CLEO-c Measurements of Purely Leptonic Decays of Charmed Mesons

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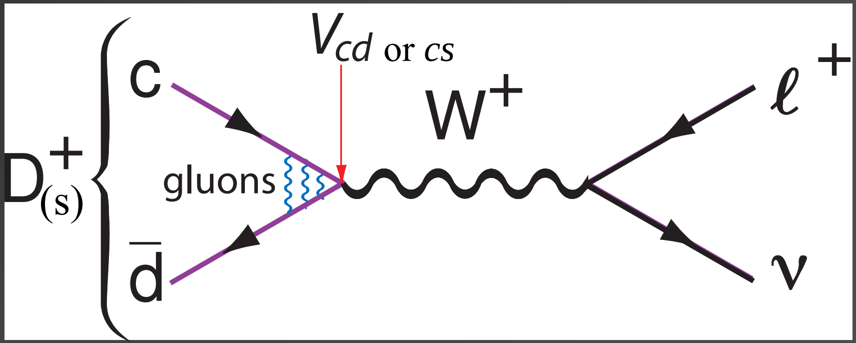
Leptonic Decays: $D \to \ell^+ \nu$

Introduction: Pseudoscalar decay constants

c and $\bar{q}$ can annihilate, probability is $\propto$ to wave function overlap

Example :



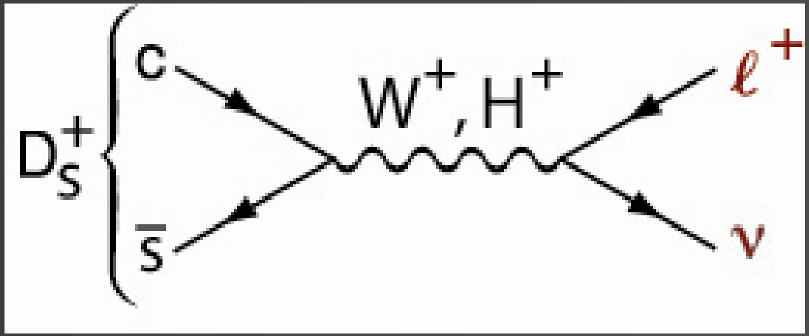
In general for all pseudoscalars:

$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if V_{Qq} is known

New Physics Possibilities

- Besides the obvious interest in comparing with Lattice & other calculations of f_P there are NP possibilities



- Another Gauge Boson

  could mediate decay

- Ratio of leptonic decays

  could be modified e.g. in Standard Model

$$\frac{\Gamma(P^+ \to \tau^+ \nu)}{\Gamma(P^+ \to \mu^+ \nu)} = m_\tau^2 \left(1 - \frac{m_\tau^2}{M_P^2}\right)^2 \Big/ m_\mu^2 \left(1 - \frac{m_\mu^2}{M_P^2}\right)^2$$

See Hewett [hep-ph/9505246] & Hou, PRD 48, 2342 (1993).

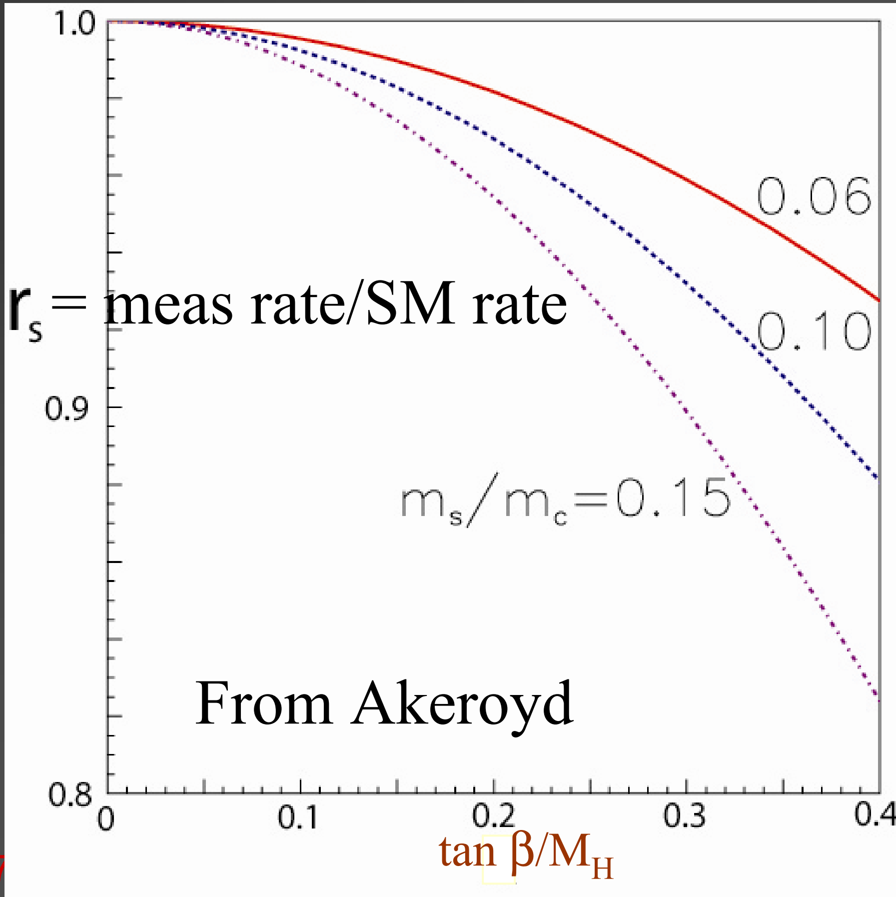
- If $H^\pm$ couples to $M^2 \Rightarrow$ no effect

New Physics Possibilities II

- Leptonic decay rate is modified by $H^{\pm}$
- Can calculate in SUSY as function of m_q/m_c,
- In 2HDM predicted decay width is x by

$$r_q = \left[1 - M_D^2 \left(\frac{\tan\beta}{M_{H^{\pm}}}\right)^2 \left(\frac{m_q}{m_c + m_q}\right)\right]^2$$

- Since m_d is ~0, effect can be seen only in D_s



See Akeryod [hep-ph/0308260]

Experimental methods

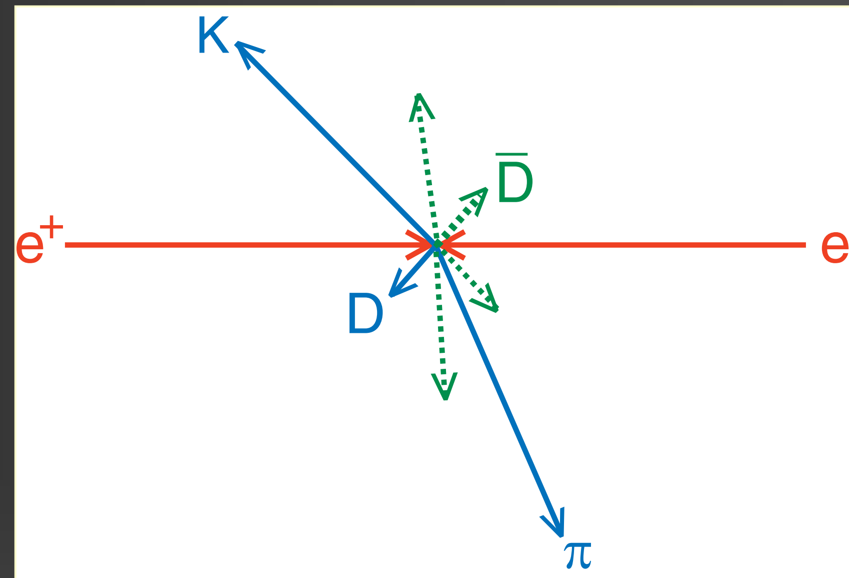
- $D\bar{D}$ production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.
  - Unique event properties
    - Only $D\bar{D}$ not $D\bar{D}x$ produced
  - Large cross sections:

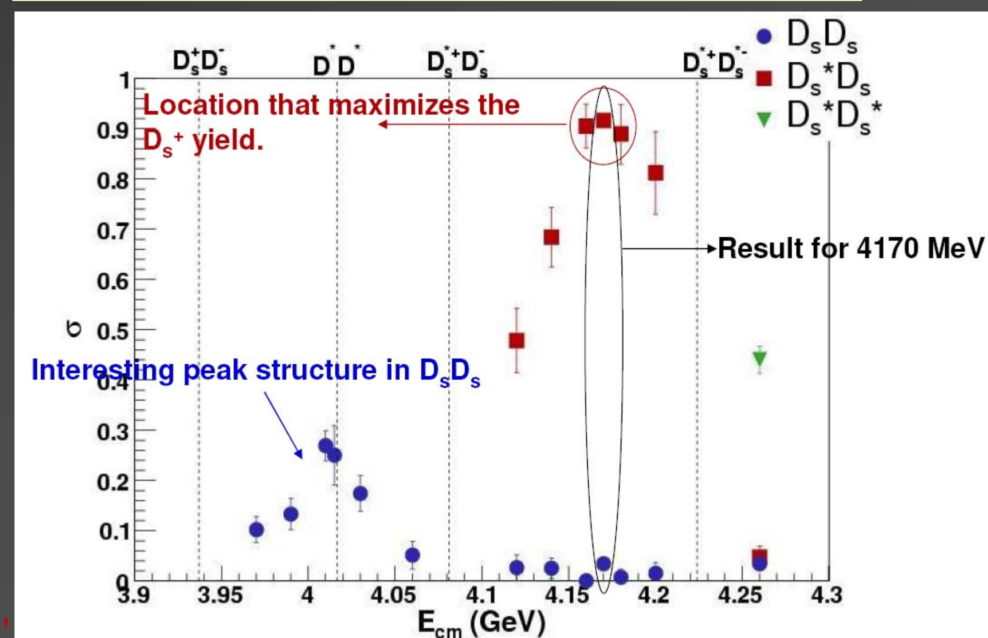
$\sigma(D^o\bar{D}^o)$ = 3.72±0.09 nb
$\sigma(D^+D^-)$ = 2.82±0.09 nb
(World Ave)

$\sigma(D_SD_S{}^*)$ = ~0.9 nb

Continuum ~12 nb

  - Ease of B measurements using "double tags"
  - $\mathcal{B}_A$ = # of A/# of D's





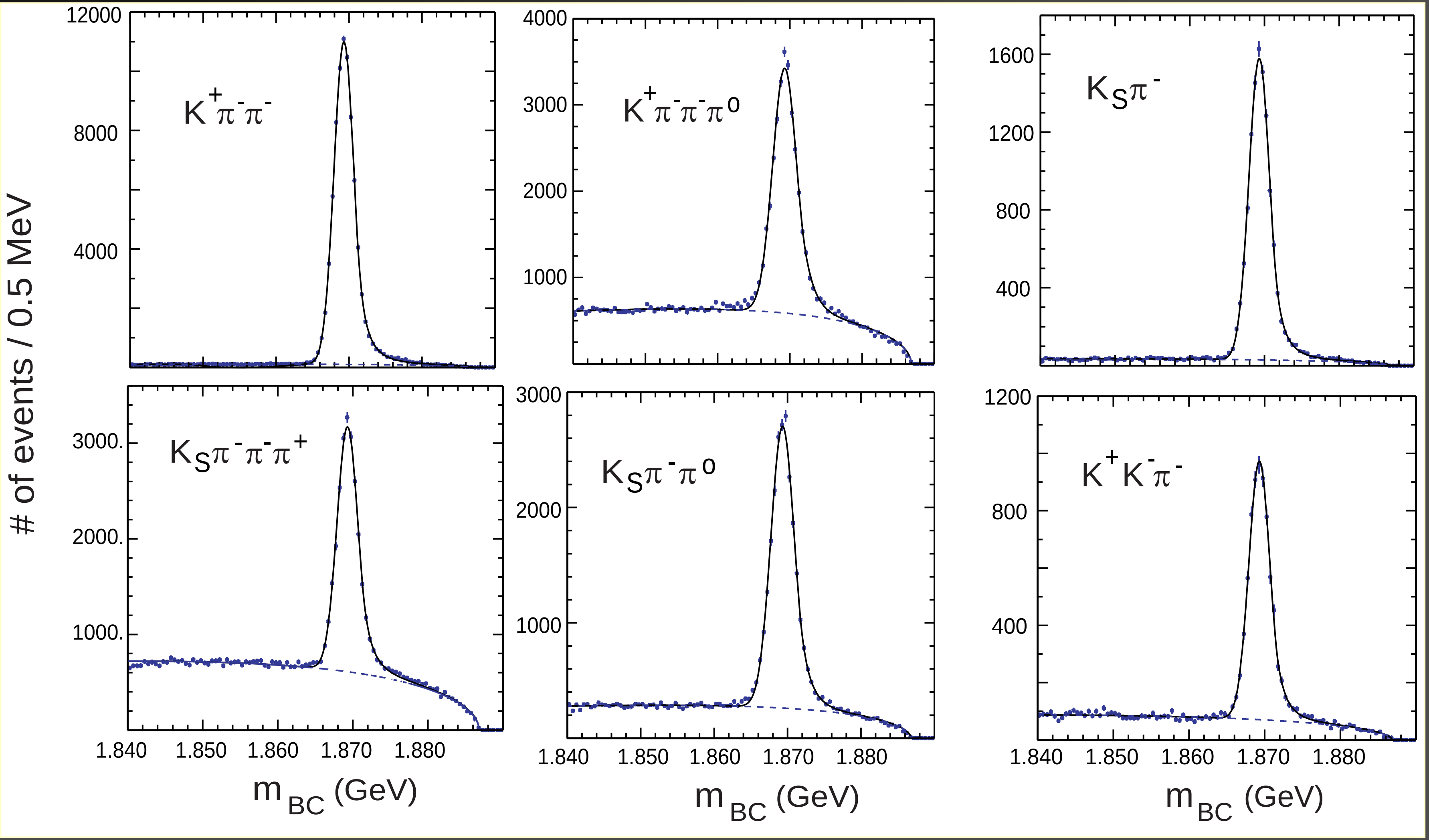
Technique for $D^+ \to \mu^+\nu$

- Fully reconstruct a D^-, and count total # of tags
- Seek events with only one additional oppositely charged track and no additional photons > 250 MeV (to veto $D^+ \to \pi^+\pi^o$)
- Charged track must deposit only minimum ionization in calorimeter
- Compute MM^2. If close to zero then almost certainly we have a $\mu^+\nu$ decay.

$$MM^2 = (E_{D^+} - E_{\ell^+})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+})^2$$

We know $E_{D^+} = E_{beam}$, $\mathbf{p}_{D^+} = -\mathbf{p}_{D^-}$

D^- Candidates (in 281 pb^{-1})

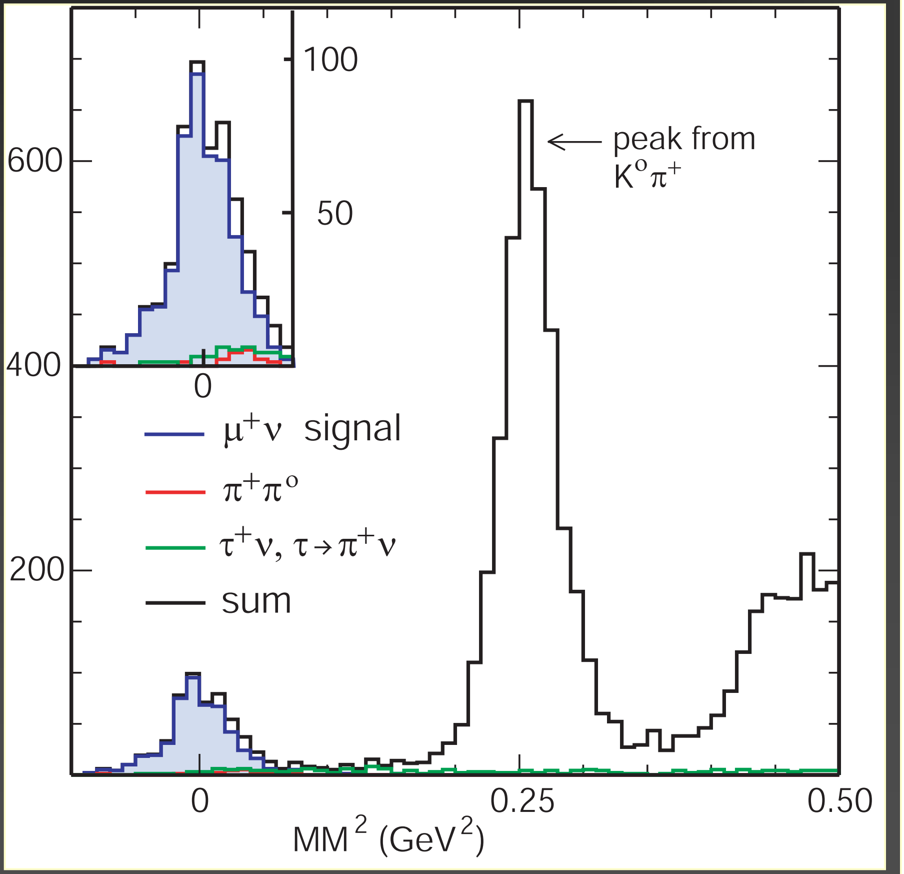


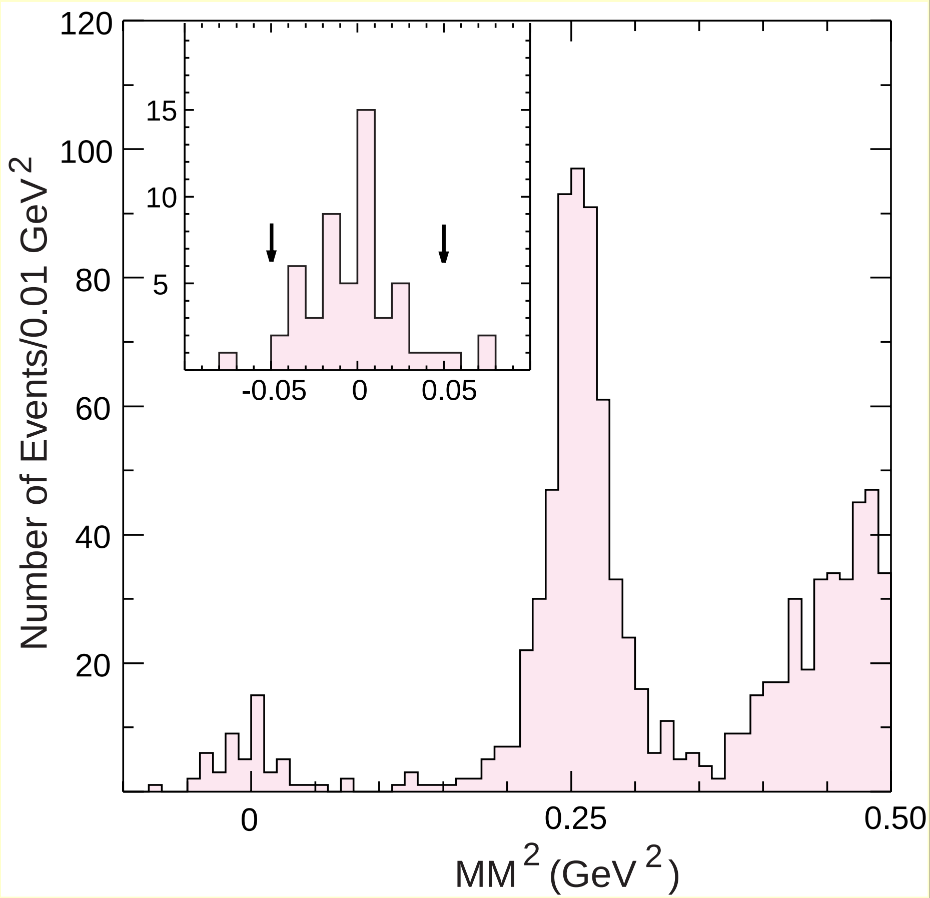
# of tags = 158,354±496, includes charge-conjugate modes

Measurement of f_{D^+}

MC Expectations from 1.7 fb^{-1}, 30 X of our data

Data: 50 events in the signal region in 281 pb^{-1}





Deriving a Value for f_{D^+}

Backgrounds		
Mode	$\mathcal{B}$(%)	# Events
$\pi^+\pi^0$	0.13±0.02	1.40±0.18±0.22
$K^0\pi^+$	2.77±0.18	0.33±0.19±0.02
$\tau^+\nu$ ($\tau \to \pi^+\nu$)	2.65*$\mathcal{B}(D^+ \to \mu^+\nu)$	1.08±0.15±0.16
Other D^+, D^o		<0.4, <0.4 @ 90% c.l.
Continuum		<1.2 @ 90% c.l.
Total		$2.81 \pm 0.30^{+0.84}_{-0.27}$

- There are 158,354 tags. ε= 67.7%
- $\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66^{+0.09}_{-0.12})\text{x}10^{-4}$
- $f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV $|V_{cd}|=.2238$
- $\mathcal{B}(D^+ \to e^+\nu) < 2.4\text{x}10^{-5}$ @ 90% c.l., rules out some non-Standard model theories

Efficiencies: μ^+ detection (69.4%); extra shower (96.1%); correction for easier tag reconstruction in $\mu^+\nu$ events (1.5%)

Systematic Errors

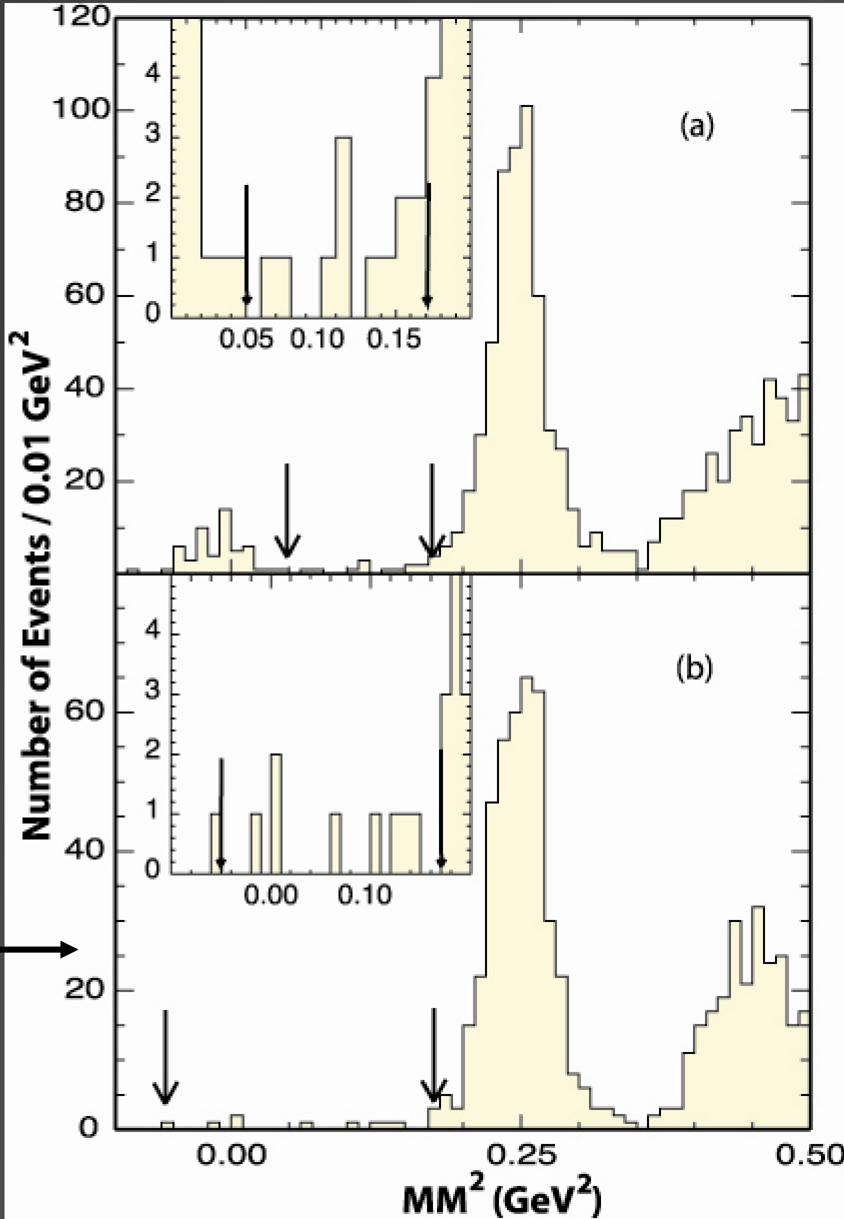
Source of Error	%
Finding the μ^+ track	0.7
Minimum ionization of μ^+ in EM cal	1.0
Particle identification of μ^+	1.0
MM^2 width	1.0
Extra showers in event > 250 MeV	0.5
Background	0.6
Number of single tag D^+	0.6
Monte Carlo statistics	0.4
Total	**2.1**

Upper limit on $D^+ \to \tau^+ \nu$

- By using intermediate MM^2 region
- $\mathcal{B}(D^+ \to \tau^+ \nu) < 2.1 \times 10^{-3}$
- $$\frac{\Gamma(D^+ \to \tau^+ \nu)}{\Gamma(D^+ \to \mu^+ \nu)} < 1.8x(2.65)$$
  - where 2.65 is SM expectation
  - both at 90% c.l

Ecal < 300 MeV

Ecal > 300 MeV

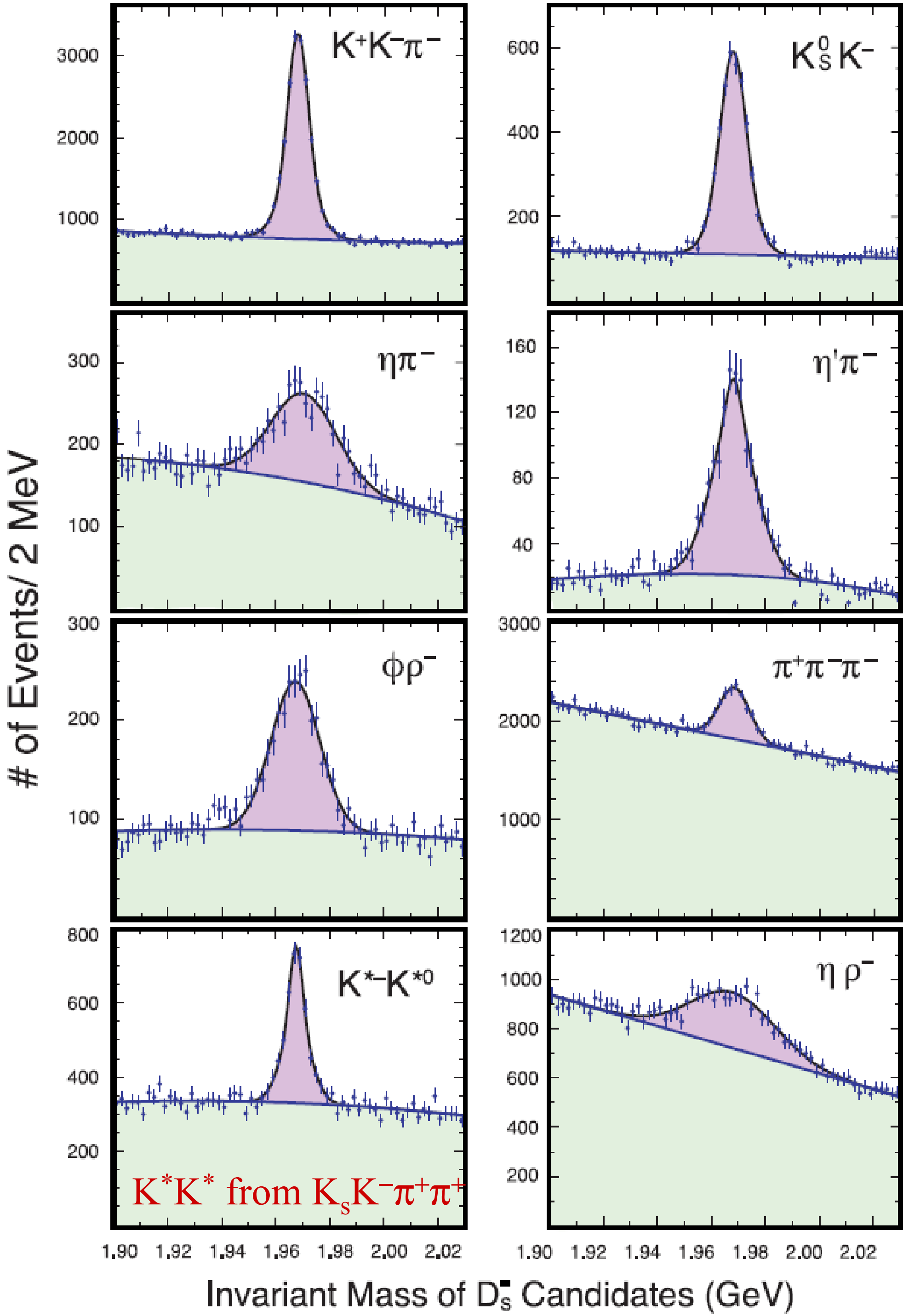


Measurements of f_{D_s}

- Two separate techniques. [Here expect in SM: $\Gamma(D_S \to \tau^+\nu)/\ \Gamma(D_S \to \mu^+\nu) = 9.72$]
  - (1) Measure $D_S^+ \to \mu^+\nu$ along with $D_S \to \tau^+\nu$, $\tau \to \pi^+\nu$. This requires finding a D_S^- tag, a γ from either $D_S^{*-} \to \gamma\, D_S^-$ or $D_S^{*+} \to \gamma\, \mu^+\nu$. Then find the muon or pion & apply kinematical constraints (mass & energy) to resolve this ambiguity & improve resolution (use 314 pb^{-1}, *results are published*)
  - (2) Find $D_S^+ \to \tau^+\nu$, $\tau \to e^+\nu\nu$ opposite a D_S^- tag (use 298 pb^{-1}, *results are final arXiv:0712.1175*)

Invariant masses

- $\mathcal{D}_S \rightarrow \mu^+\nu$ ***Study***
- D_S studies done at E_{cm}=4170 MeV
- To choose tag candidates:
  - Fit distributions & determine σ
  - Cut at ±2.5 σ
- Define sidebands to measure backgrounds 5-7.5 σ
- Total # of Tags
  = 31,302± 472 (stat)

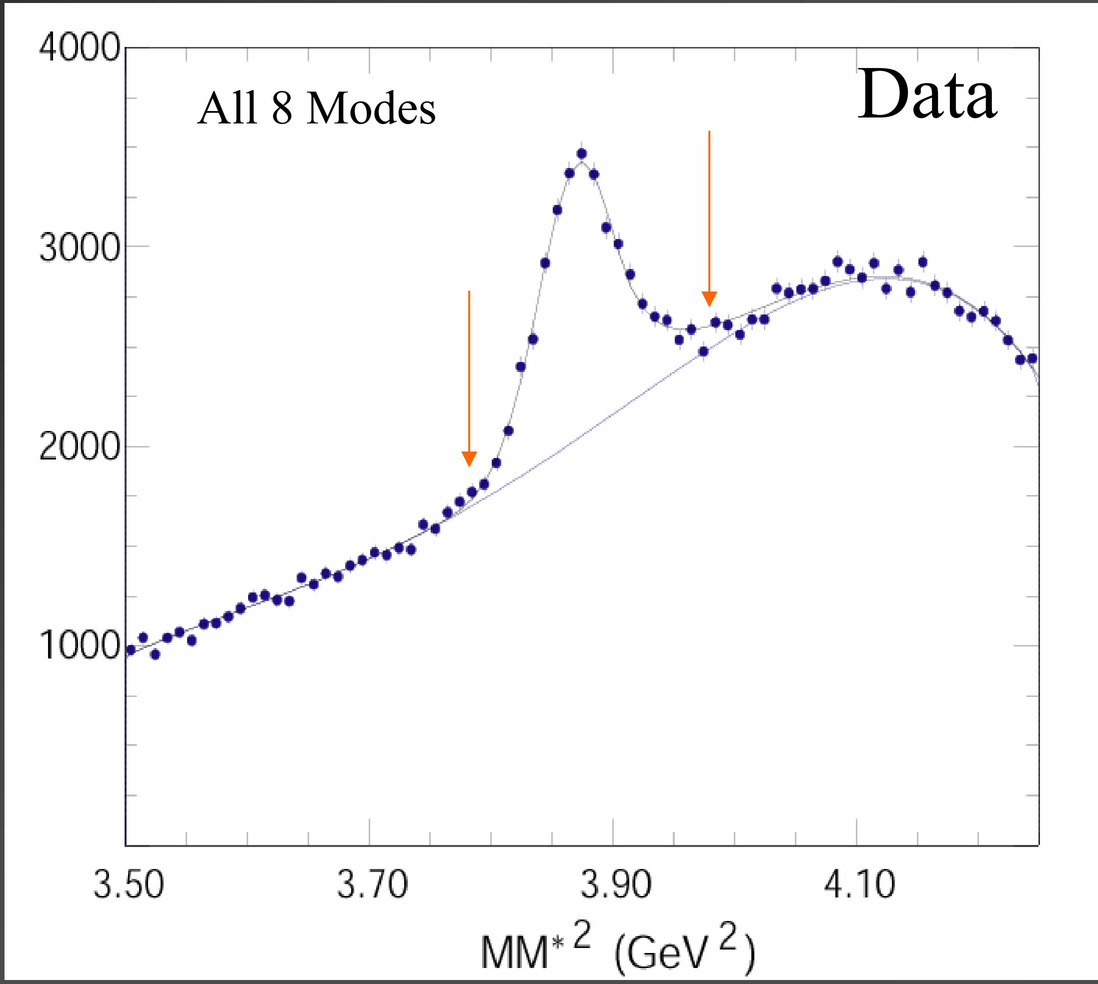


Tag Sample using γ

- First we define the tag sample by computing the MM*^{2} off of the γ & D_S tag

$$MM^{*2} = \left(E_{CM} - E_{D_s} - E_{\gamma}\right)^2 - \left(-\vec{p}_{D_s} - \vec{p}_{\gamma}\right)^2$$

- Total of 11880±399±504 tags, after the selection on MM*^{2}.



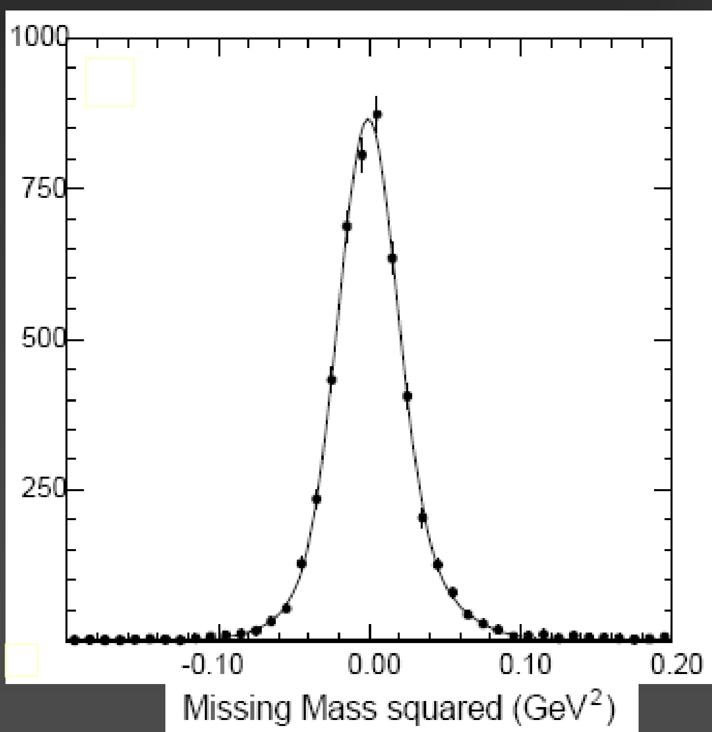
Define Three Classes

- Class (i), single track deposits < 300 MeV in calorimeter (consistent with μ) & no other $\gamma >$ 300 MeV. (accepts 99% of muons and 60% of kaons & pions)
- Class (ii), single track deposits > 300 MeV in calorimeter & no other $\gamma >$ 300 MeV (accepts 1% of muons and 40% of kaons & pions)
- Class (iii) single track consistent with electron & no other $\gamma >$ 300 MeV

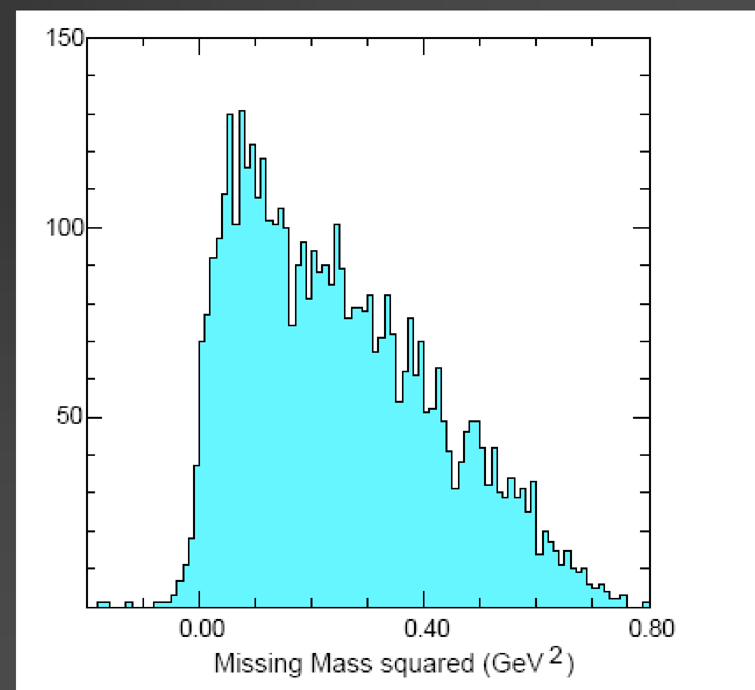
The MM^2

- To find the signal events, we compute

$$MM^2 = (E_{CM} - E_{D_S} - E_\gamma - E_\mu)^2 - (-\vec{p}_{D_S} - \vec{p}_\gamma - \vec{p}_\mu)^2$$



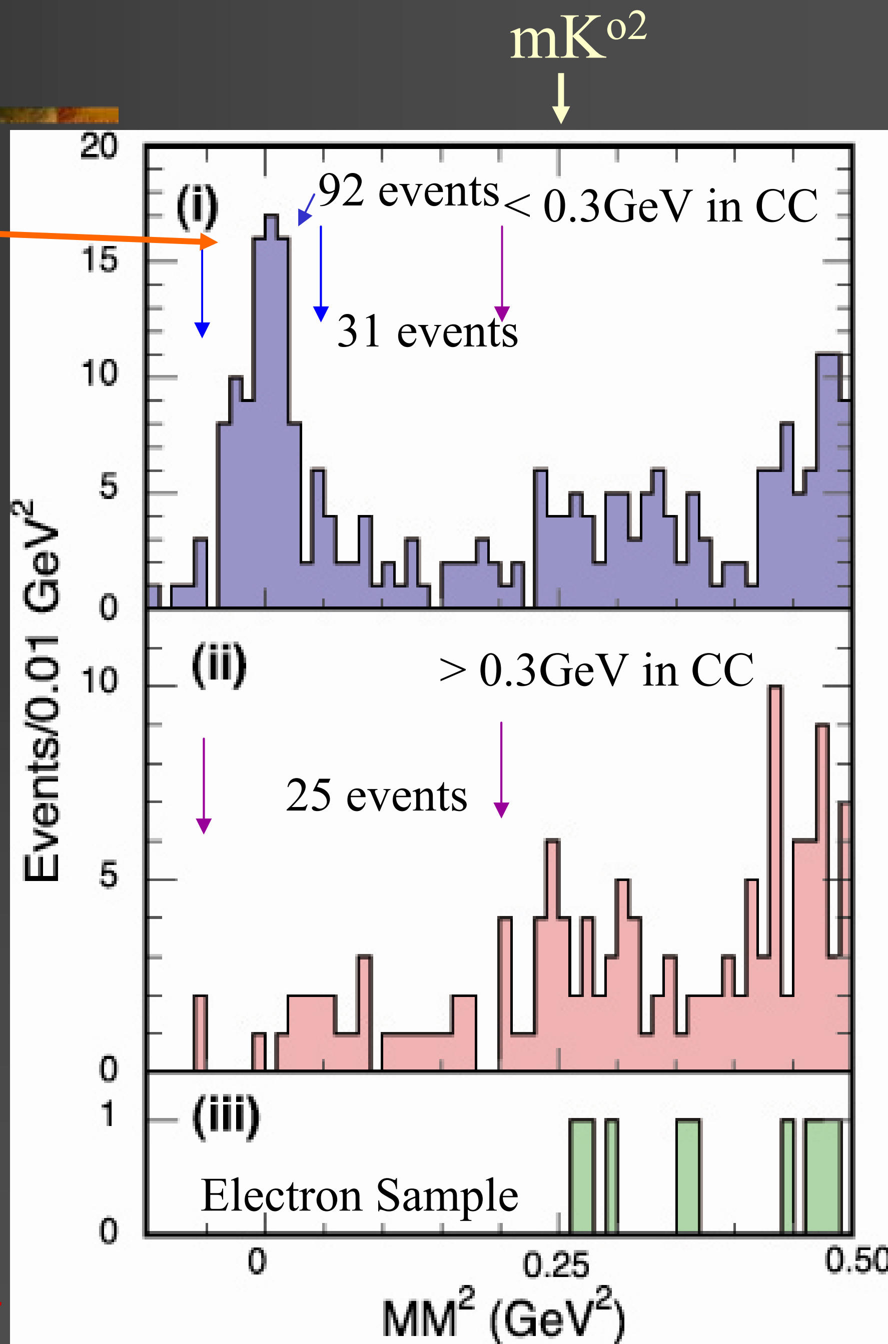
Monte Carlo Signal $\mu\nu$



Monte Carlo Signal $\tau\nu$, $\tau \rightarrow \pi\nu$

MM^2 In Data

- Clear $D_S^+ \to \mu^+ \nu$ signal for case (i)
- Most events <0.2 GeV^2 are $D_S \to \tau^+ \nu$, $\tau \to \pi^+ \nu$ in cases (i) & (ii)
- No $D_S \to e^+ \nu$ seen, case (iii)



Branching Ratio & Decay Constant

- $D_S^+ \to \mu^+ \nu$
  - 92 signal events, 3.5 background, use SM to calculate $\tau\nu$ yield near 0 MM^2 based on known $\tau\nu/\mu\nu$ ratio
  - $B(D_S^+ \to \mu^+ \nu) = (0.597 \pm 0.067 \pm 0.039)\%$
- $D_S^+ \to \tau^+ \nu$, $\tau^+ \to \pi^+ \nu$
  - Sum case (i) $0.2 > MM^2 > 0.05$ GeV^2 & case (ii) $MM^2 < 0.2$ GeV^2. Total of 56 signal and 8.6 bkgrnd
  - $B(D_S^+ \to \tau^+ \nu) = (8.0 \pm 1.3 \pm 0.4)\%$
- By summing both cases above, find

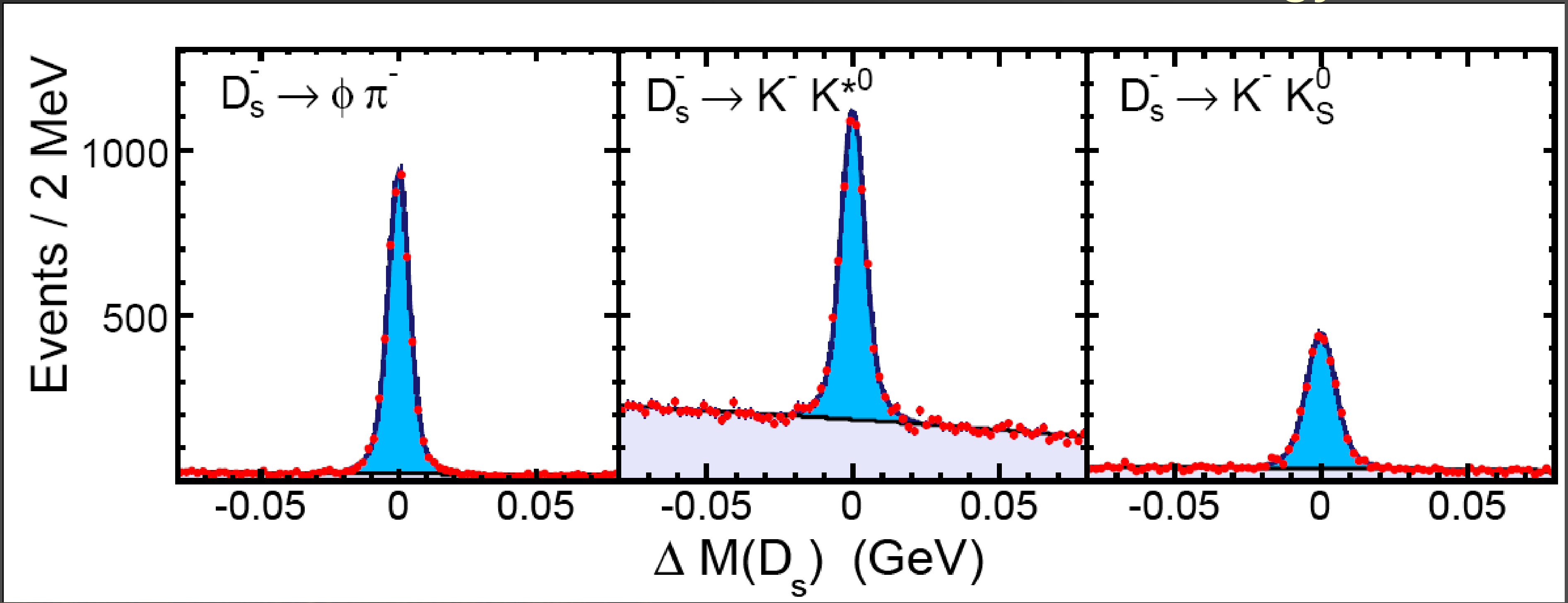
  $B^{eff}(D_S^+ \to \mu^+ \nu) = (0.638 \pm 0.059 \pm 0.033)\%$
- $f_{Ds} = 274 \pm 13 \pm 7$ MeV, for $|V_{cs}| = 0.9738$
- $B(D_S^+ \to e^+ \nu) < 1.3 \times 10^{-4}$

$\mathcal{B}(D_s^+ \to \mu^+ \nu)$ Systematic errors

Error Source	Size (%)
Track finding	0.7
Photon veto	1
Minimum ionization	1
Number of tags	5
Total	5.2

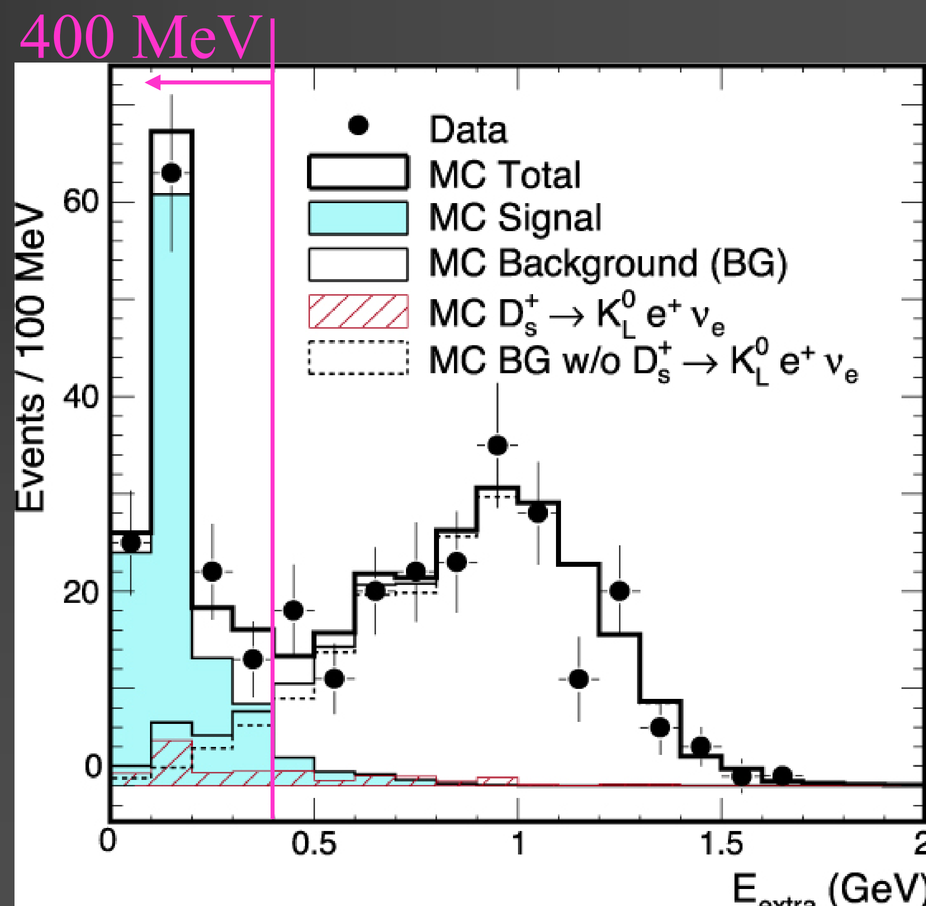
Measuring $D_S^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

- $B(D_S^+ \to \tau^+\nu) \bullet B(\tau^+ \to e^+\nu\nu) \sim 1.3\%$ is "large" compared with expected $B(D_S^+ \to Xe^+\nu) \sim 8\%$
- We will be searching for events opposite a tag with one electron and not much other energy



Measuring $D_S^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

- Technique is to find events with an e^+ opposite D_S^- tags & no other tracks, with Σ calorimeter energy < 400 MeV
- No need to find γ from D_S^*
- $B(D_S^+ \to \tau^+\nu) = (6.17 \pm 0.71 \pm 0.36)\%$
- $f_{Ds} = 273 \pm 16 \pm 8$ MeV



f_{D_s} & f_{D_s} / f_{D^+}

- Weighted Average: f_{Ds}=274±10±5 MeV, the systematic error is mostly uncorrelated between the measurements
- Using $f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV[†]

  M. Artuso et al., Phys .Rev. Lett. 95 (2005) 251801
- [†] f_{Ds}/f_{D^+}=1.23±0.10±0.03
- $\Gamma(D_S^+ \to \tau^+ \nu)/\Gamma(D_S^+ \to \mu^+ \nu)$=

  11.0±1.4±0.6, SM=9.72,

  consistent with lepton universality

Radiative Corrections

- Not just final state radiation which is already corrected for.
- Includes $D \rightarrow D^* \rightarrow \gamma D \rightarrow \gamma \mu^+ \nu$. Based on calculations of Burdman et al.
- $\Gamma(D_{(S)}{}^+ \rightarrow \gamma \mu^+ \nu) / \Gamma(D_{(S)}{}^+ \rightarrow \mu^+ \nu) \sim 1/40 - 1/100$
- Using narrow MM^2 region makes this much smaller
- Other authors in general agreement, see Hwang Eur. Phys. J. C46, 379 (2006), except Korchemsky, Pirjol & Yan PRD 61, 114510 (2000)
- Wang, Chang & Feng [hep-ph/0102251] find a -8% correction for $\Gamma(D_S \rightarrow \tau^+ \nu)$, negligible for $\Gamma(D_S \rightarrow \mu^+ \nu)$.
- Somebody please help!

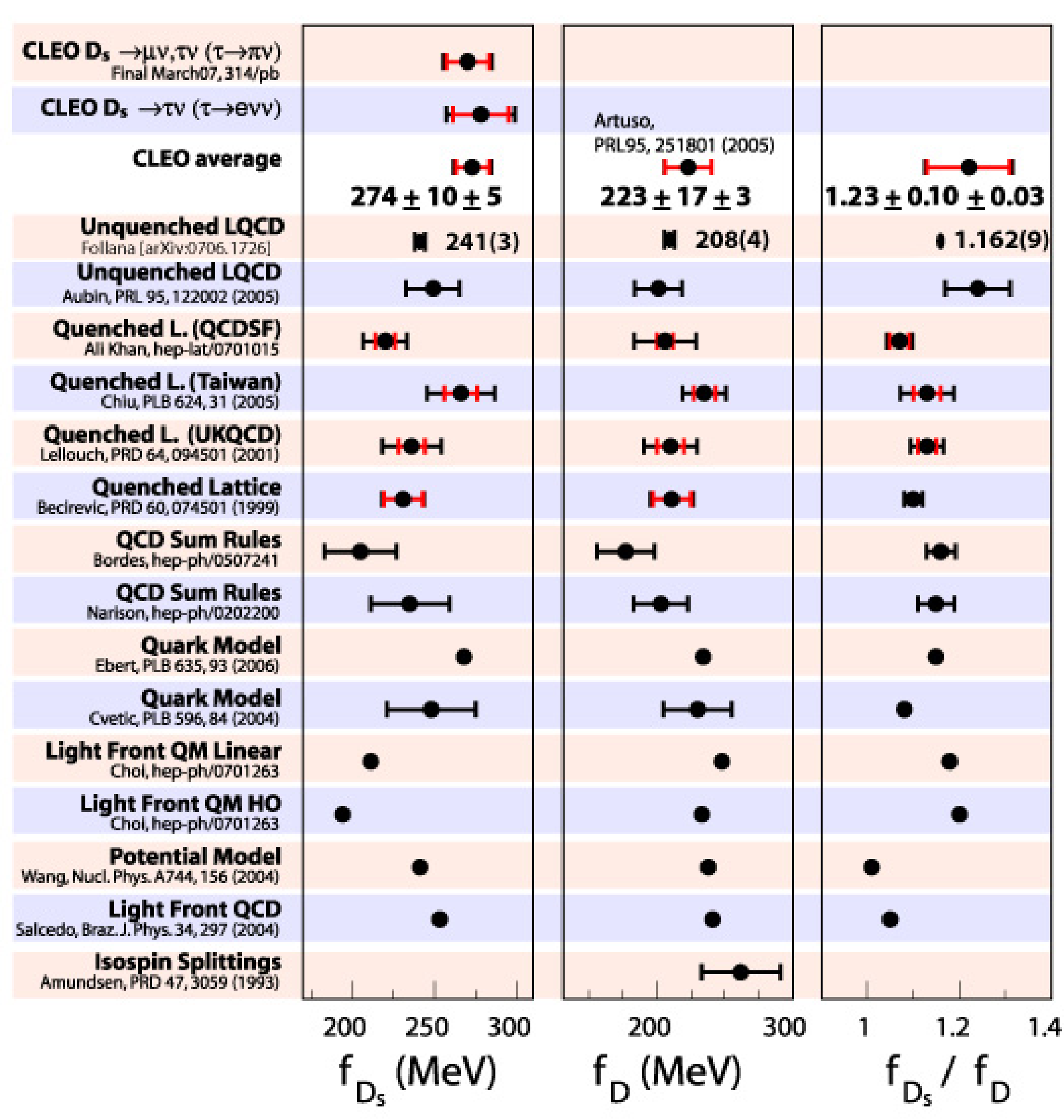
Comparison with Other Experiments

Exp.	Mode	$\mathcal{B}_{\phi\pi}$ (%)	$f_{D_s^+}$ (MeV)
CLEO-c	$\mu^+\nu$ [7]		$264 \pm 15 \pm 7$
CLEO-c	$\tau^+\nu$ [7]		$310 \pm 25 \pm 8$
CLEO-c	$\tau^+\nu$ [8]		$273 \pm 16 \pm 8$
CLEO-c	combined		$274 \pm 10 \pm 5$
Belle [9]	$\mu^+\nu$	preliminary Manchester EPS	$275 \pm 16 \pm 12$
Average			274 ± 10
CLEO [10]	$\mu^+\nu$	3.6±0.9	$273 \pm 19 \pm 27 \pm 33$
BEATRICE [11]	$\mu^+\nu$	3.6±0.9	$312 \pm 43 \pm 12 \pm 39$
ALEPH [12]	$\mu^+\nu$	3.6±0.9	$282 \pm 19 \pm 40$
ALEPH [12]	$\tau^+\nu$		
L3 [13]	$\tau^+\nu$		$299 \pm 57 \pm 32 \pm 37$
OPAL [14]	$\tau^+\nu$		$283 \pm 44 \pm 41$
BaBar [15]	$\mu^+\nu$	4.71±0.46	$283 \pm 17 \pm 7 \pm 14$

- CLEO-c is most precise result to date for both f_{D_s} & f_{D^+}

Comparisons with Theory

- We are ~3σ above Follana et al. Either:
  - Calculation is wrong
  - There is new physics that interferes constructively with SM
  - Note: No value of M_H is allowed in 2HDM at 99.5% c.ℓ.
- Comparing measured f_{D_S}/f_{D^+} with Follana prediction we find m_H>2.2 GeV tanβ
- Using Follana ratio find $|V_{cd}/V_{cs}|$=0.217±0.019 (exp) ±0.002(theory)



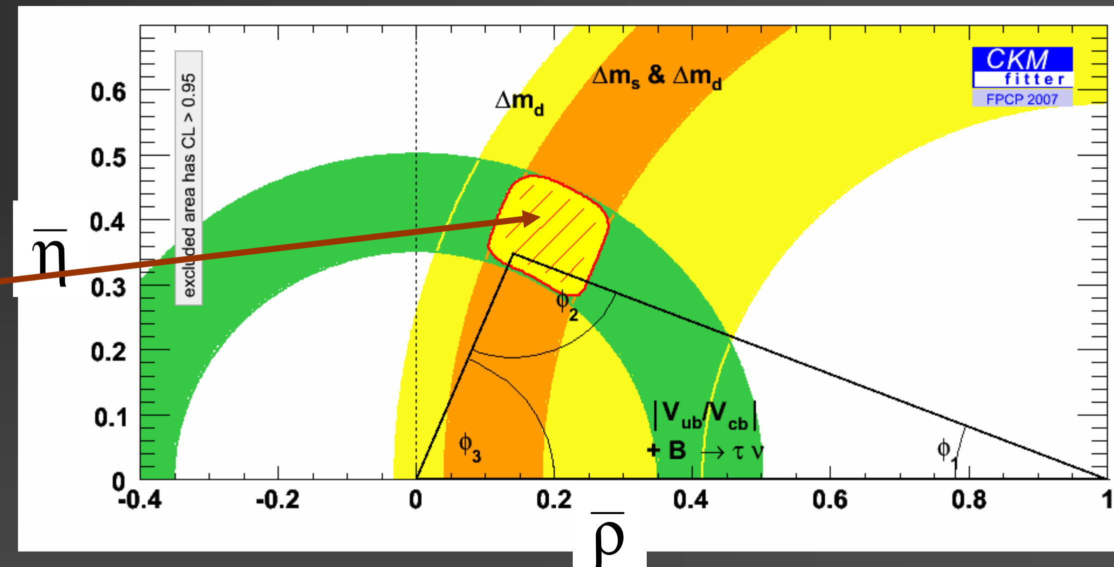
Projections

- We will almost triple the D^+ sample, including some improvements in technique, error in f_{D^+} should decrease to ~3.7% (8 MeV)
- We will likely double the D_S sample, may improve technique, expect error in f_{Ds} to decrease to ~2.6% (7 MeV)

The End

Goals in Leptonic Decays

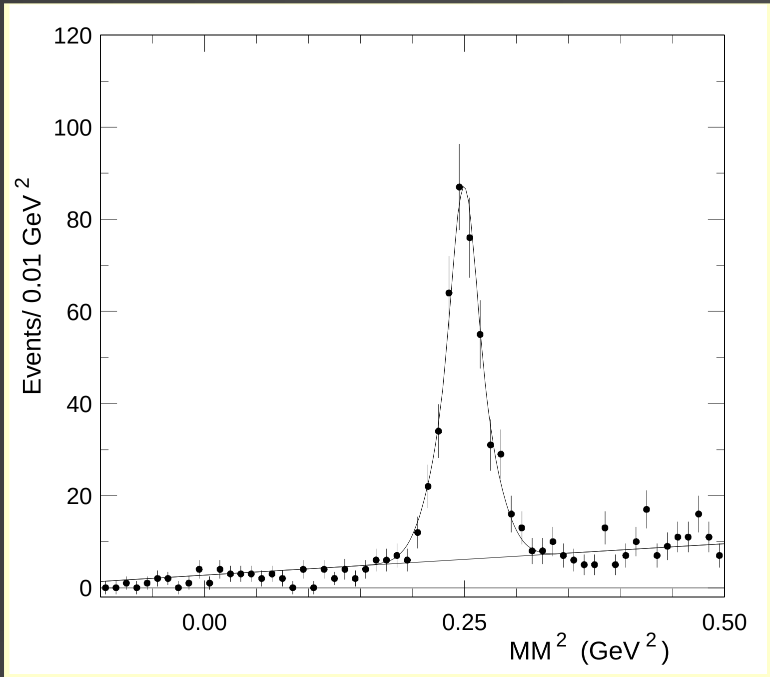
- Test theoretical calculations in strongly coupled theories in non-perturbative regime
- f_B & f_{Bs}/f_B needed to improve constraints from Δm_d & $\Delta m_S/\Delta m_d$. Hard to measure directly (i.e. $B \to \tau^+\nu$ gives $V_{ub}f_B$), but we can determine f_D & f_{Ds} using $D\to\ell^+\nu$ and use them to test theoretical models (i.e. Lattice QCD)



Constraints from V_{ub}, Δm_d, Δm_s & $B \to \tau^+\nu$

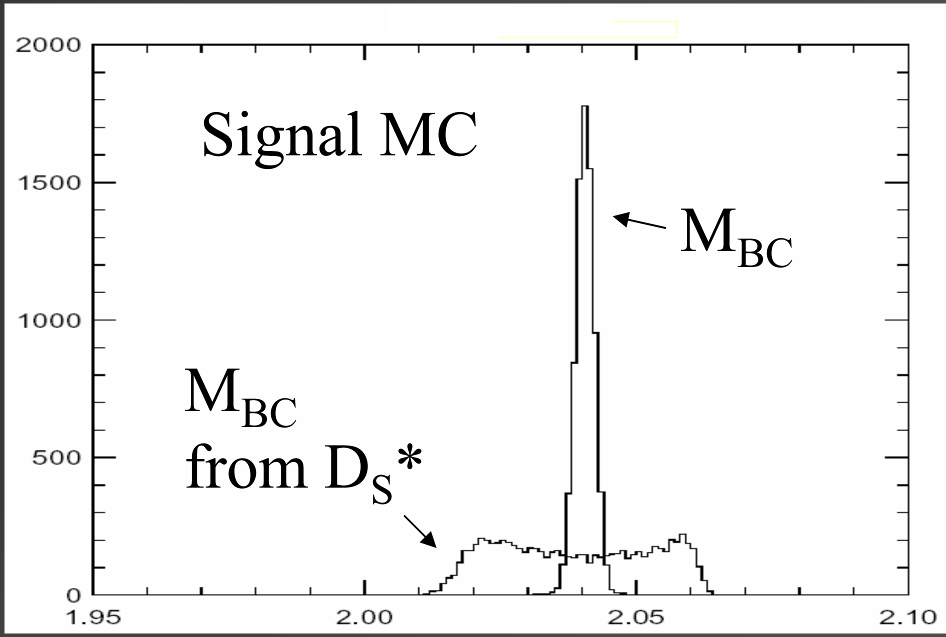
Check: $\mathcal{B}(D_s^+ \rightarrow K^+ K^o)$

- Do almost the same analysis but consider MM^2 off of an identified K^+
- Allow extra charged tracks and showers so not to veto K^o decays or interactions in EM
- Signal verifies expected MM^2 resolution
- Find (2.90±0.19±0.18)%, compared with result from double tags (3.00±0.19±0.10)%



CLEO D_S^+ Results at 4170 MeV

- Since $e^+e^-\to D_S^* D_S$, the D_S from the D_S^* will be smeared in beam-constrained mass.
- $M_{BC}^2 = E_{beam}^2 - \sum_i \vec{p}_i^2$
- $\therefore$ cut on M_{BC} & plot invariant mass (equivalent to a p cut)
- We use 314 pb^{-1} of data



Beam Constrained Mass (GeV)

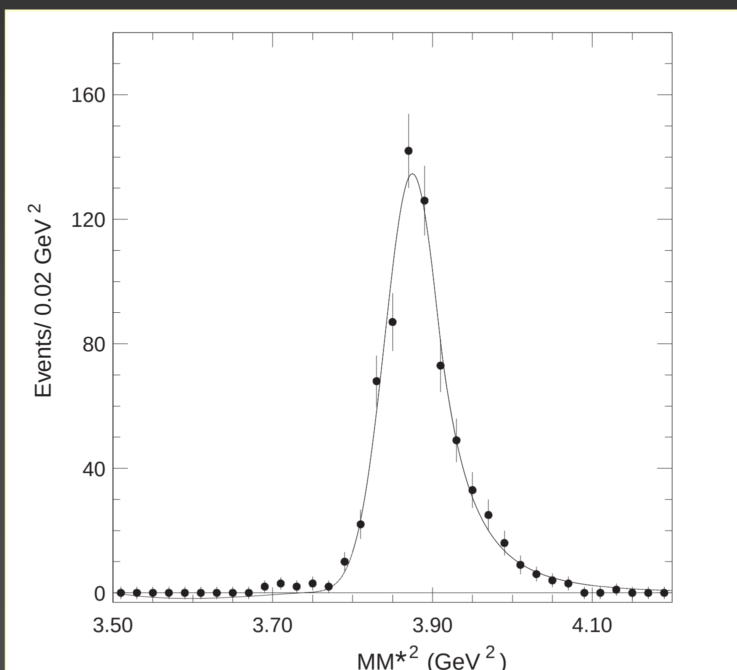
#Tags: $D_s + \gamma$

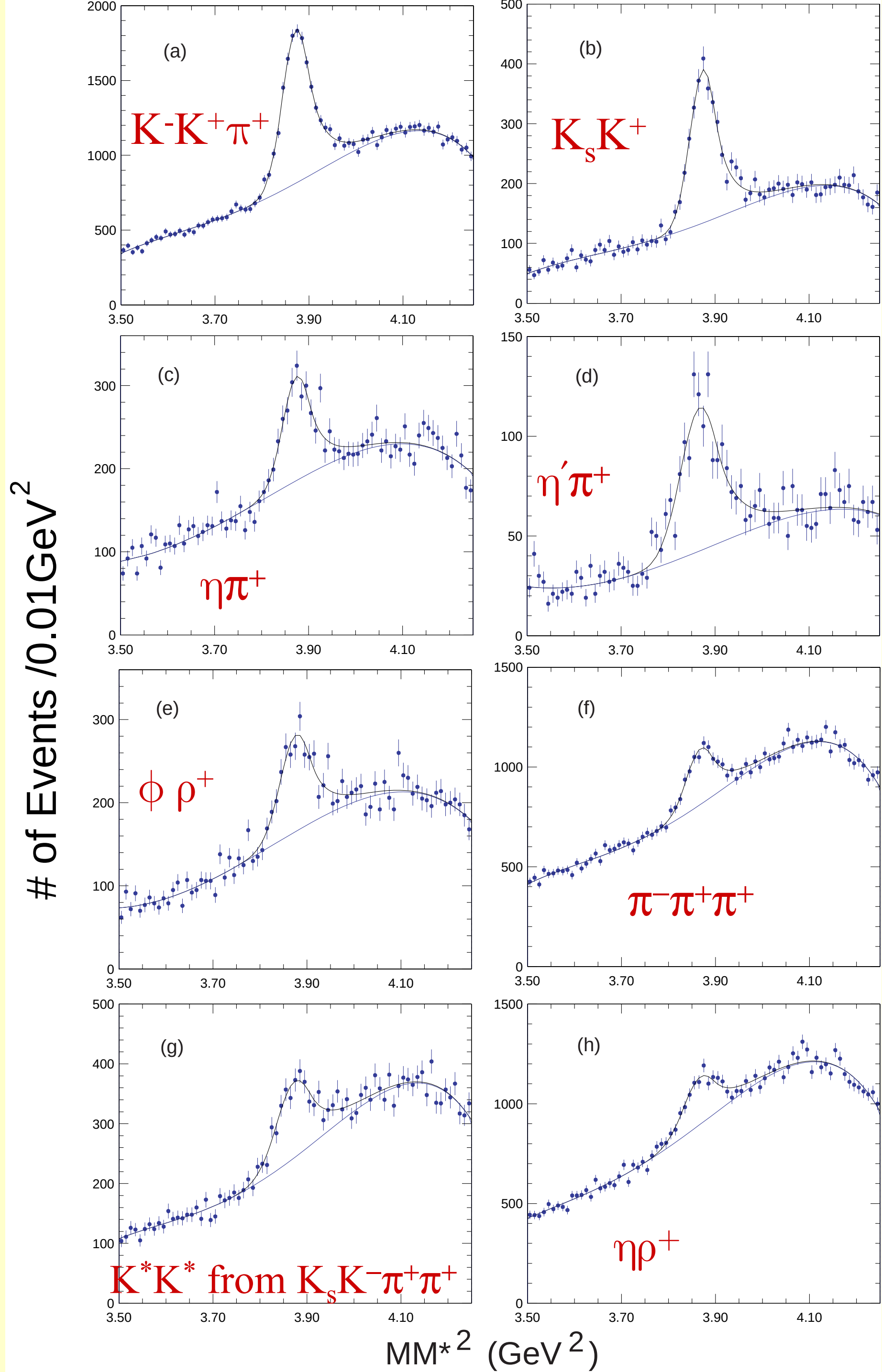
- Compute MM^{*2}

$$MM^{*2} = \left(E_{CM} - E_{D_s} - E_\gamma\right)^2 - \left(-\vec{p}_{D_s} - \vec{p}_\gamma\right)^2$$

in each individual mode

- Use $D_S^*D_S$ sample to measure shape of tail





Measurement of $D_S^+ \to \mu^+\nu$

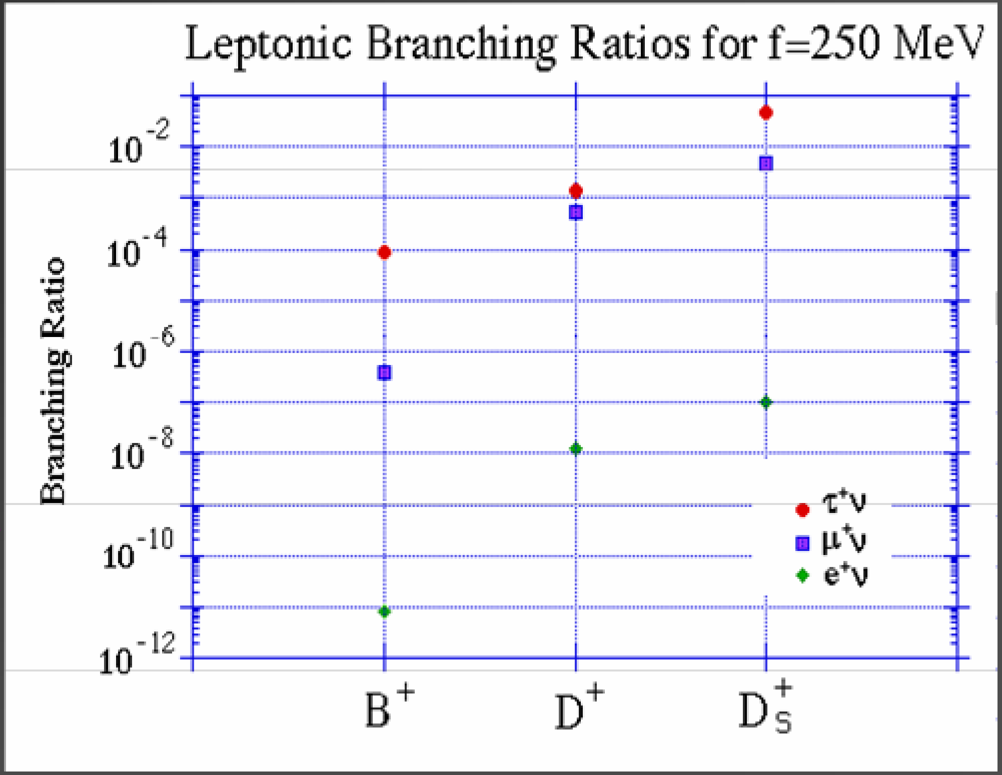
- In this analysis we use $D_S^* D_S$ events where we detect the γ from the $D_S^* \to \gamma D_S$ decay
- We see all the particles from $e^+e^- \to D_S^* D_S$, γ, D_S (tag) + μ^+ except for the ν
- We use a kinematic fit to (a) improve the resolution & (b) remove ambiguities
  - Constraints include: total p & E, tag D_S mass, $\Delta m = M(\gamma D_S) - M(D_S)$ [or $\Delta m = M(\gamma\mu\nu) - M(\mu\nu)$] = 143.6 MeV, E of D_S (or D_S^*) fixed
  - Lowest χ^2 solution in each event is kept
  - No χ^2 cut is applied

Expected $\mathcal{B}$ for $P^+ \to \ell^+ \nu$ decays

- We know:

  f_π = 131.73±0.15 MeV

  f_K= 160.6±1.3 MeV
- The D_s has the largest $\mathcal{B}$, for $\mu^+\nu$ rate is ~0.5%
- f_{Ds} Measured by several groups, best CLEO II, but still poorly known
- $e^+\nu$ rate is ~4 orders of magnitude smaller than $\mu^+\nu$, in the Standard Model



Combining Semileptonics & Leptonics

- Semileptonic decay rate into Pseudoscalar:

$$\frac{d\Gamma\left(D \to Pe\nu\right)}{dq^2} = \frac{\left|V_{cq}\right|^2 P_P^3}{24\pi^3}\left|f_+(q^2)\right|^2$$

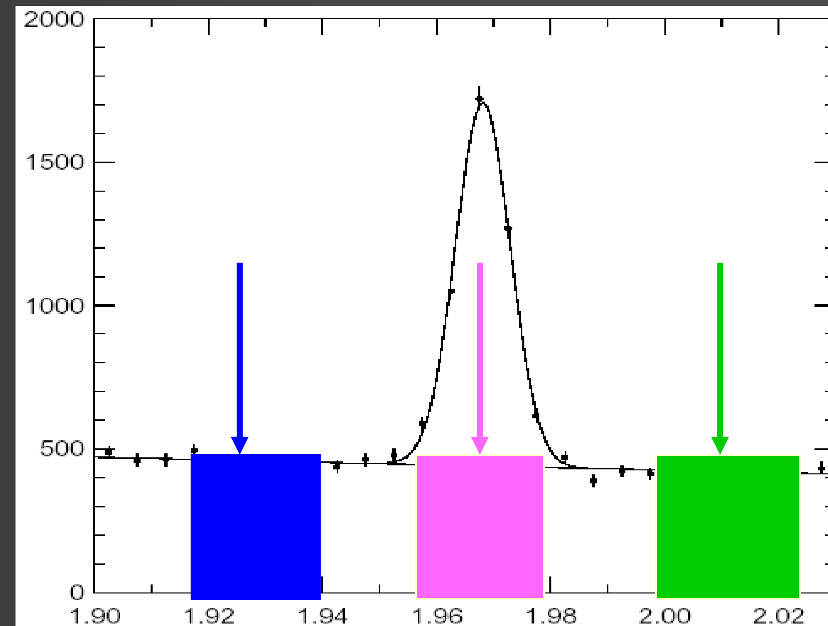
- Note that the ratio below depends only on QCD:

$$\frac{1}{\Gamma\left(D^+ \to \ell\nu\right)}\frac{d\Gamma\left(D^+ \to \pi e\nu\right)}{dq^2} \;\alpha\; \frac{P_\pi^3\left|f_+(q^2)\right|^2}{f_{D^+}^2}$$

Background Samples

- Two sources of background
- A) Backgrounds under invariant mass peaks – Use sidebands to estimate
- In $\mu^+\nu$ signal region 3.5 background (92 total)
- bkgrnd MM^2<0.20 GeV^2= 9.0±2.3
- B) Backgrounds from real D_S decays, e.g. $\pi^+\pi^o\pi^o$, or $D_S \rightarrow \tau^+\nu$, $\tau \rightarrow \pi^+\pi^o\nu$.... < 0.2 GeV^2, none in $\mu\nu$ signal region
- B($D_S \rightarrow \pi^+\pi^o$) < 1.1x10^{-3} &

γ energy cut yields <0.2 evts



Low SB region | Signal region | High SB region

Backgrounds from real D_S^+

TABLE III: Backgrounds in the $D_s^+ \rightarrow \tau^+\nu$, $\tau^+ \rightarrow \pi^+\overline{\nu}$ sample for correctly reconstructed tags, case (i) for 0.05<MM^2 < 0.20 GeV^2 and case (ii) for -0.05<MM^2 < 0.20 GeV^2.

Source	$\mathcal{B}$(%)	# of events case (i)	# of events case(ii)	Sum
$D_s^+ \rightarrow X\mu^+\nu$	8.2	$0^{+1.8}_{-0}$	0	$0^{+1.8}_{-0}$
$D_s^+ \rightarrow \pi^+\pi^0\pi^0$	1.0	0.03±0.04	0.08±0.03	0.11±0.04
$D_s^+ \rightarrow \tau^+\nu$	6.4			
$\tau^+ \rightarrow \pi^+\pi^0\overline{\nu}$	1.5	0.55±0.22	0.64±0.24	1.20±0.33
$\tau^+ \rightarrow \mu^+\overline{\nu}\nu$	1.0	0.37±0.15	0	0.37±0.15
Sum		$1.0^{+1.8}_{-0}$	0.7±0.2	$1.7^{+1.8}_{-0.4}$

Sum of $D_S^+ \to \mu^+\nu + \tau^+\nu$, $\tau \to \pi^+\nu$

- As we will see, there is very little background present in any sub-sample for $MM^2 < 0.2$ GeV^2