Particle-Flow Algorithm Development
and
Charm Physics with BaBar

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Part I. Particle-Flow Algorithm Development

- **Motivation**
- **Work so far is in context of the SiD detector concept**
  - **But is applicable elsewhere**
  - **Part of larger study of SiD global parameters**
    - **Especially those relating to calorimetry**
    - **Keep in mind physics performance vs. cost as well as jet energy resolution vs. global parameters**
- **Variations in hadronic calorimeter (HCAL) design**
  - **Thickness in interaction lengths**
  - **Inner radius**
  - **Length**
  - **Transverse segmentation**
  - **Layer thickness**
  - **Material**
  - **Readout**
- **Jet energy studies**
- **Particle-Flow Algorithm summary**

MIT HCAL variants study

- This study covers variations in sid02 HCAL parameters
  - "sid02" is a current benchmark for SiD studies
    - Uses generic component shapes (cylinders, planes; faster than more detailed descriptions)
  - HCAL λ_{total} = 4.0, 4.5, 5.0, 5.5, 6.0 λ_{int}
  - Number layers = 30, 40, 50, 60
  - Cell size 1x1 cm^2
  - Data sets
    - 10k qqbar events at 100, 200, 350, 500, and 1000 GeV
    - 10k events ZZ→ nunubar, uds at 500 GeV
- Recently began running on CMS Tier-2 center at MIT
  - Running one variant (at all energies for qqbar & ZZ) takes < 2 days
    - Was 3-4 weeks on old Condor system
- Becomes practical to investigate a larger range of global parameter space
- Obvious things to do include
  - Update to latest lcsim software
  - Vary HCAL cell size, length, …
  - Compare to PandoraPFA running in lcsim package

Notes on Simulation

- λ_{total} for each variant calculated as
  - λ_{total} = total absorber depth + (λ_{int} /readout layer) x (# readout layers)
- Readout layer geometry is fixed across all variants
  - 0.8 cm thickness per readout layer
  - 0.0096 λ_{int} per readout layer
  - Fraction of λ_{total} due to readout layers varies:
    - 30 layers: 0.29 λ_{int}
    - 60 layers: 0.58 λ_{int}
- Statistical uncertainties on RMS90 values
  - On order of ±0.1–0.2 percentage points

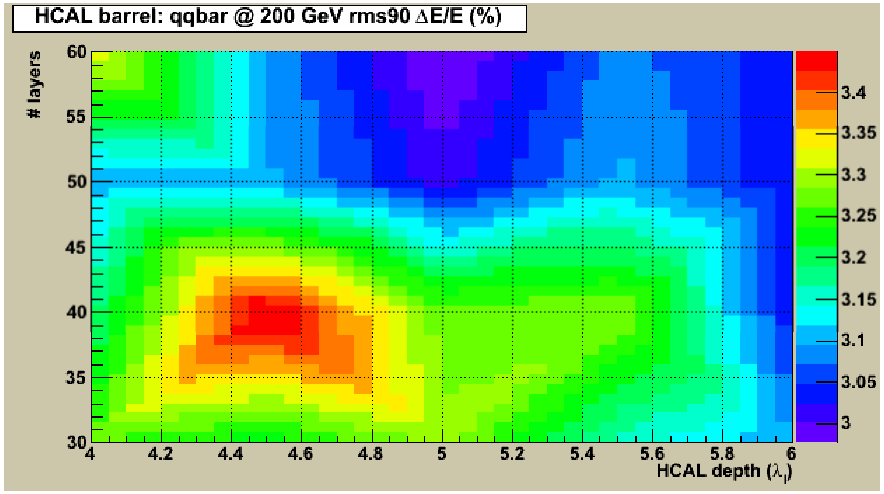
Sample of results at λ_{total} = 6.0, barrel region

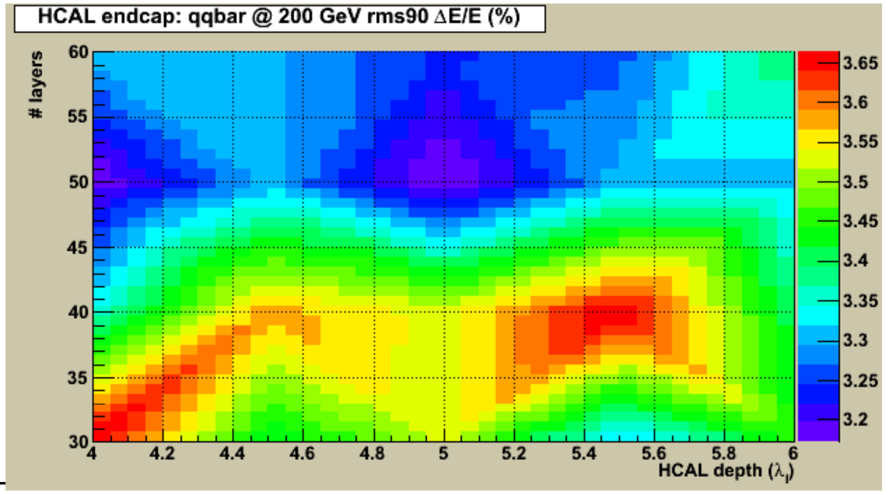
Variant	30 layers		40 layers		50 layers		60 layers		sid02 default*	
All in GeV	m90	r90	m90	r90	m90	r90	m90	r90	m90	r90
qq100 Event energy	−1.7 (7278)	3.9%	−2.3 (7278)	3.6%	−2.1 (7278)	3.7%	−2.1 (7278)	3.6%	−1.8	3.7%
qq200 Event energy	−5.2 (7275)	3.1%	−6.7 (7275)	3.0%	−6.1 (7275)	3.0%	−5.8 (7275)	3.0%	−4.9	3.0%
qq350 Event energy	−7.8 (7177)	3.1%	−11.0 (7177)	3.0%	−9.2 (7177)	3.5%	−6.9 (7177)	3.2%	N/A	N/A
qq500 Event energy	−11.5 (7332)	3.6%	−17.3 (7332)	3.5%	−9.6 (7332)	3.9%	−6.4 (7332)	3.8%	−13.6	3.5%
qq1000 Event energy	−22.9 (6523)	5.9%	−38.3 (6876)	5.7%	−2.8 (6876)	6.3%	+1.4 (6876)	6.1%	N/A	N/A
ZZ500 Dijet mass	−1.3 (2370)	4.8%	−2.1 (2370)	4.7%	−1.6 (2370)	4.8%	−1.4 (2370)	4.8%	−1.2	4.7%

(nnnn) = # entries in aida cloud
* = M. Charles, LCWS08

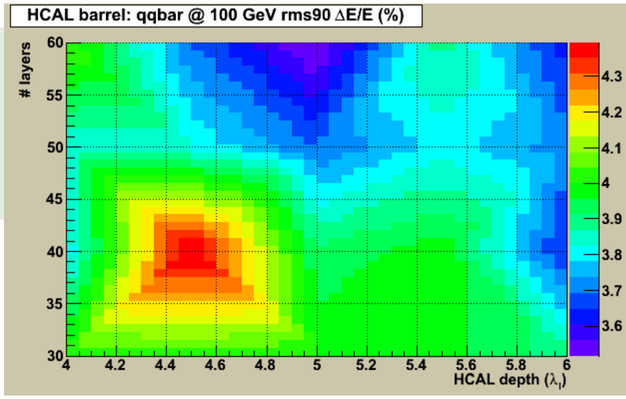
SiD rms90 qqbar 200 GeV

- **Interpolated contour plots of jet energy resolution**
  - 20 points (5 depth x 4 #layers combos)
  - Barrel/endcap definition
    - $\cos(\theta_{beam}) \equiv$ polar angle of generated Z→qqbar
    - Barrel region
      - $|\cos(\theta_{beam})| < 0.8$
    - Endcap region
      - $0.8 < |\cos(\theta_{beam})| < 0.95$
- **Average, general trends are evident**
  - Thicker calorimeter, more layers improves resolution
  - But more to understand about the details

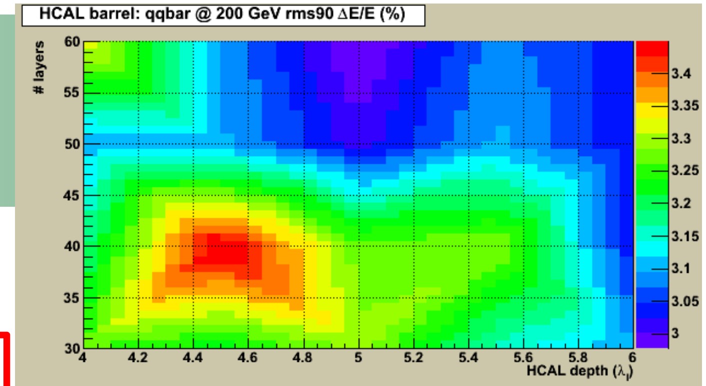




qqbar
100 GeV

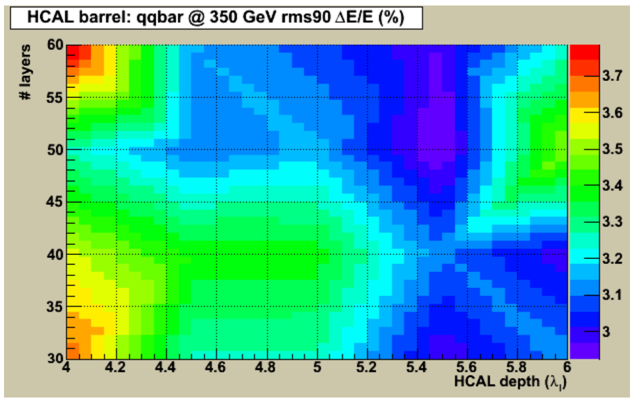


qqbar
200 GeV

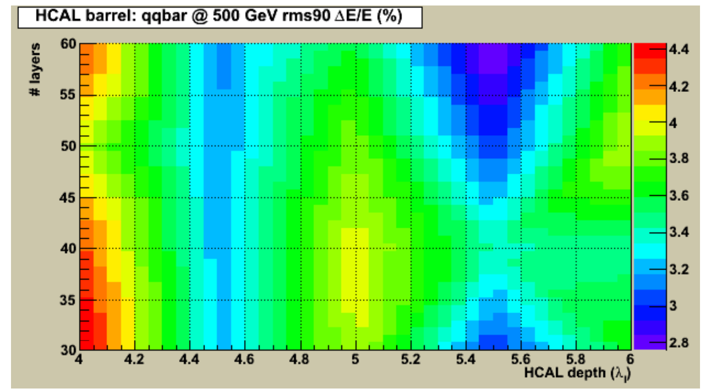


BARREL

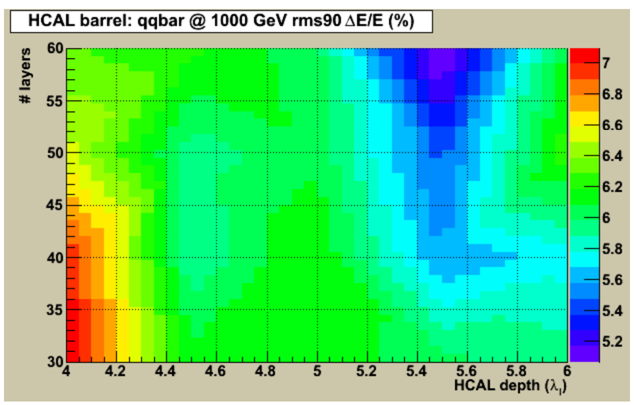
qqbar
350 GeV



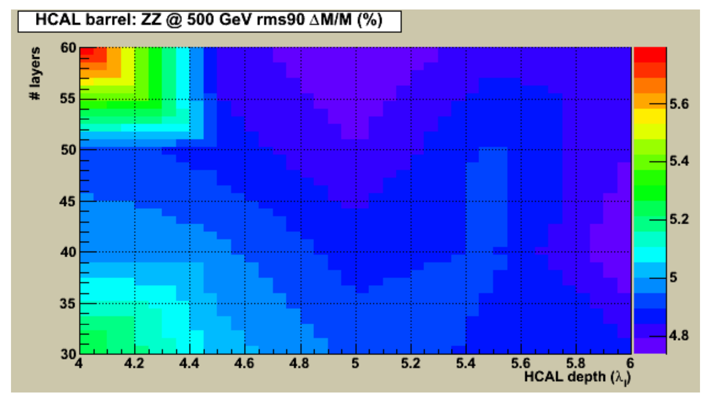
qqbar
500 GeV



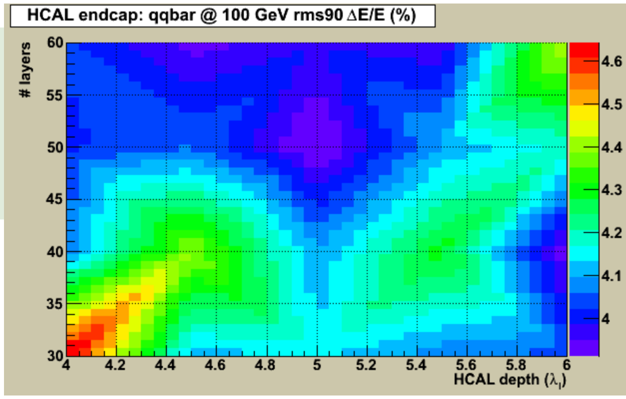
qqbar
1000 GeV



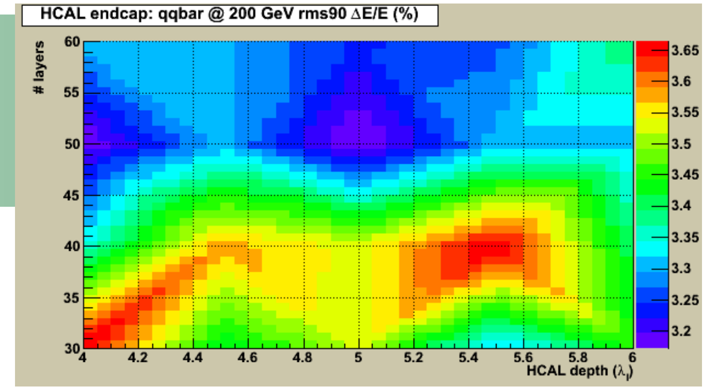
ZZ
500 GeV



qqbar
100 GeV

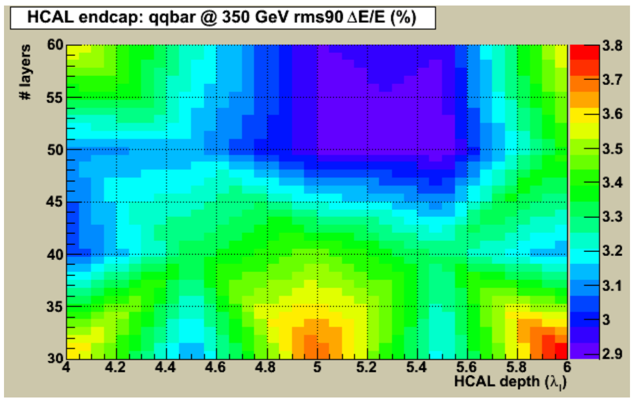


qqbar
200 GeV

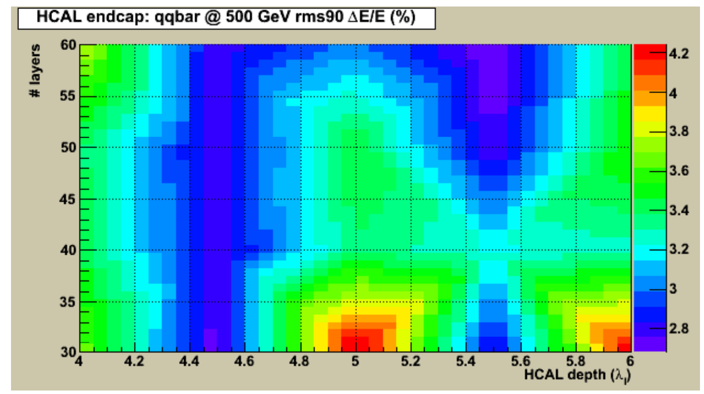


ENDCAP

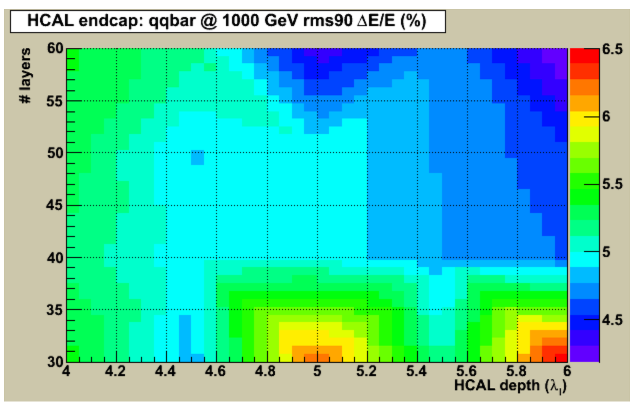
qqbar
350 GeV



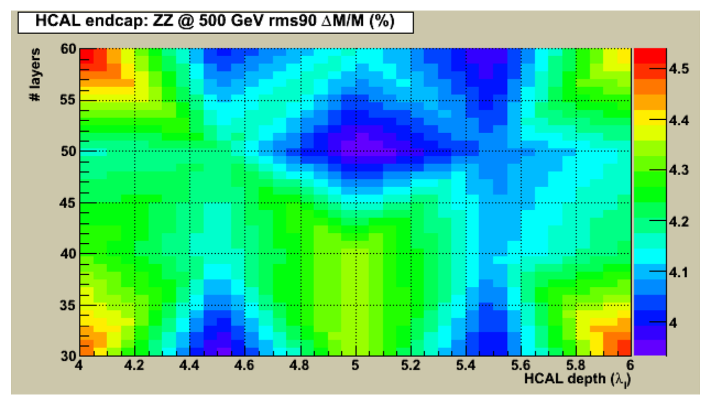
qqbar
500 GeV



qqbar
1000 GeV

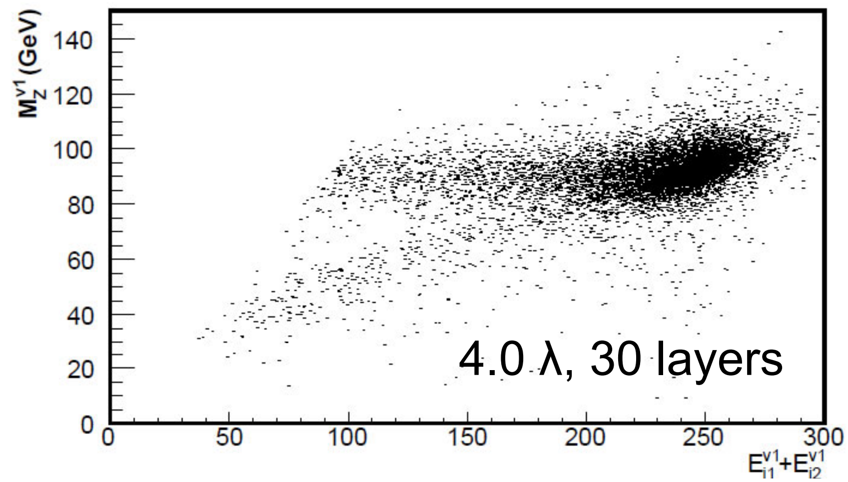


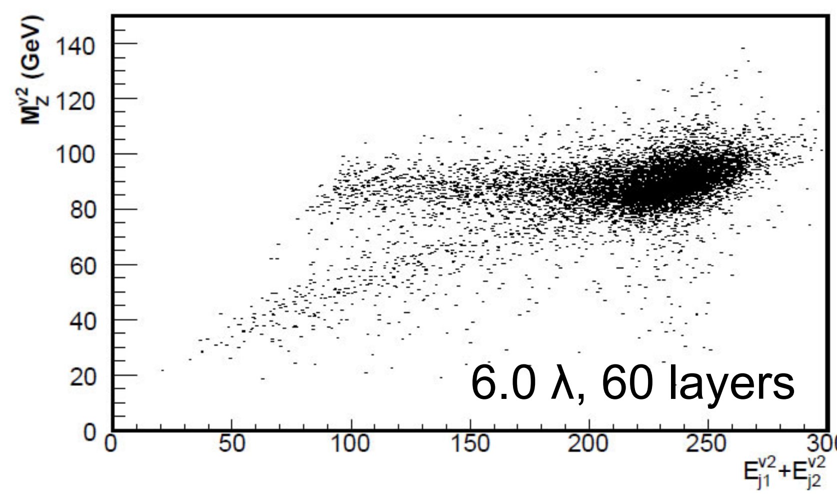
ZZ
500 GeV



Another way to compare HCAL variants

- **Compare two HCAL variants**
  - **Variant 1 (v1): 4.0 λ, 30 layers, cell size 1x1 cm^2**
  - **Variant 2 (v2): 6.0 λ, 60 layers, cell size 1x1 cm^2**
- **Simulated events**
  - **$e^+e^- \rightarrow ZZ$ @ 500 GeV**
    - **1st Z → ν anti-ν**
    - **2nd Z → *uds* quark jets**
    - **Includes gluon radiation and beamstrahlung**
- **Shows improved Z mass resolution of variant 2 w.r.t. variant 1**
  - **Band at constant M_Z is due to events with significant amounts of beamstrahlung and gluon radiation**
  - **Interesting feature is the diagonal tail**
    - **Needs more investigation**





Additional Ideas

- **Remember that the PFA approach is being used outside the context of ILC detectors**
  - ♦ Example: CMS
    - Joe Incandela: *"Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and Emiss_T"* http://cms-physics.web.cern.ch/cms-physics/public/PFT-09-001-pas.pdf
- **It may be useful to keep in touch with folks outside the ILC PFA community as well**
  - ♦ We wonder if it might make sense at some point to hold a PFA workshop addressing both the ILC and non-ILC PFA community
- **Can other shower characteristics be used to divide showers into categories with different statistical behavior?**
  - ♦ What about the effect of leading particles in showers?
  - ♦ Can consideration of lateral vs. longitudinal spread provide information?
  - ♦ Some studies along this line have been done before
    - Is it useful to do so again?
- **Look at effects of HCAL cross-talk/noise using digisim**
- **Choose two or three variants to use as testbed for PFA development**
  - ♦ Get a better idea of how detector and software improvements change energy resolutions

PFA summary

- Initial results of sid02 HCAL global parameters study show
  - Average behavior is that resolution improves
    - With increasing λ_{total}
    - With increasing # layers for fixed λ_{total}
  - But there are questions
    - E.g., poorer resolution at $\lambda_{total} = 4.0\ \lambda_{int}$ and 60 layers
- We will write a cone jet algorithm just for comparison
- We will write a technical note on this study
- We are running now
  - sid02 with cell sizes 3x3 cm^2, 5x5 mm^2
- Access to substantially more CPU cycles
  - By factor of 10–20x
  - Permits addressing these and other issues

Part II. Charm physics with BaBar

- Highlights & history
- Motivation & phenomenology
- Current & future work
- Wrapping up BaBar effort
  - Current K3π analysis
    - Extend to amplitude analysis
    - Considering $K_s\pi\pi\pi 0$
      - Natural extension of K3π
  - Leverage long-term investment in BaBar
  - Leverage the wonderful BaBar dataset
    - BaBar published results across the physics spectrum remain competitive with Belle published results
      - Even in light of Belle’s 80% more data
  - Contribute to the BaBar/Belle physics legacy book (2012 timescale)

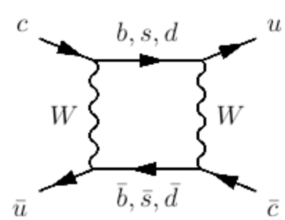
Charm mixing highlights & history

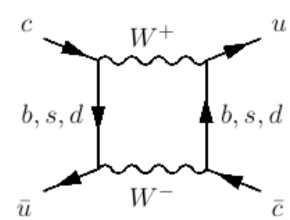
- **Highlights**
  - Working on charm mixing since 2002
    - UC Santa Cruz joined in the effort in 2004
    - Stanford in 2006
  - Unexpectedly strong evidence for mixing ~4σ
    - Discovered in 2007 using $D^0 \rightarrow K\pi$ decays
  - Coincident with strong evidence from Belle at same time
  - Started new flurry activity in the field that continues today
    - Vigorous pursuit of both mixing and CPV in the charm sector
    - CLEO, BaBar, Belle, CDF, D0, others
    - Expect interesting new results from LHCb, other LHC
  - Charm mixing analyses in BaBar make use of the decay modes
    - $D^0 \rightarrow K\pi$, KK, $\pi\pi$, $K\pi\pi 0$, $K_s\,\pi\pi$, $\pi\pi\pi^0$
- **Our main efforts have been in**
  - $K\pi$ — PRL 98:211802,2007 ("TopCite 100+" in SPIRES)
  - $KK/K\pi$ (tagged) — PRD 78 011105(R) (2008)
  - $KK/K\pi$ (untagged) — PRD 80 071103(R) (2009)
  - $K3\pi$ — in progress
- **Support other efforts in BaBar (not primary analysts) — especially:**
  - CPV search using T-odd moments (uses $KK\pi\pi$ mode) — Phys. Rev. D 81, 111103(R) (2010)
  - Update of $KK/K\pi$ lifetime ratio — in progress
- **Although combined evidence for mixing is about 10σ (HFAG)**
  - No single analysis yet provides evidence above 5σ

Charm meson mixing

Why is observation of charm mixing interesting?

- It completes the picture of quark mixing already seen in the *K*, B_d, and B_s systems
  - *K* — PR 103, 1901 (1956); PR 103, 1904 (1956)
  - B_d — PL B186, 247 (1987); PL B192, 245 (1987)
  - B_s — PRL 97, 021802 (2006); PRL 97, 242003 (2006)
- It provides information about processes with down-type quarks in the mixing box diagram





- It provides strong constraints on new physics
  - E. Golowich, J. Hewett, S. Pakvasa, A. Petrov PRD 76, 095009 (2007)
- It is a significant step toward observation of *CP* violation in the charm sector—which would very likely signal new physics

Charm mixing phenomenology

Neutral *D* mesons

are produced as *flavor eigenstates* D^0 and $\bar{D}^0$

and are governed by

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

with *mass, lifetime eigenstates* D_1, D_2

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

where $|q|^2 + |p|^2 = 1$ and

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

D_1, D_2 have masses M_1, M_2 and widths Γ_1, Γ_2

Mixing occurs when

there is a *non-zero* mass

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

For convenience define quantities *x* and *y*

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

where

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Short- and long-distance effects

Short-distance effects from the mixing box diagrams primarily contribute to *x*

- ***b*** **quark contribution is CKM-suppressed**
- ***s*** **and** ***d*** **quarks contributions are GIM suppressed**
- **Expect** ***O*****(10^{-5}) or less**

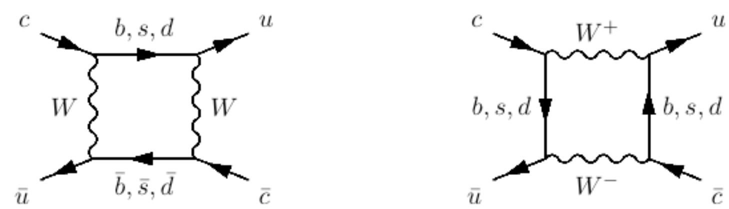
Long-distance effects primarily contribute to *y*

- **Non-perturbative**
- **Expect** ***O*****(10^{-2}) or less**

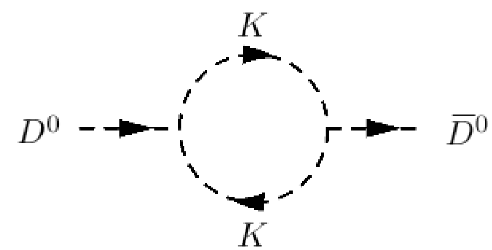
New physics would be indicated if

- $x \gg y$
- ***CP*** **violation is observed**

Short-distance



Long-distance



Patricia Ball, hep-ph/0703245, Moriond 2007:
"The central problem of all these calculations is that the D is too heavy to be treated as light and too light to be treated as heavy."

CP violation

CP violation (CPV) can be classified as occurring

- In direct decay: $|\overline{A}_{\overline{f}}/A_f| \neq 1$

  where $A_f = BB\langle f|H_{\rm w}|D^0\rangle\,, \quad \overline{A}_{\overline{f}} = \langle \overline{f}|H_{\rm w}|\overline{D}{}^0\rangle$
- In mixing: $|q/p| \neq 1$
- In the interference between them: $\mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0$

CPV introduces an asymmetry in the time-dependence between D^0 and $\overline{D}{}^0$ decays

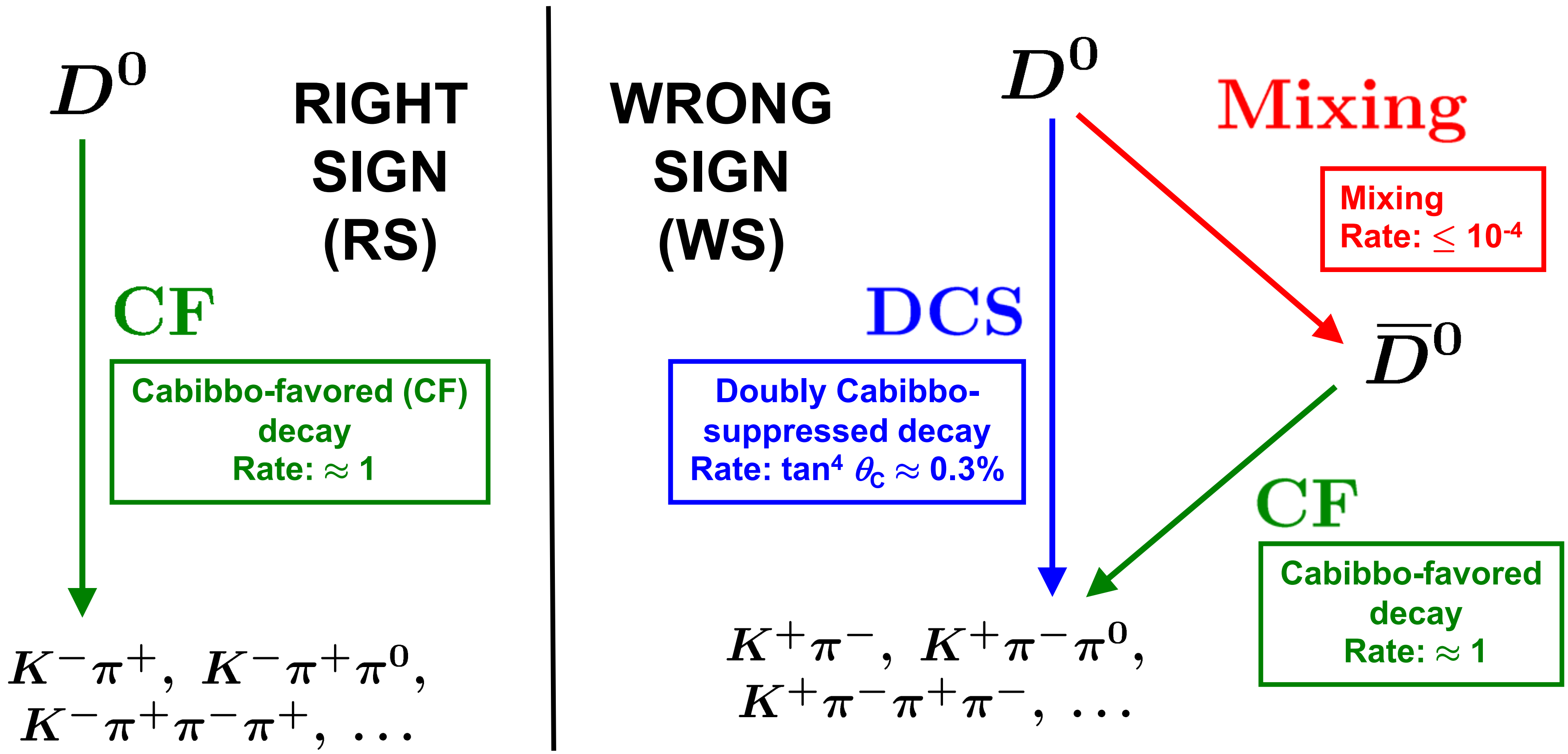
$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \quad \propto \quad e^{-\Gamma t} \times \left[R_{\rm D} + \sqrt{R_{\rm D}}\left|\frac{q}{p}\right|(y'\cos\varphi - x'\sin\varphi)\Gamma t + \left|\frac{q}{p}\right|^2 \frac{x'^2+y'^2}{4}(\Gamma t)^2\right]$$

$$\frac{d\Gamma}{dt}[|\overline{D}{}^0(t)\rangle \to \overline{f}] \quad \propto \quad e^{-\Gamma t} \times \left[R_{\rm D} + \sqrt{R_{\rm D}}\left|\frac{p}{q}\right|(y'\cos\varphi + x'\sin\varphi)\Gamma t + \left|\frac{p}{q}\right|^2 \frac{x'^2+y'^2}{4}(\Gamma t)^2\right]$$

where φ is the phase angle of $\lambda_f = \left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right)$

Wrong-sign D^0 decays

Determine the $\overline{D}^0$ flavor at production and at decay



Time-dependent decay rate

For $x, y \ll 1$

$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \rightarrow f] \propto e^{-\Gamma t}\left(R_{\mathrm{D}} + \sqrt{R_{\mathrm{D}}}y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$

DCS decay

Interference between DCS and mixing

Mixing

Allows for a strong phase difference $\delta_{K\pi}$ between CF and DCS direct decay

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}, \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

This phase may differ between decay modes

Time-integrated mixing rate R_M defined by $R_M = \frac{x^2 + y^2}{2}$

D^0 decay reconstruction

Reconstruction

- Identify as $D^0/\bar{D}^0$ at production & decay
- Determine $m_{K\pi}$, Δm, proper-time t and error δ_t

$$\Delta m = m(D^{*+}_{\rm rec}) - m(D^0_{\rm rec})$$

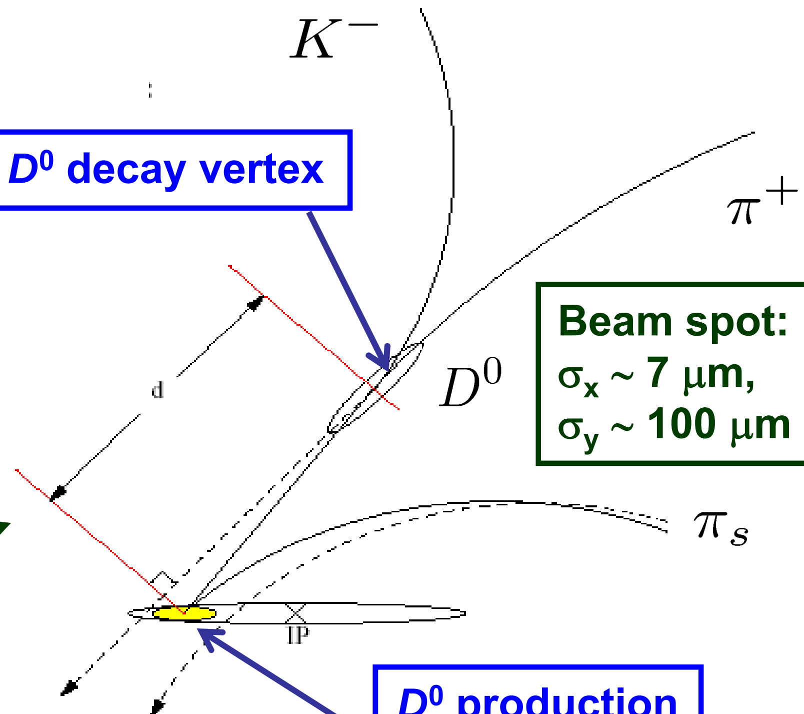
Vertex fit uses beamspot constraint

- Improves the decay-time error
- Improves the Δm resolution

Typical D^0 flight length $d \sim 240\ \mu$m
Average resolution $\sigma_d \sim 95\ \mu$m

Shown: two-body, right-sign decay

$$D^{*+} \to \pi_s^+ D^0,\ D^0 \to K^-\pi^+$$



Beam spot:
$\sigma_x \sim 7\ \mu$m,
$\sigma_y \sim 100\ \mu$m

D^0 production vertex

Charm mixing: *KK*/*K*π lifetime result

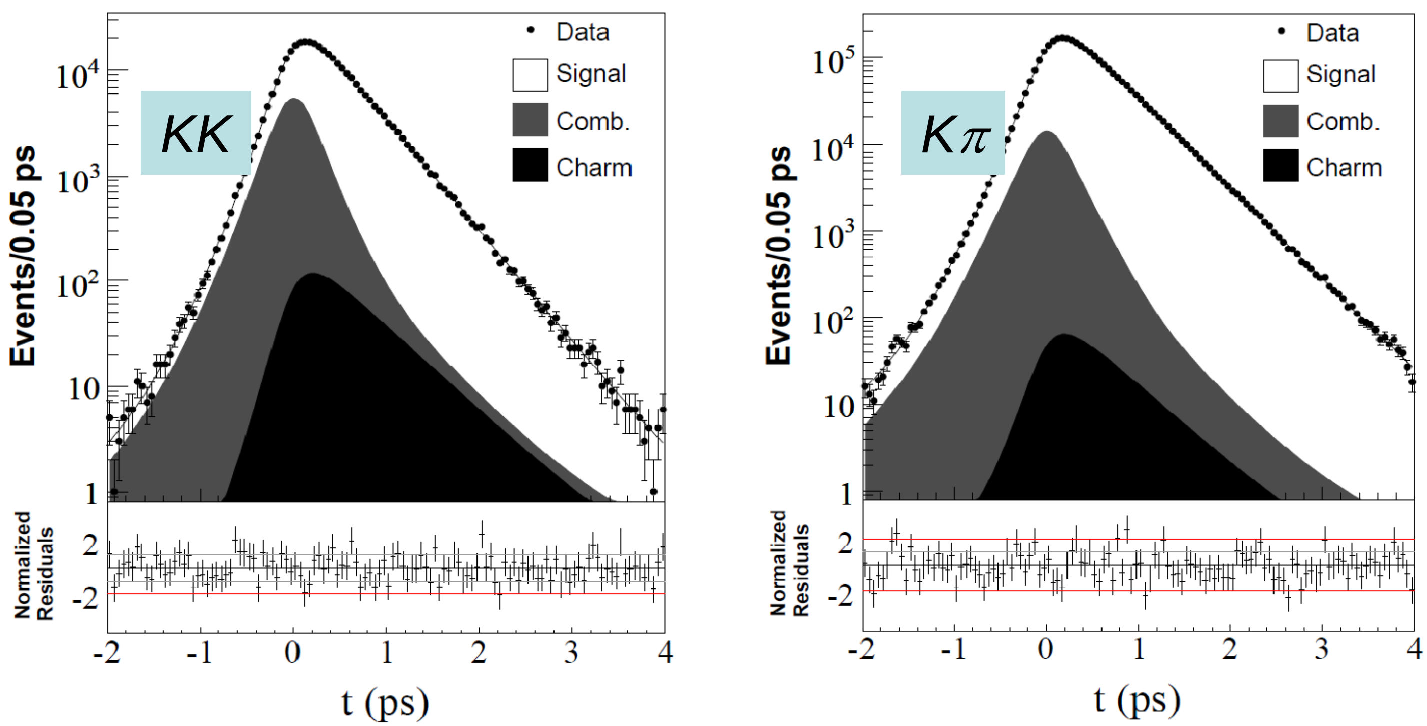
Y_{CP} (untagged) = [1.12 ± 0.26 (stat.) ± 0.22 (syst.)]% PRD 80 071103(R) (2009)

Y_{CP} (tagged) = [1.24 ± 0.39 (stat.) ± 0.13 (syst.)]% PRD 78 011105(R) (2008)

Significance of combined tagged and untagged results:

4.1σ (including 100% correlated systematics)

KK and *K*π lifetime fits



Update in progress

Analysis improvements

- **Significant improvements in BaBar reconstruction in last two years**
  - Improved two-body KK, $K\pi$ statistical uncertainties by 40%
    - PID improvements (1.10x)
    - Tracking improvements (1.09x)
    - Selection cuts (1.13x)
    - Use of entire on/off resonance dataset (1.17)
  - Will have similar effect on the four-body $K3\pi$ analysis
    - No prior analysis to compare with
  - Given the excellent state of the BaBar dataset and reconstruction,
  - And the importance of charm mixing and CPV in the search for new physics,
  - We believe it is most important to pursue these analyses to the fullest extent possible with BaBar
    - As it may be some time before new data in these areas becomes available

Charm mixing: $D^0 \rightarrow K\pi\pi\pi$

Similar to 2007 BaBar $K\pi$ discovery analysis

- Uses $K\pi\pi\pi$ mode
- More complex backgrounds
- Similar statistics
  - B.R. x efficiency is approximately the same as for $K\pi$

Improvements:

- Four-body decay gives better decay vertex measurement
- Using latest improvements in tracking and PID
- Using full, final BaBar dataset
- Possibility of $> 5\sigma$ significance for mixing in this decay mode
  - Best to date is the 4.1σ in $KK/K\pi$ lifetime ratio result

K3pi plot goes here

$D^0 \rightarrow K\pi\pi\pi$ plot caption

Charm mixing summary

- **Our long-time effort in BaBar is winding down**
  - Started in 1995
- **But not completely done yet**
  - Would like to see the project through to the end
  - Ramp from about 20% of Cowan's time down to zero over next three years
    - Support BaBar efforts through the "steady analysis period"
    - Finish K3π mixing
    - Possibly extend K3π to include amplitude analysis
      - Or work with other collaborators on $K_S\pi\pi\pi^0$ (e.g., U. of Cincinnati)
    - Contribute to BaBar/Belle legacy book effort
      - Charm section of "Physics of the B-Factories"
      - See http://www.slac.stanford.edu/xorg/BFLB/

Extra slides

- **Extra slides**