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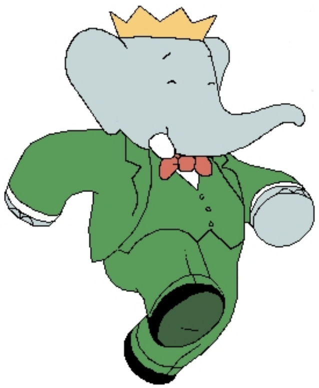
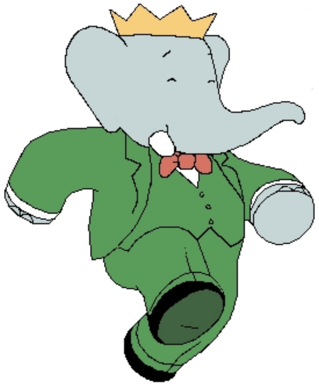
Recent BaBar results on charm mesons



Fergus Wilson
Rutherford Appleton Laboratory
For the BaBar collaboration
Lake Louise Workshop 2016

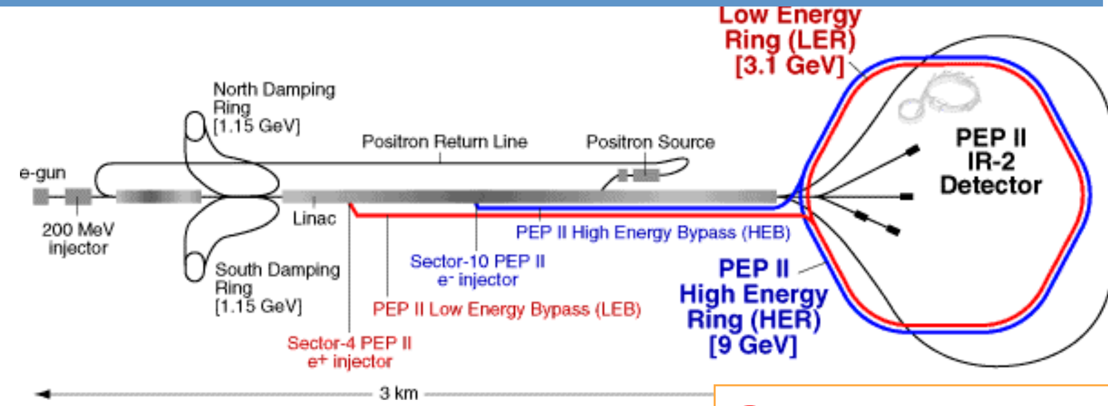


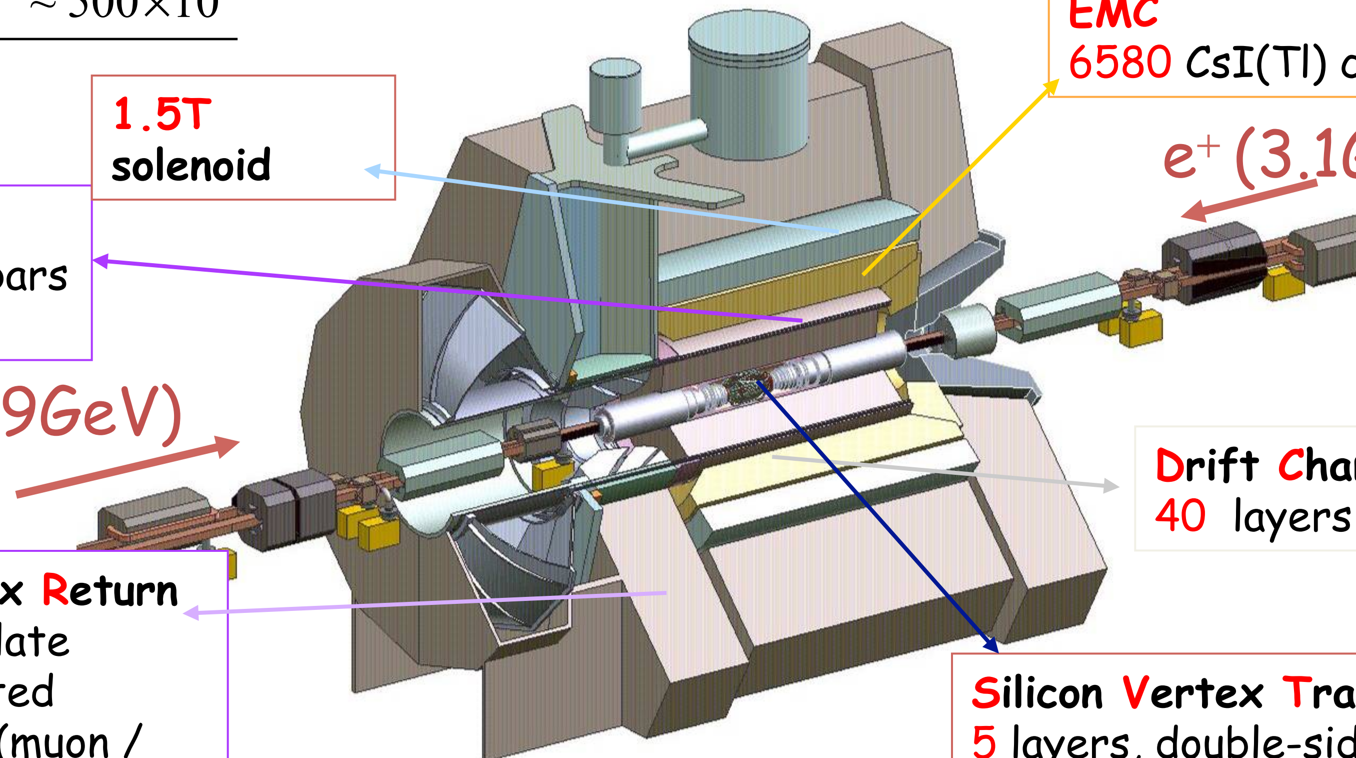
Outline

1. D^0-$\bar{D}^0$ mixing with $D^0 \to \pi^+\pi^-\pi^0$ decays
   - Measurement of *x* and *y* mixing parameters
   - To be submitted to PRD (this week)
2. $D^0 \to \pi^- e^+ \nu_e$
   - Differential branching fractions
   - CKM elements
   - Form factors
   - PRD 91, 052022 (2015)

PEP II and BaBar

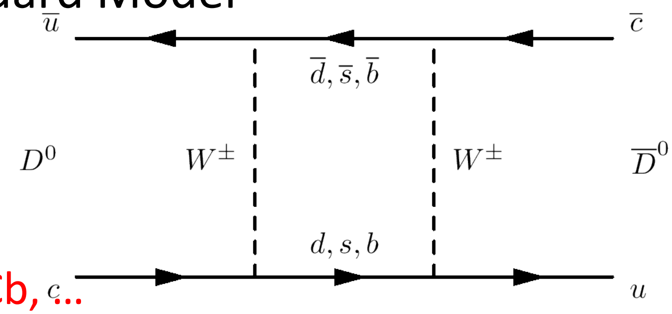
	Lumi	$B\bar{B}$ Events
$\Upsilon(4S)$	424 fb^{-1}	471×10^6
$\Upsilon(3S)$	28 fb^{-1}	121×10^6
$\Upsilon(2S)$	14 fb^{-1}	99×10^6
$c\bar{c}$		$\sim 500\times10^6$

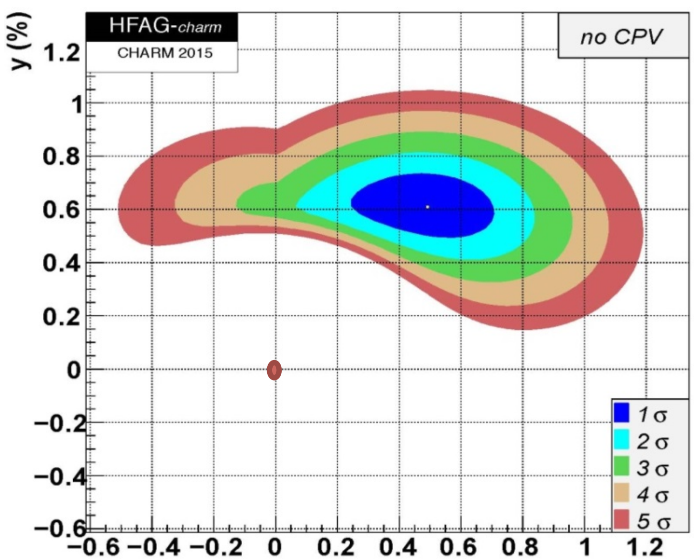




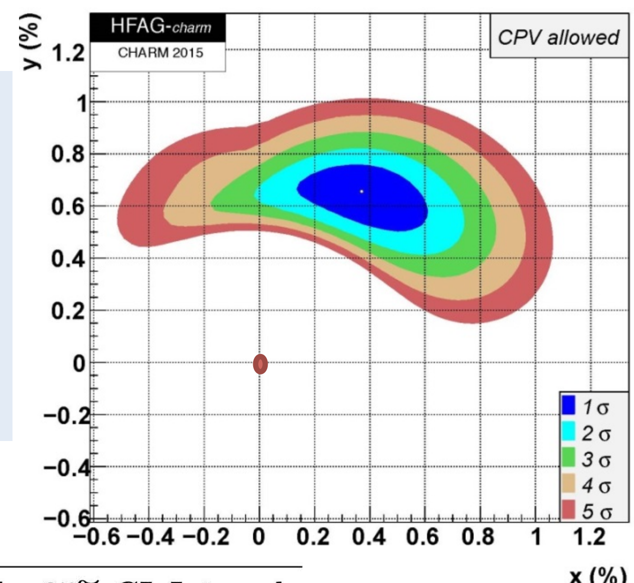
Time-dependent D^0 mixing in $D^0 \to \pi^+\pi^-\pi^0$

- Charm is an up-type quark. Complementary to studies in the K and B sectors.
- Mixing and CP Violation (CPV) are small in the Standard Model
  - CPV < 0.1% - 1% (depending on assumptions)
  - Potentially Sensitive to New Physics.
- D^0 mixing well-established now:
  - First measured in 2007 by BaBar and Belle
  - Confirmed and extended by CLEO-c, CDF, BES-III, LHCb, ...





$$x = (m_1 - m_2)/\Gamma_D$$
$$y = (\Gamma_1 - \Gamma_2)/2\Gamma_D$$
$$\Gamma_D = (\Gamma_1 + \Gamma_2)/2$$
$$\tau_D = 1/\Gamma_D$$



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]

Time-dependent D^0 mixing in $D^0 \to \pi^+\pi^-\pi^0$

474 fb^{-1}

$$D^*(2010)^+ \to D^0 \pi_s^+ , D^0 \to \pi^+ \pi^- \pi^0$$

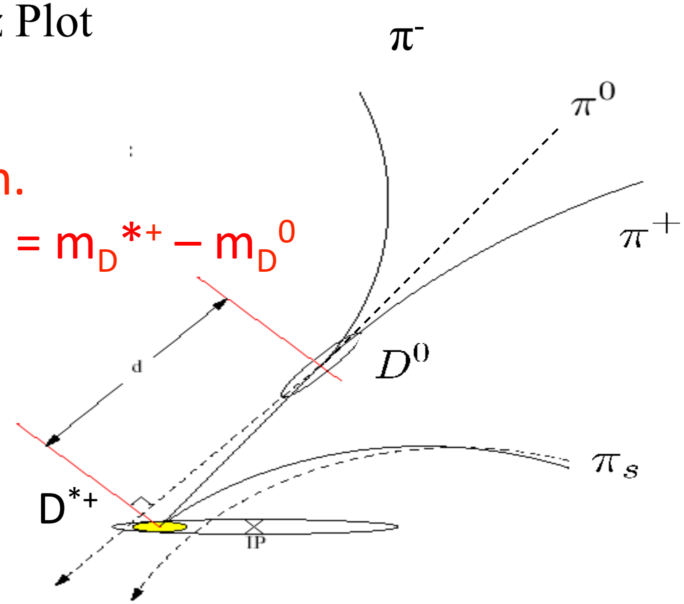
$$|M(D^0)|^2 \propto \frac{1}{2} e^{-\Gamma_D t} \Big\{ |A_f|^2 \left[\cosh(y\Gamma_D t) + \cos(x\Gamma_D t)\right]$$
← Direct decay $D^0 \to \pi^+\pi^-\pi^0$

$$+ \left|\frac{q}{p}\bar{A}_f\right|^2 \left[\cosh(y\Gamma_D t) - \cos(x\Gamma_D t)\right]$$
← Mixing $D^0 \to \bar{D}^0 \to \pi^+\pi^-\pi^0$

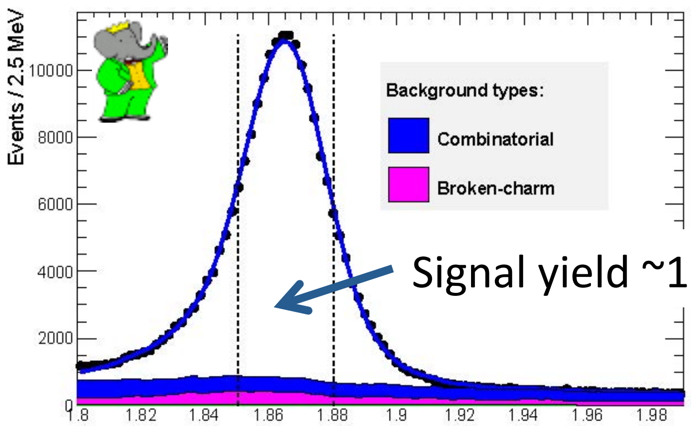
$$-2\left[\Re e\left(\frac{q}{p}A_f^* \bar{A}_f\right)\sinh(y\Gamma_D t) - \Im m\left(\frac{q}{p}A_f^* \bar{A}_f\right)\sin(x\Gamma_D t)\right]\Big\}$$
← Interference

Amplitudes A_f depend on position in Dalitz Plot

- Sign of π^+_s identifies D^0 flavour at production.
- Yield extracted from a 2-D fit to $m_D{}^0$ and $\Delta m = m_D{}^{*+} - m_D{}^0$
- Ignore CP Violation
- Fit time-dependent Dalitz plot
- Extract x, y, τ_D and resonance parameters

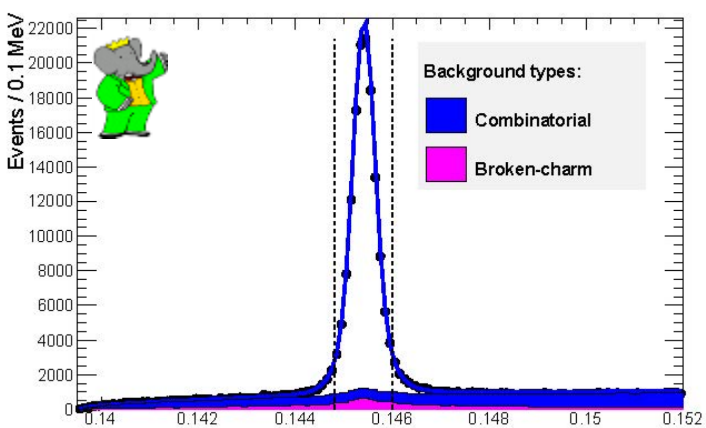


Yields and Dalitz Plot Amplitudes



Signal yield ~125,000

$m(\pi^+\pi^-\pi^0)[\text{GeV}]$



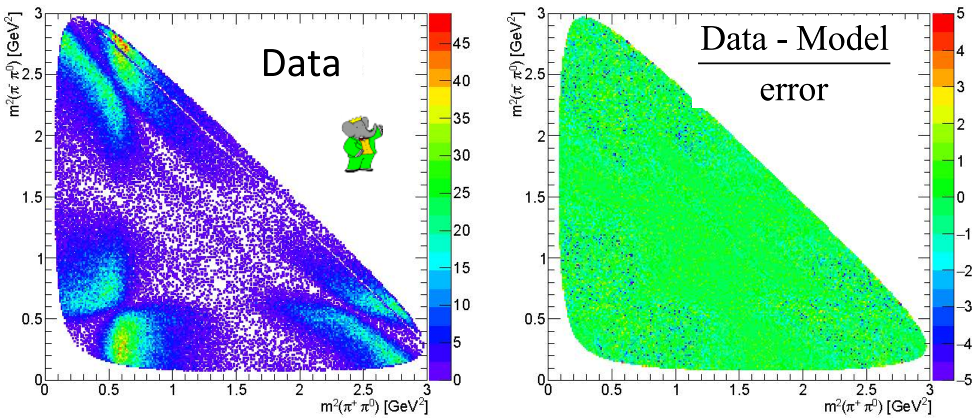
$\Delta m = m(\pi^+\pi^-\pi^0\pi_s^+) - m(\pi^+\pi^-\pi^0)[\text{GeV}]$

Initial choice of Dalitz Plot amplitudes comes from BaBar's $B^+ \to D^0(\to\pi^+\pi^-\pi^0)K^+$ paper: PRL 99, 251801 (2007).

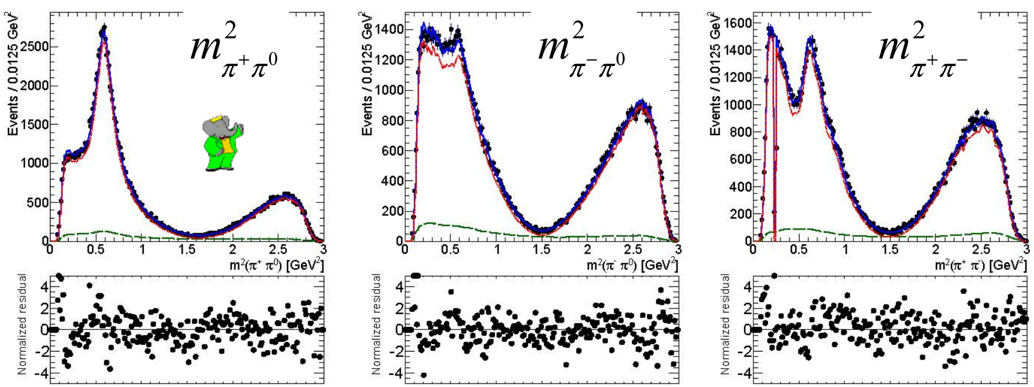
State	Resonance parameters		
	J^{PC}	Mass (MeV)	Width (MeV)
$\rho(770)^+$	1^{--}	775.8	150.3
$\rho(770)^0$	1^{--}	775.8	150.3
$\rho(770)^-$	1^{--}	775.8	150.3
$\rho(1450)^+$	1^{--}	1465	400
$\rho(1450)^0$	1^{--}	1465	400
$\rho(1450)^-$	1^{--}	1465	400
$\rho(1700)^+$	1^{--}	1720	250
$\rho(1700)^0$	1^{--}	1720	250
$\rho(1700)^-$	1^{--}	1720	250
$f_0(980)$	0^{++}	980	44
$f_0(1370)$	0^{++}	1434	173
$f_0(1500)$	0^{++}	1507	109
$f_0(1710)$	0^{++}	1714	140
$f_2(1270)$	2^{++}	1275.4	185.1
$f_0(500)$	0^{++}	500	400
NR			

"Broken charm" : mis-reconstructed signal and other D^0 decays

Dalitz Plot Fit and mixing results



State	J^{PC}	Resonance parameters Mass (MeV)	Width (MeV)	Fit to data results Magnitude	Phase (°)	Fraction f_r (%)
$\rho(770)^+$	1^{--}	775.8	150.3	1	0	66.4±0.5
$\rho(770)^0$	1^{--}	775.8	150.3	0.55±0.00	16.10±0.43	23.9±0.3
$\rho(770)^-$	1^{--}	775.8	150.3	0.73±0.01	−1.58±0.51	35.6±0.4
$\rho(1450)^+$	1^{--}	1465	400	0.55±0.07	−7.69±8.17	1.1±0.3
$\rho(1450)^0$	1^{--}	1465	400	0.19±0.07	−70.39±15.91	0.1±0.1
$\rho(1450)^-$	1^{--}	1465	400	0.53±0.06	8.15±6.66	1.0±0.2
$\rho(1700)^+$	1^{--}	1720	250	0.91±0.15	−23.34±10.27	1.5±0.5
$\rho(1700)^0$	1^{--}	1720	250	0.60±0.13	−56.32±16.03	0.7±0.3
$\rho(1700)^-$	1^{--}	1720	250	0.98±0.17	78.88±8.48	1.7±0.6
$f_0(980)$	0^{++}	980	44	0.06±0.00	−58.75±2.89	0.3±0.0
$f_0(1370)$	0^{++}	1434	173	0.20±0.03	−19.63±9.45	0.3±0.1
$f_0(1500)$	0^{++}	1507	109	0.18±0.02	7.41±7.40	0.3±0.1
$f_0(1710)$	0^{++}	1714	140	0.40±0.08	42.92±8.84	0.3±0.1
$f_2(1270)$	2^{++}	1275.4	185.1	0.25±0.01	8.84±2.61	0.9±0.0
$f_0(500)$	0^{++}	500	400	0.26±0.01	−4.12±3.67	0.9±0.1
NR				0.43±0.07	−22.10±11.70	0.4±0.1



Blue = full fit

Red = signal

Green = background

Consistent with previous results

This result	World avg.
$x = (1.50 \pm 1.17 \pm 0.56)\%$	$(0.49^{+0.14}_{-0.15})\%$
$y = (0.19 \pm 0.89 \pm 0.46)\%$	$(0.61 \pm 0.08)\%$
$\tau_D = (410.2 \pm 3.8)\,\text{fs}$	$(410.1 \pm 1.5)\,\text{fs}$

$D^0 \to e^+\pi^-\nu_e$ decays and V_{cd}, V_{ub}, and f^{π}_{+D}

PRD 91, 052022 (2015)

- CKM elements measured in nuclear β decays and semi-leptonic decays of π, K, D, and B mesons
  - Semi-leptonic D decay rate depends on square of product of CKM element V_{cd} and form factor f.

$$\frac{d\Gamma}{dq^2 d\cos\theta_e} = \frac{G_F^2}{32\pi^3}(|V_{cd}| \times |f^{\pi}_{+,D}(q^2)|)^2 p_{\pi}^{*3}(q^2)\sin^2\theta_{e^+}$$

    - (p^*_{π} = π momentum in D^0 rest frame; $q=(p_D-p_{\pi})$; θ_e = angle of e^+ in the $e^+\nu_e$ rest-frame w.r.t. direction of π in D^0 rest-frame)
  - Form factors come from models, calculations, and parameterisations.
- Exploit large $e^+e^-\to c\bar{c}$ x-section at BaBar (1.3nb)
  - $D^{*+}\to D^0\pi^+_s$, $D^0\to\pi^- e^+\nu_e$
  - π^+_s determines flavour of initial D^0
  - Measure $D^0\to K^-\pi^+$ as a calibration channel
  - Similar to $D^0\to K^- e^+\nu_e$ approach [PRD76, 052005 (2007)]

Form Factor Calculation

PRD 91, 052022 (2015)

- General Expression:

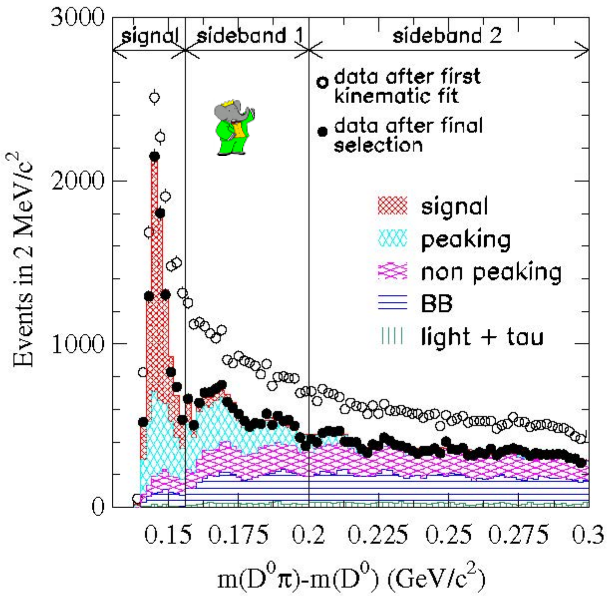
$$f_{+,D}^{\pi}(q^2) = \frac{1}{\pi}\int_{(m_D+m_\pi)^2}^{\infty} dt \frac{\Im m(f_{+,D}^{\pi}(t))}{t-q^2-i\varepsilon}$$

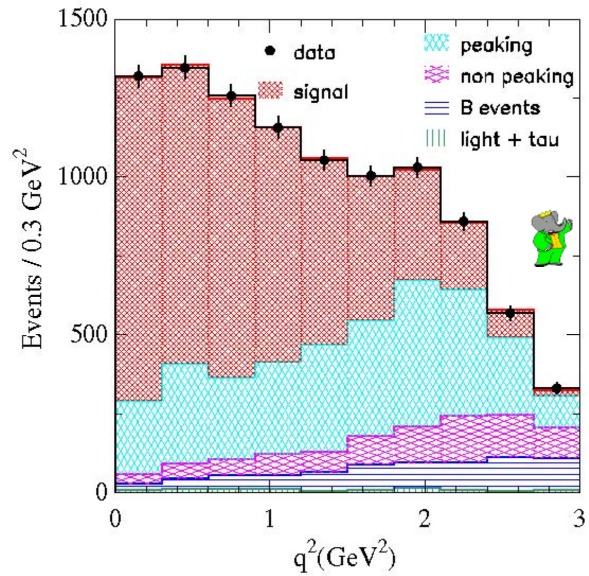
- Different theoretical approaches including:
  - Dispersive.
  - Multipole (“fixed pole” and “effective pole”).
  - Z expansion (model independent).
  - Quark model ISGW2 (PRD 52, 2783 (1995)).
- (See backup slide for more details and formulae)

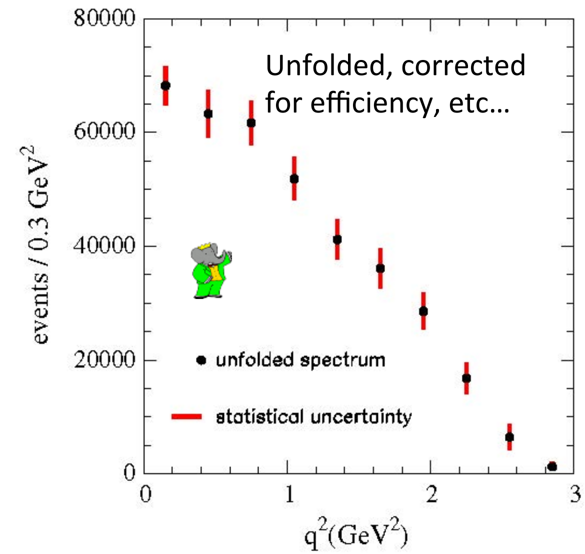
Differential decay rate

PRD 91, 052022 (2015)

- Exploit 2-jet structure of $c\bar{c}$ decays by splitting event into two hemispheres in the CM system around thrust axis. One hemisphere will contain the $D^0 \rightarrow \pi^- e^+ \nu_e$ decay.
- Additional knowledge
  - Estimate ν energy E_ν from missing energy in hemisphere with $D^0 \rightarrow \pi^- e^+ \nu_e$ decay.
  - D^0 direction can be estimated from sum of particles in other hemisphere.
  - Perform kinematic fit to $\pi^- e^+ \nu_e$ with E_ν, D^0 direction, and D^0 mass as additional constraints







9926 signal, 4623 background events

Branching fractions and $V_{cd} \times f^{\pi}_{+D}$

PRD 91, 052022 (2015)

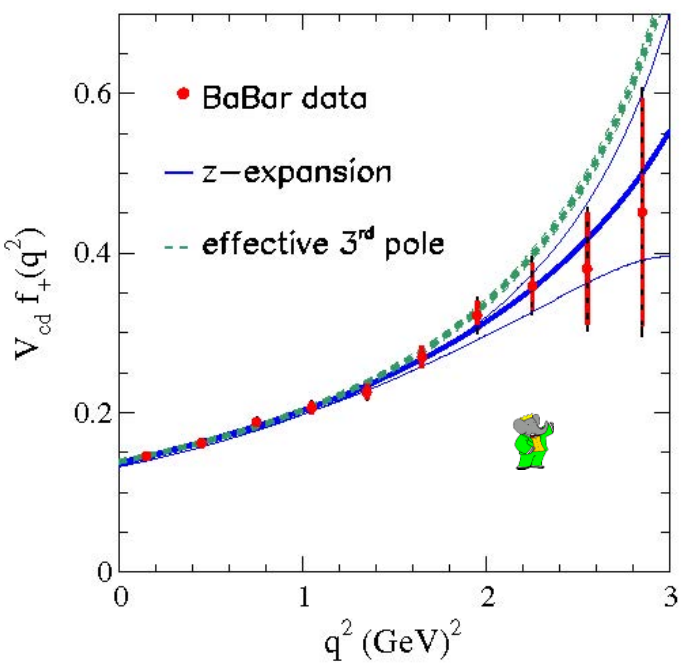
$$R_D = \frac{B(D^0 \to \pi^- e^+ \upsilon_e)}{B(D^0 \to K^- \pi^+)} = (0.0713 \pm 0.0017 \pm 0.0024)$$

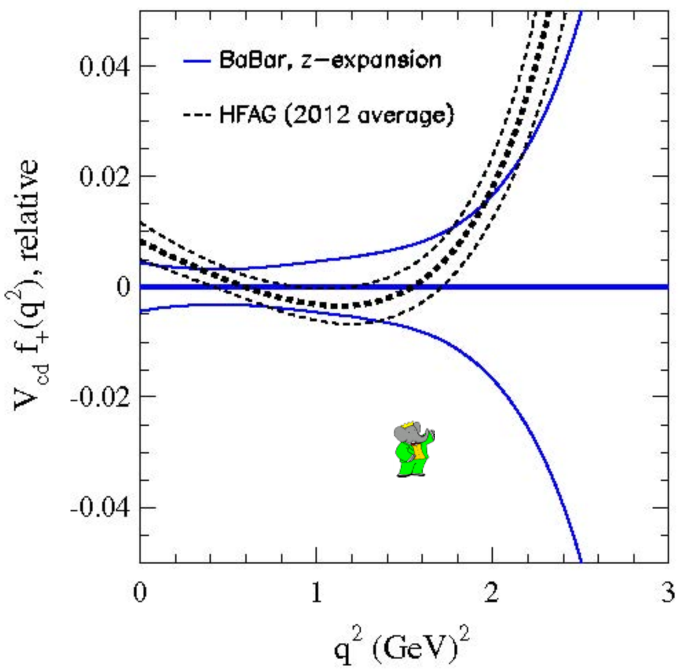
$$\Rightarrow B(D^0 \to \pi^- e^+ \upsilon_e) = (2.770 \pm 0.068 \pm 0.092 \pm 0.037) \times 10^{-3}$$

$$|V_{cd}| \times f^{\pi}_{+,D}(0) = \sqrt{\frac{24\pi^3}{G_F^2} \frac{B(D^0 \to \pi^- e^+ \upsilon_e)}{\tau_{D^0} I}}$$

(Using Z expansion to calculate I)

$$|V_{cd}| \times f^{\pi}_{+,D}(0) = 0.1374 \pm 0.0038 \pm 0.0022 \pm 0.0009$$





Comparison with earlier measurements

PRD 91, 052022 (2015)

- This result: $|V_{cd}| \times f^{\pi}_{+,D}(0) = 0.1374 \pm 0.0038 \pm 0.0022 \pm 0.0009$

Experiment	Ref.	$\lvert V_{cd}\rvert \times f^{\pi}_{+,D}(0)$
Belle (2006)	[6]	$0.140 \pm 0.004 \pm 0.007$
CLEO-c untagged (2008)	[7]	$0.140 \pm 0.007 \pm 0.003$
CLEO-c untagged (2008)	[7]	$0.138 \pm 0.011 \pm 0.004$
CLEO-c tagged (2009)	[8]	$0.150 \pm 0.004 \pm 0.001$
BESIII (2012)(prel.)	[42]	$0.144 \pm 0.005 \pm 0.002$
HFAG average (2012)	[40]	0.146 ± 0.003
BESIII (2014)(prel.)	[9]	$0.1420 \pm 0.0024 \pm 0.0010$
This analysis		$0.137 \pm 0.004 \pm 0.002 \pm 0.001$
LQCD predictions	Ref.	$\lvert V_{cd}\rvert \times f^{\pi}_{+,D}(0)$
FNAL/MILC (2004)	[43]	0.144 ± 0.016
ETMC (2011)	[44]	0.146 ± 0.020
HPQCD (2011)	[41]	0.150 ± 0.007
HPQCD (2013)	[45]	0.153 ± 0.009

- Lattice QCD gives $f^{\pi}_{+D}(0) = 0.666 \pm 0.029$:

PRD 84, 114505 (2011)

$$|V_{cd}| = 0.206 \pm 0.007 \pm 0.009_{LQCD}$$

$$|V_{cd}^{PDG}| = 0.225 \pm 0.008$$

- Assuming $|V_{cd}| = |V_{us}| = 0.2252 = \lambda$ (Wolfenstein):

$$f^{\pi}_{+,D}(0) = 0.610 \pm 0.020 \pm 0.005$$

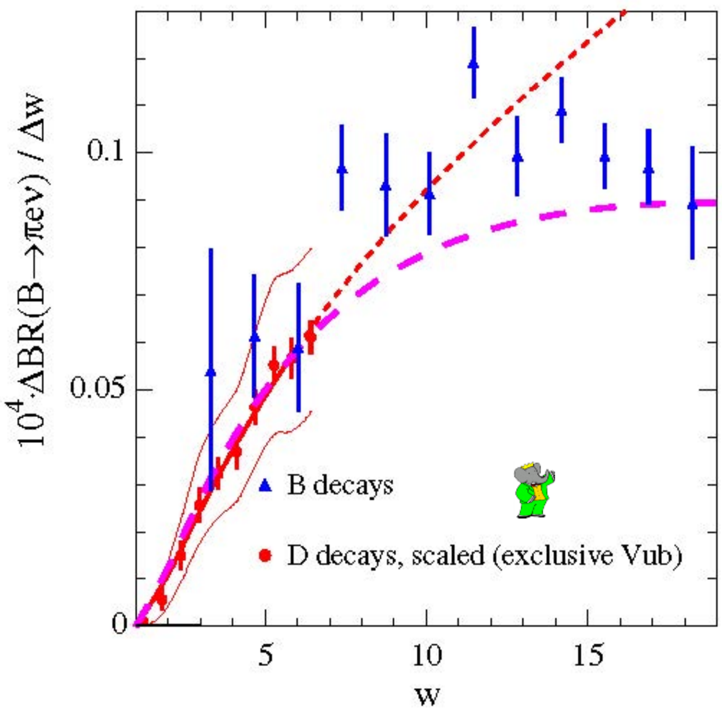
Extrapolation to $B^0 \to e^+\pi^-\nu_e$ and V_{ub}

PRD 91, 052022 (2015)

- Extrapolate D^0 measurements to B^0 regime:

$$\frac{dB^B}{dw} = \frac{dB^D}{dw}\bigg|_{meas} \frac{m_B \tau_B}{m_D \tau_D} \left(\frac{|V_{ub}|}{|V_{cd}|} \right)^2 R^2_{BD}, \qquad w = E^*_\pi / m_\pi$$

R^2_{BD} : ratio of B and D form factors from LQCD
Fit to $D^0 \to e^+\pi^-\nu_e$ with LQCD predictions for $R^2_{BD} = 1.8 \pm 0.2$



"Fixed" 3-pole ansatz

"Effective" 3-pole ansatz

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

Compare with PDG value:

$$|V_{ub}|^{excl} = (3.23 \pm 0.31) \times 10^{-3}$$

Conclusions

- BaBar continues to exploit its charm dataset.
- $D^0 \rightarrow \pi^+\pi^-\pi^0$:
  - First measurement of D^0-$\bar{D}^0$ mixing parameters from a time dependent analysis of $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays.
  - Consistent with other measurements.
- $D^0 \rightarrow \pi^- e^+ \nu_e$:
  - Differential decay rates allow comparison between different approaches to form factor calculations and extraction of CKM elements.
  - Effective 3-pole model describes data well but other models not ruled out.
  - Dominant systematic errors should improve with further Lattice QCD calculations and so help inform form factor calculations.

Form Factor Calculation

PRD 91, 052022 (2015)

- General Expression:

$$f_{+,D}^{\pi}(q^2) = \frac{1}{\pi}\int_{(m_D+m_\pi)^2}^{\infty} dt \frac{\Im m(f_{+,D}^{\pi}(t))}{t-q^2-i\varepsilon}$$

- Theoretical Approaches:
  - Dispersive Approach:
    - D* pole, sum of radially excited $J^P=1^-$ $D_1^{*\prime}$, and Dπ continuum
  - Multipole Approach:
    - Limit to 1 (D*) , 2 (D* + first $D_1^{*\prime}$), or 3 dominant poles + constraints
    - 3rd pole is either a $D_1^{*\prime}$ ("fixed" ansatz) or sum of higher $D_1^{*\prime}$ ("effective" ansatz)
    - Other assumptions and constraints can modify the approximations.

$$f_{+,D}^{\pi}(q^2) = \frac{f_{+,D}^{\pi}(0)}{1-c_2-c_3}\left(\frac{1}{1-\frac{q^2}{m_{D^*}^2}} - \sum_{i=2}^{3}\frac{c_i}{1-\frac{q^2}{m_{D_i^{*\prime}}^2}}\right).$$

  - Z expansion:
    - Model independent based on analyticity, unitarity and crossing symmetries

$$z(t,t_0) = \frac{\sqrt{t_+-t}-\sqrt{t_+-t_0}}{\sqrt{t_+-t}+\sqrt{t_+-t_0}}$$

$$f_{+,D}^{\pi}(t) = \frac{1}{P(t)\Phi(t,t_0)}\sum_{k=0}^{\infty} a_k(t_0)z^k(t,t_0),$$

  - Quark model ISGW2 (PRD 52, 2783 (1995)):

$$f_{+,D}^{\pi}(q^2) = f(q^2_{\max})\left(1+\frac{1}{12}\alpha_I(q^2_{\max}-q^2)\right)^{-2},$$