# Opportunities and Challenges in Hadronic D Decay Measurements

Rich set of phenomena in hadronic D decays

Significant theoretical challenges

Cornucopia of measurements to come

Powerful detectors with good kinematic resolutions, PID

Related talks in this Workshop:

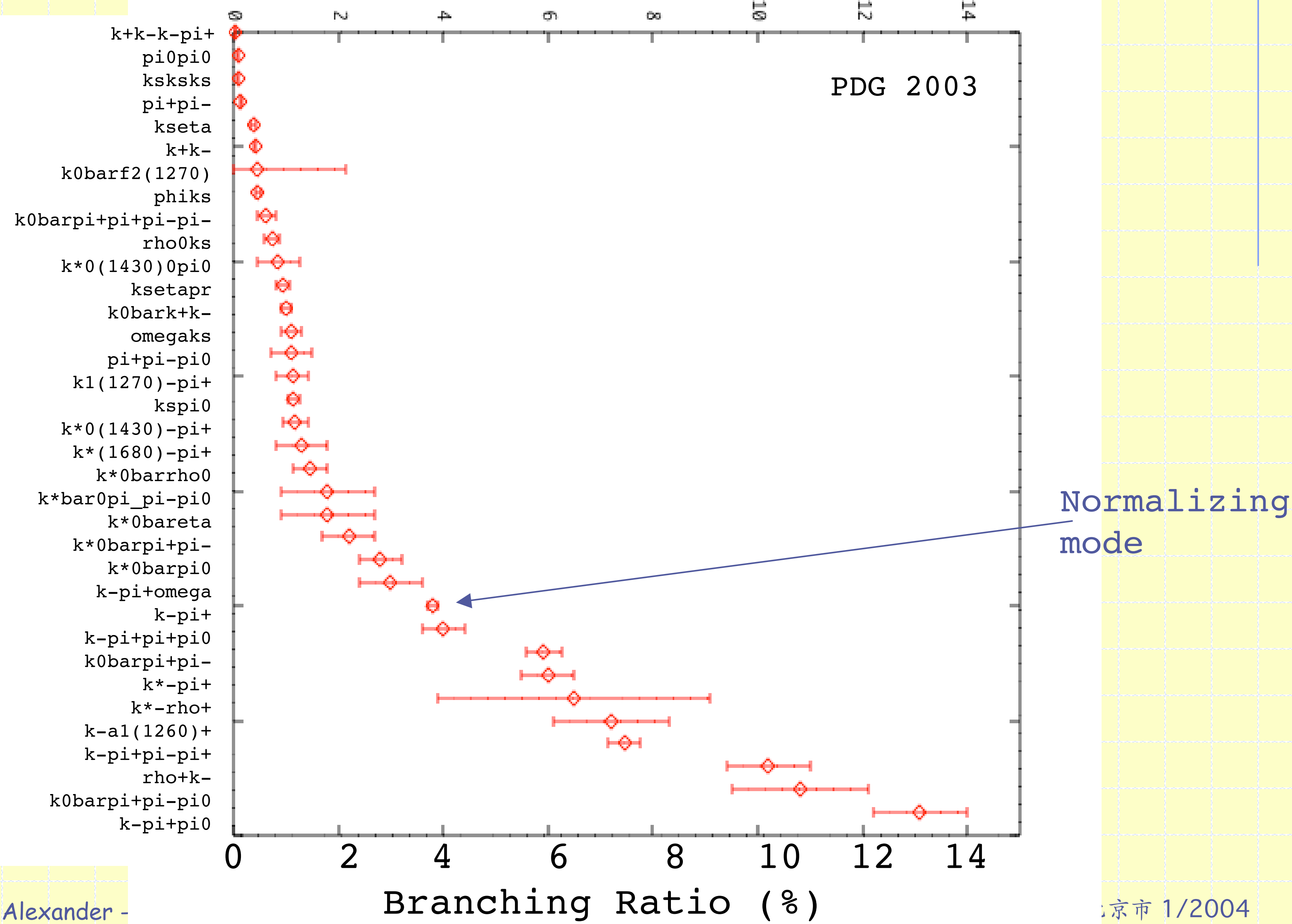
| | |
|---|---|
| Theoretical Challenges in Charm Physics | Ikaros Bigi - Th |
| Precision Charm Experiment and Precision LQCD | Shoji Hashimoto - Th |
| Charm Effects in phi_3 Measurements | Alex Bondar |
| Charm Baryons | John Yelton |
| DDbar mixing CPV and Rare D Decays Theory | Ikaros Bigi - Th |
| DDbar mixing CPV and Rare D Decays Experiment | David Asner |

This Talk: Overview - Absolute BR Measurements

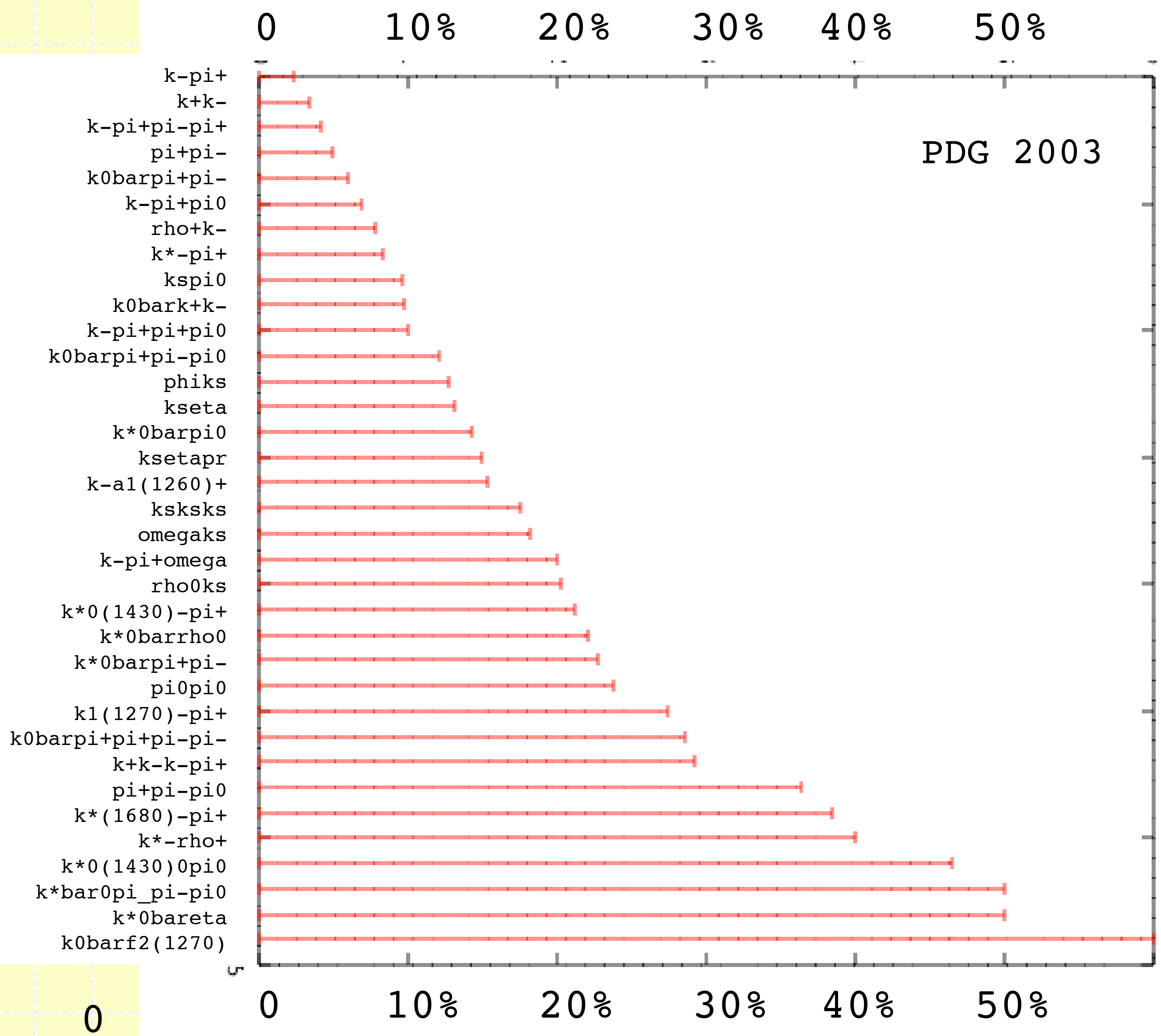
# Why measure the D hadronic decay modes?

1. It is useful engineering:
   - Fix absolute scale of heavy quark decay rates.
     - Affects CKM measurements
     - Resolve charm counting issues in B decay
     - Understand two-body B decays
   - Measure strong phases
     - Useful for CPV work in B decays
     - Identify targets for Acp measurements in D
   - Part of understanding what is SM behaviour
2. It is interesting science:
   - QCD dynamics is rich and vibrant in D system.
   - Measurements will drive theory… maybe *future* theory
3. We can do it.

# Hadronic $D^0$ Br Measurements

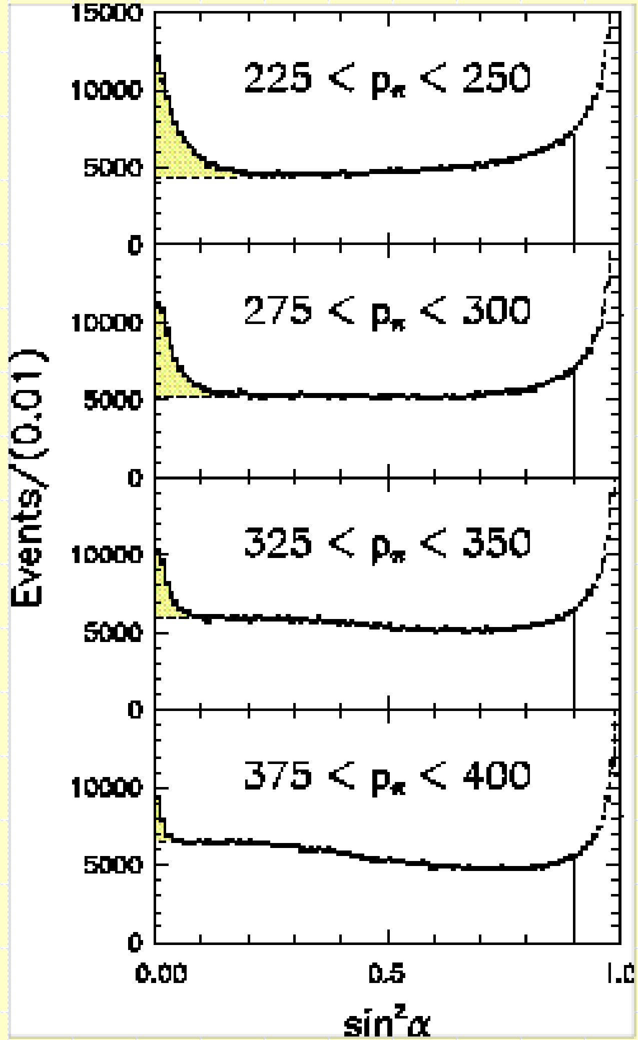


# Relative Precision: $\delta Br/Br$ $(D^0)$



# Absolute Branching Ratio: $D^0 \to K^- \pi^+$

| $\mathcal{B}$ (%) | Error(%) | Source |
|---|---|---|
| 3.82±0.07±0.12 | 3.6 | CLEO |
| 3.82±0.09±0.12 | 3.8 | ALEPH |
| 3.83±0.09 | 2.3 | PDG |

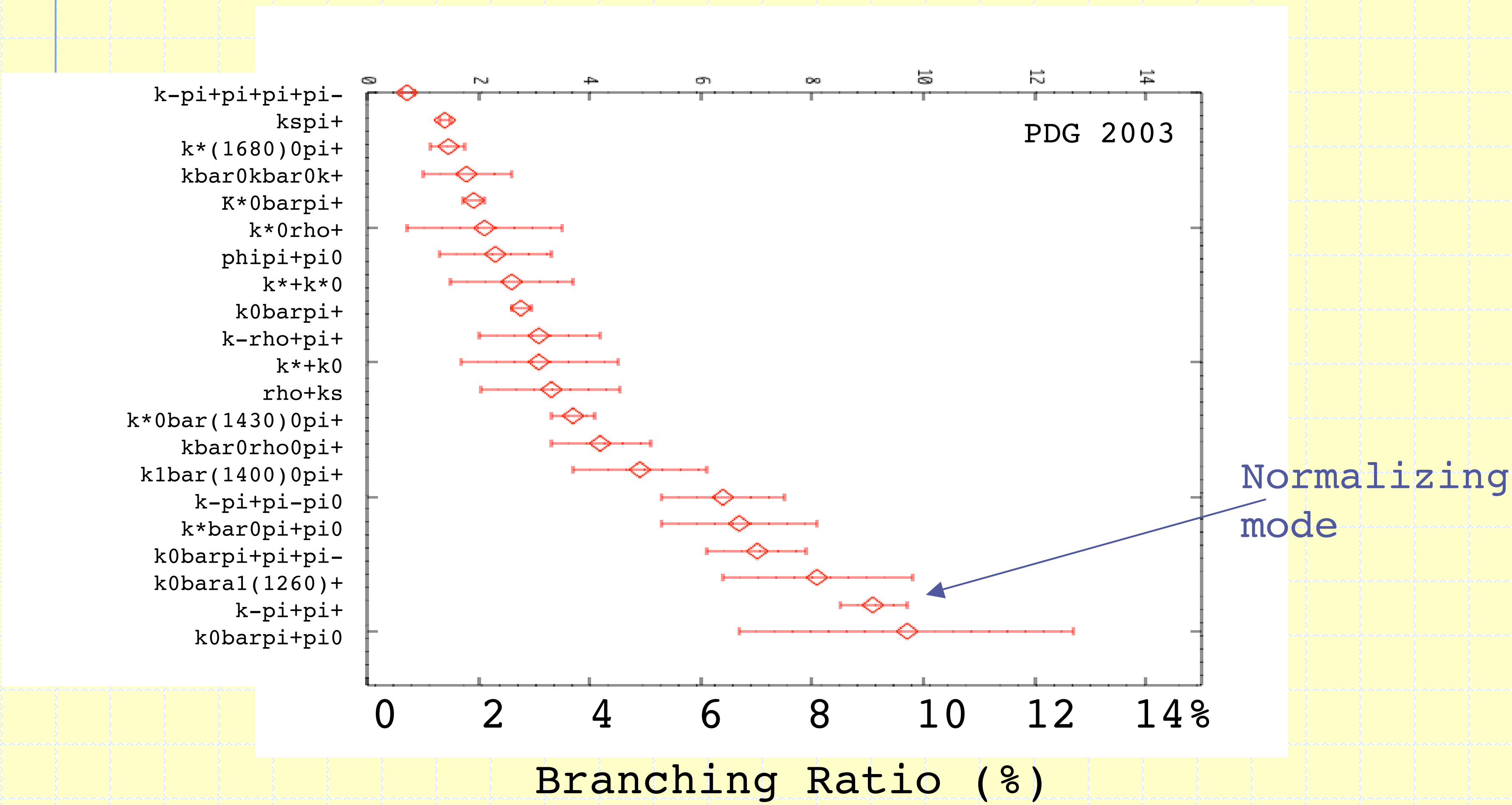



- Method: Detect $D^{*+} \to \pi^+ D^o$, when
  $D^o \to K^- \pi^+$ and
  $D^o \to$ anything.

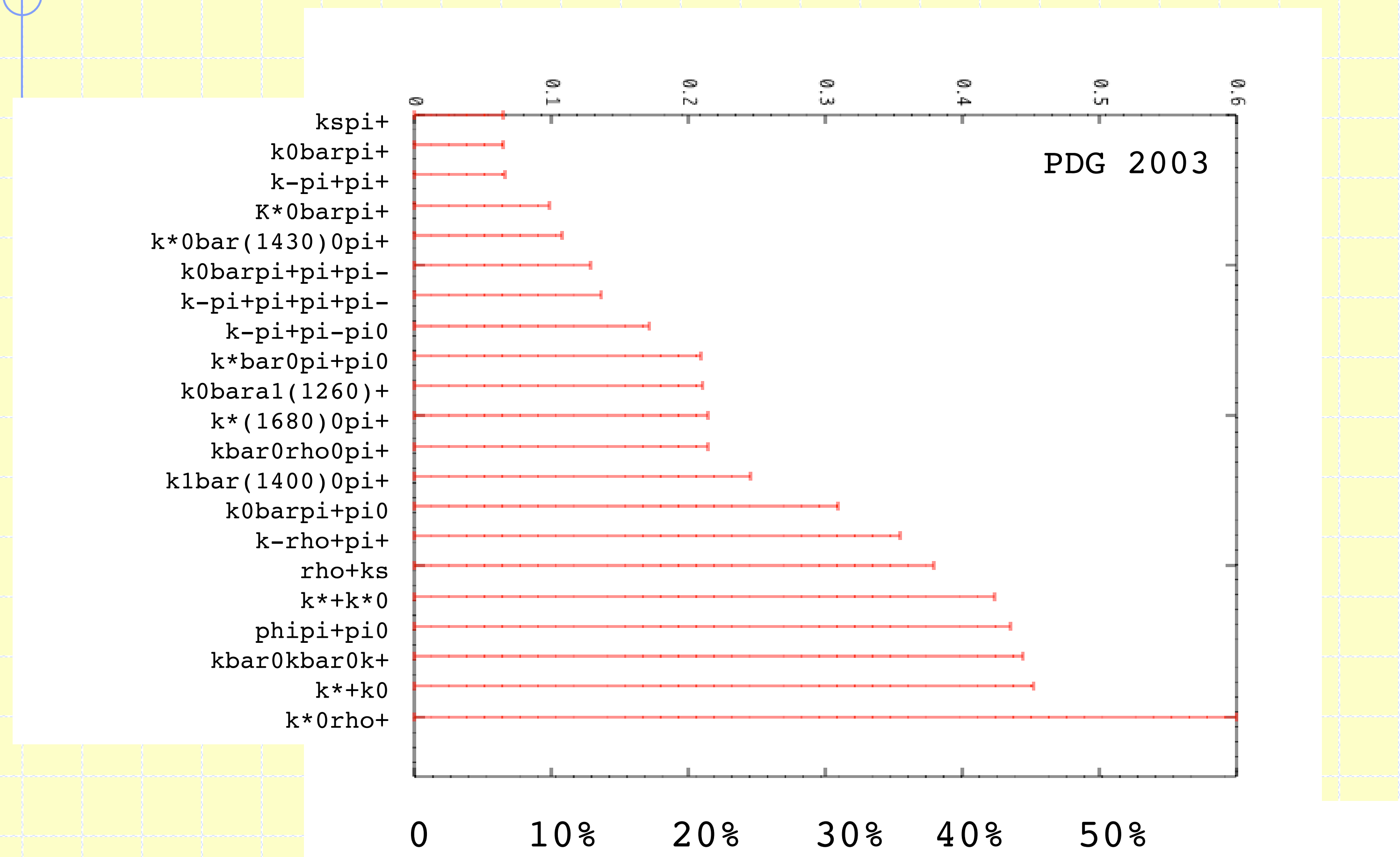
- Problem: Systematic error due to background extrapolation

$\alpha$ is angle between thrust axis & slow $\pi^+$

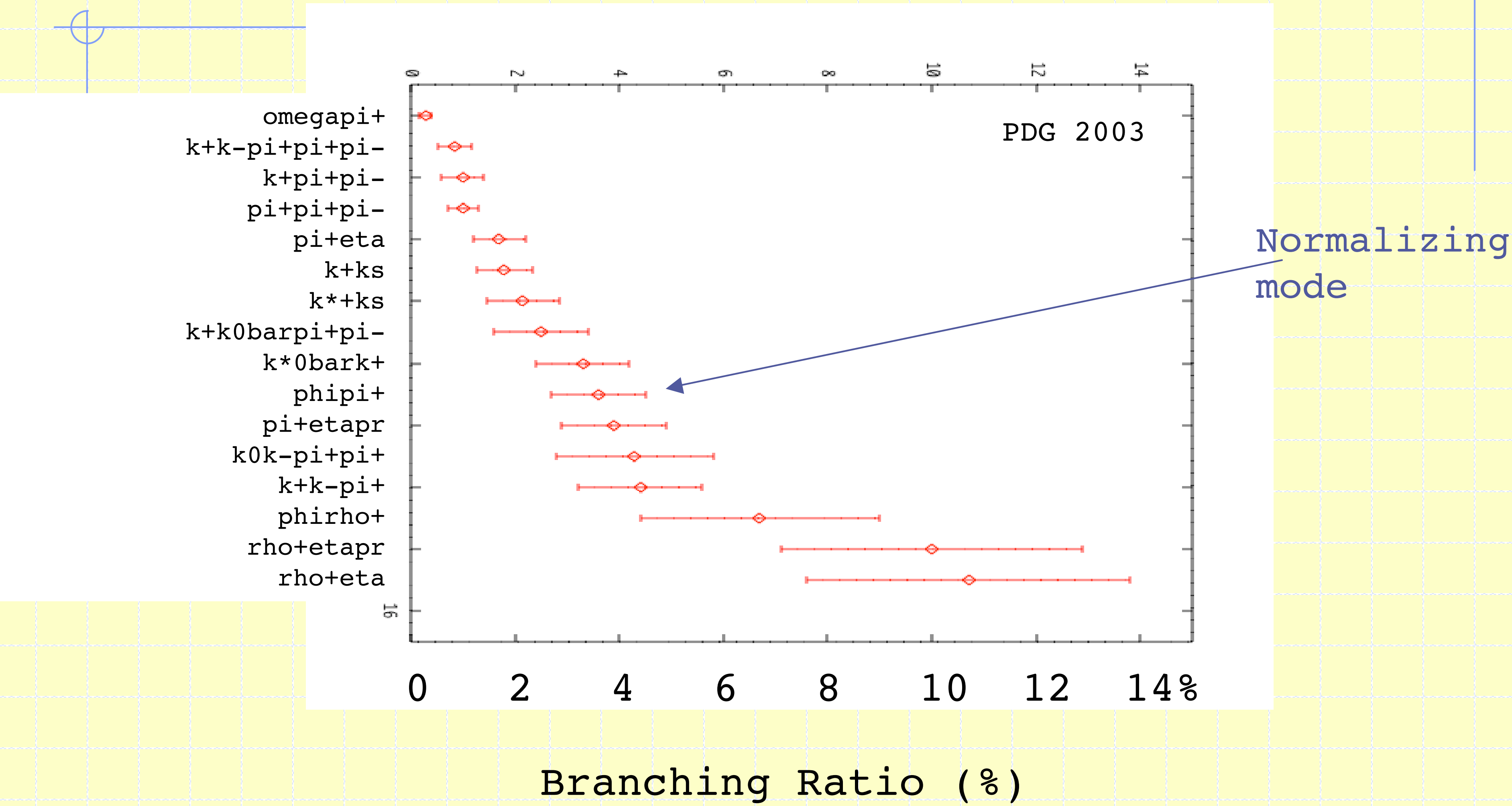
# Hadronic D+ Br Measurements



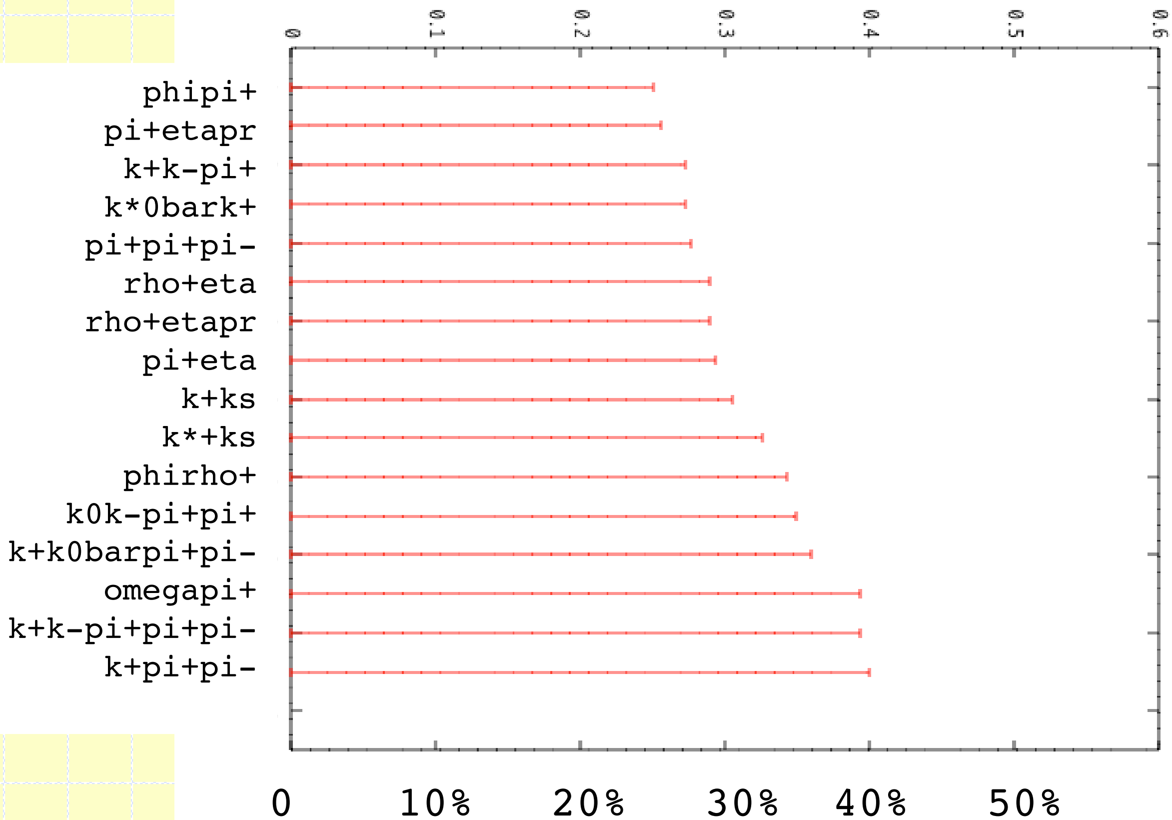
# Hadronic D+ δBr/Br



# Hadronic $D_s$ Br Measurements

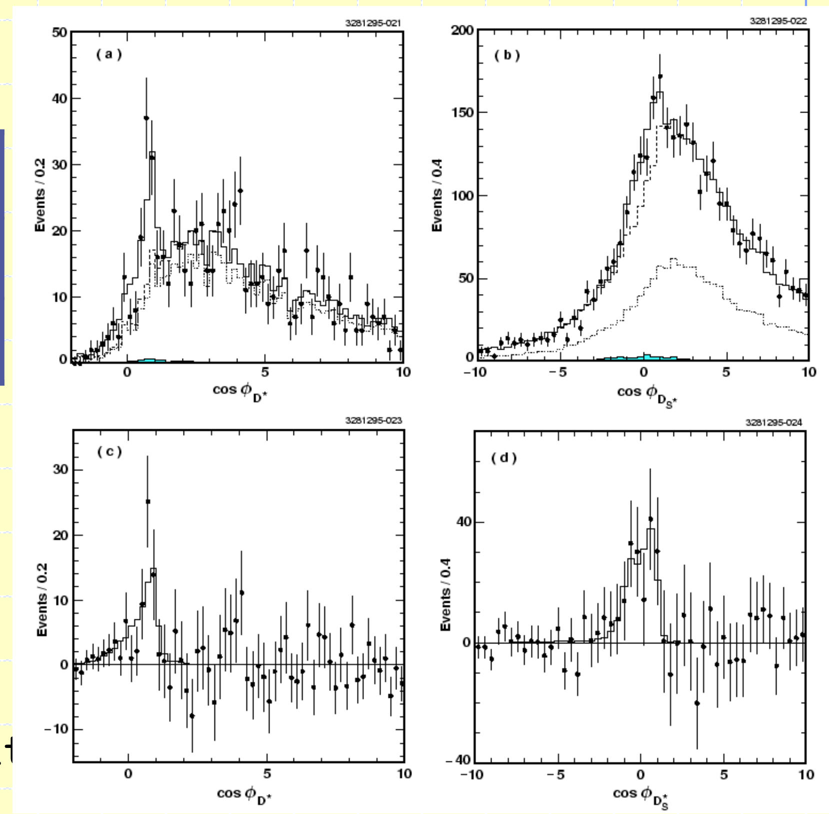


# Hadronic $D_s$ $\delta Br/Br$



# Absolute Branching Ratio: $D_s \to \phi \pi^+$

| $\mathcal{B}$ (%) | Err (%) | Source |
|---|---|---|
| 3.59±0.77±0.48 | 25.3 | CLEO |
| 3.6±0.9 | 25.0 | PDG |




- Method: Reconstruct B-> $D_s$* D* by partial reconstruction twice - once for $D_s$, once for $D^0$
- Observe signal both with & without explicit $D_s$ or $D^0$ reconstruction
- Ratio measures $\mathcal{B}(D_s \to \phi\pi^+)/\mathcal{B}(D^0 \to K^-\pi^+)$
- Large backgrounds associated with partial reconstruction methods

# Experiments

Past
Present
Future

| | Υ(4S) | Fixed Target | Collider | Psi(3770) |
|---|---|---|---|---|
| | Babar<br>Belle<br>CLEO II<br>CLEO III | FOCUS<br>E791<br>E691 | CDF<br>D0<br>BTeV<br>LHCb | MARK III<br>BES II<br>CLEO-c<br>BES III |
| DATA SAMPLE | Large | Large | Huge | (Large) |
| SIGNAL/BKG | Moderate | Moderate | Low | High |
| PARTICLE ID? | Excellent | Excellent | ( ) | (excellent) |
| FEATURES? | displ vtx | displ vtx | displ vtx<br>vtx trigg | tagging;<br>coherence |

# Unique features available with charmonium initial state

1. Cleanliness

   Charged multiplicity ~ 2.5/D meson

   Neutral multiplicity ~ 1.3/D meson

   No other particles in event

2. Tagging

   DDbar state produced with no extra particles

   - Exploit large branching ratios,
   - Abundant kinematic constraints.
     - Reduce combinatorics
     - Obtain absolute BR via double/single tag
     - CP tagging for CPV studies

3. Quantum Coherence

   D mixing studies: Doubly Cabibbo Suppressed mode = 0

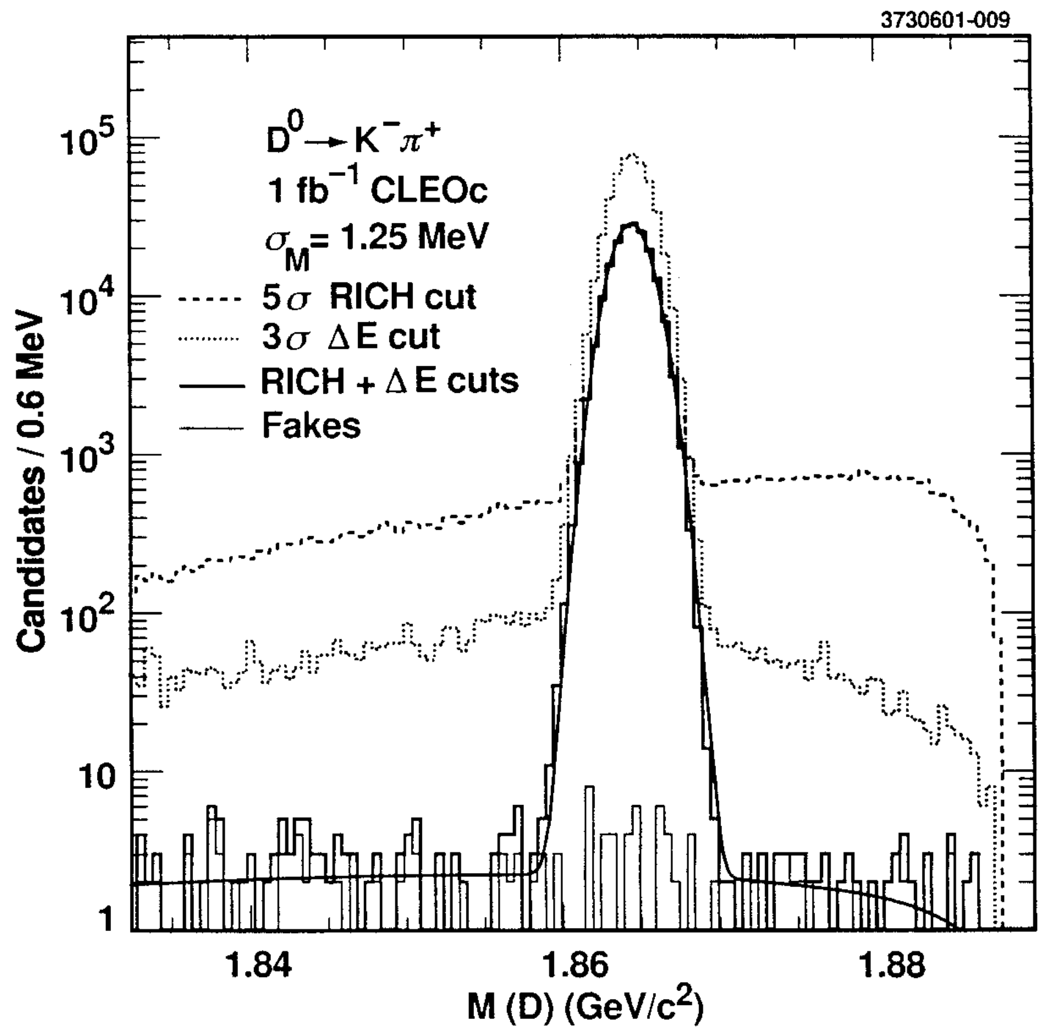
   CP Violation searches

# CLEO-c, 1fb$^{-1}$, $D^0$, $D^+$ yields

TABLE 2. Production and detection rates with 1 fb$^{-1}$ of data for a number of $D^0$ and $D^+$ decay modes at $\sqrt{s} = 3.77$ GeV. The efficiencies $\epsilon_{MC}$ and $\epsilon_S$ are from the Monte Carlo and numerical calculations, respectively.

| $D$ and Daughter Decay Modes | | $\mathcal{B}$ (%) | Produced | $\epsilon_{MC}$ (%) | $\epsilon_S$ (%) | Detected |
|---|---|---|---|---|---|---|
| $D^0 \to K^-\pi^+$ | | 3.83 | 442,703 | 41.1 | 42.4 | 182,068 |
| $D^0 \to K^0_S\pi^0$ | $K^0_S \to \pi^+\pi^-$ | 0.72 | 83,954 | 47.4 | 43.7 | 39,790 |
| $D^0 \to K^-\pi^+\pi^0$ | | 13.90 | 1,611,401 | 41.9 | 35.7 | 675,201 |
| $D^0 \to K^-\pi^+\pi^+\pi^-$ | | 7.49 | 886,682 | 38.0 | 36.9 | 336,595 |
| $D^0 \to K^-\pi^+\pi^0\pi^0$ | | 15.00 | 1,133,552 | 31.8 | 23.2 | 360,178 |
| | | | 4,158,292 | | | 1,593,832 |
| $D^+ \to K^-\pi^+\pi^-$ | | 9.00 | 755,816 | 50.0 | 45.1 | 377,747 |
| $D^+ \to K^0_S\pi^+\pi^0$ | $K^0_S \to \pi^+\pi^-$ | 3.33 | 297,891 | 33.0 | 35.8 | 98,263 |
| $D^+ \to K^-\pi^+\pi^+\pi^0$ | | 6.40 | 537,468 | 29.6 | 29.3 | 159,225 |
| | | | 1,591,175 | | | 635,235 |

# $D^0 \to K^- \pi^+$ Tag mass plots



# $D_s \to \phi\, \pi$

TABLE 3. Production and detection rates with 1 $fb^{-1}$ of data for a number of $D_s$ decay modes at $s = 4.028$ GeV. The efficiencies $\epsilon_{MC}$ and $\epsilon_S$ are from the Monte Carlo and numerical calculations, respectively.

| $D$ and Daughter Decay Modes | | $\mathcal{B}$ (%) | Produced | $\epsilon_{MC}$ (%) | $\epsilon_S$ (%) | Detected |
|---|---|---|---|---|---|---|
| $D_s^+ \to K^-K^+\pi^+$ | | 4.40 | 54,405 | 40.4 | 36.8 | 21,965 |
| $D_s^+ \to K^-K^+\pi^+\pi^0$ | | 4.43 | 57,026 | 19.8 | 23.9 | 11,314 |
| $D_s^+ \to \eta\pi^+$ | | 1.70 | | | | |
| | $\eta \to \gamma\gamma$ | 0.67 | 6,738 | 57.1 | 53.3 | 3,849 |
| | $\eta \to \pi^0\pi^0\pi^0$ | 0.54 | 5,520 | 25.0 | 22.5 | 1,378 |
| | $\eta \to \pi^+\pi^-\pi^0$ | 0.39 | 4,122 | 43.5 | 35.8 | 1,793 |
| $D_s^+ \to \eta\rho^+$ | | 10.8 | | | | |
| | $\eta \to \gamma\gamma$ | 4.24 | 41,731 | 37.4 | 34.6 | 15,612 |
| | $\eta \to \pi^0\pi^0\pi^0$ | 3.46 | 34,066 | 18.4 | 14.6 | 6,260 |
| | $\eta \to \pi^+\pi^-\pi^0$ | 2.48 | 25,306 | 26.8 | 23.3 | 6,791 |
| $D_s^+ \to \eta'\pi^+$ | | 3.9 | | | | |
| $\eta' \to \eta\pi^+\pi^-$ | $\eta \to \gamma\gamma$ | 0.68 | 6,191 | 28.2 | 35.8 | 1,743 |
| $\eta' \to \eta\pi^+\pi^-$ | $\eta \to \pi^0\pi^0\pi^0$ | 0.55 | 5,232 | 11.9 | 15.1 | 624 |
| $\eta' \to \eta\pi^+\pi^-$ | $\eta \to \pi^+\pi^-\pi^0$ | 0.40 | 3,872 | 17.8 | 24.1 | 690 |
| $\eta' \to \gamma\rho$ | | 1.15 | 11,277 | 40.6 | 44.5 | 4,583 |
| $D_s^+ \to \eta'\rho^+$ | | 10.1 | | | | |
| $\eta' \to \eta\pi^+\pi^-$ | $\eta \to \gamma\gamma$ | 1.8 | 17,011 | 16.6 | 23.3 | 2,819 |
| $\eta' \to \eta\pi^+\pi^-$ | $\eta \to \pi^0\pi^0\pi^0$ | 1.4 | 13,982 | 7.9 | 9.8 | 1,108 |
| $\eta' \to \eta\pi^+\pi^-$ | $\eta \to \pi^+\pi^-\pi^0$ | 1.0 | 10,417 | 10.4 | 15.7 | 1,086 |
| $\eta' \to \gamma\rho$ | | 3.0 | 30,072 | 29.1 | 28.9 | 8,747 |
| | | | 326,968 | | | 90,362 |

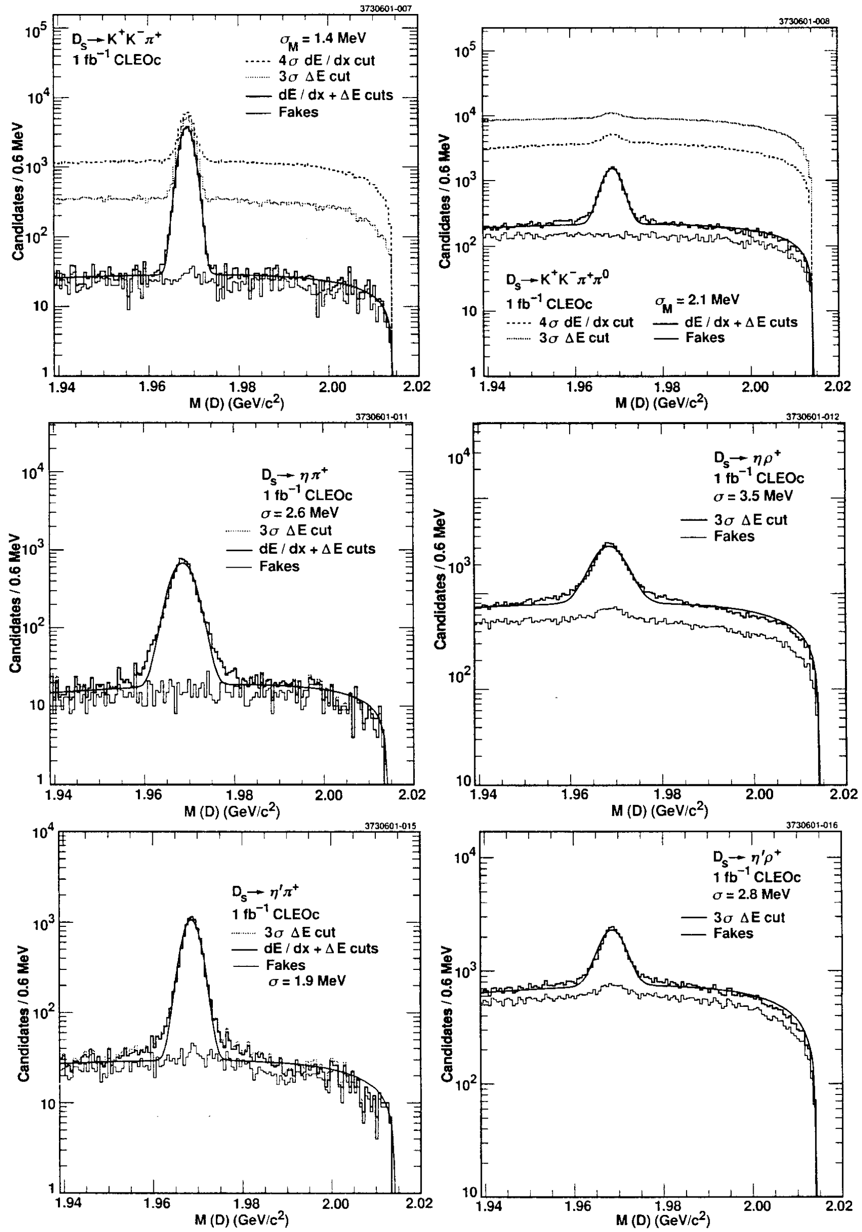



FIGURE 13. Reconstructed $D$ mass $M(D)$ for different $D_s$ decays.

# Double Tagged BR

Singles yield

$$S_i \sim N_{D\bar{D}} B_i \varepsilon_i$$

Doubles yield

$$D_{ij} \sim N_{D\bar{D}} B_i B_j \varepsilon_{ij}$$

Absolute Branching Ratio

$$B_i \sim \frac{D_{ij}/\varepsilon_{ij}}{S_j/\varepsilon_j}$$

TABLE 13. Double tag rates and double tagging efficiencies for $D^0\bar{D}^0$ and $D^+D^-$ double tags from 1 $\mathrm{fb}^{-1}$ of simulated data for each $D$ species at 3.77 GeV. The first line for each combination of modes gives the numbers of reconstructed events. The second line gives the reconstruction efficiencies for the double tag. The third line gives estimates of the number of fake events in the signal region.

| $D^0\bar{D}^0$ | | | | |
|---|---|---|---|---|
| Mode | $K^+\pi^-$ | $K^0_S\pi^0$ | $K^+\pi^-\pi^0$ | $K^+\pi^-\pi^+\pi^-$ |
| $K^-\pi^+$ | 1,500<br>17.7%<br>*0* | 604<br>19.2%<br>*26* | 10,251<br>16.7%<br>*16* | 5,255<br>15.4%<br>*57* |
| $K^0_S\pi^0$ | | 55<br>17.9%<br>*7* | 2,242<br>19.2%<br>*135* | 1,162<br>17.9%<br>*94* |
| $K^-\pi^+\pi^0$ | | | 18,289<br>16.3%<br>*64* | 18,571<br>15.1%<br>*327* |
| $K^-\pi^+\pi^+\pi^-$ | | | | 4,946<br>14.6%<br>*148* |

| $D^+D^-$ | | | | |
|---|---|---|---|---|
| Mode | $K^+\pi^-\pi^-$ | $K^0_S\pi^-\pi^0$ | $K^+\pi^-\pi^-\pi^0$ | |
| $K^-\pi^+\pi^+$ | 8,446<br>25.1%<br>*25* | 4,344<br>16.2%<br>*194* | 7,135<br>14.6%<br>*57* | |
| $K^0_S\pi^+\pi^0$ | | 521<br>10.0%<br>*40* | 1,736<br>9.1%<br>*120* | |
| $K^-\pi^+\pi^+\pi^0$ | | | 1,498<br>8.7%<br>*86* | |

# Systematics of Absolute BR Measurements

For CLEO-c projections we have estimated the systematic uncertainty of the efficiency, due to track finding.

CLEO II: 0.7% achieved in clean events.

CLEO-c: evaluate systematic error by partial reconstruction: (tag event), observe K-… require Missing Mass consistent with Pion. Compare with case of reconstructed Pion. --> MC study indicated 0.2% achievable by this method.

# Reach of double tag technology

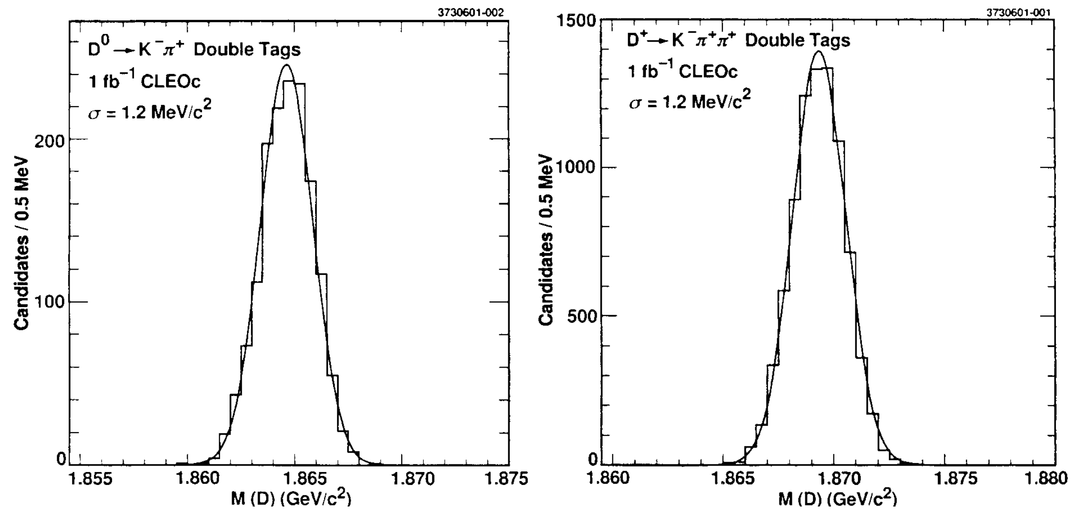



TABLE 15. Total number of double tag events and statistical precisions on absolute charm branching fractions for 3 fb$^{-1}$ of data for each type of $D$ meson.

| Particle | # of Double tags | Statistical Error | Systematic Error | Background Error | Total Error |
|---|---|---|---|---|---|
| $D^0$ Kπ | 53,000 | 0.4% | 0.4% | 0.06% | 0.6% |
| $D^+$ Kππ | 60,000 | 0.4% | 0.6% | 0.1% | 0.7% |
| $D_s^+$ φπ | 6,000 | 1.3% | 1.1% | 0.9% | 1.9% |

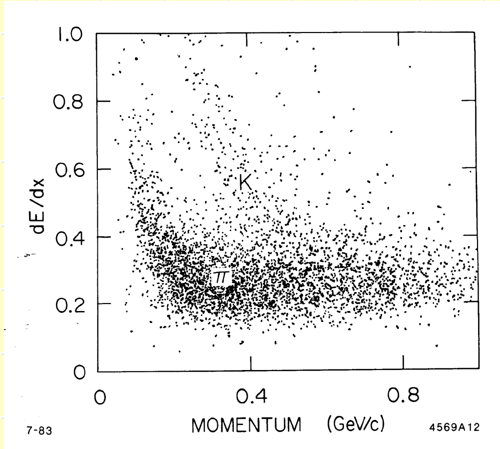
# 温故知新

Translation: “Study MARK III experience before plunging ahead with CLEo-c and BES III.”

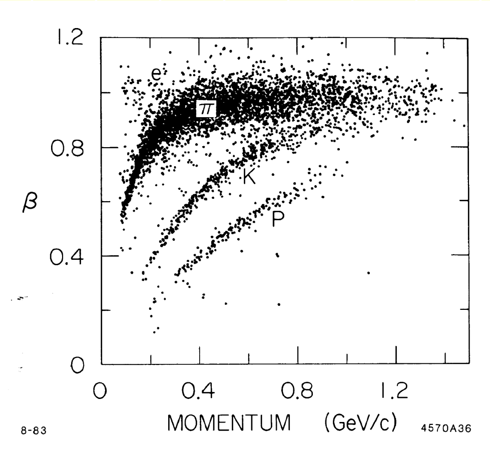
Original MARK III doubletagged BR measurements were wrong by 21-24% due to *unsubtracted* backgrounds:

| | | | |
|---|---|---|---|
| Feed-across: | D->KK, D->pipi | ---misID--> | D->Kpi |
| Feed-down: | D->Kpipi0 | ---pi0Loss--> | D->Kpi |

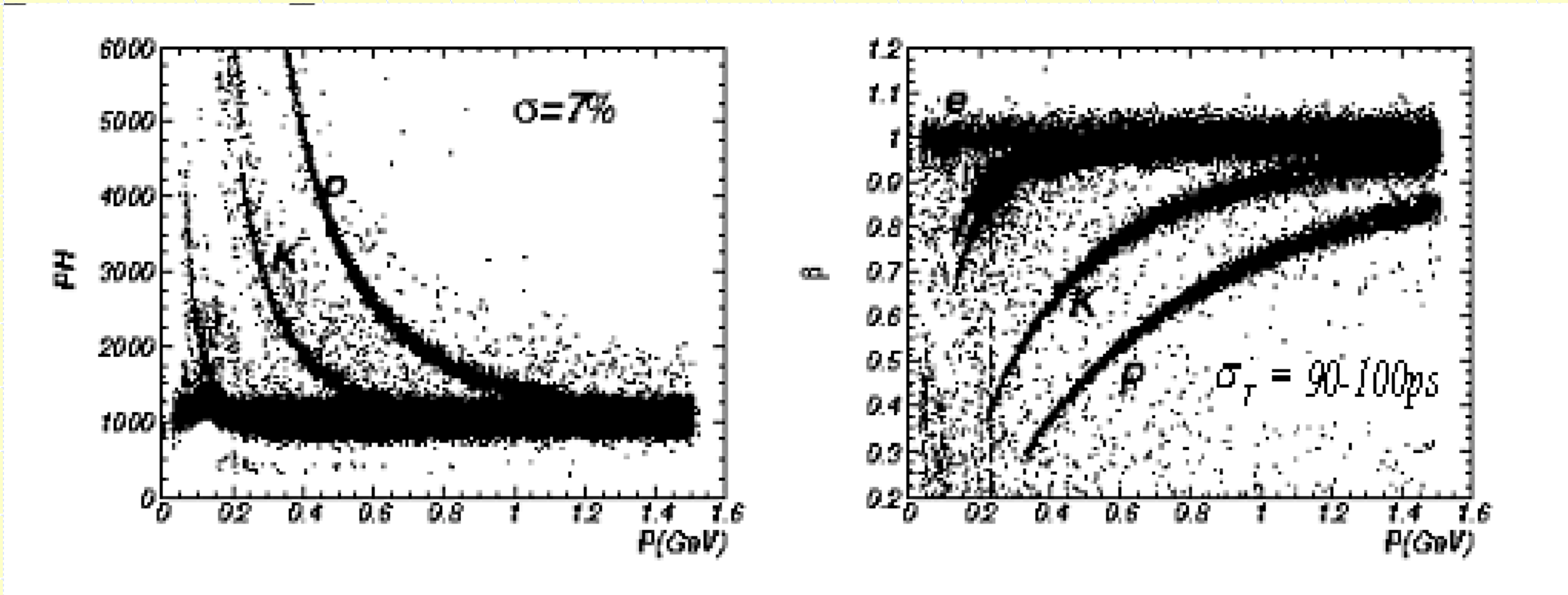
dE/dx resolution ~10%




TOF resolution 189ps



# BES III Particle ID



| | MARK III | CLEO-c | BES III |
|---|---|---|---|
| Momentum Resolution @500 MeV/c | 1.7% | 0.5% | 0.5% |
| dE/dx Resolution @min-I | 10% | 5-6% | 6-7% |
| RICH K/pi Separation @ 1GeV | - | ~20σ | - |
| TOF res | 190ps | - | 100ps |
| PID solid Angle | 75% | 90% | 90% |
| Photon E res @1GEV | 17% | 2.1% | 2.5% |

# Summary

Charm physics at threshold returns to center stage

Powerful, modern detectors (PID!  Pi0! Hermetic!)

High luminosity accelerators: 10-100M D decays possible

Absolute charm branching ratios will be measured with unprecedented precision: 1-2%