Recent Results in Charm Physics

Topics

- Rare Charm Processes as probes of New Physics

- Spectroscopy of New States

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CLEO, CMS and BES III Collaborations

Thanks to ICHEP reviews of David Asner and Galina Pakhlova

SPLIT 2008

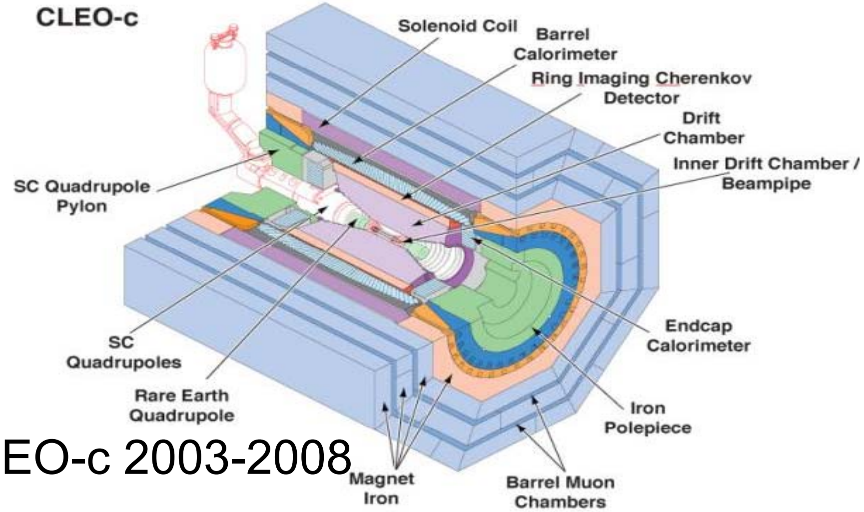
The Experiments

THREE DIFFERENT ENVIRONMENTS STILL OPERATING

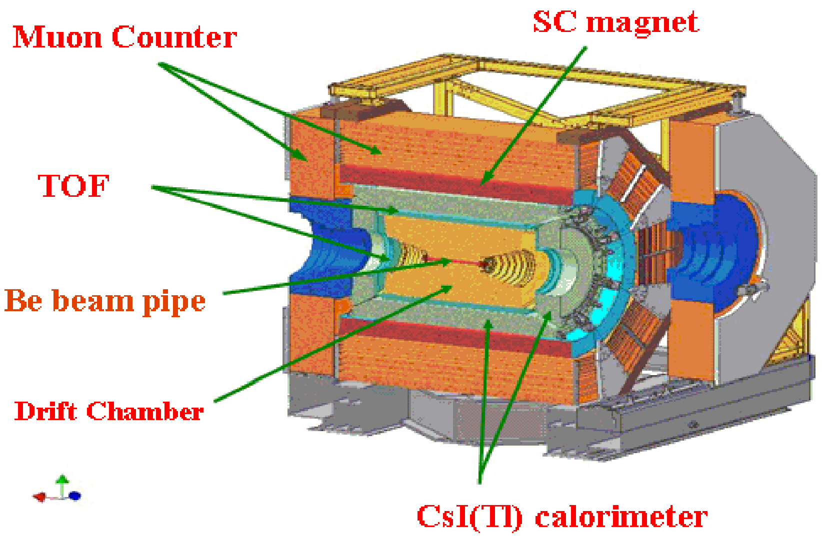
1. e^+e^- colliders in the charmonium region

Very clean! Can only run at one energy at a time.

BES II 1996-2004



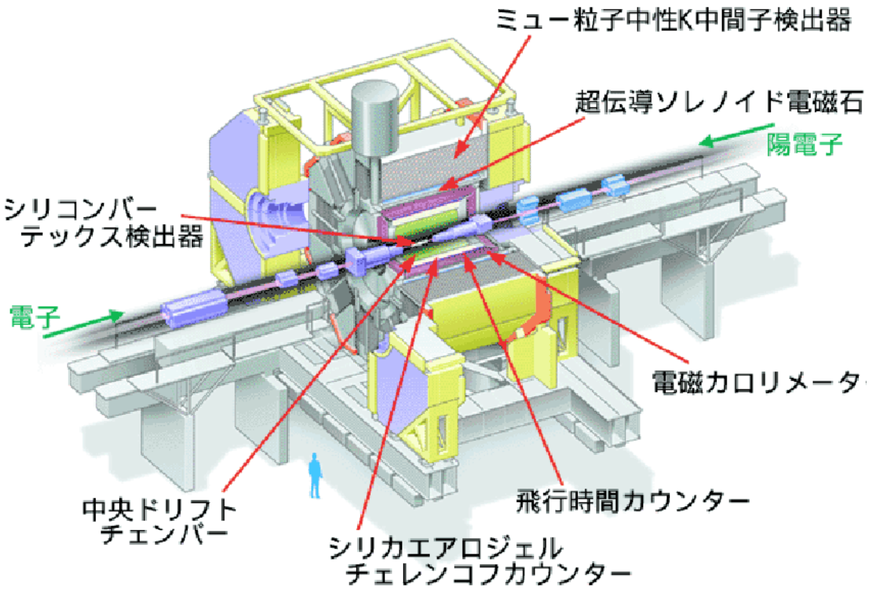
CLEO-c 2003-2008



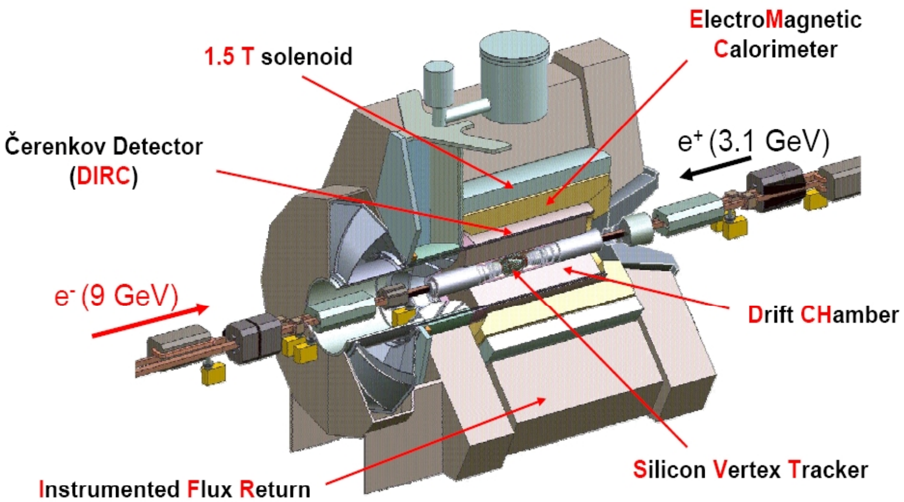
The Future –

BES III (running on the $\Psi(2S)$ as we speak)

2. *e^+e^- in the bottomium energy range*



BELLE 1998-date

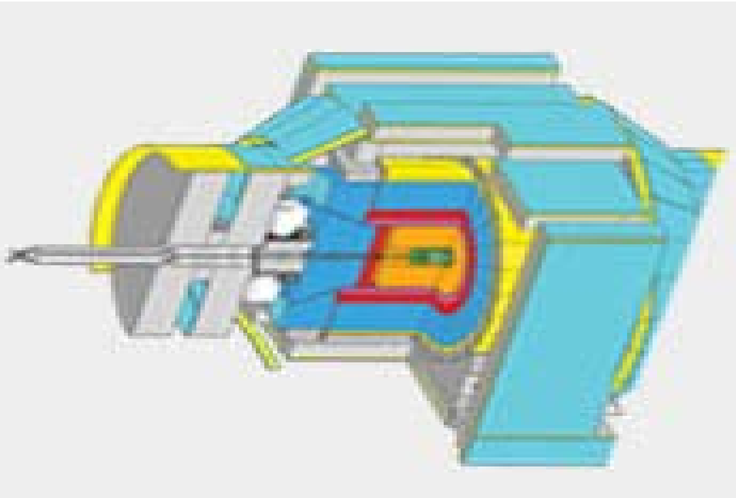


BaBar 1998-2008

Clean environment – several different ways of studying charm

a) Continuum
b) B-decays to charm
c) ISR to scan the charmonium resonances

3. Hadron colliders



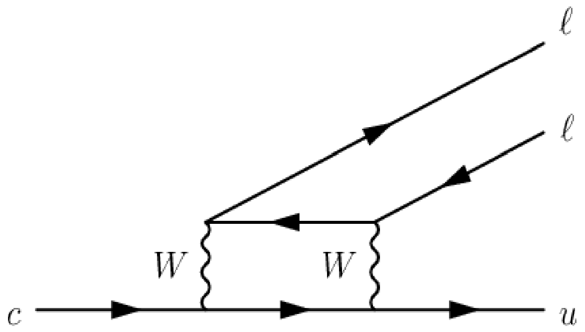
CDF

D0

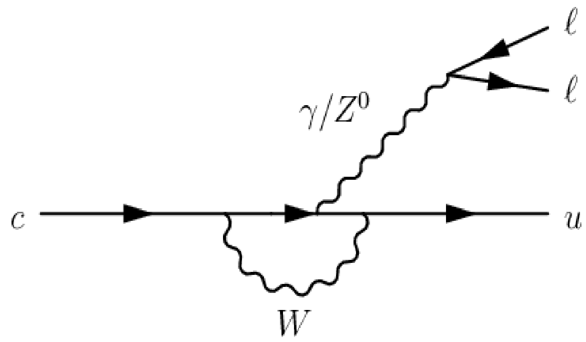
Huge cross section for charm – but complicated environment.
Physics can be done because of the kinematically clean decays of D^{*+} and J/ψ

The Future: LHC-b, and maybe CMS and ATLAS. Huge production rates,
but only LHC-b designed with a view specifically B and thus c physics.

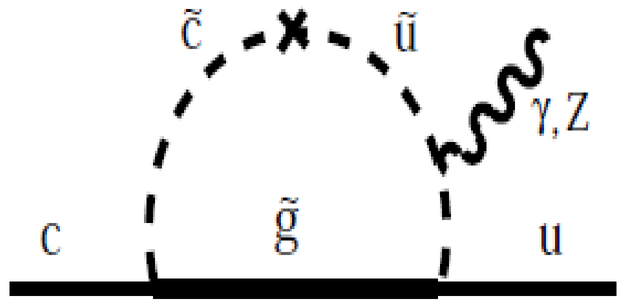
Search for New Physics (NP) in Charm Sector



SM



SM



NP

Very low SM rates (BF($c \rightarrow ull$)~10^{-8}) for loop processes provide unique window to observe NP in rare charm processes

Rare Decays, D^0-$\bar{D}^0$ oscillations & CP Violation

NP can introduce new particles into loop

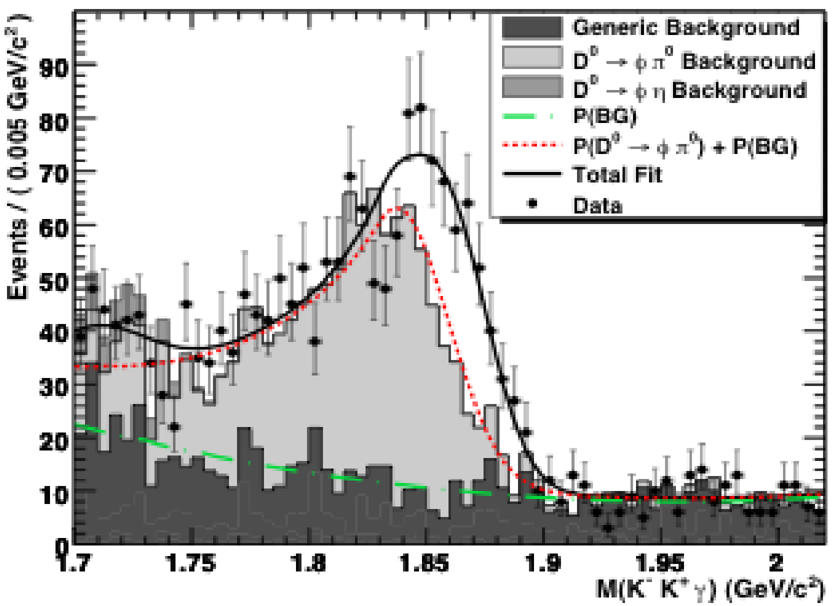
Particles and couplings in rare charm processes are NOT the same as in rare B and K processes

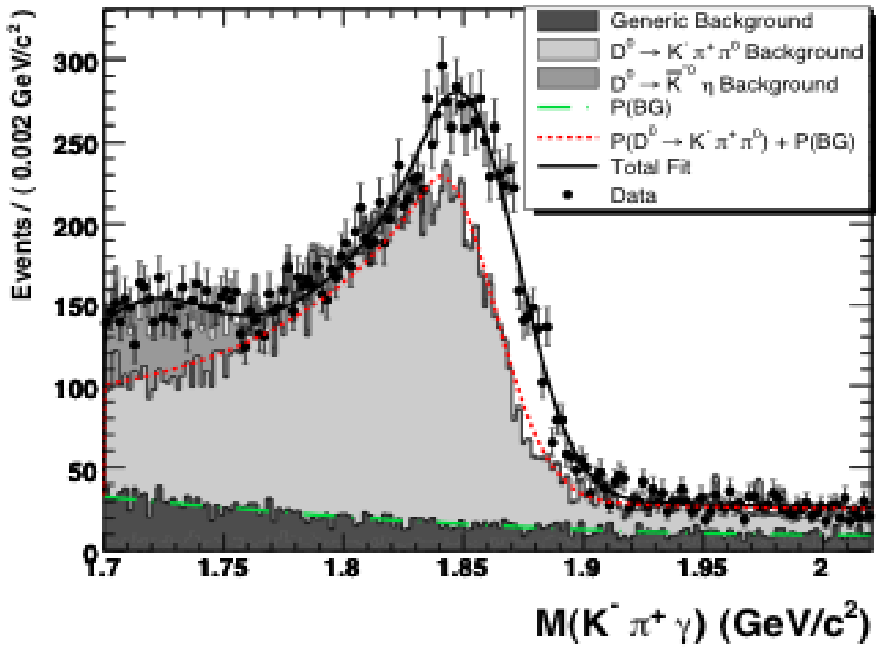
Rare Charm Decay Rates Modified by NP

- Radiative - $D \to (\gamma, \phi, K^*)\gamma$ SM 10^{-4} -10^{-6}
  - CLEO $D \to \gamma\gamma$ < 2.6×10^{-5} @90% C.L.
  - BABAR $D \to \phi\gamma$ $(2.73 \pm 0.30 \pm 0.36) \times 10^{-5}$ (new)
  - BABAR $D \to K^*\gamma$ $(3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$ (new)
- Leptonic $D \to \mu\mu$ SM<10^{-13} RPV SUSY~10^{-7}
  - CDF < 4.3×10^{-7} @90% C.L. (new)
- GIM Suppressed $D \to \pi ll$ SM~10^{-6}
  - Distinguish NP from SM with dilepton invariant mass, FB asymmetries
    - D0 $D \to \pi\mu\mu$ < 3.9×10^{-6}
    - CLEO-c $D \to \pi ee$ < 4.7×10^{-6}
- Lepton Flavor Violation - BABAR @90% C.L.
  - $D \to e^+\mu^-$ < 8.1×10^{-7} $D^+ \to K^+ e^- \mu^+$ < 3.7×10^{-6}
  - $D_s^+ \to K^+ e^- \mu^+$ < 3.6×10^{-6} $\Lambda_c^+ \to p e^- \mu^+$ < 7.5×10^{-6}
- Lepton Number Violation $D^+ \to \pi^- e^+ e^+$
  - CLEO-c < 3.6×10^{-6} @90% C.L

Radiative D decays

- Radiative - D→(ϕ,K*)γ SM 10^{-4}-10^{-6}
  - BABAR D→ϕγ (2.73±0.30±0.36) x 10^{-5} (new at ICHEP)
  - BABAR D→K*γ (3.22±0.20±0.27)x 10^{-4} (new at ICHEP)

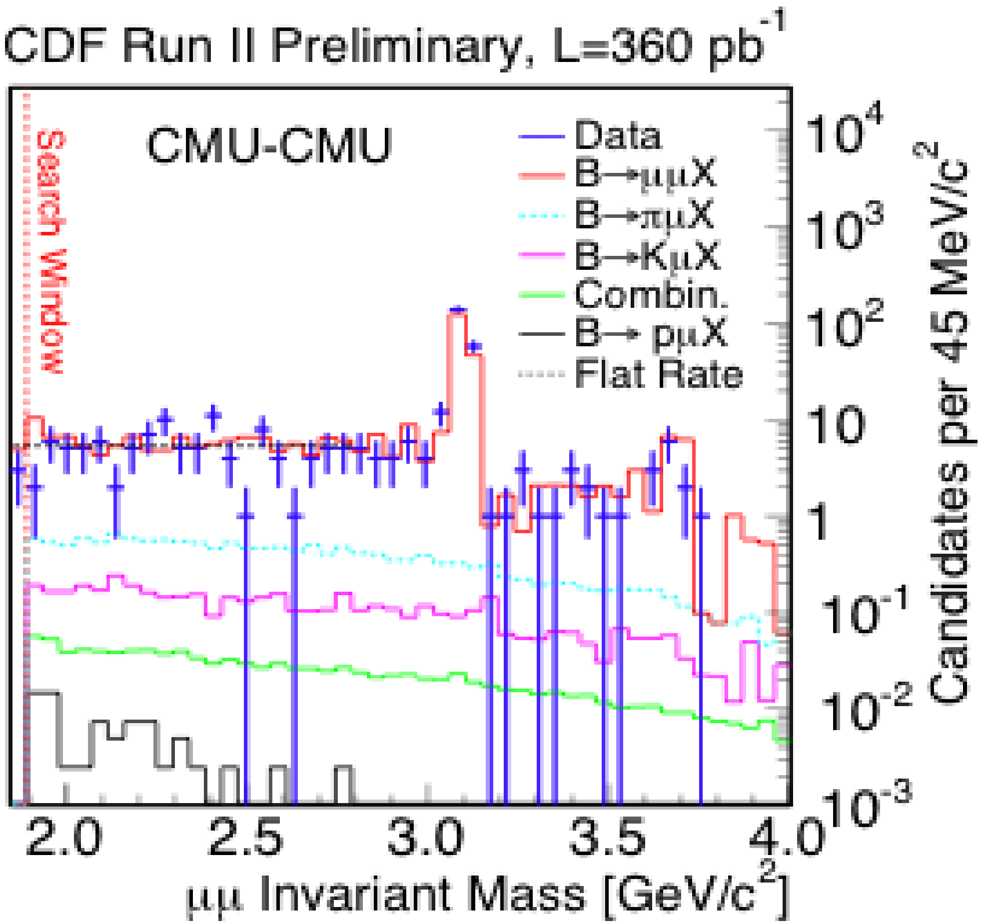




SLAC-PUB-13352, hep-ex/arXiv:0808:1838

Though interesting, these observations do not indicate new physics, they indicate final state interactions.

Purely Leptonic Decay D→μμ



No evidence of a signal

D →μμ < 4.3×10^{-7} @90% C.L.

SM<10^{-13}

RPV SUSY~10^{-7}

This gives constraints on R-parity violating SUSY models

CDF Public Note 9226

D^0-$\overline{D}^0$ Mixing

Two state system: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$

Mass Eigenstates≠Flavor Eigenstates

D^0–$\overline{D}^0$ transitions observables

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma} \qquad R_M = \tfrac{1}{2}\left(x^2 + y^2\right)$$

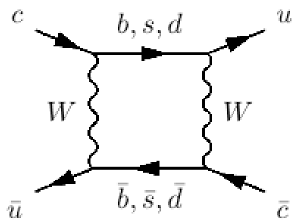
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$
$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} \qquad \left|\frac{q}{p}\right| \qquad Arg\left(\tfrac{q}{p}\right)$$

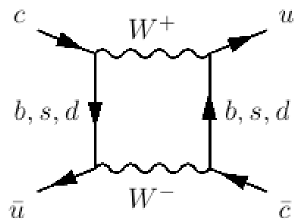
SM calculations based on box diagrams alone gives $x \sim 10^{-5}$, $y \sim 10^{-7}$ [Falk et al. PRD 65 (2002) 054034]

Long distance effects dominate x, y

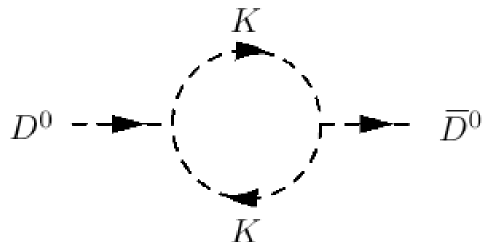
Any CPV in this system would be clear evidence for New Physics

Short-distance



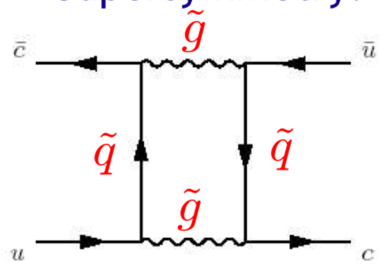


Long-distance

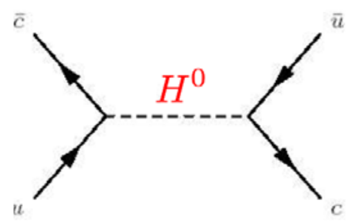


New-physics

Supersymmetry:



Extended Higgs:



D^0-$\overline{D}^0$ Mixing:

- 'Wrong sign' $K^{(*)}e\nu$ (R_M)

  BELLE PRD 77 (2008) 112003

  BaBar PRD 76 (2007) 014018

- 'Wrong sign' $K\pi$ (x'^2, y')

  BELLE PRL 96 (2006) 151801

  BaBar PRL 98 (2007) 211802 ←

  CDF PRL 100 (2008) 121802 ←

- Eigenstate lifetime analyses:

  y_{CP}

  BaBar PRD 78 (2008) 011105 ←

  BELLE PRL 98 (2007) 211803 ←

- $K_S\pi^+\pi^-$ Dalitz analyses: x,y

  BELLE PRL 99 (2007) 131803

- Quantum Correlation: $\delta_{K\pi}$

  CLEO-c PRL 100 (2008) 221801

New 2008 (unpublished)

BABAR: 'wrong-sign' $D^0 \rightarrow K^+\pi^-\pi^0$
arXiV:0807.4544
Finds:

$x' = 2.61^{+0.57}_{-0.68} \pm 0.39$ ←

Belle: y_{CP} $D^0 \rightarrow K_S K^+ K^-$
(Preiminary ICHEP. No significant mixing found in this CP- mode.)

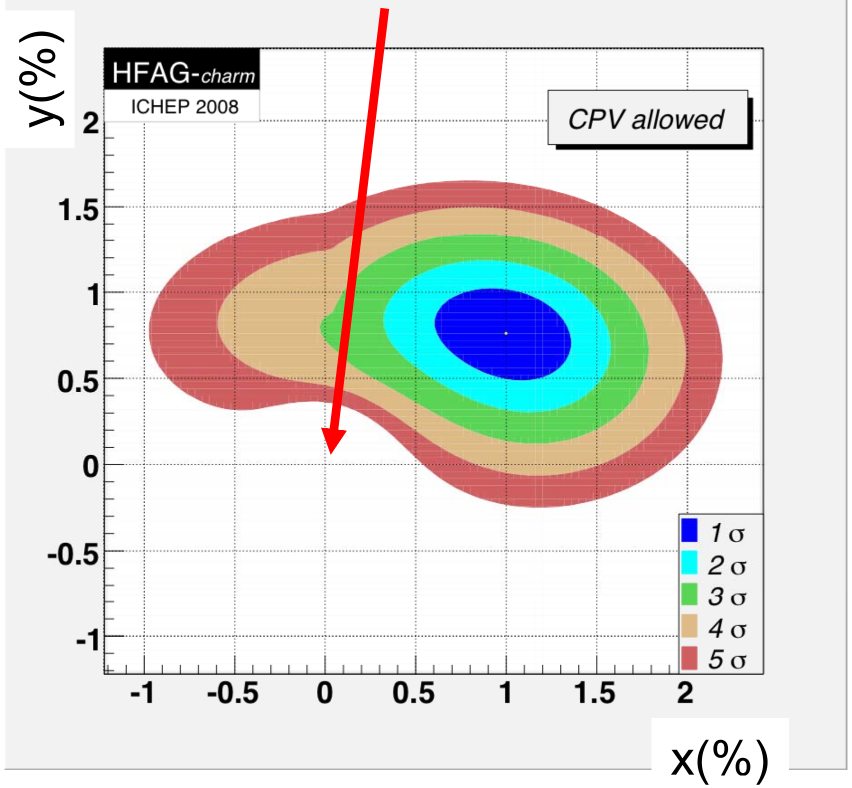
HFAG Average for ICHEP08

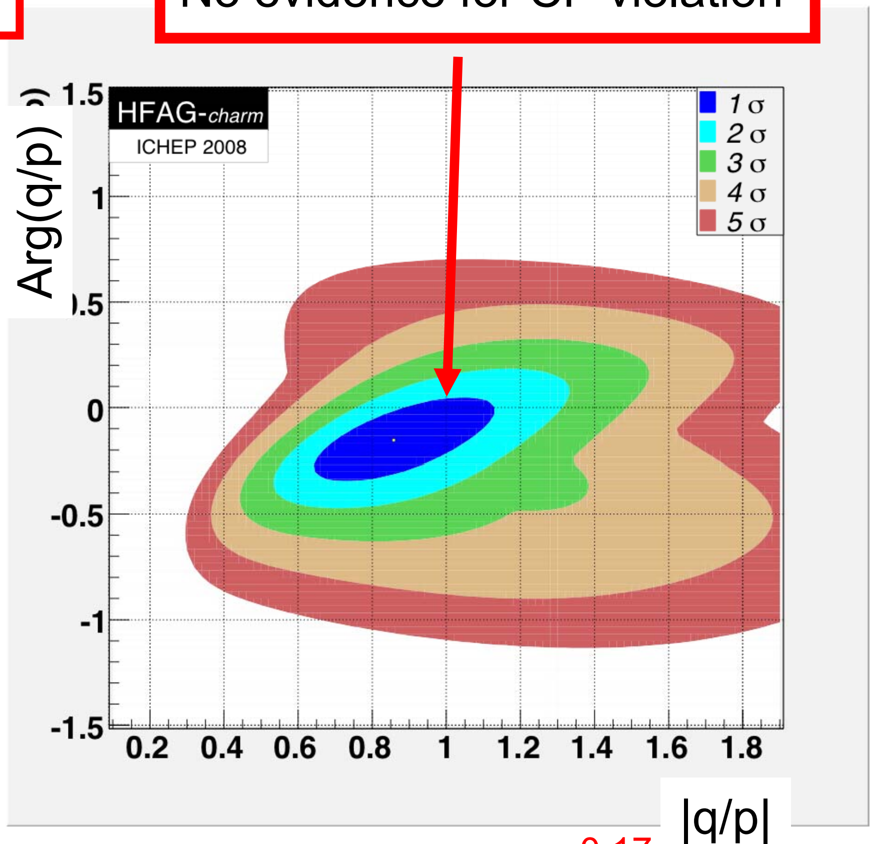
http://www.slac.stanford.edu/xorg/hfag/charm/index.html

D^0-$\overline{D}^0$ Mixing:

No mixing $(x,y) \neq (0,0)$ excluded at 9.8σ

No evidence for CP violation





$x = 1.00 \pm^{0.24}_{0.25}$ % 3.4σ

$y = 0.76 \pm^{0.17}_{0.18}$ % 4.1σ

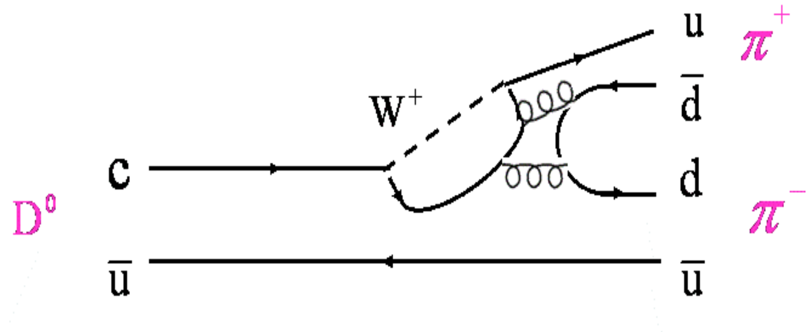
$|q/p| = 0.86 \pm^{0.17}_{0.15}$

$\text{Arg}(q/p) = (8.8 \pm^{7.6}_{7.2})^{\circ}$

MIXING HAPPENS! Why? Could be long range interactions, but could be NP
(Extra fermions, guage bosons, scalars, dimensions, symmetries etc.)

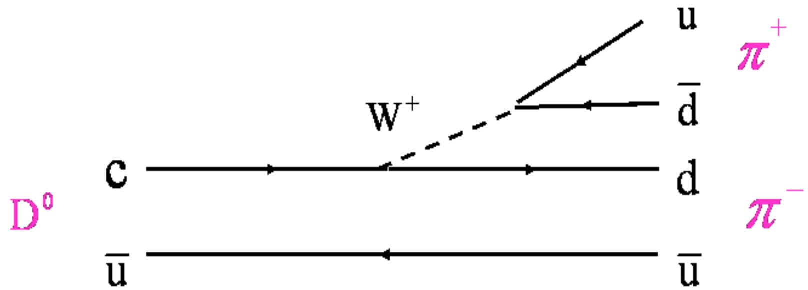
Direct CPV

In Singly Cabibbo Suppressed decays, interference between penguin & tree can generate direct CP asymmetries which:



- Could reach ~10^{-3} in SM - may be observable!

- In NP models effects of ~10^{-2} possible
  (Grossman, Kagan, Nir, PRD 75 (2007) 036008)



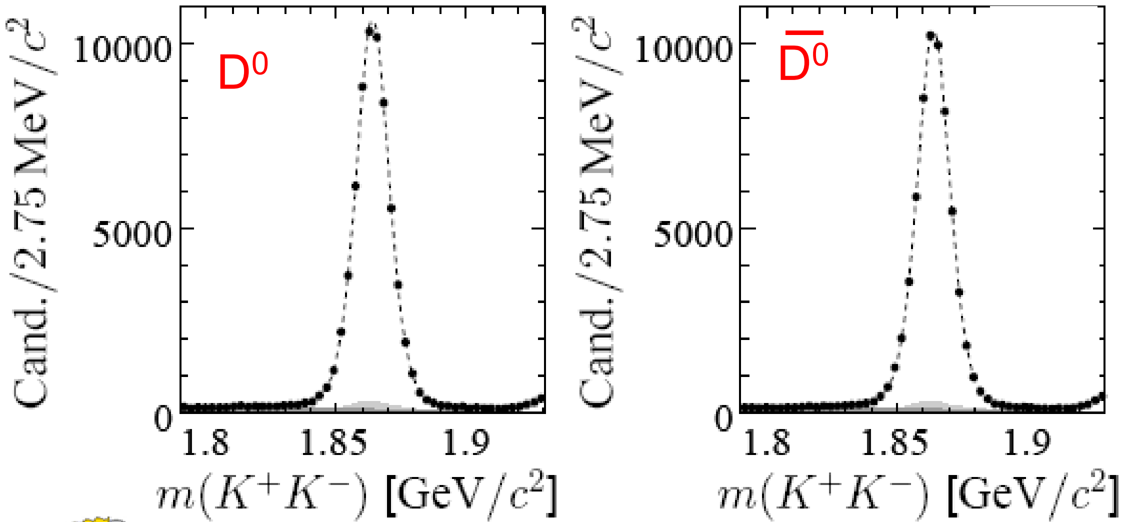
CPV searches in $D^0 \to KK$ (or $\pi\pi$)

Measure asymmetry in time integrated rates:

$$A_{CP} = \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D}^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D}^0 \to KK)}$$

Distinguish D flavor from 'slow pion' charge in $D^* \to D^0\pi$

BaBar, PRD 100 (2008) 061803 386 fb^{-1} , ~130k KK events



Also, limits in *multi*-hadron decays from BaBar and CLEO-c!

BaBar $A(KK)_{CP}$ = [0.00 ± 0.34 (stat) ± 0.13 (syst)]%

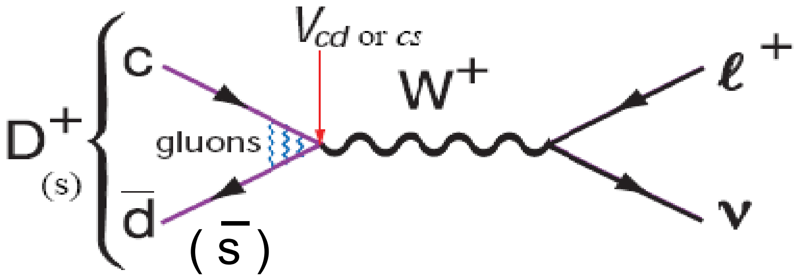
Belle $A(KK)_{CP}$ = [-0.43 ± 0.30 (stat) ± 0.11 (syst)]%

Entering interesting territory !

ArXiV:0807.0148 submitted to PLB

Leptonic D Decays and Decay Constants

In D^+ and D_s c and spectator quark can annihilate to produce leptonic final state:



In general, for all pseudoscalars:

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

Since V_{cd} and V_{cs} well known, can extract f_D and f_{D_s} and compare with lattice !

Measurements of $D_{(s)} \rightarrow l\nu$ Branching Fractions

Precise measurements now exist for:

D_s

- $\mu^+\nu$, $\tau^+ (\rightarrow\pi^+\nu)\upsilon$ CLEO-c (PRL 99 (2007) 071802; arXiv:0704.0437 + FPCP08)
- $\mu^+\nu$ BELLE (Phys.Rev.Lett.100:241801,2008 arXiv:0709.1340)
  & BaBar (Phys.Rev.Lett.98:141801,2007 hep-ex/0607094)
- $\tau^+ \rightarrow (e^+\nu\nu)\nu$ CLEO-c (PRL 100 (2008) 161801)

D^+

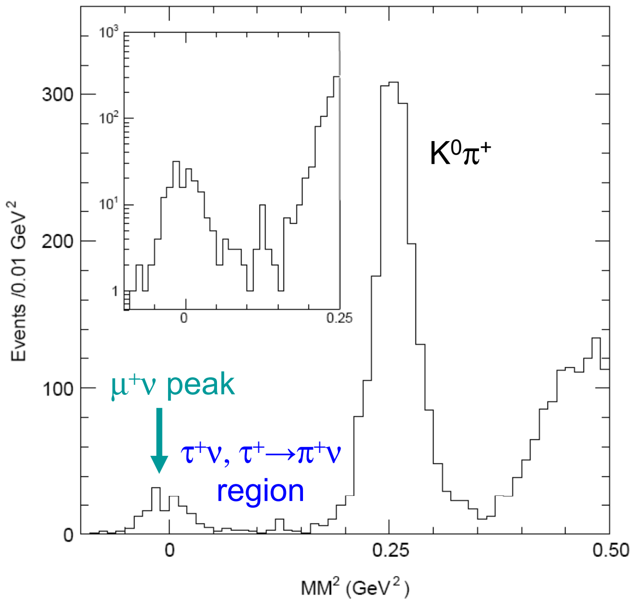
- $\mu^+\nu$ CLEO-c (Phys. Rev. D 78, 052003 , 2008)

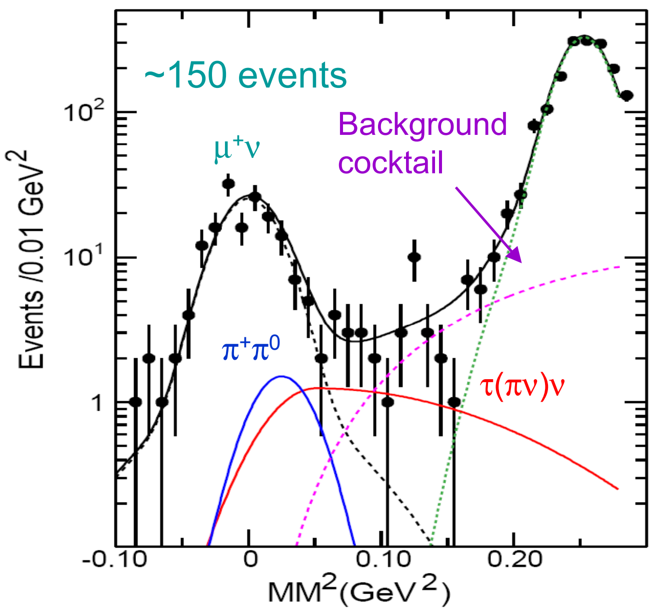
Basic methods for $\mu\nu$ measurement:

- CLEO-c: for f_D reconstruct one D^+ , look for MIP (μ), and then compute missing mass squared (similar for f_{Ds}, but here exploit $D_sD_s^*$ production in 4170 MeV dataset)
- Belle: infer presence of D_s from recoiling mass against reconstructed D & fragmentation. Add candidate μ and compute missing mass
- BaBar: Select e+e- $\rightarrow$ cc events with high momentum D^0, D^+, D_s, D^{*+} close to B kinematic end-point. Search for $D_s^* \rightarrow \gamma$, $D_s \rightarrow \gamma\mu\nu$ in the recoil

CLEO-c $D^+ \to \mu^+\nu$

Missing mass squared distribution (including log zoom with fit):





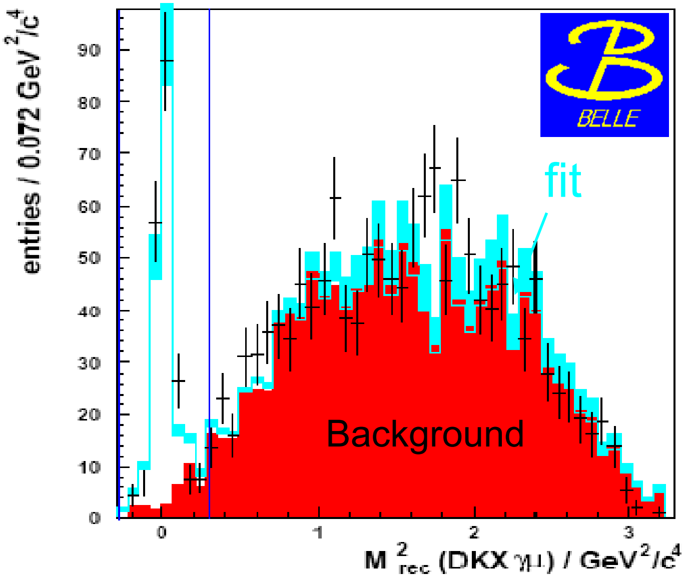
$BR(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$

$f_D = (205.8 \pm 8.5 \pm 2.5)$ MeV

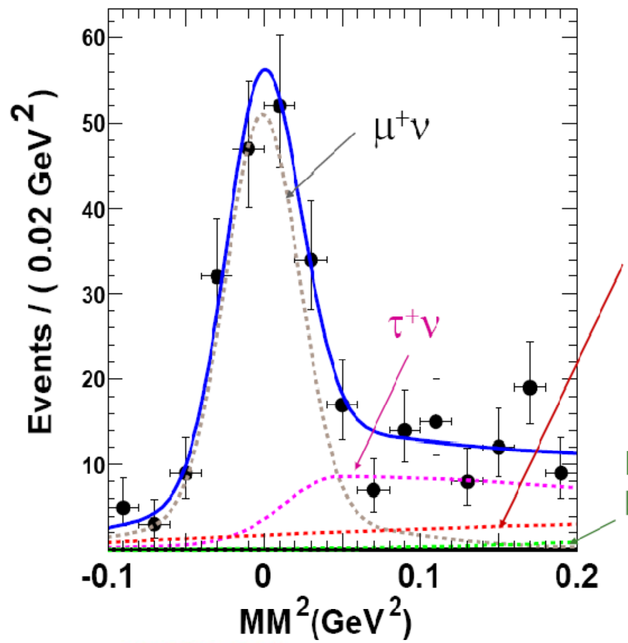
(result with $\tau\nu/\mu\nu$ fixed at SM expectation)

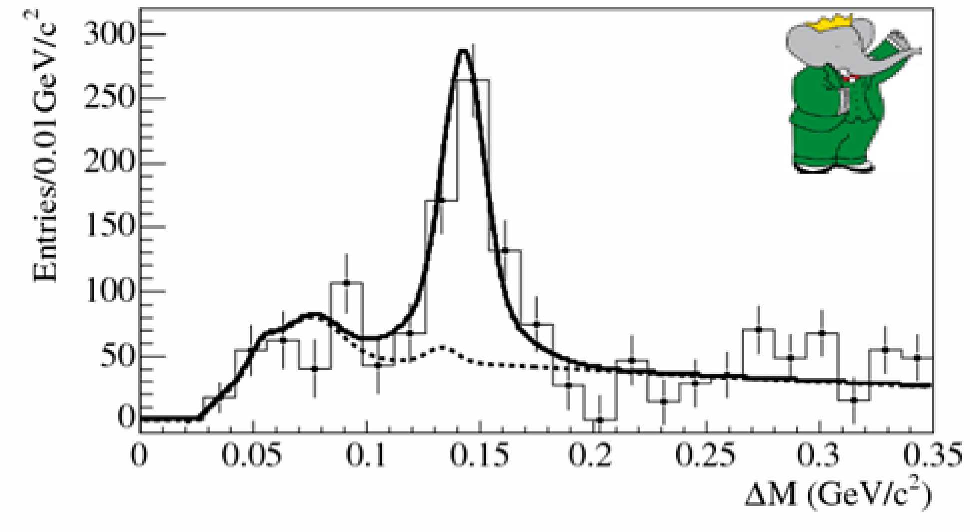
$D_s \to \mu^+\nu$ & $D_s \to \tau^+\nu$

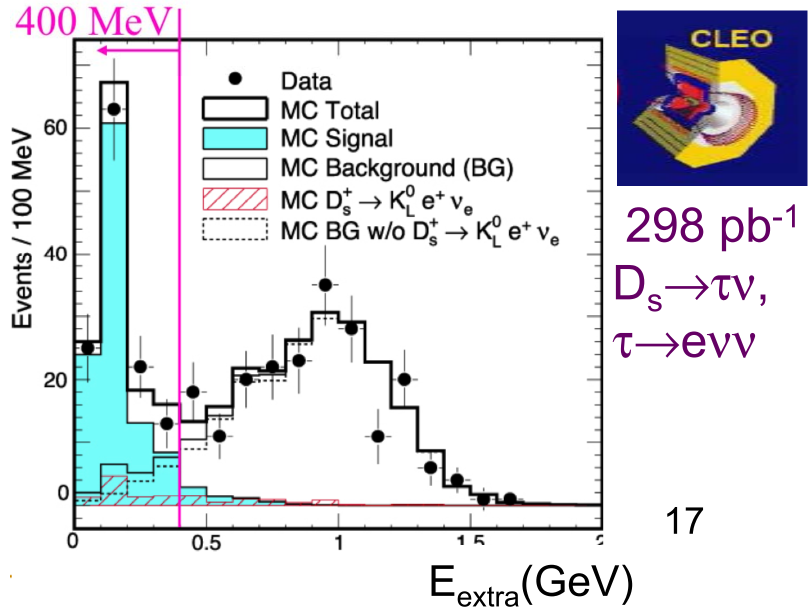
548 fb^{-1}



CLEO-c prelim: 424 pb^{-1}
$D_s \to \mu\nu + D_s \to \tau\nu,\ \tau \to \pi\nu\nu$

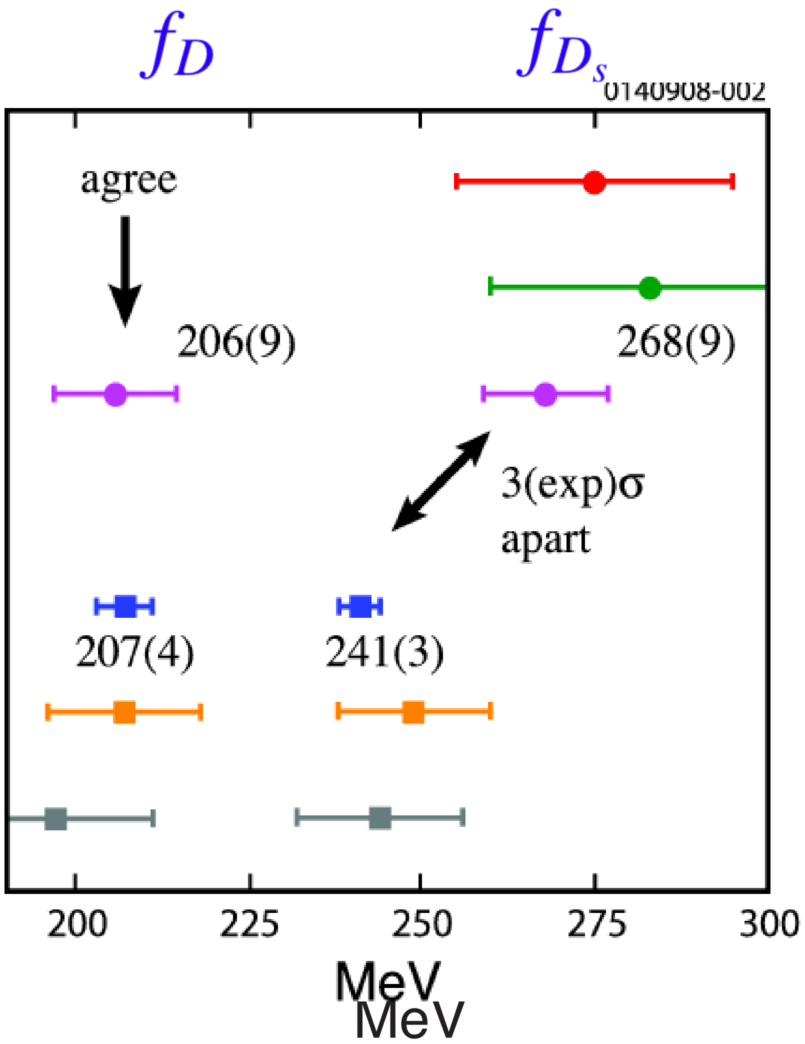






298 pb^{-1}
$D_s \to \tau\nu$,
$\tau \to e\nu\nu$

D^+ and D_s Decay Constants



Belle
0709.1340 [hep-ex]
PRL 100:241801 (2008)

BABAR
PRL 98, 141801 (2007)

CLEO-c
0806.2112 subm to PRD
PRL 100, 161801 (2008)
PRL 99, 071802 (2007)

HPQCD HISQ u,d,s sea
PRL 100, 062002 (2008)

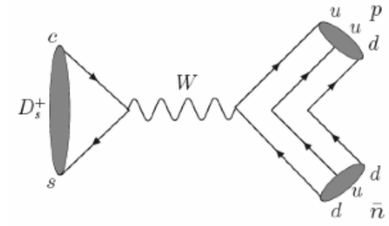
FNAL/MILC u,d,s sea
LAT08 prelim.

ETMC u,d sea
LAT08 prelim.

no s in sea as yet

Final D_s results from CLEO-c expected soon with full data sample

Current CLEO results use 70% of data for $D_s \to \mu\nu$ + $D_s \to \tau\nu$, $\tau \to \pi\nu\nu$ and use 50% of data for $D_s \to \tau\nu$, $\tau \to e\nu\nu$

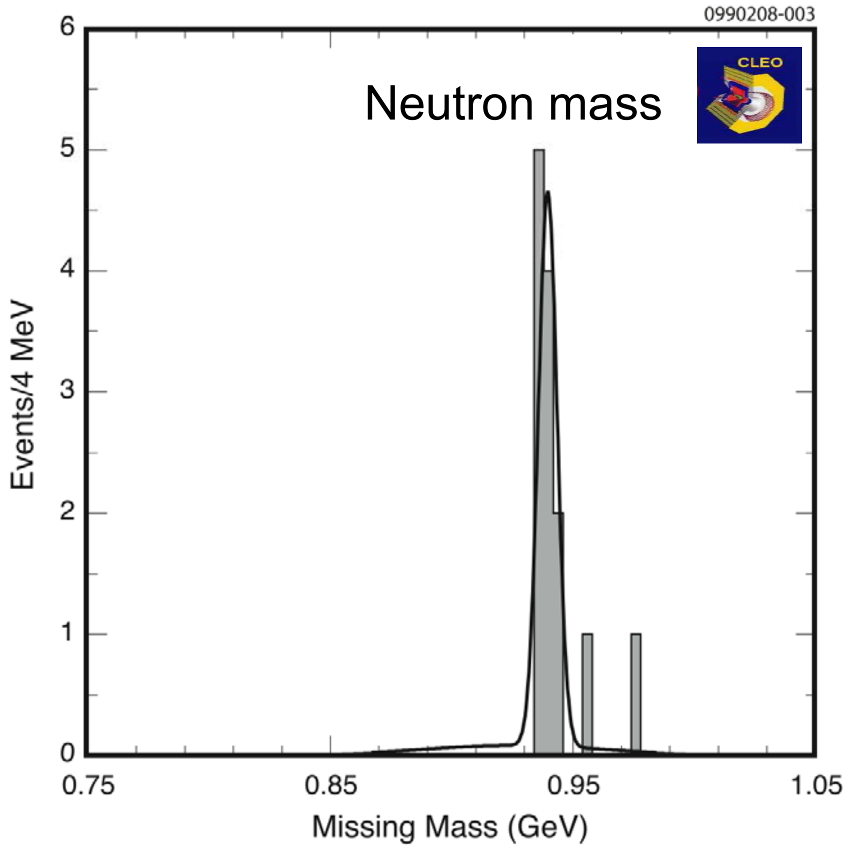


$D_s \rightarrow p\bar{n}$: First Observation

PRL 100, 181802 (2008)

- Same analysis technique as $D \rightarrow \mu\nu$
- Only kinematically allowed D meson baryonic decay
- Consequence for understanding W annihilation dynamics

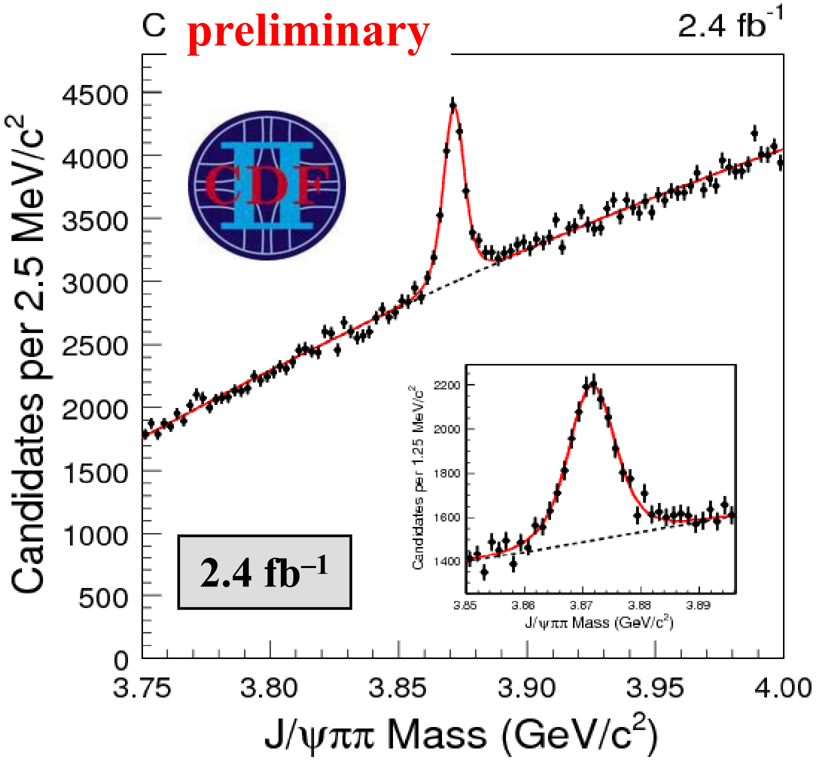
Chen, Cheng, Hsiao 0803.2910v3 [hep-ph]



$$\mathcal{B}(D_s^+ \rightarrow p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.10}) \times 10^{-3}$$

Spectroscopy of the ***XYZ*** charmonium-like states

It all started with BELLE 5 years ago, finding the X(3872) resonance in $B \to XK \to (J/\Psi\pi\pi)K$. This particle since confirmed by BaBar, D0, and CDF



	M(X(3872)), MeV/c^2
$B \to XK$	3871.46±0.37±0.07
$X \to J/\psi\pi^+\pi^-$	3871.61±0.16±0.19
PDG07	3871.4±0.6
$M(D^0)+M(D^{*0})$	3871.81±0.35

Possible explanations:

Unlikely to be conventional charmonium

Tetraquark

Hybrid

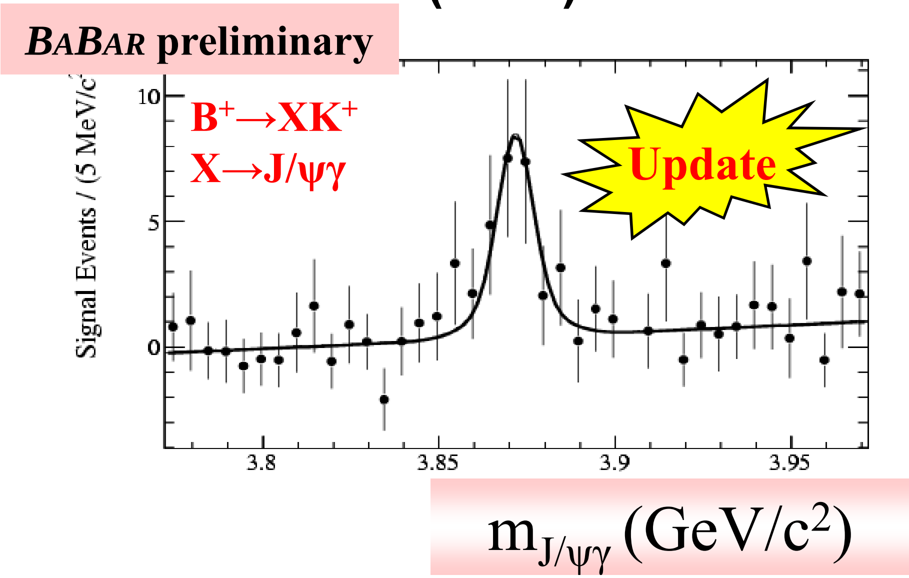
Threshold Cusp

D^0D^{*0} molecular state?

CDF most accurate mass measurement

http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-X-Mass

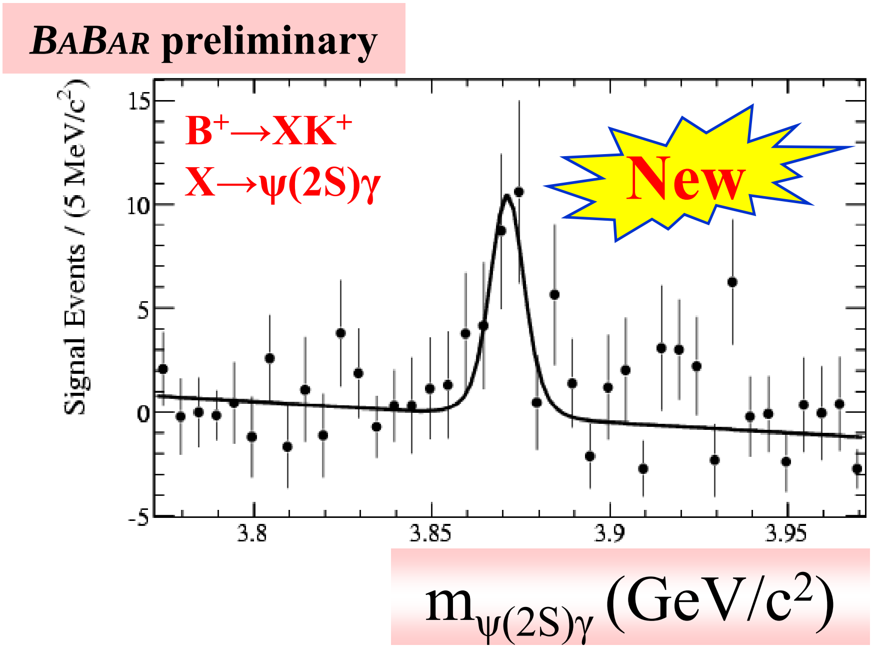
X(3872) Radiative Decays



Observation of radiative decays $X \to J/\psi\gamma$ and $X \to \psi(2S)\gamma$ at these levels disfavor a D^0D^{*0} molecular state identification.

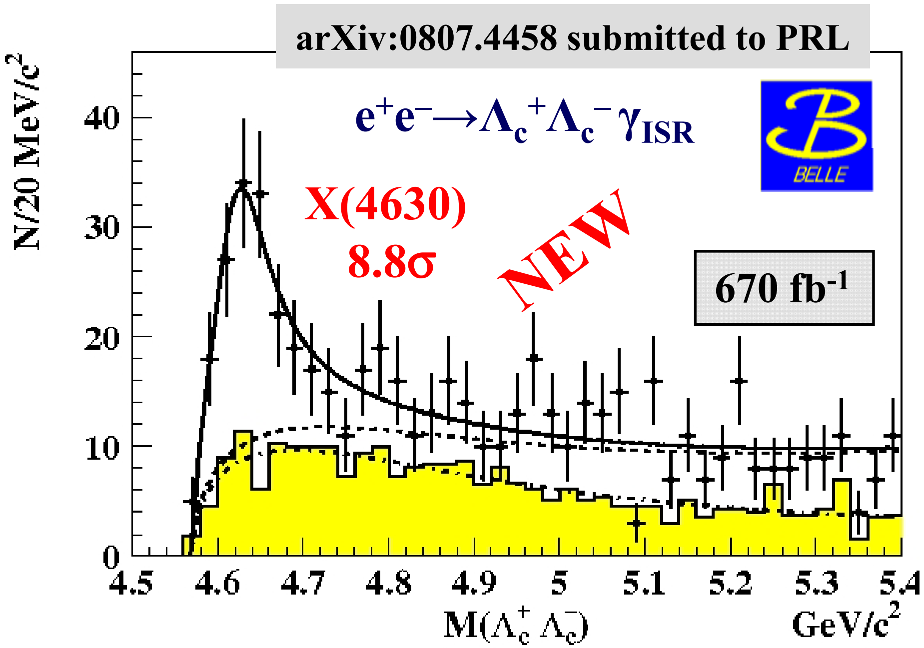
Question: is the peak in D^0D^* and $D^0D^0\pi^0$ the same particle?

Answer: probably yes.



State	M, MeV/c^2	Γ_{tot}, MeV	Decay Modes	
X(3875)	$3875.2 \pm 0.7^{+0.9}_{-1.8}$	$1.22 \pm 0.31^{+0.23}_{-0.30}$	$D^0\bar{D}^0\pi^0$	BELLE
X(3872)	$3872.6^{+0.5}_{-0.4} \pm 0.4$	$3.9^{+2.5+0.5}_{-1.3-0.3}$	$D^0\bar{D}^{*0}$	BELLE
X(3875)	$3875.1^{+0.7}_{-0.5} \pm 0.5$	$3.0^{+1.9}_{-1.4} \pm 0.9$	$D^0\bar{D}^{*0}$	
X(3872)	3871.81±.22	< 2.3	$\pi^+\pi^- J/\psi$	CDF

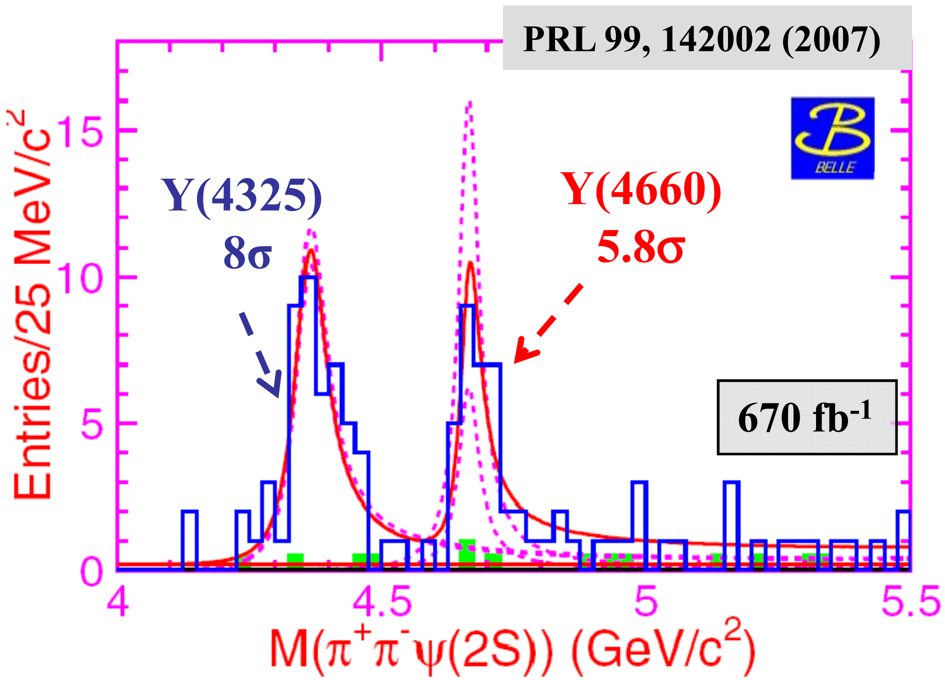
etc.



New peak found in $e^+e^- \to \Lambda_c^+\Lambda_c^-\gamma_{ISR}$

Named the X(4630). Interpretation?

Is it the same as the Y(4660) found by BELLE in $e^+e^- \to \psi(2S)\,\pi^+\pi^-\,\gamma_{ISR}$?

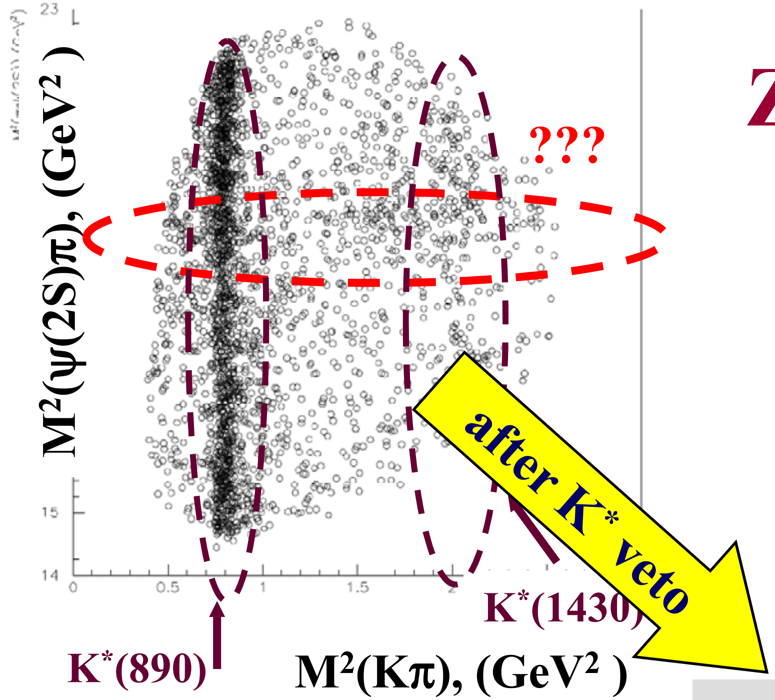


X(4630) = Y(4660)? $J^{PC}=1^{--}$

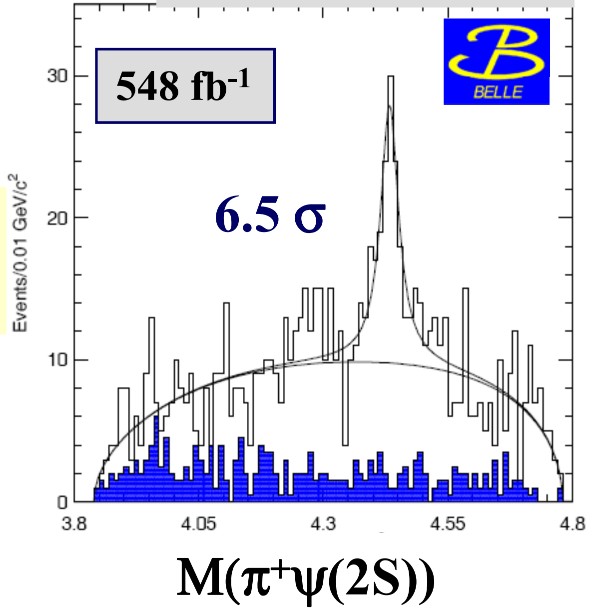
State	M, MeV/c^2	Γ_{tot}, MeV
X(4630)	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

$Z(4430)^+$ first report of a *charged* charmonium like state

$B \to KZ,\ Z(4430)^+ \to \pi^+\psi(2S)$
$K=K^-, K^0_s$; $\psi(2S) \to \ell^+\ell^-, \pi^+\pi^- J/\psi$



PRL 100, 142001 (2008)



$M = (4433 \pm 4 \pm 2)$ MeV
$\Gamma = (45^{+18}_{-13}\,{}^{+30}_{-13})$ MeV

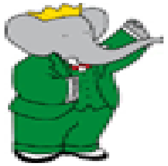
Interpretations:

- S –wave D^*D_1 threshold effect
- D^*D_1 molecular state
- Radially excited tetraquark
- Baryonium state
- Hadro-charmonium

$BF(B \to KZ) \times BF(Z \to \psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.3)\ 10^{-5}$

BUT…

Results are not confirmed by BaBar .Extensive study $B^{-0}\rightarrow\psi\pi^{-}K^{0+(*)}$ making sure to include all reflections. Find no significant peaks and place limits on the “BELLE” peak.

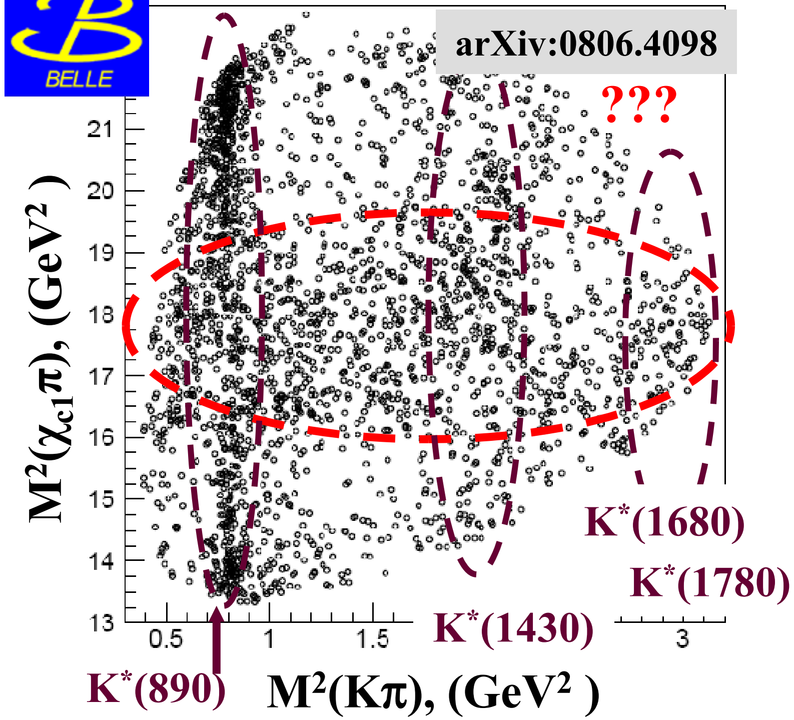


Decay mode	$Z(4430)^-$ signal	Branching fraction ($\times10^{-5}$)	Upper limit ($\times10^{-5}$) (@95% C.L.)
$B^-\rightarrow Z^-K^0$, $Z^-\rightarrow J/\psi\pi^-$	-16 ± 140	-0.1 ± 0.8	<1.5
$B^0\rightarrow Z^-K^+$, $Z^-\rightarrow J/\psi\pi^-$	-666 ± 203	-1.2 ± 0.4	<0.4
$B^-\rightarrow Z^-K^0$, $Z^-\rightarrow\psi(2S)\pi^-$	110 ± 118	1.3 ± 1.4	<3.8
$B^0\rightarrow Z^-K^+$, $Z^-\rightarrow\psi(2S)\pi^-$	327 ± 170	1.4 ± 0.7	<2.6

2σ peak! Not significant

$$BF(B\rightarrow KZ)\times BF(Z\rightarrow\psi(2S)\pi) = (4.1\pm1.0\pm1.3)\ 10^{-5}$$

$Z^+_{1,2} \to \chi_{c1}\pi^+$



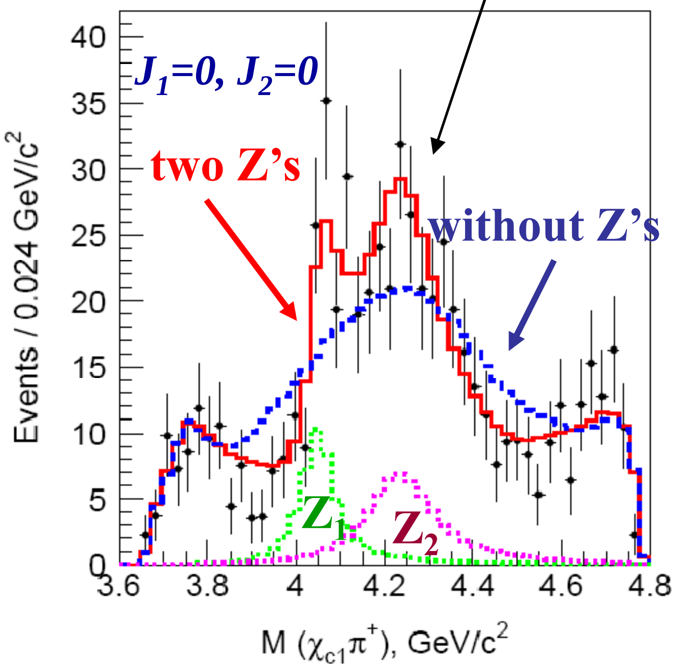
$B^0 \to \chi_{c1}\pi^+K^-$; $\chi_{c1} \to J/\psi\gamma$

Dalitz analysis : fit $B^0 \to \chi_{c1}\pi^+K^-$ amplitude by coherent sum of contributions from:

- **known $K\pi$ resonances**
- **K^*'s + one $(\chi_{c1}\pi)$ resonance**
- **K^*'s + two $(\chi_{c1}\pi)$ resonances**

PRELIMINARY and UNCONFIRMED

Make projections onto $\chi_{c1}\pi^+$



$M_1=(4051\pm14^{+20}_{-41})$ MeV/c^2
$\Gamma_1=(82^{+21}_{-17}{}^{+47}_{-22})$ MeV
$M_2=(4248^{+44}_{-29}{}^{+180}_{-35})$ MeV/c^2
$\Gamma_1=(177^{+54}_{-39}{}^{+316}_{-61})$ MeV

$$\mathcal{B}(\overline{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+\chi_{c1}) = (3.1^{+1.5+3.7}_{-0.9-1.7}) \times 10^{-5},$$

$$\mathcal{B}(\overline{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+\chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-\ 0.5}) \times 10^{\ \ 5}.$$

Summary & Outlook

Rare Charm Decays: **Experiments entering interesting territory - expect more results soon from CLEO/BES, B-factories and Tevatron that provide constraints on New Physics.**

Charm Mixing: **Discovery of D^0-$\bar{D}^0$ oscillation points the way forward to searches for CPV and New Physics**

CP Violation: **None found, but experiments entering interesting territory**

f_{Ds} **Growing disagreement between experiment and lattice calculations: sign of new physics?**

XYZ **More new questions than answers. Is our view of all hadrons being $q\bar{q}$ or qqq incorrect?**

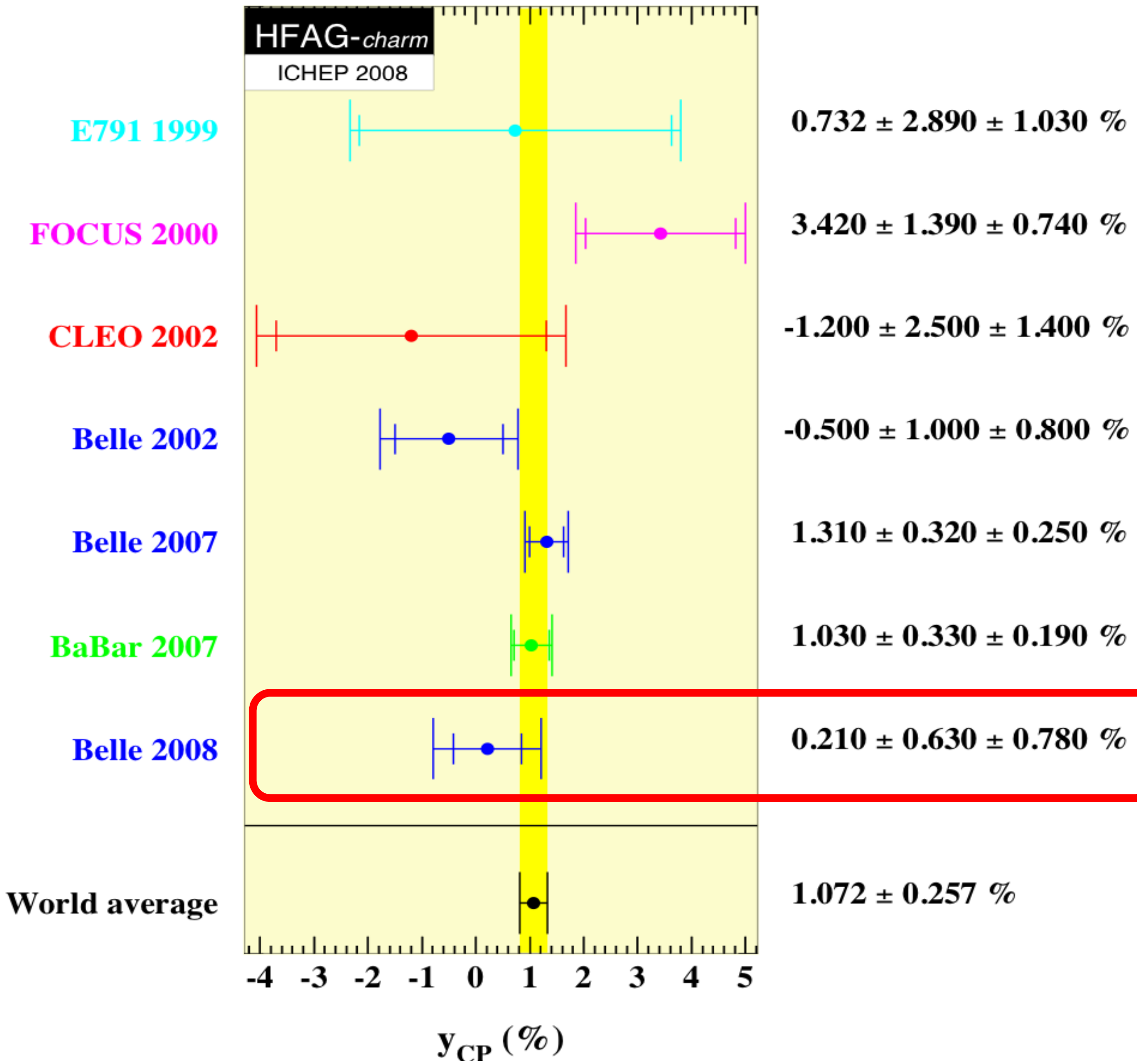
Future: **Tighter constraints on New Physics, more stringent tests of LQCD, more precise input to B-physics expected soon from CLEO, B-factories & Tevatron. In the near future charm results from BESIII & LHCb. Higher luminosity B factories (SuperB) will lead to better understanding NP observed at LHC.**

- EXTRAS

D^0-$\overline{D^0}$ Mixing:

New HFAG Average for ICHEP08

http://www.slac.stanford.edu/xorg/hfag/charm/index.html



Previous measurements all from $D^0 \to KK, \pi\pi$ (CP+)

New Belle result uses Dalitz plot analysis of $D^0 \to K_S K^+ K^-$, dominated by $D^0 \to K_S \phi$ (CP-)
arXiv:0808.0074

CPV Searches in Multibody (n≥3) Decays

BaBar & Belle study of $D^0 \to K^+K^-\pi^0, \pi^+\pi^-\pi^0$

CLEO study of $D^+ \to K^+K^-\pi^+$

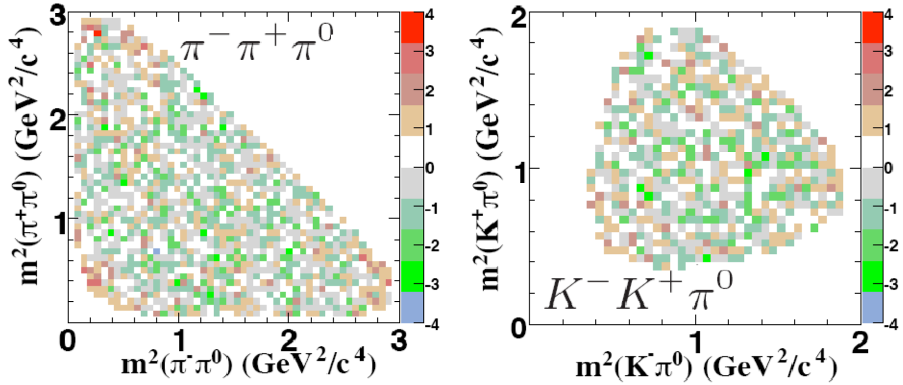
Several complementary analyses:

Increased Sensitivity: $O(\%)$ → $O(‰)$

- Look for phase space integrated asymmetry.
- Form residuals of D^0, $\overline{D}^0$ w.r.t. mean in Dalitz space
- Look for difference in angular moments of D^0 & $\overline{D}^0$ distributions
- Compare amplitude fits of D^0 & $\overline{D}^0$ Dalitz plot (model dependent)

No CPV observed

BABAR 385 fb^{-1}, arXiv:0802.4035



Consistent with no CPV at 33% and 17%

CLEO 818 pb^{-1}, arXiv:0807.4545