Charm overview

PDG Collaboration Meeting 6 Nov 2014

Part I: Jonas Rademacker (University of Bristol)
Part II: Charles Wohl (LBL)

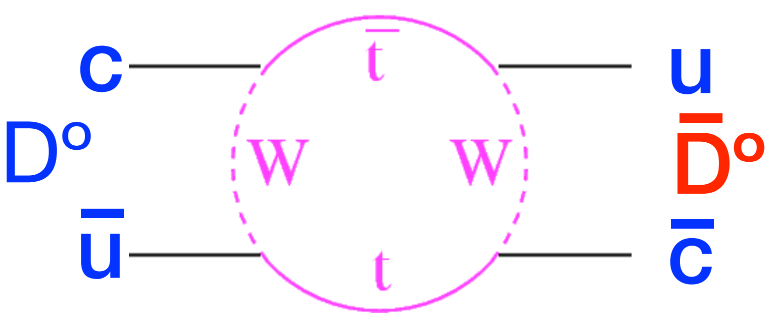
Charm Mixing

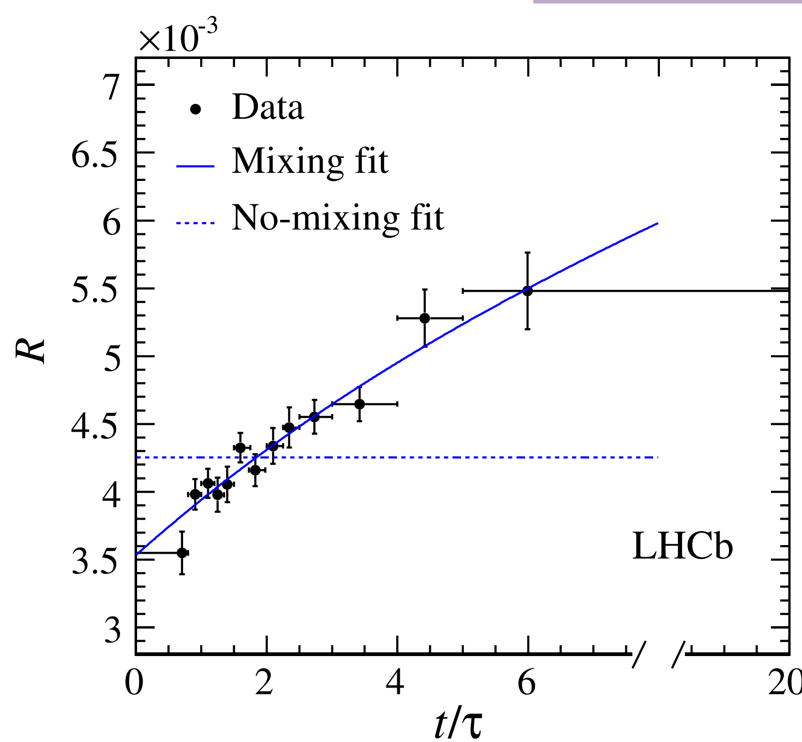
Phys. Rev. Lett. 110 (2013) 101802
Phys. Rev. Lett. 111 (2013) 251801

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}(t)$$

numerator: mixing amplitude $D^o \to \bar{D}^o \to K^+\pi^-$ significant

denominator: for normalisation (mixing negligible)





First single measurement with >5σ observation of charm mixing.

Charm Mixing

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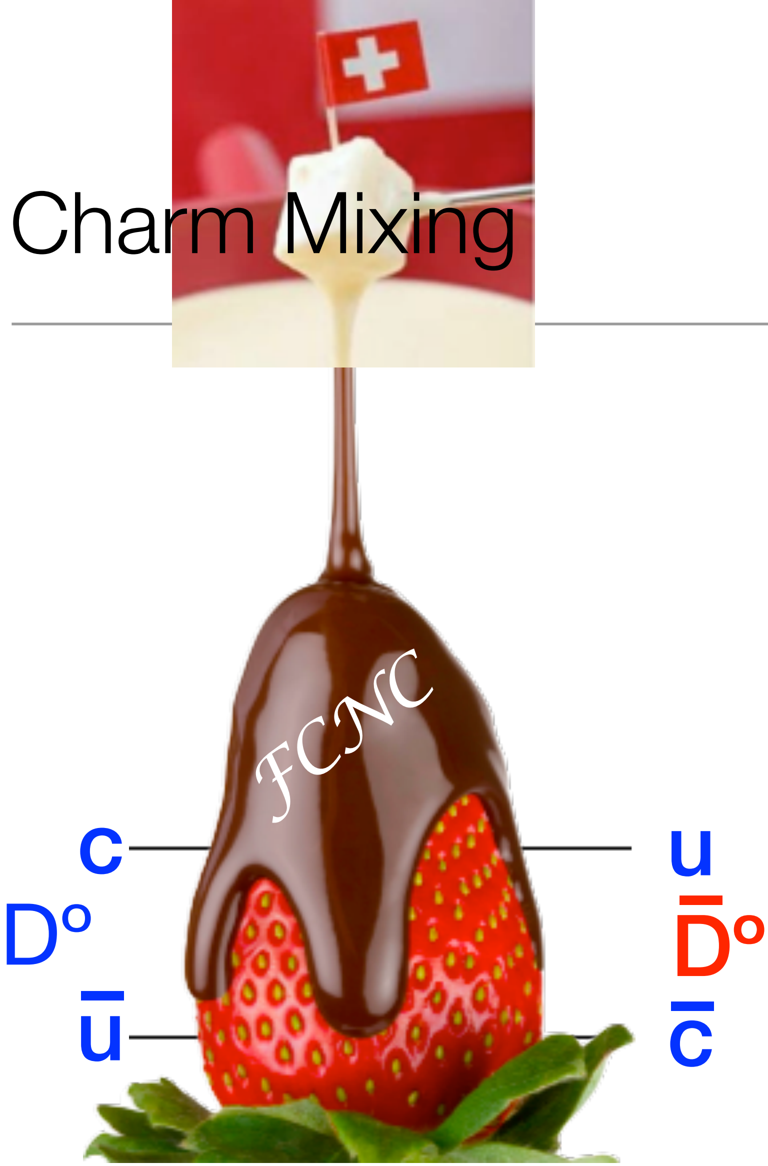

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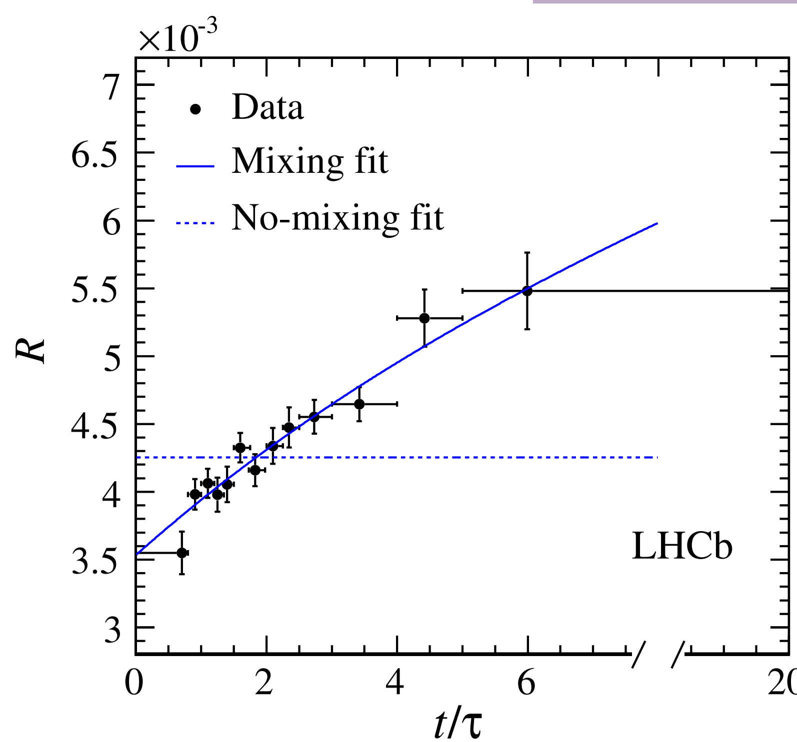

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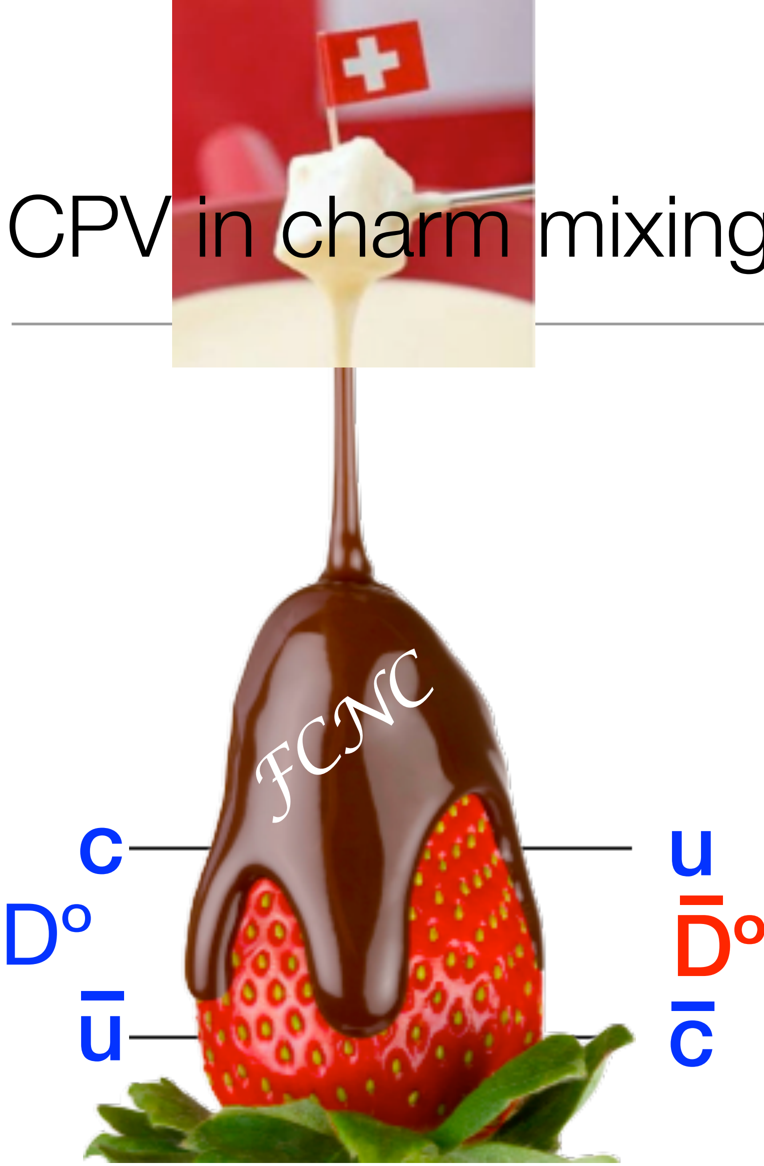
CPV in charm mixing



[Phys. Rev. Lett. 110 (2013) 101802](#)
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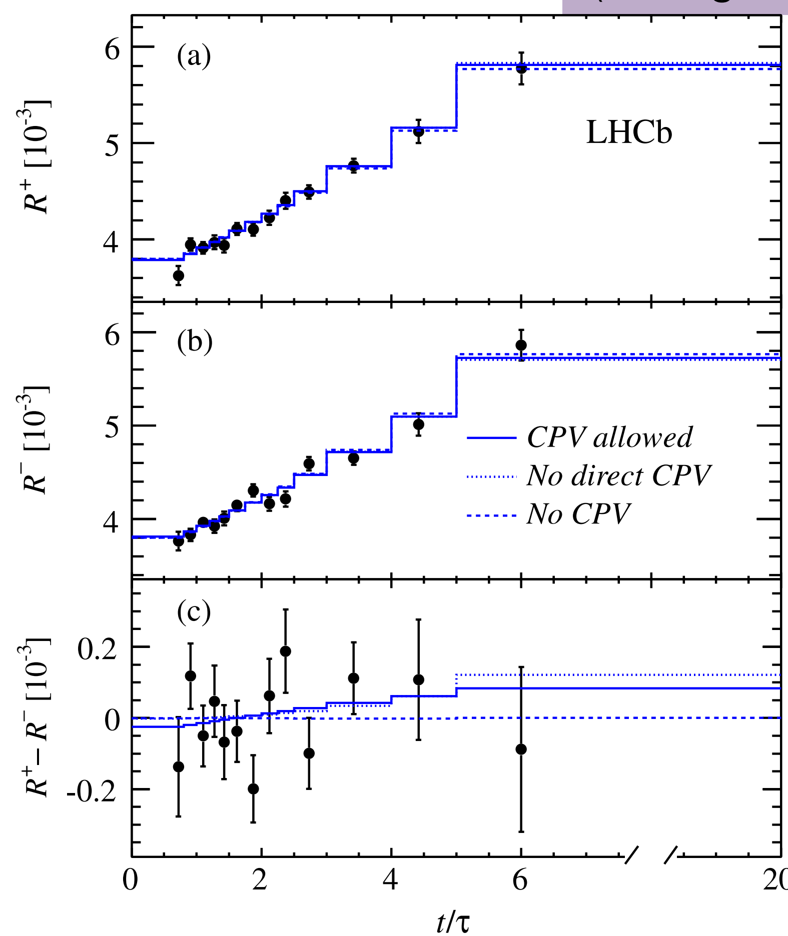

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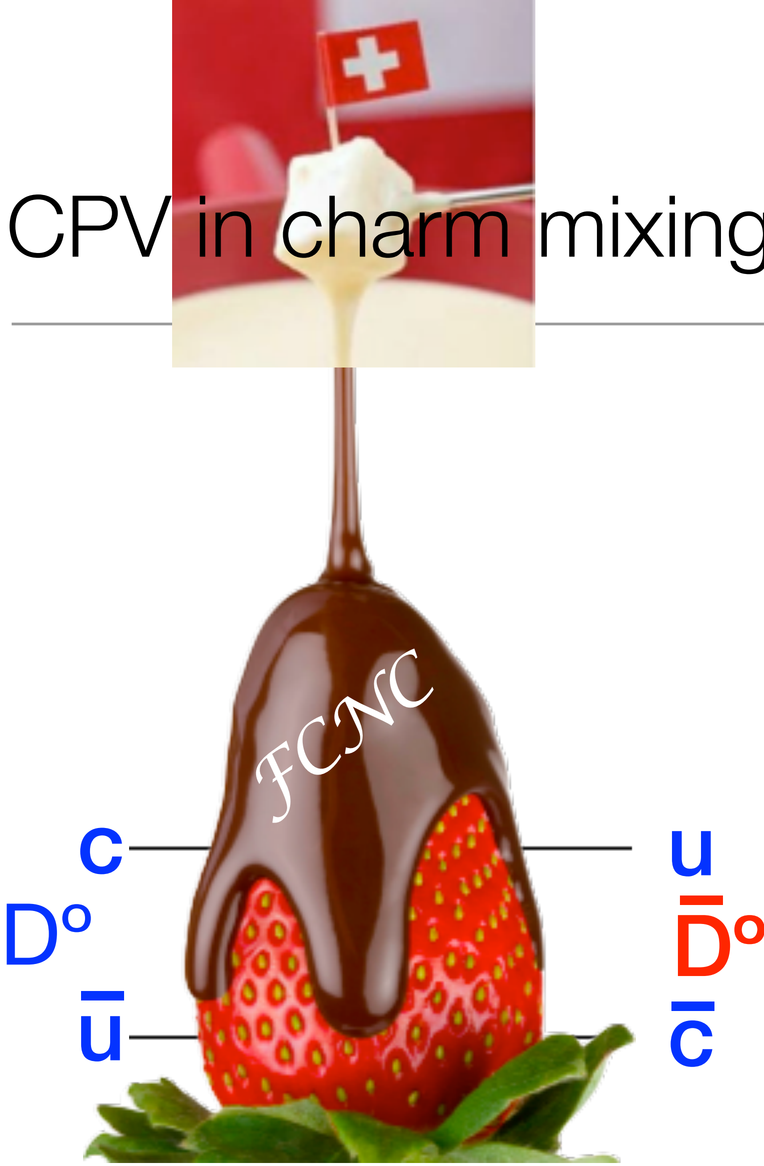

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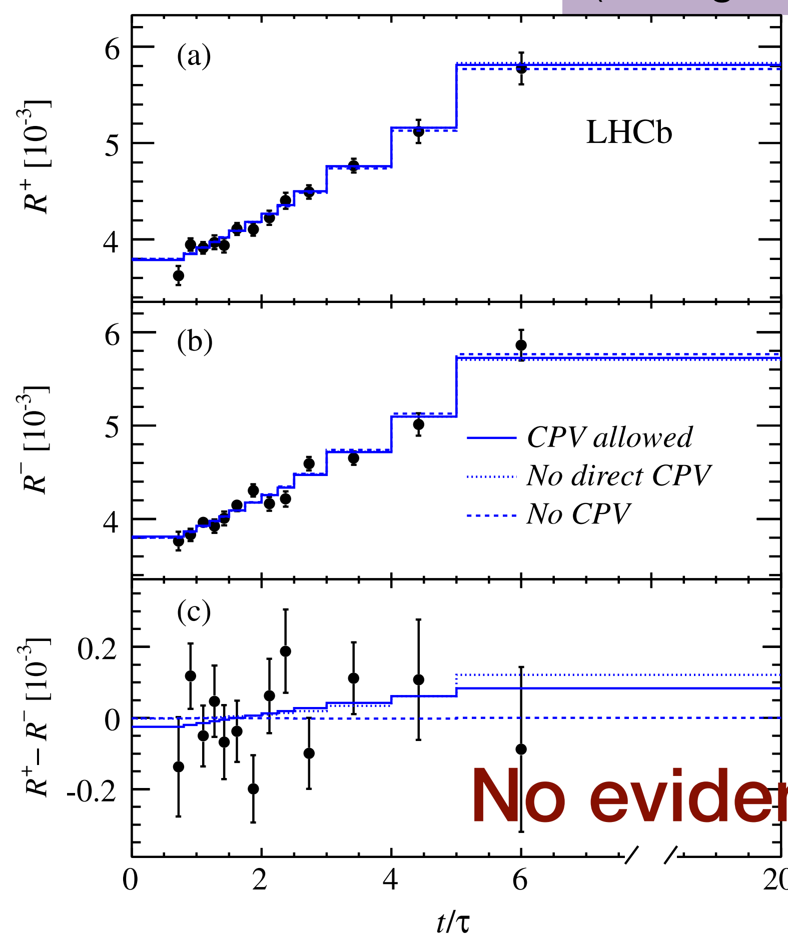
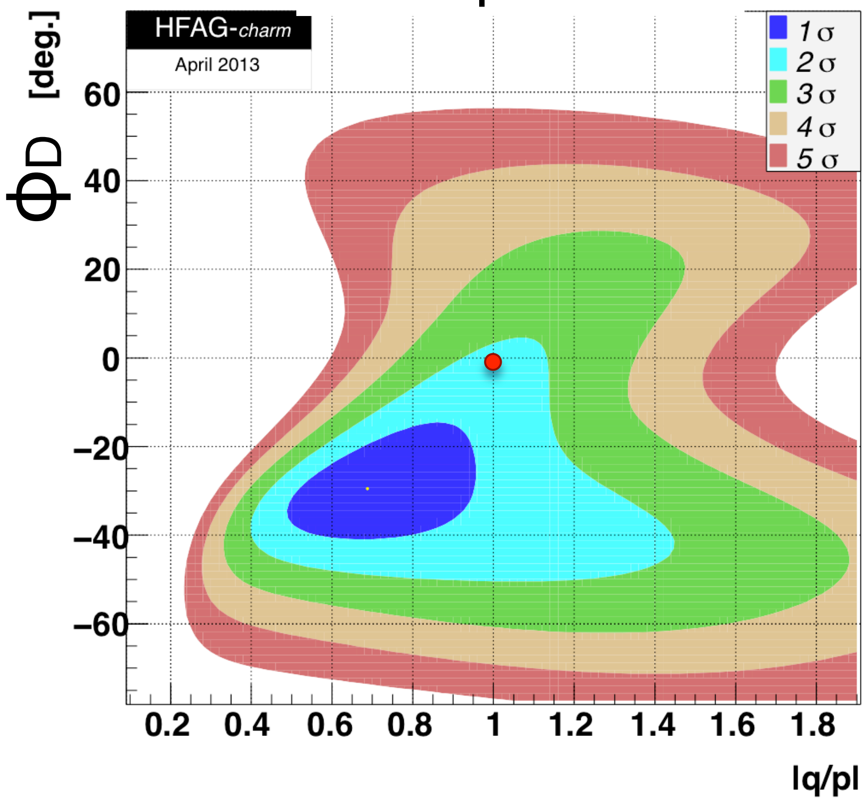


No evidence for CPV

Impact on world average for CPV in mixing & interference between mixing and decay.

Average by HFAG

2 Sep 2013



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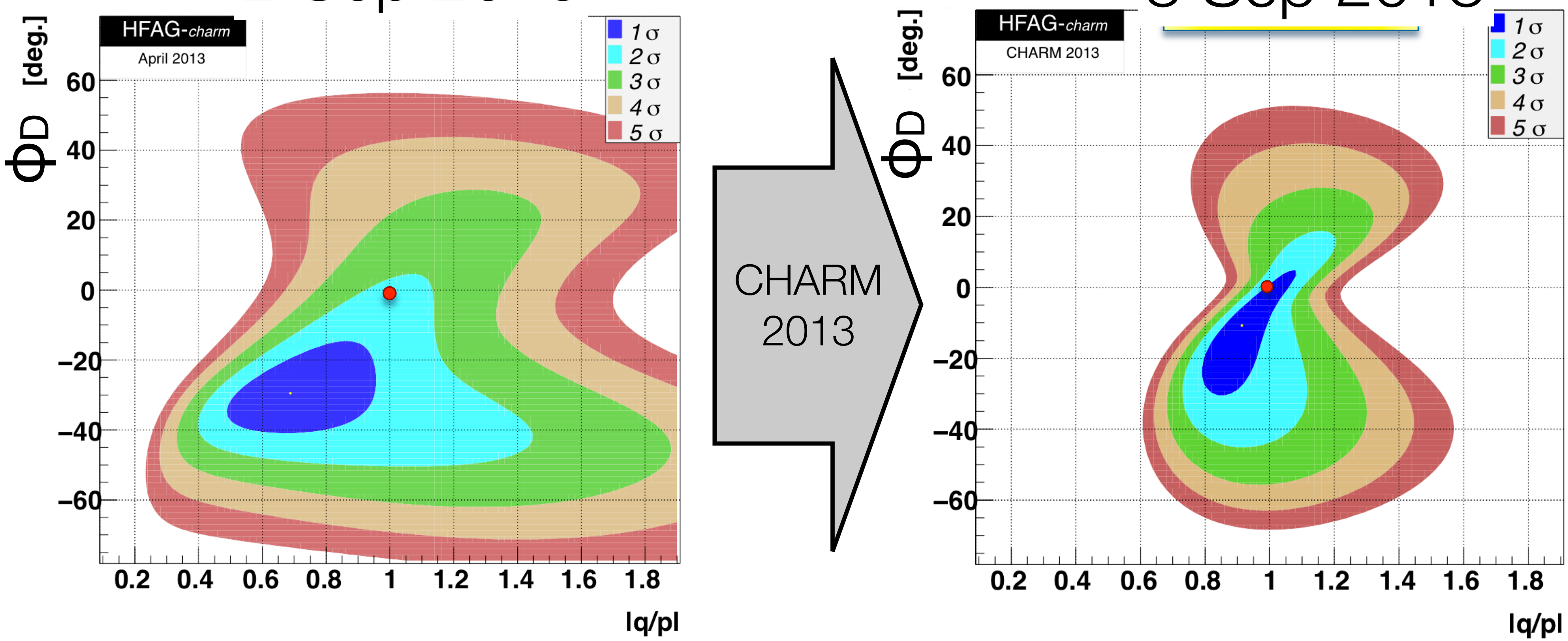
Average by HFAG

2 Sep 2013 3 Sep 2013



Again, no evidence of CP violation or new physics - but a very impressive improvement in our knowledge

Impact on world average for CPV in mixing & interference between mixing and decay.

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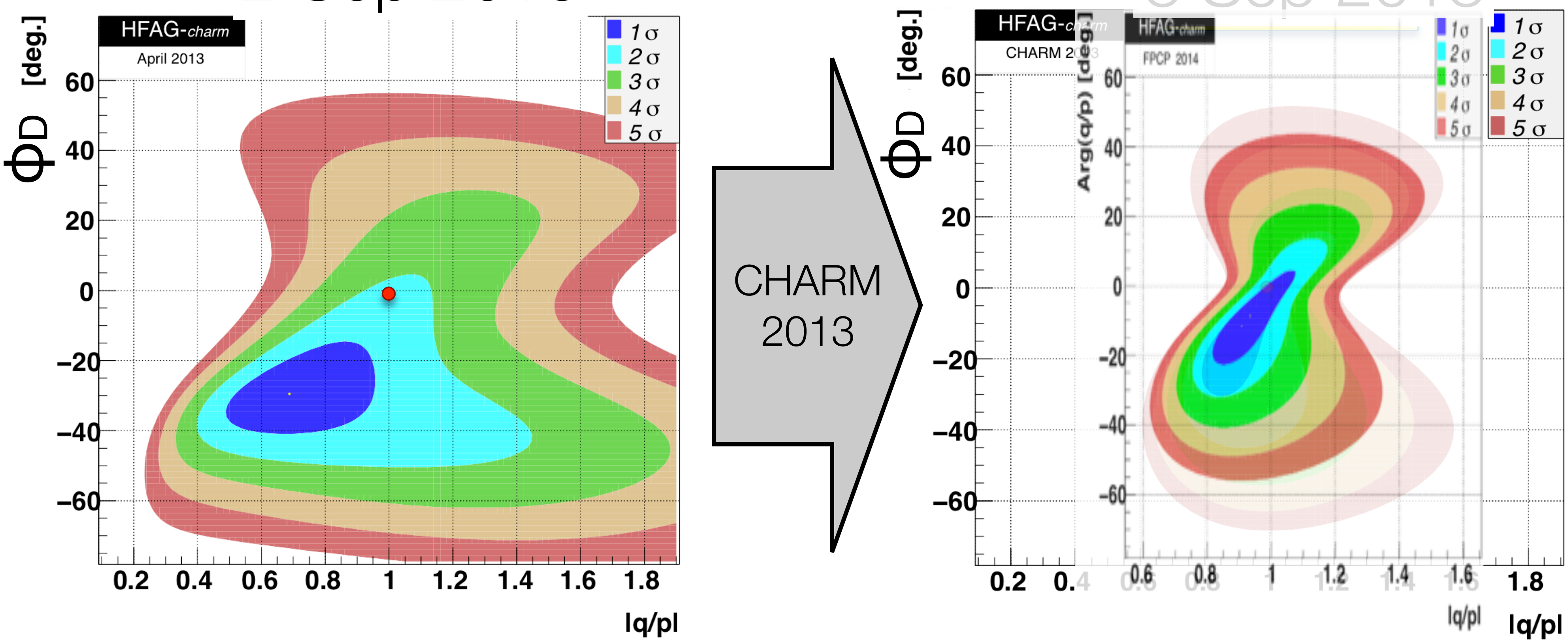
2 Sep 2013 FPCP 2014



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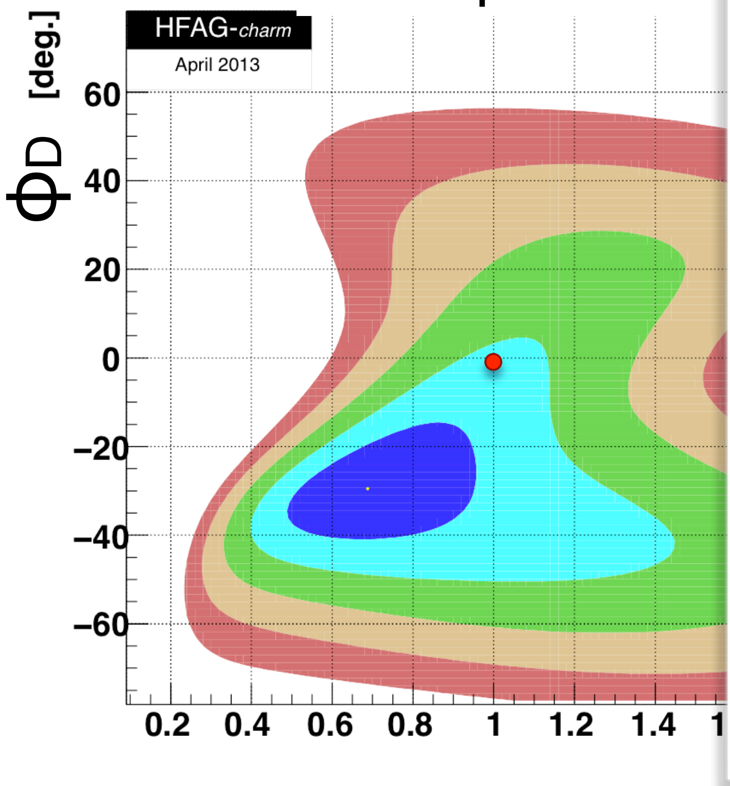
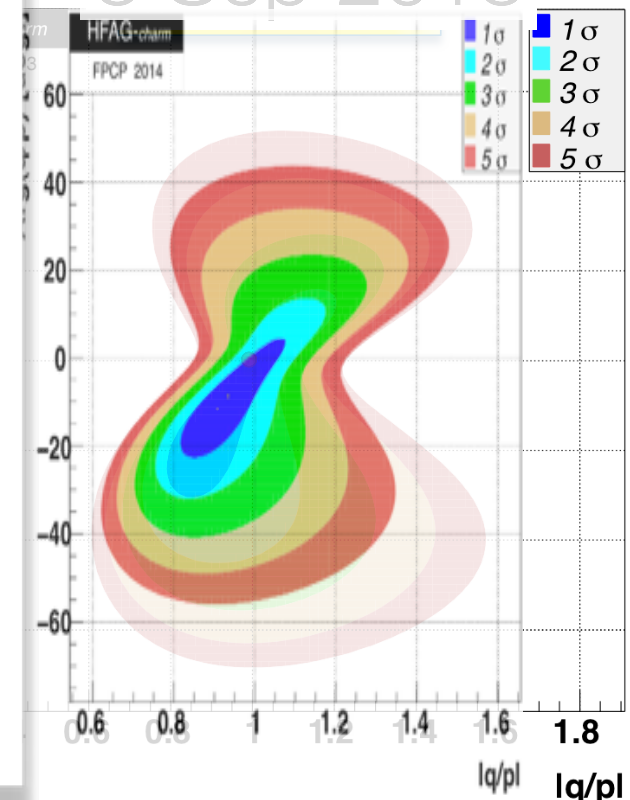


Results since 2012

PRD 87 (2013) 012004
arXiv:1212.3478 (Dec 2012)
PRD 86 (2012) 112001
PRL 110 (2013) 101802
LHCb-CONF-2013-003,
PLB 723 (2013) 33
PRL 111 (2013) 231802]
PRL 111 (2013) 251801
PRL 112 (2014) 041801
PRD 89 (2014) 091103
PRL 112 (2014) 111801]
JHEP 1407 (2014)
arXiv:0411410.5435 (2014)

FPCP 2014



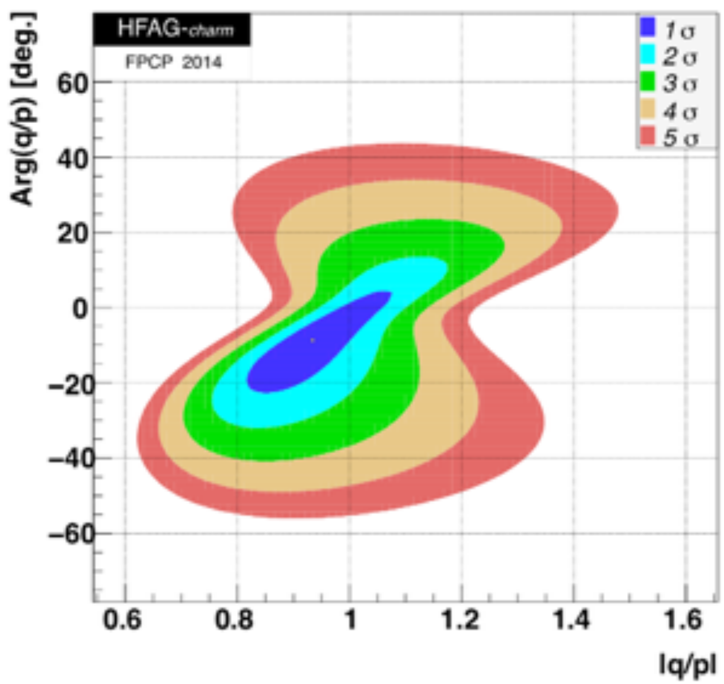
Again, no evidence of CP violation or new physics - but a very impressive improvement in our knowledge

CPV constraints assuming no direct CPV in DCS

"usual" CPV constraints

"Superweak approx.": Assume no direct CPV in DCS decays
Phys.Rev. D80 (2009) 076008

ϕ_D



$$\tan\phi = \frac{x(1-|q/p|^2)}{y(1+|q/p|^2)}$$

$$\sigma(|q/p|) : 8.7\% \rightarrow 1.4\%$$

$$\sigma(\phi) : 8.9^\circ \rightarrow 0.6^\circ$$

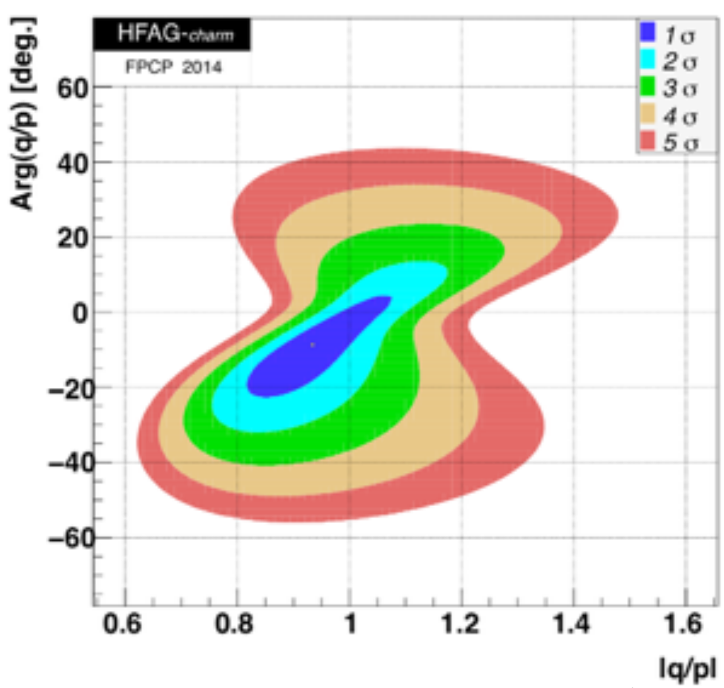
CPV constraints assuming no direct CPV in DCS

"usual" CPV constraints

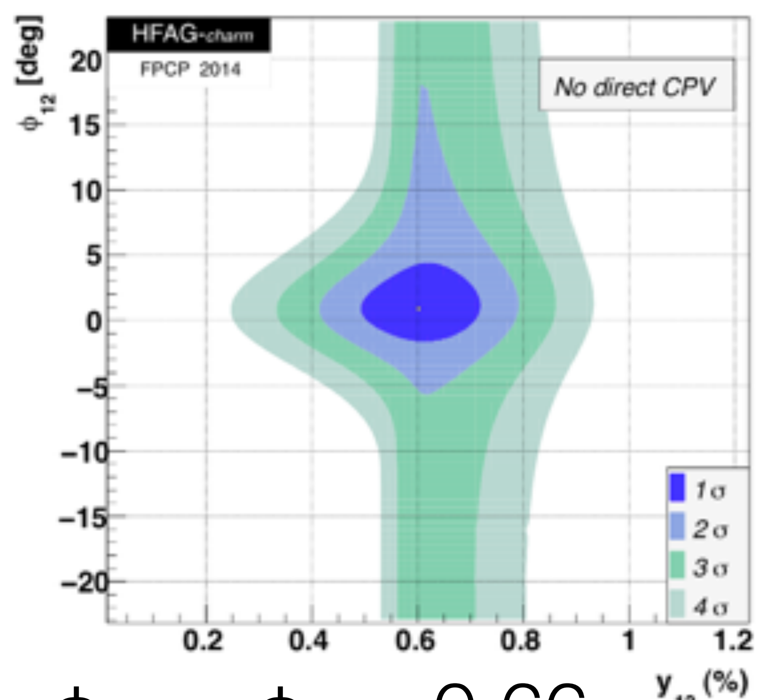
"Superweak approx.": Assume no direct CPV in DCS decays
Phys.Rev. D80 (2009) 076008

ϕ, x, y, |q/p| —apply constraint→ ϕ_{12}, x_{12}, y_{12}

ϕ_D



ϕ_{12}



$$\tan 2\phi = -\frac{\sin 2\phi_{12}}{\cos 2\phi_{12} + y_{12}^2/x_{12}^2}$$

$\phi_D \approx \phi_{12} \cdot 0.66$
(with current results for x_{12}, y_{12})

CPV constraints assuming no direct CPV in DCS

“usual” CPV constraints

“Superweak approx.”: Assume no direct CPV in DCS decays

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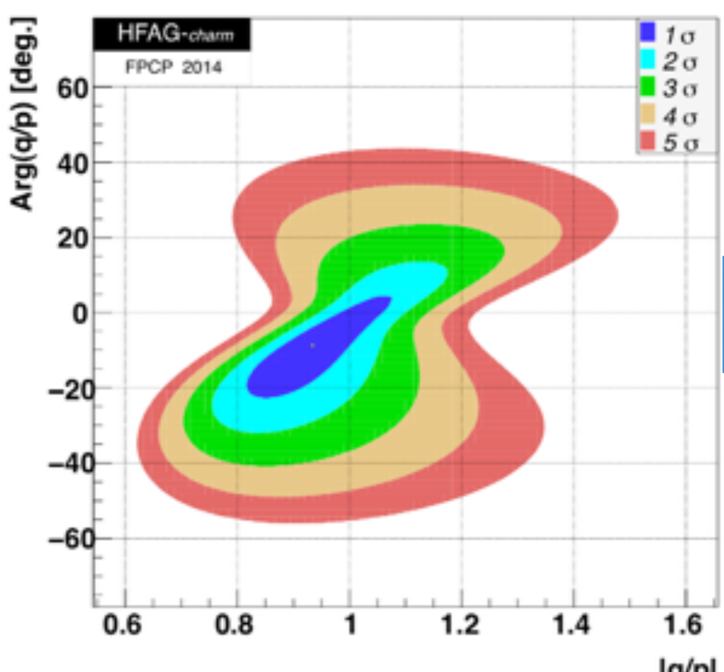
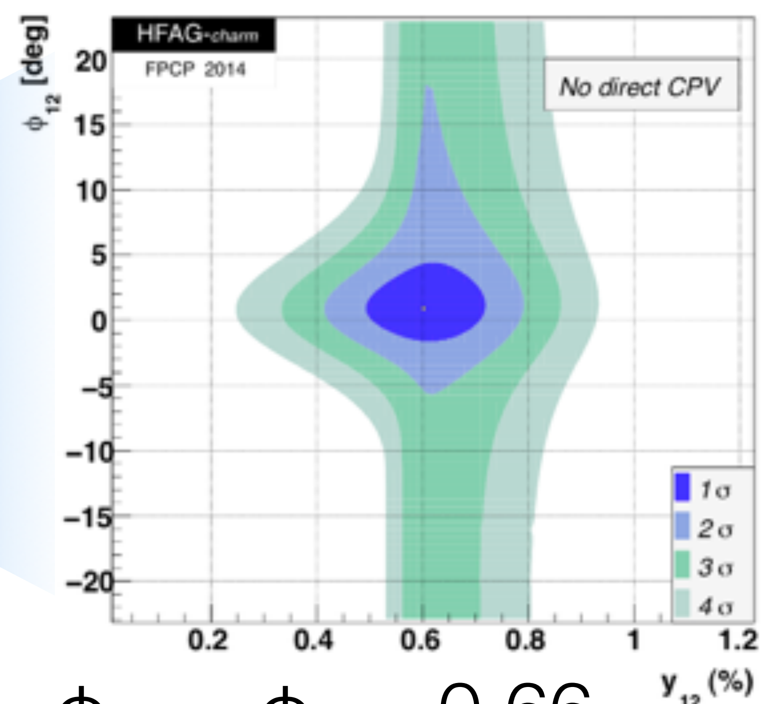
ϕ_D



ϕ_{12}



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$\phi_D \approx \phi_{12} \cdot 0.66$

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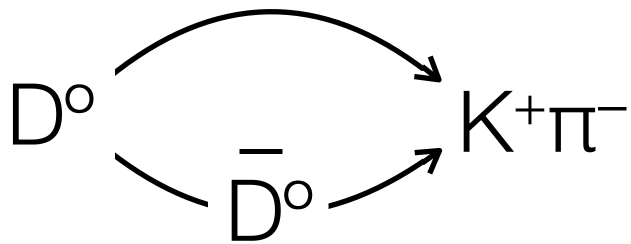
Quantum-correlated news from the threshold

- Mixing sensitive to interference between $D \to K^+\pi^-$ and $D \to K^+\pi^-$.



- Phase difference between amplitudes needed to interpret results in terms of mixing parameters x, y.

- Accessible at charm threshed. Latest measurement by BES III in 2014:

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

- **1st BES III result exploiting quantum correlations in this way.**

Phys.Lett. B734 (2014) 227

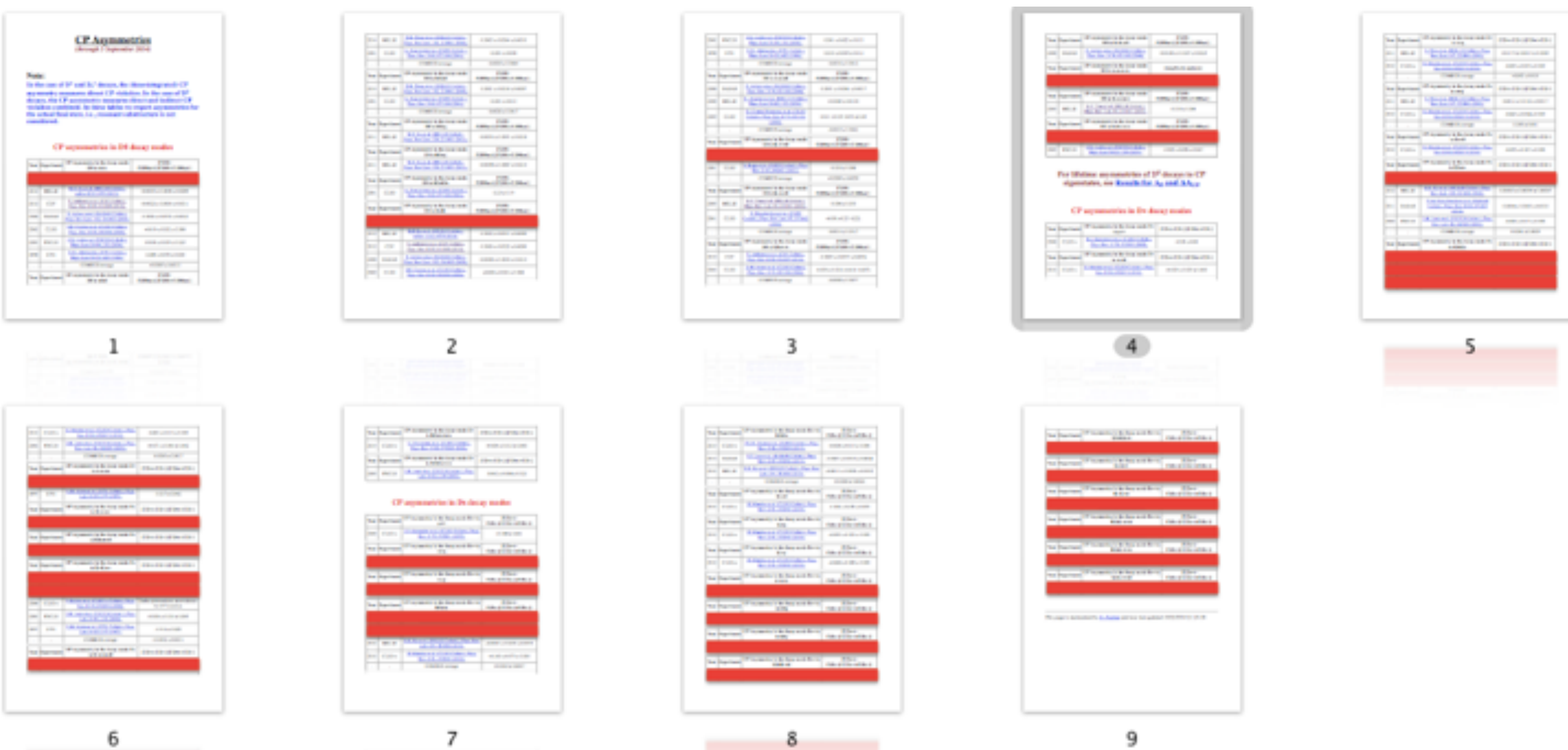
- Also: updates on similar parameters in $KK\pi\pi$ and $KK\pi^o$, using CLEO-c data

Phys.Lett. B731 (2014) 197-203

Direct CPV such as $D^{o} \to KK$ vs $\bar{D}^{o} \to KK$

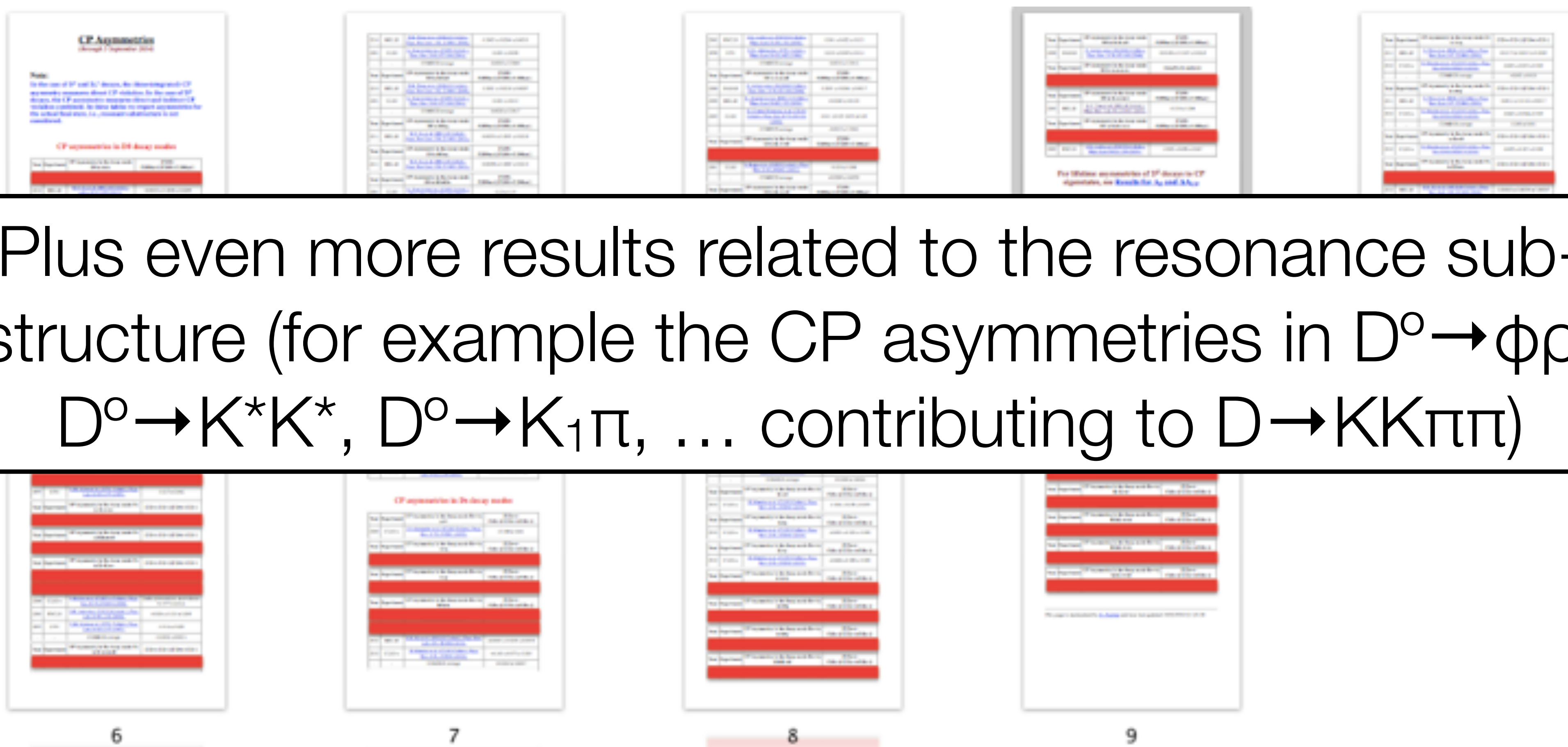
Plenty of results.

Direct CPV such as $D^o \to KK$ vs $\bar{D}^o \to KK$



Plenty of results. Lots of them **new (since 2013)**.

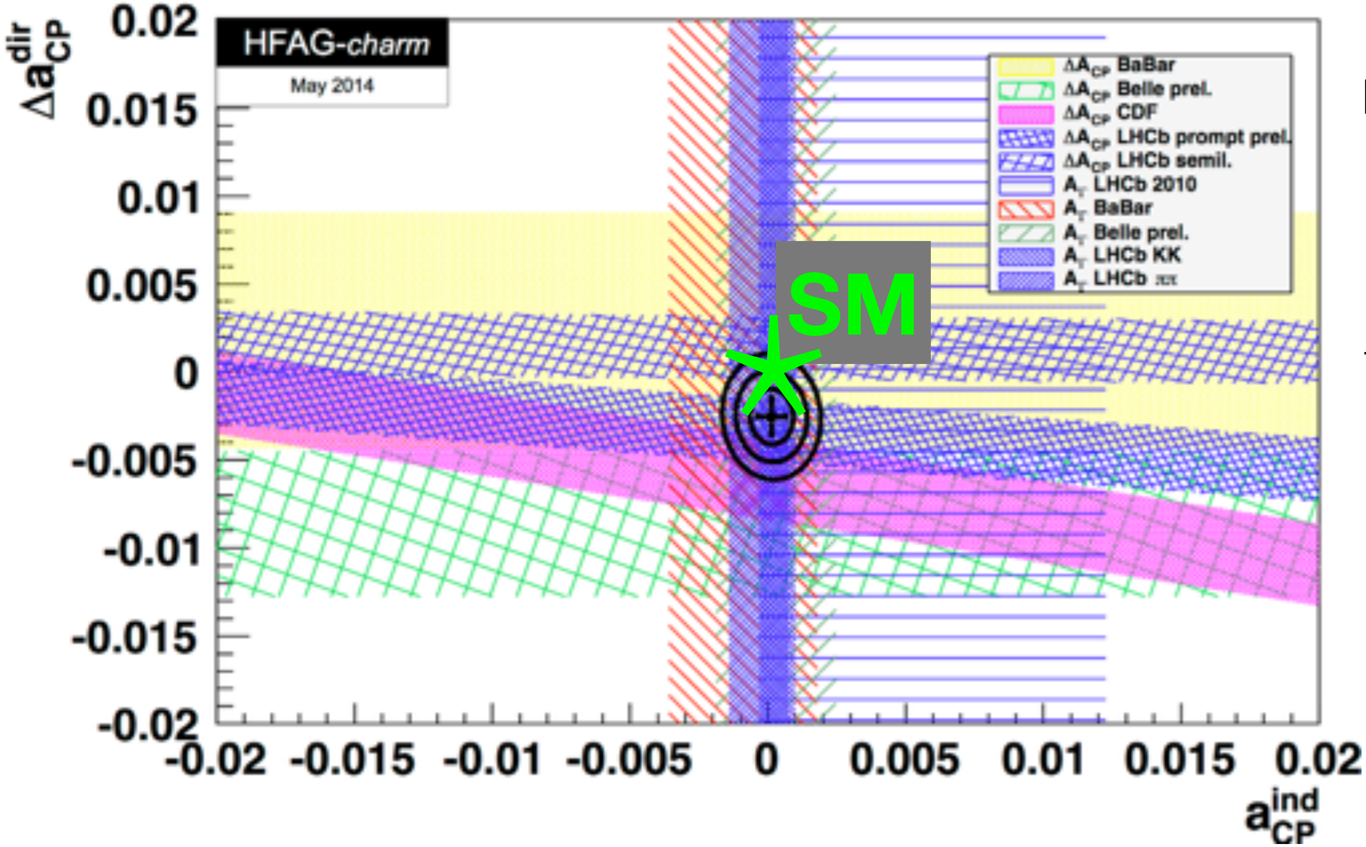
Direct CPV such as $D^0 \to KK$ vs $\bar{D}^0 \to KK$



Plus even more results related to the resonance sub-structure (for example the CP asymmetries in $D^0 \to \phi\rho$, $D^0 \to K^*K^*$, $D^0 \to K_1\pi$, … contributing to $D \to KK\pi\pi$)

Plenty of results. Lots of them **new (since 2013)**.

CPV in D→KK, ππ



Not included: CDF's recent, unpublished A(KK), A(ππ) measurement http://arxiv.org/abs/1410.5435

Excitement from 2012 dissipated a bit - latest averages compatible with SM at ~2σ (plus many theorists believe now that the SM allows more CPV than thought).

Model-independent searches for CPV in multi-body decays.

CPV in $D^\pm \to K^+K^-\pi^\pm$

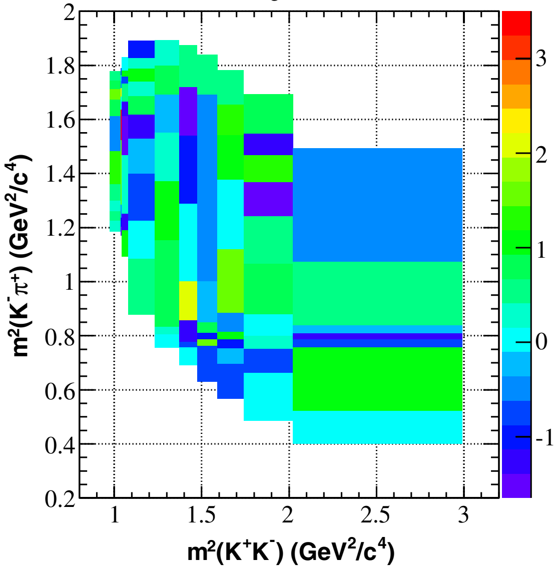
BaBar Phys.Rev. D87 (2013) 052010

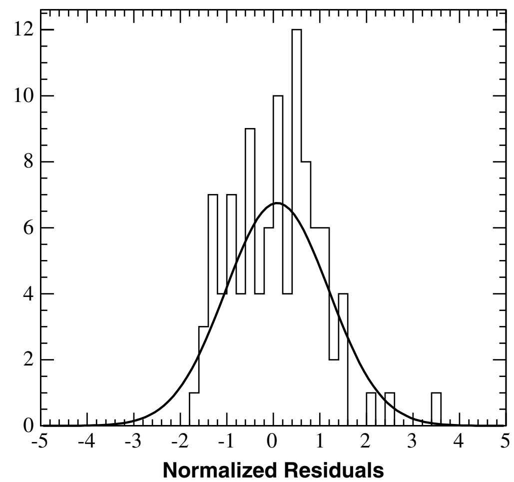
- Binning to achieve equal event yields in each bin.
- Define pull variable for event yields in CP-conjugate bins:

$$S_{CP} = \frac{N_i - \alpha \overline{N}_i}{\sigma(N_i - \alpha \overline{N}_i)} \qquad \alpha = \frac{N_{\text{total}}}{\bar{N}_{\text{total}}}$$

where α normalises out global effects - global CPV as well as global production and detection asymmetries.

- Calculate $\chi^2 = \sum_i (S^i_{CP})^2$ = 90, for 100 bins.
- Corresponds to a p-value for no CPV of 72%



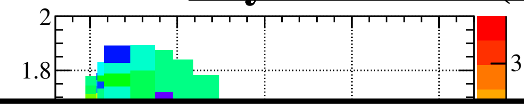


Model-independent searches for CPV in multi-body decays.

CPV in $D^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$

- Binning to achieve equal event yields in each bin.

BaBar Phys.Rev. D87 (2013) 052010



We don't include those. Although there are plenty of them, e.g.

LHCb D->KKππ, D->4π Phys.Lett. B726 (2013) 623-633
LHCb D->KKπ Phys.Rev.D.84.112008 (2011)
LHCb D->3π Phys.Lett. B728 (2014) 585-595
CDF D->K_Sππ Phys.Rev.D 86, 032007 (2012)
LHCb D->ϕπ, D->K_Sπ JHEP 1306 (2013) 112
BaBar Phys.Rev. D87 (2013) 052010
LHCb: arXiv:1410.4170 (2014).

maybe we should include them?

Proposed listing & averaging of χ^2-based model-independent searches of direct CPV:

D->KKpi	chi2	ndof	p-val
LHCb (2011):	32	24	13%
BaBar (Lees 13F, 2013):	90.2	100	72%
Combination:	122.2	124	52%

Spectroscopy

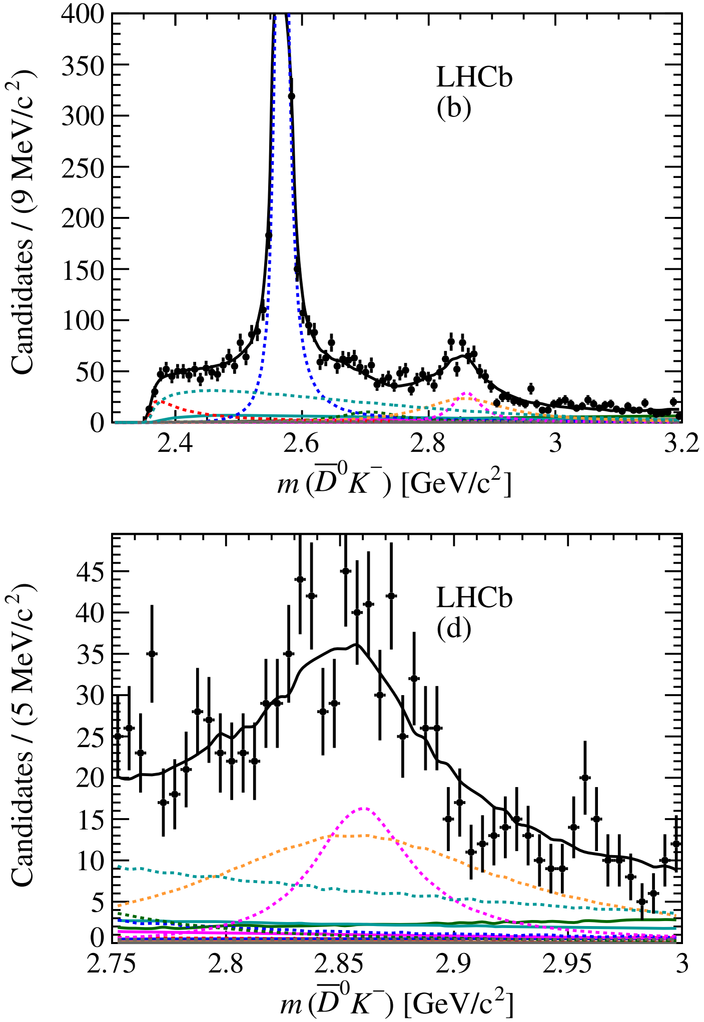
- Amongst many new results: The $D^*_{sJ}(2860)$ does exist - not only once, but twice:

  $B \to \bar{D}K^-\pi^+$ Dalitz plot analysis finds two particles in the same mass region, one with spin 1, one with spin 3.

- This result came out after our deadline. But previous evidence of a $D_s(2860)$ (and others heavy charm states) have disappeared from the 2014 PDG live listing (but were listed in 2012).

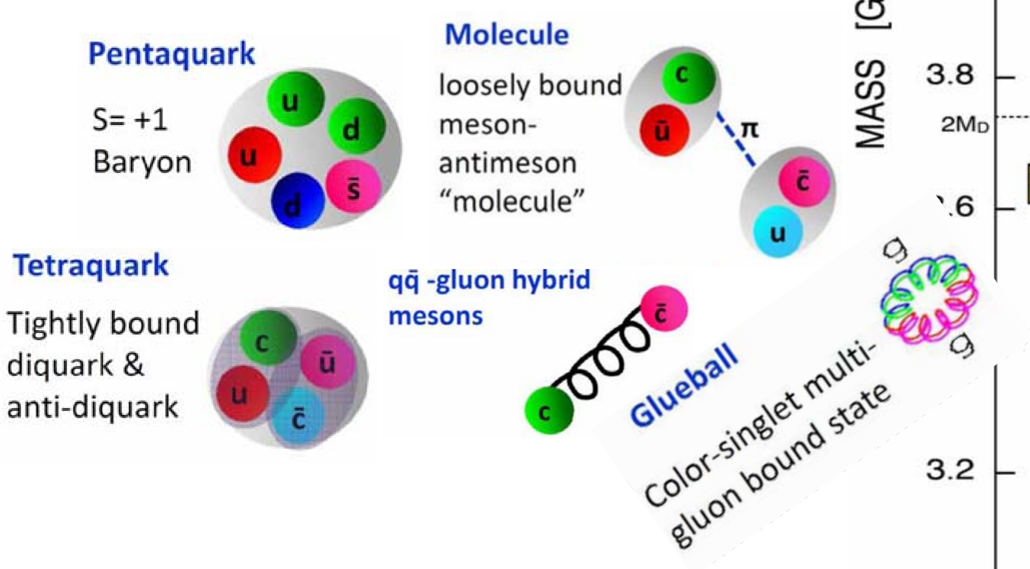
- How should we treat unconfirmed/controversial claimed resonances? Keeping track of them is certainly very helpful for analysts. Maybe we should re-instate them.

DK spectra in $B \to \bar{D}K^-\pi^+$ at LHCb (Phys.Rev. D90 (2014) 072003)

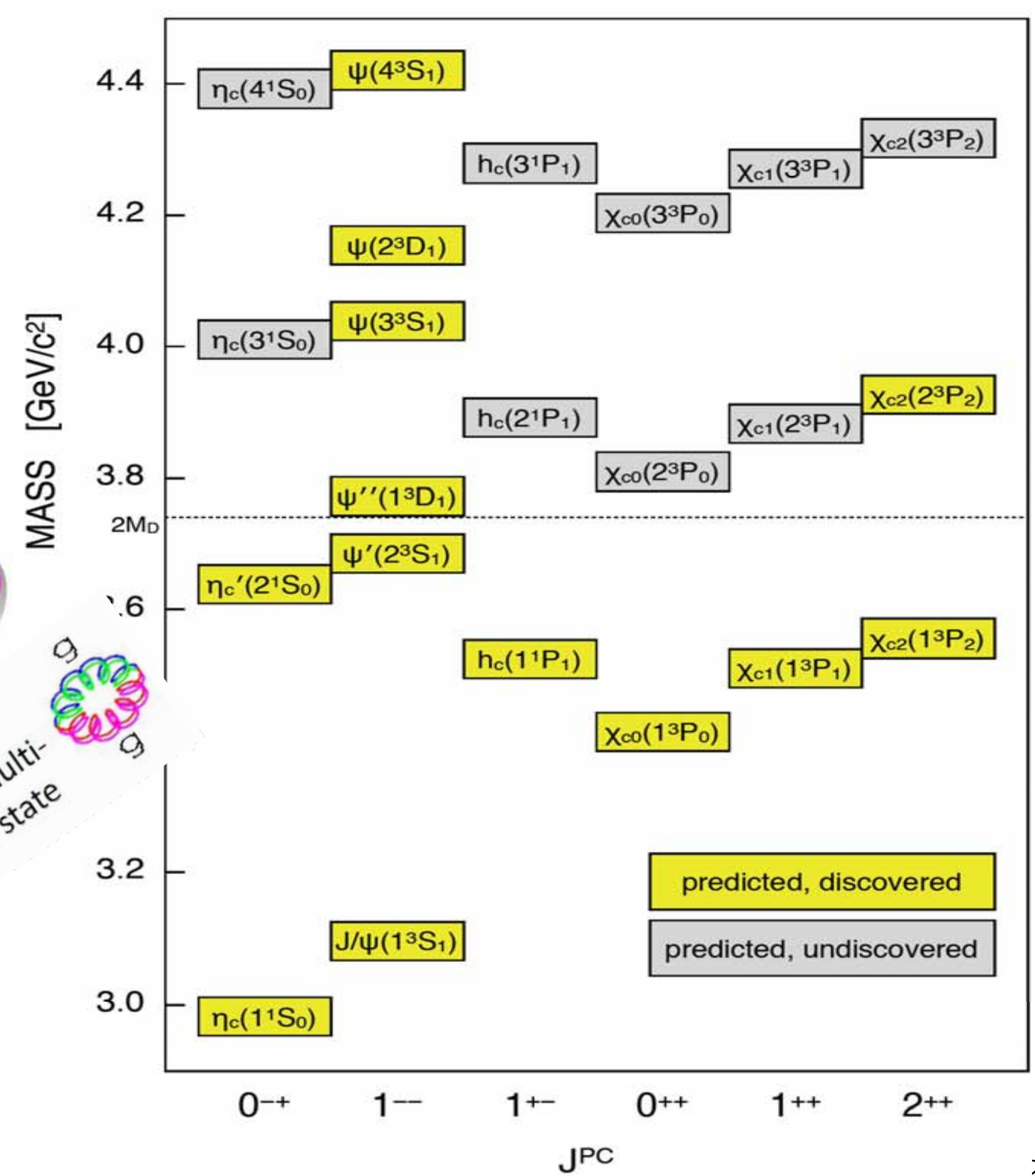


XYZ like states

- Plenty of new charmonium like states discovered.
- What are they? (And in some cases: Are they?)



- and how/where do we list them?



Diagrams and many results from Chengping Shen's talk at B2TIP Workshop, 28-31 October 2014, KEK

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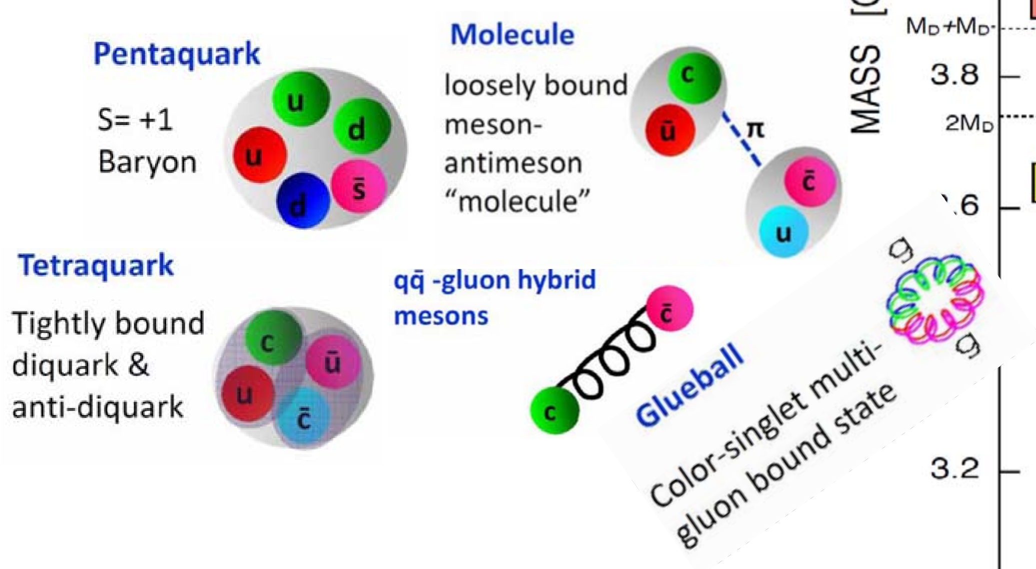

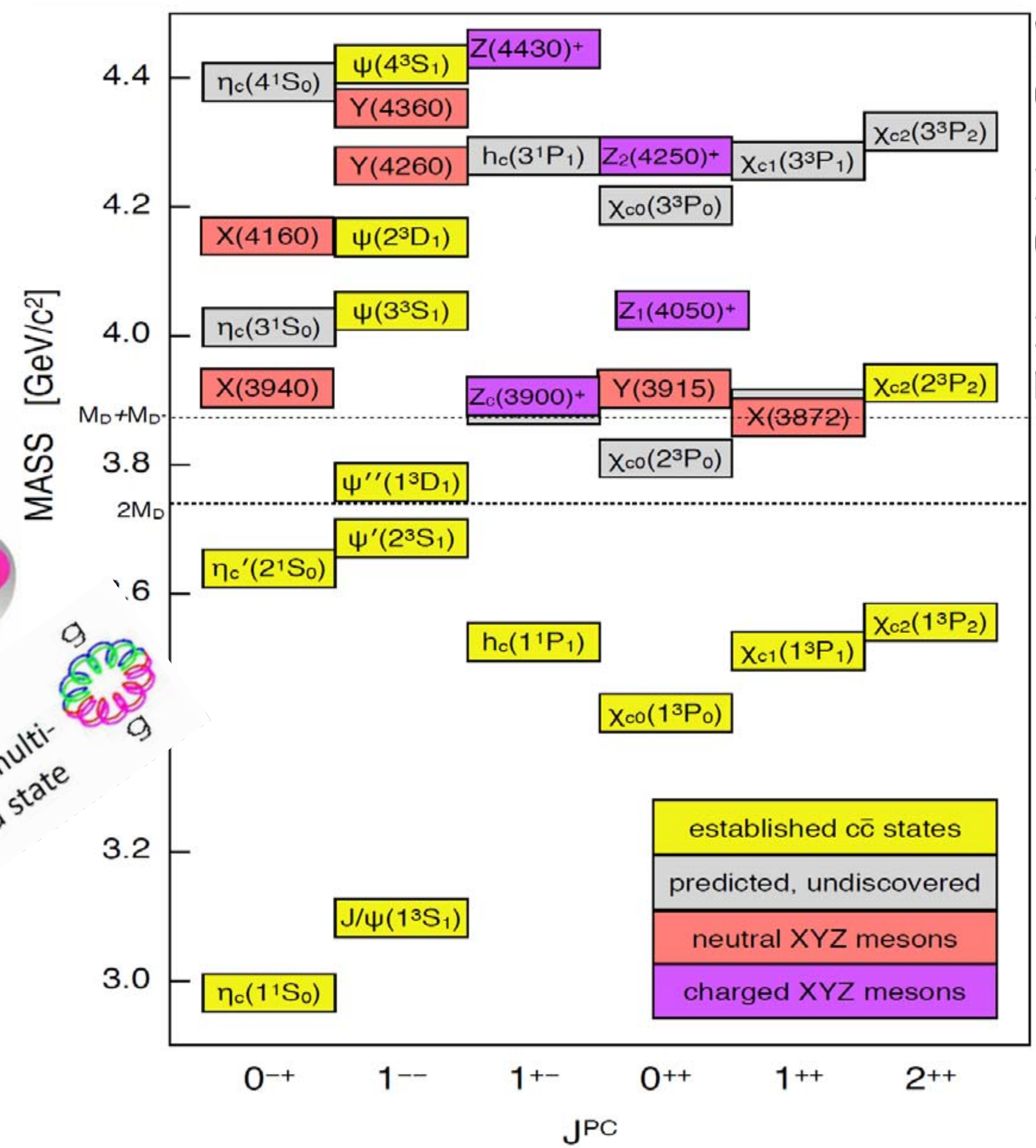

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XYZ like states

XYZ papers published in 2013 and 2014 (incomplete list)

X(3872)

LHCb: PRL 110, 222001 (2013)

BES III: Phys. Rev. Lett. 112, 092001 (2014)

BELLE: Phys. Rev. Lett. 110 252002 (2013)

Y(4008, 4260, 4360, 4660)

BES III Phys. Rev. Lett. 110, 252001 (2013)

Z(3900, 4020, 4200, 4430)

BELLE: Phys. Rev. Lett. 110 252002 (2013)

BELLE: Phys. Rev. D 89, 072015 (2014)

LHCb (2014): Phys.Rev.Lett. 112 (2014) 222002

BELLE (2014): Phys.Rev. D88 (2013) 074026

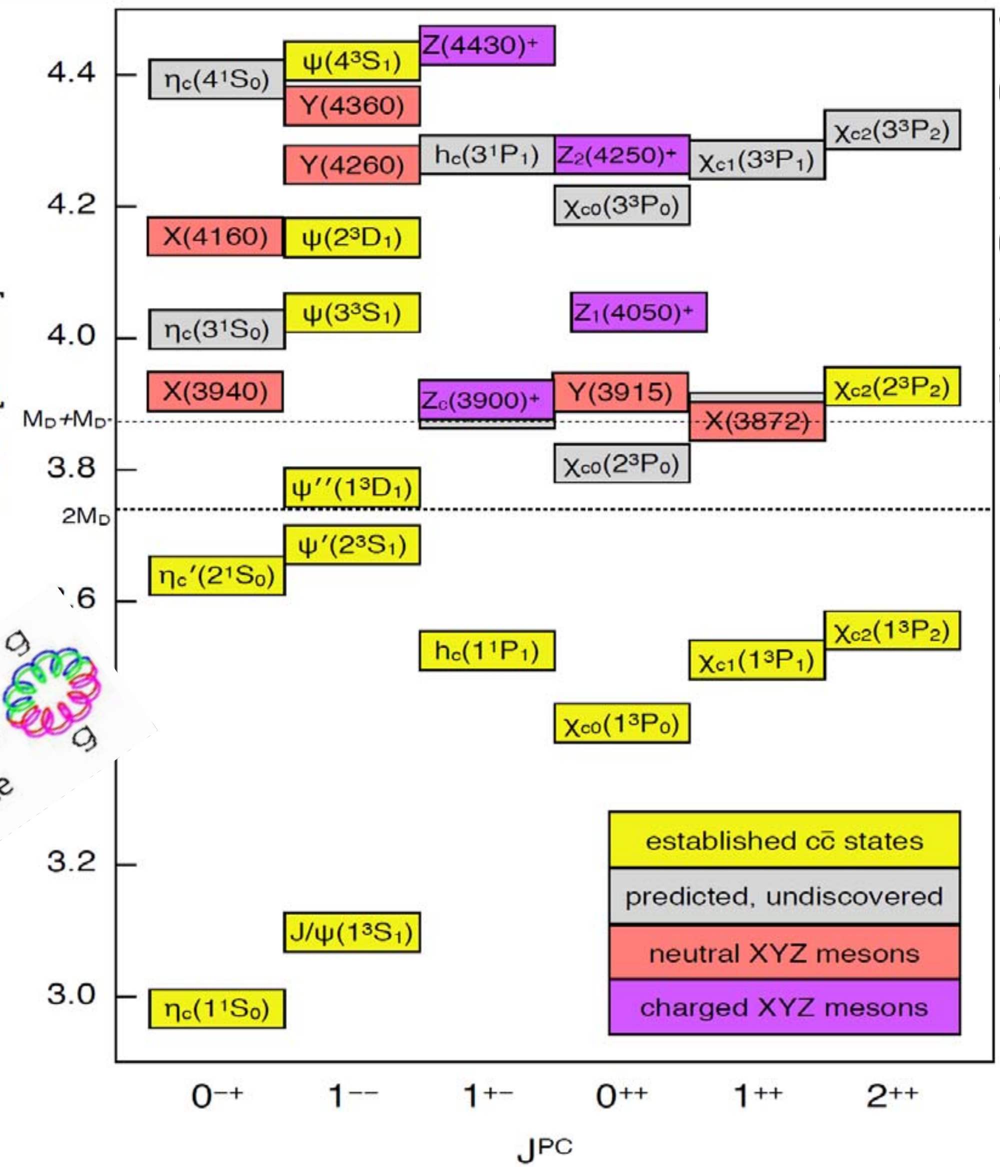
(no) Zcs

BES III Phys. Rev. Lett. 111, 242001 (2013)

BaBar: PRD 89, 111103(R) (2014)

BES III: PRL 111, 032001 (2013)X(3823)

- and how/where do we list them?



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XYZ like states

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BELLE (2014): Phys.Rev. D88 (2013) 074026

(no) Zcs

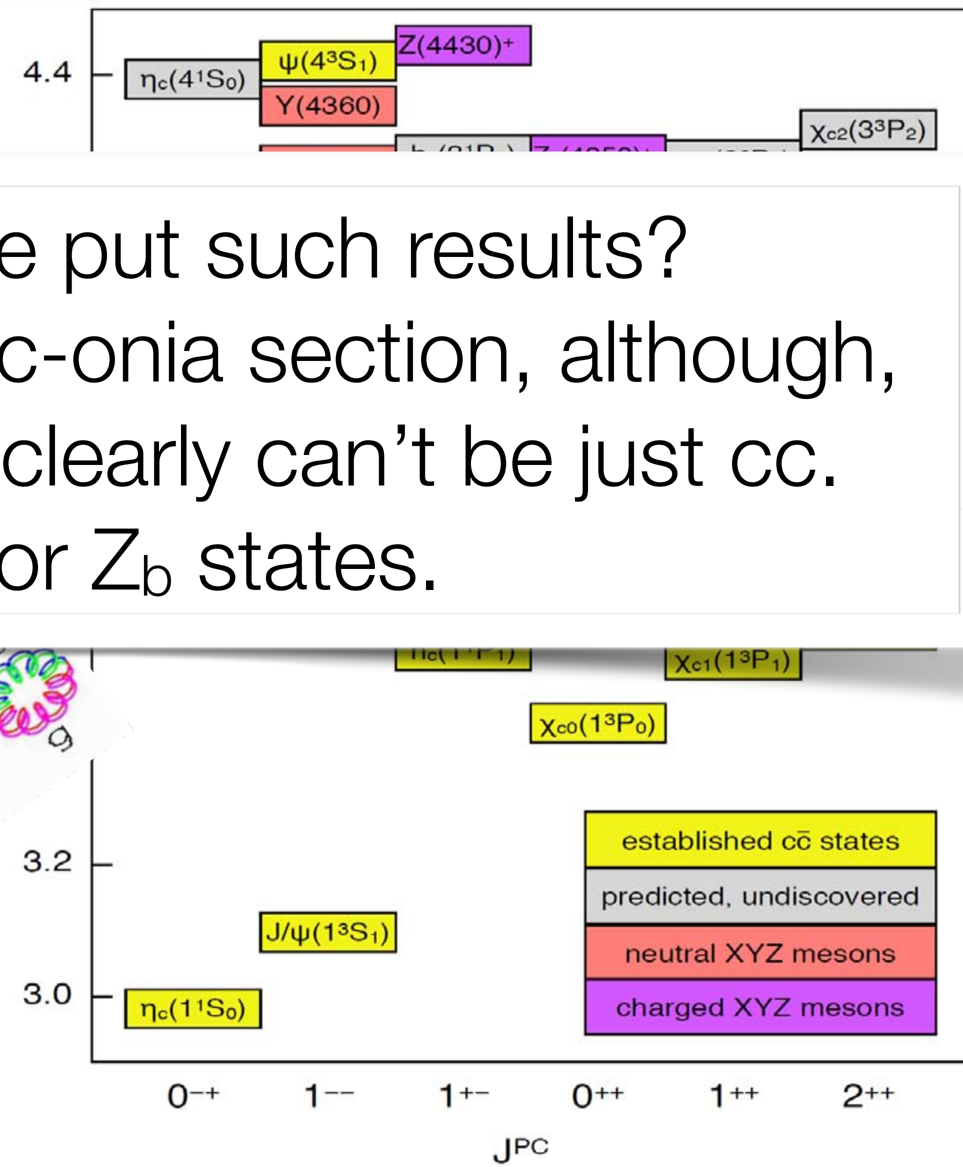
BES III Phys. Rev. Lett. 111, 242001 (2013)

BaBar: PRD 89, 111103(R) (2014)

BES III: PRL 111, 032001 (2013)X(3823)

Where should we put such results?
Currently Z_c is in the cc-onia section, although, given it's charged, it clearly can't be just cc.
Similarly for Z_b states.

- and how/where do we list them?



Diagrams and many results from Chengping Shen's talk at B2TIP Workshop, 28-31 October 2014, KEK

Summary of Part I

- Showed lots of progress on
  - Mixing, CPV
  - Amplitudes, phases
  - New resonances, often with unsuspected properties
- Also loads of progress on important topics not mentioned here, such as Branching Fractions (e.g. PRD89 (2014) 7, 072002, PRD88 (2013) 3, 032009), masses (e.g. JHEP 1306 (2013) 065), rare decay searches (e.g. PLB725 (2013) 15-24, PLB724 (2013) 203-212, PLB728 (2014) 234-243).

- Not all results fit easily in our format, some are even left out altogether as a consequence — it's worth thinking about ways of including them.

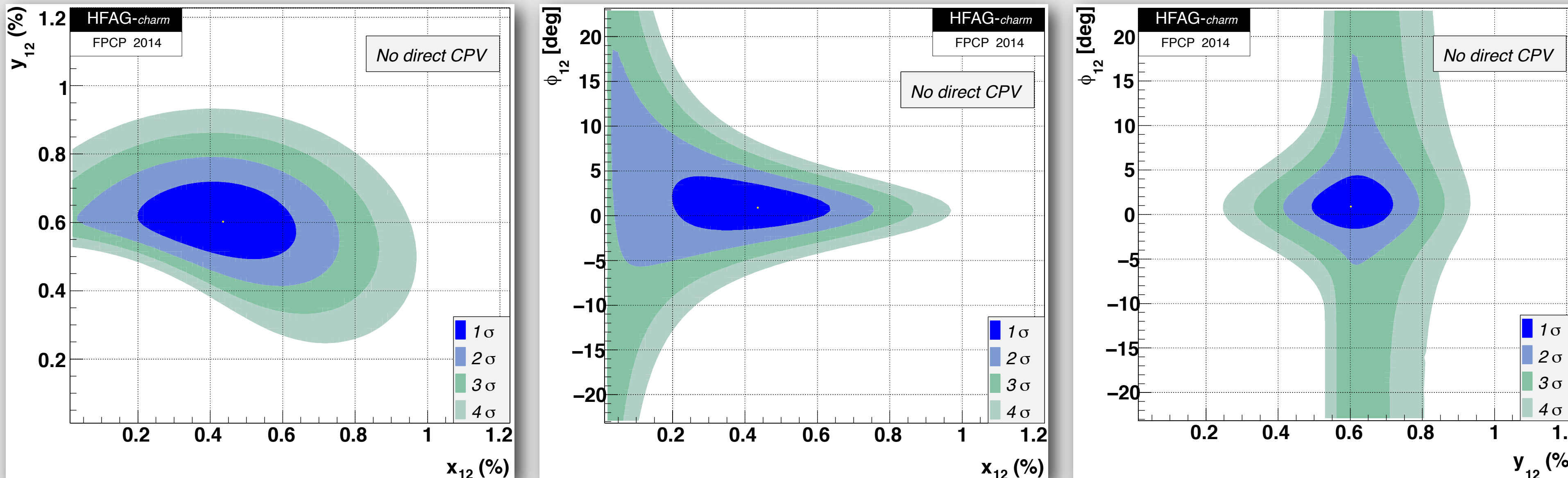
- Part II: Ideas on charm baryons by Charles.

Backup

MANCHESTER 1824
The University of Manchester

Super-weak approximation

HFAG-charm
CKM 2014



- Assume no direct CPV in DCS decays
- Can reduce 4 observables to 3 using
  - ➡ $\tan\varphi = (1-|^q/_p|^2)/(1+|^q/_p|^2) \times (^x/_y)$
- Gives much improved sensitivity
  - ➡ $\sigma(^q/_p)$ reduced from 8.7% to 1.4%
  - ➡ $\sigma(\varphi)$ reduced from 8.9° to 0.6°
  - ➡ Still no sign of indirect CP violation

Alternatively re-write set of parameters as $x_{12}, y_{12}, \varphi_{12}$ as shown in plots

x_{12} (%)	$0.43^{+0.14}_{-0.15}$
y_{12} (%)	0.60 ± 0.07
ϕ_{12}(°)	$0.9^{+1.9}_{-1.7}$

Quantum-Correlated D^o-$\bar{D}^o$ decays

Phys.Rev.D80:031105,2009

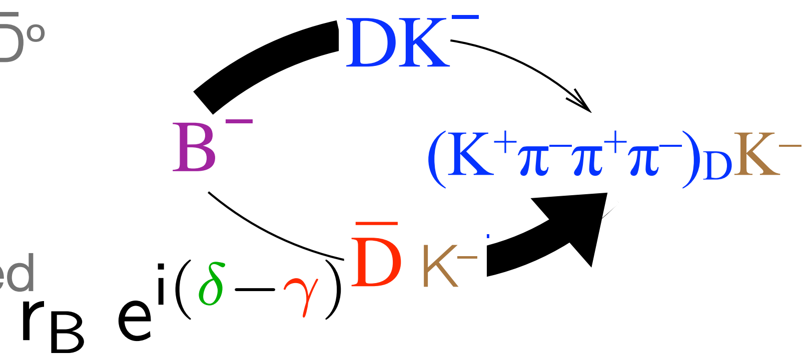
Phys.Lett. B731 (2014) 197-203

- Operating at the ψ(3770) (CLEO-c, BES III) provides well-defined D^o, $\bar{D}^o$ superpositions.

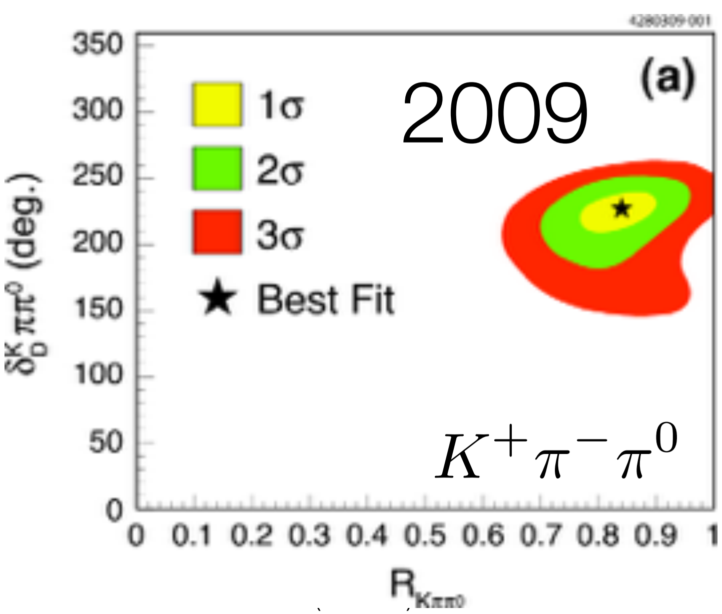
e.g. CP even D:

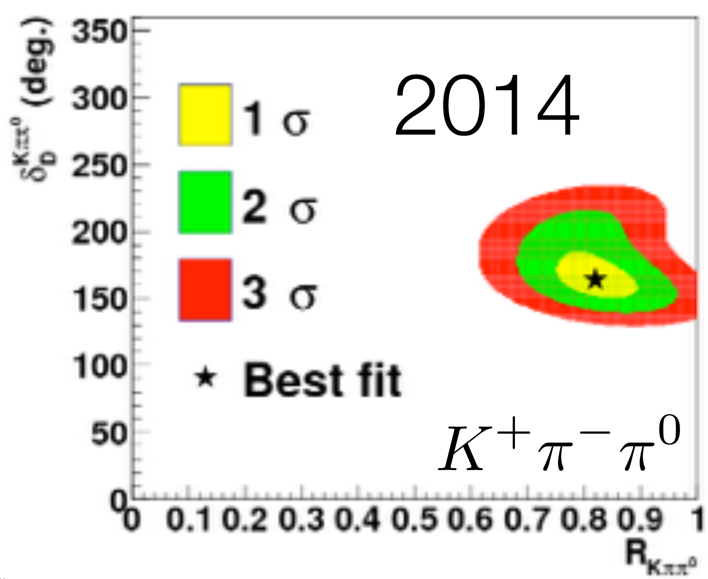
$$\frac{1}{\sqrt{2}}\left(D^0+\overline{D}^0\right)\rightarrow K^+\pi^-\pi^+\pi^-$$

- These provide crucial information on the D^o-$\bar{D}^o$ interference that affect γ from B→DK.



- These interference effects can be summarised in a complex number *R exp(i δ_D)*





FCNC through rare charm decays

$BR(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ @ 90% CL

Phys.Lett. B725 (2013) 15-24

$BR(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$ @ 90% CL

$BR(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1 \times 10^{-7}$ @ 90% CL

Phys.Lett. B724 (2013) 203-212

$BR(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$ @ 90% CL

Phys.Lett. B728 (2014) 234-243

All of the above are > 1 order of magnitude better than previous limits.

A_{CP} for D^0, $\overline{D}^0 \rightarrow K^+ K^- \pi^+ \pi^-$ amplitude components

CLEO: Phys.Rev. D85 122002 (2012)

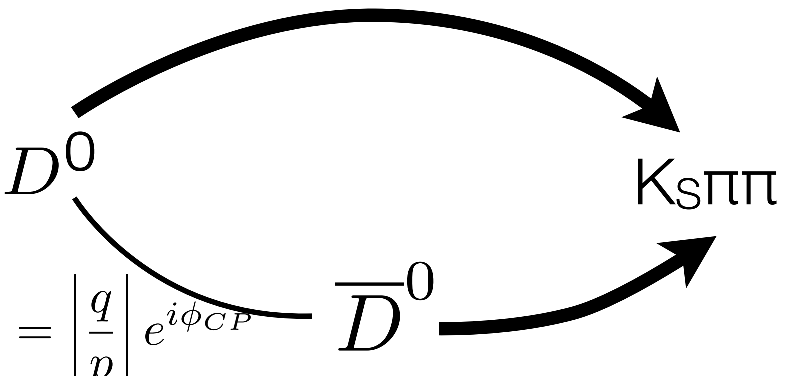
	Fit fraction (%)		A_{CP}
	D^0 Decays	$\overline{D^0}$ Decays	(%)
$K_1(1270)^+(K^{*0}\pi^+)K^-$	7.4 ± 1.1	7.5 ± 1.1	-0.7 ± 10.4
$K_1(1270)^-(\overline{K^{*0}}\pi^-)K^+$	0.9 ± 0.4	1.1 ± 0.5	-10.0 ± 31.5
$K_1(1270)^+(\rho^0 K^+)K^-$	4.3 ± 1.1	4.9 ± 1.1	-6.5 ± 16.9
$K_1(1270)^-(\rho^0 K^-)K^+$	6.3 ± 1.1	5.2 ± 1.0	9.6 ± 12.9
$K^*(1410)^+(K^{*0}\pi^+)K^-$	3.2 ± 0.9	4.8 ± 1.0	-20.0 ± 16.8
$K^*(1410)^-(\overline{K^{*0}}\pi^-)K^+$	4.6 ± 0.9	4.7 ± 0.9	-1.1 ± 13.7
$K^{*0}\overline{K^{*0}}$ S wave	6.9 ± 1.2	5.7 ± 1.2	9.5 ± 13.5
$\phi\rho^0$ S wave	37.9 ± 2.9	40.0 ± 2.9	-2.7 ± 5.3
$\phi\rho^0$ D wave	2.2 ± 0.8	4.8 ± 1.2	-37.1 ± 19.0
$\phi\{\pi^+\pi^-\}_S$	9.0 ± 1.4	10.7 ± 1.5	-8.6 ± 10.4
$\{K^-\pi^+\}_P\{K^+\pi^-\}_S$	11.3 ± 1.7	10.7 ± 1.6	2.7 ± 10.6

No significant CPV

Time-dependent CPV $D^o \rightarrow K_S\pi\pi$

New prelim Result from BELLE - see Longke Li's talk earlier today.

see also previous result: Phys. Rev. Lett. 99, 131803 (2007).



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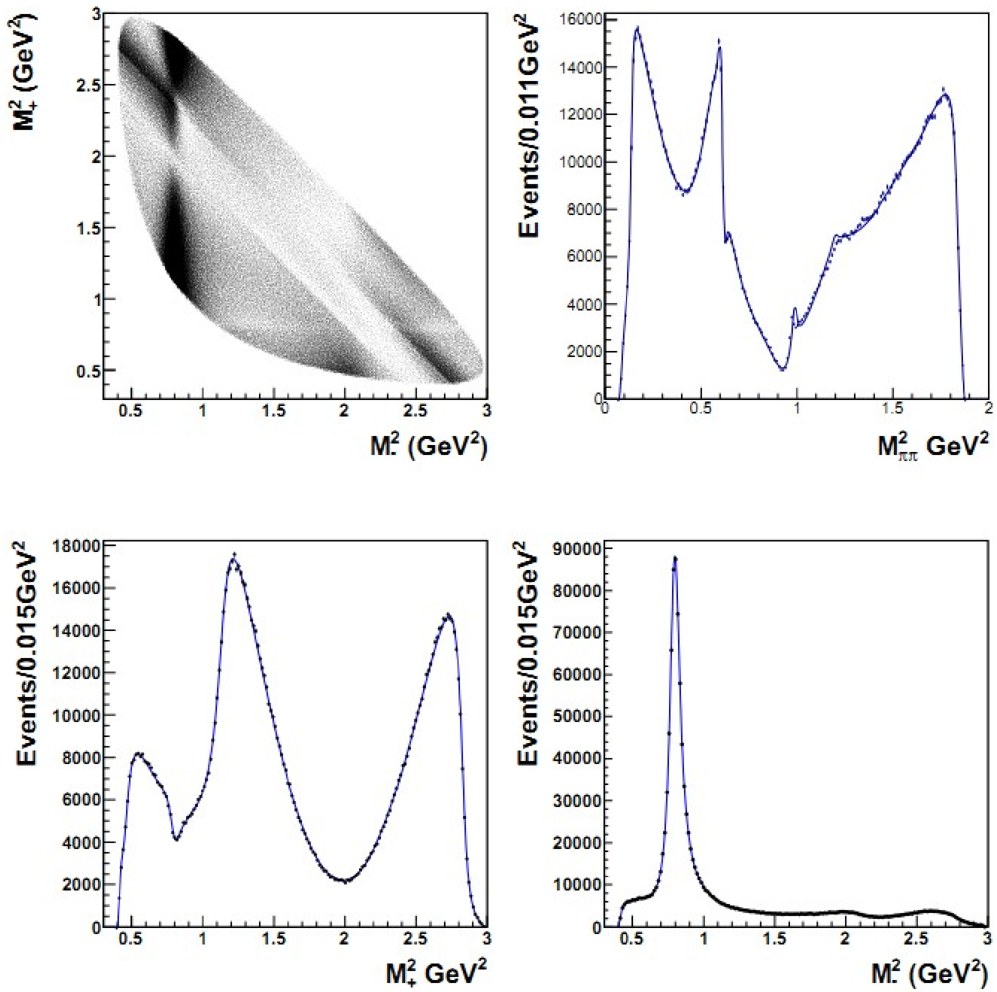

(Belle preliminary)

Fit case	Parameter	Fit new result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
No dCPV	$\lvert q/p\rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg q/p(^o)$	$-6 \pm 11^{+3+3}_{-3-4}$

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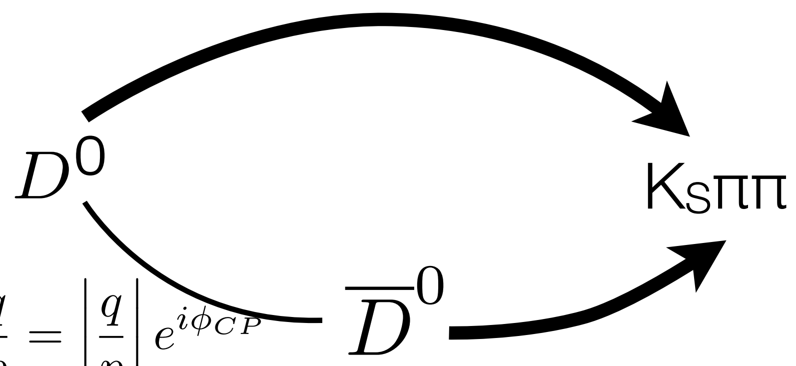

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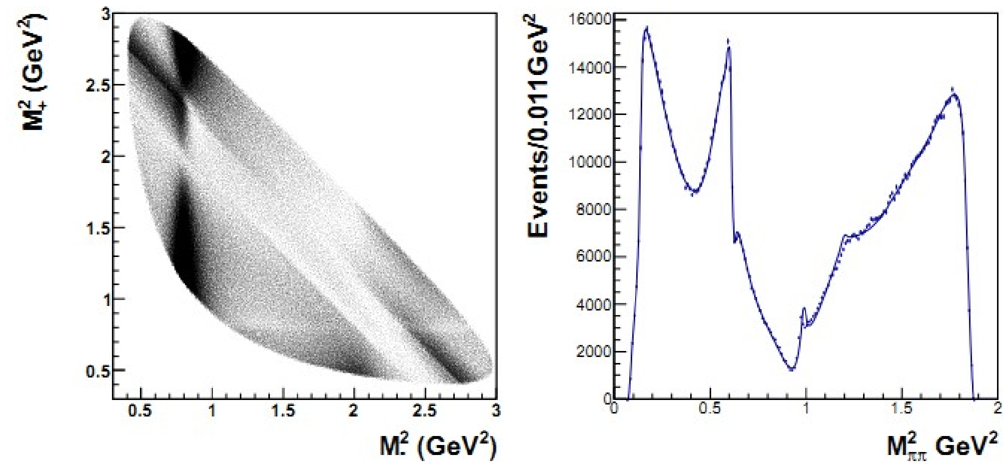

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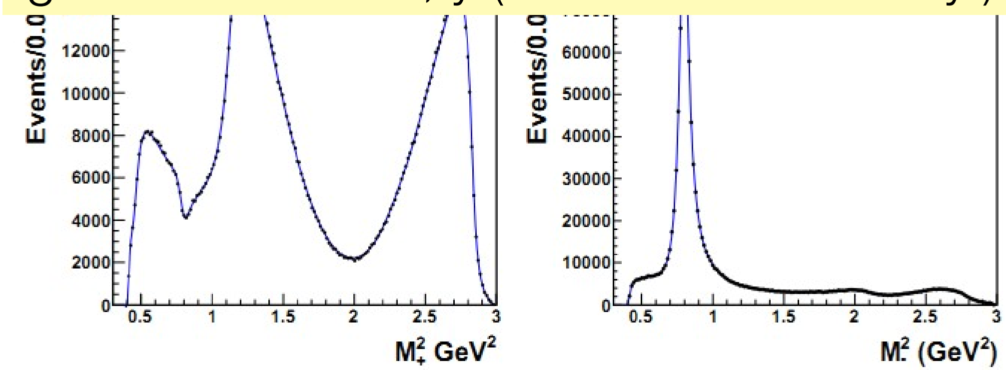

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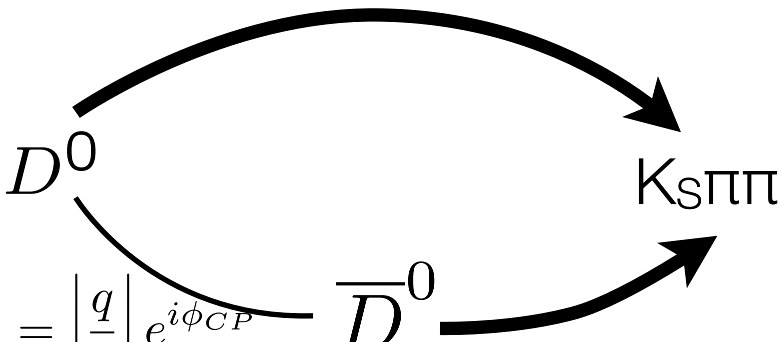

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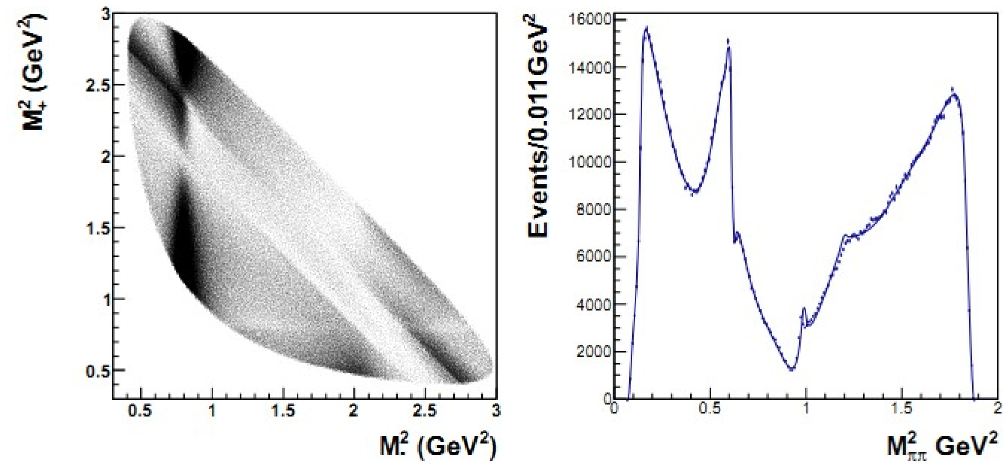

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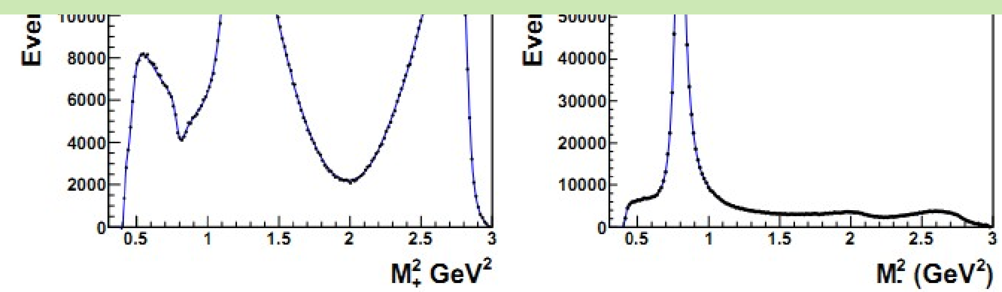
No evidence of CP violation



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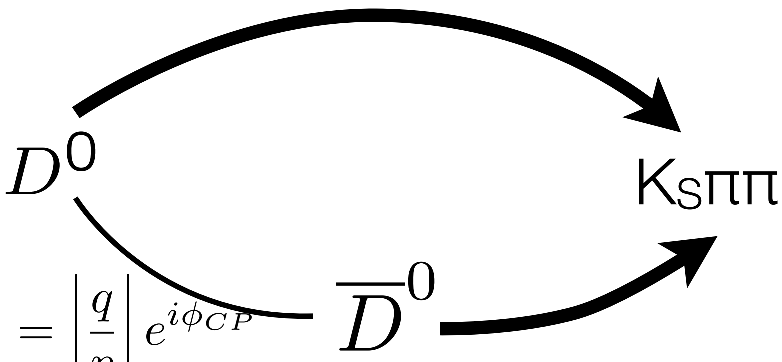

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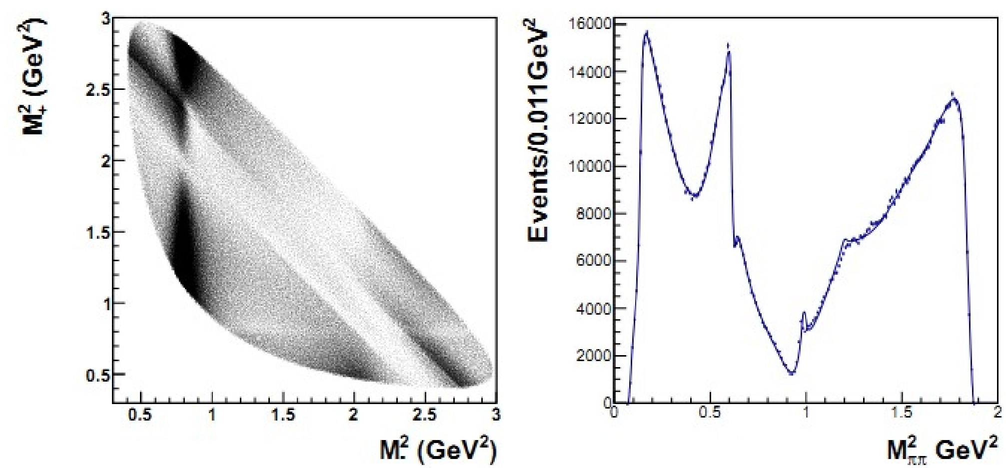

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Magic of Dalitz plot (sensitivity to phases) gives access to x, y (rather than x'^{2} and y')

No evidence of CP violation

Significant systematic uncertainty from amplitude model dependence. (Could be limiting with future LHCb/upgrade statistics.)

see also BaBar Phys. Rev. Lett. 105, 081803 (2010) and CLEO-c Phys. Rev. D 72, 012001 (2005).

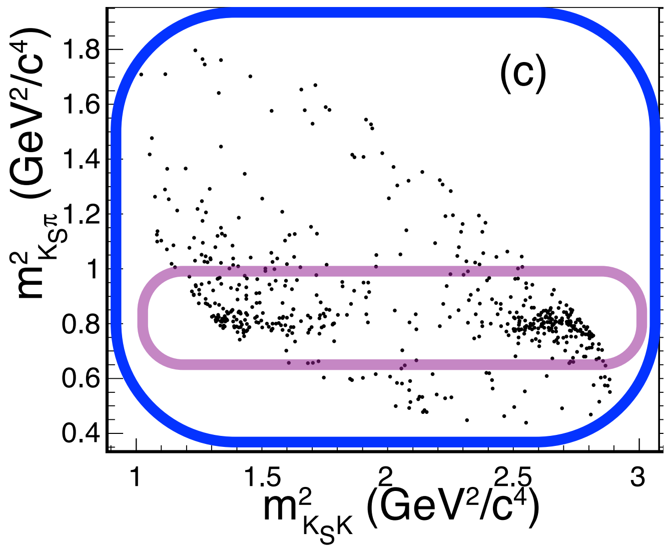
Input from the charm threshold for $D^o \to K_S K \pi$

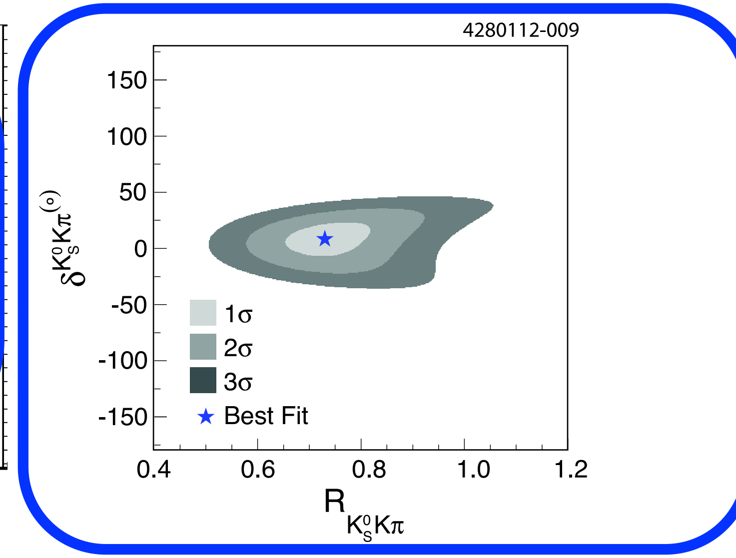
CLEO-c Phys.Rev. D85 092016 (2012)

- Similar input as for $K_S\pi\pi$, $K_S KK$, different nomenclature:

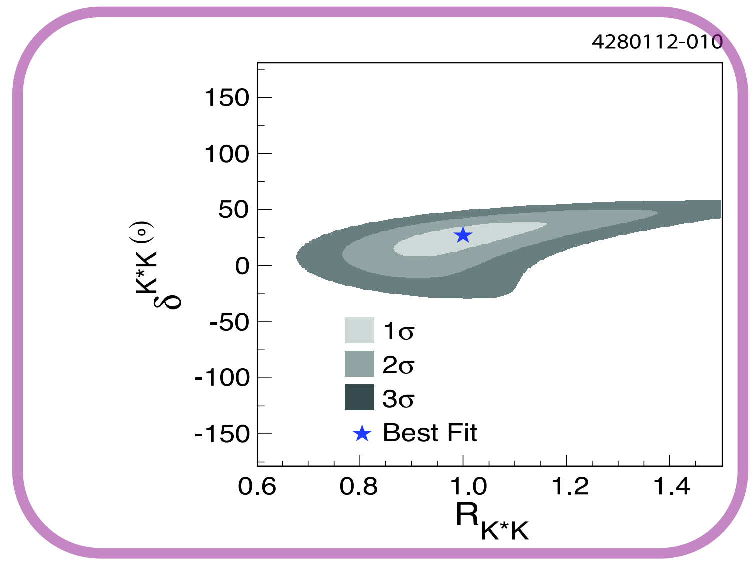
$$R_{D\,k} e^{-i\delta_k} = c_k + i s_k$$

- Typically measured in one single bin across Dalitz space, but analyses with several bins (where statistics allow) could increase sensitivity.





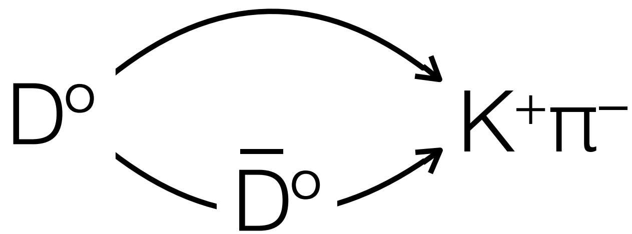
Dalitz plot shows CF decay for illustration. Sensitivity to mixing comes from the DCS decay, and CLEO-c's sensitivity to R_D, δ_D from well-defined superpositions of D^o and D^obar accessible at the charm threshold



D→Kπ mixing phase

CLEO-c: Phys.Rev.D80:031105,2009
Using CLEO-c data: Phys.Lett. B731 (2014) 197-203
BES III: Phys.Lett. B734 (2014) 227

- Mixing sensitive to interference between $D \to K^+\pi^-$ and $D \to K^+\pi^-$.

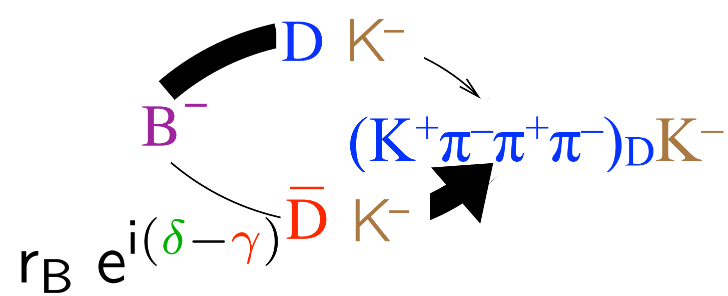


- Phase difference between amplitudes needed to interpret results in terms of mixing parameters x, y.
- Accessible at charm threshed. Latest measurement by BES III in 2014:

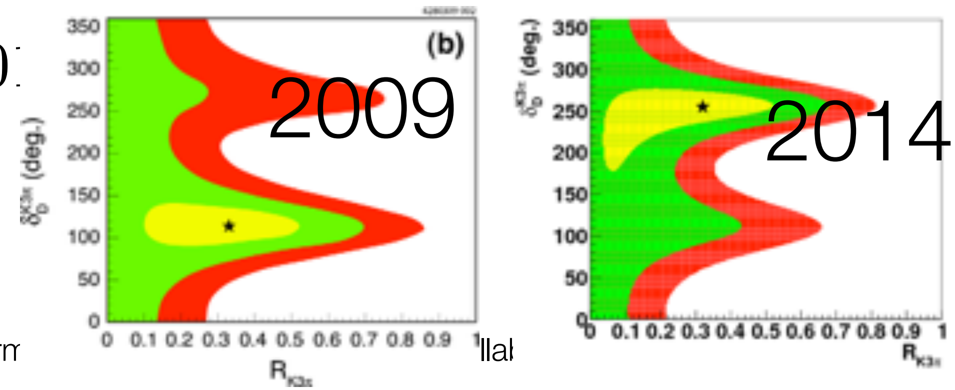
$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.0$$

- **1st BES III result exploiting quantum correlations in this way.**

- Same interference effects also affect γ measurements, not only for D→Kπ, but also multi body decays:

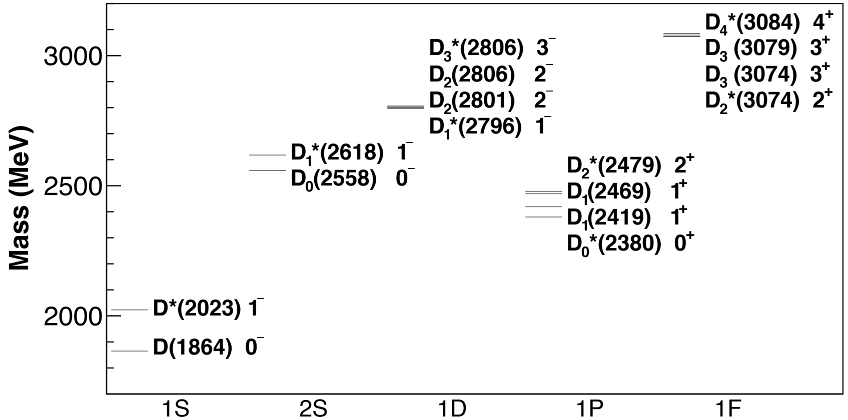


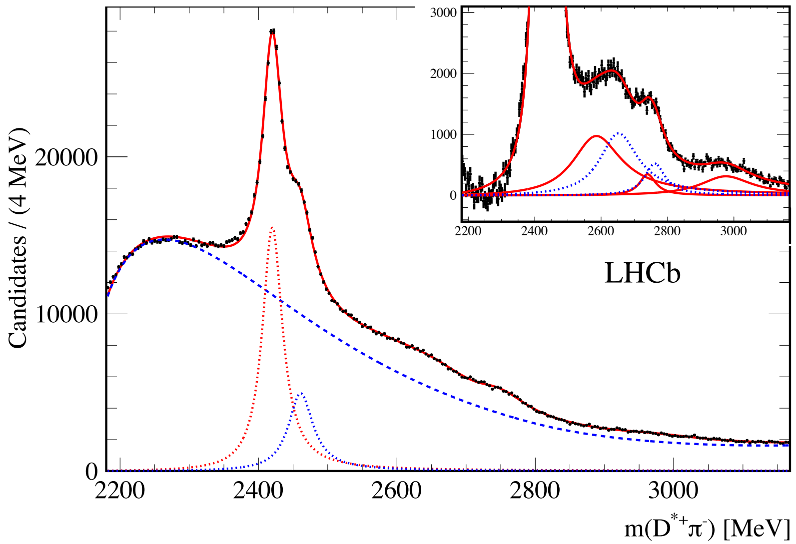
- Need to measure magnitude R and phase δ. Recent update based on CLEO-c data:



Spectroscopy

- Lots of new results
- D_J states (see left). New results from LHCb (some of them in some tension to prev. results)
- X, Y, Z states and their quantum numbers (see next page)





Tetraquark Candidate:
Z(4430)→ψ(2S)π⁻ in B→ψ(2S)π⁻ K⁺?

BELLE (2008): Phys.Rev.Lett. 100 (2008) 142001
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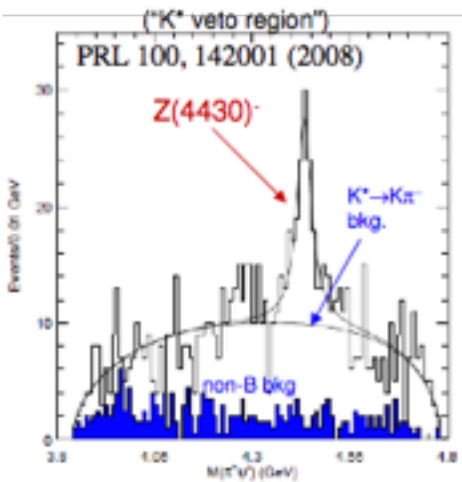
Belle 2008

Yes.



Analysed only 1-D projection - **very controversial.**

$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18}_{-13}\,{}^{+30}_{-13}$ MeV

significance 6.5σ

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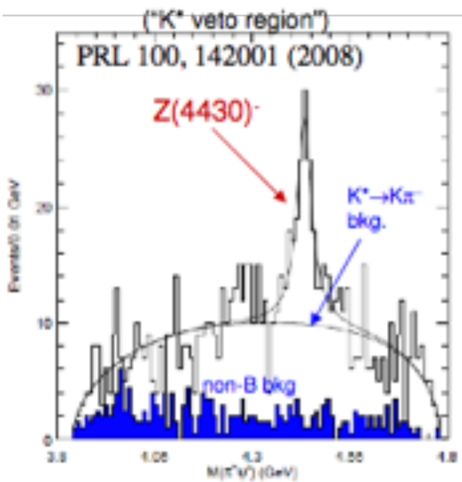

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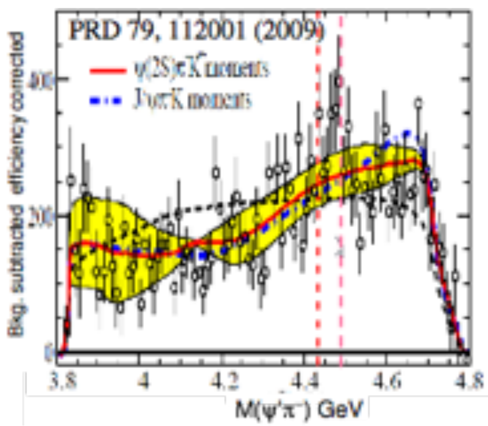

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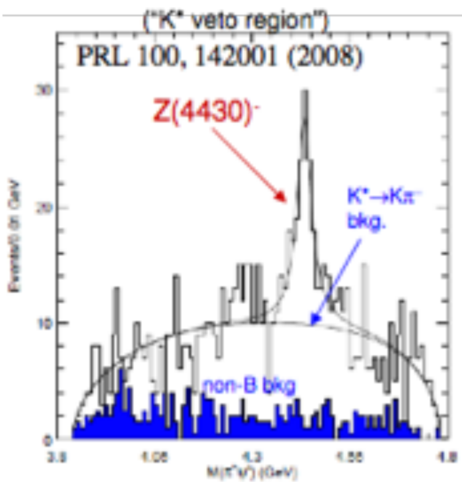

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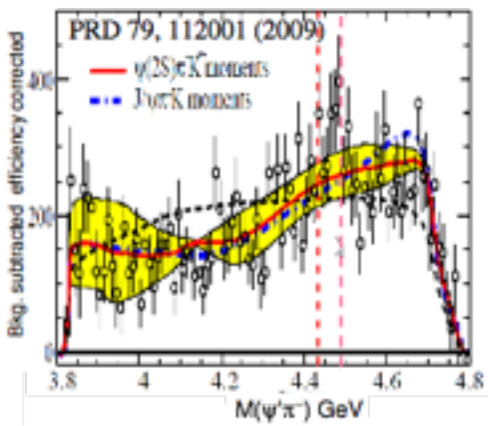

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Belle 2013

Yes, really

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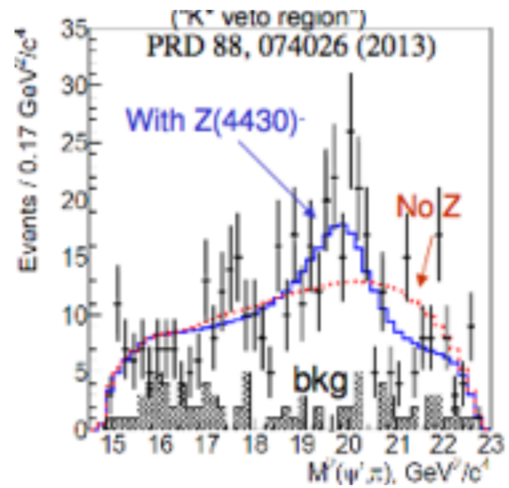

Full 4-D analysis

$M(Z) = 4485^{+22}_{-22}{}^{+28}_{-11}$ MeV

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6.4σ (5.6σ with sys.)

$J^P = 1^+$ preferred by $>3.4\sigma$

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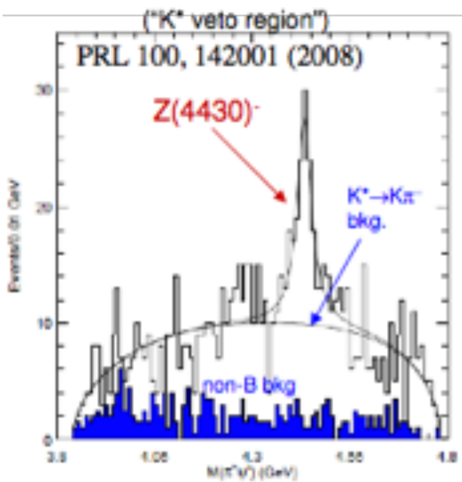

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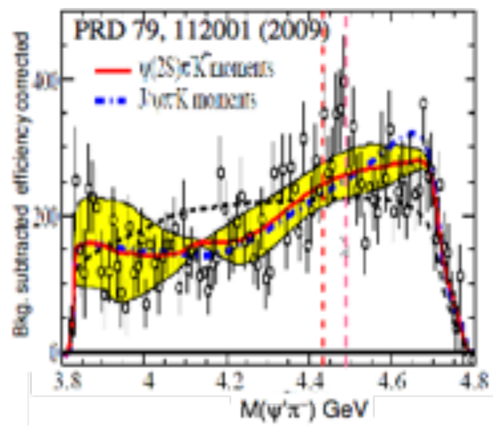

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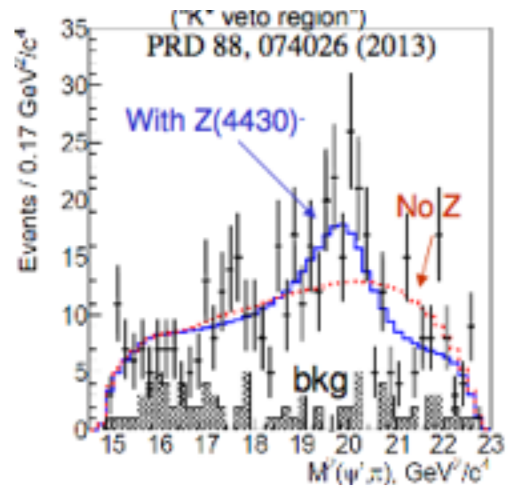

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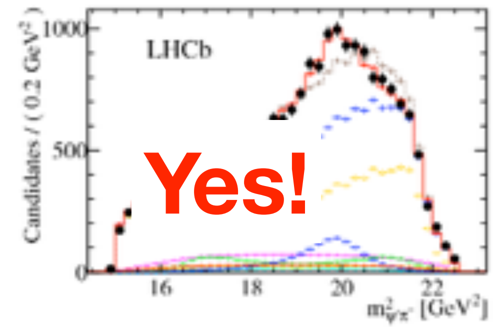

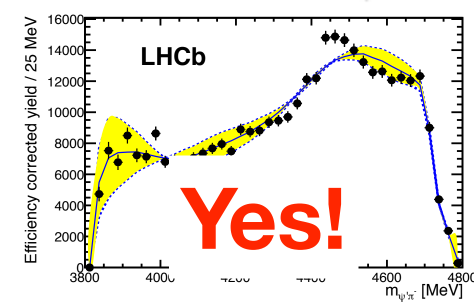

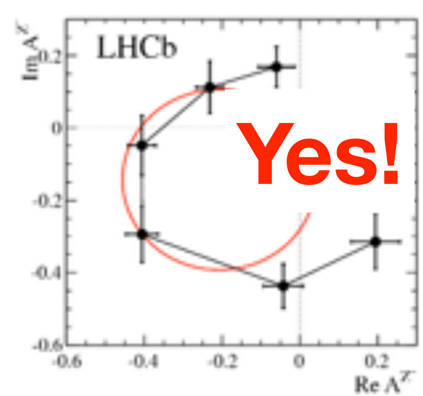

Quantum-Correlated D°-$\overline{D}$° decays

Phys.Rev.D80:031105,2009

Phys.Lett. B731 (2014) 197-203

- Operating at the ψ(3770) (CLEO-c, BES III) provides well-defined D°, $\overline{D}$° superpositions.
- These provide crucial information on the D°-$\overline{D}$° interference that affect γ from B→DK.
- These interference effects can be summarised in a complex number *R exp(i δ_D)*

e.g. CP even D:

$$\frac{1}{\sqrt{2}}\left(D^0 + \overline{D}^0\right) \to K^+\pi^-\pi^+\pi^-$$