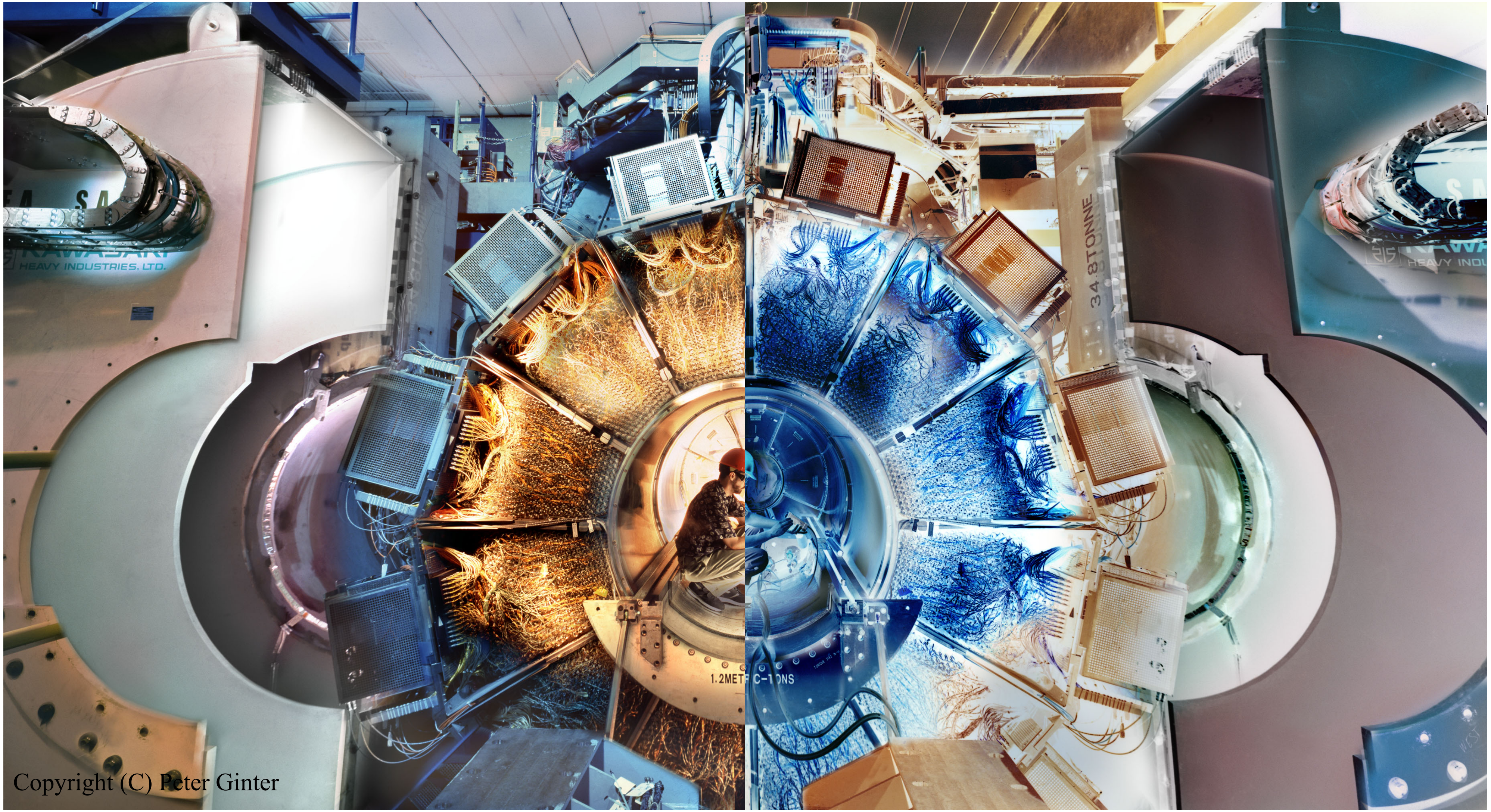


Recent Results from BaBar on Charmed Mesons

DESY 11-15th April 2016

Adrian Bevan

Queen Mary
University of London

Outline

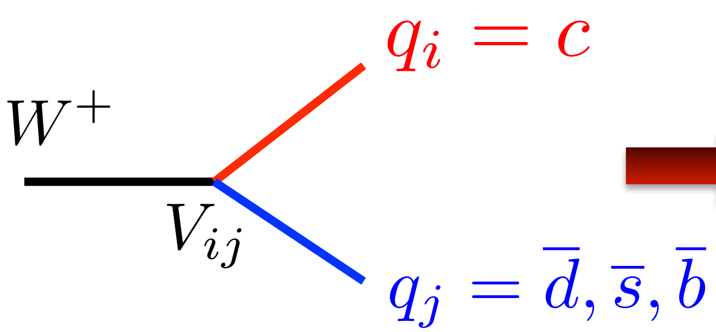
- Physics motivation
- PEP II and the BaBar Detector
- Data sets
- Results:
  - Mixing parameters for the time-dependent amplitude analysis of $D^0 \to \pi^+\pi^-\pi^0$.

    arXiv:1604.00857, submitted to PRD
  - Differential branching fraction, form factor and CKM element extraction from $D^0 \to \pi^- e^+ \nu_e$.

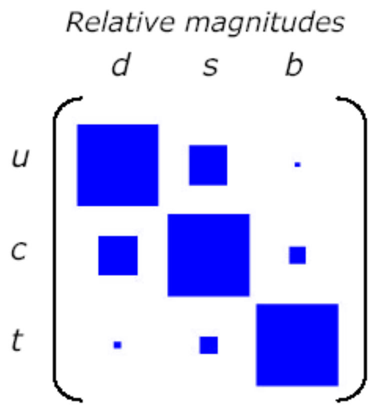
    Phys.Rev. D**91** (2015) no.5, 052022

Physics motivation

- The charm quark is the heaviest up type quark that forms a bound state: D^0, $D^{\pm}_{(s)}$.
- Unique laboratories to study nature: e.g.
  - (differential) Branching fractions;
  - Neutral meson mixing, and CP violation;
  - CKM matrix element determination;
  - Form factor measurements.



$$V_{ij} =$$



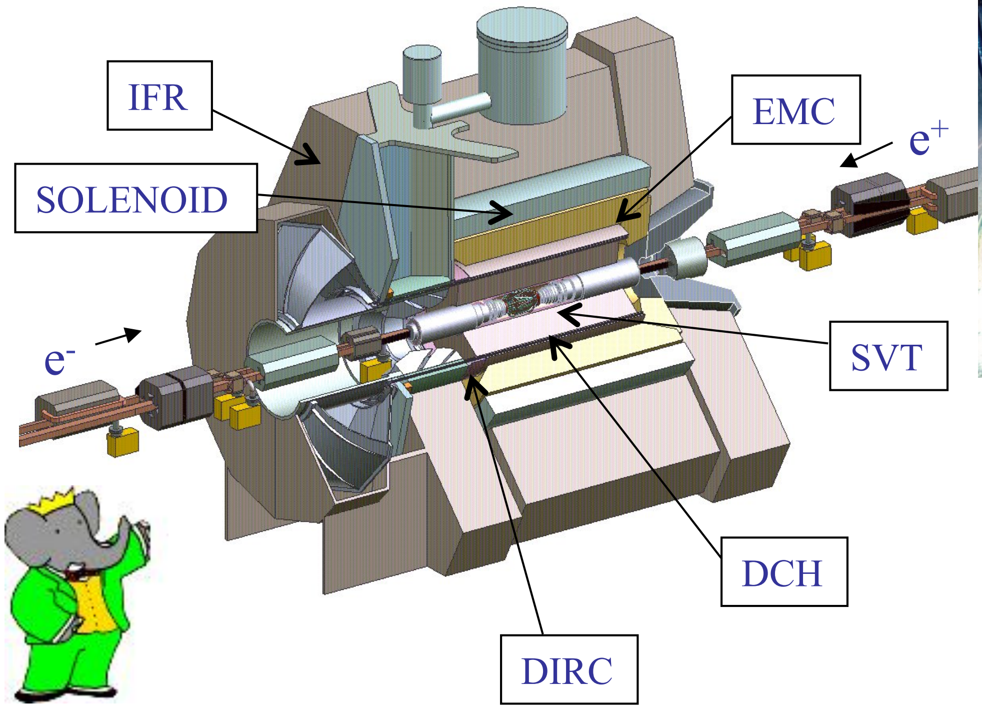
$$= \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ \boxed{V_{\mathrm{cd}} \quad V_{\mathrm{cs}} \quad V_{\mathrm{cb}}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

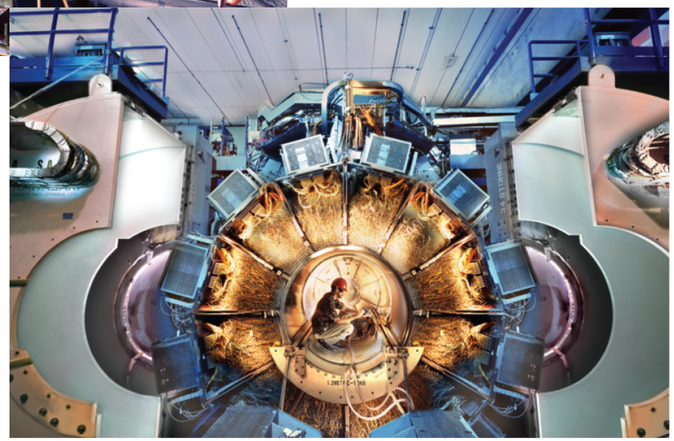
BaBar & PEP-II

- Asymmetric energy e^+e^- collider operating primarily at the $\Upsilon(4S)$.

At the SLAC National Laboratory

- Asymmetric design.
- Central tracking system
- Particle Identification System
- Electromagnetic Calorimeter
- Solenoid Magnet
- Muon/K^0_L Detection System
- High operation efficiency



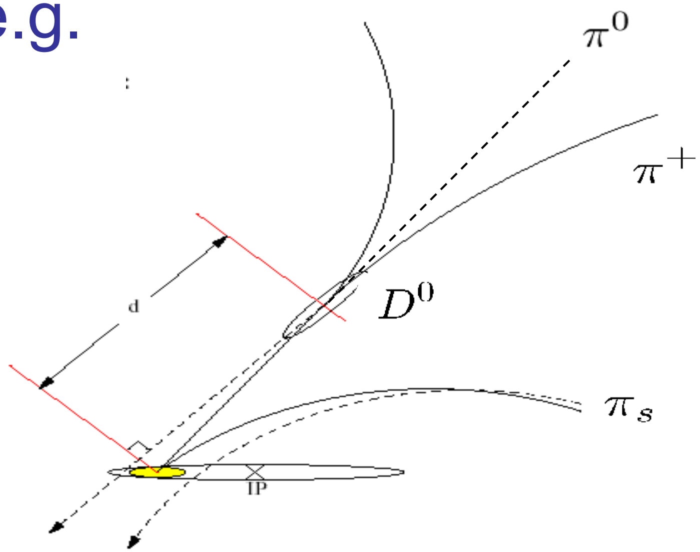


B Factories are charm factories

- BaBar recorded 524fb^{-1} during the operational lifetime.
  - ~500M B pairs (σ=1.2nb for $b\bar{b}$ production).
  - ~500M D mesons (σ=1.3nb for $c\bar{c}$ production).
- Reconstruct events using a D* tag via:

$$e^+e^- \to c\bar{c} \to D^{*+}X; \;\; D^{*+} \to D^0\pi_s^+$$

- e.g.



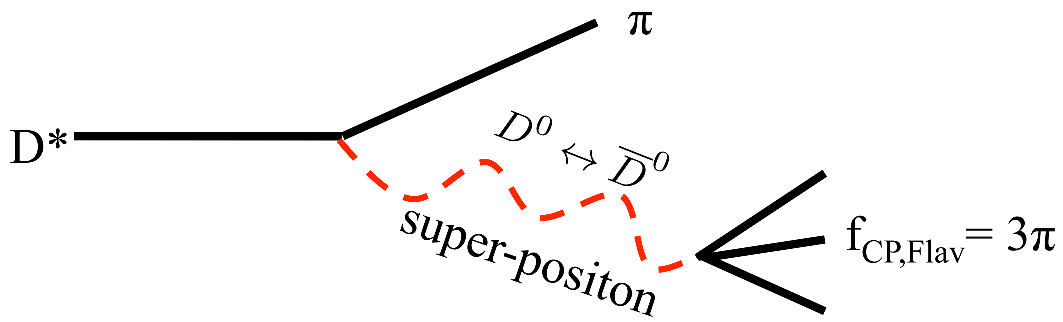
- Charge of slow pion tags the flavour of the D^0 at point of creation.
- Δm=m(D*)-m(D) is a powerful background suppression variable.
- B background and other D decay background may also need to be suppressed.

- RESULTS: $D^0 \to \pi^+\pi^-\pi^0$
  - Using 468.1 fb^{-1} of on- and off-peak data.

arXiv:1604.00857

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

- Study mixing in charm using the small ΔM and ΔΓ approximations:



$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$
$$\Delta M = m_1 - m_2$$
$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$
$$\Gamma = (\Gamma_1 + \Gamma_2)/2$$

- x and y are O(%) level parameters given by:

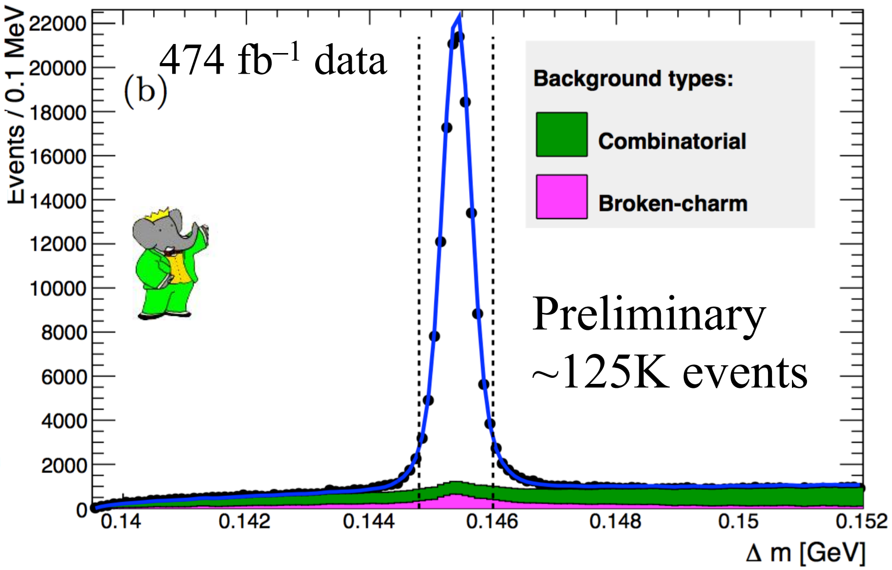
$$x = \frac{\Delta M}{\Gamma} \text{ and } y = \frac{\Delta\Gamma}{2\Gamma}$$

- Assume |q/p|=1 (no CP violation in mixing).

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

- Measurements of *x* and *y* teach us about $D^0 \leftrightarrow \overline{D}^0$ mixing.
- Final state is analysed as a function of the Dalitz plot coordinates $s_\pm = m^2(\pi^\pm\pi^0)$:

$$
\begin{aligned}
|\mathcal{M}(D^0)|^2 \propto \frac{1}{2}e^{-\Gamma_D t}\{&|A_f|^2\left[\cosh(y\Gamma_D t)+\cos(x\Gamma_D t)\right] \\
&+|\frac{q}{p}\overline{A}_f|^2\left[\cosh(y\Gamma_D t)-\cos(x\Gamma_D t)\right] \\
&-2\left[\mathrm{Re}\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sinh(y\Gamma_D t)\right. \\
&\left.-\mathrm{Im}\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(x\Gamma_D t)\right]\}, \qquad (1)
\end{aligned}
$$



- Dalitz analysis uses Isobar model description as a sum over many intermediate partial waves

$$\overline{A}_f(s_-, s_+) = A_f(s_+, s_-) = \sum_k c_k \mathcal{W}_k(s_+, s_-)$$

- Unbinned extended ML fit using GooFit.

R. Andreassen et al., IEEE Access 2, 160 (2014).
R. Andreassen et al., J. Phys.: Conf. Ser. 513 052003, 2014.

http://github.com/GooFit/GooFit

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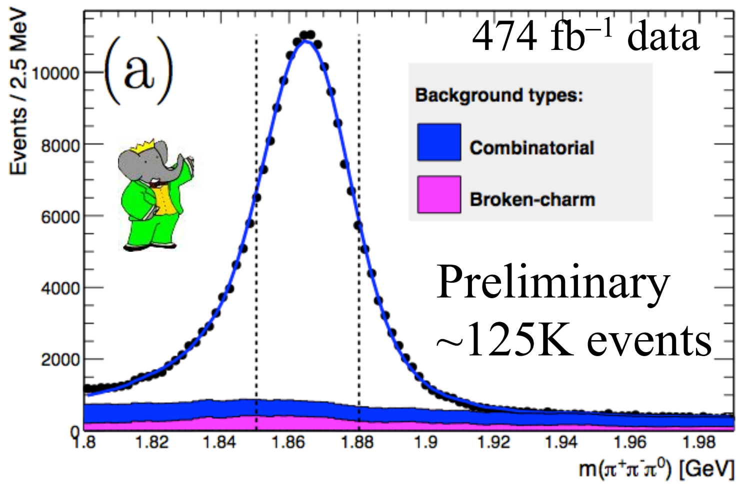

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& + |\frac{q}{p}\overline{A}_f|^2\left[\cosh(y\Gamma_D t) - \cos(x\Gamma_D t)\right] \\
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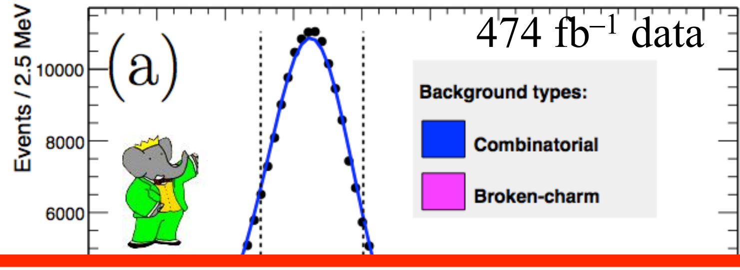

This measurement allows us to extract x and y independently from the fit via the interference terms

- Dalitz analysis uses Isobar model description as a sum over many intermediate partial waves

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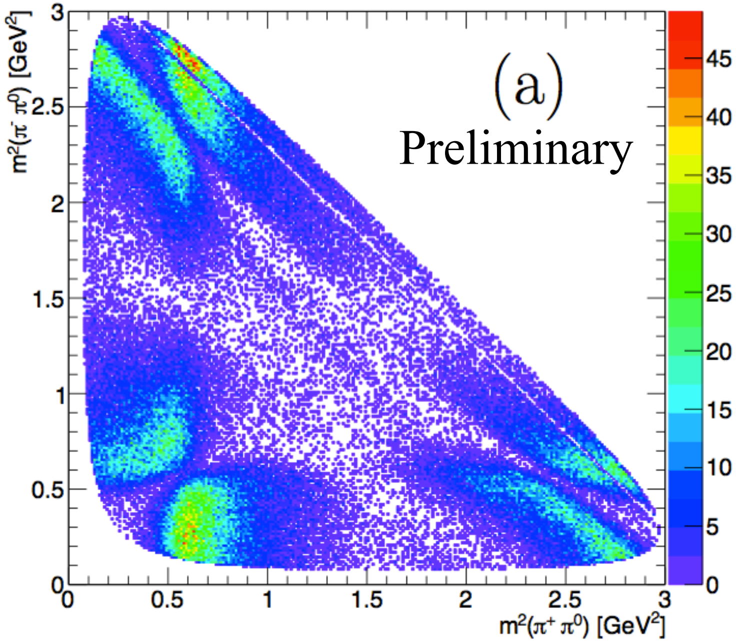
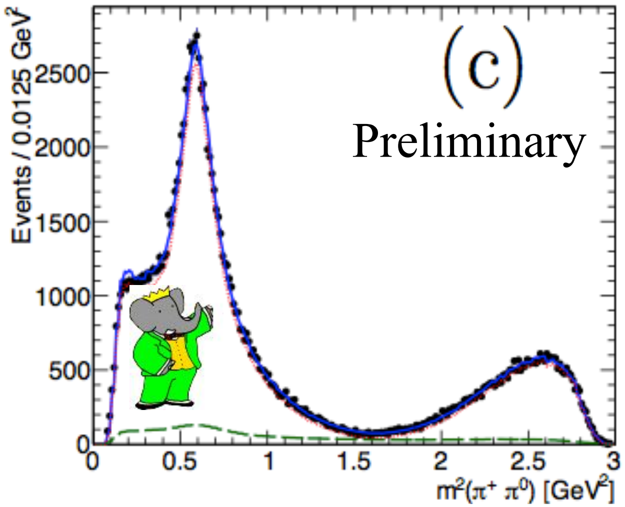
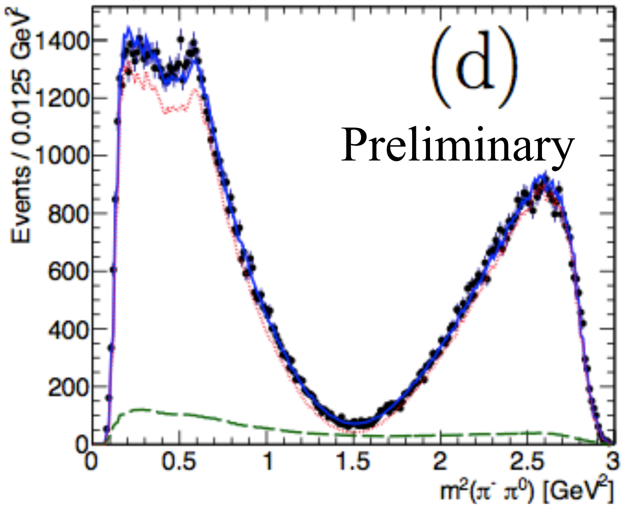
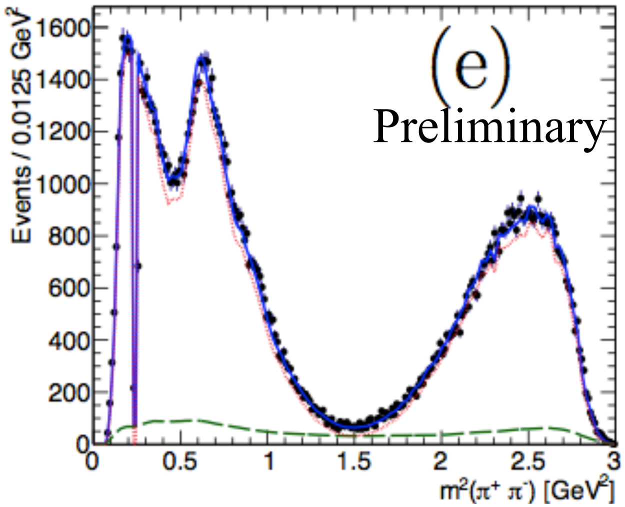


State	J^{PC}	Resonance parameters Mass (MeV)	Width (MeV)	Fit to data results Magnitude	Phase (°)	Fraction f_r (%)
$\rho(770)^+$	1^{--}	775.8	150.3	1	0	66.4±0.5
$\rho(770)^0$	1^{--}	775.8	150.3	0.55±0.00	16.10±0.43	23.9±0.3
$\rho(770)^-$	1^{--}	775.8	150.3	0.73±0.01	−1.58±0.51	35.6±0.4
$\rho(1450)^+$	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

Choice of amplitudes comes from: PRL **99**, 251801 (2007).







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

- Results: $x = (1.50 \pm 1.17 \pm 0.56)\%$

  $y = (0.19 \pm 0.89 \pm 0.46)\%$

- Fit for τ_D as a crosscheck: good agreement found with PDG:

  Measure τ_D = 410.2 ± 3.8 fs vs PDG value of 410.1±1.5 fs

- Statistically limited measurement; systematics are:

Source	x [%]	y [%]
"Lucky" false slow pion fraction	0.01	0.01
Time resolution dependence on reconstructed D^0 mass	0.03	0.02
Amplitude-model variations	0.31	0.12
Resonance radius	0.02	0.10
DP efficiency parametrization	0.03	0.03
DP normalization granularity	0.03	0.04
Background DP distribution	0.21	0.11
Decay time window	0.18	0.19
σ_t cutoff	0.01	0.01
Number of σ_t ranges	0.11	0.26
σ_t parametrization	0.05	0.03
Background-model MC time distribution parameters	0.06	0.11
Fit bias correction	0.29	0.02
SVT misalignment	0.20	0.23
Total	0.56	0.46

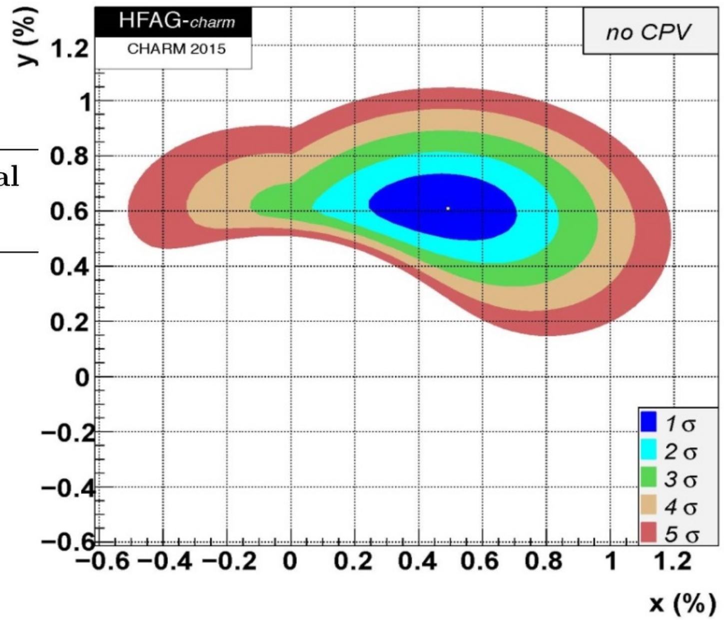
dominant for x

dominant for y

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

- Results: $x = (1.50 \pm 1.17 \pm 0.56)\%$
  $y = (0.19 \pm 0.89 \pm 0.46)\%$
  (Consistent with WA)
- Proof of principle time-dependent Dalitz plot mixing analysis for charm.
- c.f. World Average as of Charm 2015.

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]



- Belle II will have 100x the data to improve on this result.

- RESULTS: $D^0 \to \pi^- e^+ \nu_e$
  - Uses 347 fb^{-1} on-peak and 36.6 fb^{-1} off-peak data.

$D^0 \to \pi^- e^+ \nu_e$

Phys. Rev. D**91** 052022
arXiv:1412.5502

- Measurements of:
  - Differential branching fraction;
  - CKM matrix elements: $|V_{cd}|$ and impact on $|V_{ub}|$;
  - Form factors.

- Semi-leptonic rate is:

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

p_π*: π momentum in *D* rest frame
q^2 : $(p_D - p_\pi)^2$
θ_e : angle between e^+ in the $e\nu$ rest frame and the π in the D^0 rest frame.
$f^{\pi}_{+,D}(q^2)$: form factor

$D^0 \to \pi^- e^+ \nu_e$

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Differential rate provides a baseline measurement to interpret underlying physical properties of these decays.

Also report the product $|V_{cd}| \times f_{+,D}^{\pi}(q^2)$

$D^0 \to \pi^- e^+ \nu_e$

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Using Lattice QCD we can extract $|V_{cd}|$.

$D^0 \to \pi^- e^+ \nu_e$

Phys. Rev. D**91** 052022
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Using CKM Unitarity: $|V_{cd}| = |V_{us}| = \lambda$, we can extract $f_{+,D}^{\pi}(q^2)$.

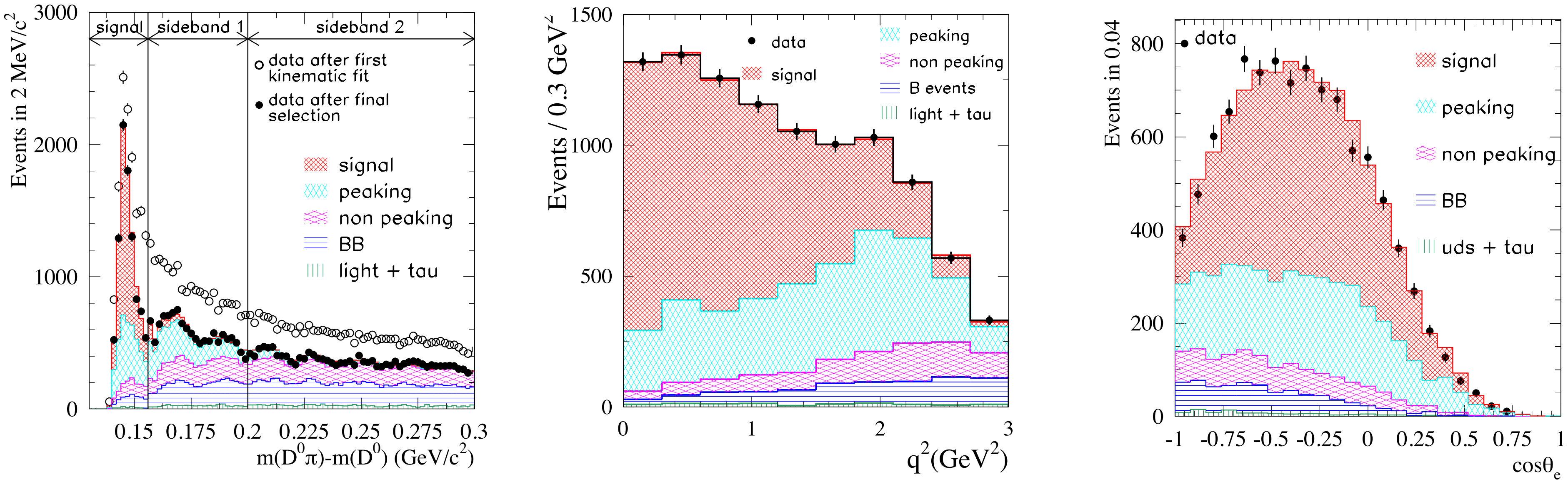
$|V_{us}| = 0.2252 \pm 0.0009$; PDG

Phys. Rev. D**91** 052022, arXiv:1412.5502

$D^0 \to \pi^- e^+ \nu_e$: branching fraction

- Use Fisher discriminants to suppress backgrounds from $e^+e^- \to B\overline{B}$ and $e^+e^- \to c\overline{c}$.

- Obtain 9926 events with an estimated background of 4623 events.



- Normalise signal to $D^0 \to K^-\pi^+$:

$$R_D = \frac{\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)}{\mathcal{B}(D^0 \to K^- \pi^+)}$$

$$R_D = 0.0702 \pm 0.0017 \pm 0.0023$$

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

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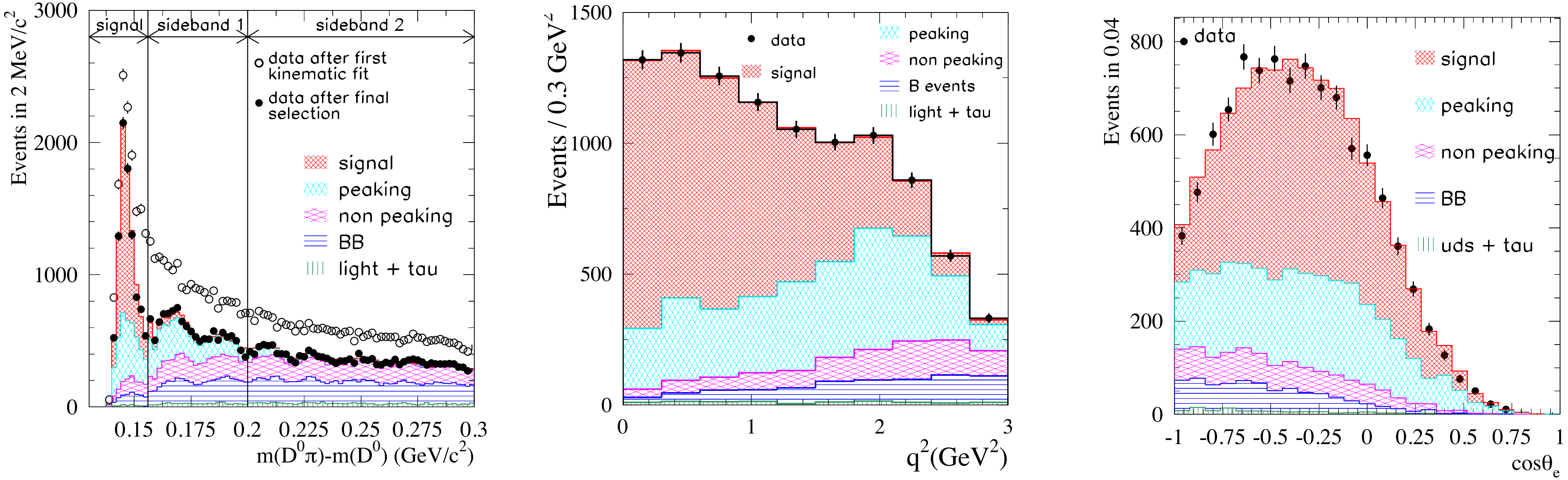

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$$R_D = \frac{\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)}{\mathcal{B}(D^0 \to K^- \pi^+)}$$

c.f. PDG 2014:
BR = $(2.89 \pm 0.08) \times 10^{-3}$

$$R_D = 0.0702 \pm 0.0017 \pm 0.0023$$

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$D^0 \to \pi^- e^+ \nu_e$: $|\mathbf{V_{cd}}|$

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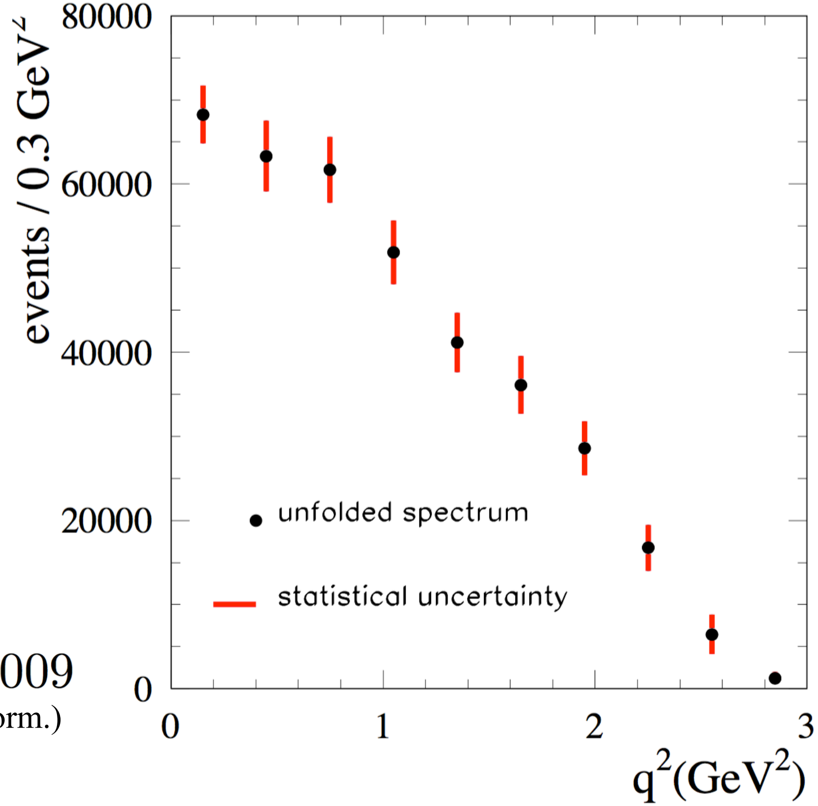
$$|V_{cd}| \times f^{\pi}_{+,D}(0) = \sqrt{\frac{24\pi^3}{G_F^2}\frac{\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)}{\tau_{D^0}\, I}}$$

- τ_D is D^0 lifetime (410 fs)

$$I = \int_0^{q^2_{max}} \frac{|\vec{p}^{\,*}_\pi(q^2)|^3 |f^{\pi}_{+,D}(q^2)|^2}{|f^{\pi}_{+,D}(0)|^2} dq^2$$

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



- From Lattice QCD $f^{\pi}_{+,D}(0)=0.666\pm0.029$.

H. Na, C.T. Davies, E. Follana, J. Koponen, G.P. Lepage, et al., Phys. Rev. D **84**, 114505 (2011).

- Hence:

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

$D^0 \to \pi^- e^+ \nu_e$: $f^{\pi}_{+,D}(0)$

Phys. Rev. D**91** 052022
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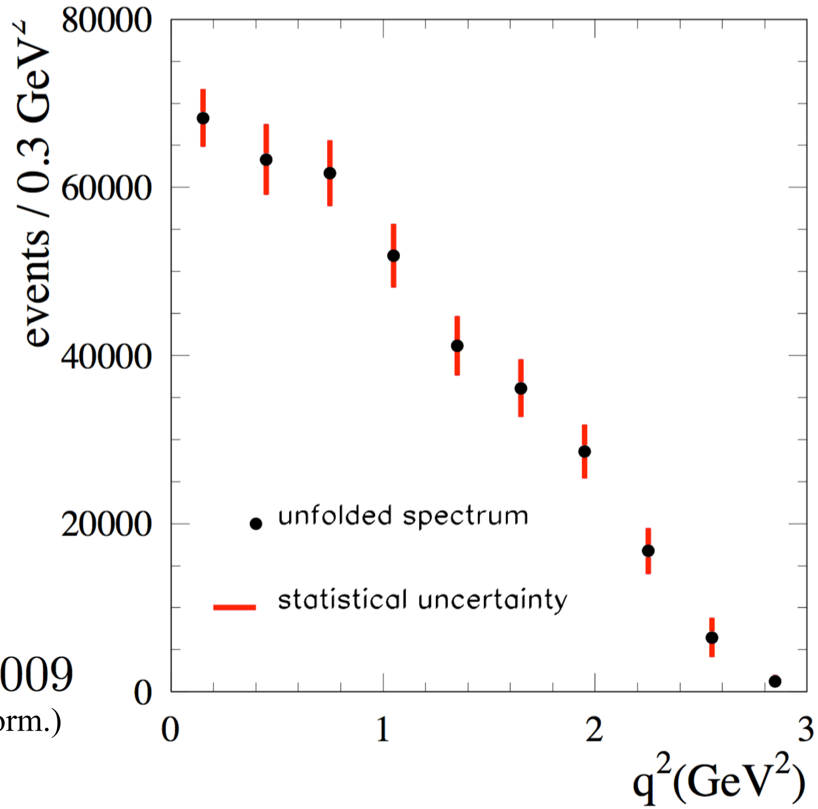

- Assume CKM Unitarity: $|V_{cd}| = |V_{us}| = 0.2252 \pm 0.0009$.

- Thus:

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

$D^0 \to \pi^- e^+ \nu_e$: $|V_{cd}| f^{\pi}_{+,D}(q^2)$

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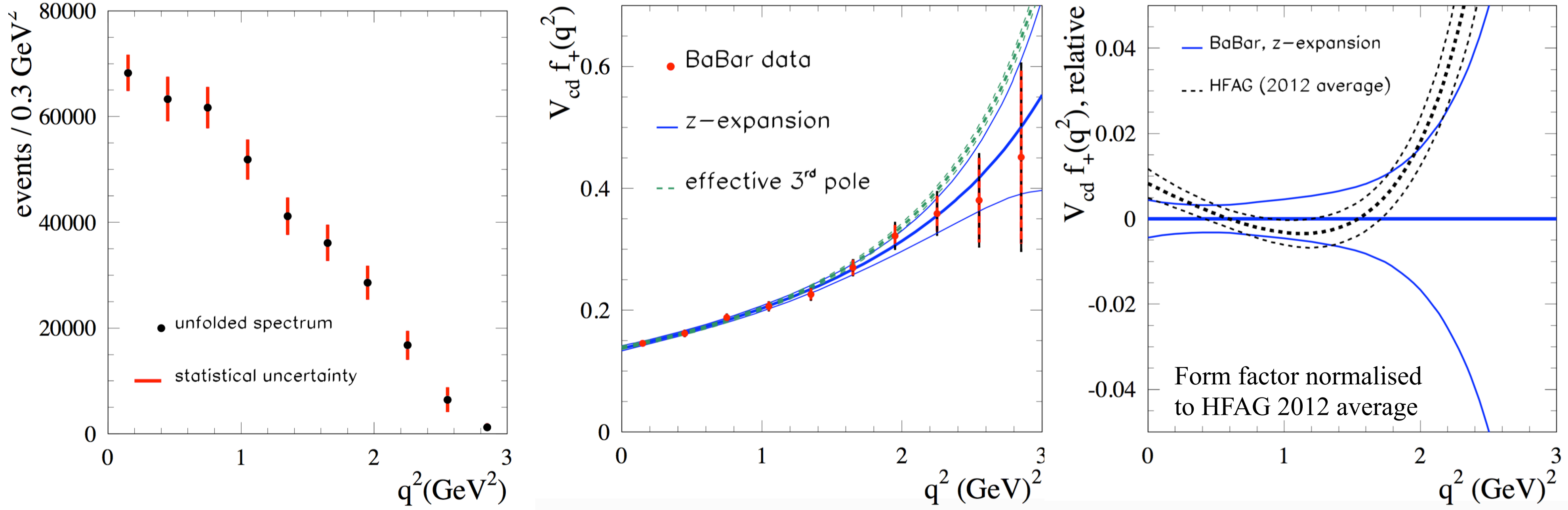
- Unfolded differential decay rate translates into a differential measurement of $|V_{cd}| f^{\pi}_{+,D}(q^2)$:

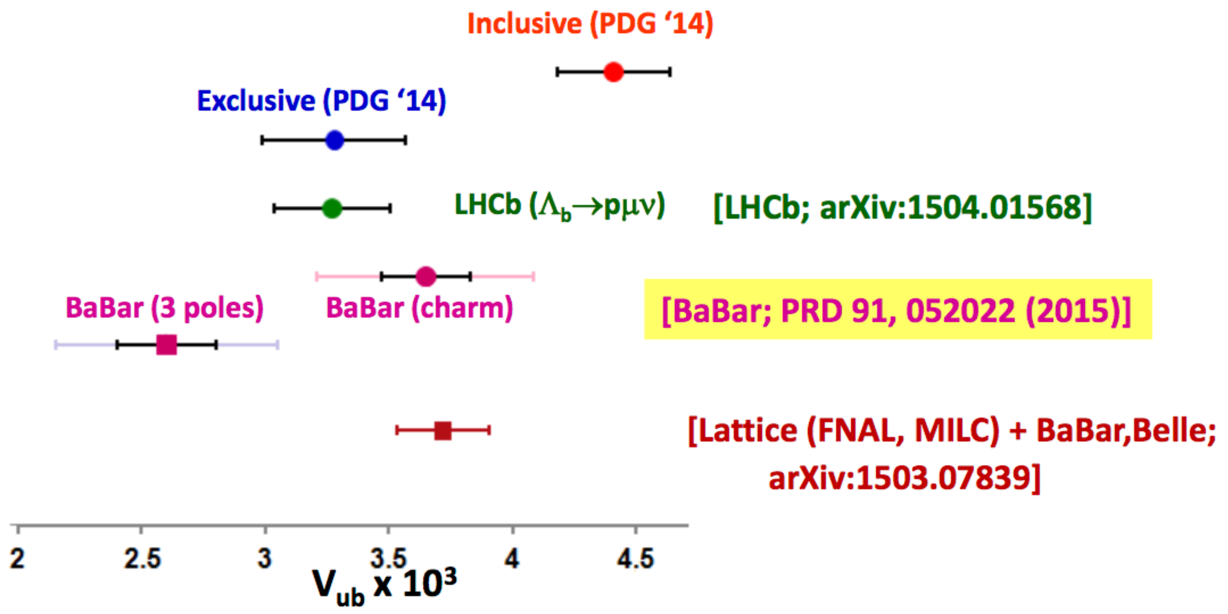


- Good agreement with z-pole expansion model over all q^2.
- Good agreement with HFAG.

Implications for $|V_{ub}|$

Application: V_{ub} extraction

- Comparison with other V_{ub} determinations:



- BaBar systematics of different origin, expected to be reduced by Lattice calculations:

→ ● $f_B(q^2)/f_D(q^2)$ form factor ratio as function of E_π (or w)

→ ■ $g_{H^*H\pi}$ couplings

HEP-EPS, Vienna | Arantza Oyanguren | 15

Conclusions

- First time-dependent mixing parameter amplitude analysis in $D^0 \to \pi^+\pi^-\pi^0$ that yields

$$x = (1.50 \pm 1.17 \pm 0.56)\%$$

$$y = (0.19 \pm 0.89 \pm 0.46)\%$$

  - Results consistent with World Average.
  - Used GooFit (fitting package based on CUDA).
  - Proof of principle measurement: Belle II will be able to take this much further with their expected larger data samples.
- Measured the branching ratio of $D^0 \to \pi^- e^+ \nu_e$ and used this to determine

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

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

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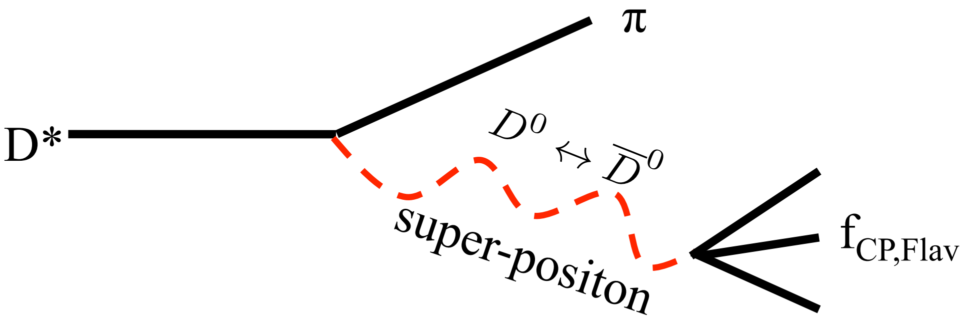
Additional material

- Time evolution of charm decays.
- More on the accelerator.
- Background suppression and differential branching fraction for $D^0 \to \pi^- e^+ \nu_e$.
- Where to find out about the broader physics programme of the B Factories.

Time-evolution of a D^0 meson

- Reconstruct the signal via $e^+e^- \to c\bar{c} \to D^{*+}X; \quad D^{*+} \to D^0\pi_s^+$



$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$
$$\Delta M = m_1 - m_2$$
$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$
$$\Gamma = (\Gamma_1 + \Gamma_2)/2$$

$$\Gamma(P^0 \to f) \propto e^{-\Gamma_1 t}\left[\frac{(1+e^{\Delta\Gamma t})}{2} + \frac{Re(\lambda_f)}{1+|\lambda_f|^2}(1-e^{\Delta\Gamma t}) + e^{\Delta\Gamma t/2}\left(\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M t - \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M t\right)\right]$$

$$\Gamma(\overline{P}^0 \to f) \propto e^{-\Gamma_1 t}\left[\frac{(1+e^{\Delta\Gamma t})}{2} + \frac{Re(\lambda_f)}{1+|\lambda_f|^2}(1-e^{\Delta\Gamma t}) + e^{\Delta\Gamma t/2}\left(-\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M t + \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M t\right)\right]$$

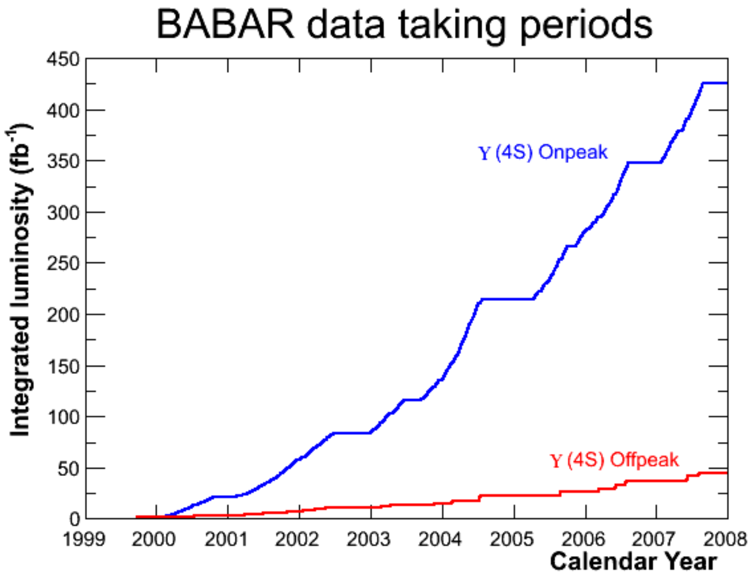
- Neglect CP violation (small) and use the fact that ΔΓ and ΔM are small to analyse in terms of *x* and *y*.

$$x = \frac{\Delta M}{\Gamma} \quad \text{and} \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

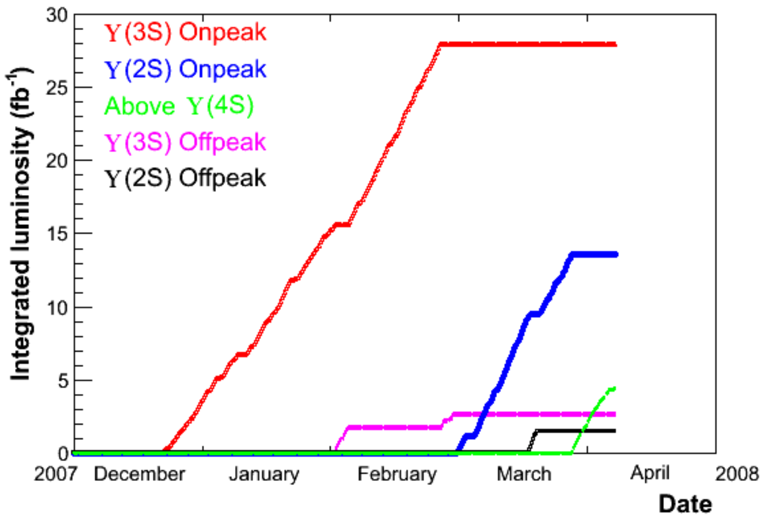
$$\lambda_f = \underbrace{\left|\frac{q}{p}\right|}_{1} e^{i\phi_{MIX}} \left|\frac{\overline{A}}{A}\right| \underbrace{e^{i\phi_{CP}}}_{0}$$

BaBar & PEP-II

- Data was taken from 1999 through 2008
  - Mostly at the *Υ(4S)*;
  - Some "off-peak" just below the *Υ(4S)*; at the *Υ(2S)*, *Υ(3S)* and a high energy scan.



  - $524 fb^{-1}$ recorded in total.
  - High operational efficiency throughout data taking.



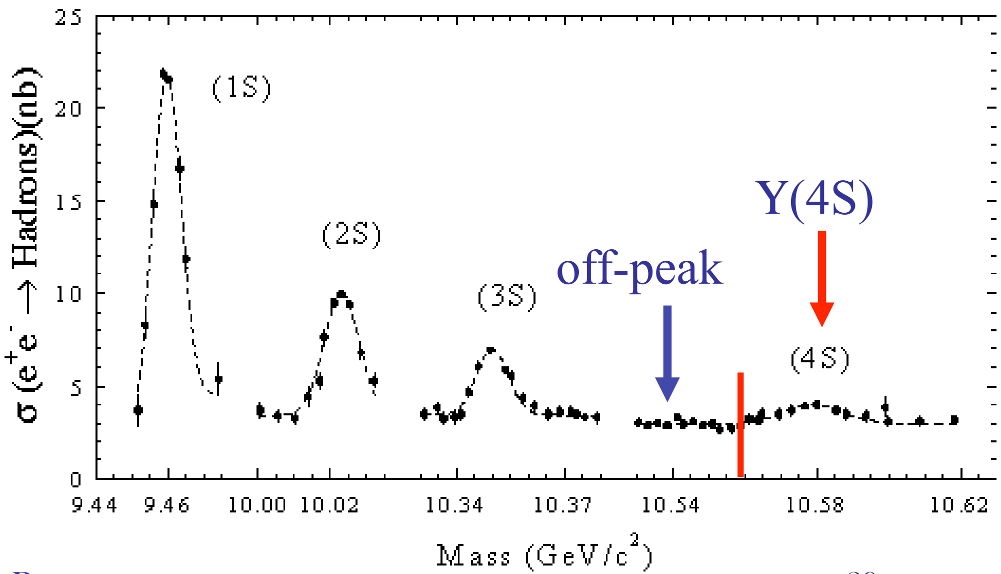
- Re: charm: large cross section

$$\sigma(e^+e^- \to c\bar{c})_{10.58\,GeV} = 1.3nb$$

PEP-II

Parameters			PEP-II
Beam energy		(GeV)	9.0 (e^-), 3.1 (e^+)
Beam current		(A)	1.8 (e^-), 2.7 (e^+)
Beam size at IP	x	(μm)	140
	y	(μm)	3
	z	(mm)	8.5
Luminosity		(cm^{-2} s^{-1})	1.2×10^{34}
Number of beam bunches			1732
Bunch spacing		(m)	1.25
Beam crossing angle		(mrad)	0 (head-on)

- Υ(4S) boost: βγ=0.56.
- Two separate rings brought together at BaBar IP for collisions.



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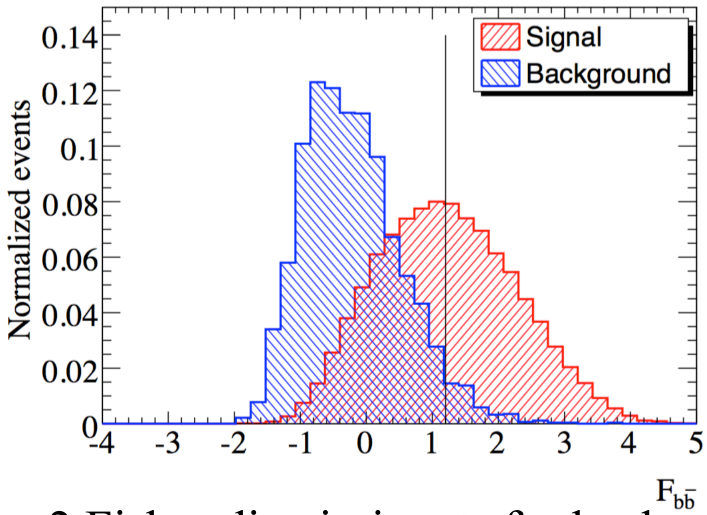
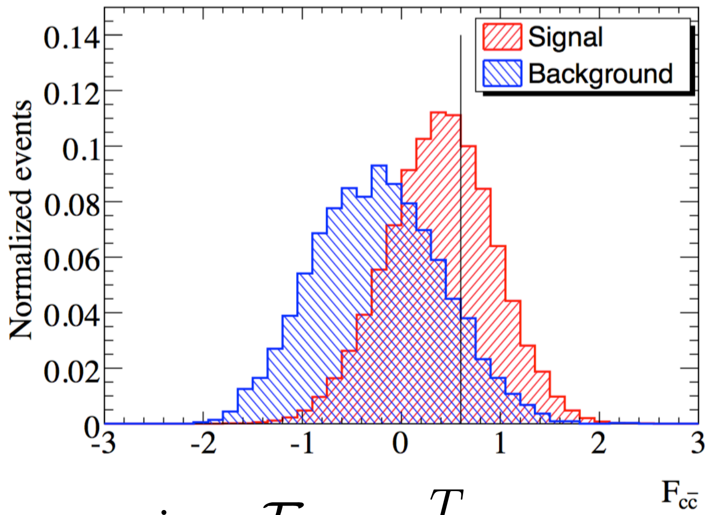
$D^0 \to \pi^- e^+ \nu_e$ background suppression

1.3nb for ccbar; 0.525nb for B^+B^- and B^0B^0bar; 2.09nb for uds continuum events





Use 2 Fisher discriminants for background suppression: $\mathcal{F} = \alpha^T x$.

For B suppression we use:

- R_2 ; the ratio of 2nd to 0th FW moments;
- Total multiplicity of charged and neutral particles detected;
- Momentum of the slow pion: $\pi^{\pm}_s$ used to reconstruct the D*.

For D suppression we use:

- D momentum;
- mass of spectators in the signal hemisphere (i.e. no signal);
- Angle between momentum sum and thrust;
- |p| for leading spectator;
- Angle between leading spectator and D0 directions;
- Angle between leading spectator and thrust axis;
- Direction of lepton relative to pion in eν frame;
- Charged lepton momentum in CM frame.

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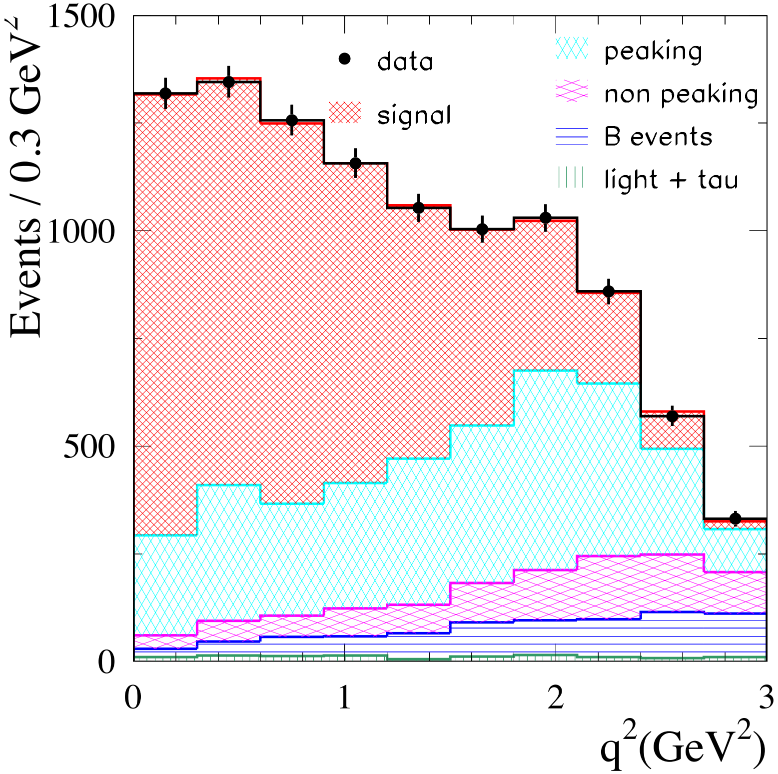
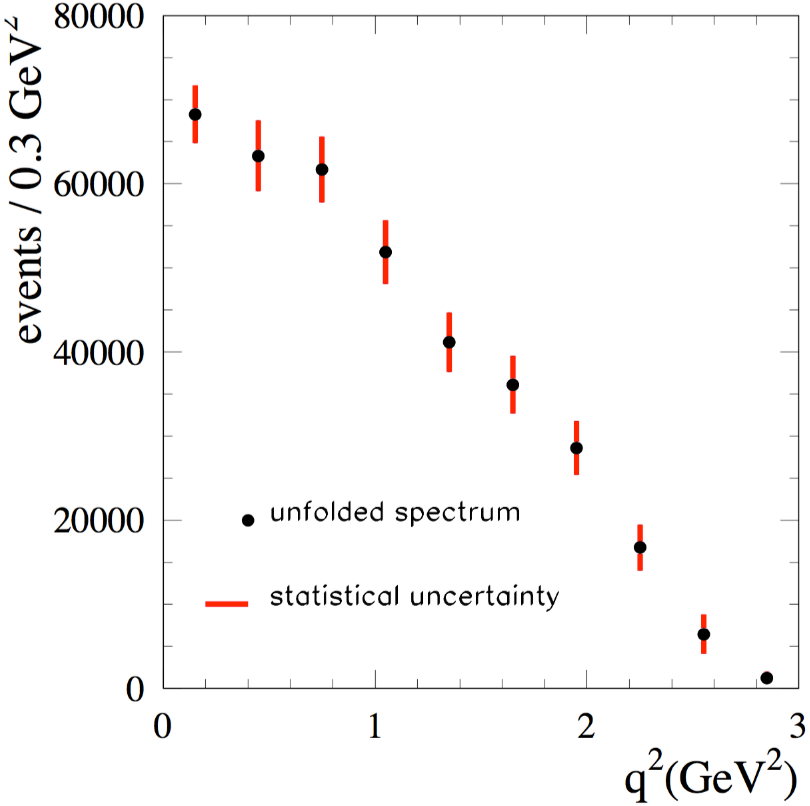
efficiency for $D^0 \to \pi^- e^+ \nu_e$

- Efficiency varies linearly with q^2 from 1.6% at low q2 to 1.0% at high q^2.



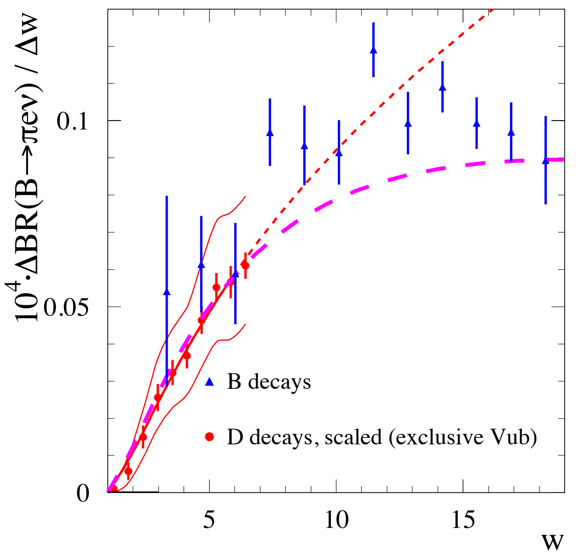


(1) Impact on V_{ub}

- Relate D decay to B decay via:

$$\frac{d\mathcal{B}^B}{dw} = \left.\frac{d\mathcal{B}^D}{dw}\right|_{\text{meas.}} \frac{m_B\ \tau_B}{m_D\ \tau_D}\left(\frac{|V_{ub}|}{|V_{cd}|}\right)^2 R_{BD}^2$$

$R_{BD} = 1.8 \pm 0.2$
(average of available calculations)



Scaling the differential spectrum from this result using the exclusive V_{ub} result from BaBar shows good agreement between the two.

Required as the same V_{ub} is being used for both parts of the comparison.

This plot uses:

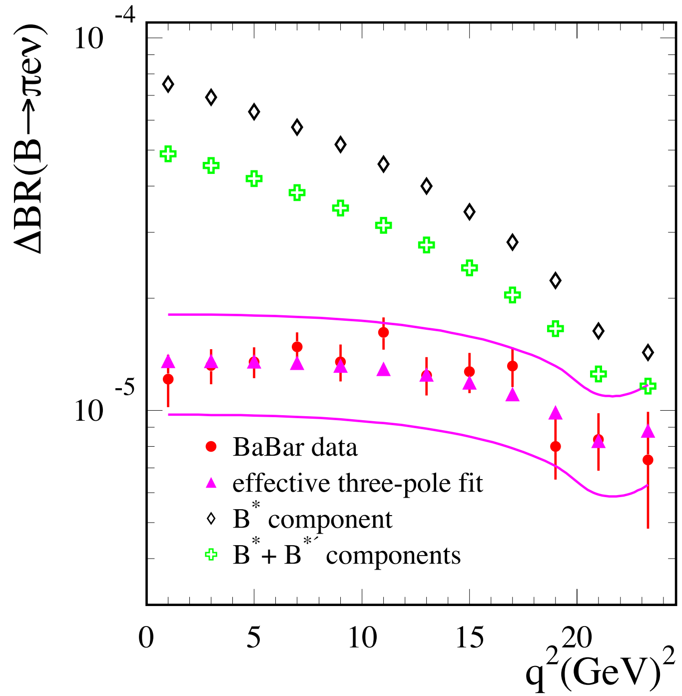
$$|V_{ub}|^{excl.} = (3.23 \pm 0.31) \times 10^{-3}$$

- Fitting the D decay spectrum with a 3-pole model allows us to obtain: $|V_{ub}| = (3.65 \pm 0.18_{exp.} \pm 0.40_{R_{BD}}) \times 10^{-3}$

(2) Impact on V_{ub}

- Relate D decay to B decay via residues in the 3-pole anzatz:

$$f^{\pi}_{+,B}(q^2) = Res(f^{\pi}_{+,B})_{B^*}\left(\frac{1}{m^2_{B^*}-q^2} - \frac{d_2}{m^2_{B_1^{*\prime}}-q^2} - \frac{d_3}{m^2_{B_2^{*\prime}}-q^2}\right), \text{ with } d_3 = 1 - d_2.$$



The ratio of residues is:

$$\frac{Res(f^{\pi}_{+,B})_{B^*}}{Res(f^{\pi}_{+,D})_{D^*}} = \frac{m^{3/2}_{B^*} m^{1/2}_{B}}{m^{3/2}_{D^*} m^{1/2}_{D}} \frac{f_{B^*}}{f_B} \frac{f_D}{f_{D^*}} \frac{\hat{g}_B}{\hat{g}_D} = 6.0 \pm 0.2 \pm 1.0$$

where:

$m(B^*) = 5.941$ GeV
$f_{D^*}/f_D = 1.02 \pm 0.02$ (lattice)
$f_{B^*}/f_B = 1.06 \pm 0.01$ (lattice + data)
effective mass of the third pole is (7.4 ± 0.4) GeV

- Yields:

$$|V_{ub}| = (2.6 \pm 0.2_{\text{exp.}} \pm 0.4_{\text{theory}}) \times 10^{-3}$$

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$D^0 \to \pi^- e^+ \nu_e$ differential branching fraction

TABLE VI: Differential branching fractions ($\Delta\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$) in ten bins in q^2, spanning from 0 to $q^2_{\rm max}$ in GeV^2 (second row), with separate statistical and systematic uncertainties and correlation matrices below. The second row lists the values of the differential branching fraction integrated over 0.3 GeV^2 intervals (quoted in the first row). The off-diagonal elements of the correlation matrices are provided for both the statistical (upper half) and systematic (lower half) uncertainties. The diagonal elements refer to the uncertainties ($\times 10^3$). The uncertainty on the normalization channel (see Eq. (15)) must be added when evaluating the total uncertainty.

q^2 bin (GeV^2)	[0.0, 0.3]	[0.3, 0.6]	[0.6, 0.9]	[0.9, 1.2]	[1.2, 1.5]	[1.5, 1.8]	[1.8, 2.1]	[2.1, 2.4]	[2.4, 2.7]	[2.7, $q^2_{\rm max}$]
$\Delta\mathcal{B} \times 10^3$	0.5037	0.4672	0.4551	0.3827	0.3037	0.2664	0.2110	0.1235	0.0477	0.0090
stat.	0.0257	-0.3345	-0.1429	0.0732	0.0121	-0.0097	-0.0024	0.0004	0.0004	0.0003
uncert.		0.0315	-0.1420	-0.2417	0.0401	0.0311	-0.0034	-0.0050	-0.0007	0.0003
and			0.0290	-0.0852	-0.2376	0.0205	0.0368	0.0034	-0.0062	-0.0062
correl.				0.0283	-0.0110	-0.2395	-0.0223	0.0330	0.0119	0.0034
					0.0263	0.0702	-0.2221	-0.0600	0.0281	0.0382
						0.0254	0.2619	-0.1551	-0.1050	-0.0614
							0.0239	0.3904	-0.1211	-0.2012
								0.0200	0.5148	0.2643
									0.0174	0.9233
										0.0057
syst.	0.0133	0.7488	0.7239	0.6568	0.6321	0.3769	0.0735	0.0309	0.1667	0.2194
uncert.		0.0174	0.8281	0.3433	0.6907	0.4597	0.1576	0.1800	0.3585	0.4216
and			0.0136	0.4608	0.6949	0.6524	0.3740	0.3482	0.4333	0.4196
correl.				0.0119	0.7096	0.4462	0.2939	0.2055	0.2310	0.1772
					0.0103	0.7076	0.4513	0.4597	0.6588	0.6371
						0.0120	0.8772	0.8344	0.7076	0.5088
							0.0181	0.9644	0.6184	0.3135
								0.0156	0.7439	0.4539
									0.0087	0.9345
										0.0025

$D^0 \to \pi^- e^+ \nu_e$ $|V_{cd}| f^{\pi}_{+,D}(0)$

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This result:

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

TABLE VII: Measurements of the normalization factor $|V_{cd}| \times f^{\pi}_{+,D}(0)$ and of the parameters r_1 and r_2 used in the z-expansion parameterization of the hadronic form factor. The two sets of values for the CLEO-c (2008) untagged analysis correspond to the $\pi^- e^+ \nu_e$ and $\pi^0 e^+ \nu_e$ channels, respectively. Predictions based on four LQCD calculations, obtained using $|V_{cd}| = |V_{us}|$, are listed at the bottom.

Experiment	ref.	$\lvert V_{cd}\rvert \times f^{\pi}_{+,D}(0)$	r_1	r_2
Belle (2006)	[6]	$0.140 \pm 0.004 \pm 0.007$		
CLEO-c untagged (2008)	[7]	$0.140 \pm 0.007 \pm 0.003$	-2.1 ± 0.7	-1.2 ± 4.8
CLEO-c untagged (2008)	[7]	$0.138 \pm 0.011 \pm 0.004$	-0.22 ± 1.51	-9.8 ± 9.1
CLEO-c tagged (2009)	[8]	$0.150 \pm 0.004 \pm 0.001$	$-2.35 \pm 0.43 \pm 0.07$	3 ± 3
BESIII (2012)(prel.)	[42]	$0.144 \pm 0.005 \pm 0.002$	$-2.73 \pm 0.48 \pm 0.08$	$4.2 \pm 3.1 \pm 0.4$
HFAG average (2012)	[40]	0.146 ± 0.003	-2.69 ± 0.32	4.18 ± 2.16
BESIII (2014)(prel.)	[9]	$0.1420 \pm 0.0024 \pm 0.0010$	$-1.84 \pm 0.22 \pm 0.07$	$-1.4 \pm 1.5 \pm 0.5$
This analysis		$0.137 \pm 0.004 \pm 0.002 \pm 0.001$	$-1.31 \pm 0.70 \pm 0.43$	$-4.2 \pm 4.0 \pm 1.9$

LQCD Predictions	ref.	$\lvert V_{cd}\rvert \times f^{\pi}_{+,D}(0)$	r_1	r_2
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	-1.93 ± 0.20	0.37 ± 0.93

The Physics of the *B* Factories

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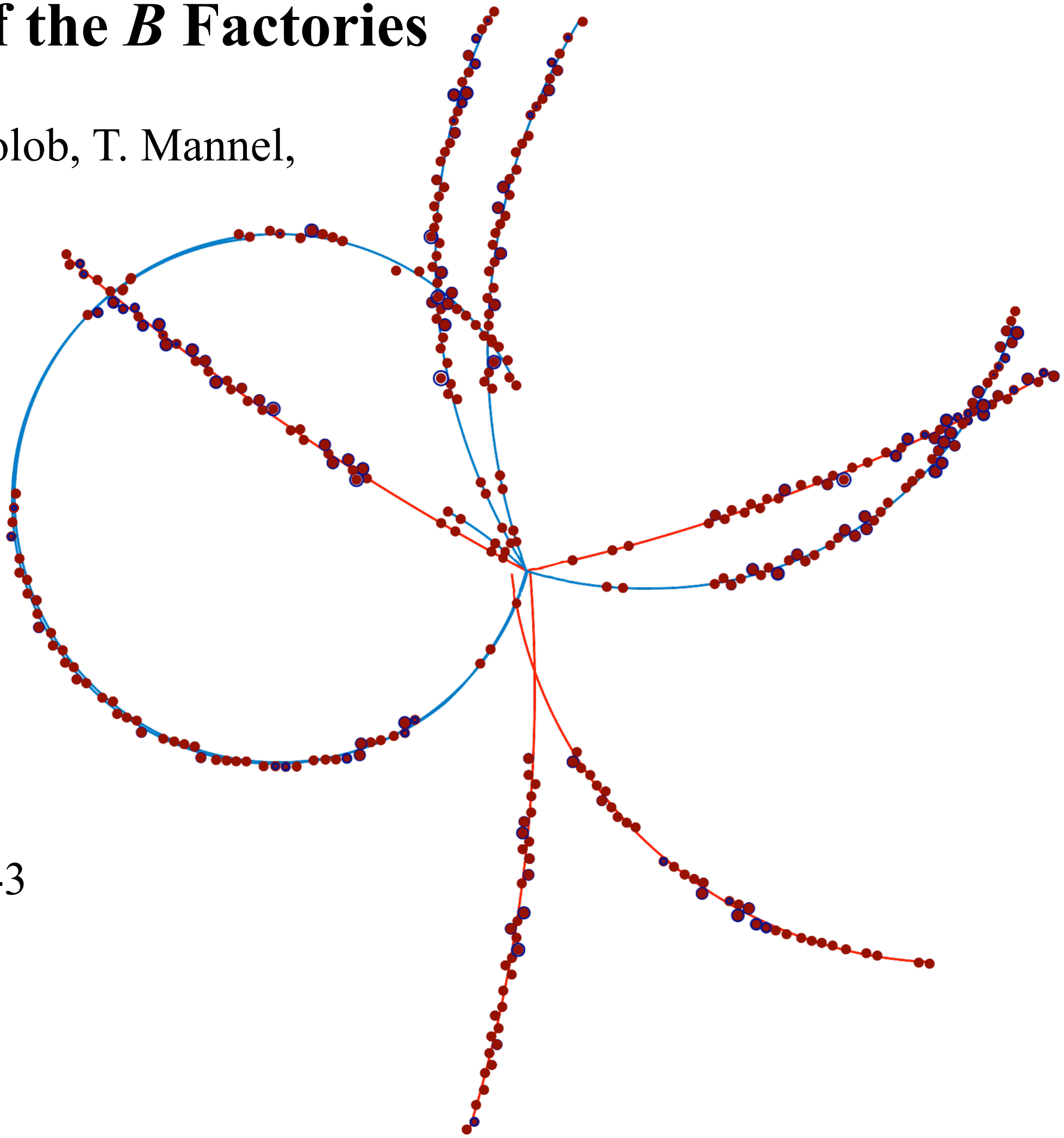

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