# B Physics in the LHC Era

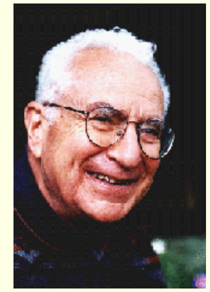
R. Cahn

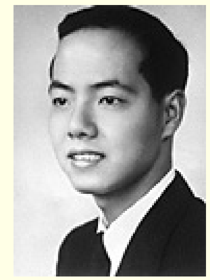
Beauty 2003 - Carnegie Mellon University

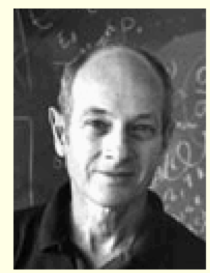
October 17, 2003

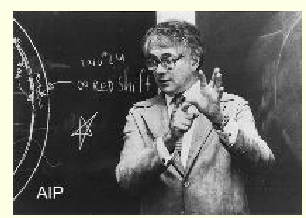
# Is the $B$ the $K$ of the 21st Century?

$K$ meson has driven particle physics:







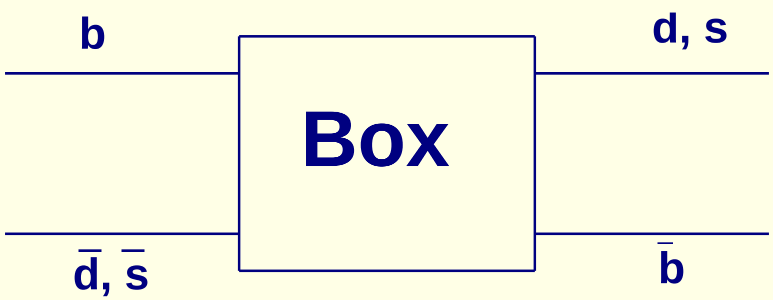


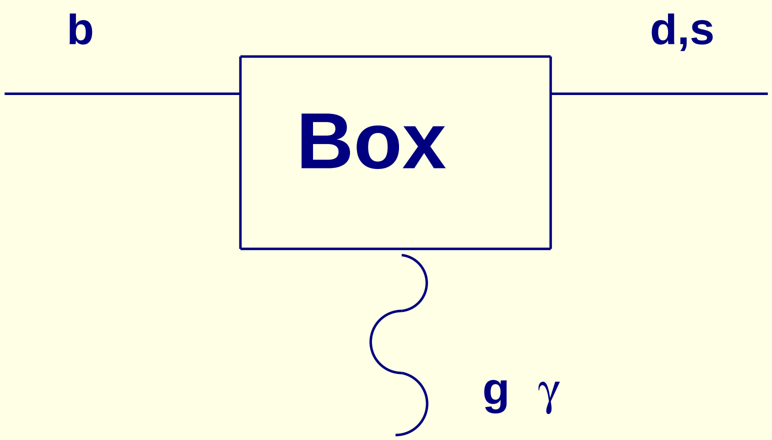

- Strangeness
- Mixing of neutral kaons
- $\tau - \theta$ puzzle leads to parity violation
- Strangeness leads to $SU(3)$ leads to quarks
- CP violation in $K_L$ decay
- Absence of neutral weak currents leads to charm
- $\epsilon'/\epsilon$ shows direct CP violation

# 21st Century Agenda: Page One


- Electroweak-Symmetry Breaking
- Grand Unification/Extra Dimensions
- Baryon-Antibaryon Asymmetry
- Dark Matter
- Dark Energy

# $B$ Physics: Virtual Attack



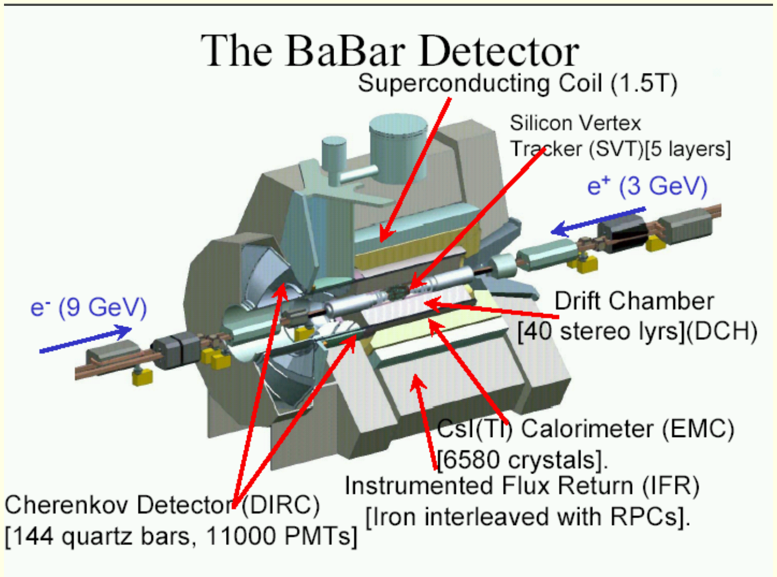




- $B_d \to J/\psi\, K_S$
- $B_s \to J/\psi\, \phi$

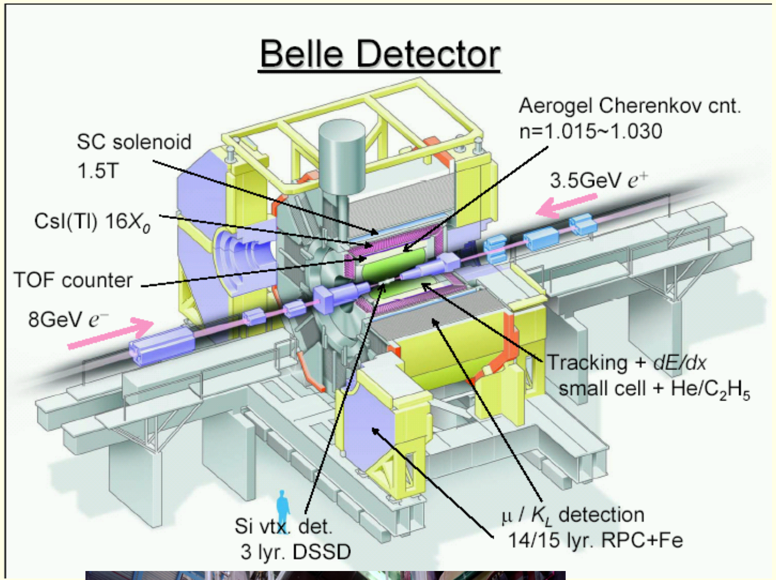
- $B_d \to K^*\gamma$, $K^*\ell^+\ell^-$
- $B_d \to \phi K_S$, $K^+K^-K_S$, $\eta' K_S$

What's in the box? SUSY?, extra generations, extra dimensions?

# Today

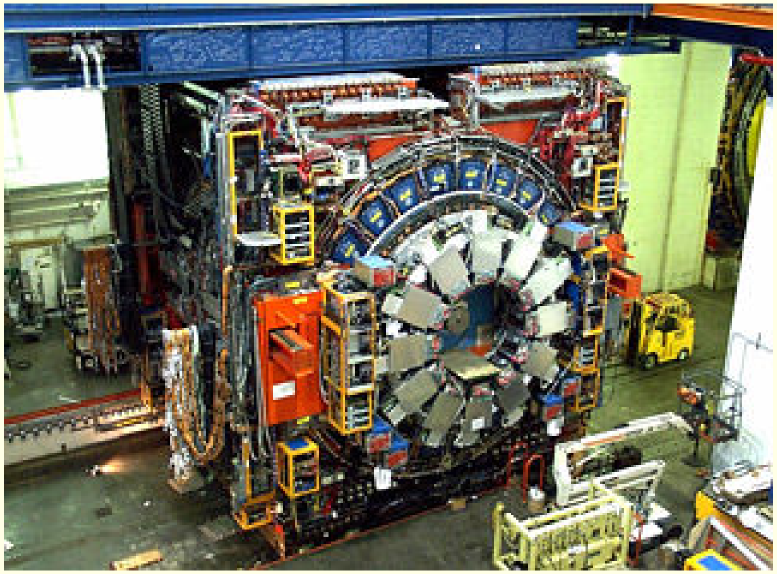


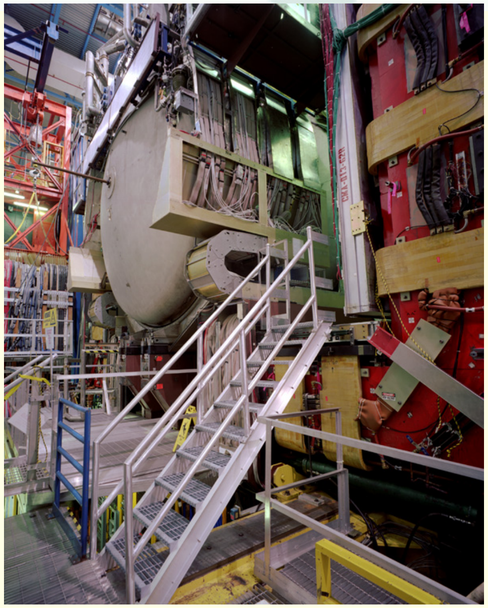
The BaBar Detector
Superconducting Coil (1.5T)
Silicon Vertex Tracker (SVT)[5 layers]
e+ (3 GeV)
e- (9 GeV)
Drift Chamber [40 stereo lyrs](DCH)
CsI(Tl) Calorimeter (EMC) [6580 crystals].
Instrumented Flux Return (IFR) [Iron interleaved with RPCs].
Cherenkov Detector (DIRC) [144 quartz bars, 11000 PMTs]

Belle Detector
SC solenoid 1.5T
Aerogel Cherenkov cnt. n=1.015~1.030
3.5GeV $e^+$
CsI(Tl) $16X_0$
TOF counter
8GeV $e^-$
Tracking + $dE/dx$ small cell + He/$C_2H_5$
Si vtx. det. 3 lyr. DSSD
$\mu$ / $K_L$ detection 14/15 lyr. RPC+Fe


CDF

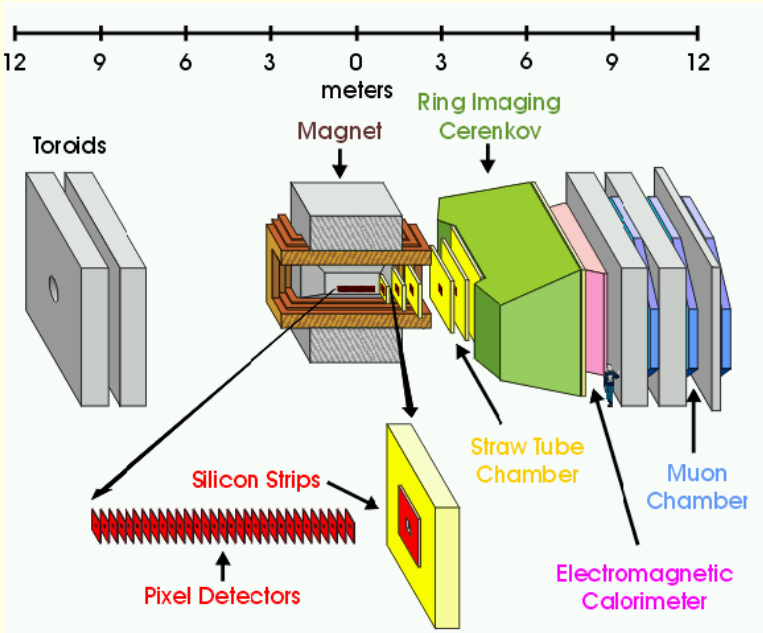


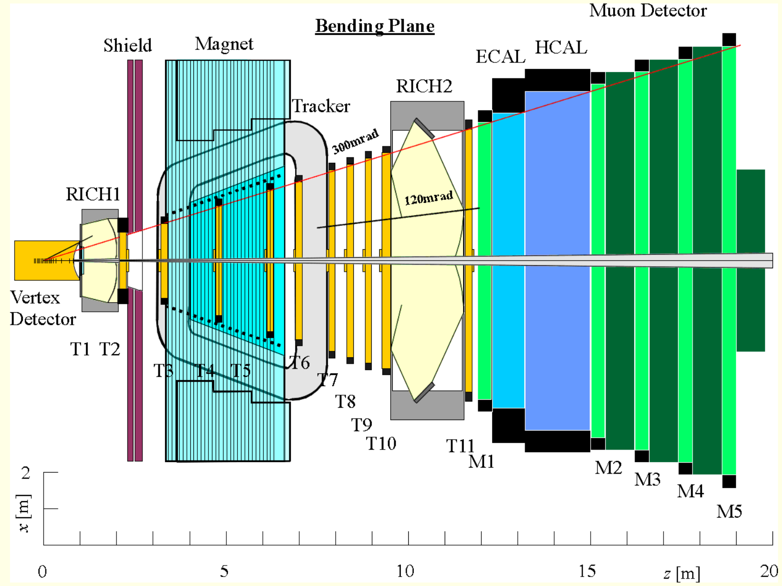


D0

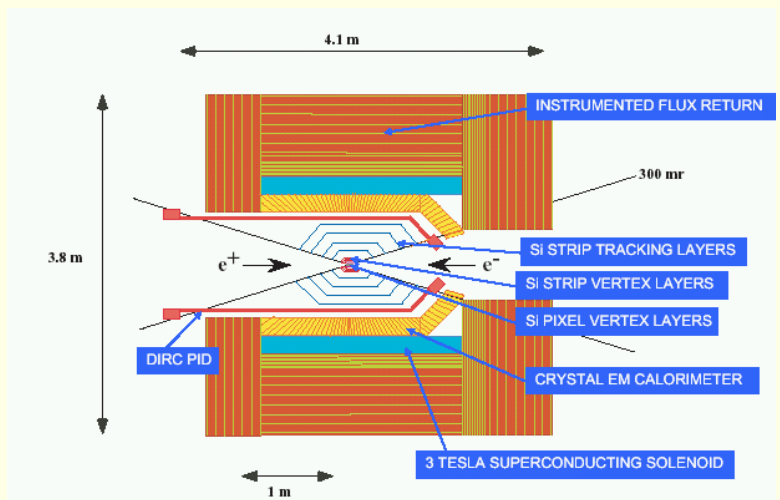
# Tomorrow

BTeV



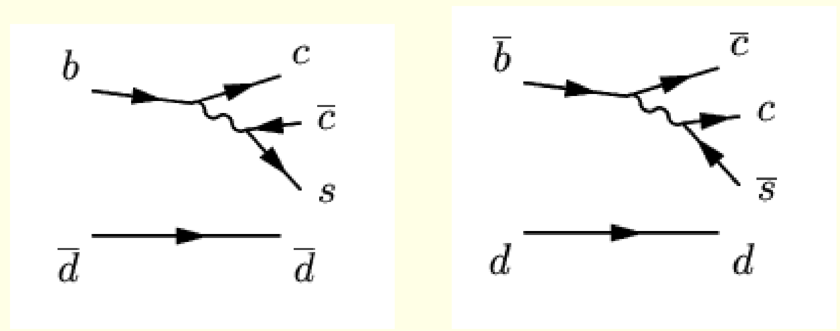

LHCb




$10^{36}$

# $B \to J/\psi K_S$

1. Measure: mixing angle
2. Theory problems: none
3. Experimental problems: none
4. Precision in $\sin 2\beta$



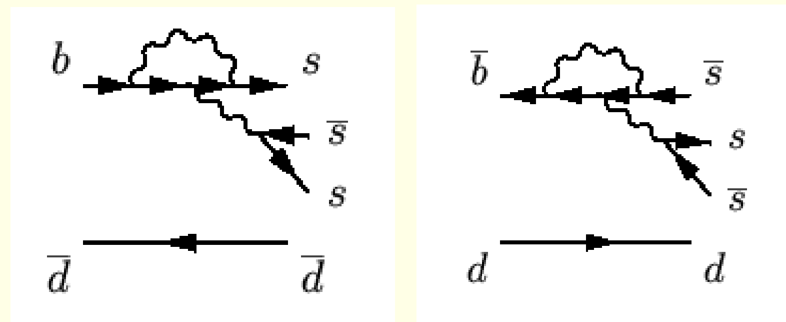

| BaBar | Belle | $e^+e^-$ | BTeV/LHC-b | Super B |
|---|---|---|---|---|
| $0.08\ \mathrm{ab}^{-1}$ | $0.14\ \mathrm{ab}^{-1}$ | $0.5\ \mathrm{ab}^{-1}$ | $10^7$ s | $10\ \mathrm{ab}^{-1}$ |
| $0.067 \oplus 0.033$ | $0.057 \oplus 0.028$ | $0.03$ | $0.017$ | $0.008$ |

# $B \to \phi K_S$

1. Measure: mixing angle and possible new physics

2. Theory motivation: new physics could compete

3. Experimental problems: low branching ratio




4. Precision in $\sin 2\beta$

| BaBar/Belle | | BTeV/LHC-b | Super B |
|---|---|---|---|
| $0.11\ \mathrm{ab}^{-1}$ | $0.5\ \mathrm{ab}^{-1}$ | $10^7$ s | $10\ \mathrm{ab}^{-1}$ |
| $0.43 \oplus 0.07$ | $0.23$ | $0.14$ | $0.056$ |

# $B_s$ oscillations: $x_s$

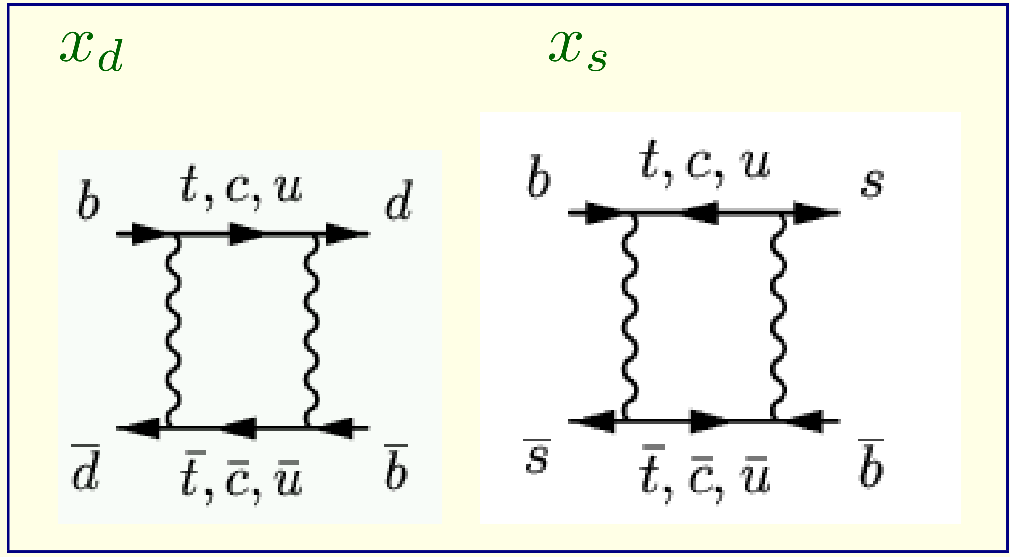
1. Measure: mixing in $B_s - \overline{B}_s$ system

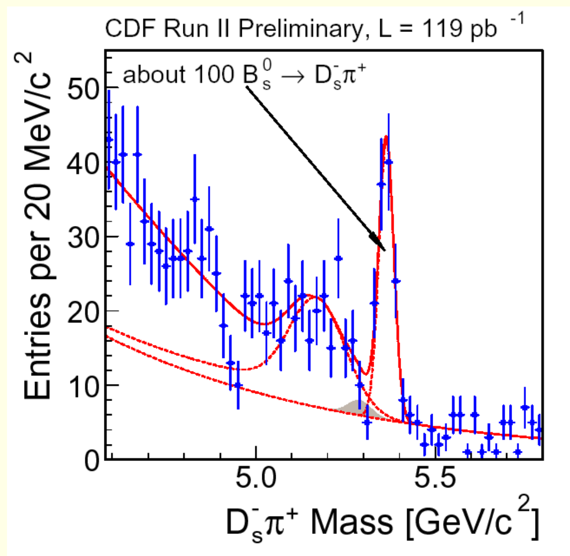
2. $\frac{x_s}{x_d} = \frac{m_{B_s}\eta_{B_s}B_{B_s}f^2_{B_s}}{m_{B_d}\eta_{B_d}B_{B_d}f^2_{B_d}}|V_{ts}/V_{td}|^2 \rightarrow$ 10% uncertainty in $|V_{td}/V_{td}|$

3. Experimental problems: need $B_s$!

4. CDF/D0 should measure $x_S$ with good precision

5. Lattice calculations needed to get full benefit of measurement



# Could this be LHC Era Physics?
# CDF Estimate [K. Pitts, L-P 2003]

- Currently
  - 1600 signal events / fb $^{-1}$
  - Tagging efficiency: $\epsilon D^2 = 4\%$
  - Time resolution: $\sigma = 67\ fs$
  - Sensitivity: 2$\sigma$ for $\Delta m_s = 15\,\mathrm{ps}^{-1}$ with $\approx 0.5\,\mathrm{fb}^{-1}$
- "Modest Improvements"
  - 2000 signal events / fb $^{-1}$ [better trigger, more modes]
  - Tagging efficiency: $\epsilon D^2 = 5\%$ [kaon tagging]
  - Time resolution: $\sigma = 50\ fs$
  - Sensitivity: 5$\sigma$ for $\Delta m_s = 18\,\mathrm{ps}^{-1}$ with $\approx 1.7\,\mathrm{fb}^{-1}$
  - Sensitivity: 5$\sigma$ for $\Delta m_s = 24\,\mathrm{ps}^{-1}$ with $\approx 3.2\,\mathrm{fb}^{-1}$

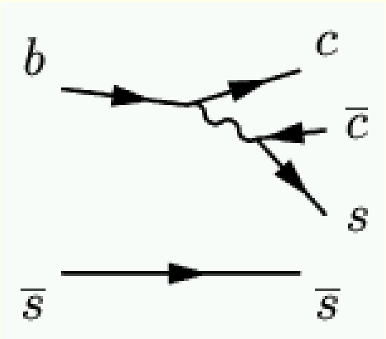
# $B_s \to J/\psi\phi, J/\psi\eta'$

1. Measure: analog of $B \to J/\psi K_S$ No asymmetry to lowest order.

2. Theory motivation: new physics with phase of $B_d - \overline{B}_d$ mixing would show up

3. Experimental problems: requires $B_s$, good spatial resolution

4. BTeV reach in $\sin 2\chi : \pm 0.024$

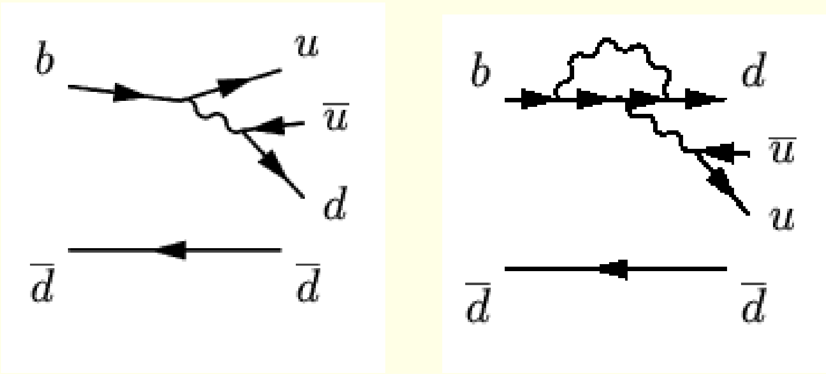


# $B \rightarrow \pi\pi$

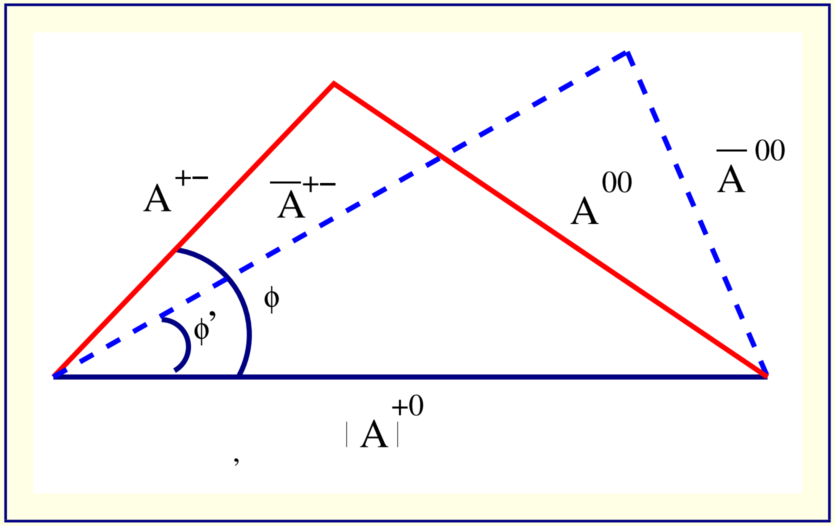
- Measure: mixing angle (arg $M_{12}$) plus $2\gamma$, i.e. $2\pi - 2\alpha$
- Theory concern: prominent penguin contribution
- Experimental problems: small branching ratio for $\pi^0\pi^0$
- Penguins are $\Delta I = 1/2$ operators, trees $\Delta I = 3/2, 1/2$
- Use isospin to isolate $I = 2$ final state (no penguin contribution)

Tree

Penguin



# Fighting Penguins in $B \to \pi\pi$




$\alpha_{eff}$ from time-dep. $B^0, \overline{B}^0 \to \pi^+\pi^-$

$2\alpha = 2\alpha_{eff} + \phi - \phi'$

(Four-fold) Ambiguity: $\phi \to -\phi$

- Measure time-integrated $\Gamma(B^+ \to \pi^+\pi^0) = \Gamma(B^- \to \pi^-\pi^0)$

- Separately measure time-integrated $\Gamma(B^0 \to \pi^0\pi^0)$, $\Gamma(\overline{B}^0 \to \pi^0\pi^0)$

$$\cos\phi = \frac{\mathcal{B}(\pi^+\pi^0) + \frac{1}{2}\mathcal{B}(\pi^+\pi^-) - \mathcal{B}(\pi^0\pi^0)}{\sqrt{2\mathcal{B}(\pi^+\pi^-)\mathcal{B}(\pi^+\pi^0)}}$$

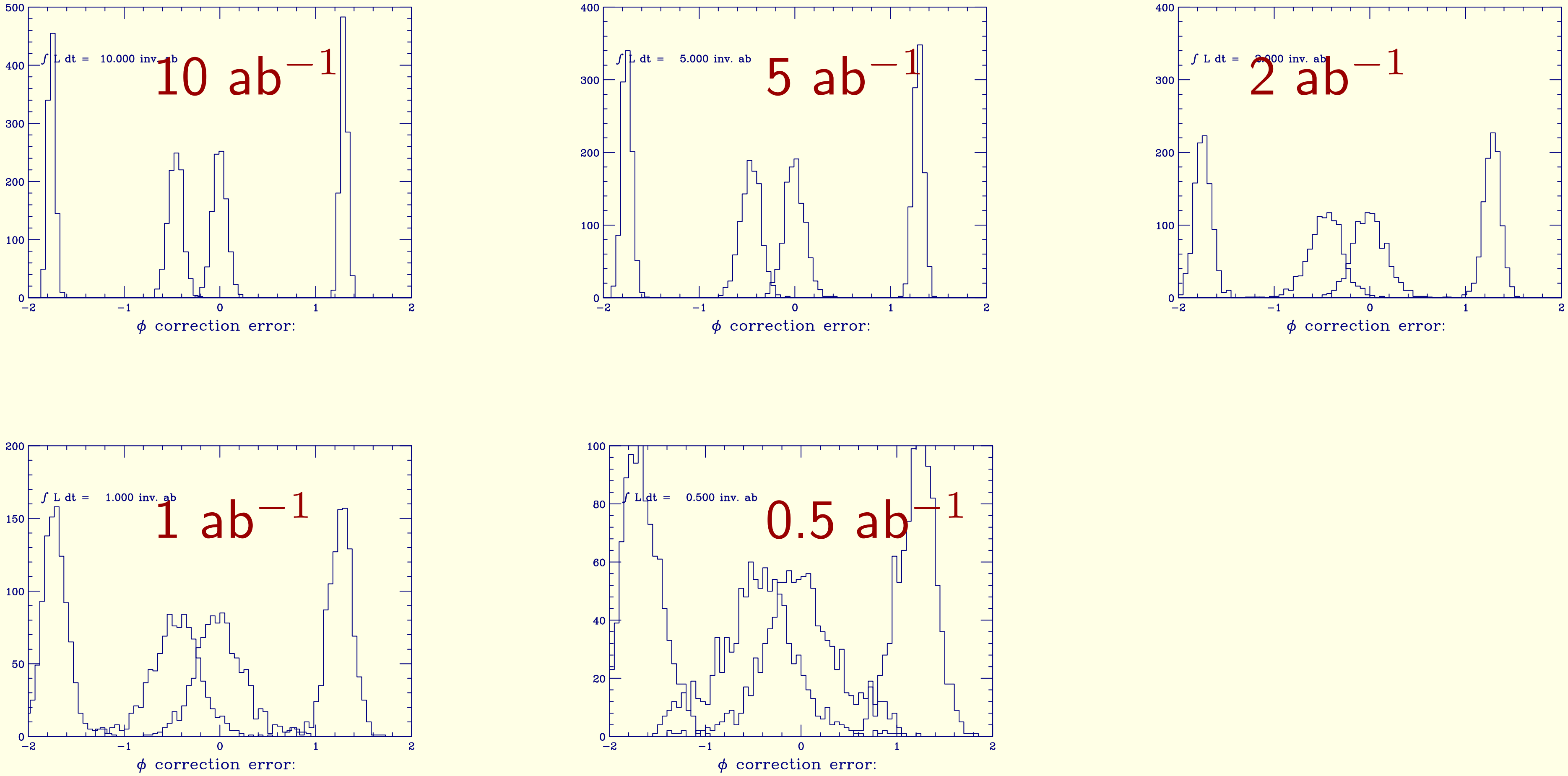
# MC Study Shows Ambiguities Bite

- Toy Monte Carlo study (RNC and Roodman):
- $BR(B^0 \to \pi^0\pi^0)$ now known:
  - $(2.1 \pm 0.6 \pm 0.3) \times 10^{-6}$ [BaBar]
  - $(1.7 \pm 0.6 \pm 0.2) \times 10^{-6}$ [Belle]

Histogram of 1000 experiments: input

- Branching ratios are in units of $10^{-6}$.
- Background based on BaBar results

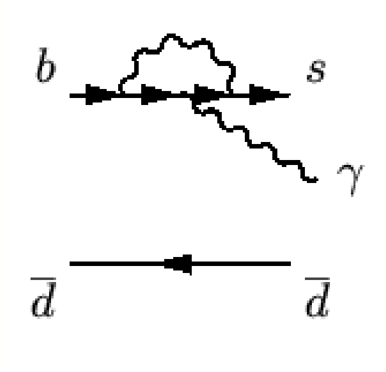
| | |
|---|---|
| $B^\pm \to \pi^\pm\pi^0$ | $4.1$ |
| $B^0 \to \pi^+\pi^-$ | $4.7$ |
| $\bar{B}^0 \to \pi^+\pi^-$ | $4.7$ |
| $B^0 \to \pi^0\pi^0$ | $2.5$ |
| $\bar{B}^0 \to \pi^0\pi^0$ | $1.5$ |




- Precision in $\alpha$ in $\pi\pi$ requires enormous integrated luminosity
- This seems to be a possibility only for a $10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $e^+e^-$ machine
- Alternatives $\rho\pi$ and even $\rho\rho$ look interesting

# $b \to s\gamma$

1. Major $\gamma$ bkgd from $\pi^0$, $\eta$, etc.
2. Lowest order is one loop so new physics should be prominent
3. Need model to get full spectrum




- To reduce background, require $E_\gamma^* > E_{min}$
- Require lepton from other $B$ to remove continuum.
- Need theory for spectrum, not just total rate
- Prediction for spectrum above 2.2 GeV uncertain by about 15%

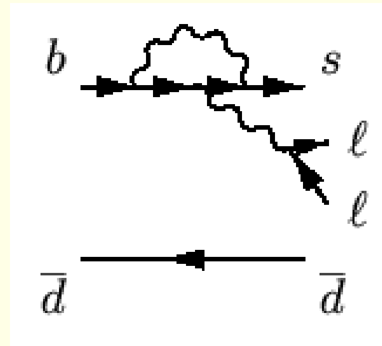
# $b \longrightarrow s\ell\bar{\ell}$

1. Measure exclusive decays and sum, excluding in $J/\psi$ etc.

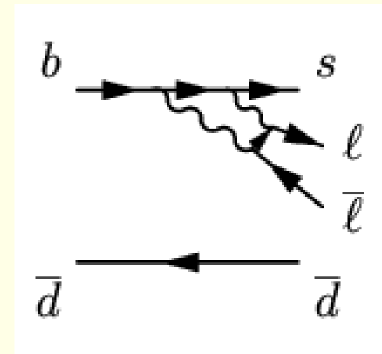
2. Theory issue: probes $\gamma, Z$ and $W$ box diagrams

3. Experimental: clean for $K^*\ell\bar{\ell}$

$\gamma, Z$

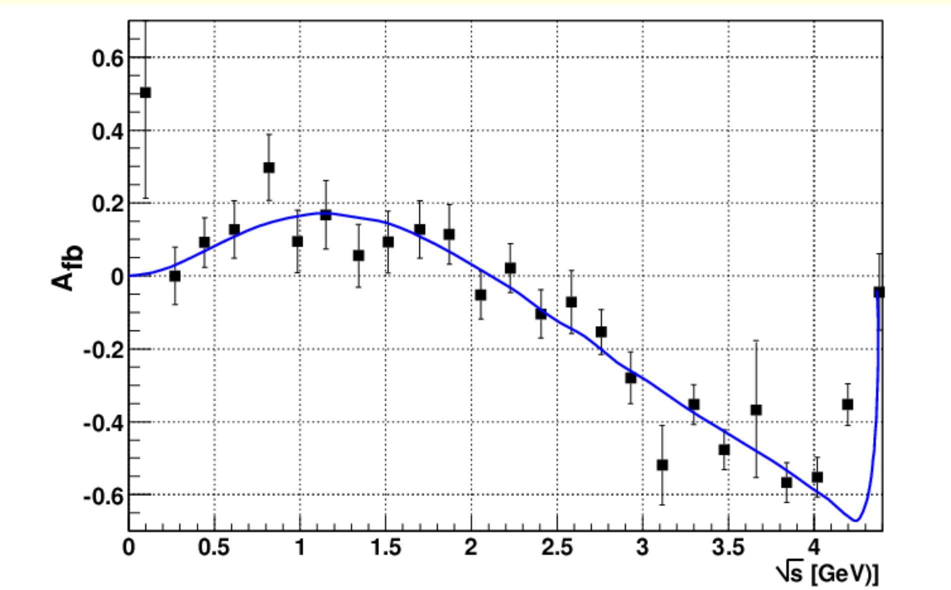



$W$ box



# $b \to s\ell\bar{\ell}$ Forward-Backward Asymmetry

- Comes from interference between axial ($\mathcal{O}_{10}$) and vector ($\mathcal{O}_{7,9}$)
- Need to understand various form factors evaluated at $s = m^2_{\ell\bar{\ell}}$
- New Physics can enter through $\mathcal{C}_{7,9,10}$




Simulation from BTeV, 2500 events/y

# Traditional goal of $B$-physics experiments

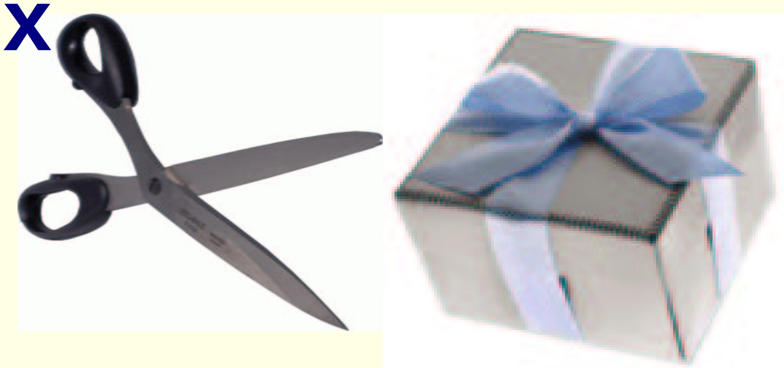
- High precision using lots of data
- Find discrepancy with Standard Model
- Ascribe difference to virtual particles in Box
- Read announcement of discovery of supersymmetry in NYT

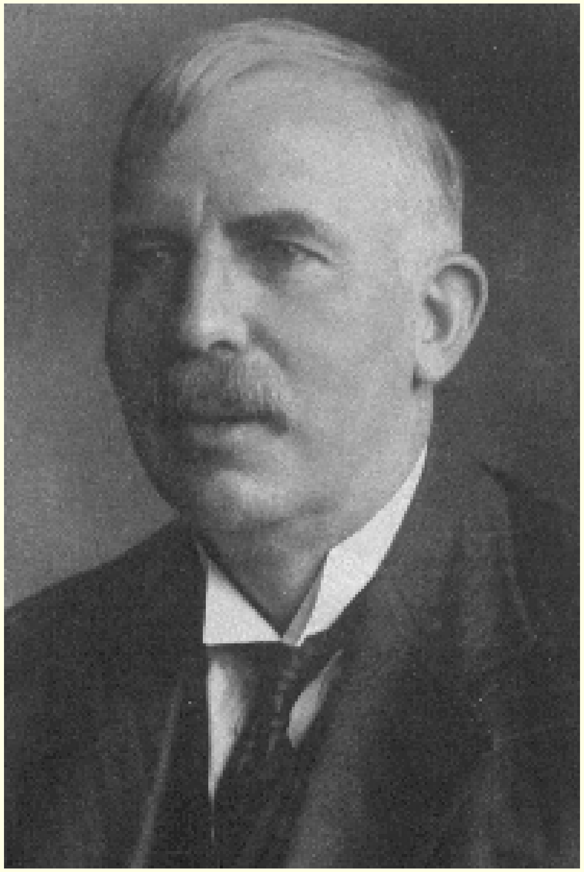
# Two approaches:

**B physics:**

**shake the Box, listen**

**LHC: open the Box**





# Who discovered the $W$ boson?

# History of Virtual Discoveries

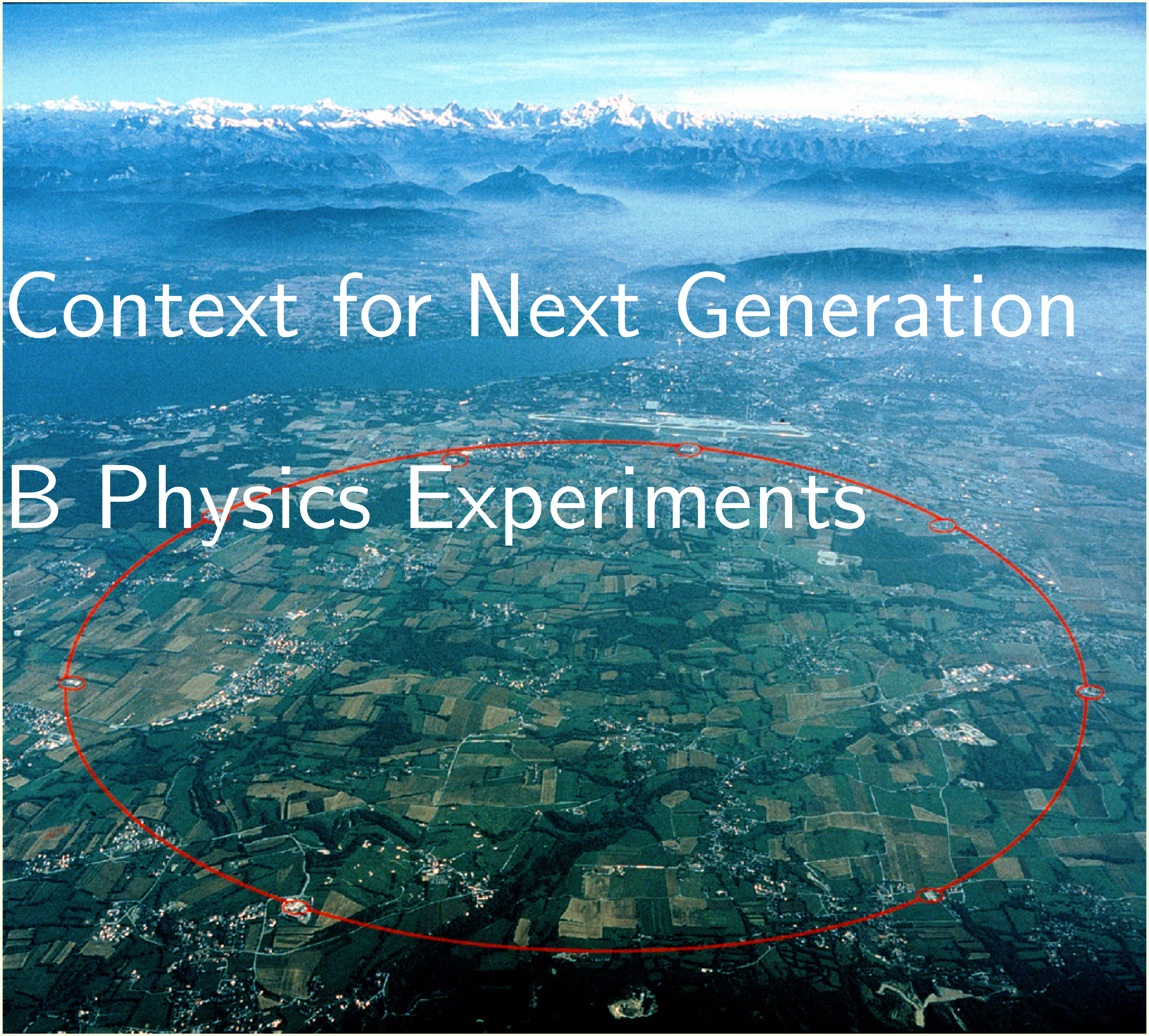
- 1934: Enrico Fermi (or Ernest Rutherford in 1898) discovered the $W$
- 1973: Gargamelle discovered the $Z$
- 1974: Ben Lee and Mary K. Gaillard discovered charmed particles
- 1994: LEP discovered the t quark

**Predictions of real particles from virtual effects are astonishing.**

**But few are convincing until the real thing appears.**

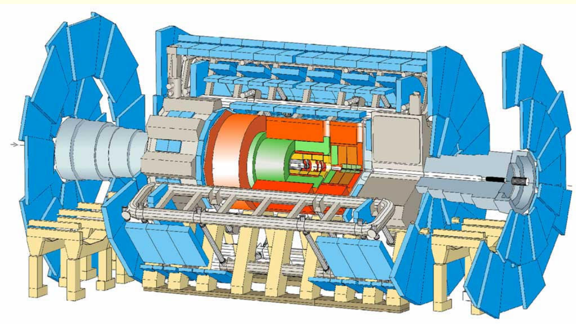
# Context for Next Generation

# B Physics Experiments



# Possible scenarios at LHC

ATLAS



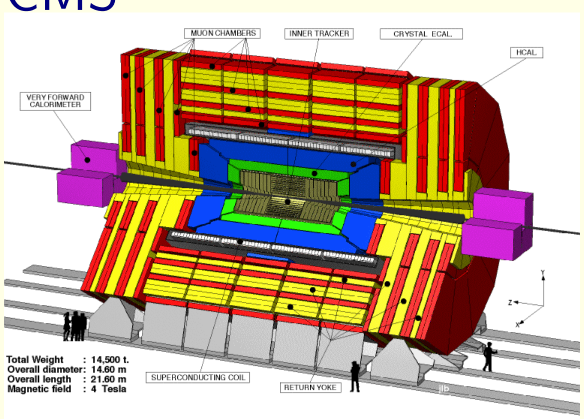
- Discover new spectroscopy:

  jackpot for particle physics

- Discover single, orthodox Higgs boson:

  happy for 24 hours

CMS




- Strongly interacting $W$, $Z$ (disfavored):

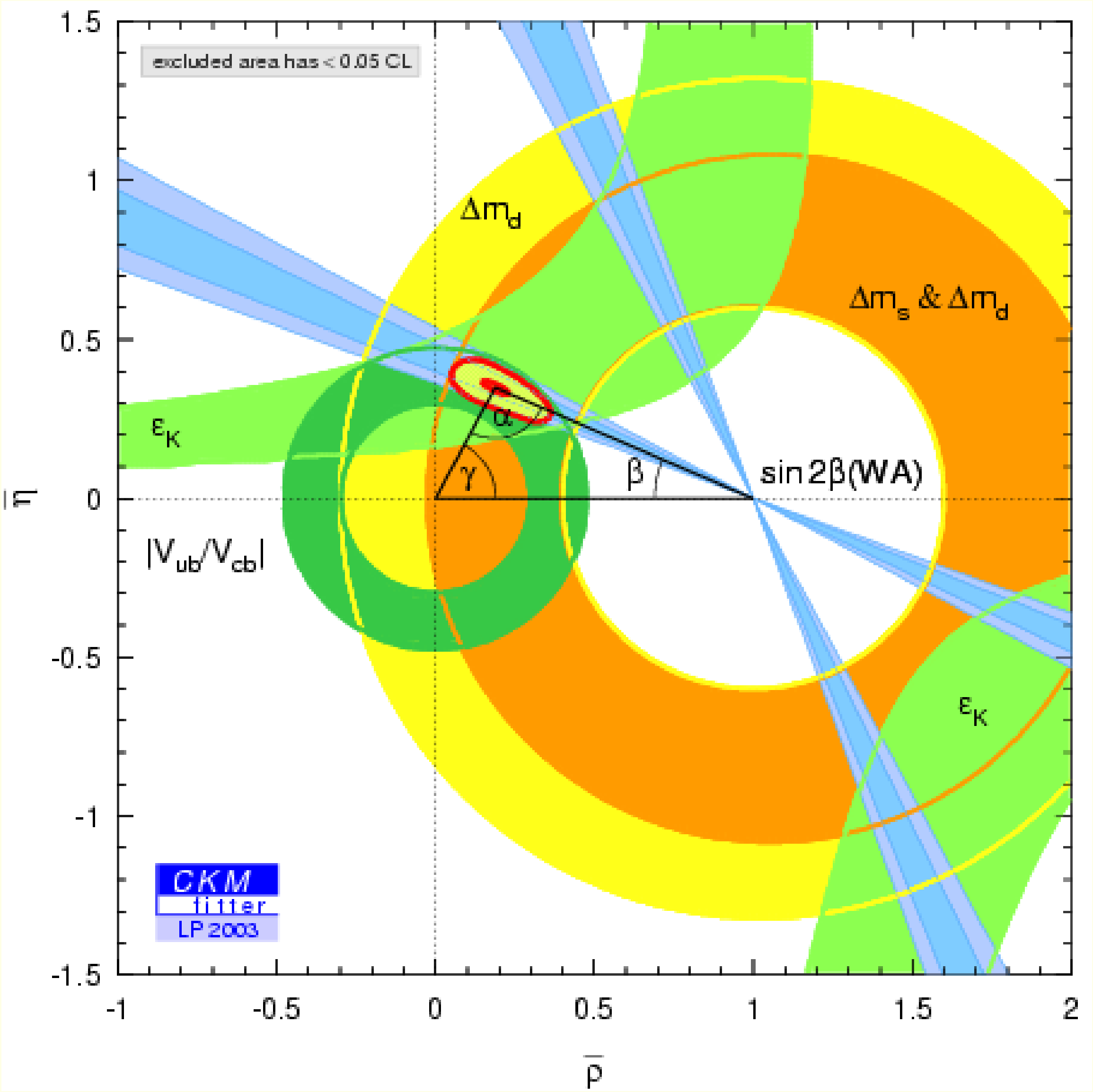
  life is tough

- ???

# Quark Flavor Physics in LHC Era

- If there is a new spectroscopy:
  - Confirm predicted radiative corrections?
  - Discriminate between possible models?
- If there is an orthodox Higgs
  - Confirm Standard Model predictions
- Something else
  - Confirm (modified?) Standard Model predictions
- A higher standard:
  - With competition from LHC, it will not be enough to find hints of new physics. The demands on precision and clean interpretation will be much greater.

# Current Unitarity Triangle




- Precise experiments
- Theory uncertainties dominate

# Theory Must Become as Rigorous as Experiment

- Lattice gauge calculations needed to sharpen tests of unitarity triangle.
- Effective theories derived from QCD needed for dynamical understanding.
- An experimental result lacking statistical and systematic errors is meaningless.
- Theory must meet same standard if it is to be used to challenge standard model.
- Give consideration to increased support for lattice work, contingent on review comparable to review of proposed experiment: real schedule for attaining verifiable performance standards.

# Spirit of Next Generation Flavor Physics

- Standard Model likely to have been verified to basic level:
  - Success of SM in $\sin 2\beta$ impressive
  - Had been likely target for deviation
- Only deviations that are truly convincing are likely to be interesting
  - 2 $\sigma$: 50 theory papers
  - 3 $\sigma$: 250 theory papers
  - 5 $\sigma$: strong sign of effect

# $B$ Physics isn't just looking for New Physics

- Standard Model is extraordinary. It deserves thorough elucidation.
- Unitarity Triangle demands verification despite LHC advantage in New Physics.
- QCD remains incompletely understood. $B$ decays provide excellent stage for examination.
- $B$ mesons are source for other phenomena
  - $B \to D D_s(2317)$
  - $B \to \psi(3870) K$

# Particle Physics circa 2010

- If a new spectroscopy is found at LHC
  - Those at LHC will be ecstatic.
  - Electrophiles will have a compelling case for LC.

- If no new spectroscopy is found at LHC
  - Mood at CERN will not be good.
  - LC is very improbable.

- In either case, there will be an active $B$ physics program
  - At CERN, LHCb might be the most interesting experiment.
  - BTeV could be leading (only?) non-neutrino HEP experiment in US.
  - At SLAC and KEK, accelerators will be pushed to higher and higher luminosity.