Experimental Summary:
step-by-step towards new physics

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CHARM 2015:
The 7th International Workshop on Charm Physics
Wayne State University, USA
May 22nd, 2015

- *Production*
- *X/Y/Z Quarkonium*
- *Hadronic decays*
- *Semileptonic/ leptonic decays*
- *Rare/forbidden/radiative decays*
- *T violation*
- *Mixing + CP violation*

CHARM'15 Experimental Program

blue = plenary
black = parallel

Quarkonium/Exotics

- Wang - Belle
- Korner - BESIII
- Palano – LHC
- Presad - BESIII
- Ping - BESIII
- Bian - BESIII
- Anulli - BaBar
- Whitehead - LHCb

Production

- Sokoloff - BaBar
- Yi - CMS
- Yabsley – ATLAS
- Frawley
- Dainese
- Vogt - LHC
- LaPointe - ALICE
- Feng - STAR
- Lebedev - PHENIX
- Branchin – ALICE
- Yu - PHENIX

Rare/radiative

- Gobel
- Zhao - BESIII
- Vacca – LHCb
- Nanut – Belle

BSM searches

- Prasad
- Nachtman CMS
- t -> Dγ CMS
- H-> γγ CMS

Semileptonic/Leptonic

- Eidelman - Belle
- Ma - BESIII
- An – BESIII
- Oyanguren – BaBar

CPV/Mixing

- Leo - CDF
- Naik - LHCb
- Pilloni – Belle/BaBar
- Gersabeck - LHCb
- Libby – CLEOc
- Malde - CLEOc
- Onur - BESIII
- Reichert – LHCb
- Martinelli - LHCb

Dalitz/Hadronic

- Muramatsu – BESIII
- Palano - BaBar
- Weidenkaff – BESIII

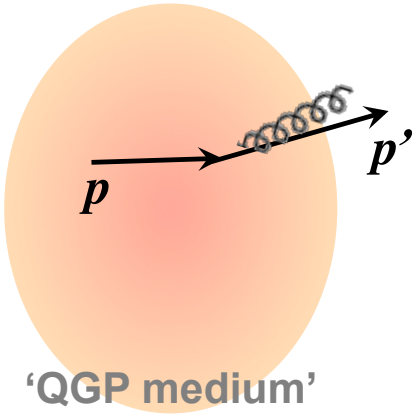
Baryons/B+τ decays/other

- Ogilvy – LHCb
- Lyu – LHCb
- Harrison – LHCb
- Vinokurova – Belle
- Bhardwaj – Belle
- Purohit – BaBar
- Wang - ATLAS

1. Production

Heavy flavor production in AA/pA

Dainese



Nuclear modification factor:

$$dN_{AA}/dp_T \;<\; \langle N_{coll}\rangle dN_{pp}/dp_T$$

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll}\rangle}\frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} < 1$$

Parton Energy Loss predicted to depend on:

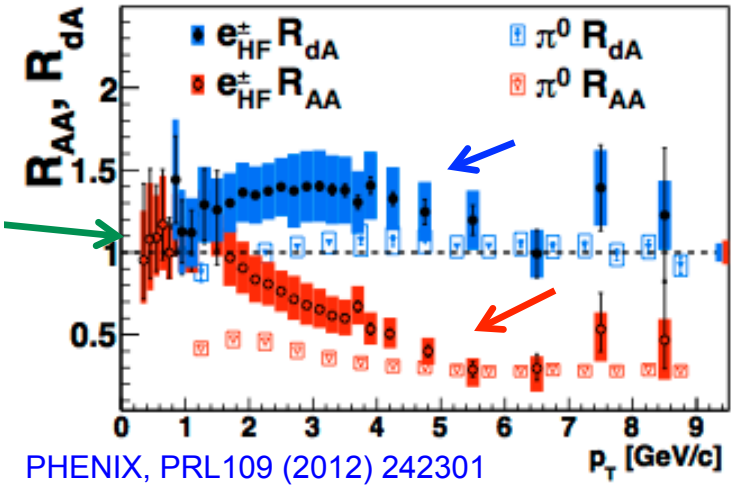
- Color charge C_R (larger for gluons)
- Mass m (larger for heavy quarks)

$$\Delta E(\varepsilon_{medium}; C_R, m)$$

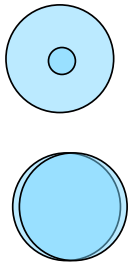
pred: $\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$

$$\rightarrow \quad R_{AA}^{\pi} \le R_{AA}^{D} < R_{AA}^{B}$$

Au-Au high-pT suppression:

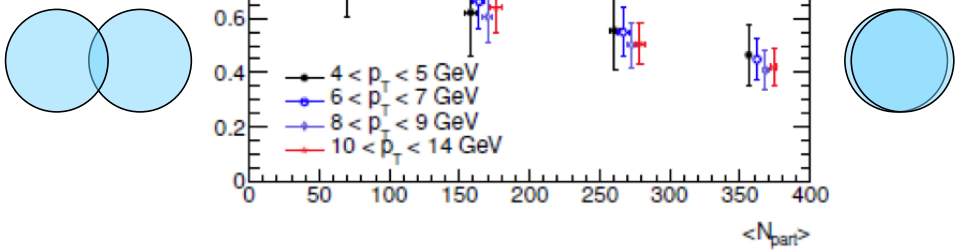


PHENIX, PRL109 (2012) 242301



suppression vanishes in peripheral collisions:

ATLAS-CONF-2012-081

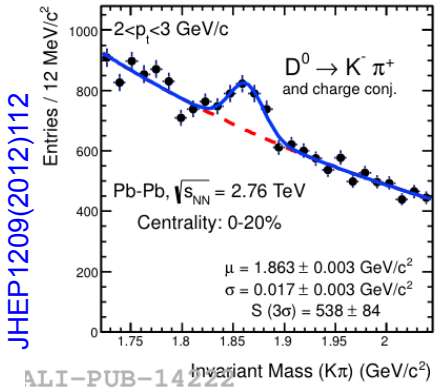


Heavy flavor production in AA/pA

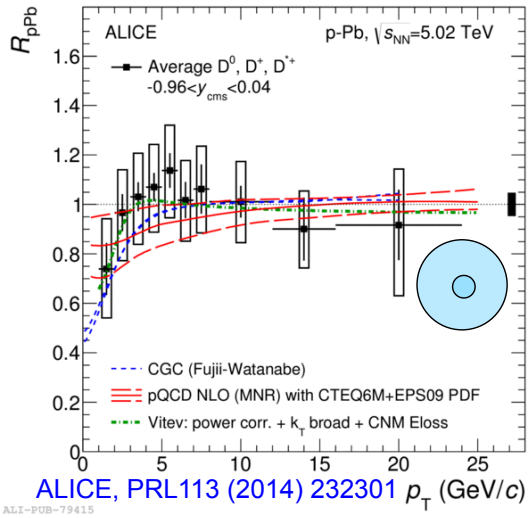
Dainese

ALICE

Pb-Pb collisions, reconstruct vertices, $D^0 \rightarrow K^-\pi^*$ signal:

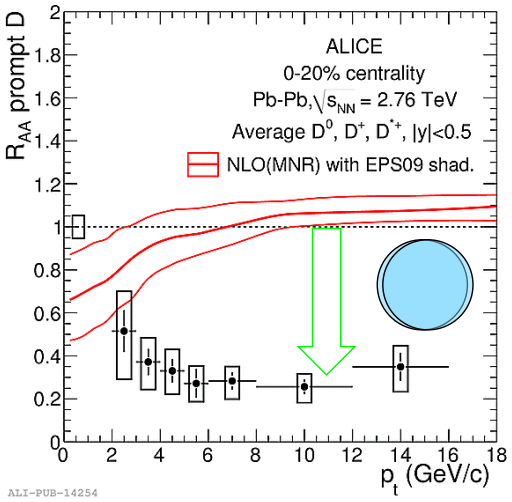


p-Pb, no suppression

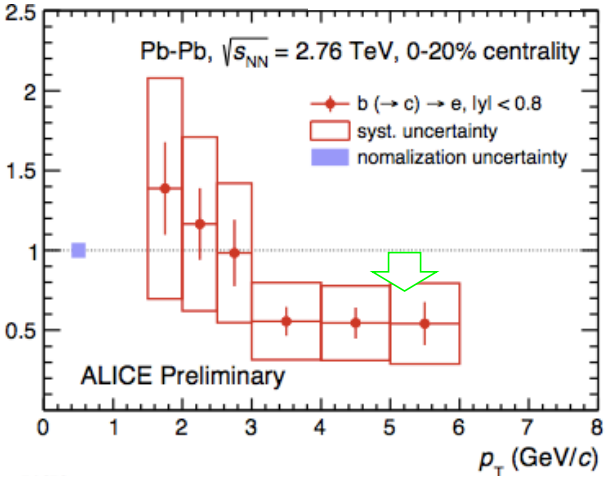


ALICE, PRL113 (2014) 232301

Pb-Pb, significant suppression

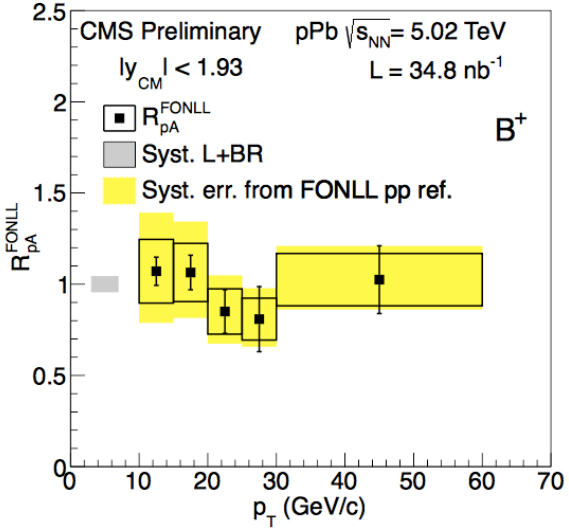


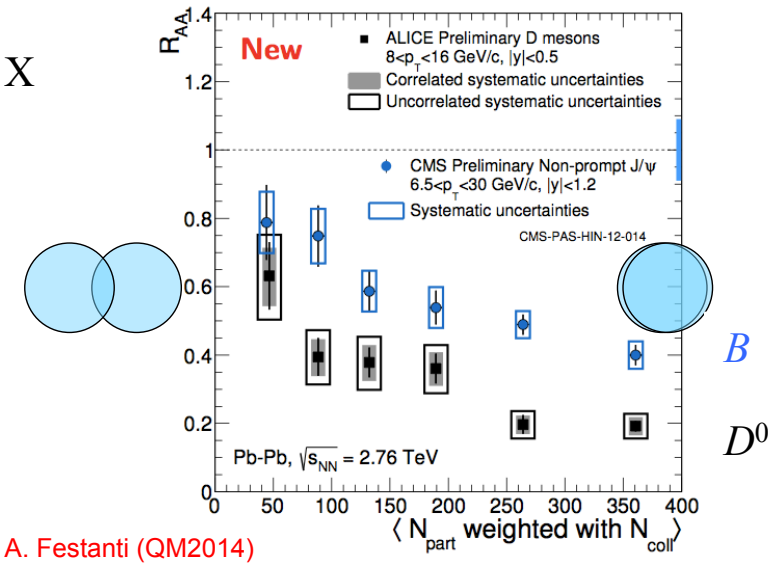
Pb-Pb collisions, $B \rightarrow e^-$ X



CMS

p-Pb collisions, $B \rightarrow J/\psi$ X





A. Festanti (QM2014)

- First clear indication of: $R_{AA}^{B} > R_{AA}^{D}$

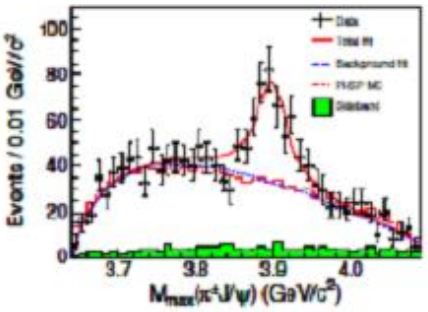
2. XYZ Quarkonium

BESIII Results for X/Y/Z

Kornicer, Lyu

$Z_c(3900)^+$

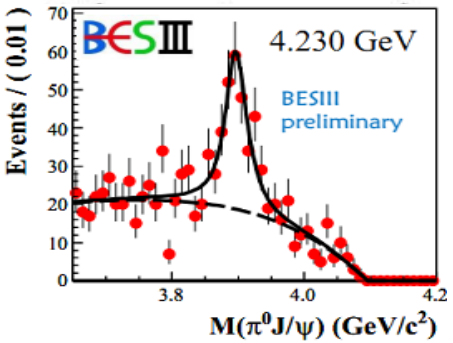
m= 3899.0 ±3.6±4.9



$e^+e^- \to \pi^-\pi^+ J/\psi$

$Z_c(3900)^0$

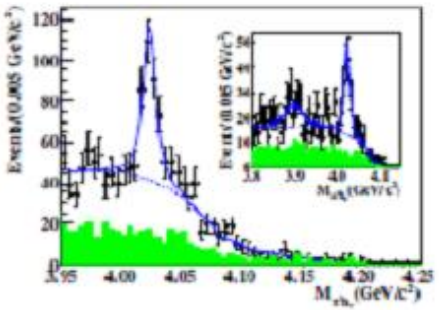
m= 3894.8 ±2.3±2.7



$e^+e^- \to \pi^0\pi^0 J/\psi$

$Z_c(4020)^+$

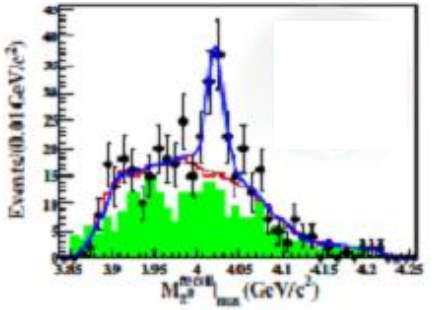
m= 4022.9 ±0.8±2.7



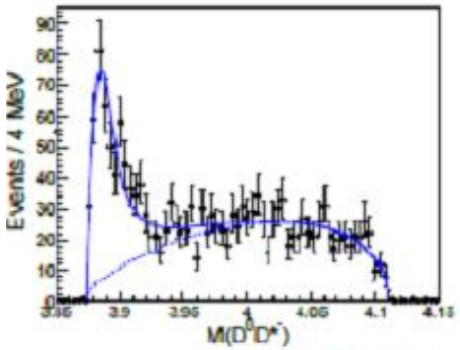
$e^+e^- \to \pi^-\pi^+ h_c$

$Z_c(4020)^0$

m= 4023.9 ±2.2±3.8



$e^+e^- \to \pi^0\pi^0 h_c$

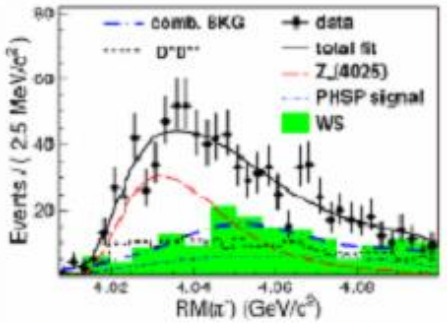


$e^+e^- \to \pi^- (D\bar{D}^*)^+$

m= 3884.3 ±1.2 ±1.5

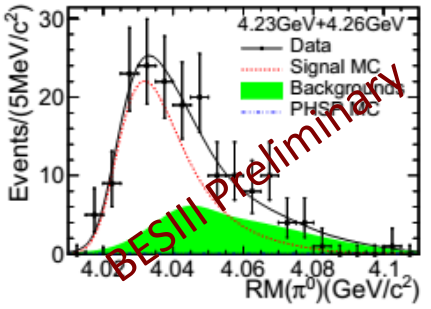
BESIII

soon …



$e^+e^- \to \pi^- (D^*\bar{D}^*)^+$

m= 4026.3 ±2.6±3.7



$e^+e^- \to \pi^0 (D^*\overline{D^*})^0$

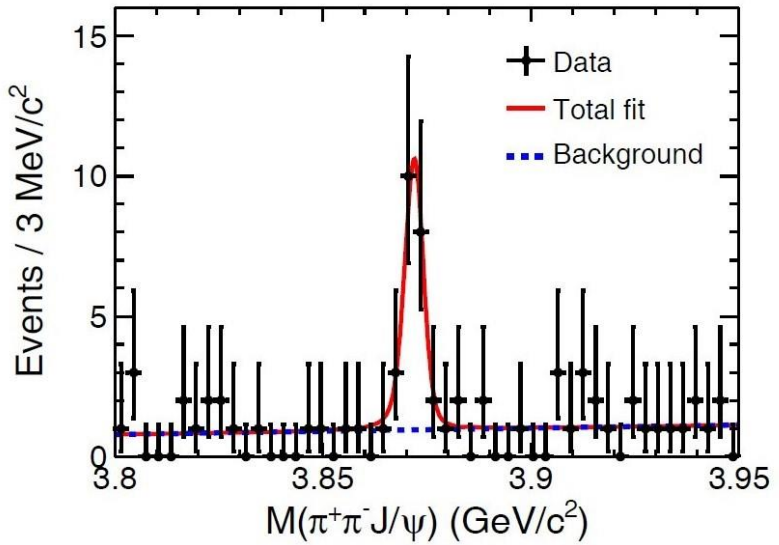
m= 4025.5 $^{+2.0}_{-4.7}$±3.1

BESIII Results for X/Y/Z

$e^+e^- \to \gamma\, \pi^+\pi^-\, J/\psi$ reconstructed at E_{CM} = 4.2-4.6 GeV

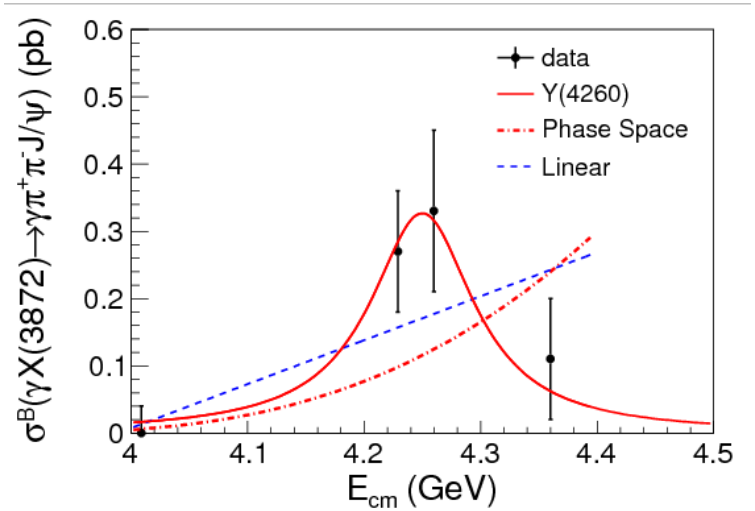
X(3872) → ππ J/ψ

M = **3871.9 ± 0.7 ± 0.2** MeV/c²



Suggestive of

Y(4260) → γ X(3872)



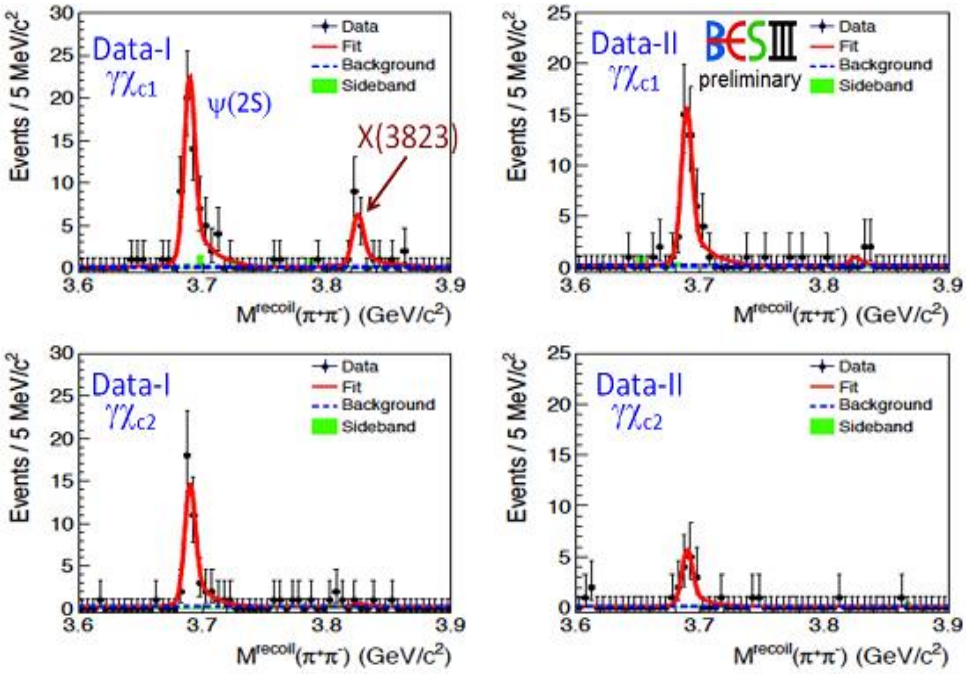
$$\frac{B(Y(4260)\to \gamma X(3872))}{B(Y(4260)\to \pi^+\pi^- J/\psi)} \approx 0.1$$

BESIII Results for X/Y/Z

Kornicer, Lyu

$e^+e^- \to \gamma\,\pi^+\pi^-\chi_c$ reconstructed at E_{CM} = 4.2-4.6 GeV

Reconstruct $\chi_c \to \gamma\, J/\psi \to \gamma\, l^+l^-$
look for $\pi\pi$ recoil



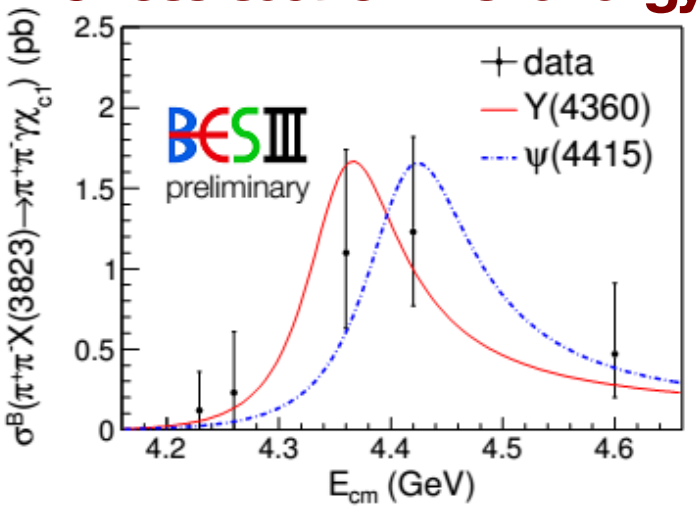
$M = 3821.7 \pm 1.3 \pm 0.7$ MeV, significance 6.7σ

$\Gamma < 16$ MeV at 90% C.L.

X(3823) candidate consistent with
$\psi(1^3D_2) \to \gamma\,\chi_c$

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_c$

Cross-section v.s. energy



Line shape consistent with both Y(4260) & Y4360

Belle Results for X/Y/Z

Wang

Search for X, $Z \to \eta_c\,\pi(\pi)$ decays
$\Rightarrow$ nothing seen

Upper limits of $\mathcal{B}(B^{\pm} \to K^{\pm} X(\to \eta_c h)) \ (\times 10^{-5})$

	Decay mode	Yield	UL
$X_1(3872)$	$\eta_c\pi^+\pi^-$	17.9 ± 16.5	3.0
	$\eta_c\omega$	6.0 ± 12.5	6.9
$X(3730)$	$\eta_c\eta(\gamma\gamma)$	13.8 ± 9.9	4.6
	$\eta_c\eta(\pi^+\pi^-\pi^0)$	1.4 ± 1.0	
$X(3730)$	$\eta_c\pi^0$	-25.6 ± 10.4	5.7
$X(4014)$	$\eta_c\eta(\gamma\gamma)$	8.9 ± 11.0	3.9
	$\eta_c\eta(\pi^+\pi^-\pi^0)$	1.3 ± 1.6	
$X(4014)$	$\eta_c\pi^0$	-8.1 ± 13.2	1.2

Upper limits of branching fractions at 90% C.L.

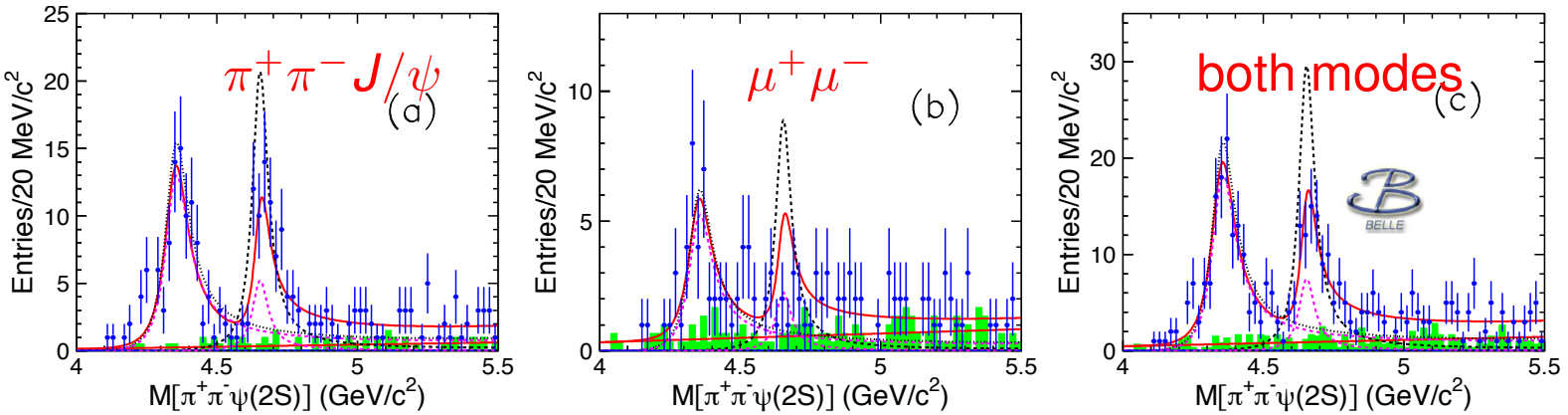
Resonance	Decay mode	$\mathcal{B}(B \to K + R)$
$Z^0(3900)$	$\eta_c\pi^+\pi^-$	4.7×10^{-5}
$Z^0(4020)$		1.6×10^{-5}
$X(3915)$	$\eta_c\eta$	3.3×10^{-5}
	$\eta_c\pi^0$	1.8×10^{-5}

Belle Results for X/Y/Z

Wang

NEW

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$: $Amp = BW_1 + e^{i\phi} \cdot BW_2$.



Parameters	Solution I	Solution II
$M_{Y(4360)}$ (MeV/c^2)	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$ (MeV)	$103 \pm 9 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV)	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$ (MeV/c^2)	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$ (MeV)	$68 \pm 11 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV)	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ (°)	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

$\chi^2/ndf = 18.7/21$.

- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.

including Y(4260) in the fit gives 4 solutions, changes Y(4360), Y(4660) masses/widths by 8-20 MeV

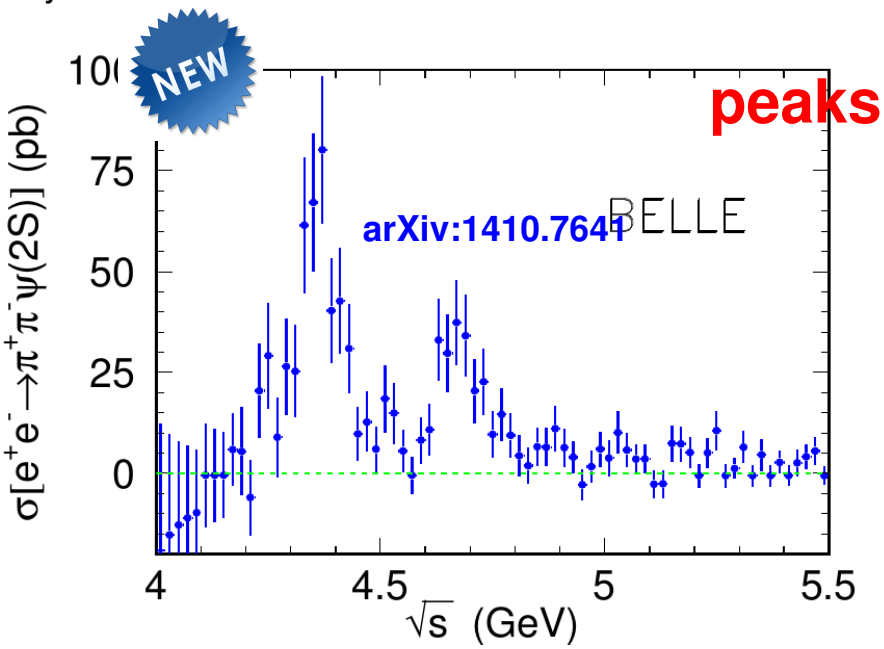
Belle Results for X/Y/Z

Wang

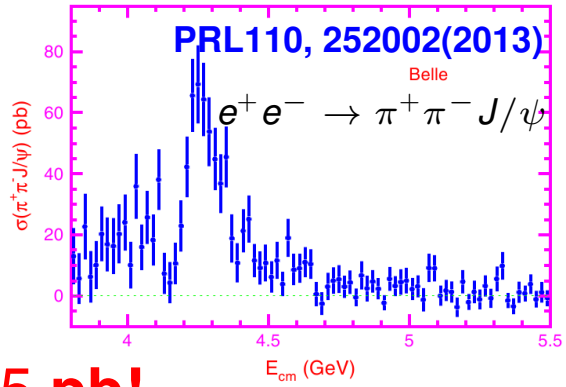
$e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section is calculated with

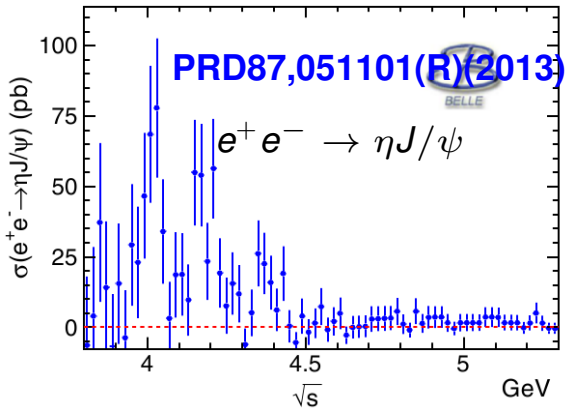
$$\sigma_i = \frac{n_i^{\rm obs} - n_i^{\rm bkg}}{\mathcal{L}_i \sum_{j=1}^{2} \varepsilon_{ij}\mathcal{B}_j},$$

where *i* indicates the mass bin and *j* indicates the $\psi(2S)$ decay mode.



Other cross sections from ISR:





The $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ at $Y(4260)$, $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ at $Y(4360)$ and $\sigma(e^+e^- \to \eta J/\psi)$ at $\psi(4040)$ are almost the same!!!

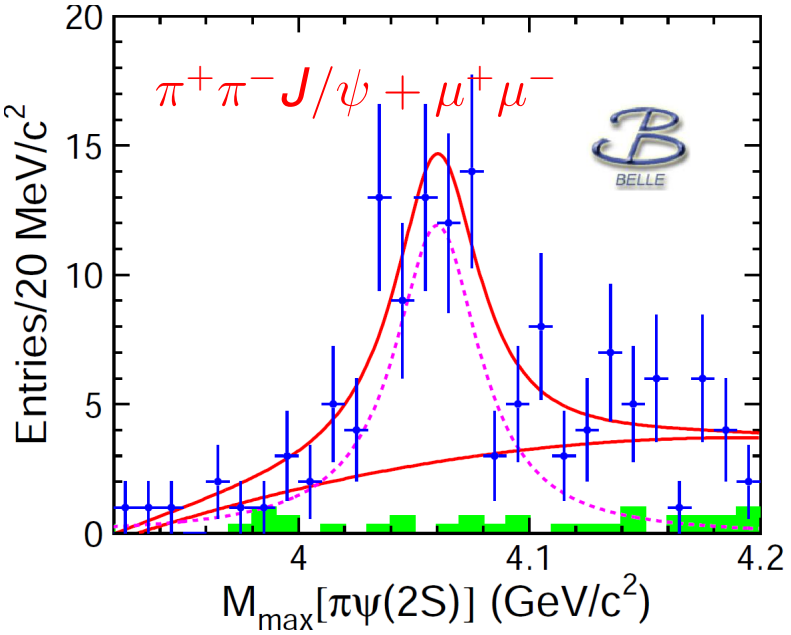
Belle Results for X/Y/Z

Wang

Search for structure in $Y(4360) \to \psi(2S)\pi^+\pi^-$ decays $\Rightarrow Z_c(4050)$?

An unbinned maximum-likelihood fit is performed on the distribution of $M_{\max}(\pi^{\pm}\psi(2S))$, the maximum of $M(\pi^+\psi(2S))$ and $M(\pi^-\psi(2S))$, simultaneously with both modes.

NEW



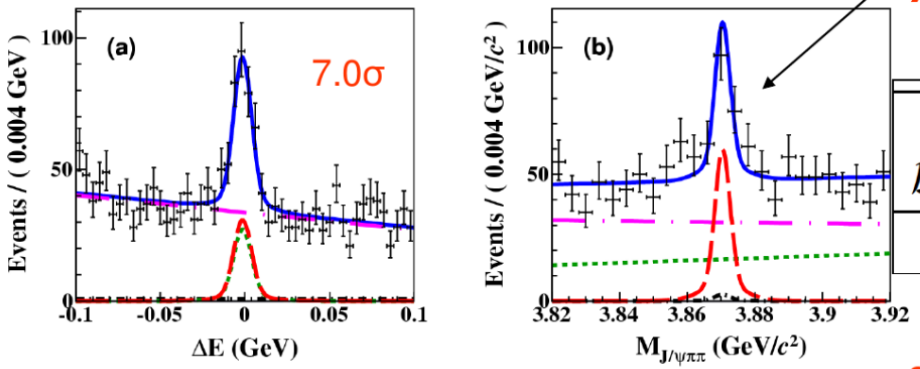
- $M = (4054 \pm 3(\text{stat.}) \pm 1(\text{syst.}))$ MeV/c^2
- $\Gamma = (45 \pm 11(\text{stat.}) \pm 6(\text{syst.}))$ MeV
- The significance is 3.5σ.

No structure seen in $Y(4660) \to \psi(2S)\pi^+\pi^-$ decays

Belle Results for X/Y/Z

Wang, Bhardwaj

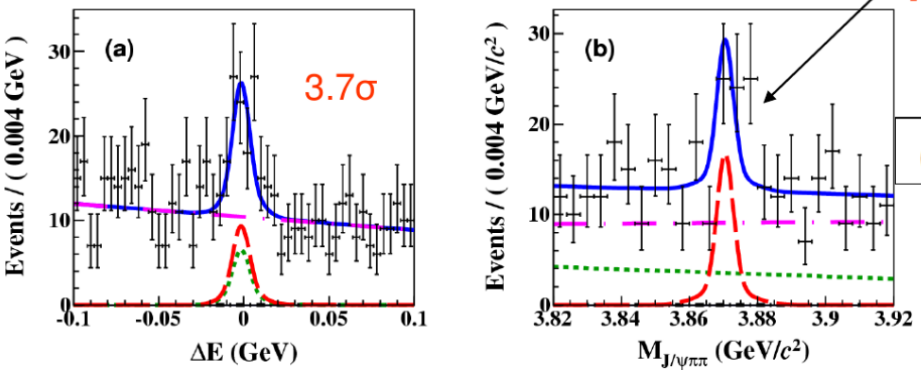
$B^0 \to X(3872)K^+\pi^-$



116±19
X(3872)

$$\frac{\mathcal{B}(B \to X(3872)K\pi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{(7.9 \pm 1.3 \pm 0.4) \times 10^{-6}}$$

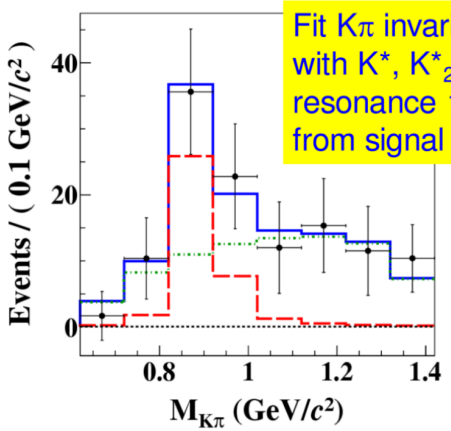
$B^+ \to X(3872)K_S\pi^+$



35±10
X(3872)

$$(10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$$

$$\frac{\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to X(3872)K^+\pi^-)} = 0.34 \pm 0.09(stat.) \pm 0.02(syst.).$$



Fit Kπ invariant mass with K*, K*$_2$ and Non-resonance terms from signal MC

Quarkonia Studies at ATLAS

Yabsley

Production cross-sections:

J/ψ differential, prompt & non-prompt	NPB 850, 387 (2011)
$\Upsilon(1S)$ fiducial	PLB 705, 9 (2011)
$\Upsilon(nS)$ differential	PRD 87, 052004 (2013)
$\chi_{c1,c2}$ differential, prompt & non-prompt	JHEP 07 (2014) 154
$\psi(2S)$ differential, prompt & non-prompt	JHEP 09 (2014) 079

Spectroscopy:

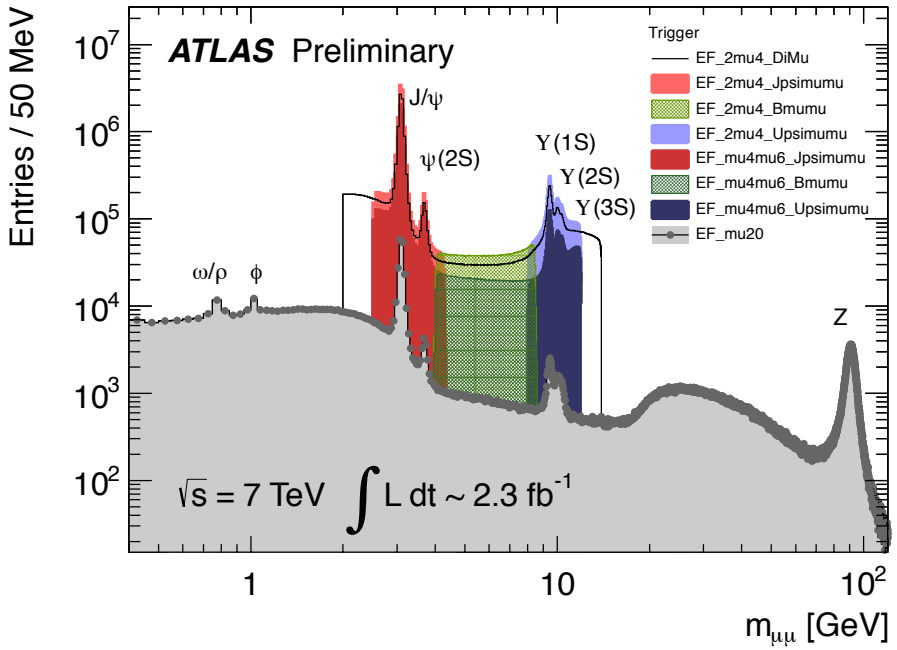
$\chi_{bJ}(nP)$; $\chi_{bJ}(3P)$ first observation	PRL 108, 152001 (2012)
$X_b \to \pi^+\pi^-\Upsilon(1S)$ search	PLB 740, 199 (2015)

Associated production:

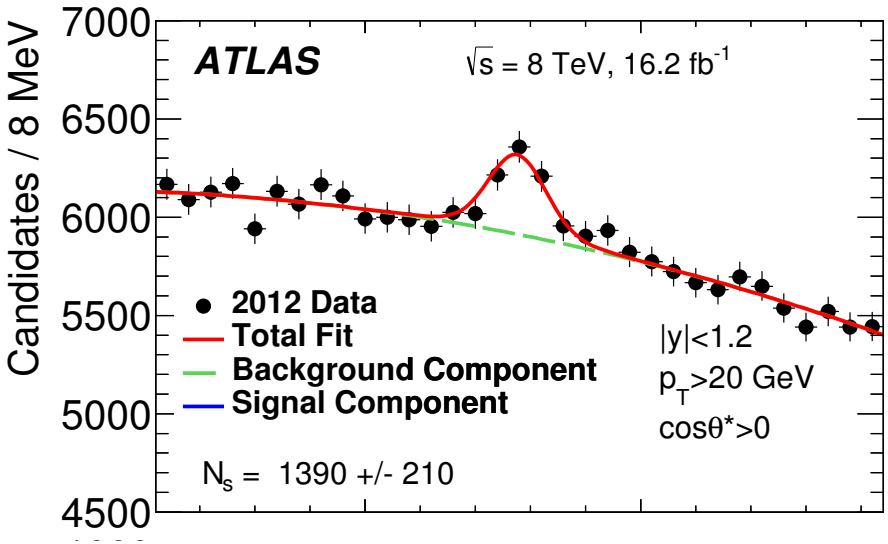
prompt J/ψ in association with $W^\pm$	JHEP 04 (2014) 172
prompt J/ψ in association with Z^0	`arXiv:1412.6428` $\to$ EPJC

Quarkonia Studies (X_b) at ATLAS

Yabsley



Combine Y with $\pi\pi$, plot mass spectrum in 2 x 2 x 2 bins of (|y|, p_T, cosθ):*



- excludes $R = \sigma\mathcal{B}/(\sigma\mathcal{B})_{\Upsilon(2S)} = 6.56\%$ throughout search range
  - *cf.* $\pi\pi\psi$ [CMS, *JHEP* **04** (2013) 154]: $(\sigma\mathcal{B})_{X(3872)}/(\sigma\mathcal{B})_{\psi(2S)} = 6.56\%$
  - if X_b exists, relative production σ/σ_{2S} or branching $\mathcal{B}/\mathcal{B}_{2S}$, or both, are weaker than for $X(3872)$
- an X_b is not in general a carbon copy of the $X(3872)$:
  - $X(3872)$ is within sub-MeV resolution of $D^0\overline{D}^{*0}$ threshold
  - even a molecular X_b is bound by tens of MeV

3. Hadronic Decays

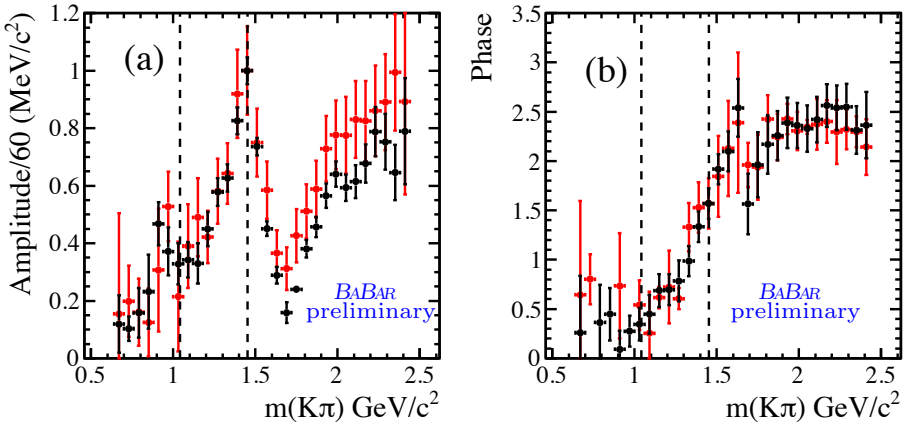
Dalitz Plots Analyses @ BaBar

Palano

- $\eta_c \to K_S K^+ \pi^-$
- $\eta_c \to K^+ K^- \pi^0$
- $J/\psi \to \pi^+ \pi^- \pi^0$
- $J/\psi \to K^+ K^- \pi^0$

Model-independent Dalitz plot analysis: fit independent magnitudes and phases in 30 bins of mass

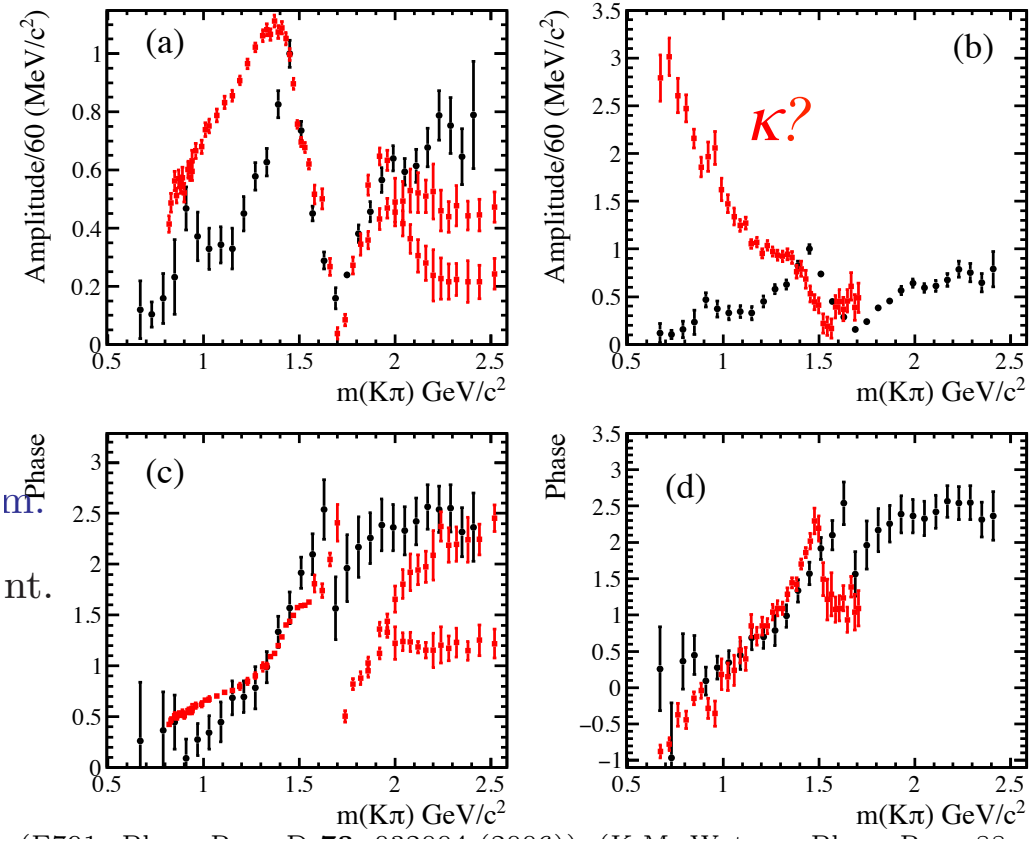
$\eta_c \to K_S K^+ \pi^-$ $\eta_c \to K^+ K^- \pi^0$



⇒ *good agreement between samples, clear $K^{*0}(1430)$ resonance*

...but very different behavior than that measured with other data:

LASS ($K\pi$ scatt.) *E791 ($D^+ \to K^-\pi^+\pi^+$)*



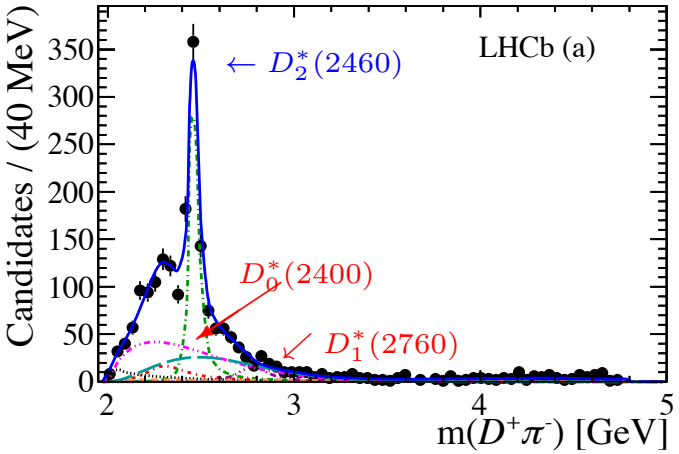
Dalitz Plots Analyses @ LHCb

Palano

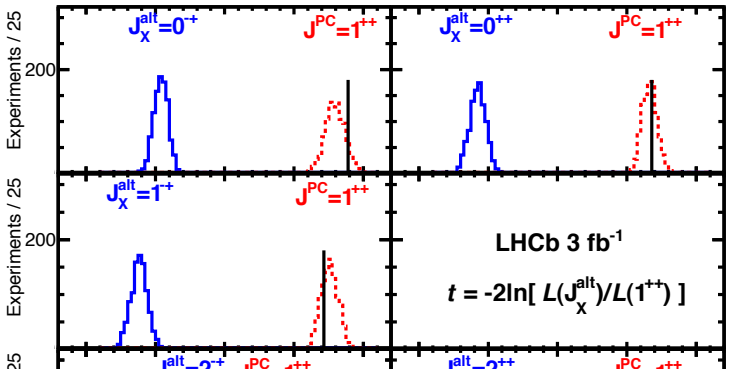
- $B^- \to D^+ K^-\pi^-$
- $B^0 \to D^0 \pi^+\pi^-$
- $B^0 \to D^0 K^+\pi^-$
- $B_s \to D^0 K^-\pi^+$

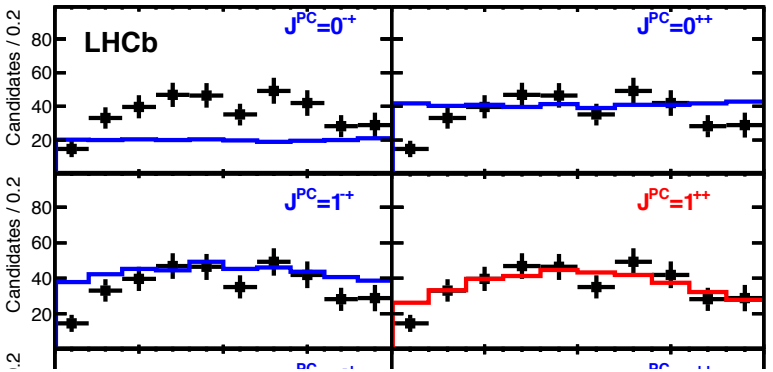
□ $D^+\pi^-$ fit projection (arXiv:1503.02995).

Resonance	Fit fraction
$D_0^*(2400)^0$	$8.3 \pm 2.6 \pm 0.6 \pm 1.9$
$D_2^*(2460)^0$	$31.8 \pm 1.5 \pm 0.9 \pm 1.4$
$D_1^*(2760)^0$	$4.9 \pm 1.2 \pm 0.3 \pm 0.9$
S-wave nonresonant	$38.0 \pm 7.4 \pm 1.5 \pm 10.8$
P-wave nonresonant	$23.8 \pm 5.6 \pm 2.1 \pm 3.7$
$D_v^*(2007)^0$	$7.6 \pm 2.3 \pm 1.3 \pm 1.5$
B_v^*	$3.6 \pm 1.9 \pm 0.9 \pm 1.6$



$B^+ \to X(3872)\, K^+,\ X(3872) \to J/\psi\, \rho^0$ *1011 events, 80% purity, fit decay distrubution for different spin-parity assignments* ⇒ $J^{PC} = 1^{++}$





Other Hadronic Decays

SCS decays:

Wiedenkaff
Muramatsu

BESIII

Decay mode	This work	PDG value
$D^+ \to \omega\pi^+$	$(2.74 \pm 0.58 \pm 0.17) \times 10^{-4}$	$< 3.4 \times 10^{-4}$ at 90% C.L.
$D^0 \to \omega\pi^0$	$(1.05 \pm 0.41 \pm 0.09) \times 10^{-4}$	$< 2.6 \times 10^{-4}$ at 90% C.L.
$D^+ \to \eta\pi^+$	$(3.13 \pm 0.22 \pm 0.19) \times 10^{-3}$	$(3.53 \pm 0.21) \times 10^{-3}$
$D^0 \to \eta\pi^0$	$(0.67 \pm 0.10 \pm 0.05) \times 10^{-3}$	$(0.68 \pm 0.07) \times 10^{-3}$

- $BF(D_S^+ \to \eta' X)$ = (8.8±1.8±0.5)%, consistent with
  PDG = (11.7±1.7±0.7)% within ~1σ.
- $BF(D_S^+ \to \eta'\rho^+)/BF(D_S^+ \to K^+K^-\pi^+)$ = 1.04±0.25±0.07 or
  $BF(D_S^+ \to \eta'\rho^+)$ = (5.8±1.4±0.4)%
  PDG = (12.5±2.2)% from PDG,

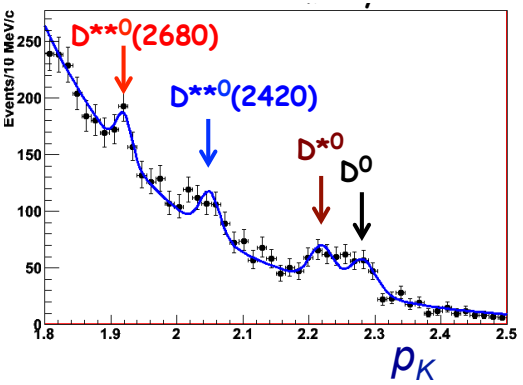
$$BF_{data}(D^0 \to K^0_S K^+ K^-) = (4.622 \pm 0.045\,(\text{stat.}) \pm 0.181\,(\text{sys.}))$$

Sokoloff

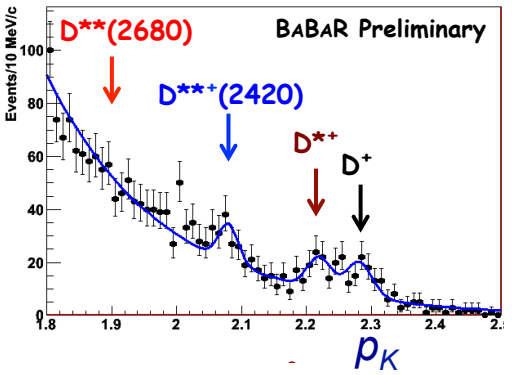
Fully reconstructed B tag, plot p of recoil K :

see $B^- \to D^{**0}(2680)\,K^-$
but no $B^0 \to D^{**+}(2680)K^-$

B^- sample:



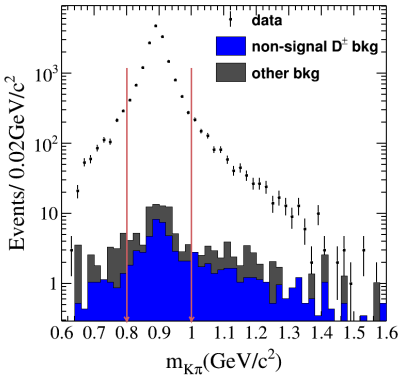
B^0 sample:



4. Semileptonic/leptonic decays

Semileptonic Decays

An, Ma



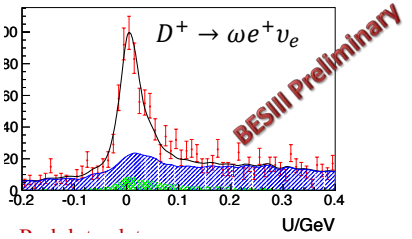
- In the study of $D^+ \to K^-\pi^+e^+\upsilon_e$:
  - Branching fractions are measured:
    $\mathrm{Br}(D^+ \to K^-\pi^+e^+\nu_e) = (3.71 \pm 0.03 \pm 0.09)\%$
    $\mathrm{Br}(D^+ \to K^-\pi^+e^+\nu_e)_{[0.8,1]} = (3.33 \pm 0.03 \pm 0.08)\%$
  - Amplitude analysis is applied:
    - Fractions of the $K\pi$ components are analyzed. S-wave contribution is observed to be $(6.05 \pm 0.22 \pm 0.18)\%$.

$U = E_{miss} - |\vec{p}_{miss}|, \quad E_{miss} = E_{beam} - E_{\omega(\phi)} - E_e$

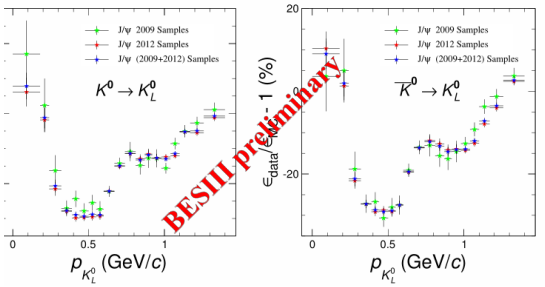
$\vec{P}_{miss} = -\vec{P'}_{tag} - \vec{P}_{\omega(\phi)} - \vec{P}_e, \quad \vec{P'}_{tag} = \vec{P}_{tag}\sqrt{E^2_{beam} - m^2_D}$

- In the study of $D^+ \to \omega(\phi)e^+\upsilon_e$:
  - Branching fractions or upper limits are provided:
    $\mathrm{Br}(D^+ \to \omega e^+\nu_e) = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$
    $\mathrm{Br}(D^+ \to \phi e^+\nu_e) < 1.3 \times 10^{-5}$ (@90% C. L.)
  - Form factor parameters in $D^+ \to \omega e^+\upsilon_e$ are first measured:
    $r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06; \quad r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$

U distribution for the $D^+ \to \omega(\phi)e^+\upsilon_e$ decay:



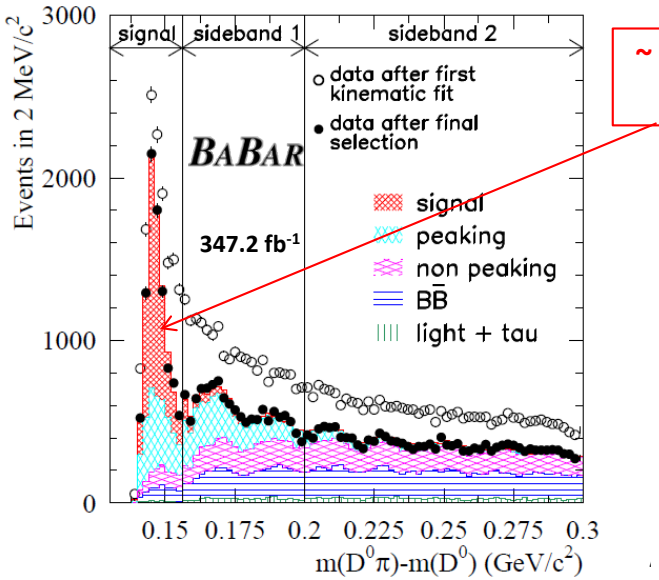
- In the study of $D^+ \to K_L e^+\upsilon_e$:
  - Branching fractions and CP assymetry are measured:
    $\bar{B}(D^+ \to K_L e^+\nu_e) = (4.482 \pm 0.027 \pm 0.103)\%, \quad A_{CP}^{D^+ \to K_L e^+\nu_e} = (-0.59 \pm 0.60 \pm 1.50)$
  - Form factor related parameters are also measured:
    $f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$, $r_1 \equiv a_1/a_0 = 1.91 \pm 0.33 \pm 0.24$



Semileptonic Decays

Oyanguren

- **Signal events selected in $\delta m = m_{D^{*+}} - m_{D^0}$**



~ 10000 candidates
50 % background

$$R_D = \frac{\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)_{data}}{\mathcal{B}(D^0 \to K^- \pi^+)_{data}} = 0.0702 \pm 0.0017 \pm 0.0023$$

Using the world average for BR($D^0 \to K^-\pi^+$):

$$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (2.770 \pm 0.068 \pm 0.092 \pm 0.037) \times 10^{-3}$$

PDG 2014 : BR($D^0 \to \pi e^+ \nu$) = (2.89 ± 0.08) x 10^{-3}

from z expansion normalization:

$$|V_{cd}| f^{\pi}_{+,D}(0) = 0.1374 \pm 0.0038_{\text{stat.}} \pm 0.0022_{\text{syst.}} \pm 0.0009_{\text{ext.}}$$

$$|V_{cd}| = |V_{us}| = 0.2252 \pm 0.0009 \longrightarrow f^{\pi}_{+,D}(0) = 0.610 \pm 0.017 \pm 0.010 \pm 0.005$$

$$f^{\pi}_{+,D}(0) = 0.666 \pm 0.029 \longrightarrow |V_{cd}| = 0.206 \pm 0.007_{\text{exp.}} \pm 0.009_{\text{LQCD}}$$

Lattice average (arXiv:1310.8555)

$$\frac{d\Gamma(B \to \pi \ell \nu)/dw_B}{d\Gamma(D \to \pi \ell \nu)/dw_D} = \left|\frac{V_{ub}}{V_{cd}}\right|^2 \left(\frac{M_B}{M_D}\right) \left|\frac{f_+^{B\to\pi}}{f_+^{D\to\pi}}\right|^2$$

1) From Lattice

2) From a phenome-nological model

$$|V_{ub}| = (3.65 \pm 0.18 \pm 0.40) \times 10^{-3}$$

Experimental

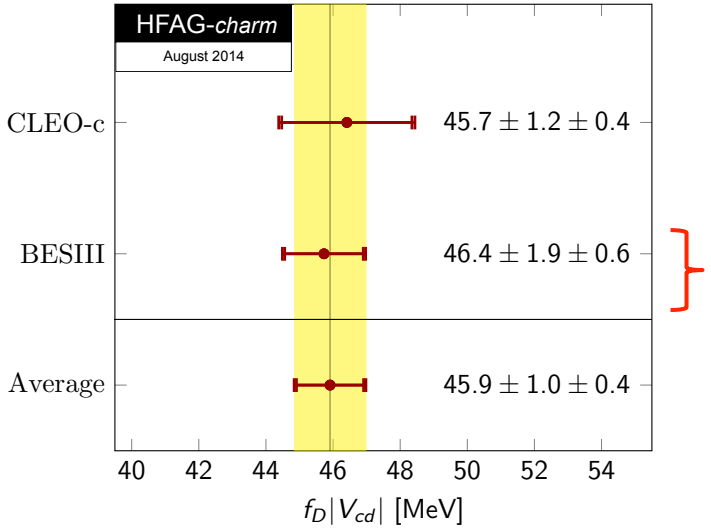
Form factor ratio = 1.8 ± 0.2

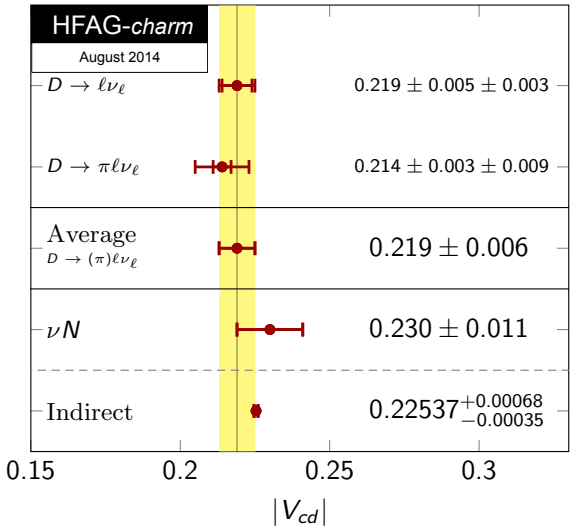
Leptonic Decays

Eidelman Ma

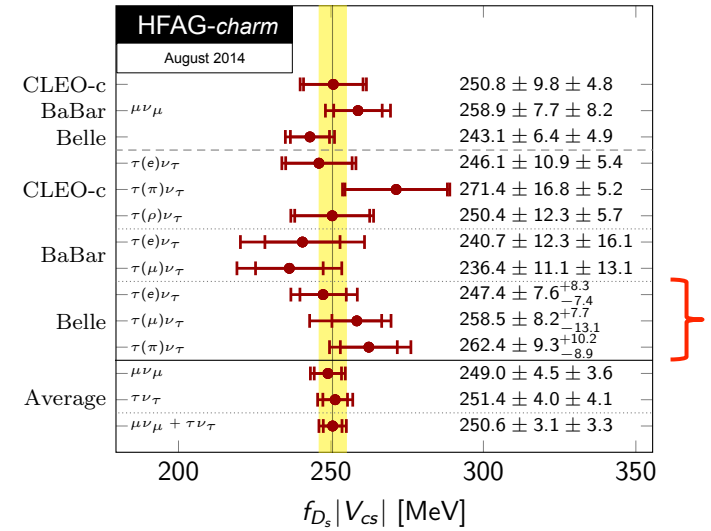
http://www.slac.stanford.edu/xorg/hfag/charm/index.html:

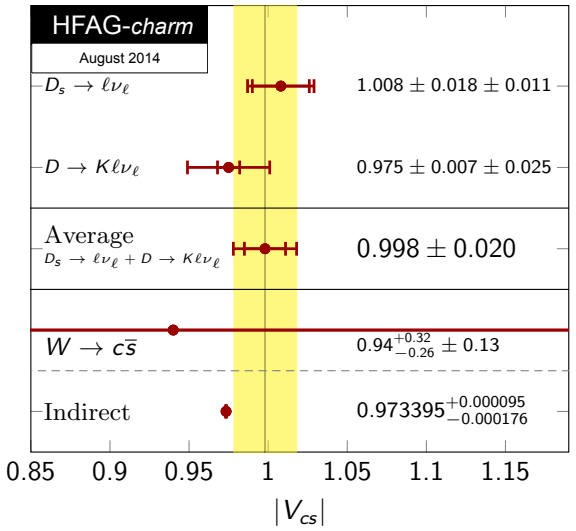
$D^+ \to e^+\nu$
$D^+ \to \mu^+\nu$
$D^+ \to \tau^+\nu$





$D^+_s \to e^+\nu$
$D^+_s \to \mu^+\nu$
$D^+_s \to \tau^+\nu$





5. Rare/forbidden/radiative decays

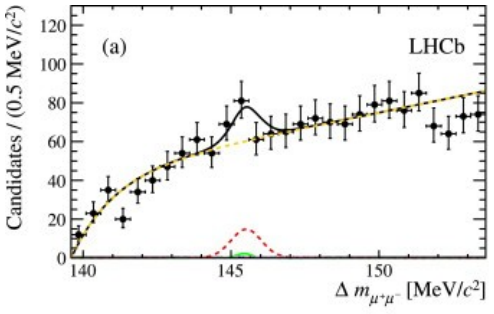
LHCb Rare/forbidden Decays

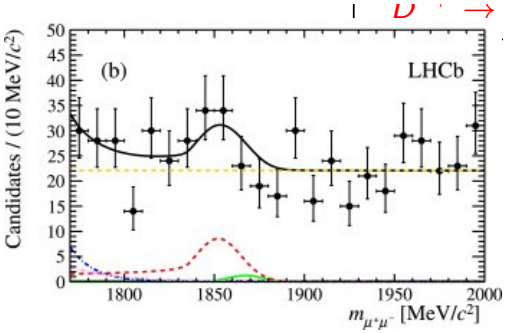
Gobel, Vacca

$D^0 \to \mu^+\mu^-$

$\mathcal{B} < 6.2 \times 10^{-9}$ (90% CL)

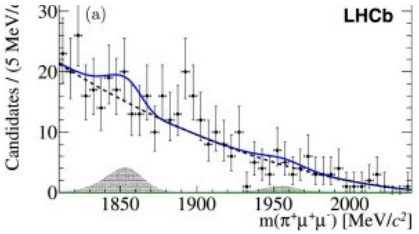
[~100x above SM]

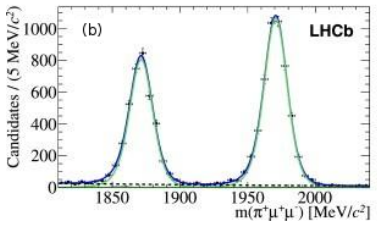


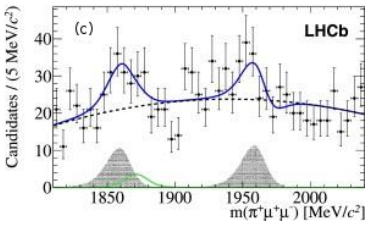


$D^+_{(s)} \to \pi^+\mu^+\mu^-$

[~10x > NP]







$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3(8.3) \cdot 10^{-8}$ at 90%(95%) CL

$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1(4.8) \cdot 10^{-7}$ at 90%(95%) CL

$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5) \cdot 10^{-8}$ at 90%(95%) CL

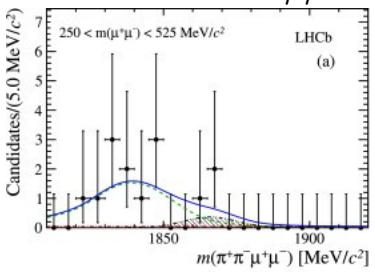
$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2(1.4) \cdot 10^{-7}$ at 90%(95%) CL

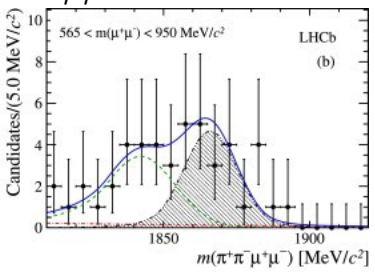
$D^0 \to \pi^+\pi^-\mu^+\mu^-$

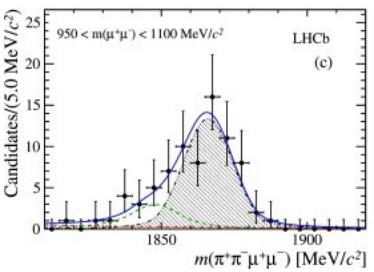
$\mathcal{B} < 5.5 \times 10^{-7}$ (90% CL)

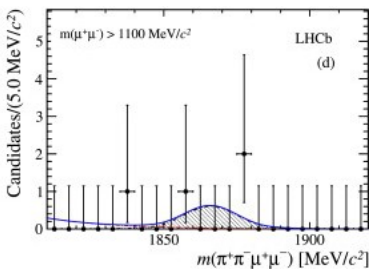
[~100x above SM]

$\Delta m = m_{\pi\pi\mu\mu\pi} - m_{\pi\pi\mu\mu}$:







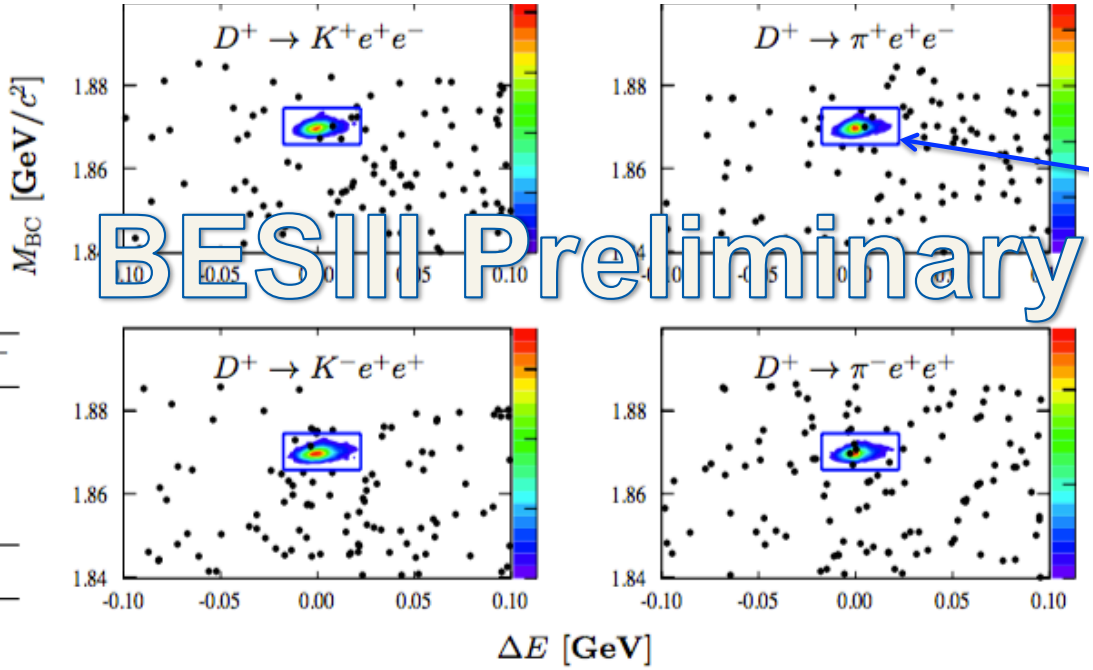


BESIII Rare/forbidden Decays

Zhao

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

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



$\mathcal{B}(D^+ \to) \setminus [\times 10^{-6}]$	$K^+e^+e^-$	$K^-e^+e^+$	$\pi^+e^+e^-$	$\pi^-e^+e^+$
CLEO	3.0	3.5	5.9	1.1
Babar	1.0	0.9	1.1	1.9
PDG	1.0	0.9	1.1	1.1
This work	1.2	0.6	0.3	1.2

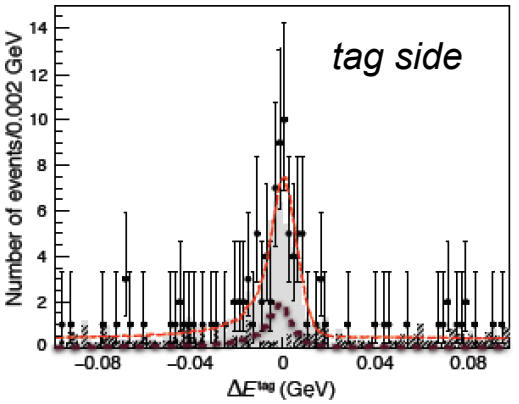
world's best

$D^0 \to \gamma\gamma$ *(2.9 fb^{-1})*

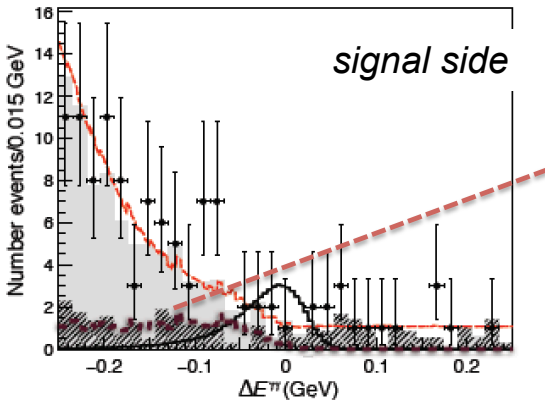
$\mathcal{B} < 3.8 \times 10^{-6}$ (90% CL)

world's best by BaBar (2012):
$\mathcal{B} < 2.2 \times 10^{-6}$ (90% CL)

Belle result this summer



arXiv: 1505.03087



6. T Violation

T Violation @ LHCb

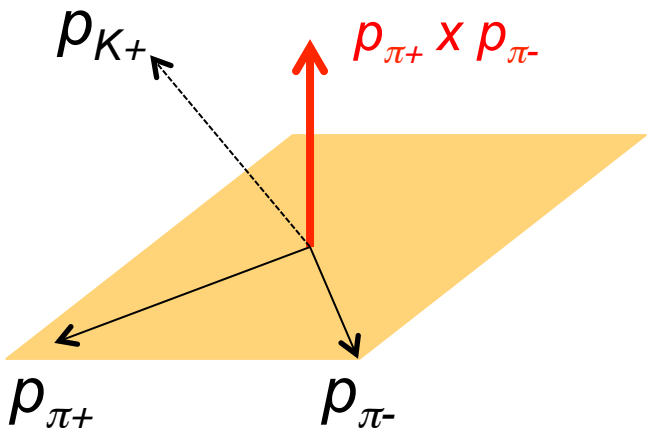
Martinelli (see also Bevan)

$D^0 \to K^+K^-\pi^+\pi^-$ $\quad C_T = p_{K+}{}^* (p_{\pi+} \times p_{\pi-})$

$\bar{D}^0 \to K^+K^-\pi^+\pi^-$ $\quad \bar{C}_T = p_{K-}{}^* (p_{\pi-} \times p_{\pi+})$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma}$$

$$\bar{A}_T = \frac{\bar{\Gamma}(-\bar{C}_T > 0) - \bar{\Gamma}(-\bar{C}_T < 0)}{\bar{\Gamma}}$$



T-violating asymmetry:

$$a_{CP}^{T-\text{odd}} = \frac{1}{2}(A_T - \bar{A}_T)$$

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

T-violating asymmetries in D0 decay-rates

Year	Experiment	T-violating Asymmetry in the decay mode D0 to K+K-π+π-	$A_{T\ viol.} = (A_T - \bar{A}_T)/2$
2014	LHCb	R. Aaij et al. (LHCb Collab.), arXiv:1408.1299.	+0.0018 ± 0.0029 ± 0.0004
2010	BABAR	P. del Amo Sanchez et al. (BABAR Collab.), Phys. Rev. D81, 111103 (2010).	+0.0010 ± 0.0051 ± 0.0044
2005	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).	+0.010 ± 0.057 ± 0.037
.	.	COMBOS average	+0.0017 ± 0.0027

T-violating asymmetries in D+ decay-rates

Year	Experiment	T-violating Asymmetry in the decay mode D+ to K0sK+π+π-	$A_{T\ viol.} = (A_T - \bar{A}_T)/2$
2011	BABAR	J.P. Lees et al. (BABAR Collab.), Phys. Rev. D 84, 031103 (2011).	-0.0120 ± 0.0100 ± 0.0046
2005	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).	+0.023 ± 0.062 ± 0.022
.	.	COMBOS average	-0.0110 ± 0.0109

T-violating asymmetries in Ds+ decay-rates

Year	Experiment	T-violating Asymmetry in the decay mode Ds+ to K0sK+π+π-	$A_{T\ viol.} = (A_T - \bar{A}_T)/2$
2011	BABAR	J.P. Lees et al. (BABAR Collab.), Phys. Rev. D 84, 031103 (2011).	-0.0136 ± 0.0077 ± 0.0034
2005	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).	-0.036 ± 0.067 ± 0.023
.	.	COMBOS average	-0.0139 ± 0.0084

T Violation @ LHCb

Martinelli

Three Measurements @ LHCb:

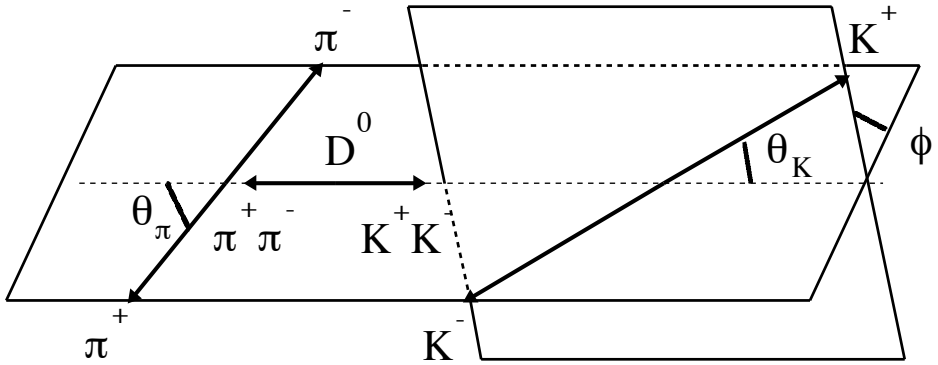
1. **Integrated**

$$a_{CP}^{T-\mathrm{odd}}(D^0) = (1.8 \pm 2.9(\mathrm{stat}) \pm 0.4(\mathrm{syst})) \times 10^{-3}$$

2. **Bins of phase-space**

No significant deviation from 0 observed

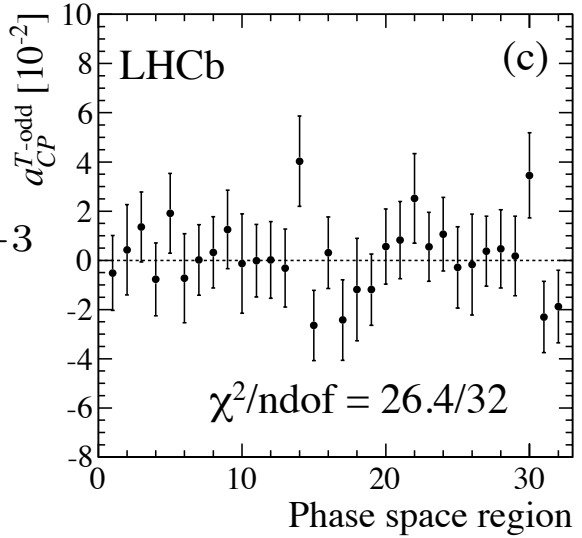
CP conservation tested with P(χ^2)=74%

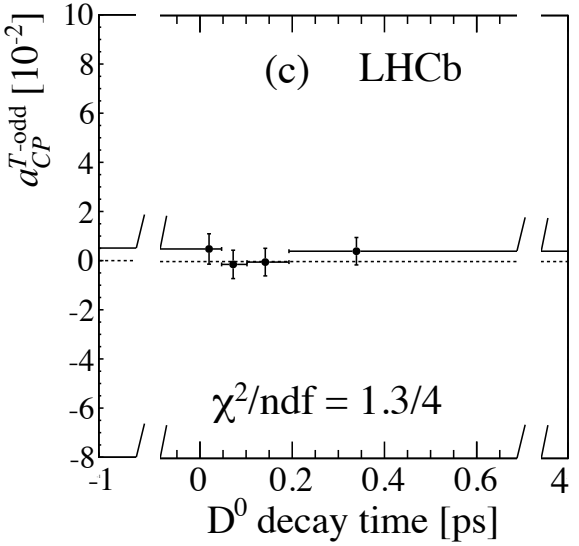


3. **Bins of D^0 decay time**

No significant deviation from 0 observed

CP conservation tested with P(χ^2)=83%





T Violation @ LHCb

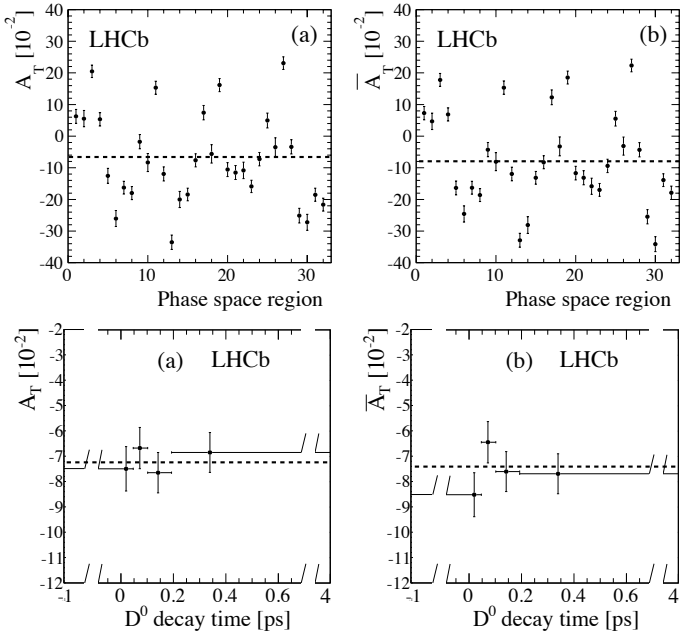
Martinelli

Local asymmetries up to 30%

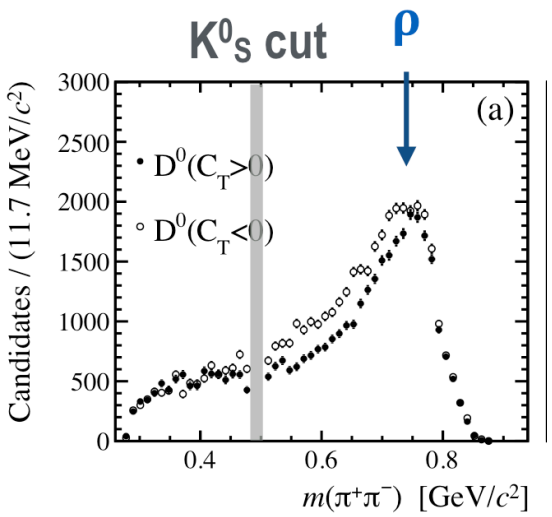
Note that A_T does not vanish:

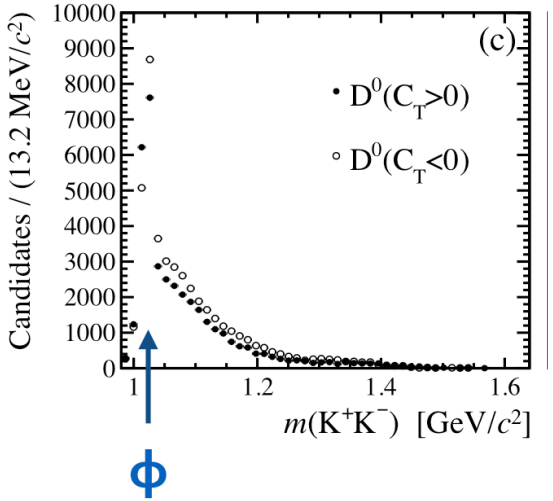
$$A_T(D^0) = (-71.8 \pm 4.1(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-3}$$
$$\bar{A}_T(D^0) = (-75.5 \pm 4.1(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-3}$$

$C_T = p_{K+}^* (p_{\pi+} \times p_{\pi-})$



But we wouldn't expect it to due to substructure:





7. Mixing and CP Violation

Charm Mixing + CP Violation

3+1 new measurements:

- *BESIII y_{CP}*
- *CDF A_Γ*
- *LHCb A_Γ*
- *CLEOc $D^0 \to \pi^+\pi\pi^0$ is CP even (Libby)*

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1 = \left(|q/p| + |p/q|\right) y \cos\phi - \left(|q/p| - |p/q|\right) x \sin\phi$$

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} = \left(|q/p| - |p/q|\right) y \cos\phi - \left(|q/p| + |p/q|\right) x \sin\phi$$

Albayrak BESIII

$$\Gamma_{CP\pm} = \Gamma(1 \pm y_{CP})$$

Branching fraction of a semileptonic decay

$$\mathcal{B}_{D_{CP\pm}\to l} \approx \mathcal{B}_{D\to l}(1 \mp y_{CP})$$

$$\longrightarrow \quad y_{CP} \approx \frac{1}{4}\left(\frac{\mathcal{B}_{D_{CP-}\to l}}{\mathcal{B}_{D_{CP+}\to l}} - \frac{\mathcal{B}_{D_{CP+}\to l}}{\mathcal{B}_{D_{CP-}\to l}}\right)$$

Decays used in the analysis

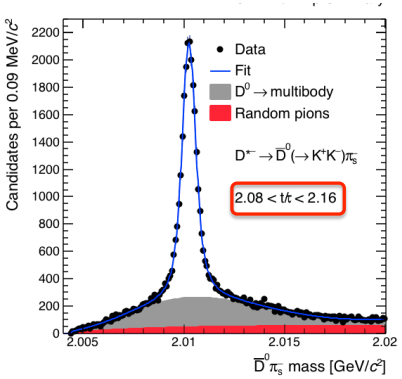
CP+	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$
CP−	$K^0_S\pi^0$, $K^0_S\omega$, $K^0_S\eta$
Semileptonic	$K^\mp e^\pm\nu$, $K^\mp\mu^\pm\nu$

$y_{CP} = (-2.0 \pm 1.3 \pm 0.7)\%$

Charm Mixing + CP Violation

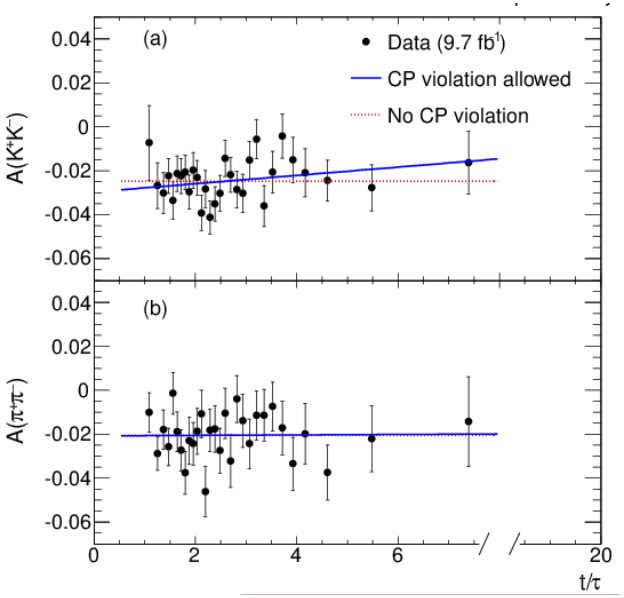
Fit for signal yield in 30 bins of decay time:

Leo



$$A_{CP}(t) = \frac{N(t)_{D^0} - N(t)_{\bar{D}^0}}{N(t)_{D^0} + N(t)_{\bar{D}^0}} \approx A(0) - \frac{t}{\tau} A_\Gamma$$

$A(0) = A_{CP}^{dir} + A_{det}$



$A_\Gamma(\pi\pi) = (-0.1 \pm 1.8(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{-3}$

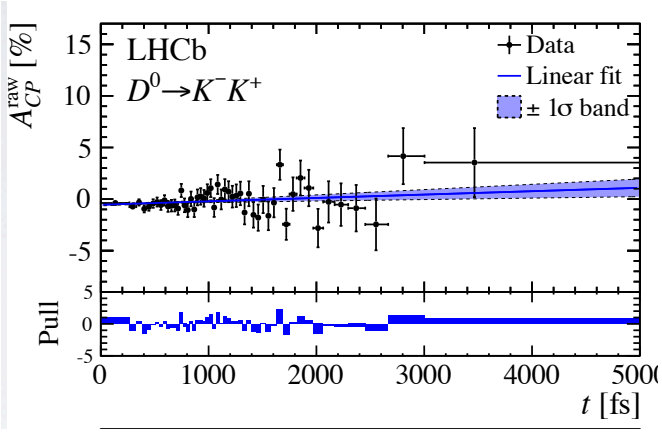
$A_\Gamma(KK) = (-1.9 \pm 1.5(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-3}$

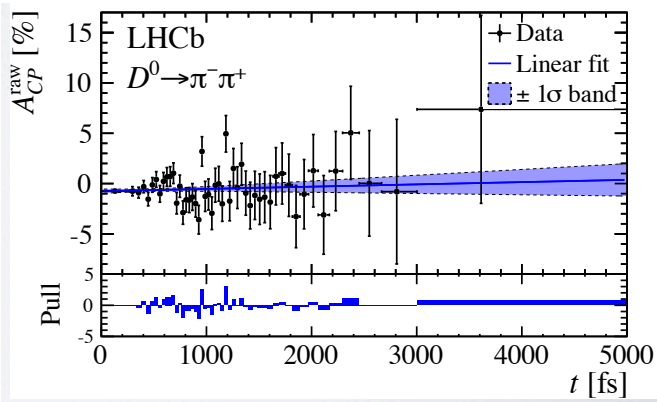
$\langle A_\Gamma \rangle = (-1.2 \pm 1.2) \times 10^{-3}$

Reichert, Naik

$$A_\Gamma(K^+K^-) = (-0.134 \pm 0.077\,^{+0.026}_{-0.034})\%$$

$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145\,^{+0.025}_{-0.033})\%$$



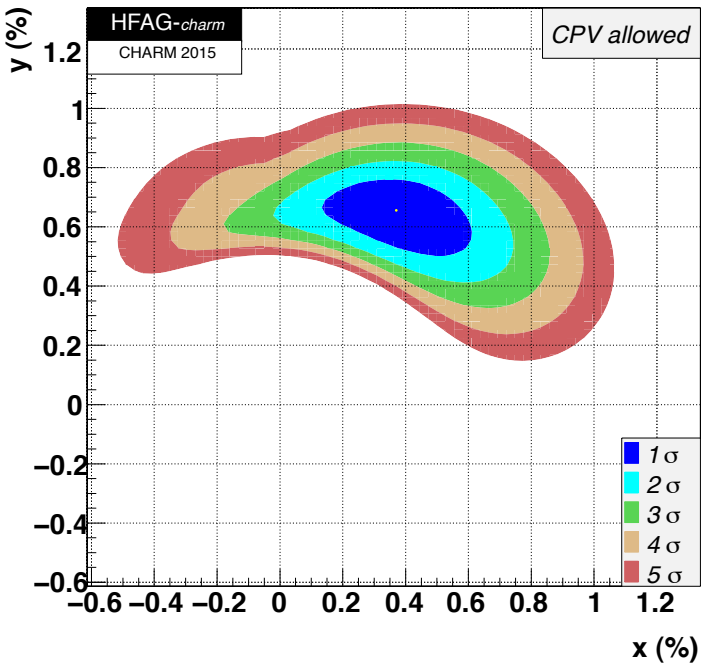


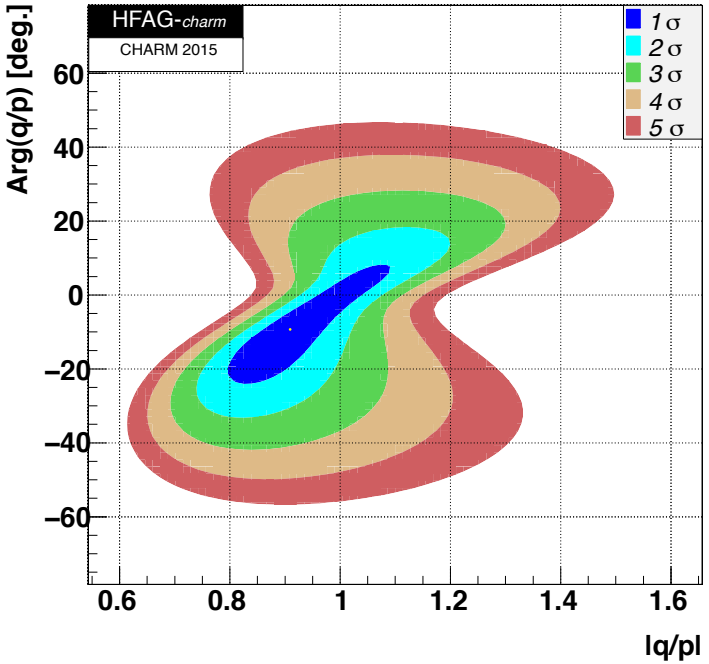
HFAG Global Fit

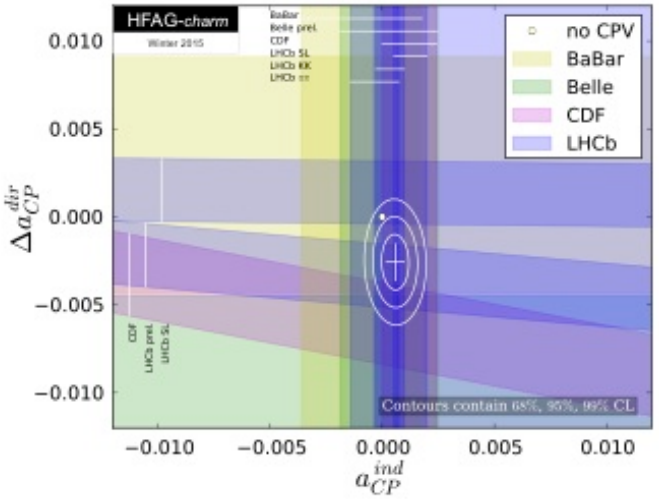
Input these results into HFAG fitter. Other results since CHARM 2013:

- *Belle 976 fb^{-1} $D^0 \to K^+\pi^-$*
- *Belle 921 fb^{-1} $D^0 \to K_S\,\pi^+\pi^-$*
- *LHCb 3 fb^{-1} $A_{CP}(KK) - A_{CP}(\pi\pi)$ with $B^0 \to D^0\mu^- X$ tagging*

Results: *(http://www.slac.stanford.edu/xorg/hfag/charm/index.html):*







$a_{CP}^{ind} = (0.058 \pm 0.040)\%$

$\Delta a_{CP}^{dir} = (-0.257 \pm 0.104)\%$

p = 0.018 of no CPV

HFAG Global Fit

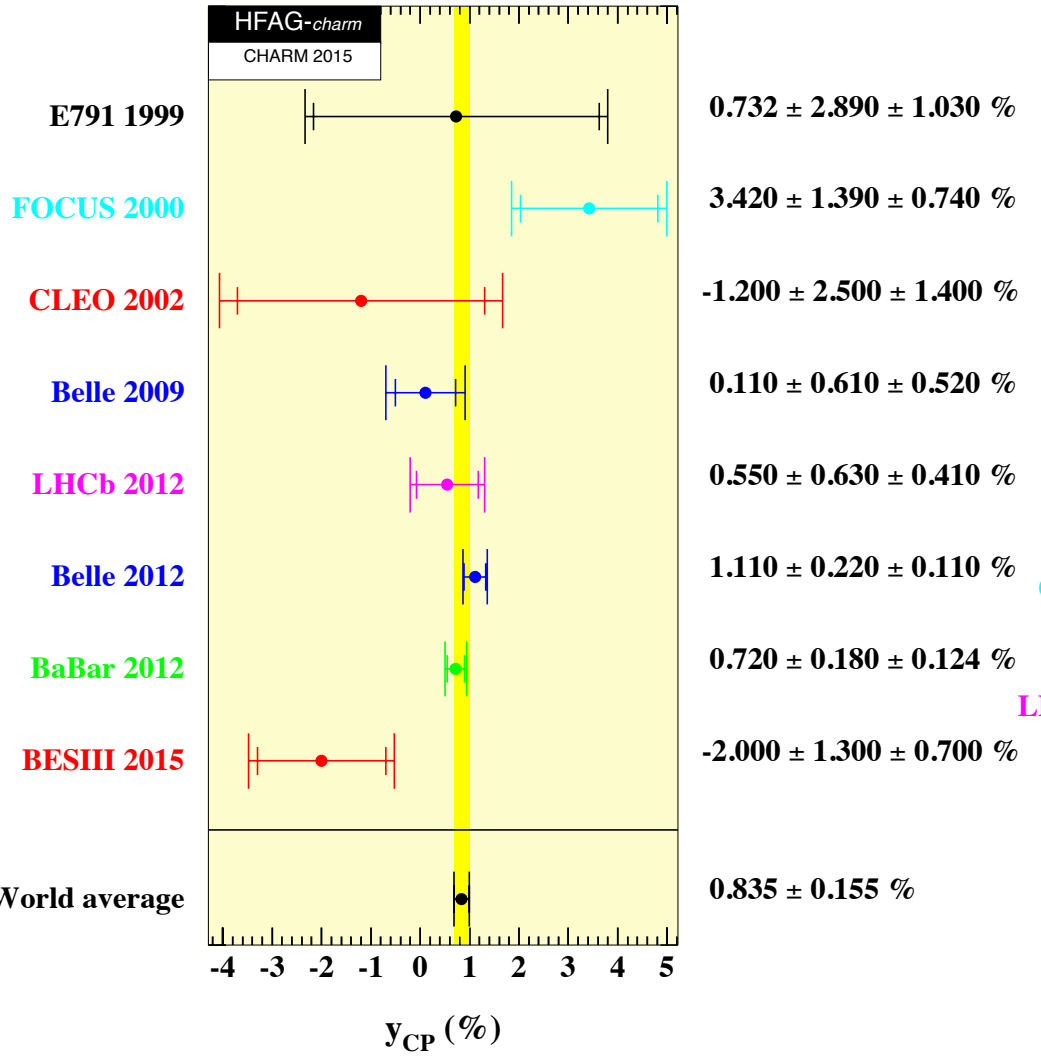
http://www.slac.stanford.edu/xorg/hfag/charm/index.html

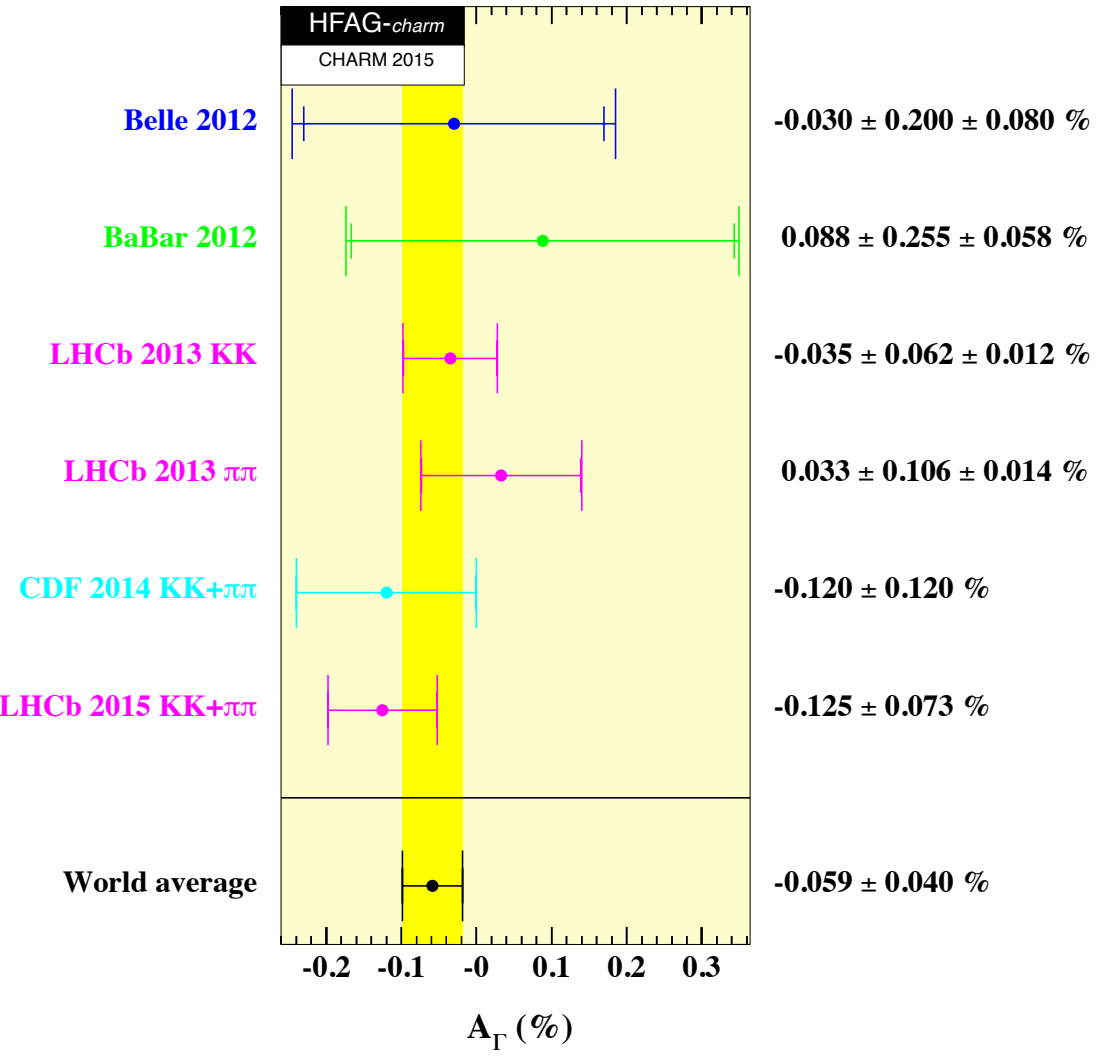
Results *(fit 41 observables for 9 or 10 parameters::*

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	95% CL Interval
x (%)	$0.49\,^{+0.14}_{-0.15}$	$0.44\,^{+0.14}_{-0.15}$	0.37 ± 0.16	[0.06, 0.67]
y (%)	0.61 ± 0.08	0.60 ± 0.07	$0.66\,^{+0.07}_{-0.10}$	[0.46, 0.79]
$\delta_{K\pi}$ (°)	$6.9\,^{+9.7}_{-11.2}$	–	$11.8\,^{+9.5}_{-14.7}$	[−21.1, 29.3]
R_D (%)	0.349 ± 0.004	–	0.349 ± 0.004	[0.342, 0.357]
A_D (%)	–	–	$-0.39\,^{+1.01}_{-1.05}$	[−2.4, 1.5]
$\lvert q/p \rvert$	–	1.001 ± 0.014	$0.91\,^{+0.12}_{-0.08}$	[0.77, 1.14]
ϕ (°)	–	-0.07 ± 0.6	$-9.4\,^{+11.9}_{-9.8}$	[−28.3, 12.9]
$\delta_{K\pi\pi}$ (°)	$18.1\,^{+23.3}_{-23.8}$	–	$27.3\,^{+24.4}_{-25.4}$	[−23.3, 74.8]
A_π	–	0.10 ± 0.14	0.10 ± 0.15	[−0.19, 0.38]
A_K	–	-0.14 ± 0.13	-0.15 ± 0.14	[−0.42, 0.12]
x_{12} (%)	–	$0.44\,^{+0.14}_{-0.15}$		[0.13, 0.69]
y_{12} (%)	–	0.60 ± 0.07		[0.45, 0.74]
ϕ_{12}(°)	–	0.2 ± 1.7		[−4.1, 4.6]

HFAG World Averages

New world averages (http://www.slac.stanford.edu/xorg/hfag/charm/index.html):





Summary of the Summary talk

- *Lots of interesting results, but no "smoking gun" of new physics yet*
- *Now seeing many new results from LHCb, including Dalitz plot analyses*
- *Now seeing a wide range of results from BESIII*
- *Results still coming in from Belle with full data-set (~950 fb^{-1})*
- *HFAG mixing averages now have only small incremental changes – several new ideas on how to improve this, i.e., make a significant change (e.g., use CP-even $D^0 \to \pi^+\pi^-\pi^0$)*
- *By CHARM 2016, should have many 3(+) fb^{-1} results from LHCb, more results from ATLAS/CMS, last results from Belle/BaBar, hopefully first signals from Belle II. See you in Italy!*

3 colleagues searching for new physics