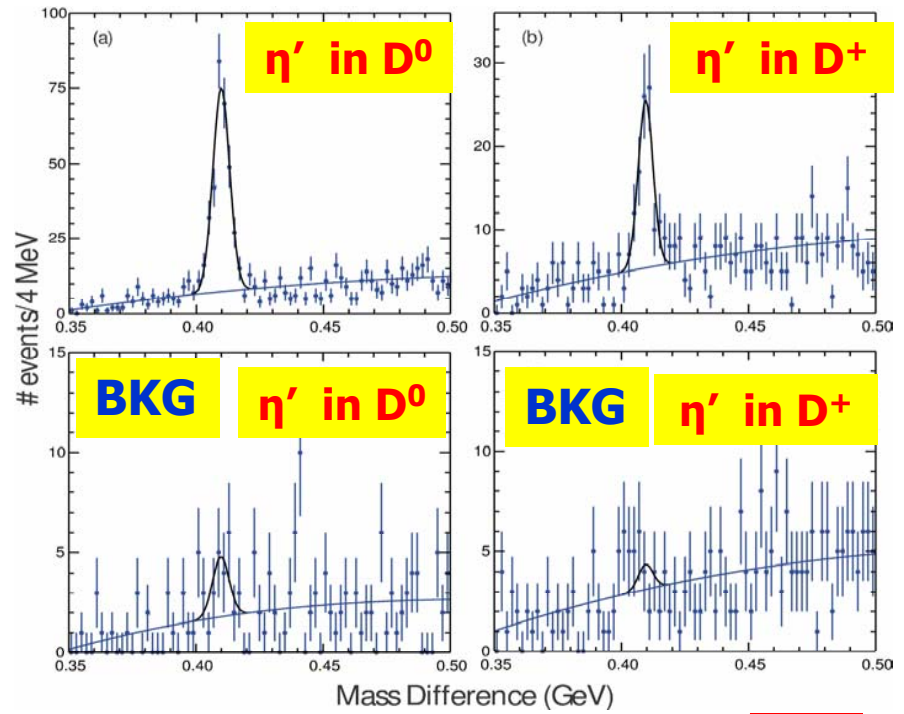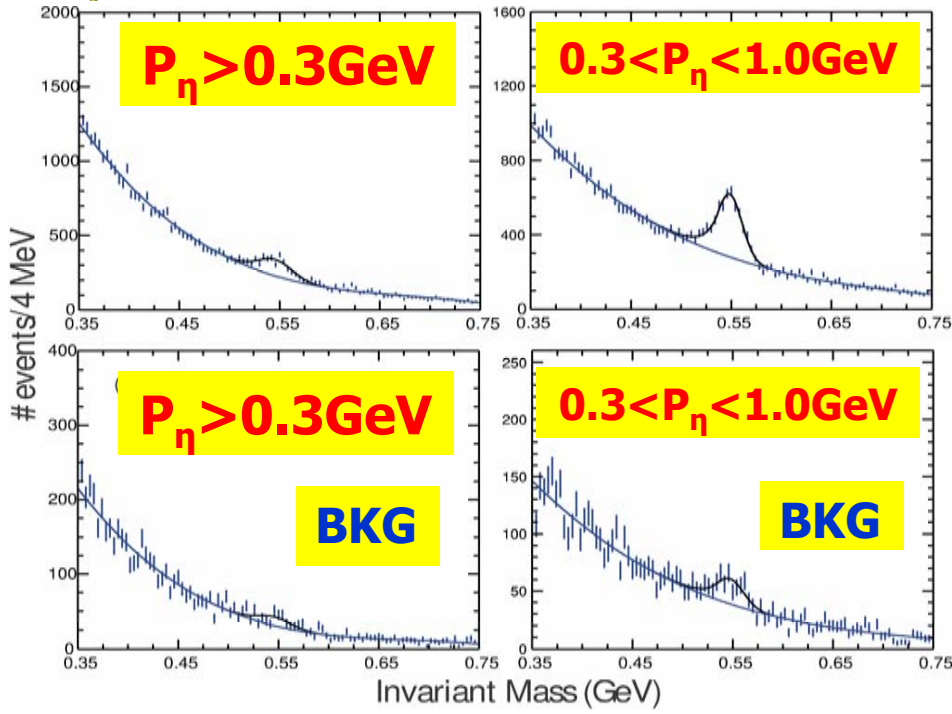
Mode	D^o(%)		D^+(%)	
	Our result	PDG	Our result	PDG
η X	$9.4\pm0.4\pm0.6$	<13	$5.7\pm0.5\pm0.5$	<13
η' X	$2.6\pm0.2\pm0.2$	-	$1.0\pm0.2\pm0.1$	-
ϕ X	$1.0\pm0.1\pm0.1$	1.7 ± 0.8	$1.1\pm0.1\pm0.2$	<1.8

Preliminary
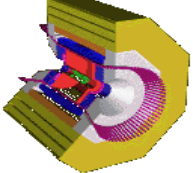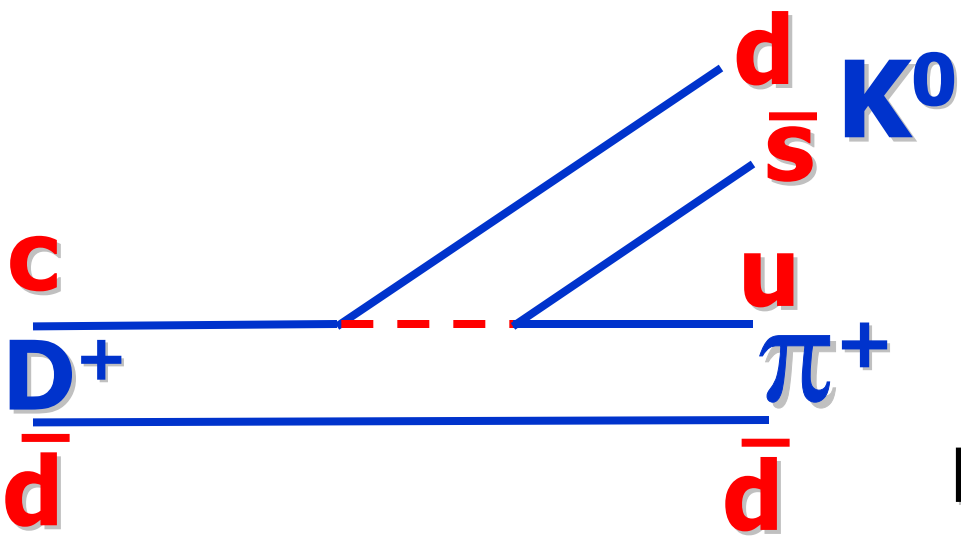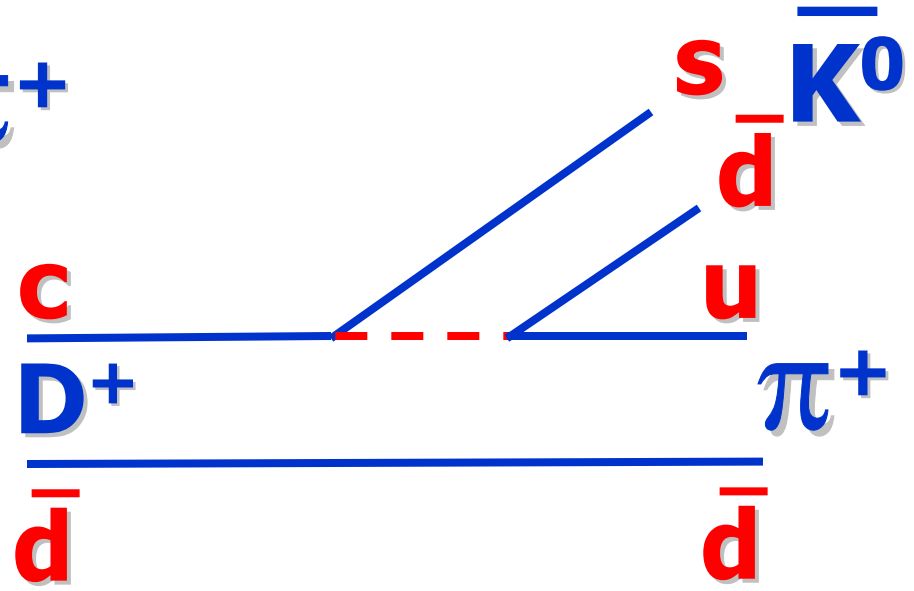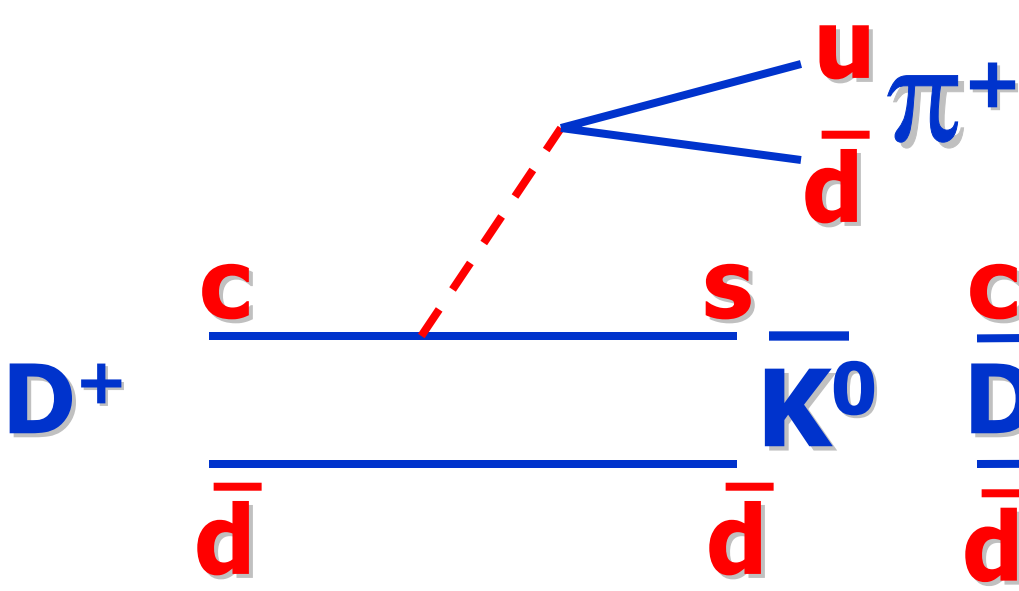
$B(D^+ \to K^0_L \pi^+) > B(D^+ \to K^0_S \pi^+)$

Phys. Lett. B349, 363 (1995)
I. Bigi & H. Yamamoto

Reconstruct D^- and π^+
Missing mass squared
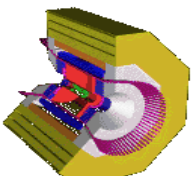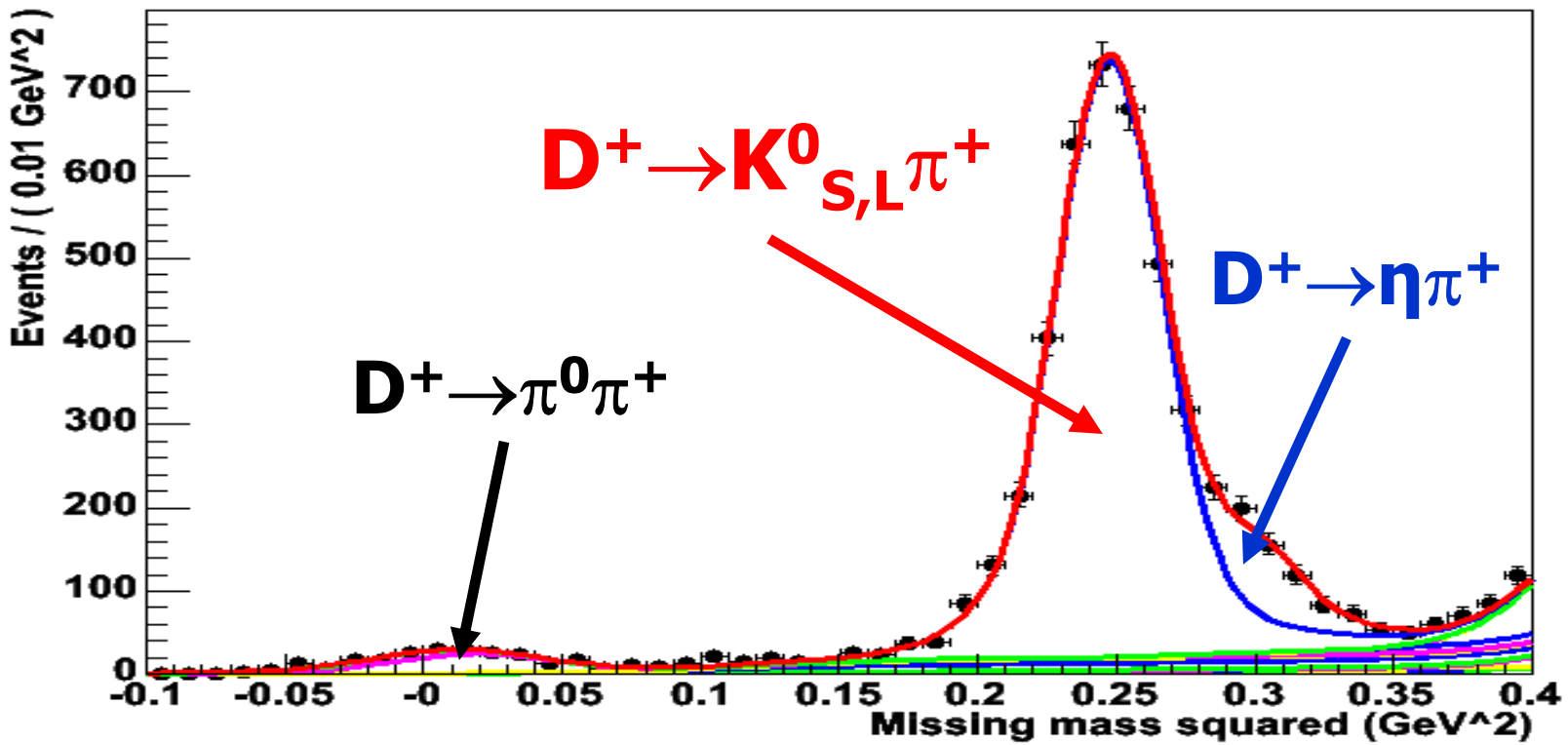
Preliminary

$D^+ \to K^0_{S,L}\pi^+$

$D^+ \to \eta\pi^+$

$D^+ \to \pi^0\pi^+$

$\text{Br}(D^+ \to K^0_{S,L}\pi^+) = (3.06 \pm 0.06 \pm 0.16)\%$

$\text{Br}(D^+ \to \eta\pi^+) = (0.39 \pm 0.03 \pm 0.03)\%$

$$\frac{\mathcal{B}(D^+ \to K^0_L\pi^+) - \mathcal{B}(D^+ \to K^0_S\pi^+)}{\mathcal{B}(D^+ \to K^0_L\pi^+) + \mathcal{B}(D^+ \to K^0_S\pi^+)} = -0.01 \pm 0.04 \pm 0.07$$

ψ(3770) non-D$\bar{D}$ decays

$\sigma(\psi'' \to D\bar{D}) = (6.39 \pm 0.10 \pm 0.21)$ nb **(CLEO, 55.8 pb⁻¹)**

$\sigma(\psi'' \to \text{hadrons}) \sim (7.9 \pm 0.6)$ nb **(J. Rosner hep-ph/0411196)**

Is there a deficit?

Search for exclusive decay modes at CLEO:

$\psi'' \to$ **two-body (VP)**   **(281 pb⁻¹/21 pb⁻¹, this talk)**

$\psi'' \to$ **multi-body**   **(55.8 pb⁻¹/21 pb⁻¹, this talk)**

$\psi'' \to$ **XJ/ψ, $\gamma\chi_{CJ}$**   **(David Miller's talk)**
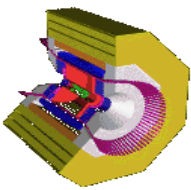
$\psi(3770) \rightarrow$ VP, multi-body

VP = ρ/ω/Φ + π/η/η', K*K, also $\pi^+\pi^-\pi^0$, $b_1\pi$

multi-body = combinations of π, K, p, η, ω,Φ

Energy conservation: $0.98 < E_{vis}/E_{cm} < 1.02$

Momentum conservation: $|P_V - P_P|/E_{cm} < 0.04$

Suppress J/$\psi \rightarrow$ μ$^+$μ$^-$ or hadronic decays

Compare ψ(3770) with scaled continuum

$\psi(3770) \to VP$ decays

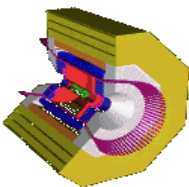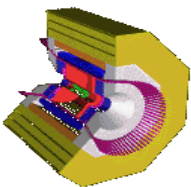| Channel	$N_{sw}^{3.67}$	$N_{sb}^{3.77}$	$N_{sw}^{3.77}$	$N_{sb}^{3.67}$	ϵ	S^{I}	S^{II}	$\sigma^{3.67\mathrm{GeV}}$ [pb]	$\sigma^{3.77\mathrm{GeV}}$ [pb]
$\pi^+\pi^-\pi^0$	74	7	576	72	0.29	2.7	–	$13.1^{+1.9}_{-1.7} \pm 2.1$	$7.4 \pm 0.4 \pm 1.2$
$\rho^0\pi^0$	21	3	130	33	0.33	2.2	2.2	$3.1^{+1.0}_{-0.8} \pm 0.4$	$1.3 \pm 0.2 \pm 0.2$
$\rho^+\pi^-$	22	2	184	12	0.23	0.9	0.6	$4.8^{+1.5}_{-1.2} \pm 0.5$	$3.2 \pm 0.3 \pm 0.3$
$\rho\pi$	43	5	314	45	0.26	2.2	1.9	$8.0^{+1.7}_{-1.4} \pm 0.9$	$4.4 \pm 0.3 \pm 0.5$
$\omega\pi^0$	54	6	696	39	0.19	1.4	0.4	$14.5^{+2.6}_{-2.3} \pm 1.5$	$14.8 \pm 0.6 \pm 1.5$
$\phi\pi^0$	1	2	2	4	0.17	0.0	0.0	< 2.2	< 0.2
$\rho\eta$	36	3	508	31	0.20	1.5	0.5	$9.6^{+2.1}_{-1.8} \pm 1.0$	$10.4 \pm 0.5 \pm 1.0$
$\omega\eta$	4	0	15	6	0.10	1.7	3.0	$2.3^{+1.8}_{-1.1} \pm 0.5$	< 0.8
$\phi\eta$	5	1	132	16	0.11	2.5	≥ 5	< 5.0	$4.5 \pm 0.5 \pm 0.5$
$\rho\eta'$	1	0	27	1	0.03	1.2	1.3	$2.0^{+4.5}_{-1.6} \pm 0.2$	$3.8^{+0.9}_{-0.8} \pm 0.5$
$\omega\eta'$	0	0	2	0	0.02	≥ 5	0.0	< 17.1	$0.6^{+0.7}_{-0.3} \pm 0.6$
$\phi\eta'$	0	0	9	2	0.01	2.4	1.2	< 12.6	< 5.2
$K^{*0}\overline{K^0}$	38	0	501	18	0.09	1.1	≥ 5	$23.5^{+4.6}_{-3.8} \pm 3.1$	$23.5 \pm 1.1 \pm 3.1$
$K^{*+}K^-$	4	1	36	32	0.16	1.4	4.2	< 3.5	< 0.6
$b_1^0\pi^0$	5	3	49	82	0.04	1.2	–	< 17.1	< 2.6
$b_1^+\pi^-$	15	2	219	18	0.18	1.0	–	$4.2^{+1.6}_{-1.3} \pm 0.6$	$4.7 \pm 0.4 \pm 0.6$
$b_1\pi$	20	4	268	67	0.11	0.5	–	$7.9^{+3.1}_{-2.4} \pm 1.8$	$7.6 \pm 0.7 \pm 1.8$

Preliminary: 281 pb⁻¹

$\psi(3770) \rightarrow$ VP decays

281 pb^{-1} data at 3.77 GeV
21 pb^{-1} data at 3.67 GeV

Preliminary

for each channel, on-$\psi(3770)$ yields consistent with continuum prediction except:

- Br($\psi(3770) \rightarrow \phi\eta$) = $(3.1\pm0.6\pm0.3\pm0.1)\times10^{-4}$

- $\psi(3770) \rightarrow \pi^+\pi^-\pi^0$, $\rho^0\pi^0$ and K*$^+$K$^-$ are suppressed.

- form factors of $\omega\pi^0$, $\rho\eta$ and $\rho\eta'$ are obtained

Form factor measurements

Channel	$\mathcal{F}(s)$ (GeV^{-1})	
	$\sqrt{s} = 3.670\,\text{GeV}$	$\sqrt{s} = 3.773\,\text{GeV}$
$\omega\pi^0$	$0.039 \pm 0.003 \pm 0.002$	$0.040 \pm 0.001 \pm 0.002$
$\rho\eta$	$0.033 \pm 0.003 \pm 0.002$	$0.034 \pm 0.001 \pm 0.002$
$\rho\eta'$	< 0.038 (90%CL)	$0.022^{+0.003}_{-0.002} \pm 0.001$
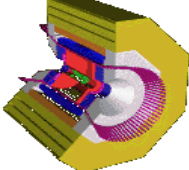
ψ(3770) → multi-body

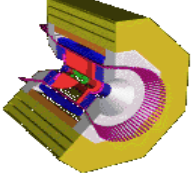| mode	continuum		f_{co}	$10 \times D\bar{D}$ MC		ψ(3770)		N_S	Sig.	ε	σ U.L.	$\mathcal{B}$ U.L.
h	S_{co}	B_{co}		S_{DD}	B_{DD}	$S_{\psi(3770)}$	$B_{\psi(3770)}$		(#σ)		(pb)	($\times 10^{-4}$)
$2(\pi^+\pi^-)$	1471	28	2.49	1	13	3411	90	-266.5	-2.5	0.4305	8.7	11.2
$2(\pi^+\pi^-)\pi^0$	350	18	2.26	15	14	647	18	-120.5	-2.6	0.1990	8.2	10.6
$\eta\pi^+\pi^-$	15	0	2.57	0	0	41	1	1.5	0.1	0.0450	9.7	12.4
$\omega\pi^+\pi^-$	43	9	2.35	0	0	107	18	9.1	0.5	0.1638	4.6	6.0
$\eta 3\pi$ [a]	27	2	2.61	8	0	67	11	-10.1	-0.6	0.0688	4.5	5.8
$\eta 3\pi$ [b]	20	9	2.64	2	1	62	23	9.8	0.6	0.0248	24.0	30.7
$\eta' 3\pi$	1	0	2.75	1	0	5	0	2.2	0.4	0.0149	19.2	24.4
$K^+K^-\pi^+\pi^-$	954	25	2.40	32	7	2262	47	-16.8	-0.2	0.3720	7.0	9.0
$\phi\pi^+\pi^-$	33	13	2.43	0	0	77	25	3.3	0.2	0.1629	3.2	4.1
ϕf_0	12	5	2.49	0	2	32	15	-0.2	0.0	0.0863	3.5	4.5
$K^+K^-\pi^+\pi^-\pi^0$	634	18	1.73	30	21	1121	32	24.9	0.5	0.1283	18.4	23.6
ηK^+K^-	3	0	2.50	0	0	3	0	-4.5	-0.7	0.0389	3.2	4.1
ωK^+K^-	62	12	2.31	0	1	114	14	-15.3	-0.7	0.1269	2.6	3.4
$2(K^+K^-)$	100	11	2.67	9	1	267	7	21.7	0.7	0.3170	4.6	6.0
ϕK^+K^-	46	15	2.59	4	0	118	22	15.2	0.7	0.1564	5.9	7.5
$2(K^+K^-)\pi^0$	20	0	2.88	8	0	50	0	-8.4	-0.6	0.1479	2.2	2.9
$p\bar{p}\pi^+\pi^-$	337	28	2.47	0	0	851	60	28.6	0.5	0.5149	4.5	5.8
$p\bar{p}\pi^+\pi^-\pi^0$	204	9	2.58	0	0	604	16	85.4	2.1	0.2259	14.4	18.5
$\eta p\bar{p}$	2	1	2.62	0	0	4	2	-0.6	-0.1	0.0469	4.2	5.4
$\omega p\bar{p}$	26	4	2.58	0	0	54	5	-7.8	-0.5	0.1421	2.2	2.9
$p\bar{p}K^+K^-$	25	1	2.62	0	0	89	3	23.0	1.5	0.4111	2.5	3.2
$\phi p\bar{p}$	2	3	2.69	0	0	2	2	0.0	0.0	0.1872	1.1	1.3
$\Lambda\bar{\Lambda}$	4	1	2.69	0	0	6	0	-2.1	-0.3	0.2154	1.0	1.2
$\Lambda\bar{\Lambda}\pi^+\pi^-$	23	4	2.37	0	0	42	7	-10.0	-0.7	0.1019	2.0	2.5
$\Lambda\bar{p}K^+$	65	7	2.57	0	0	150	11	-10.0	-0.4	0.2602	2.2	2.8
$\Lambda\bar{p}K^+\pi^+\pi^-$	29	3	2.64	0	0	94	17	8.2	0.4	0.1471	4.9	6.3

Hadronic EM Form Factors

Spacelike
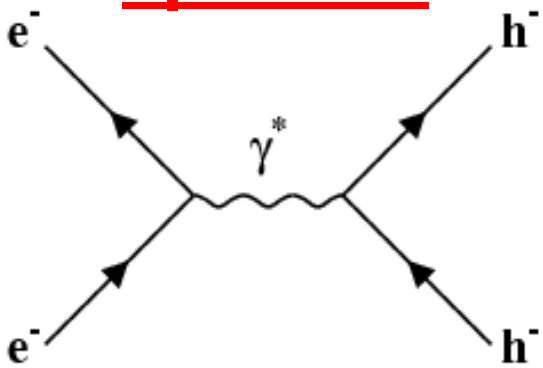
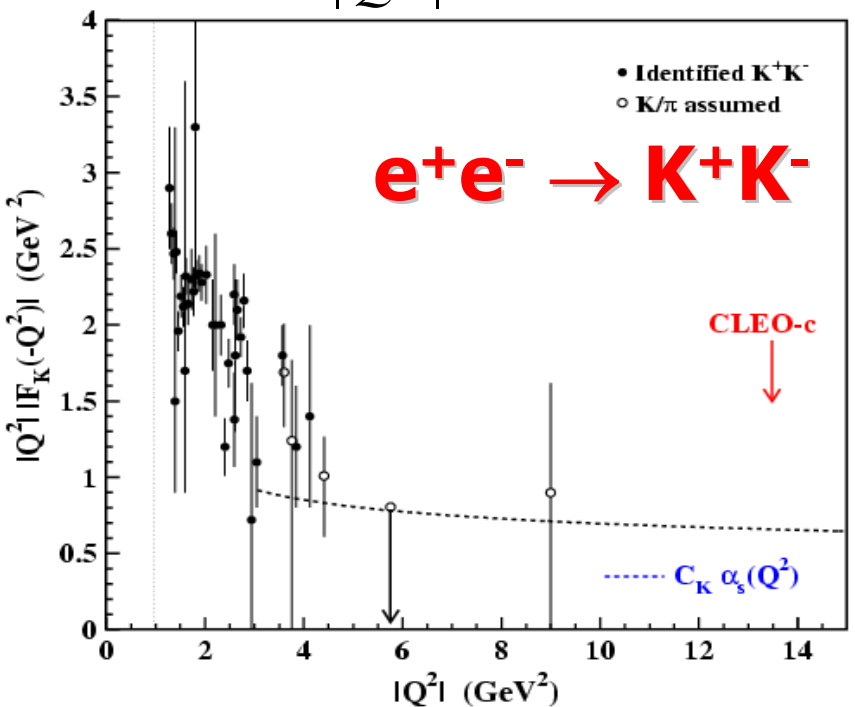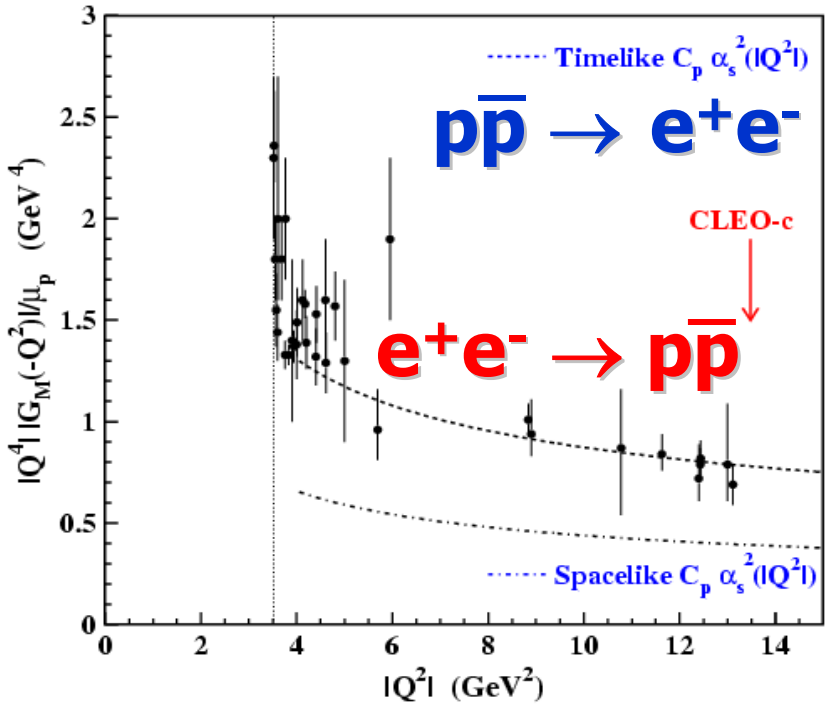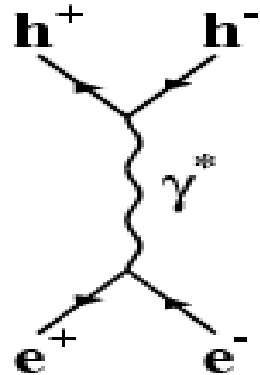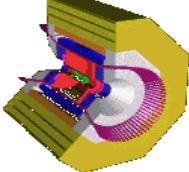**Brodsky & Lepage (PRD 22, 2157 (1980))**

Timelike

Baryons: $F(|Q^2|) \propto \dfrac{\alpha_s^2(|Q^2|)}{|Q^4|}$

Mesons: $F(|Q^2|) \propto \dfrac{\alpha_s(|Q^2|)}{|Q^2|}$

$p\bar{p} \rightarrow e^+ e^-$

$e^+ e^- \rightarrow p\bar{p}$

$e^+ e^- \rightarrow K^+ K^-$

Proton   **Preliminary**   **Charged Kaon**

$e^+e^- \rightarrow p\bar{p}$
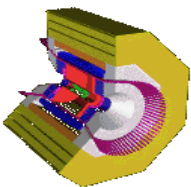
$e^+e^- \rightarrow K^+K^-$

20.7 pb^{-1} at 3.671 GeV
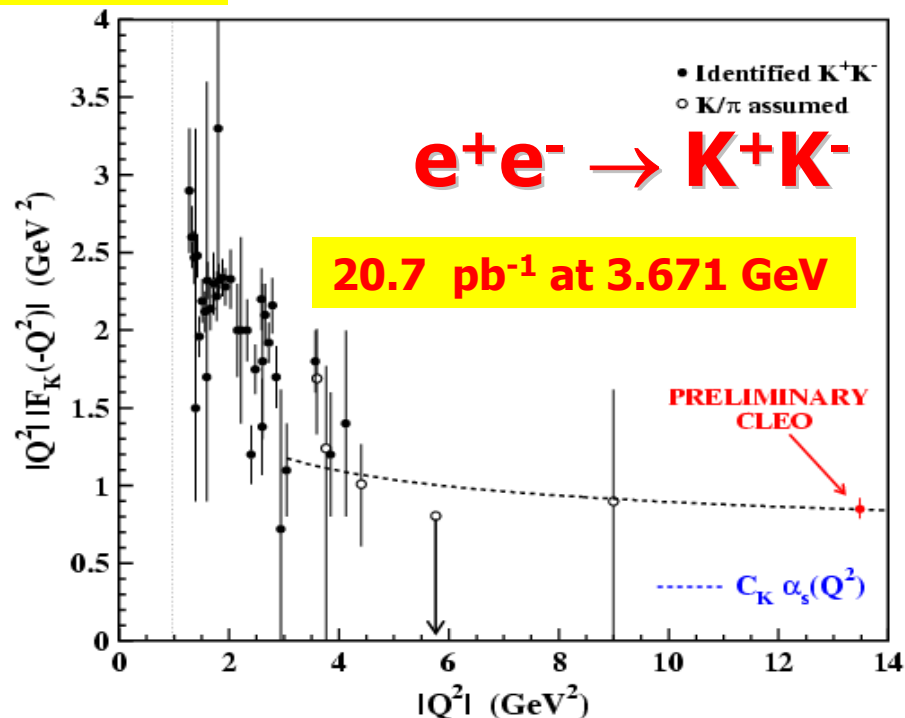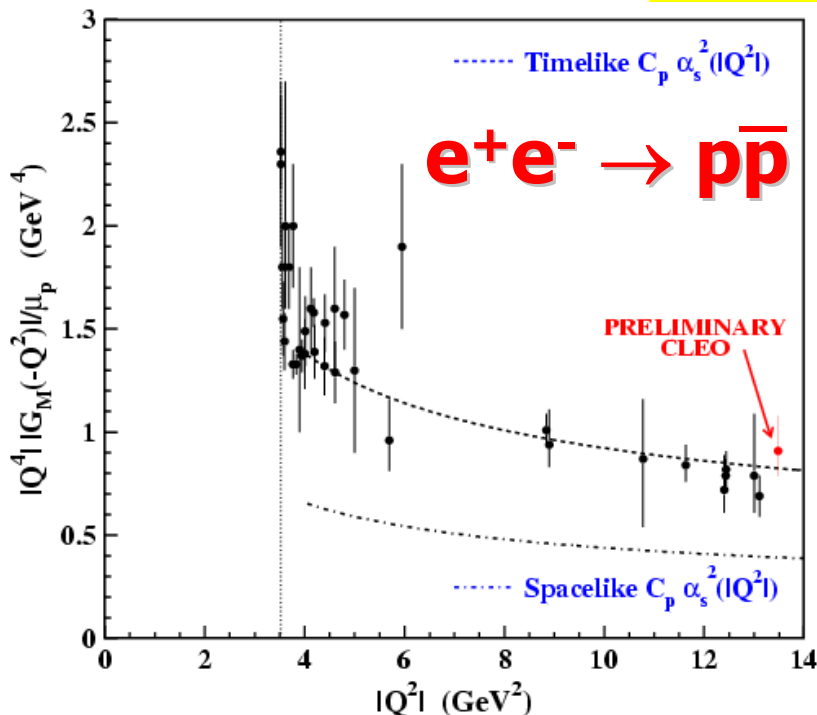
$$|G_M^P(13.5)| = (1.52^{+0.26}_{-0.20}(stat)^{+0.07}_{-0.03}(syst)) \times 10^{-2} \quad (|G_E^P(s)| = 0)$$

$$|G_M^P(13.5)| = (1.39^{+0.24}_{-0.18}(stat)^{+0.06}_{-0.03}(syst)) \times 10^{-2} \quad (|G_E^P(s)| = |G_M^P(s)|)$$

$$|F_K(13.5)| = (6.28 \pm 0.38(stat) \pm 0.14(syst)) \times 10^{-2}$$

First precision measurement

Preliminary CLEO results

Absolute D hadronic BR & $\Psi'' \rightarrow$ DD cross-section
(55.8 pb^{-1} , CLNS 05/1904, submitted to PRL)

Inclusive production of η, η′, Φ in D decays
(281 pb^{-1}, CLEO CONF 05-4)

BF measurement of $D^+ \rightarrow K^0_s / K^0_L \; \pi^+$
(281 pb^{-1})

$\Psi'' \rightarrow$ non DD final states (VP, multi-body)
(281 pb^{-1}, 55.8 pb^{-1}, CLEO CONF 05-1, CLNS 05/1921)

P and K time-like form factors at √s = 3.671 GeV
(20.7 pb^{-1}, CLEO CONF 05-9)