Recent Charm Results from CLEO-c

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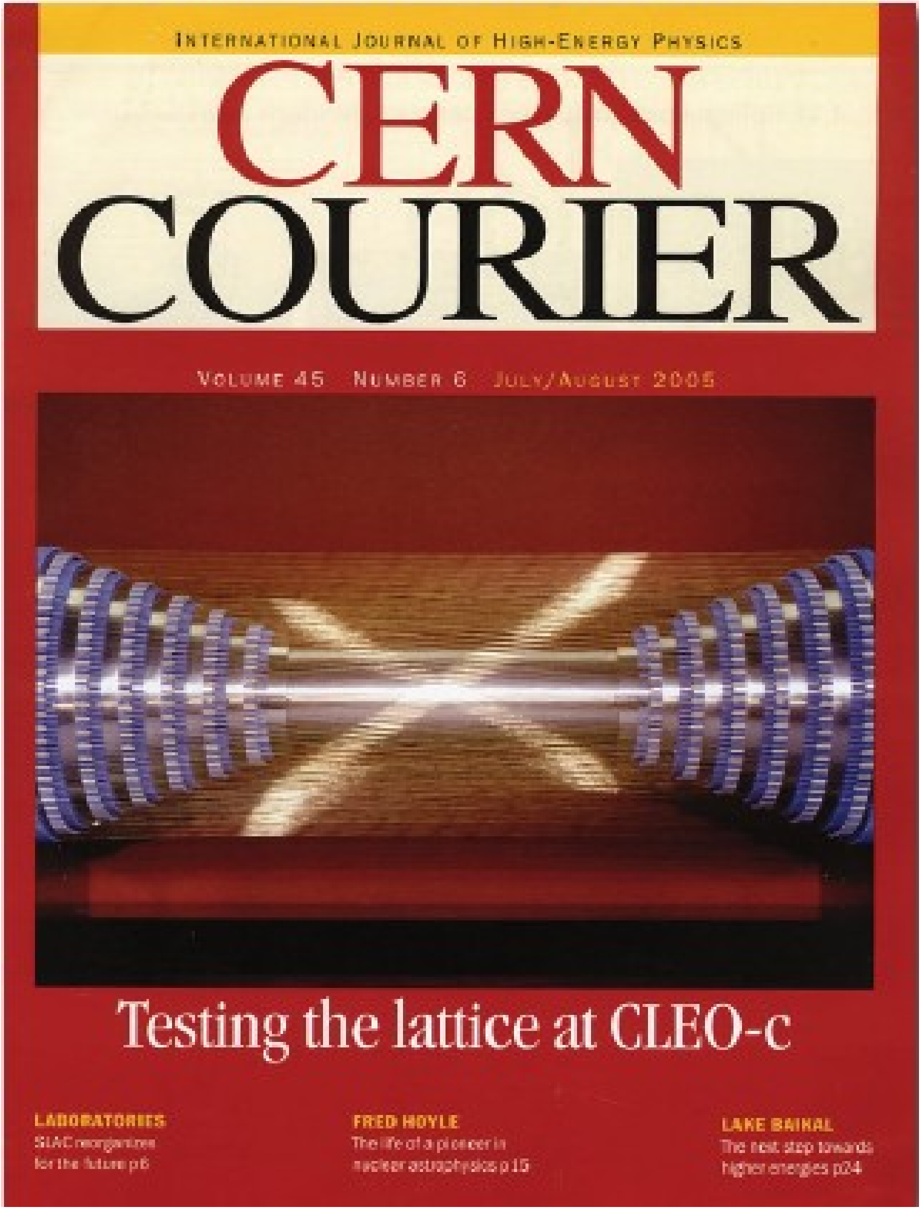
CLEO-c Physics Program

The CLEO detector is taking data at the CESR symmetric e^+e^- collider operating as a charm factory since 2003

Main physics scope:

- Provide important test and validation of strong interaction (QCD) theory in the charm sector
- Precise charm measurements are critical to extract weak physics from observables (precision CKM measurements)
- Other exciting physics possibilities (even search for new physics)

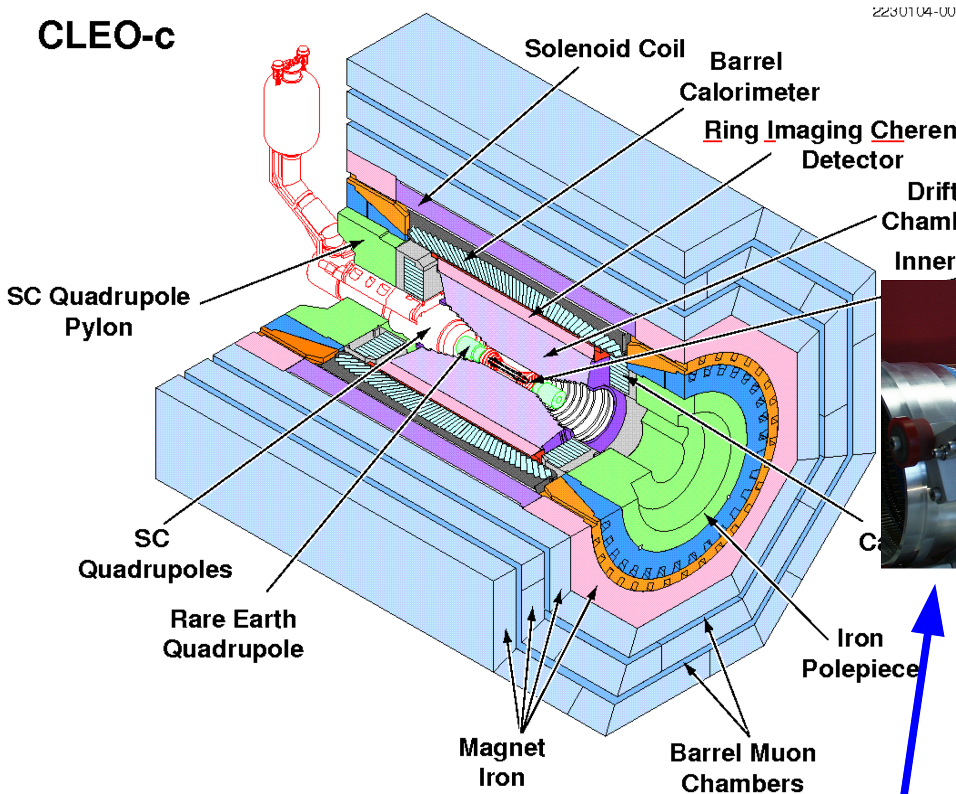


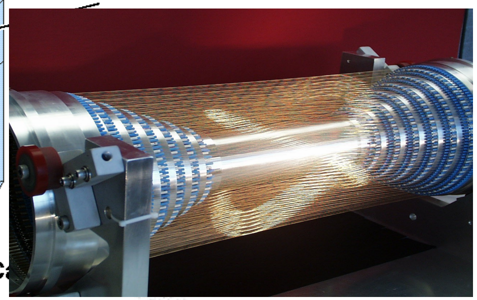
Selected topics

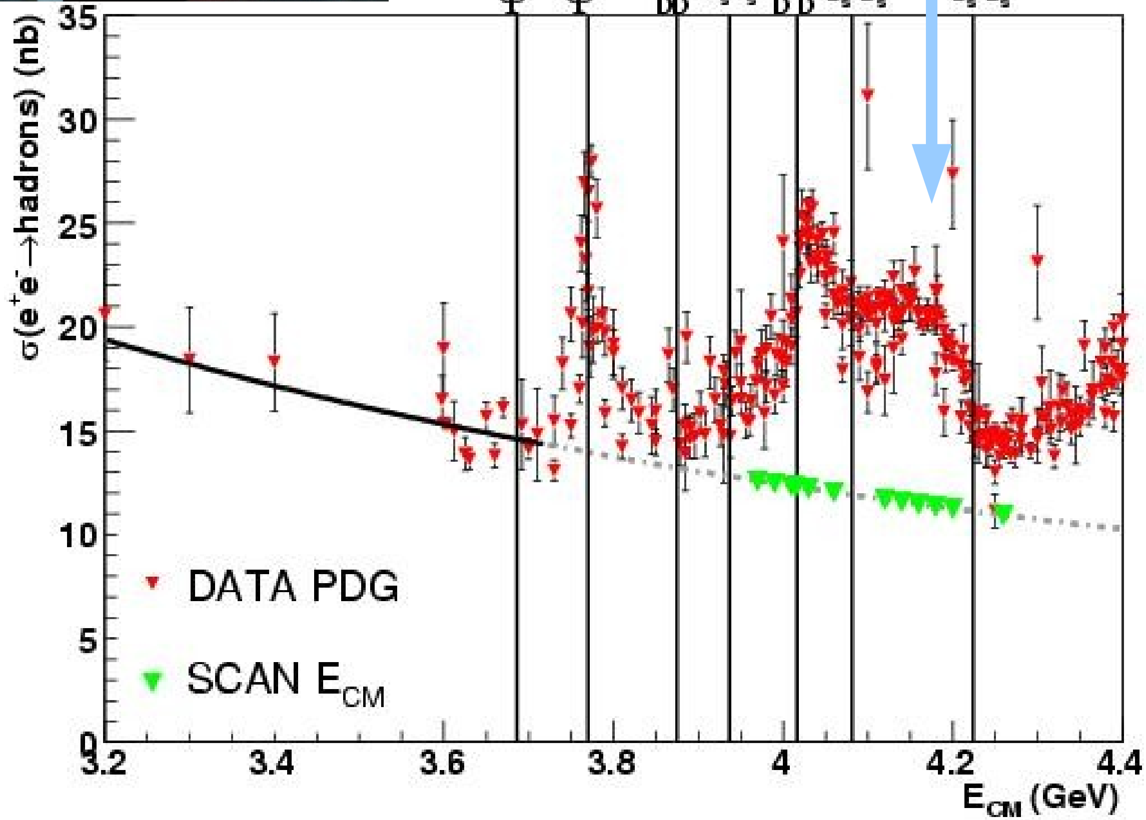
Very diverse physics topics at CLEO: D, D_s, $c\bar{c}$, $b\bar{b}$ etc.

- D^0, D^+, and D_s hadronic decays
  - absolute BF are important to normalize D decays and for precision B measurements
  - help to understand strong (final state) interactions better
- D^+ and D_s purely leptonic decays and $f_{D(s)}$
  - test non-perturbative QCD (especially Lattice QCD) calculations of $f_{D(s)}$
  - helps to determine CKM matrix elements $|V_{td}|$, $|V_{ts}|$
- Spectroscopy: D^0 mass and χ_{cJ} 3-body decays
  - help with interpretation of X(3872) charmonium-like state;
  - light meson spectroscopy

CLEO-c detector and data







- Excellent tracking, calorimetry, and particle ID
- Changes from CLEO III:

  Si vertex detector replaced by 6-layer inner drift chamber

  Magnetic field: 1.0 T (from 1.5 T)

Absolute Charm Meson Branching Fractions

D^0 and D^+ hadronic Branching Fractions

PRL **95**, 121801 (2005) with 56 pb^{-1} $D\bar{D}$ data

Preliminary results with 281 pb^{-1} data presented here

D_s hadronic Branching Fractions

Preliminary results with 195 pb^{-1} $D_s^*D_s$ data:

CLEO CONF 06-13 (hep-ex/0607079)

Tagging technique

- $D\bar{D}$ production at threshold:

  no extra particles, low multiplicity, very clean final state

- Use tagging technique (pioneered by Mark III) to fully reconstruct one (single tag) or both (double tag) D - greatly reduces combinatoric background

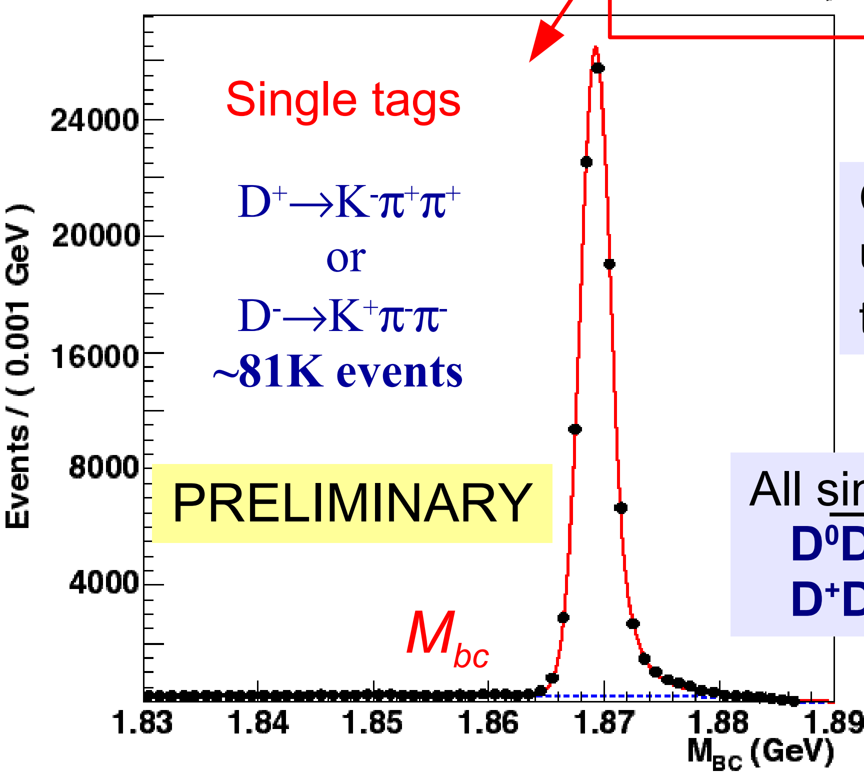
- Variables used in the tag reconstruction:

$$\Delta E = E_{D-tag} - E_{beam} \approx 0$$

$$M_{bc} = \sqrt{E_{beam}^2 - P_{D-tag}^2} \approx M_D$$

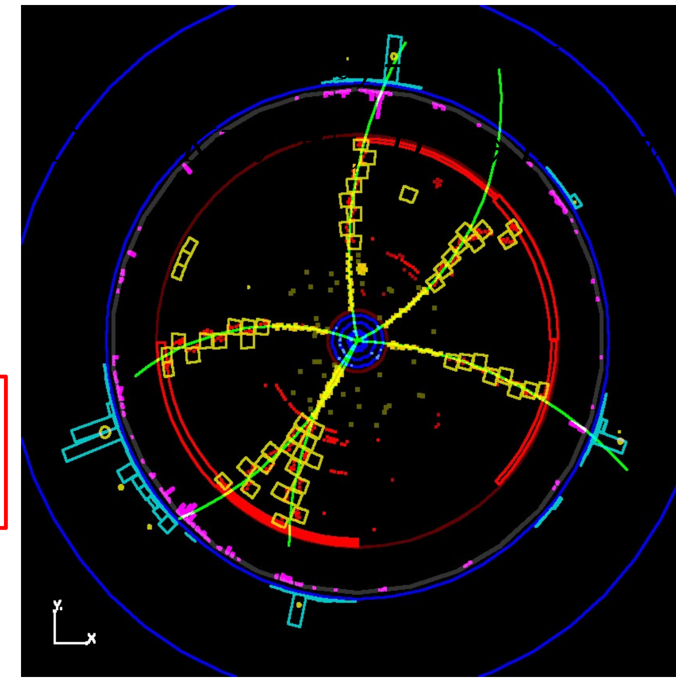
$(E_{D-tag} = E_{beam})$

Cut on ΔE ($\pm 3\delta$) and use M_{bc} to extract the signal by fitting

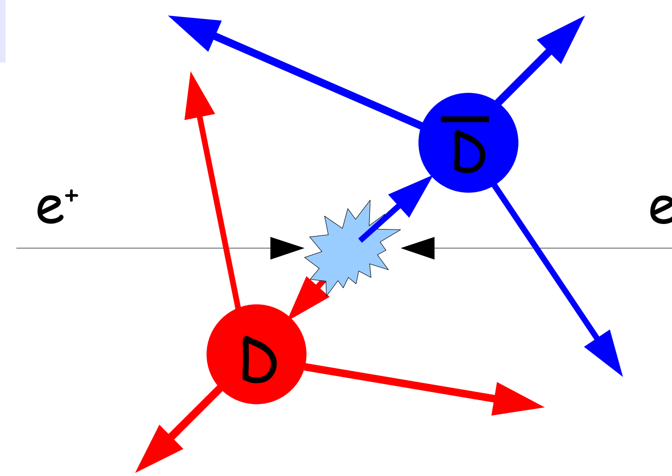


All single tags in 281 pb^{-1}:
$D^0\bar{D}^0$: ~230K
D^+D^-: ~170K

$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$



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

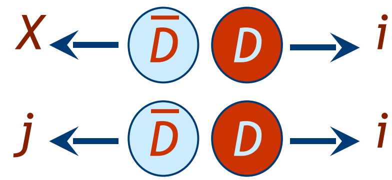


D^0 and D^+ absolute BF: method

- Measure 3 D^0 and 6 D^+ decay modes

single tags (ST): $n_i = N_{DD} B_i \varepsilon_i$

double tags (DT): $n_{ij} = N_{DD} B_i B_j \varepsilon_{ij}$



$$\Rightarrow B_i \approx \frac{n_{ij}}{n_j} \frac{\varepsilon_j}{\varepsilon_{ij}} \qquad N_{DD} \approx \frac{n_i n_j}{n_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

BF are independent of luminosity and cross section

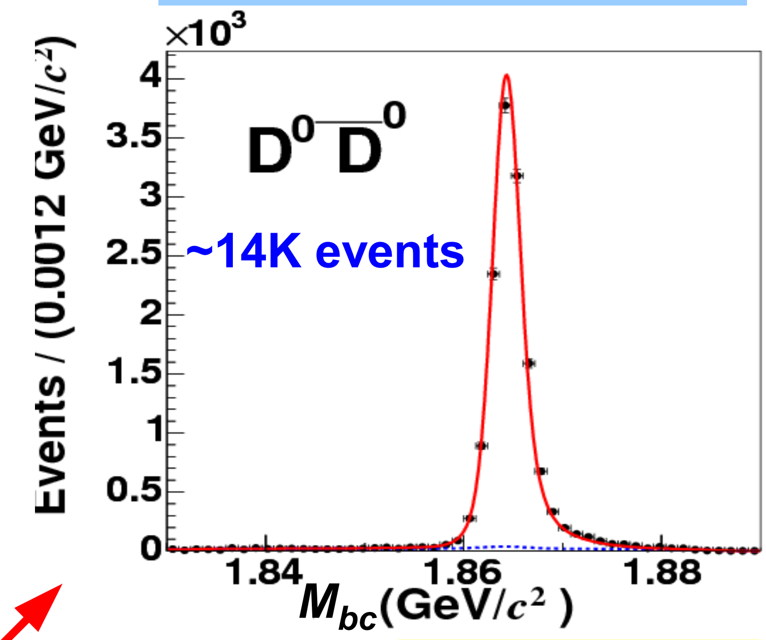
- Combine ST and DT yields for all modes in χ^2 fit to get absolute BF (and N_{DD})

Scale of statistical error is set by number of total DT yield

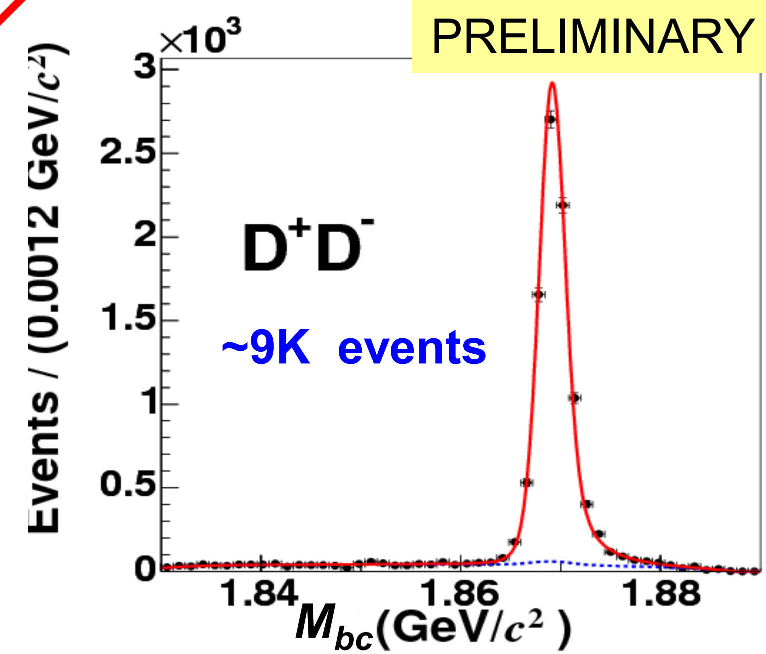
Since $\varepsilon_{ij} \approx \varepsilon_i \, \varepsilon_j$ to first order

B_i are independent of tag mode efficiencies (ε_j)

Double tags in 281 pb^{-1}



PRELIMINARY



D^0 and D^+ absolute BF: results

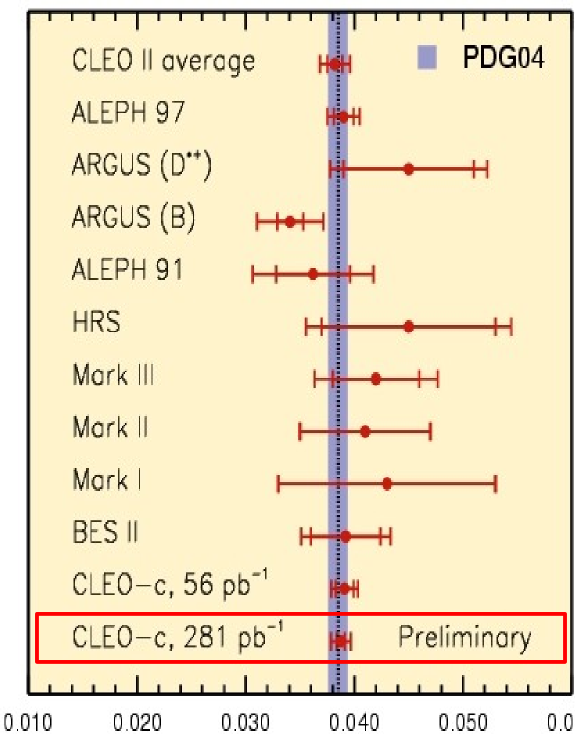
- Absolute BF's based on 56 pb^{-1} data are published (and included in PDG06)
- Updating the results with 281 pb^{-1}

  Statistical error ~1-2%, systematics limited
  (working on some improvements)

  BF corrected for FSR (up to 2% effect)

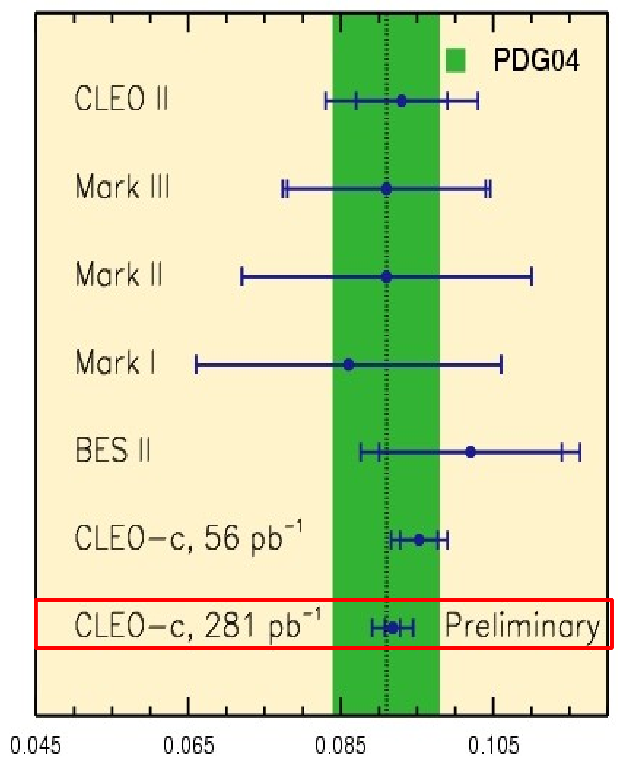
PRELIMINARY

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

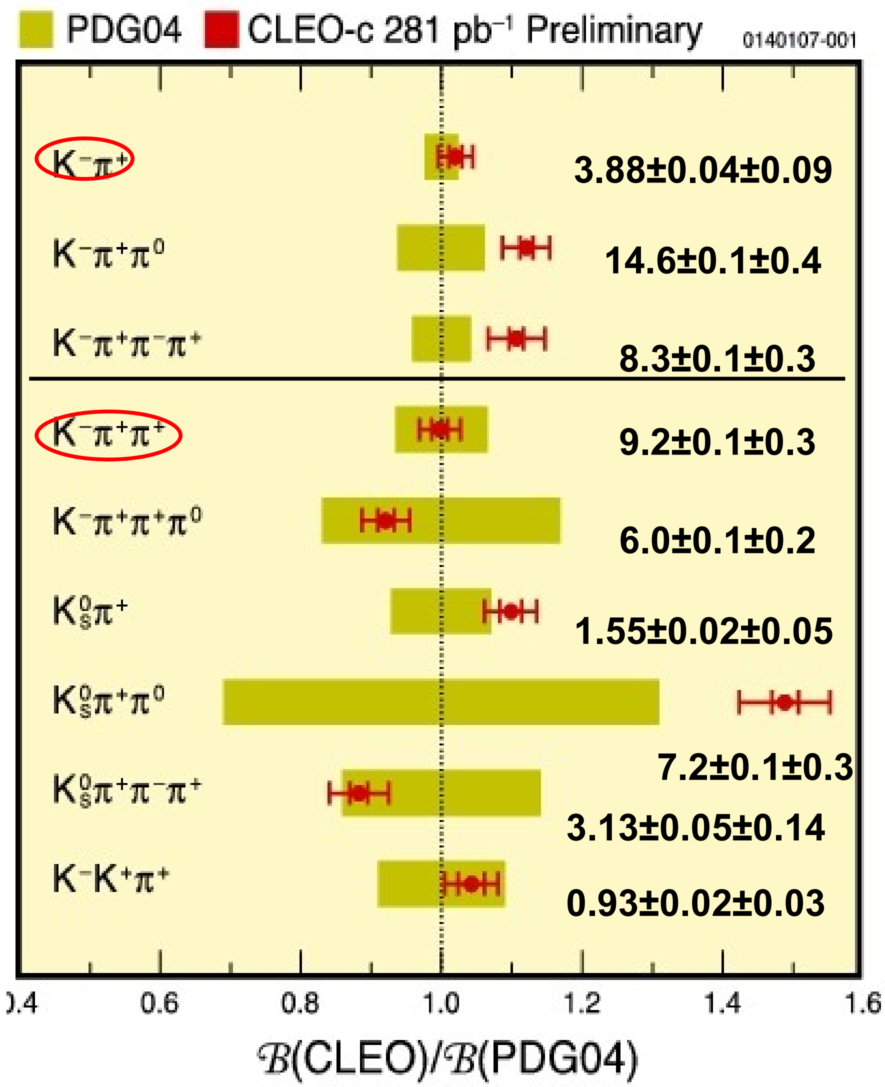


$\delta B/B \approx 2.3\%$

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



$\delta B/B \approx 2.9\%$



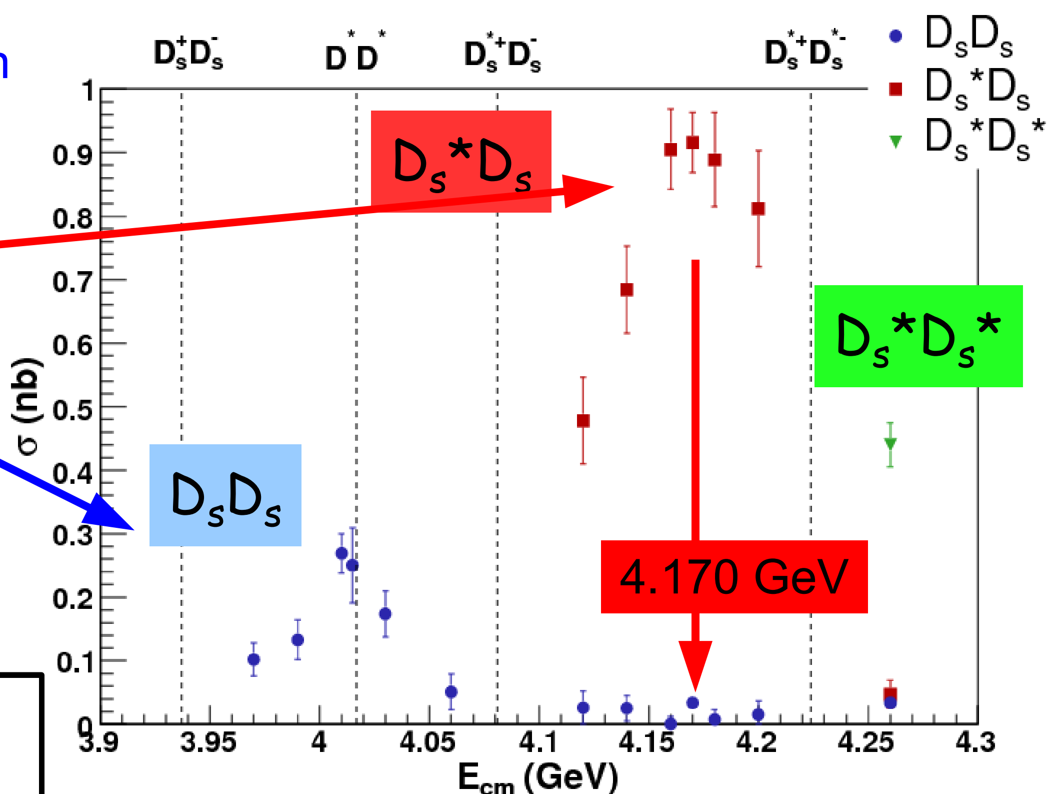
D_s absolute BF

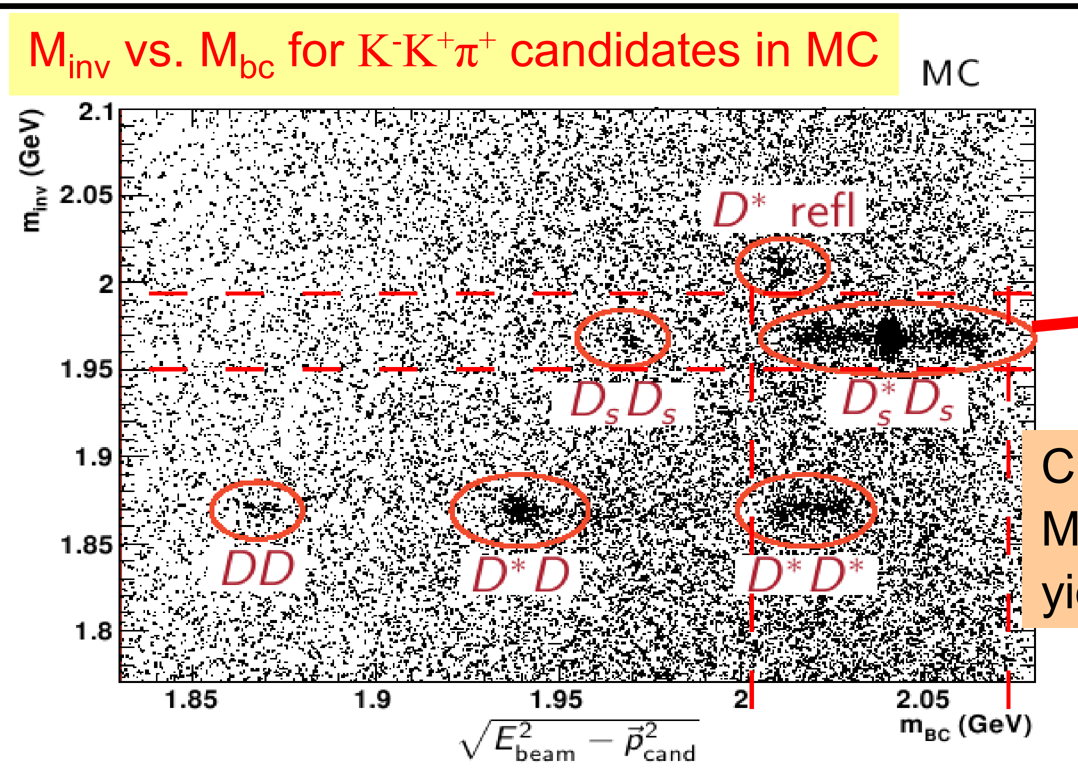
- scanned the region to maximize D_s production (12 energy points):
  - maximum cross section at 4.170 GeV
  - almost exclusively $D_s^*D_s$: $\sigma \approx 0.9$ nb

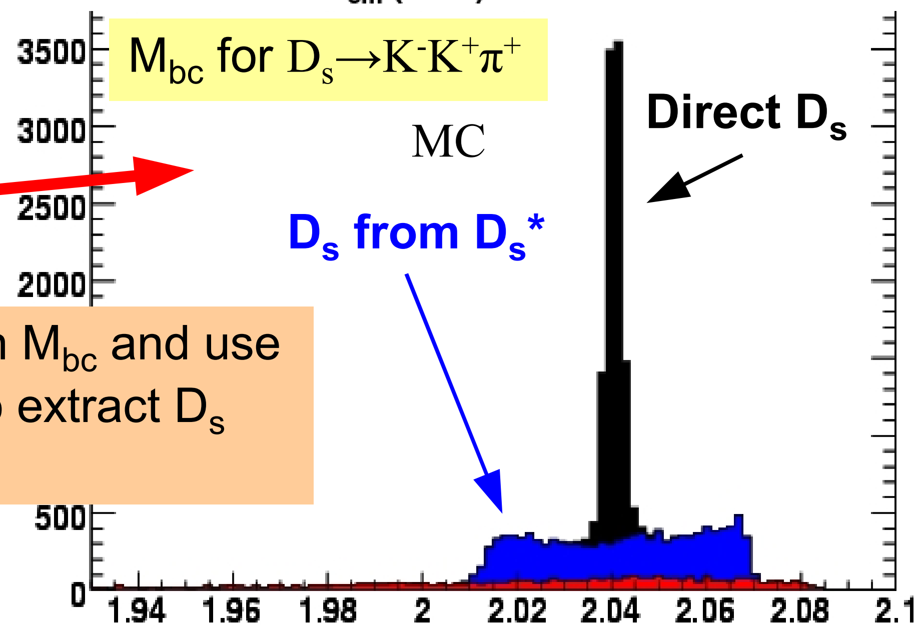
    compare to max $\sigma(D_sD_s) \approx 0.3$ nb only
- $D_s^*D_s$ has different kinematics than $D\overline{D}$:

  D_s from $D_s^* \rightarrow (\gamma, \pi^0) D_s$ has smeared momenta

  (the γ or π^0 is not reconstructed)







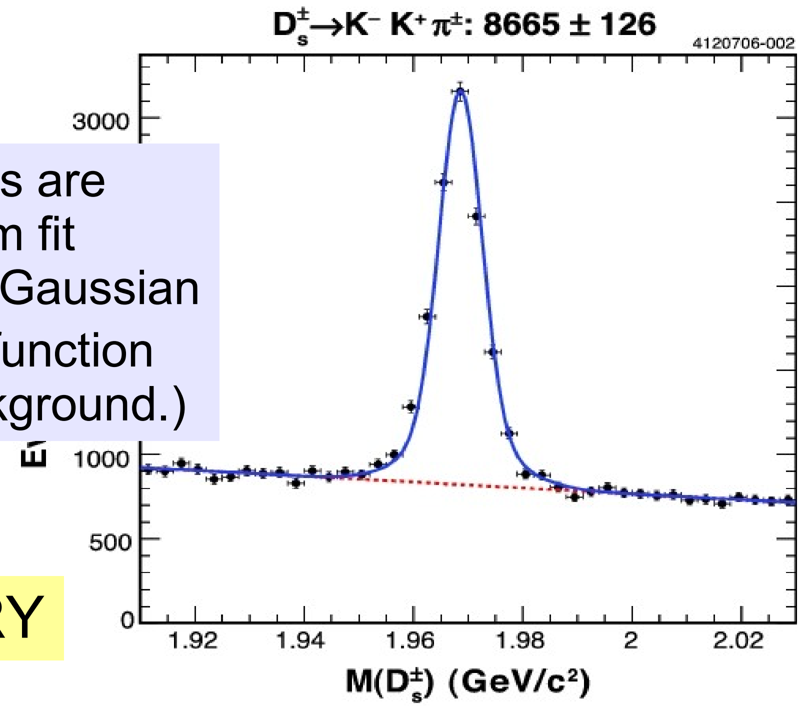
Cut on M_{bc} and use M_{inv} to extract D_s yields

D_s absolute BF

- Measure 6 D_s decay modes with similar technique to DD analysis

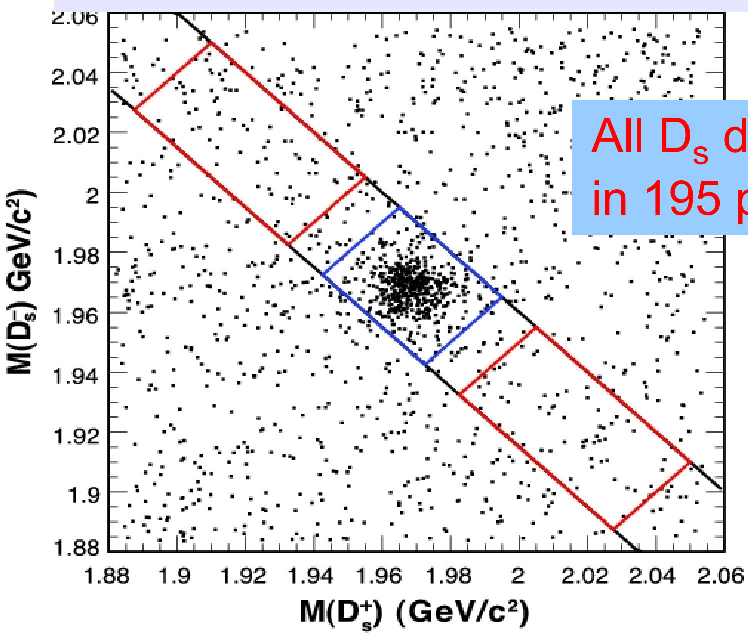
Mode	D_s+	D_s-
K_sK^+	1055±39	928±37
$K^+K^-\pi^+$	4316±89	4350±89
$K^+K^-\pi^+\pi$	1160±85	1251±84
$\pi^+\pi^-\pi^+$	970±80	947±78
$\eta\pi^+$	547±50	570±50
$\eta'\pi^+$	362±23	372±24

Single tag yields are determined from fit to M_{inv} (double Gaussian or Crystal Ball function plus linear background.)

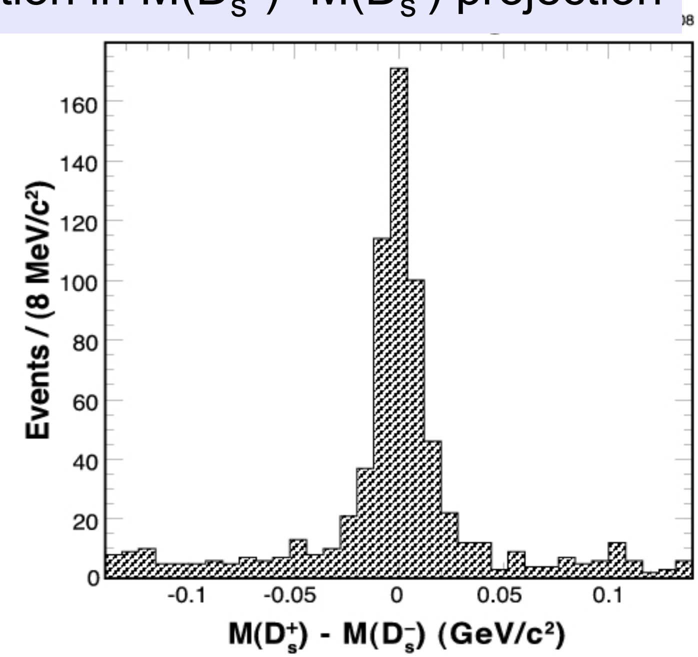


PRELIMINARY

Double tag yields are determined via side-band subtraction in $M(D_s^+)$ -$M(D_s^-)$ projection



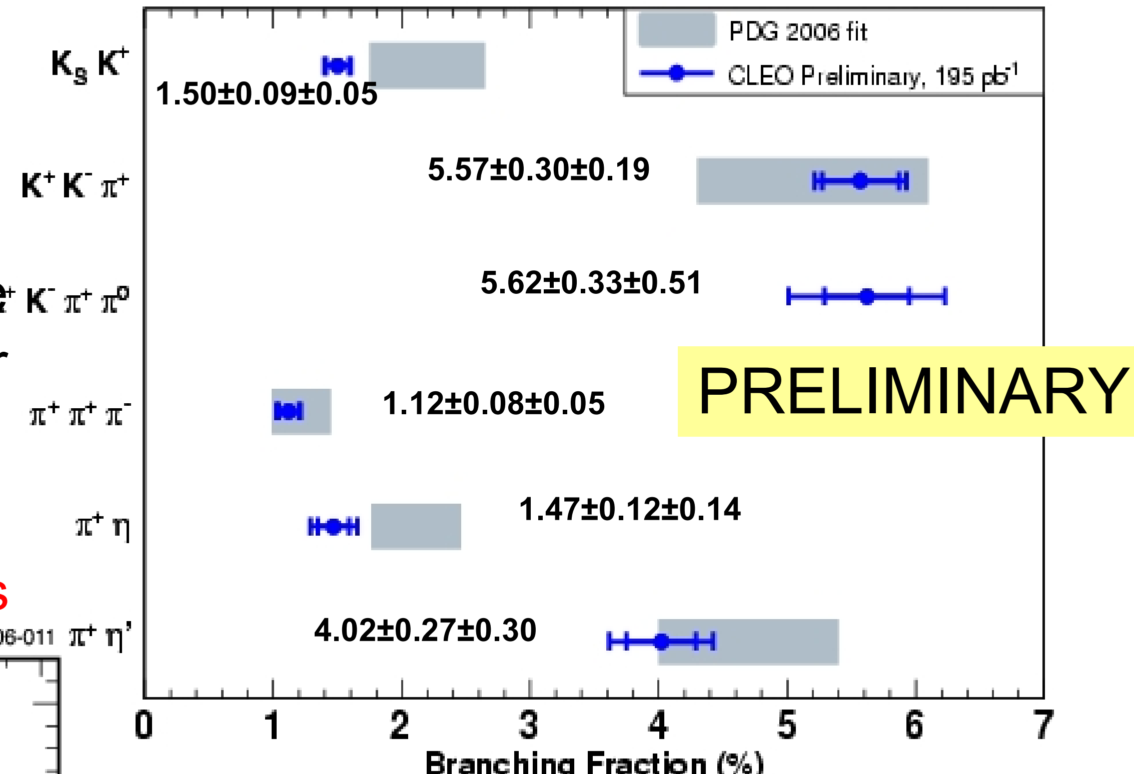
All D_s double tags combined in 195 pb^{-1}: 518 - 47(backgr.)

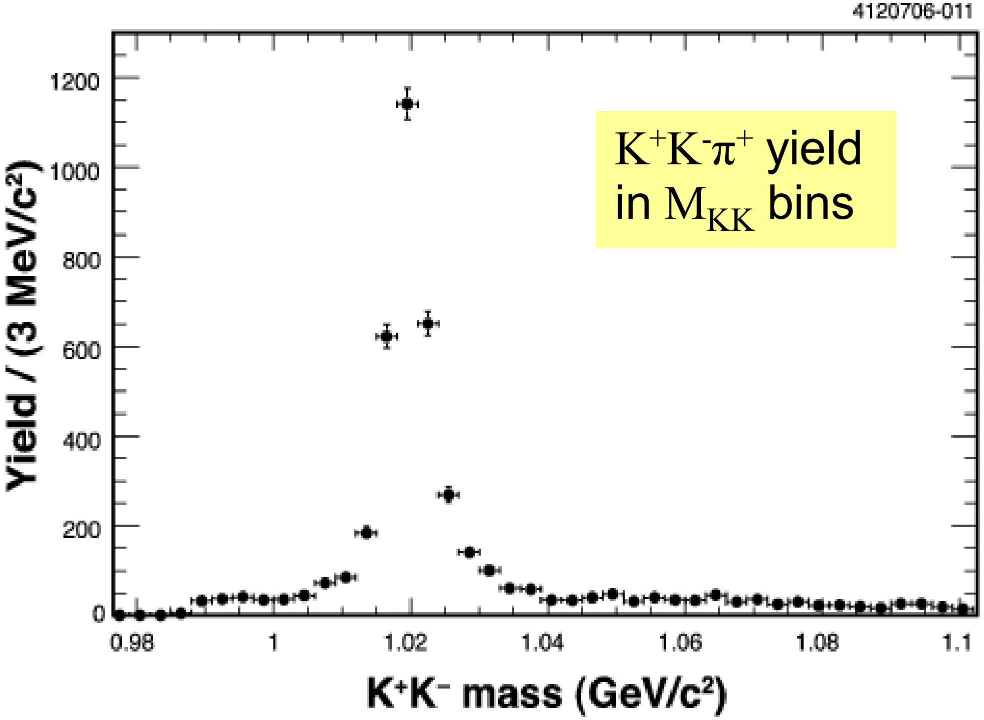


D_s absolute BF: results in 195 pb^{-1}

- Binned max likelihood fit to all modes simultaneously
- Errors are already less than PDG
- $D_s \to \varphi\pi$ is critical (used to normalize other D_s decays) but difficult: scalar $f^0(980)$ or $a^0(980)$ contribution (E687 and FOCUS)

⇒ BF depends on choice of cuts





Partial $D_s \to K^+K^-\pi^+$ branching fraction:

$M(\varphi) \pm 10$ MeV/c^2: 1.98 ± 0.12 ± 0.09 %

$M(\varphi) \pm 20$ MeV/c^2: 2.25 ± 0.13 ± 0.12 %

($\delta B/B \approx 8\%$)

PDG06: $B(D_s \to \varphi\pi) \times B(\varphi \to KK)$ = 2.16 ± 0.28% ($\delta B/B \approx 13\%$)

(not exactly comparable b/c different cuts!)

D^+ and D_s leptonic decays and decay constants

$D^+ \to \mu^+ \nu$ and f_D:

PRL 95, 251801 (2005): $D^+ \to \mu^+ \nu$ BF and $D^+ \to e^+ \nu$ UL

PRD 73, 112005 (2006): $D^+ \to \tau^+ \nu$ UL

with 281 pb^{-1} $D\bar{D}$ data

$D_s \to \mu^+ \nu$ and $\tau^+(\pi^+ \nu)\nu$:

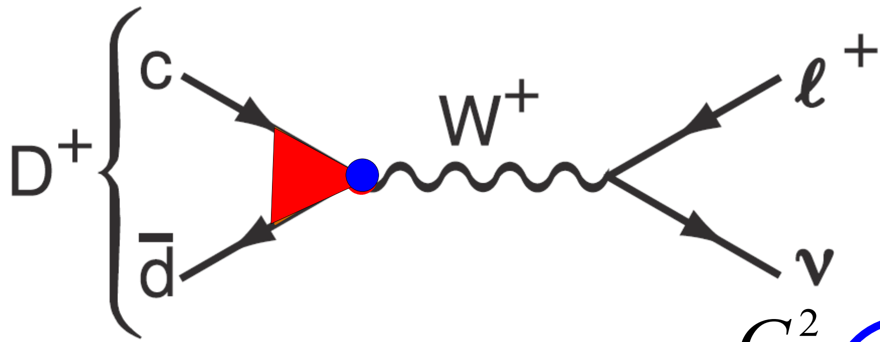
CLEO CONF 06-17 (hep-ex/0607074) with 195 pb^{-1}

Preliminary results with 314 pb^{-1} $D_s{}^*D_s$ data

$D_s \to \tau^+(e^+ \nu\nu)\nu$:

Preliminary results with 195 pb^{-1} $D_s{}^*D_s$ data

$D_{(s)} \to \ell^+\nu$: Motivation



- Using V_{cd} and V_{cs}, f_D and f_{Ds} can be determined from $D_{(s)} \to \ell^+\nu$ purely leptonic decays

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

$V_{qq'}$: CKM matrix element (weak interaction)

f_P : pseudoscalar decay constant (strong interaction between quarks)

- Measurement of $f_{D(s)}$ help to calibrate and validate Lattice QCD
- Impact on heavy flavor physics to constrain the CKM matrix:
  validated (L)QCD can calculate f_B (f_{Bs}) to determine $|V_{td}|$ ($|V_{ts}|$) from B^0 (B_s) mixing (very hard to measure since $B^+ \to \ell^+\nu$ BF is very small and $|V_{ub}|$ has large, ~15%, uncertainty)
- New physics: relative decay rate to different lepton flavors can be modified by other particle contributions (e.g. Higgs)

$$D^+ \to \ell^+\nu: \quad \Gamma(e^+\nu) : \Gamma(\mu^+\nu) : \Gamma(\tau^+\nu) = 2.3\times10^{-5} : 1.0 : 2.7$$

$$D_s \to \ell^+\nu: \quad \Gamma(e^+\nu) : \Gamma(\mu^+\nu) : \Gamma(\tau^+\nu) = 2.5\times10^{-5} : 1.0 : 9.7$$

in SM

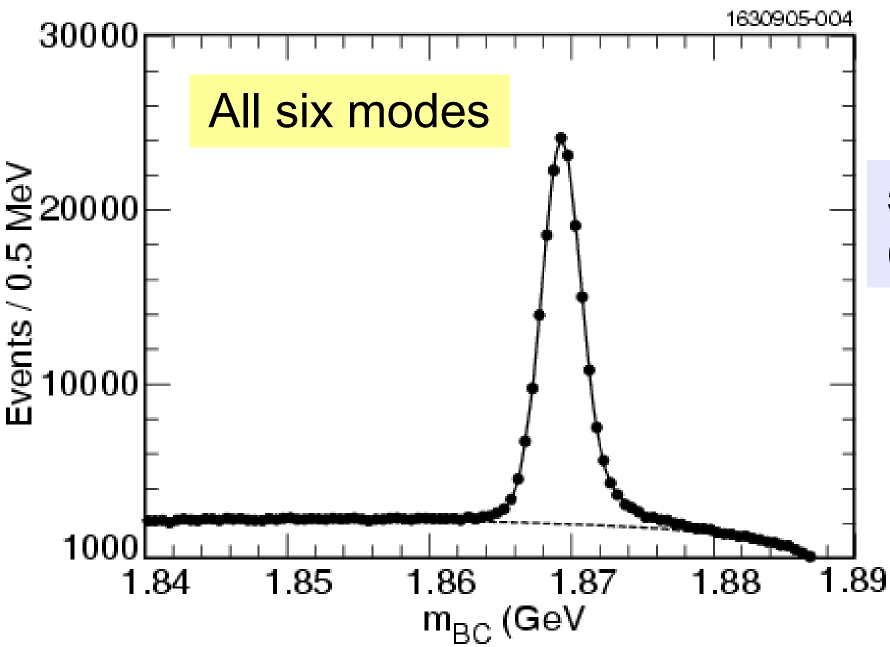
Measurement of $D^+ \to \mu^+ \nu$ and f_D

$e^+e^- \to \psi(3770) \to D^- D^+$

Tag side

Reconstruct D^- in six decay modes

Mode	Signal
$K^+\pi^-\pi^-$	77 387 ± 281
$K^+\pi^-\pi^-\pi^0$	24 850 ± 214
$K_S\pi^-$	11 162 ± 136
$K_S\pi^-\pi^-\pi^+$	18 176 ± 225
$K_S\pi^-\pi^0$	20 244 ± 170
$K^+K^-\pi^-$	6535 ± 95
Sum	158 354 ± 496



Signal side

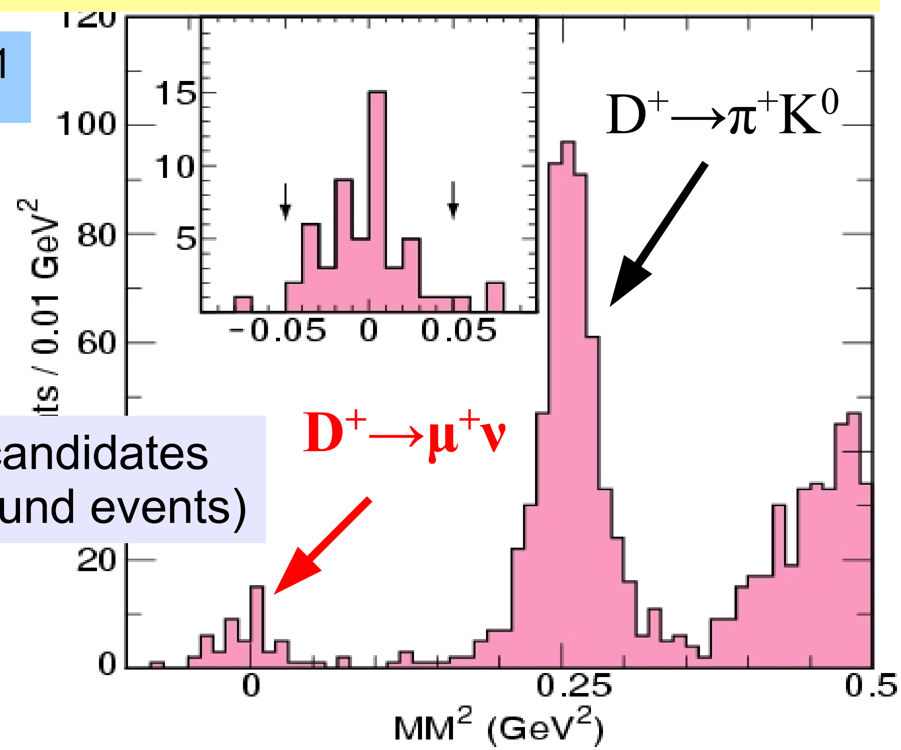
- A single muon candidate (E_{CC}<300 MeV)
- No extra track or shower with E_{CC}>250 MeV

Calculate missing mass

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

281 pb^{-1}

50 $D^+ \to \mu^+ \nu$ candidates (2.8 background events)



$B(D^+ \to \mu^+ \nu)$ = (4.4 ± 0.7 ± 0.1) x 10^{-4}

f_D = (222.6 ± 16.7 $^{+2.8}_{-3.4}$) MeV ($\delta f/f$ ~ 8%)

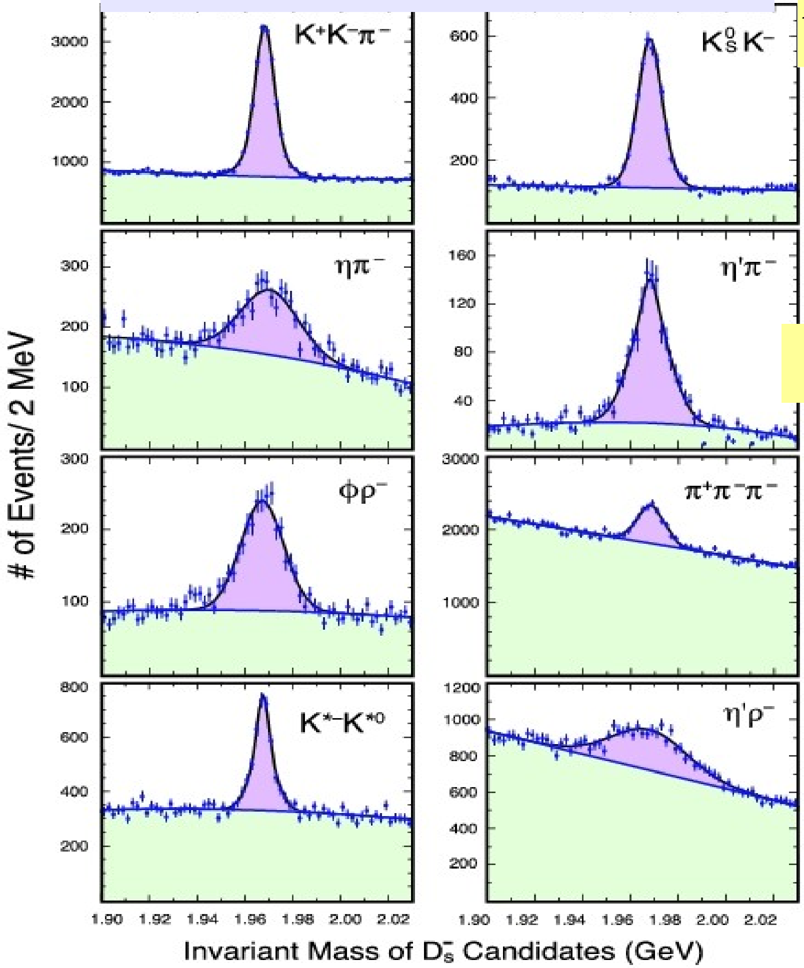
$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ (1)

- At E_{cm}=4170 MeV: use $e^+e^- \to D_s^*D_s \to \gamma D_s D_s$ [$B(D_s^* \to \gamma D_s) \approx 94\%$]
- Reconstruct one D_s decaying into 8 hadronic modes (tag)
- Require an additional photon and calculate recoil mass against the $\gamma D_{s\text{-tag}}$

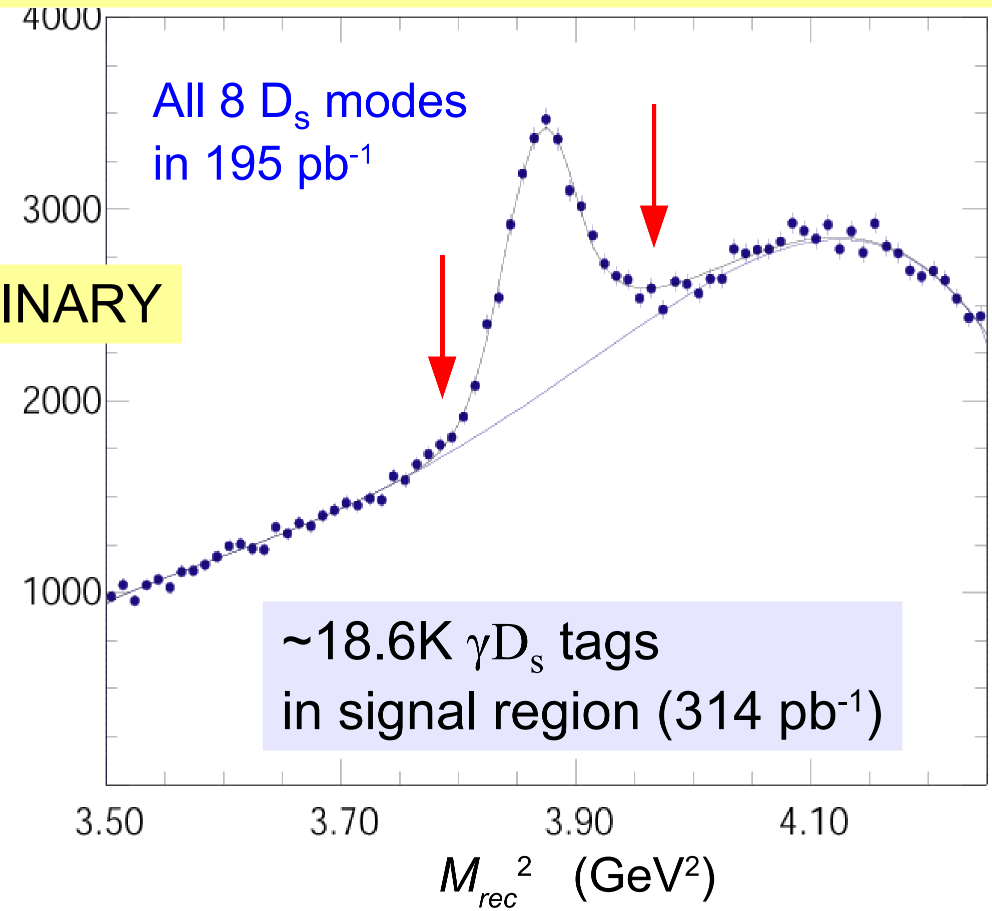
(Kinematic constraints are used to improve resolutions and remove multiple combinations)

~31.3K D_s tags in 314 pb^{-1}

$$M_{rec}^2 = (E_{CM} - E_{D_S-tag} - E_\gamma)^2 - (-\vec{p}_{D_S-tag} - \vec{p}_\gamma)^2 \approx M_{Ds}$$



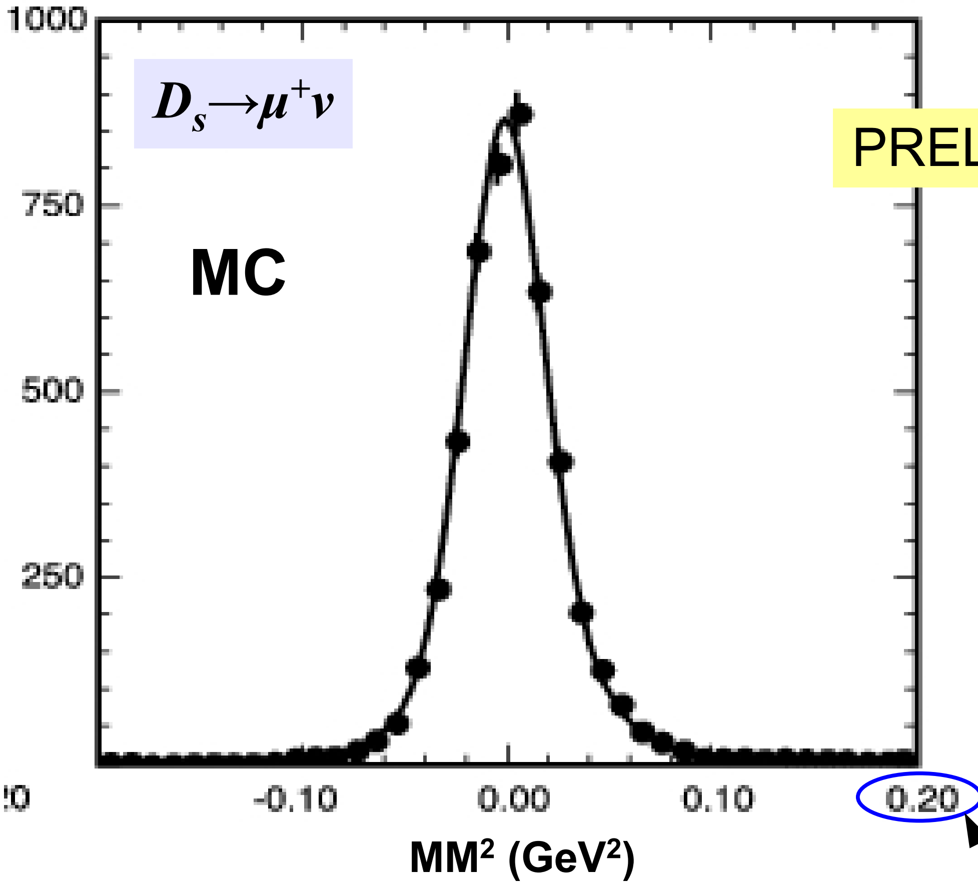
PRELIMINARY



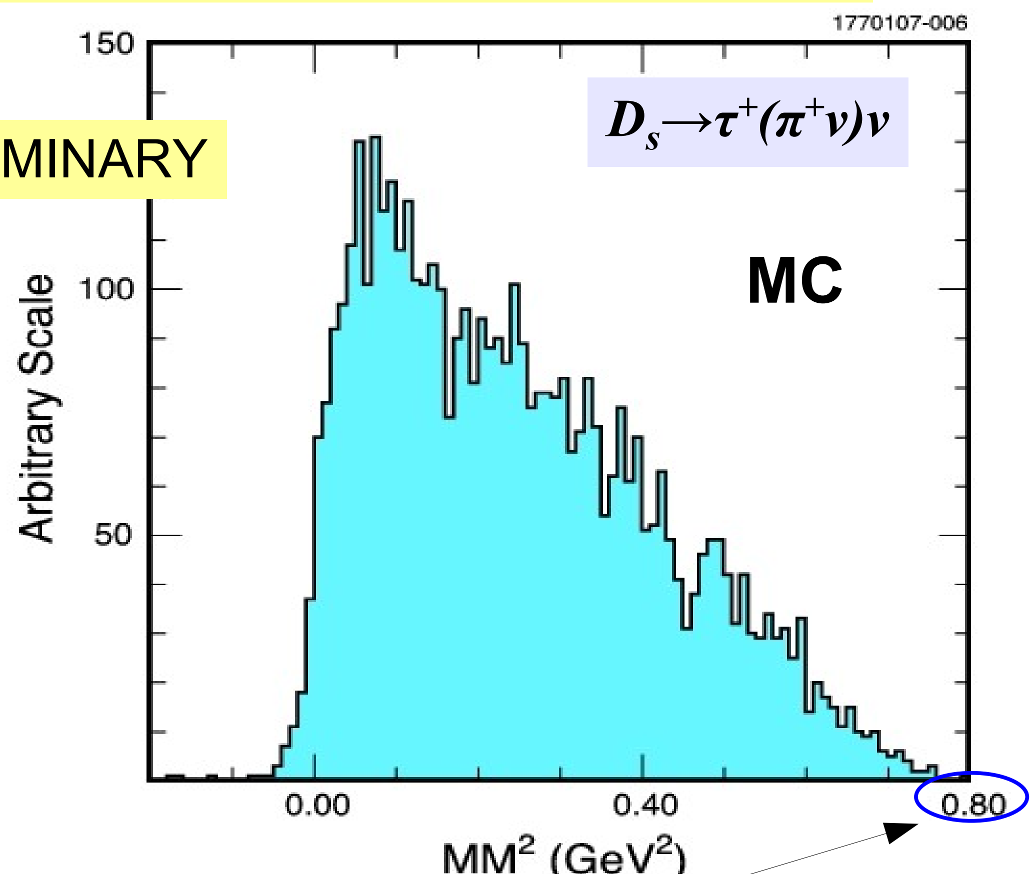
$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ (2)

- Require one additional track and no extra shower in CC with > 300 MeV
- Calculate missing mass in the event to infer the neutrino(s):

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



PRELIMINARY



Note different scale

$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ (3)

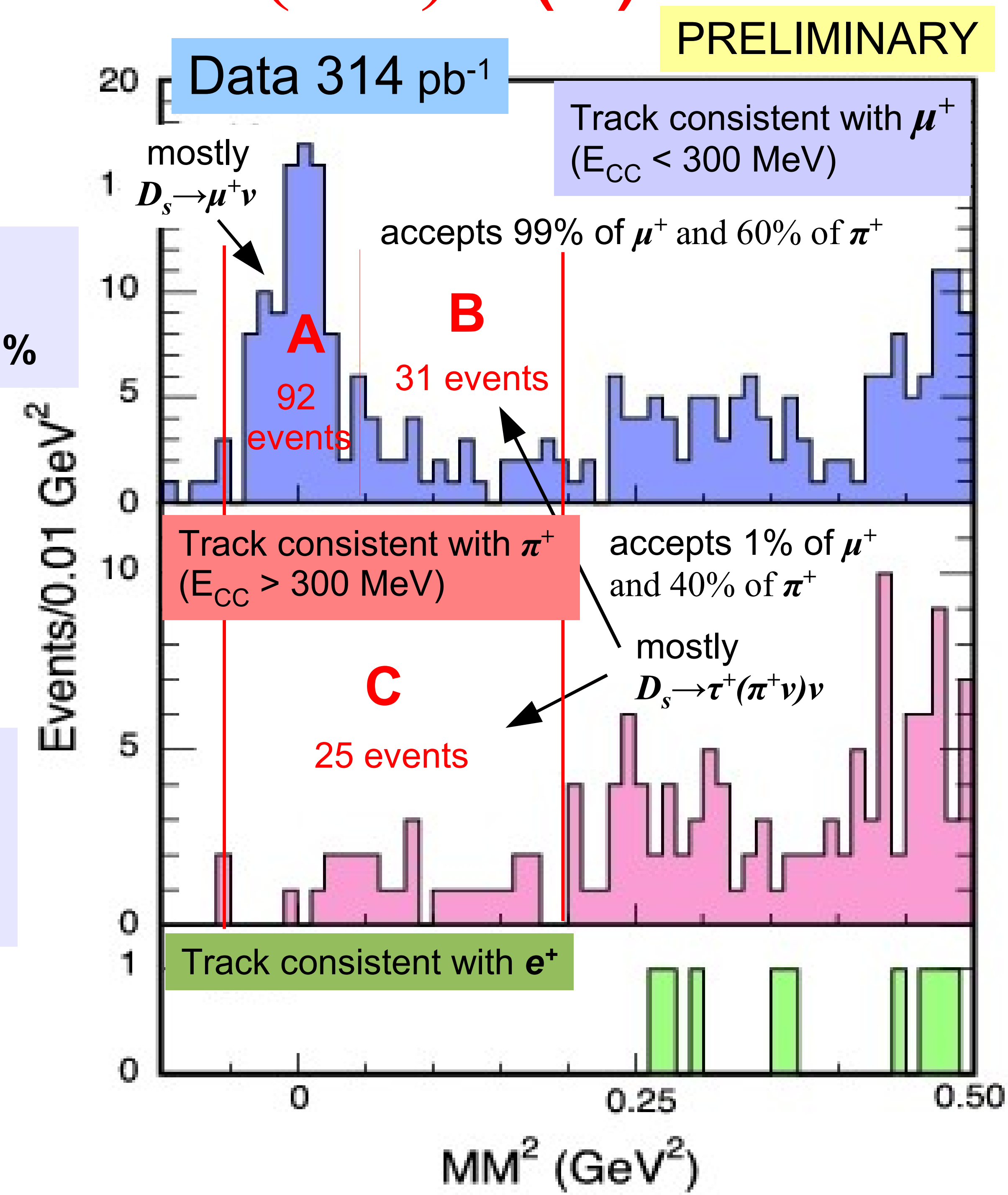
- Three cases depending on particle type:

A: 92 events (3.5 backg+7.4 $\tau^+(\pi^+\nu)\nu$) using SM τ/μ ratio
$B(D_s \to \mu^+\nu)$ = (0.594 ± 0.066 ± 0.031)%

B+C: 31+25 events (3.5+5 backg)
$B(D_s \to \tau^+\nu)$ = (8.0 ± 1.3 ± 0.4)%

A+B+C: 148 events (10.7 background) using SM τ/μ ratio
$B^{eff}(D_s \to \mu^+\nu)$ = (0.621 ± 0.058 ± 0.032)%
f_{D_s} = (270 ± 13 ± 7) MeV

$B(D_s \to e^+\nu) < 1.3 \times 10^{-4}$



$D_s \to \tau^+(e^+\nu\nu)\nu$

- Complimentary analysis using $D_s \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

$B(D_s \to \tau^+\nu)B(\tau^+ \to e^+\nu\nu) \approx 1.3\%$ significant [compare to $B(D_s \to Xe^+\nu) \approx 8\%$]

Analysis technique:

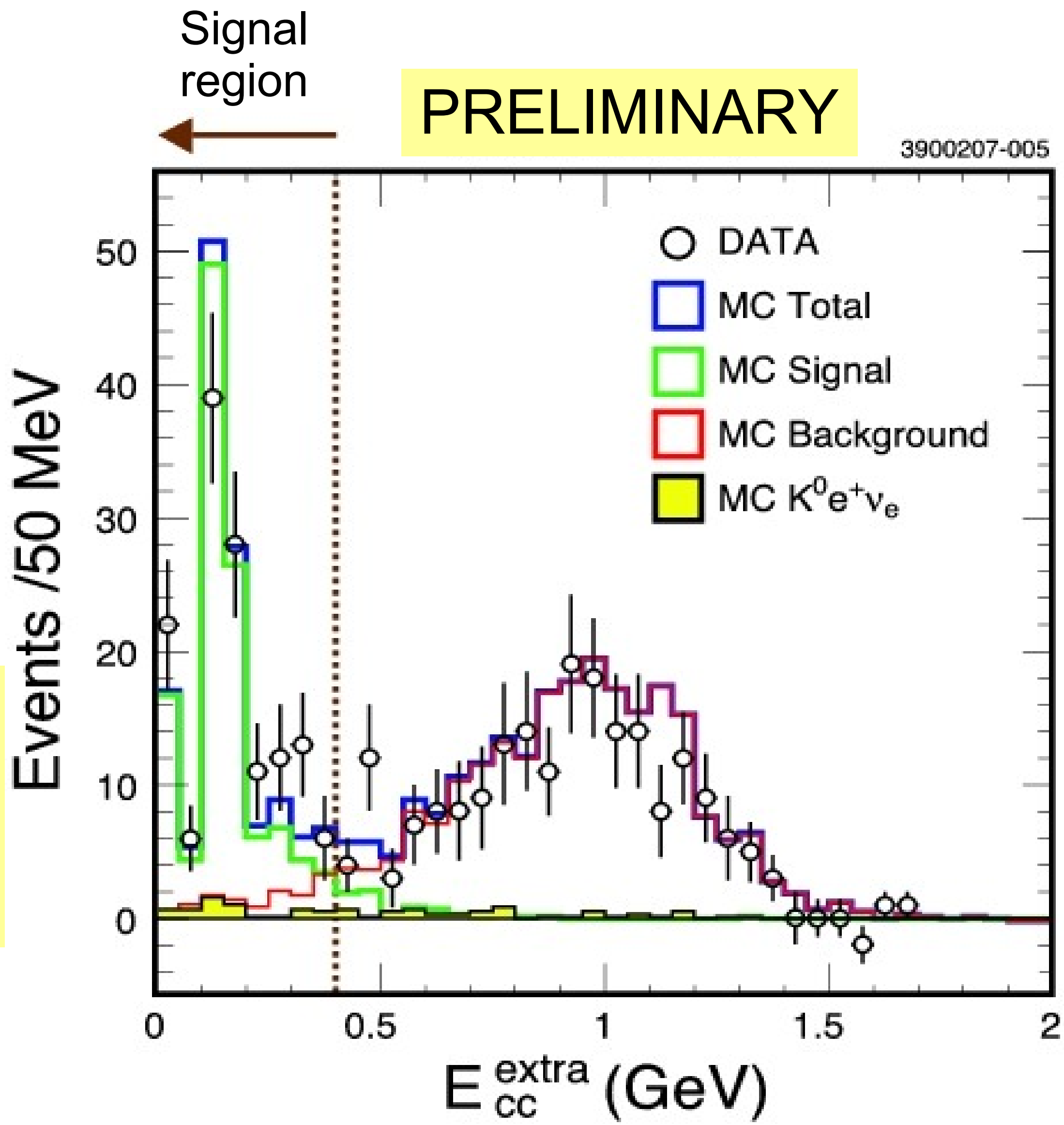
- Find D_s^- tag and e^+ (no need to find γ from D_s^*)
- No extra track
- Extra energy in CC < 400 MeV

Results:

***B($D_s \to \tau^+\nu$)* = (6.29 ± 0.78 ± 0.52)%**

[PDG06: *B($D_s \to \tau^+\nu$)* = (6.4 ± 1.5)%]

f_{Ds} = (278 ± 17 ± 12) MeV



f_D and f_{Ds} : comparison with theory

- Summary of CLEO-c results:

  f_D = (223 ± 17 ± 3) MeV

  f_{Ds} = (273 ± 10 ± 5) MeV

  (f_{Ds} weighted average of the two methods - syst. error is mostly uncorrelated)

  f_{Ds}/f_D = 1.22 ± 0.09 ± 0.03

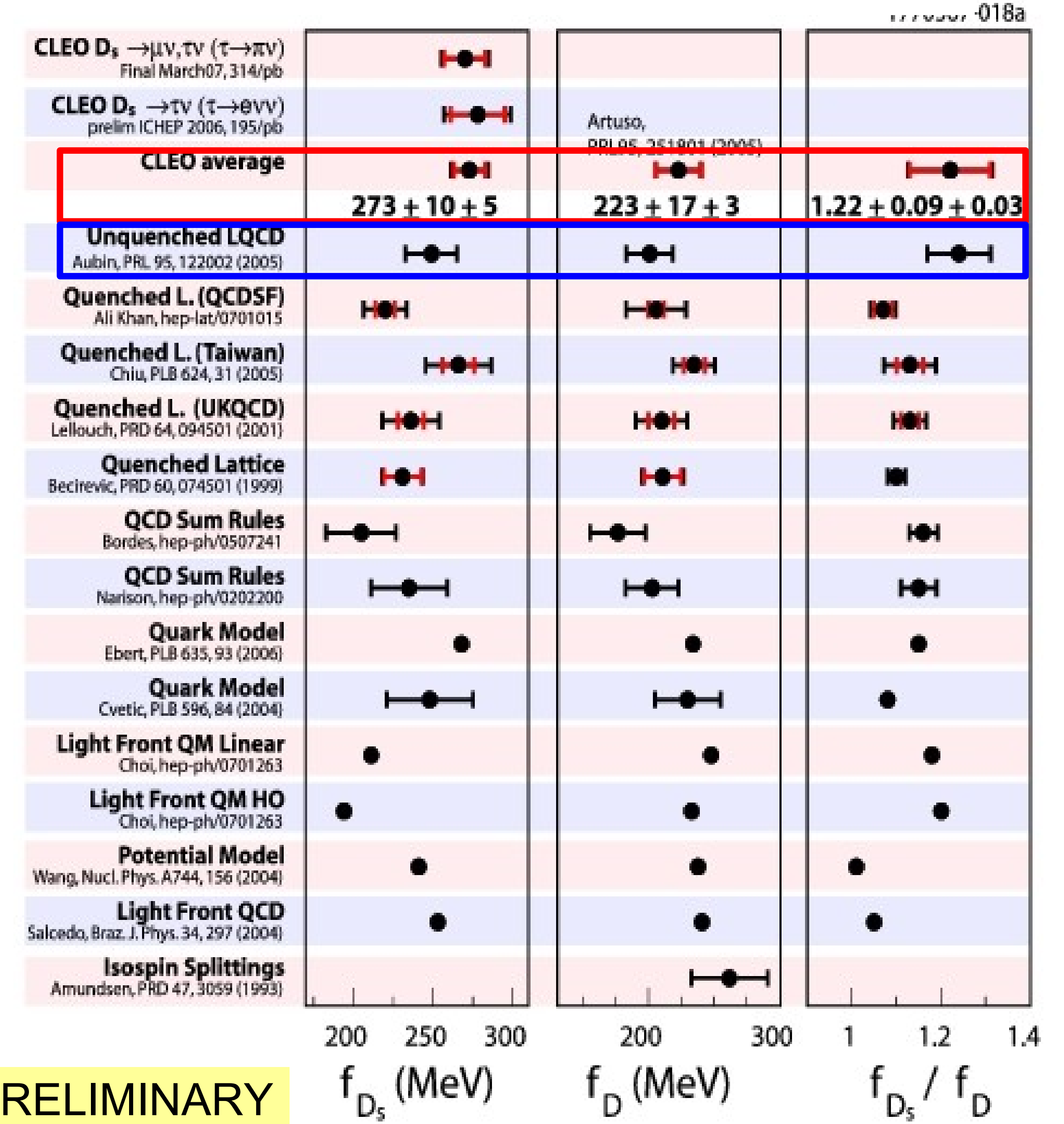
- Consistent with most models
- Statistically limited – more data is on the way!
- Lattice QCD (unquenched) PRL 95, 122002 (2005):

  f_D = (201 ± 3 ± 17) MeV

  f_{Ds} = (249 ± 3 ± 16) MeV

  f_{Ds}/f_D = 1.24 ± 0.01 ± 0.07

systematics limited!



PRELIMINARY

Spectroscopy

D^0 mass measurement and X(3872)

PRL 98, 092002 (2007)

with 281 pb^{-1} $D\bar{D}$ data

$\chi_c \rightarrow h^+ h^- h^0$ decays

PRD 75, 032002 (2007)

using 3 million $\psi(2S)$ decays

Precise D^0 mass measurement

Relevant to interpretation of X(3872): D^0D^{0*} molecule?

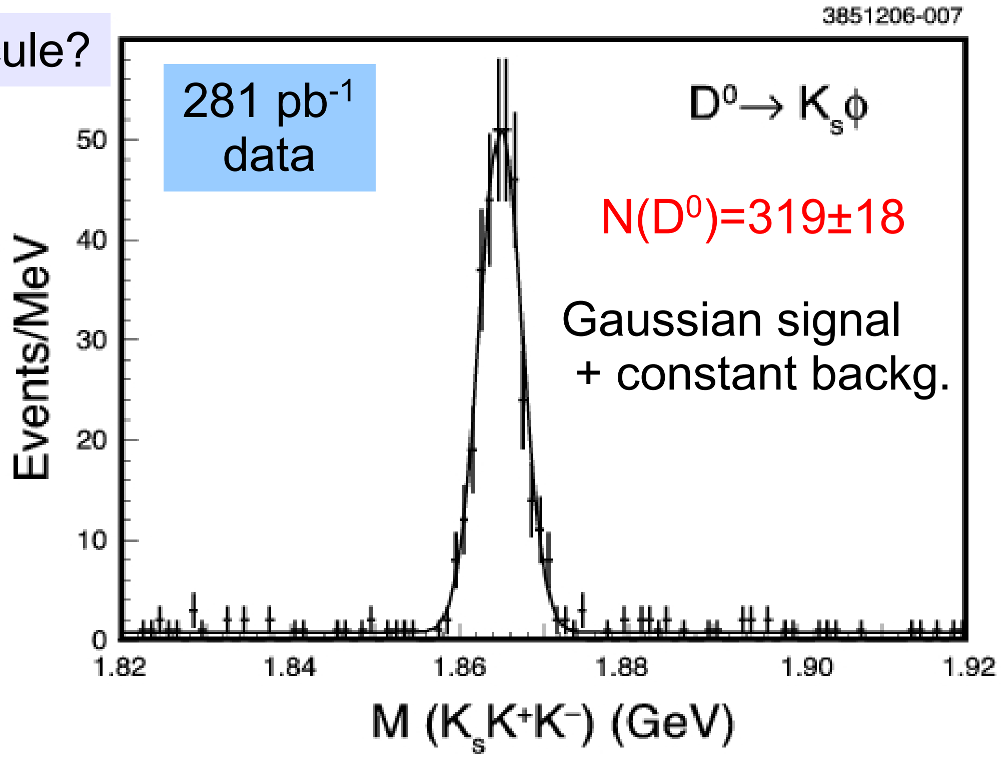
$$e^+e^- \rightarrow \Psi(3770) \rightarrow \overline{D}^0 D^0$$

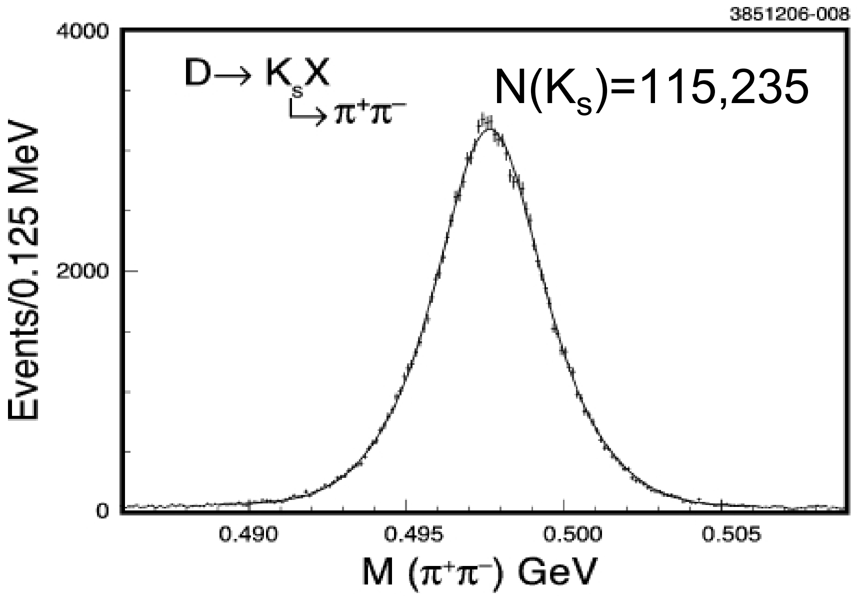
tag ($\overline{D}^0$) ; $D^0 \rightarrow K_s(\pi^+\pi^-)\varphi(K^+K^-)$

- *K and* π has small momenta: $\delta p/p$ is small
- K_s mass is constrained
- Use inclusive $K_s \rightarrow \pi^+\pi^-$ and $J/\psi \rightarrow \mu^+\mu^-$ decays to precisely calibrate D^0 mass

$M(K_s) = 497.648 \pm 0.007 \pm 0.037$ MeV/c^2

PDG06: 497.648 ± 0.022 MeV/c^2





$M(D^0) = 1864.847 \pm 0.150 \pm 0.095$ MeV/c^2

PDG06(ave.):	1864.1 ± 1.0 MeV/c^2
PDG06(fit):	1864.5 ± 0.4 MeV/c2

Binding energy of X(3872) as D^0D^{0*} molecule:

$$\Delta E_b = M_{D0D0^*} - M_{X(3872)} = (2M_{D0} + \Delta M_{D0^*-D0}) - M_{X(3872)}$$
$$= +0.6 \pm 0.6 \text{ MeV}$$

error is now limited by $\delta M_{X(3872)}$

D^0D^{0*} molecule, other 4-quark state with small binding energy, or threshold cusp?

$\chi_c \to h^+h^-h^0$ decays

- χ_{cJ} production from $\psi(2S)$ via radiative decay:

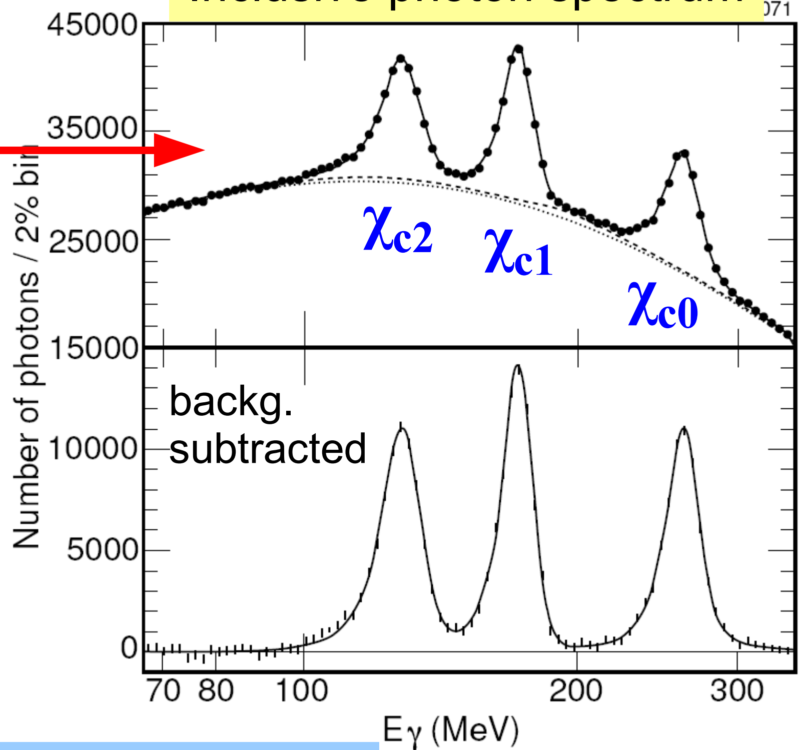
$$e^+e^- \to \psi(2S) \to \gamma\chi_{cJ} \quad (J=0,1,2)$$

$N[\psi(2S)] \approx$ 3M   CLEO III+c

$B[\psi(2S)\to\gamma\chi_{cJ}] \approx 9\%$ (for each J)

- Motivation for studying χ_{cJ} decay
  - Hadronic decays are not well known
  - Complimentary information on light hadrons and possible glueball dynamics (besides J/ψ and $\psi(2S)$ decays)

Inclusive photon spectrum

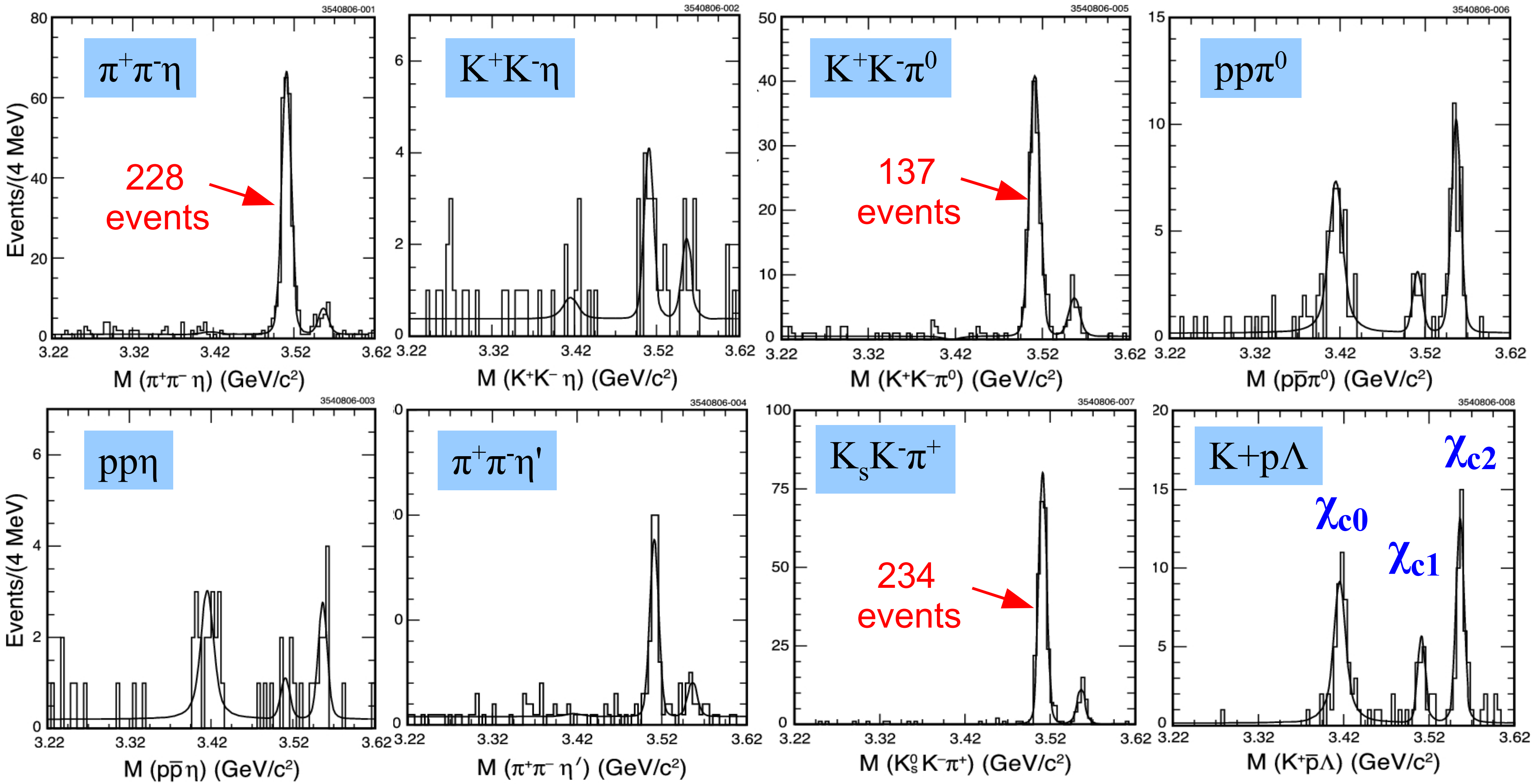


Study 8 exclusive 3-body final states – most of them are first observations:

BF x 10^3

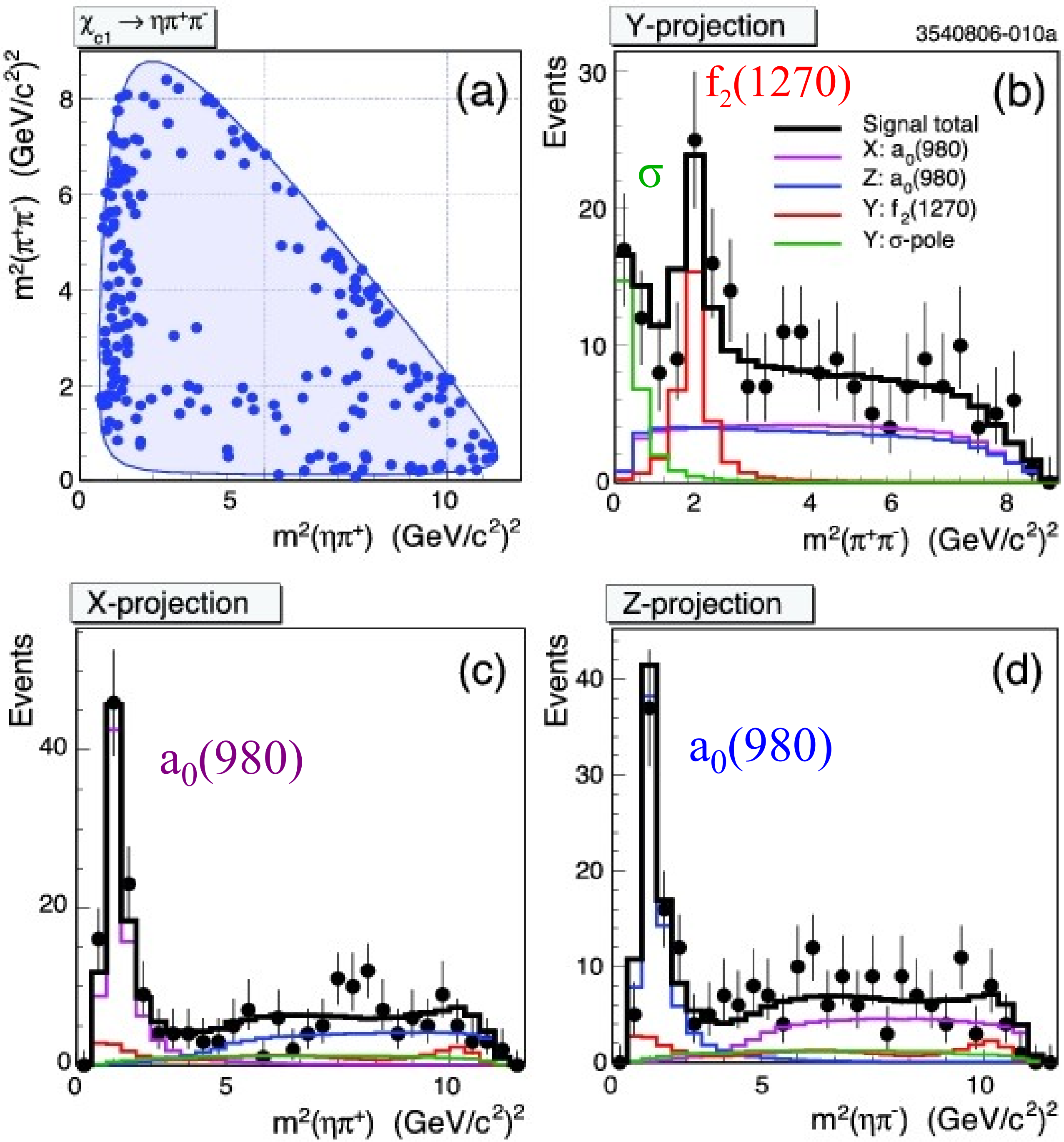
Mode	χ_{c0}	χ_{c1}	χ_{c2}
$\pi^+\pi^-\eta$	< 0.21	$5.0 \pm 0.3 \pm 0.4 \pm 0.3$	$0.49 \pm 0.12 \pm 0.05 \pm 0.03$
$K^+K^-\eta$	< 0.24	$0.34 \pm 0.10 \pm 0.03 \pm 0.02$	< 0.33
$p\bar{p}\eta$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02$	< 0.16	$0.19 \pm 0.07 \pm 0.02 \pm 0.01$
$\pi^+\pi^-\eta'$	< 0.38	$2.4 \pm 0.4 \pm 0.2 \pm 0.2$	$0.51 \pm 0.18 \pm 0.05 \pm 0.03$
$K^+K^-\pi^0$	< 0.06	$1.95 \pm 0.16 \pm 0.18 \pm 0.14$	$0.31 \pm 0.07 \pm 0.03 \pm 0.02$
$p\bar{p}\pi^0$	$0.59 \pm 0.10 \pm 0.07 \pm 0.03$	$0.12 \pm 0.05 \pm 0.01 \pm 0.01$	$0.44 \pm 0.08 \pm 0.04 \pm 0.03$
$\pi^+K^-\overline{K}^0$	< 0.10	$8.1 \pm 0.6 \pm 0.6 \pm 0.5$	$1.3 \pm 0.2 \pm 0.1 \pm 0.1$
$K^+\bar{p}\Lambda$	$1.07 \pm 0.17 \pm 0.10 \pm 0.06$	$0.33 \pm 0.09 \pm 0.03 \pm 0.02$	$0.85 \pm 0.14 \pm 0.08 \pm 0.06$

$\chi_c \rightarrow h^+h^-h^0$ decays



Statistics in $\chi_{c1} \rightarrow \pi^+\pi^-\eta$, $K^+K^-\pi^0$, $K_sK^-\pi^+$ sufficient for Dalitz analysis of resonant substructure (next two slides)

Dalitz analysis: $\chi_{c1} \to \pi^+\pi^-\eta$



- Small statistics (228 events): simple model with non-interfering resonances
- Contributions from

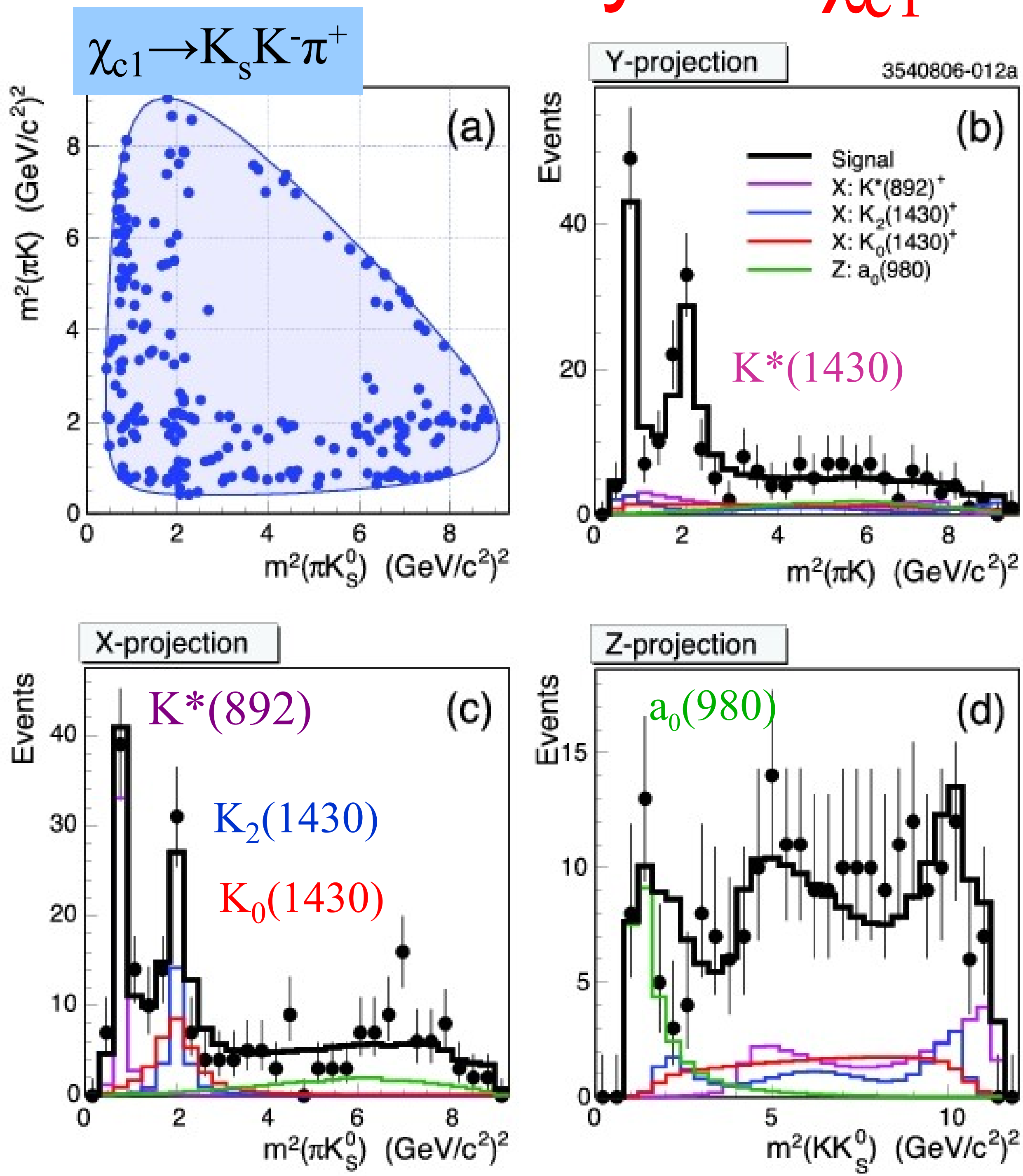
  $a_0(980)\pi$, $f_2(1270)\eta$, $\sigma\eta$

Mode	a_R	Fit fraction (%)
$a_0(980)^{\pm}\pi^{\mp}$	1	$75.1 \pm 3.5 \pm 4.3$
$f_2(1270)\eta$	$0.103 \pm 0.014 \pm 0.005$	$14.4 \pm 3.1 \pm 1.9$
$\sigma\eta$	$0.41 \pm 0.05 \pm 0.10$	$10.5 \pm 2.4 \pm 1.2$

- May offer the best way to determine $a_0(980)$ parameters with more statistics

  ~8 times more data collected (not yet analyzed)

Dalitz analysis: $\chi_{c1} \to K^+K^-\pi^0/K_SK^-\pi^+$



- Combined analysis (using isospin symmetry)
- Contributions from

K*(892)K , K*(1430)K , $a_0(980)\pi$

Mode	a_R	Fit fraction (%)
$K^*(892)K$	1	$31.4 \pm 2.2 \pm 1.7$
$K_0^*(1430)K$	$3.8 \pm 0.4 \pm 0.2$	$30.4 \pm 3.5 \pm 3.7$
$K_2^*(1430)K$	$0.44 \pm 0.06 \pm 0.04$	$23.1 \pm 3.4 \pm 7.1$
$a_0(980)\pi$	$6.1 \pm 0.6 \pm 0.6$	$15.1 \pm 2.7 \pm 1.5$

- Additional κK or non-resonant component does not improve the fit
- Need more data to do a complete PW analysis including interference

Conclusion

- Worlds best measurement of $D_{(s)}$ absolute branching fractions – aim to achieve ~4% for D_s decays with more data
- Worlds best $D_{(s)}$ decay constants provide test of Lattice QCD (and other models) and probe beyond-SM physics
- $\psi(2S)$ as well as χ_c decays provide rich opportunity to study charmonium spectroscopy, decay mechanisms, and light hadrons

More data on the way: taking data until April 2008

Stay tuned for more results from CLEO-c!

Extra slides

Constraint on new physics from $D_{(s)} \to \ell\nu$

- Relative decay rate to leptons can be modified by factor r due to H^+
- In MSSM the extra factor is (Akeroyd, hep-ph/0308260)

$$r = \left[1 - m_{D_q}^2 R^2 \left(m_q / m_c\right)^2\right]^2$$

where $R = \tan\beta / m_H$

- Larger effect for D_s: $r \propto (m_q/m_c)$
- Our results

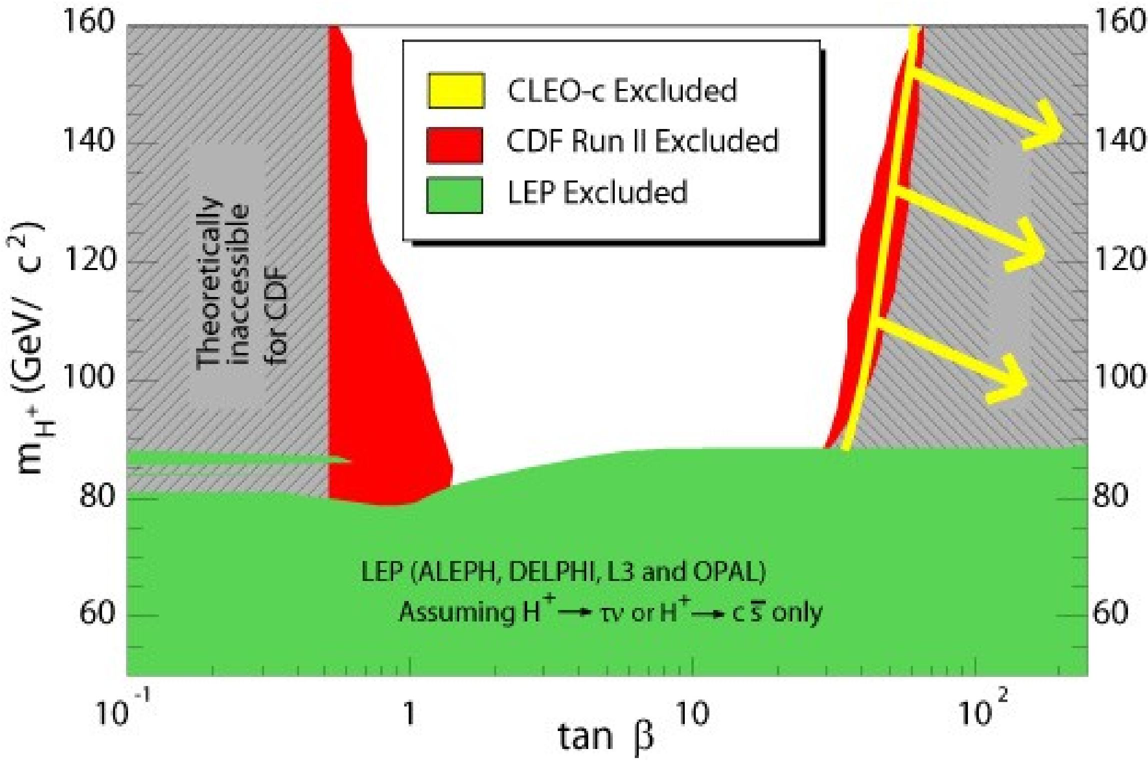
$\Gamma(D_s^+ \to \tau^+\nu)/\Gamma(D_s^+ \to \mu^+\nu) = 9.9 \pm 1.7 \pm 0.7$

(SM = 9.72)

$\Gamma(D^+ \to \tau^+\nu)/\Gamma(D^+ \to \mu^+\nu) < 4.77$ (90% cl)

(SM = 2.65)

⇨ r = Ratio/SM > 1 (Higgs: r < 1)



Can set limit on $\tan\beta$ vs. m_H plane but depends on theory – do not take seriously yet!

Dalitz plot formalizm

- Log likelihood: $$\mathcal{L} = -2\sum_{n=1}^{N} \log PDF(x_n, y_n)$$
- PDF: $$PDF(x,y) = \begin{cases} \varepsilon(x,y) \\ B(x,y) \\ fN_S|\mathcal{M}(x,y)|^2\varepsilon(x,y) + (1-f)N_B B(x,y) \end{cases}$$
- Matrix element: $$|M|^2 = \sum_R |A_R|^2\, \Omega_R^2$$

  non-interfering resonances

- Amplitude of each resonance contribution A_R:
  - Breit-Wigner parametrization with mass-dependent width (for narrow resonances)
  - Complex pole for S-wave (σ , κ): $1/(m_R^2 - m^2)$
  - Flatte parametrization for $a_0(980)$: $$\frac{1}{m_R^2 - m^2 - i(g_{\eta\pi}^2\rho_{\eta\pi} + g_{K\bar{K}}^2\rho_{K\bar{K}})}$$
- Angular distribution Ω_R:

  from V. Filippini, A. Fontana, A. Rotondi, PRD 51, 2247 (1995)