CLEO-c Measurements of Purely Leptonic Decays of Charmed Mesons & other Wonders

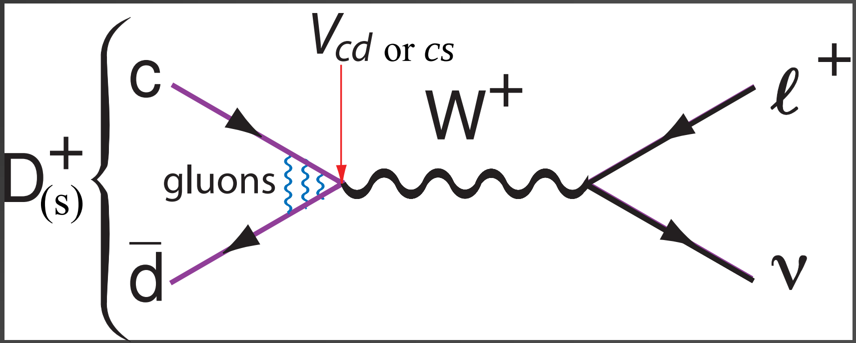
Sheldon Stone,
Syracuse University

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

Introduction: Pseudoscalar decay constants

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

Example :



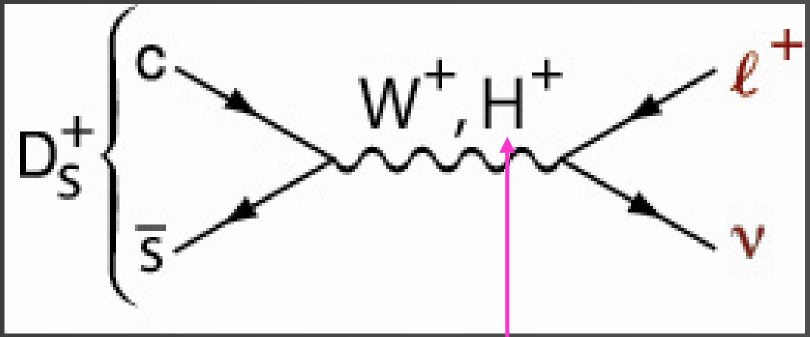
In general for all pseudoscalars:

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

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
- Or leptoquarks (see Kronfeld's talk)
- 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).

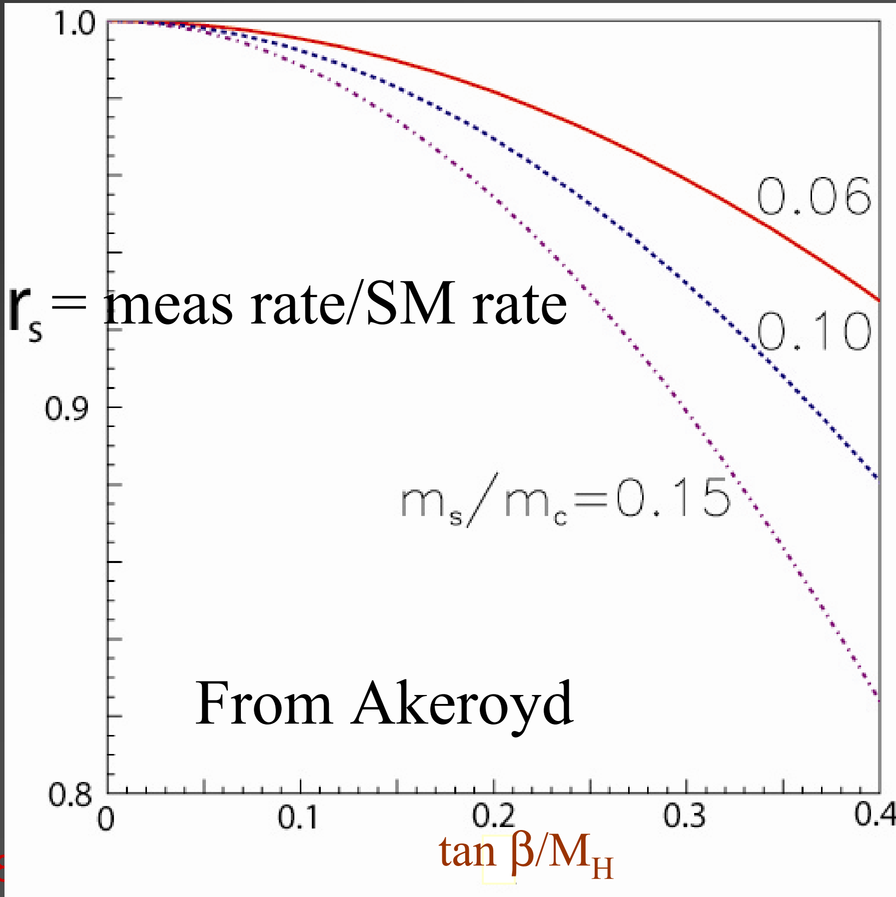
- If $H^\pm$ couples to $M^2 \Rightarrow$ no effect

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

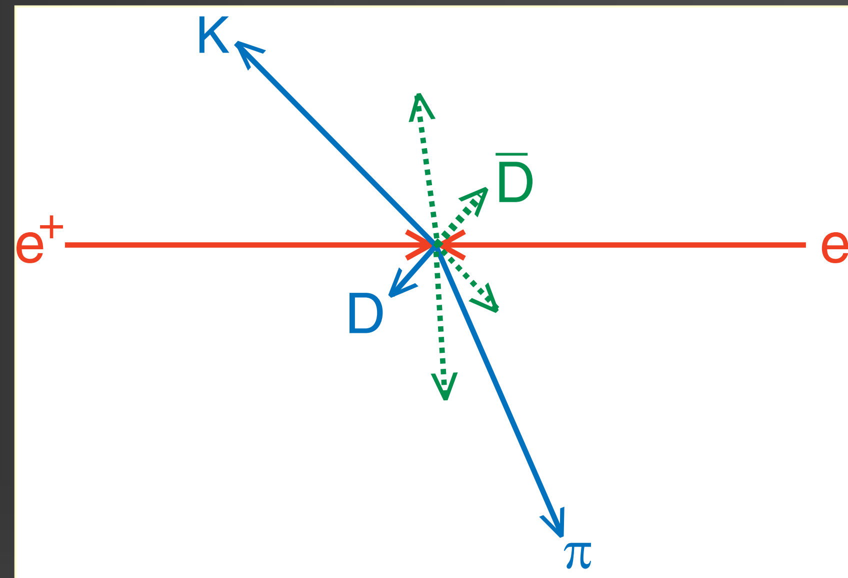
- $D\bar{D}$ production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.
  - Unique event properties
    - Only $D\bar{D}$ not $D\bar{D}x$ produced
  - Large cross sections:

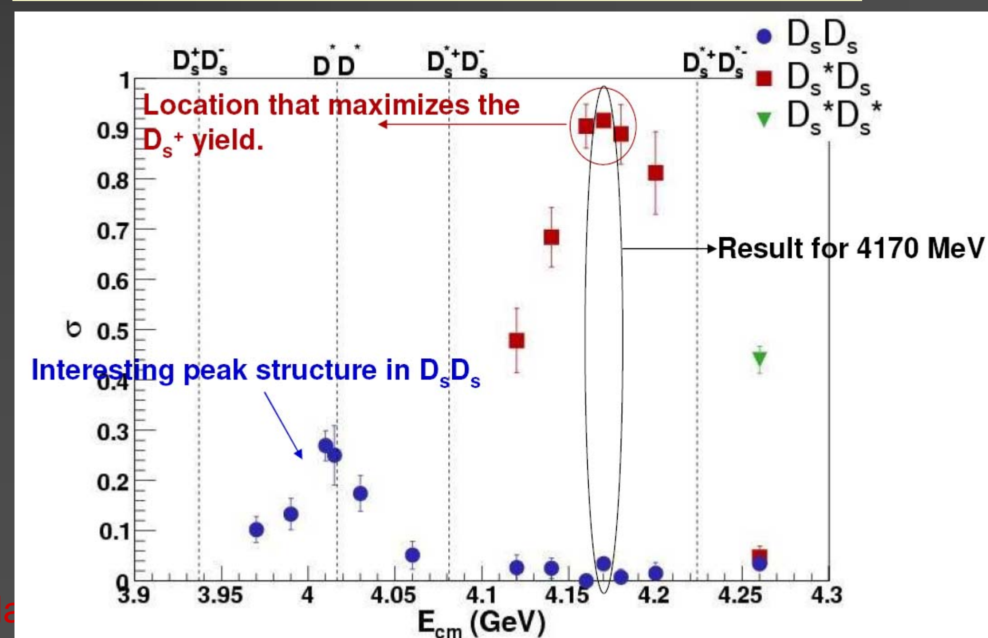
$\sigma(D^o\bar{D}^o) =$ 3.72±0.09 nb
$\sigma(D^+D^-) =$ 2.82±0.09 nb
World Ave

$\sigma(D_S D_S^*) =$ ~0.9 nb

Continuum ~12 nb

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





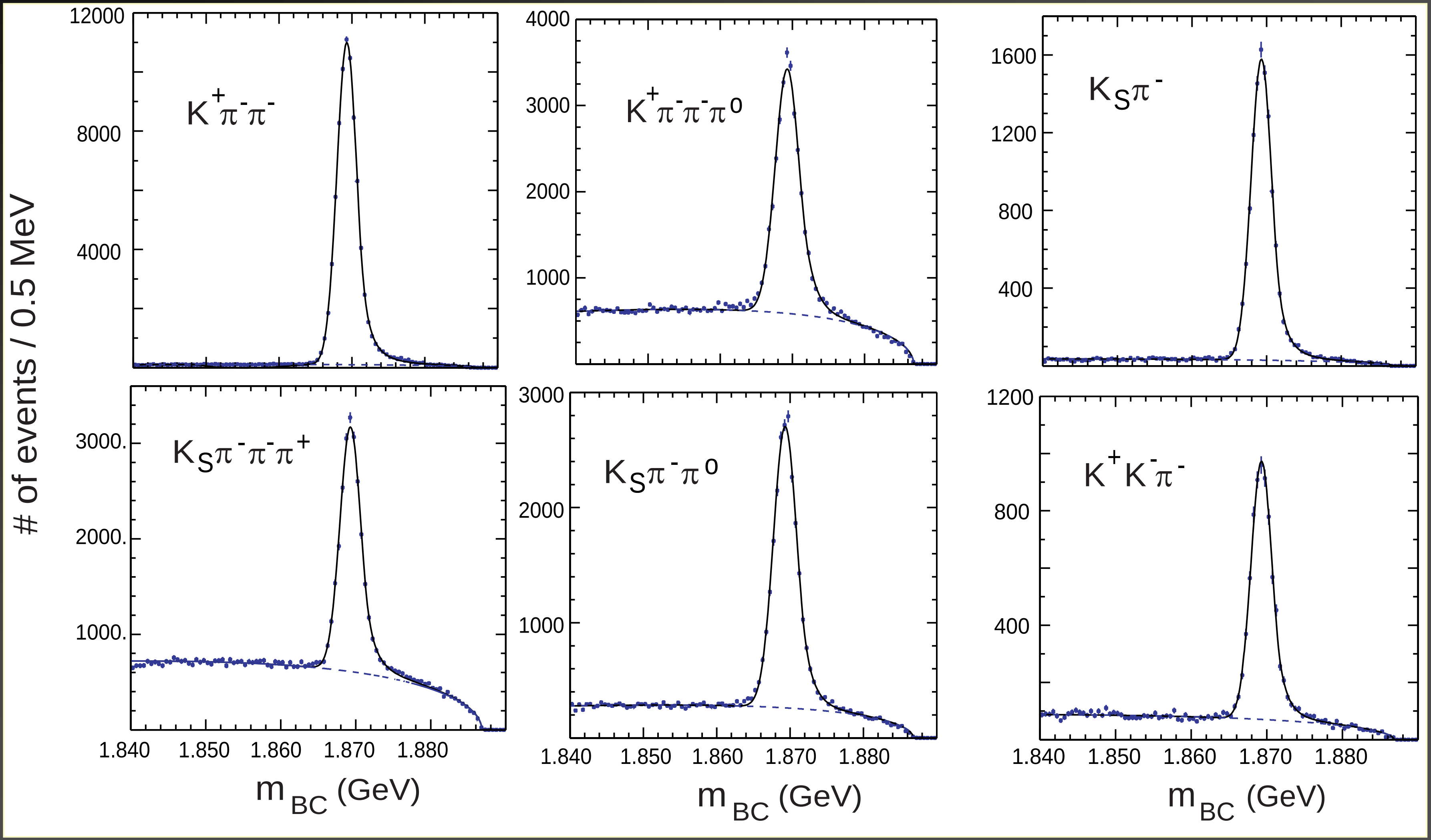
Technique for $D^+ \rightarrow \mu^+\nu$

- 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 $D^+ \rightarrow \pi^+\pi^o$)
- Charged track must deposit only minimum ionization in calorimeter (< 300 MeV case 1)
- 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})

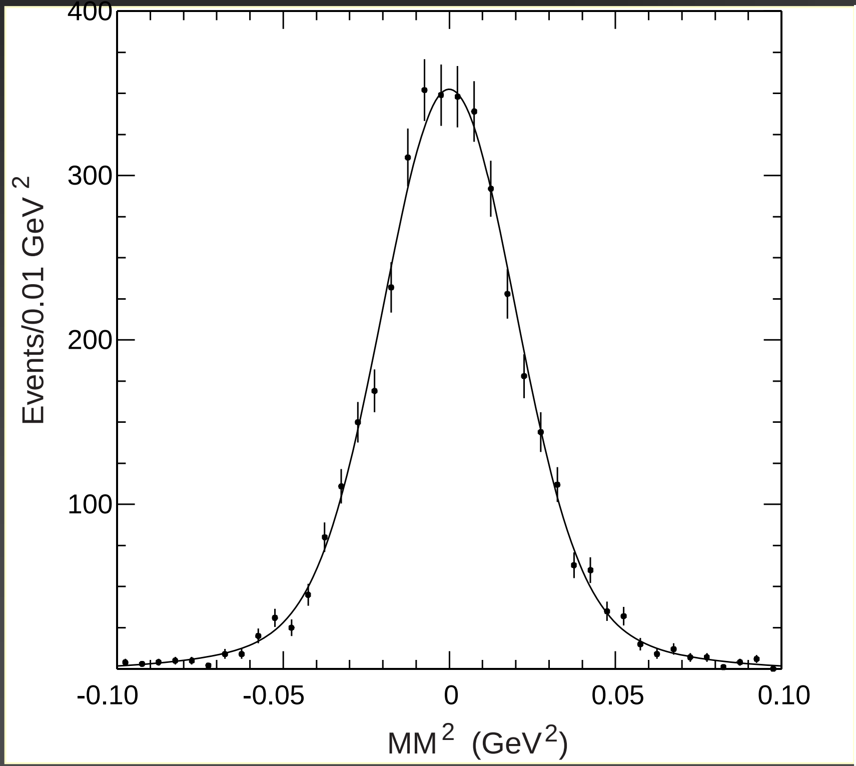


# of tags = 158,354±496, includes charge-conjugate modes

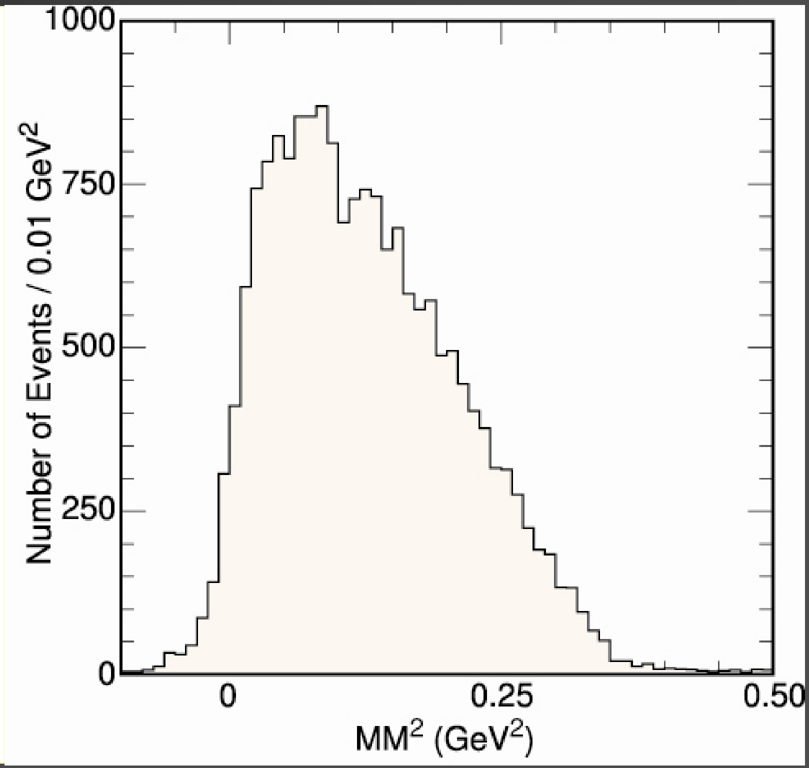
The Missing Mass Squared

- To find signal events, we compute

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



Monte Carlo Signal μν



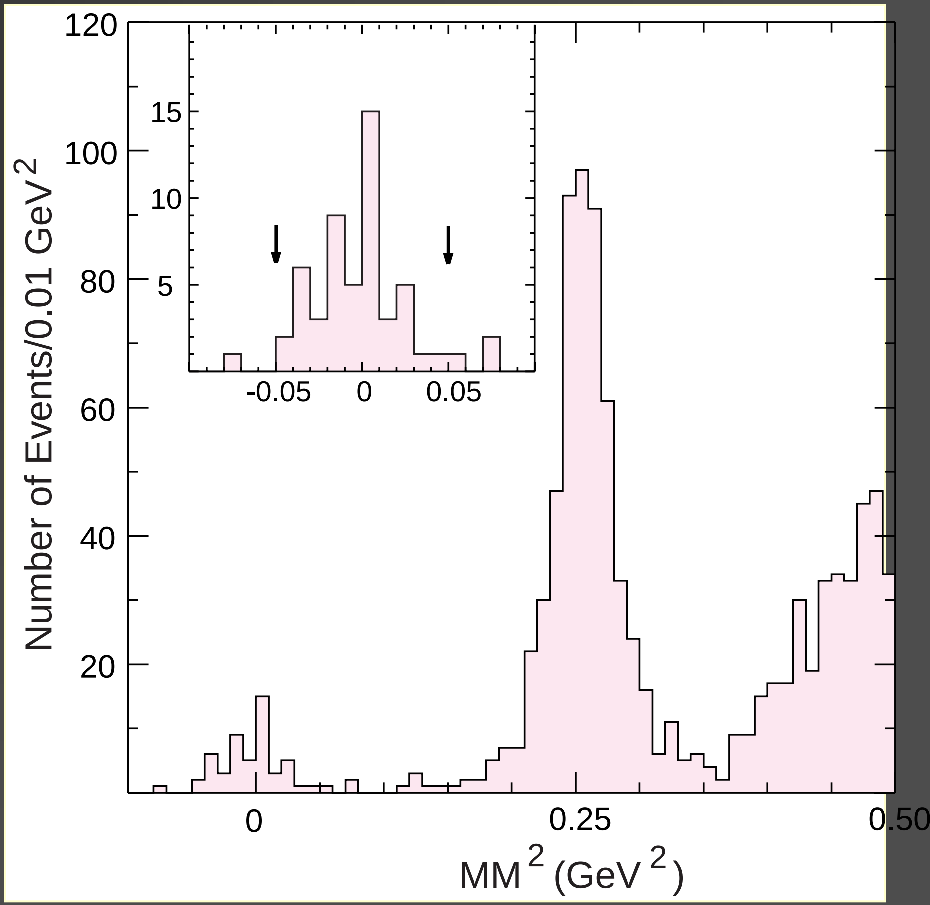
Monte Carlo Signal τν, τ→πν

Measurement of f_{D^+}

Backgrounds

Mode	# Events
$\pi^+\pi^0$	1.40±0.18±0.22
$K^0\pi^+$	0.33±0.19±0.02
$\tau^+\nu$ ($\tau\rightarrow\pi^+\nu$)	1.08±0.15±0.16
Other D^+, D^o	<0.4, <0.4 @ 90% c.l.
Continuum	<1.2 @ 90% c.l.
Total	$2.81\pm0.30^{+0.84}_{-0.27}$

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



- $\mathcal{B}(D^+\rightarrow\mu^+\nu)=(4.40\pm0.66^{+0.09}_{-0.12})\text{x}10^{-4}$
- $f_{D^+}=(222.6\pm16.7^{+2.3}_{-3.4})$ MeV

$|V_{cd}|$=.2238

- $\mathcal{B}(D^+\rightarrow e^+\nu)<2.4\text{x}10^{-5}$ @ 90% c.l.

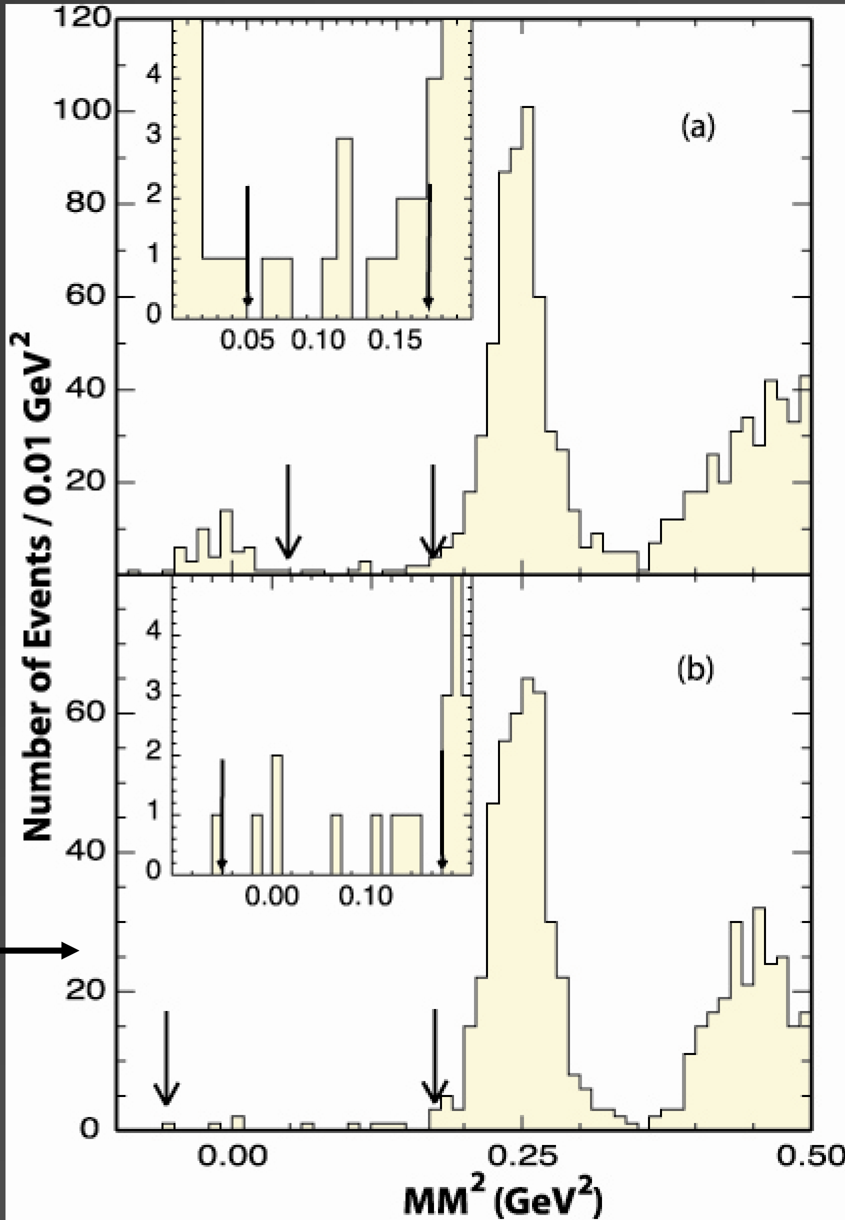
Systematic Errors

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



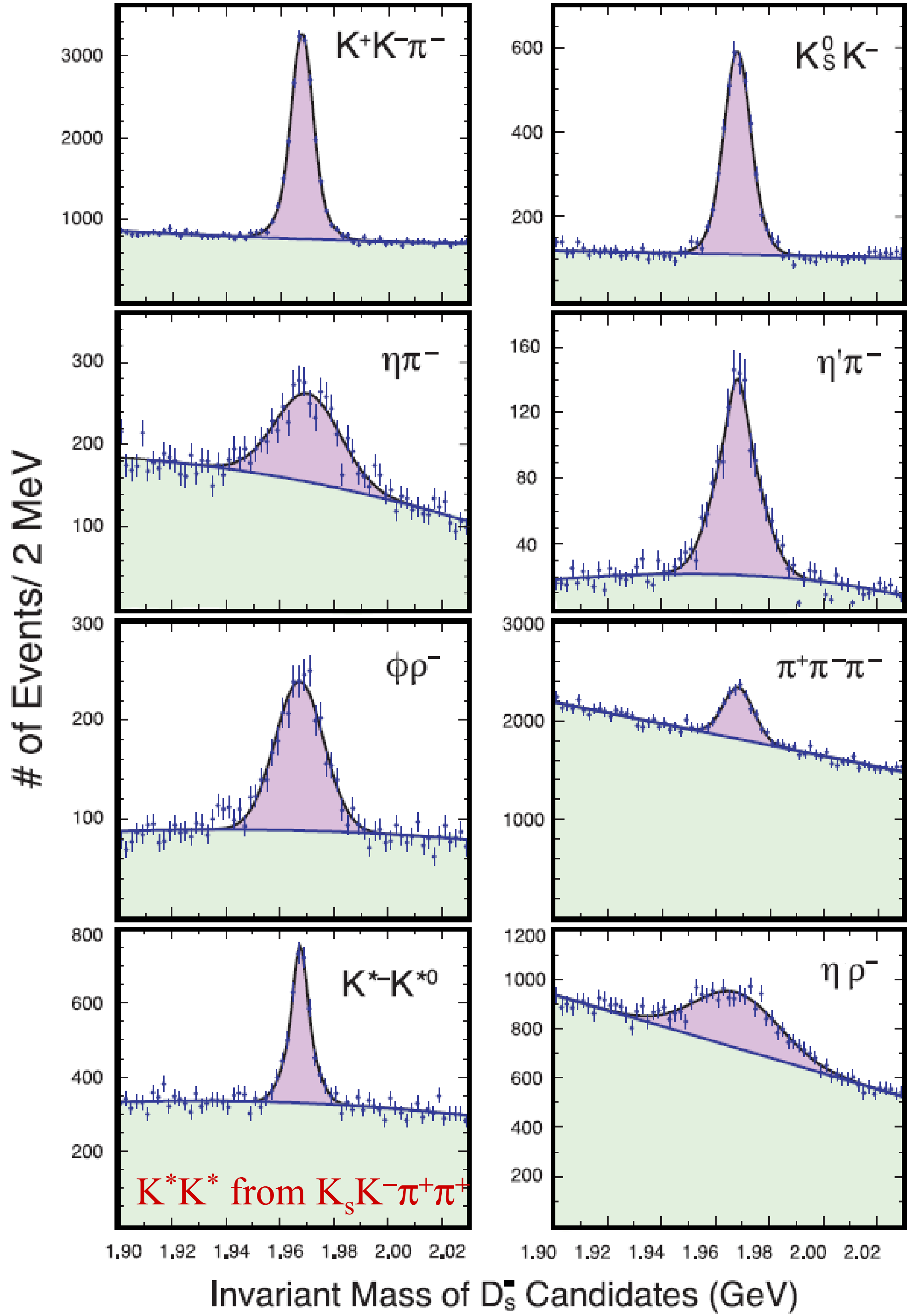
Ecal > 300 MeV

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

- 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)



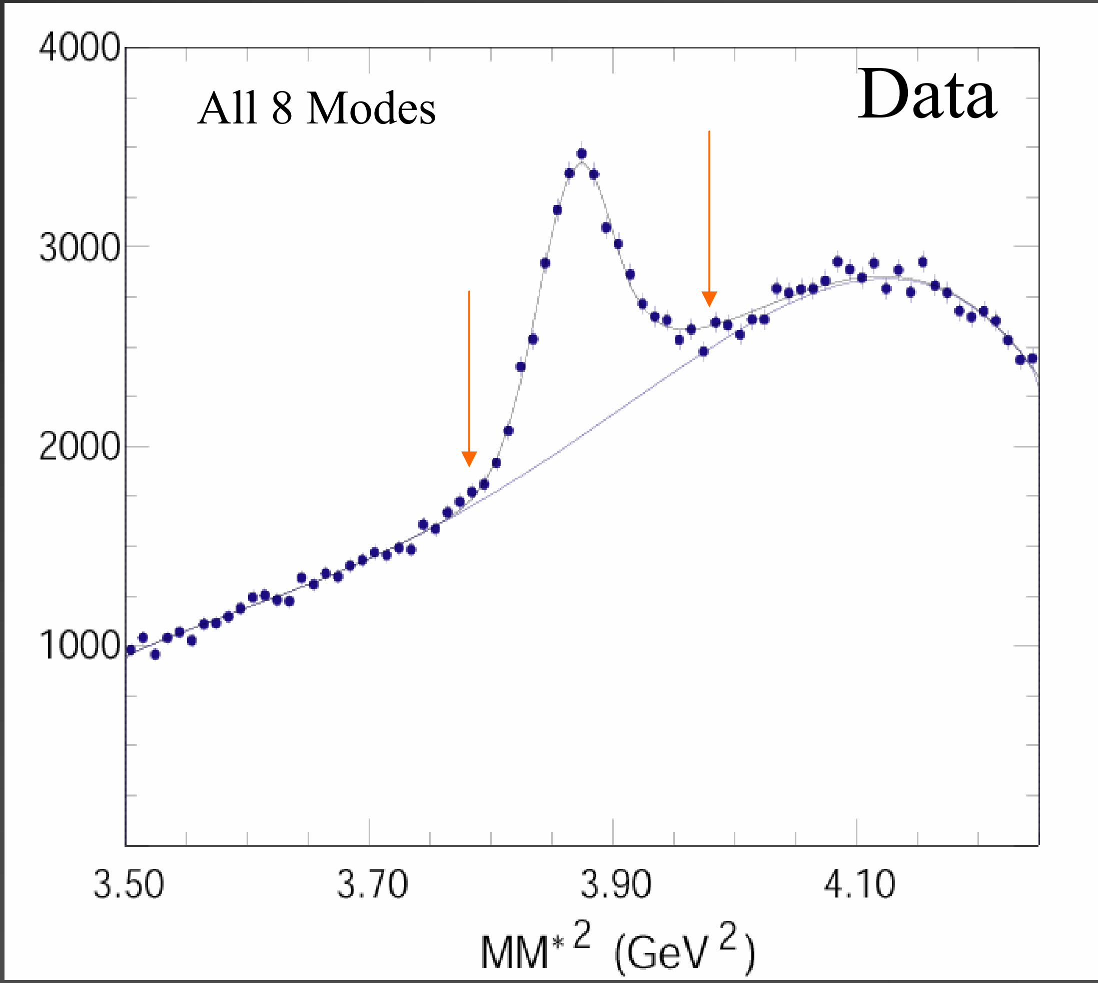
Tag Sample using γ

- 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

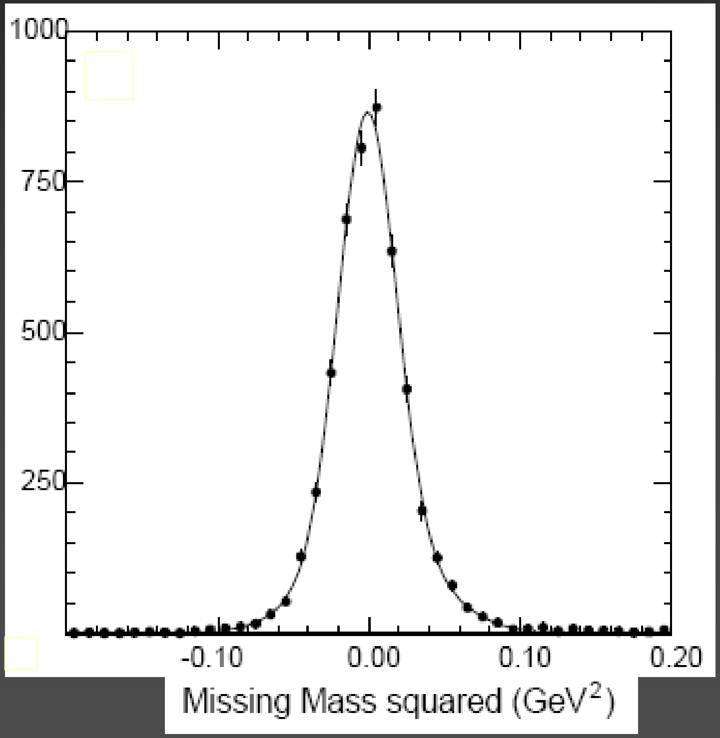
  11880±399±504 tags, after the selection on MM*2.



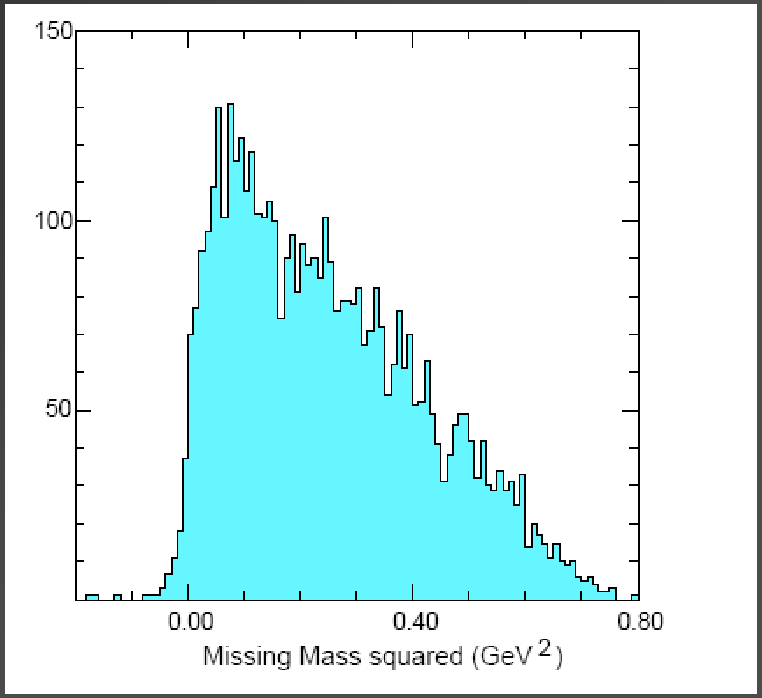
The MM^2

- To find the signal events, we compute

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



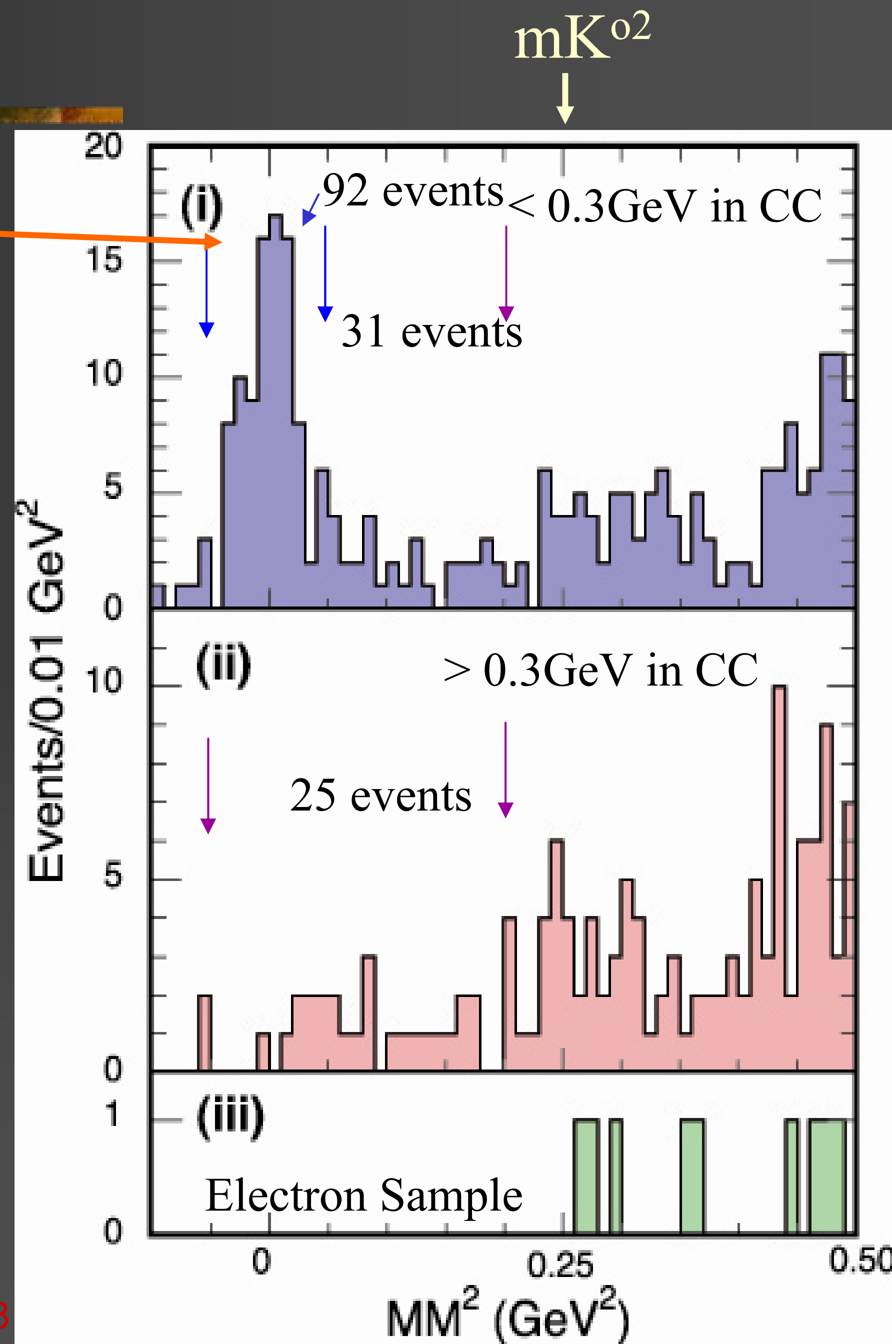
Monte Carlo Signal $\mu\nu$



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

- $D_S^+ \rightarrow \mu^+ \nu$
  - 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
  - $B(D_S^+ \rightarrow \mu^+ \nu) = (0.597 \pm 0.067 \pm 0.039)\%$
- $D_S^+ \rightarrow \tau^+ \nu$, $\tau^+ \rightarrow \pi^+ \nu$
  - 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
  - $B(D_S^+ \rightarrow \tau^+ \nu) = (8.0 \pm 1.3 \pm 0.4)\%$
- By summing both cases above, find

$B^{eff}(D_S^+ \rightarrow \mu^+ \nu) = (0.638 \pm 0.059 \pm 0.033)\%$

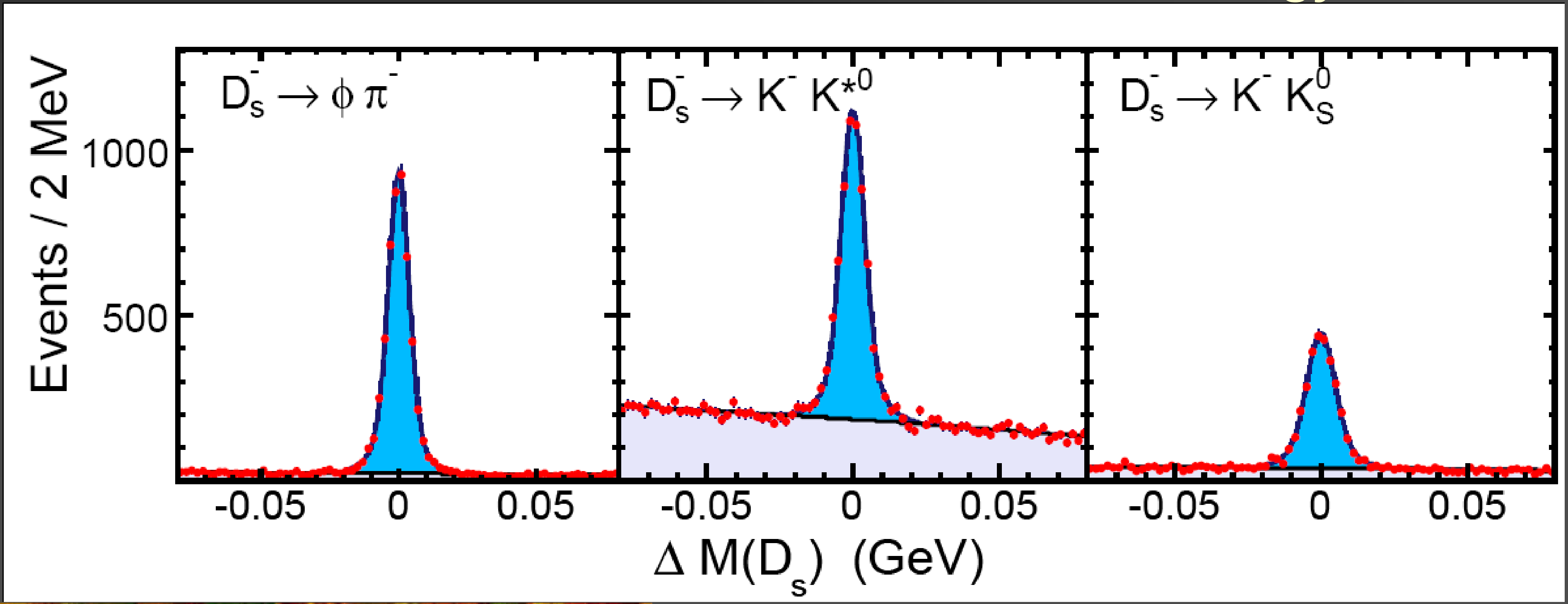
- $f_{Ds} = 274 \pm 13 \pm 7$ MeV, for $|V_{cs}| = 0.9737$
- $B(D_S^+ \rightarrow e^+ \nu) < 1.3 \times 10^{-4}$

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

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

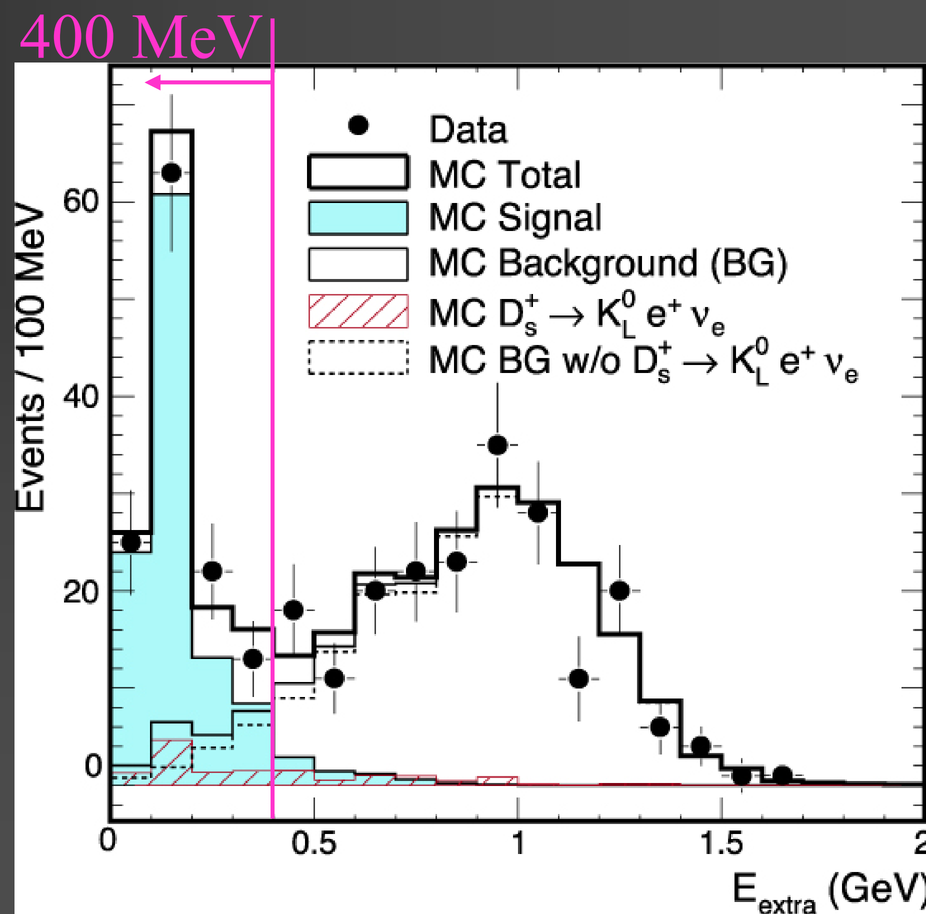
Measuring $D_S^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

- $B(D_S^+ \to \tau^+\nu) \bullet B(\tau^+ \to e^+\nu\nu) \sim 1.3\%$ is "large" compared with expected $B(D_S^+ \to X e^+\nu) \sim 8\%$
- 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 i.e. $D_S^+ \to \mu^+ \nu \gamma$ not included, estimated to be ~1% (see Burdman et al., PRD 51, 11 (1995)

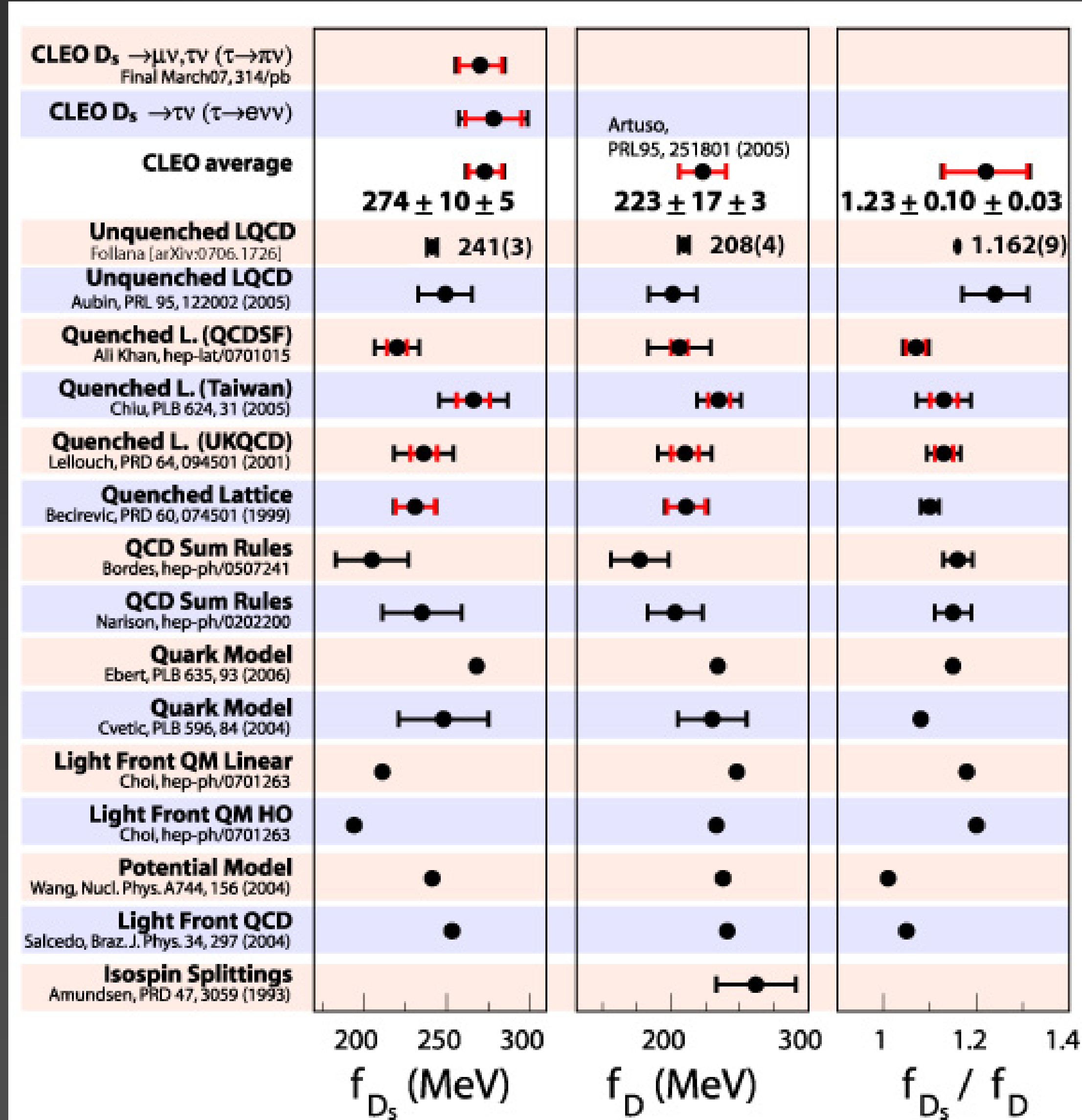
Comparison with Other Experiments

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

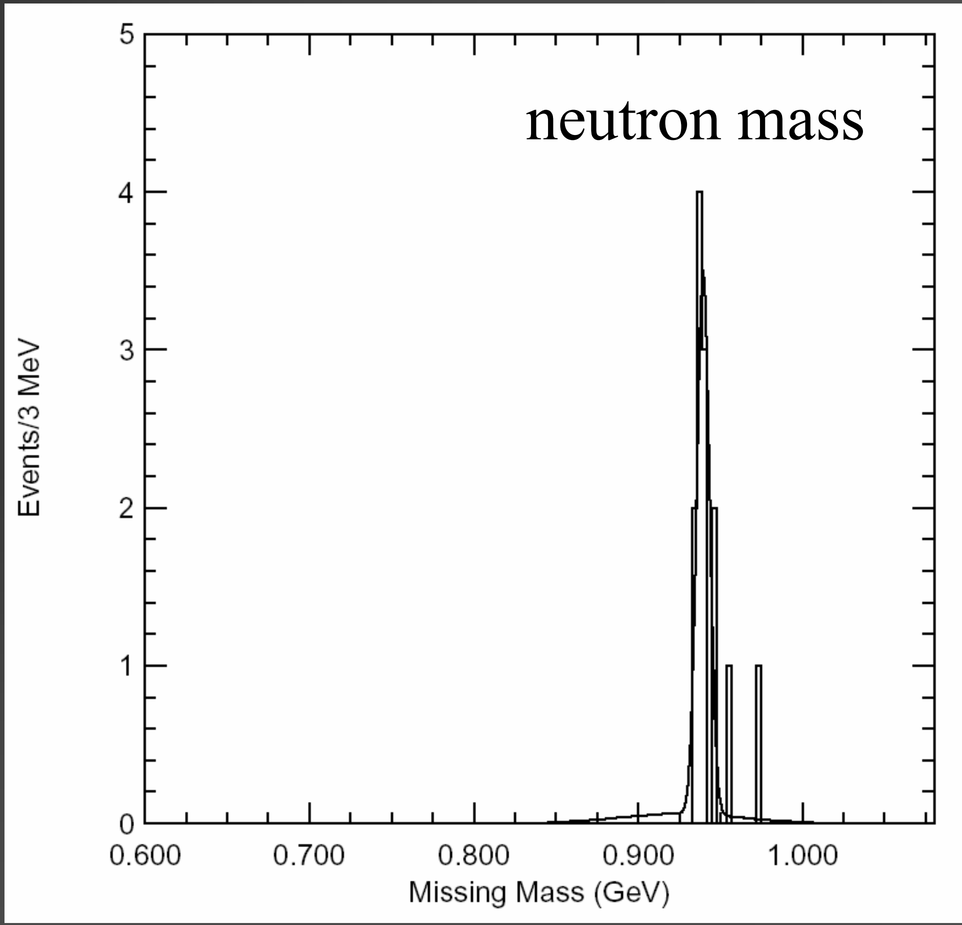


Projections

- We will almost triple the D^+ sample, including some improvements in technique, error in f_{D^+} should decrease to ~9 MeV
- We doubled the D_S sample, improved the technique, expect error in f_{Ds} to decrease to ~7 MeV

Discover of $D_s^+ \to p\bar{n}$

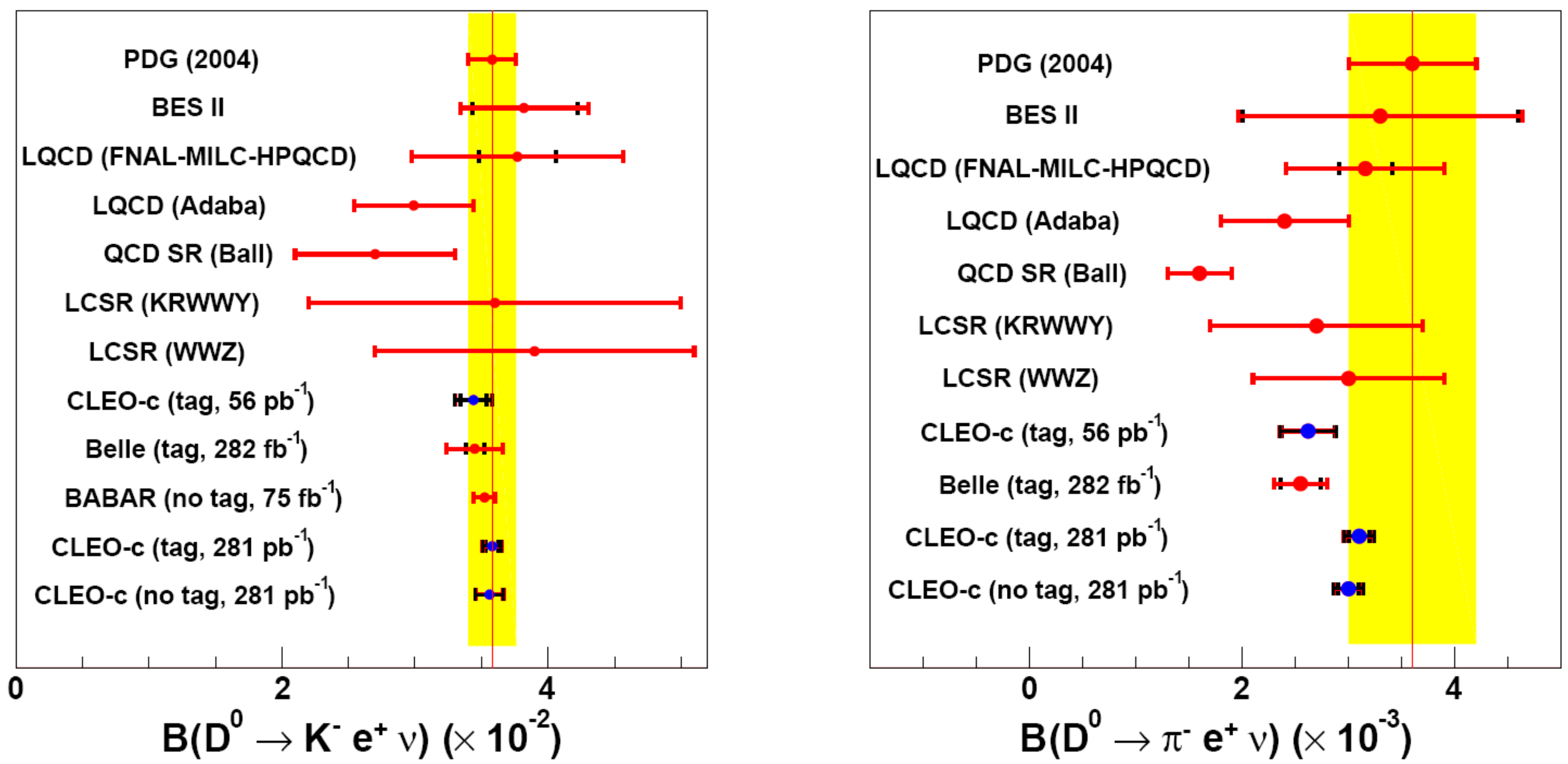
- Use same technique as for $\mu^+\nu$, but plot MM from a detected proton
- No background
- First example of a charm meson decaying into baryons



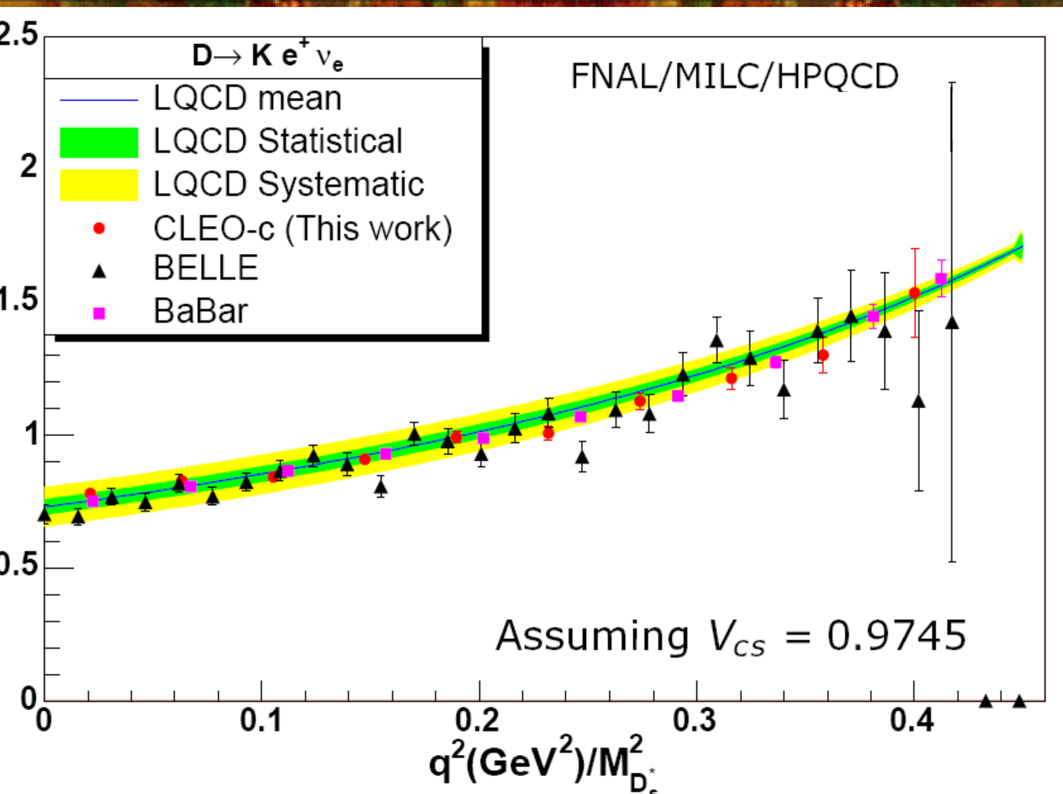
- $B(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16})\ x10^{-3}$

Semileptonic Decays

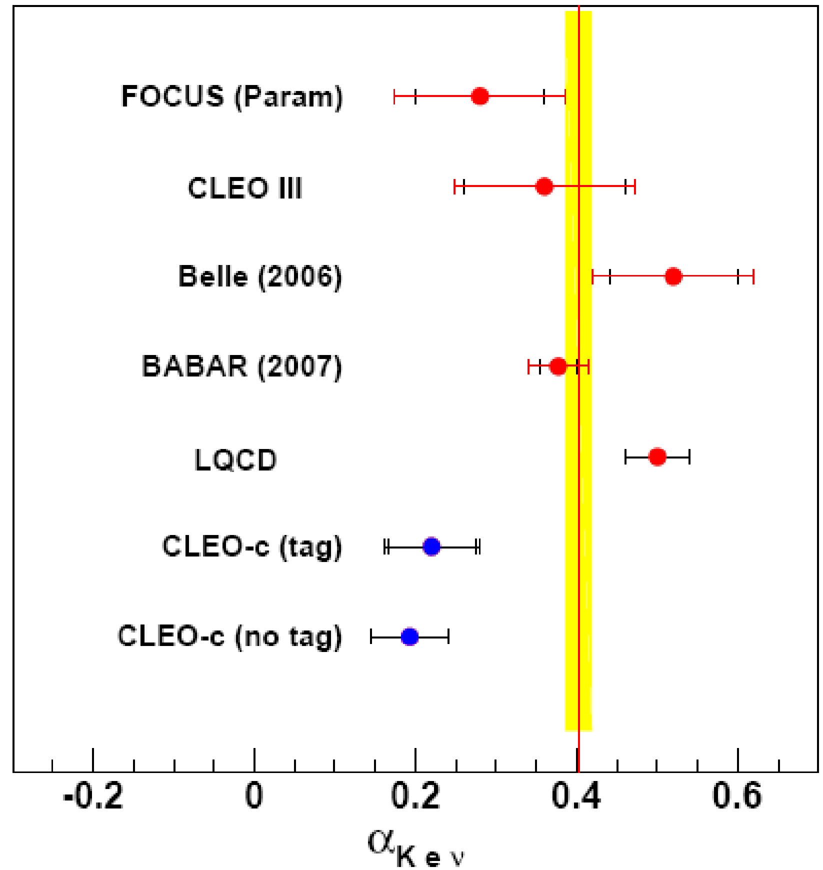
- Precise $\mathcal{B}(D^o \to K^- e^+ \nu)$ & $\mathcal{B}(D^o \to \pi^- e^+ \nu)$

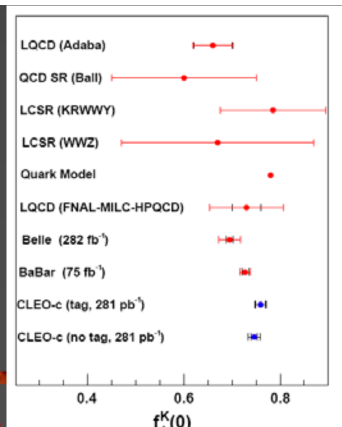


Form Factors: $D^o \to K^- e^+ \nu$

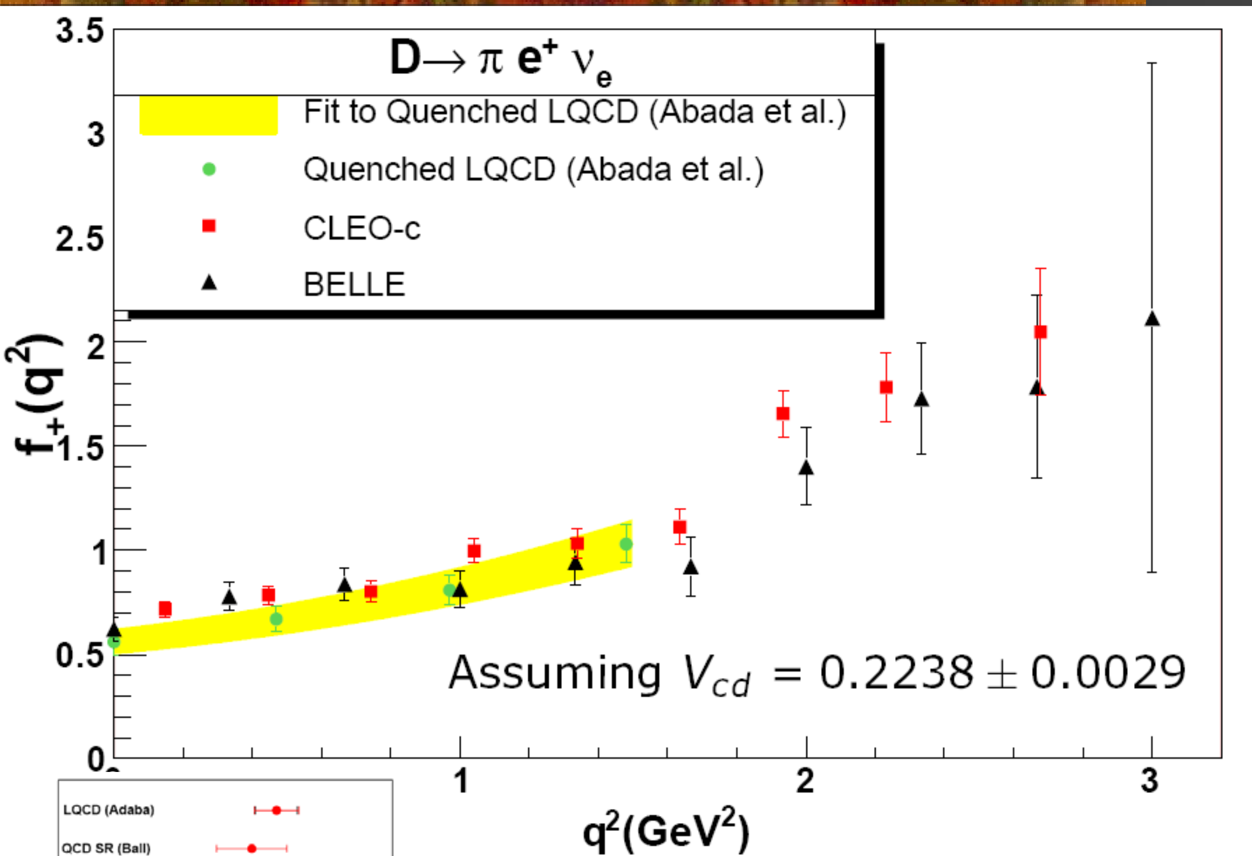


$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{pole})(1-\alpha q^2/m^2_{pole})}$$

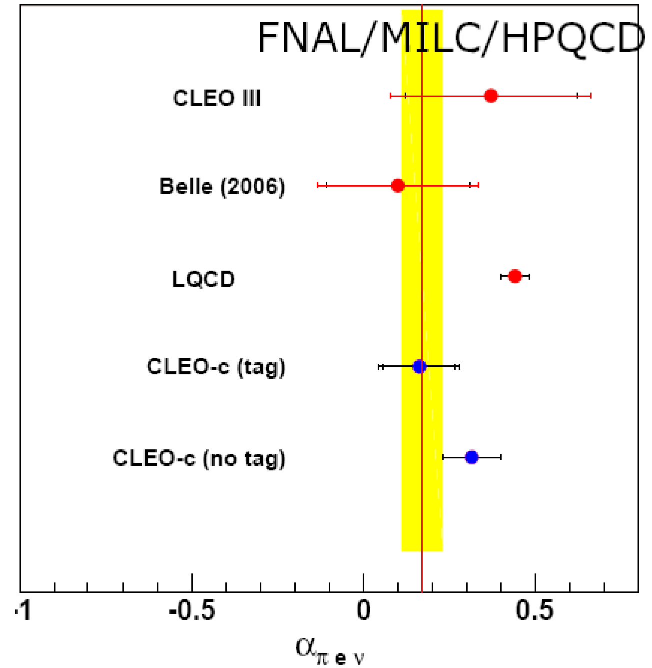


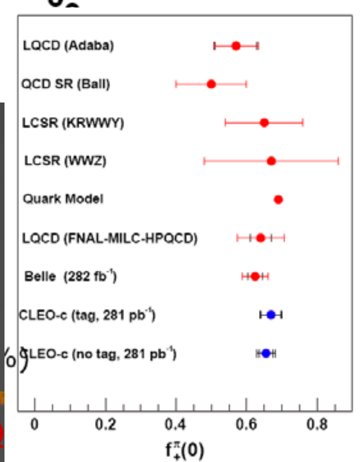


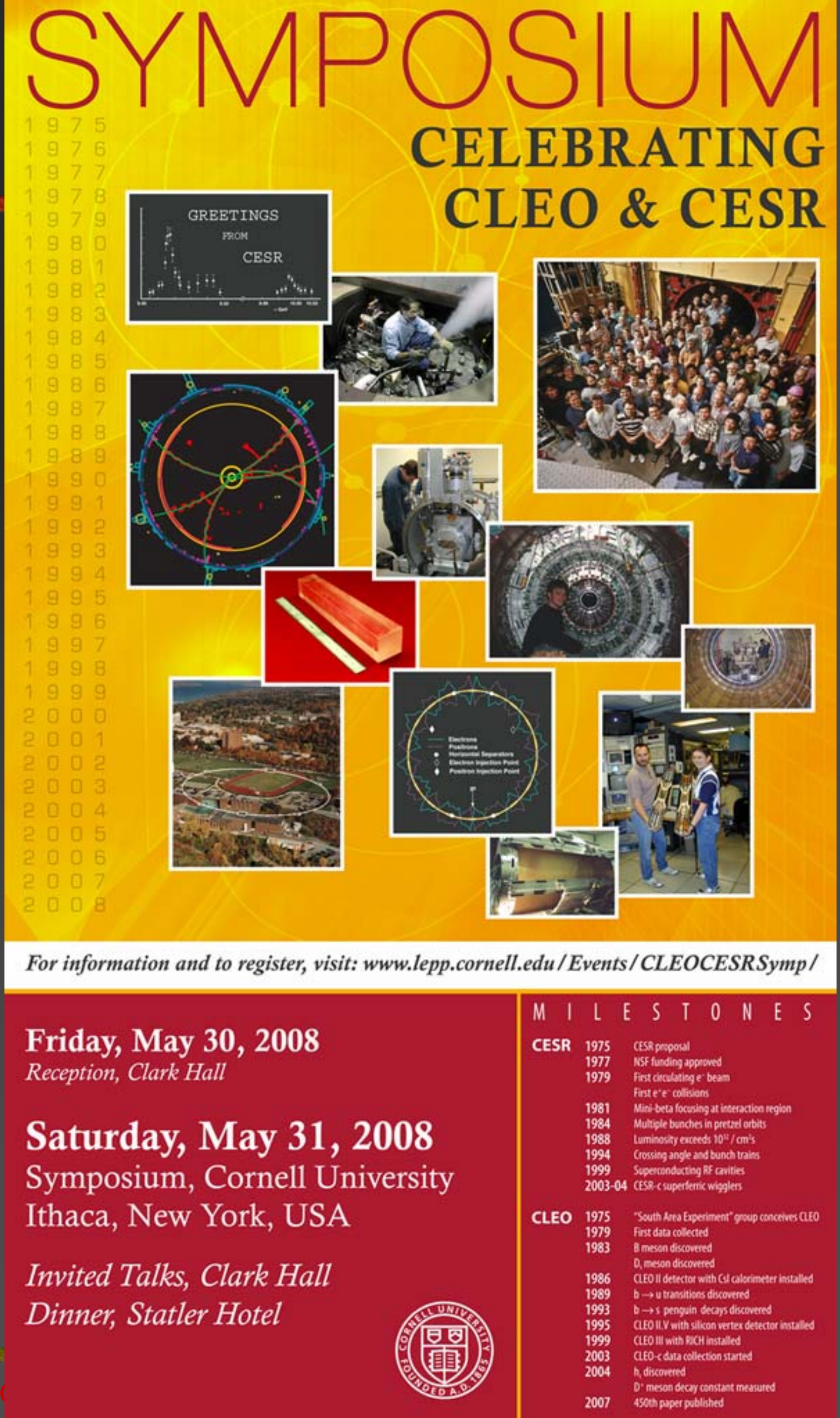
$D^o \rightarrow \pi^- e^+ \nu$



$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{pole})(1-\alpha q^2/m^2_{pole})}$$

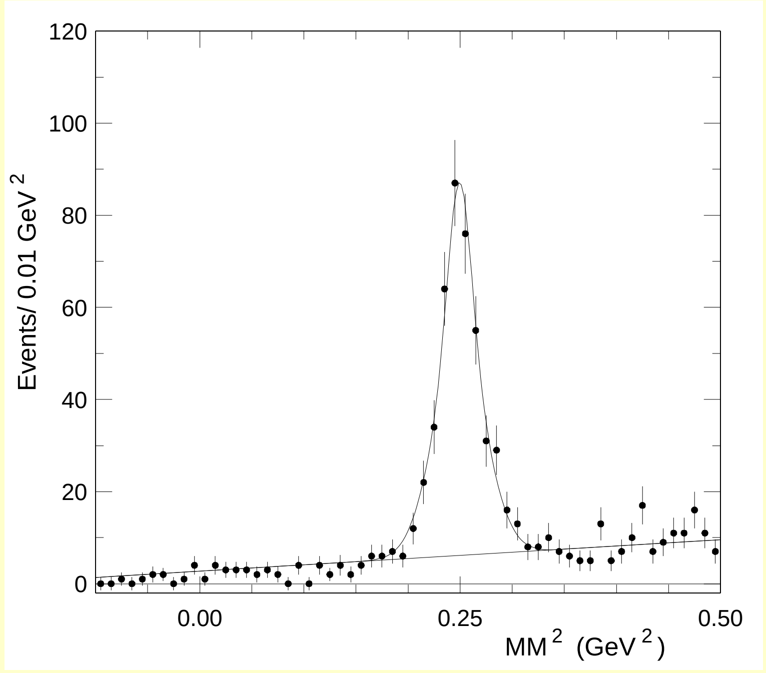





SYMPOSIUM
CELEBRATING
CLEO & CESR
GREETINGS
FROM
CESR
For information and to register, visit: www.lepp.cornell.edu/Events/CLEOCESRSymp/
Friday, May 30, 2008
Reception, Clark Hall
Saturday, May 31, 2008
Symposium, Cornell University
Ithaca, New York, USA
Invited Talks, Clark Hall
Dinner, Statler Hotel
MILESTONES
CESR 1975 CESR proposal
1977 NSF funding approved
1979 First circulating e^- beam
First e^+e^- collisions
1981 Mini-beta focusing at interaction region
1984 Multiple bunches in pretzel orbits
1988 Luminosity exceeds 10^{32} / cm^2s
1994 Crossing angle and bunch trains
1999 Superconducting RF cavities
2003-04 CESR-c superferric wigglers
CLEO 1975 "South Area Experiment" group conceives CLEO
1979 First data collected
1983 B meson discovered
D_s meson discovered
1986 CLEO II detector with CsI calorimeter installed
1989 $b \rightarrow u$ transitions discovered
1993 $b \rightarrow s$ penguin decays discovered
1995 CLEO II.V with silicon vertex detector installed
1999 CLEO III with RICH installed
2003 CLEO-c data collection started
2004 h_c discovered
D^+ meson decay constant measured
2007 450th paper published

The End

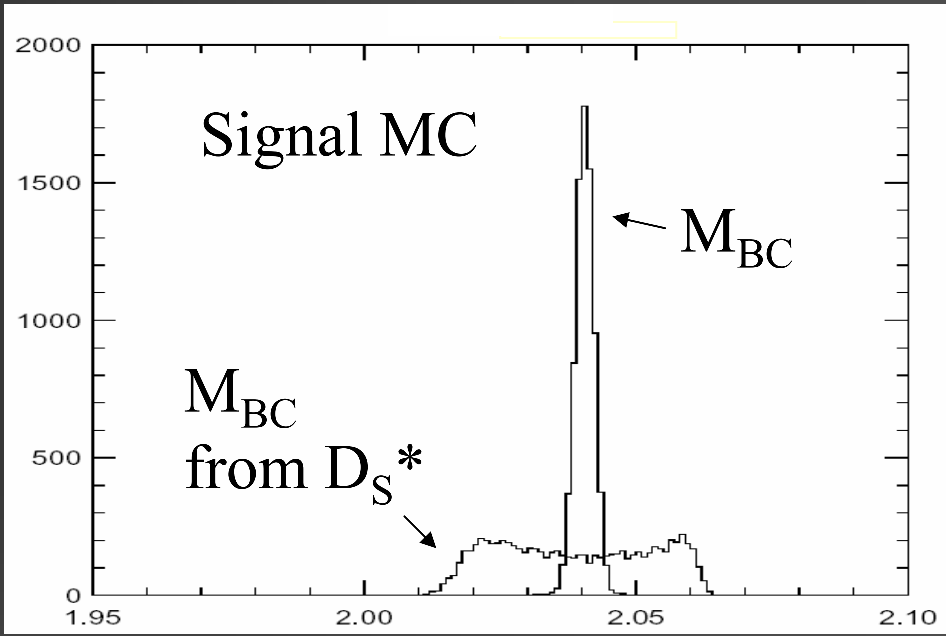
Check: $\mathcal{B}(D_S^+ \rightarrow K^+ K^o)$



- 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 $e^+e^- \rightarrow D_S^* D_S$, 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)

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

Combining Semileptonics & Leptonics

- Semileptonic decay rate into Pseudoscalar:

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

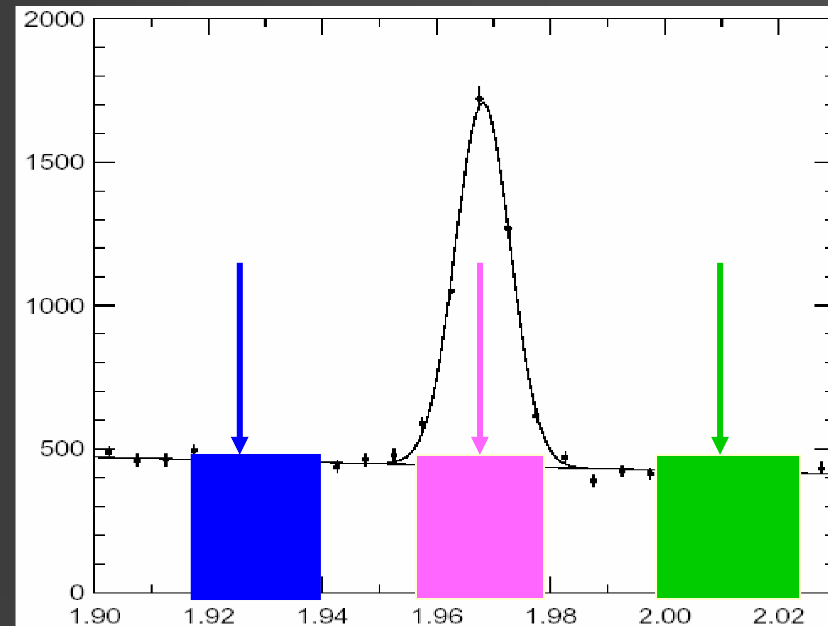
- Note that the ratio below depends only on QCD:

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

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 $D_S\to\tau^+\nu$, $\tau\to\pi^+\pi^o\nu$.... < 0.2 GeV^2, none in $\mu\nu$ signal region
- B($D_S\to\pi^+\pi^o$) < 1.1x10^{-3} &

γ energy cut yields <0.2 evts



Low SB region | Signal region | High SB region

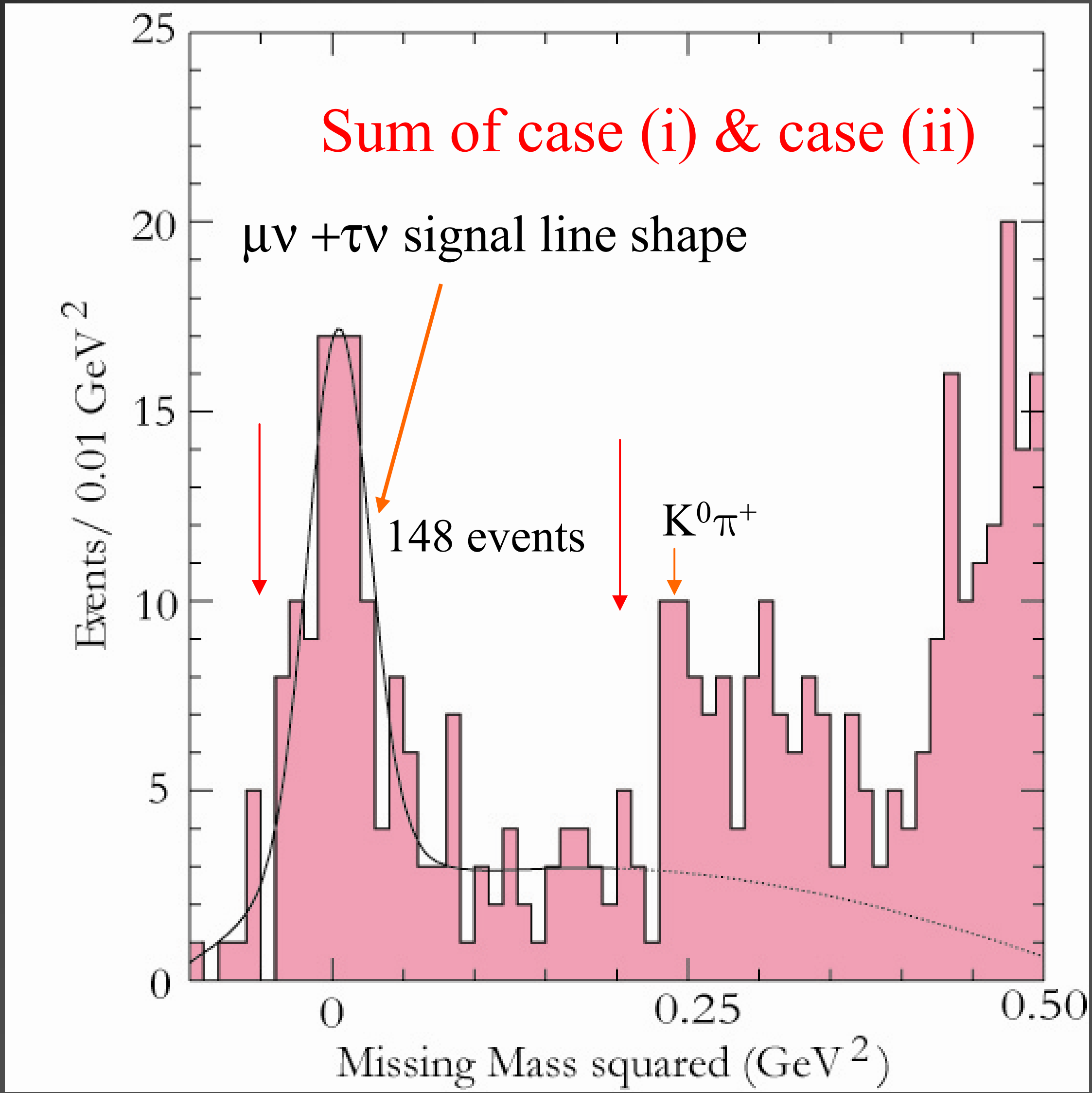
Backgrounds from real D_S^+

TABLE III: Backgrounds in the $D_s^+\to\tau^+\nu$, $\tau^+\to\pi^+\bar{\nu}$ 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
$D_s^+\to X\mu^+\nu$	8.2	$0^{+1.8}_{-0}$	0	$0^{+1.8}_{-0}$
$D_s^+\to\pi^+\pi^0\pi^0$	1.0	0.03±0.04	0.08±0.03	0.11±0.04
$D_s^+\to\tau^+\nu$	6.4			
$\tau^+\to\pi^+\pi^0\bar{\nu}$	1.5	0.55±0.22	0.64±0.24	1.20±0.33
$\tau^+\to\mu^+\bar{\nu}\nu$	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



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.
- $\Gamma(D_{(S)}{}^+ \rightarrow \gamma \mu^+ \nu) / \Gamma(D_{(S)}{}^+ \rightarrow \mu^+ \nu) \sim 1/40 - 1/100$
  - Burdman etal ~1%
- 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)