How technological innovations could influence the physics potential of b physics at hadron colliders
Reasons for Physics Beyond the Standard Model

- **Dark Matter**

- **Dark Energy: Cosmological constant**

- **Hierarchy Problem: Divergent quantum corrections to go from Electroweak scale \( \sim 100 \text{ GeV} \) to Planck scale of Energy \( \sim 10^{19} \text{ GeV} \) without “fine tuning” quantum corrections**

- **All of the above may only be related to Gravity**

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Other reasons for NP

- Flavor problem: Why 3 replications of quarks & leptons?
- Baryogenesis: The amount of CP Violation observed thus far in the quark sector is too small: \( \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-20} \) but \( \approx 6 \times 10^{-10} \) is needed. Thus New Physics must exist to generate needed CP Violation.

- To explain the values of CKM couplings, \( V_{ij} \), (both neutrino & quark)
- To explain the masses of fundamental objects. Are they related to the \( V_{ij} \)'s?
Why these values? Are the two related? Are they related to masses?
12 orders of magnitude differences not explained; t quark as heavy as Tungsten
Seeking New Physics

- Flavor Physics as a tool for NP discovery
  - While measurements of CKM elements (fundamental constants) are fun, the main purpose of HFP is to find and/or define the properties of physics beyond the SM
  - FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops is the Lamb shift in atomic hydrogen
  - A small difference in energy between $2S_{1/2}$ & $2P_{1/2}$ that should be of equal energy at lowest order

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TPC impact on flavor physics

- At PEP many interesting measurements, a few:
  - First evidence for the $F^*$ meson (now $D_{s^*}$) only 1 year after CLEO found the $F$
  - $\tau^-$ lepton studies, including branching fractions
  - Inclusive particle production in $e^+e^-$ collisions, possible because of particle ID provided
  - Test of models for quark and gluon fragmentation
  - Total hadronic cross-section in $2\gamma$ collisions
  - $f_1(1285)$ formation in photon photon fusion reactions
  \[\Rightarrow f_1(1285) \text{ is spin-1. Still an interesting state}\]
Flavor experiments at hadron colliders

- In the past: CDF & D0 (not designed for flavor)
- Now & foreseeable future: LHCb & some from CMS & ATLAS, both also not designed for flavor, but have capabilities especially on final states containing $\mu^+\mu^-$ & have 10x the LHCb
- Triggering on b & c decays is a key issue
  - LHCb is >90% for muon final states & ~50% for pure hadronic decays
  - CMS & ATLAS only use dimuons & are less efficient
- Backgrounds: at $e^+e^-$ have only $B\bar{B}$, $\sigma_B/\sigma_{tot}\sim1/4$, hadron colliders rely on detached b decay vertex

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The LHCb Detector
Detector Geometry

- Complementary to ATLAS & CMS
- Much less expensive
The primary pp collision produces a pair of $b\bar{b}$ quarks. They then form hadrons. In the forward region at LHC the $b\bar{b}$ production $\sigma$ is large.

The hadrons containing the $b$ & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for knowing if a neutral B meson started out as a $B^0$ or $\bar{B}^0$, determined by “flavor tagging”.

At $\mathcal{L}=2\times10^{32}/\text{cm}^2\cdot\text{s}$, we get $\sim6\times10^{11}$ B hadrons in $10^7\text{ sec}$ in detector.
Detector Workings

LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

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**B-Vertex Measurement**

- **Example:** $B_s \rightarrow D_s K$
  - Primary vertex
  - $d \sim 1\text{cm}$
  - Decay time resolution = 40 fs

**Vertex Locator (Velo)**
- Silicon strip detector with
  - $\sim 5\,\mu\text{m}$ hit resolution
  - $30\,\mu\text{m}$ IP resolution

**Vertexing:**
- Trigger on impact parameter
- Measurement of decay distance & decay time $= d/v = md/p$

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Momentum and Mass measurement

Momentum meas. + direction (VELO): Mass resolution for background suppression

Mass resolution $\sigma \sim 15$ MeV

$B_s^0 \rightarrow D_s^- K^+$

$\text{Primary vertex}$

$b^\text{tag}$
Hadron Identification

RICH: $K/\pi$ identification using Cherenkov light emission angle

**Bs → Ds K**

SS flavour tagging

- $\pi^+, K^+$
- $K^+, K^-$
- $\pi^-$

Primary vertex

$b_{\text{tag}}$

**Primary vertex**

**Kaon identification performance**

- $K \rightarrow K$: $96.77 \pm 0.06\%$
- $\pi \rightarrow K$: $3.94 \pm 0.02\%$

**RICH1:** 5 cm aerogel n=1.03

*4 m$^3$ C$_4$F$_{10}$ n=1.0014*

**RICH2:** 100 m$^3$ CF$_4$ n=1.0005
Calorimetry and L0 trigger

Calorimeter system:
- Identify electrons, hadrons, $\pi^0, \gamma$
- Level 0 trigger: high $E_T$ electron and hadron

ECAL (inner modules): $\sigma(E)/E \sim 8.2\% / \sqrt{E} + 0.9\%$
Muon identification and L0 trigger

Muon system:
- Level 0 trigger: High $P_t$ muons
- OS flavour tagging

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Triggering

**Hardware level (L0)**
- 40 MHz bunch crossing rate
- Search for high-$p_T$ $\mu$, $e$, $\gamma$ and hadron candidates

**Software level (High Level Trigger, HLT)**
- Farm with $\alpha(29000)$ multi-core processors
- Very flexible algorithms, writes $\sim 5$ kHz to storage

**Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have branching ratios of $<10^{-5}$**

This is the bottleneck
Detector Performance

- Detector works better than expected
- Run at $4 \times 10^{32}$ cm$^{-2}$/s instead of $2 \times 10^{32}$, with fewer bunches in the machine which is more difficult $\sim<1.5>$ interactions/crossing
- Detector efficiency $>95\%$ for all systems
- Problems: Vertex resolution slightly worse, flavor tagging somewhat poorer
- $\mathcal{L}$uminosity is leveled – small changes of $\mathcal{L}$ with time; beams are brought closer together when currents decrease
A few results
Sm branching ratio is $3.65\pm0.23\times10^{-9}$ [Bobeth et al., arXiv:1311.0903], NP can make large contributions.

Many NP models possible, not just Super-Sym
Top Down Analyses

Here we pick models and work out their consequences in many modes. Ex. (circa 2010):

\[ 10^9 \times \text{BR}(B_d \rightarrow \mu^+\mu^-) \]

\[ 10^9 \times \text{BR}(B_s \rightarrow \mu^+\mu^-) \]

Straub: arXiv:1012.3893

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Evidence for $B_s \rightarrow \mu^+ \mu^-$


\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}, \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10}, \]

- Avg: $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (2.9\pm0.7) \times 10^{-9}$
- Avg: $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$ (not significant)
Implications

Only this range allowed

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Neutral Meson Mixing

- Neutral mesons can transform into their anti-particles via 2\textsuperscript{nd} order weak interactions.
- Short distance transition rate depends on mass of intermediate $q_i$, the heavier the better, favors $s$ \& $b$ since $t$ is allowed, while for $c$, $b$ is the heaviest.
- CKM elements $V_{ij}$

New particles possible in loop

$D^0 \rightarrow \pi\pi,.. \rightarrow \overline{D}^0$ + “long distance” for $D^0$

Is this zero? from Van Kooten
Mixing data

First seen by ARGUS

First measured by CDF

LHCb preliminary

data

fit

$B^0 \to D^+_s \pi^+$

$B^0 \to D^+_s K^+$

misid. bkg.

comb. bkg.

LHCb

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

combined

Raw asymmetry

LHCb

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

combined

$\Delta m_d = 0.5156 \pm 0.0051 \text{ (stat)} \pm 0.0033 \text{ (syst)} \text{ ps}^{-1}$

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CPV measurements

- CPV measure: \[ a[f(t)] = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to f)}{\Gamma(\bar{M} \to f) + \Gamma(M \to f)} \]

- Angle probed depends on M, i.e. B^0, B_s, D^0 ... & f
- For B^0 \to J/\psi K_s, measure angle \( \beta \), which is not predicted
- For B_s \to J/\psi f_0(980), J/\psi \phi, measure angle \( \phi_s \) predicted from
- Other measurements to be small in the SM = -0.036 rad

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CPV in $B_s \rightarrow J/\psi \ X$

- Interference between mixing & decay
- For $f = J/\psi \phi$ or $J/\psi \pi^+\pi^-$
  \[
  B_s^0 \left\{ \begin{array}{l}
  b \\
  \bar{s}
  \end{array} \right\} \rightarrow W^{c \bar{c}} J/\psi
  \]
  \[
  B_s \left\{ \begin{array}{l}
  b \\
  \bar{s}
  \end{array} \right\} \rightarrow \pi^+\pi^- \text{ or } K^+K^-
  \]

- Small CPV expected, good place for NP to appear
- $B_s \rightarrow J/\psi \phi$ is not a CP eigenstate, as it’s a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

$\beta_s = -2 \arg \left( -\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -0.04 \text{ rad}$
Reconstructed \( \pi^+\pi^- \) mass spectrum

- In region between arrows, measured to be \( >97.7\% \)
- CP-odd @95\% cl

\[
a[f(t)] \sim 2 \sin \phi_s \sin(\Delta M t)
\]

\[
\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003} \text{ rad}
\]
Combining LHCb

J/ψφ & J/ψπ⁺π⁻ results:

- LHCb values
  \[\Gamma = 0.6580 \pm 0.0054 \pm 0.0066 \text{ (ps}^{-1}\text{)}\]
  \[\Delta\Gamma = 0.116 \pm 0.018 \pm 0.006 \text{ (ps}^{-1}\text{)}\]
  \[\phi_s = 0.001 \pm 0.101 \pm 0.027 \text{ (rad)}\]
Flavor as a High Mass Probe

- Already excluded ranges from box diagrams

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i, \text{ take } c_i \sim 1 \]

Ways out
1. New particles have large masses $>> 1$ TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

LHCb Upgrade

- Goals: run at $\mathcal{L}$ up to $2 \times 10^{33}$ cm/s with double efficiency on $B \rightarrow$ hadrons (x10)
- Move to an all software trigger with higher output $\sim 50$ kHz
- Higher density tracking elements
  - New pixel VELO
  - New Si strip TT called UT (US responsibility)
  - New Outer Tracker made of scintillating fibers
  - RICH switching to MAPMT’s
- Approved by LHCC

Post upgrade: The Torch
Possible additional improvements

What follows is only my speculations

Remove 250 µm thick RF foil, separating beam vacuum from VELO vacuum & replace with wires to absorb image charge from the beam. Would improve vertex resolution significantly

Not for a realistic detector

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LHCb could do more with an excellent E&M calorimeter

Although final states such as $B \rightarrow K^* \gamma$ have been done by LHCb, the efficiencies are relatively low & the resolution relatively poor

$\pi^0$’s are more difficult

$\text{PbWO}_4$ would be great, but it would cost as much as CMS. Note $\frac{1}{2}$ of the solid angle could be covered for $\frac{1}{4}$ of the cost. Could also use Noble liquids, Argon, Xenon?
Timing photons

- H. Fritsch et al., Large area picosecond timing
  - See http://psec.uchicago.edu

- In principle, can tell origin of photon by measuring the difference of time between γ’s & pions. Could be enormously useful to tell if a γ came from a particular detached B decay vertex. For 1 ps, decay length is known to 0.1 mm, where average B decay length is ~10 mm

- Also useful for low momentum charged particle ID.
How it works

Requires large-area, gain > $10^7$, low noise, low-power, long life, $\sigma(t) < 10$ psec, $\sigma(x) < 1$ mm, and low large-area system cost

Realized that an MCP-PMT has all these but large-area, low-cost:
(since intrinsic time and space scales are set by the pore sizes- 2-20μ)

window

Incoming charged particle

Radiated Cherenkov photon

Photo-electron from cathode

Output pulse of $10^7$ electrons

Photocathode on inside of window

Pair of micro-channel plates

RF strip-line anode

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Test results

- Already achieved 5 ps timing on 8”x8” area
- With 5 ps, have 0.5 mm resolution on $\gamma$ origin, already beginning to be useful to distinguish among associated primary vertices, but really would like 1 ps $\rightarrow$ 0.1 mm resolution good enough to tell if it's from a detached B decay
Final states with a missing particle

- We often want to detect B decays with a missing neutrino, such as $B \rightarrow D^{(*)}\mu^-\nu$ for $|V_{cb}|$ or $\Lambda_b \rightarrow p\mu^-\nu$ for $|V_{ub}|$.

- Also look for new scalar fields such as inflatons, Berukov & Gorbunov prediction: “Light inflaton Hunter’s Guide” (arXiv:0912.0390)

$$B(\bar{B} \rightarrow \chi X_s) \simeq 0.3 \frac{|V_{ts}V_{tb}^*|^2}{|V_{cb}|^2} \left( \frac{m_t}{M_W} \right)^4 \left( 1 - \frac{m_\chi^2}{m_b^2} \right)^2 \theta^2$$

$$\simeq 10^{-6} \cdot \left( 1 - \frac{m_\chi^2}{m_b^2} \right)^2 \left( \frac{\beta}{\beta_0} \right) \left( \frac{300 \text{ MeV}}{m_\chi} \right)^2,$$

- Here we don’t detect the $\chi$
B-factories vs LHCb

- B factories can fully reconstruct the $B$ and then measure the $\bar{B}$ decay even with a missing particle, but the efficiency is only few $10^{-3}$.

- This works because the $p$ of the $\bar{B}$ is $-p$ of the $B$. Signal appears as a peak in:

$$m^2_x = (E_B - E_X)^2 - (p_B - p_X)^2$$

An alternative technique has been used, e.g., in $D^0$ decay: Measure the $D^0$ direction from production to the primary vertex, but then we are missing the $|p_{D^0}|$. Get an extra constraint from $D^{**+} \rightarrow \pi^+ D^0$ decay, works because of large rate and narrow $D^{**+}$ width, which is 0.1 MeV, so observed width depends on detector resolution.
How can LHCb do this?

- $B^{**} \to \pi^+ B$, this doesn’t work because $B^{**}/B$ is $\sim 15\%$, unlike $D^{**}/D \sim 100\%$, & the widths are $\sim 25$ MeV & $\sim 130$ MeV

- How about $\Sigma_b^+ \to \pi^+ \Lambda_b^0$? (See Stone & Zhang arXiv:1402.4205)
  - Should be a large rate. Expect $\Sigma_b^+$ & $\Sigma_b^-$ production to be about the same size as $\Lambda_b^0$ (bud, versus buu & bdd)
  - There has even been an observation of the decay by CDF, but not a measurement of the relative rate, which appears to be quite low
CDF results: Only published measurement

- Note 4 states
- S/B not great
- Suspect poor $\varepsilon$ on low p tracks

<table>
<thead>
<tr>
<th>State</th>
<th>$Q$ value, MeV</th>
<th>Natural width, $\Gamma_0$, MeV</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma_b^-$</td>
<td>$56.2_{-0.5}^{+0.6}$</td>
<td>$4.9_{-2.1}^{+3.1}$</td>
<td>$340_{-70}^{+90}$</td>
</tr>
<tr>
<td>$\Sigma_b^{*-}$</td>
<td>$75.8 \pm 0.6$</td>
<td>$7.5_{-1.8}^{+2.2}$</td>
<td>$540_{-80}^{+90}$</td>
</tr>
<tr>
<td>$\Sigma_b^+$</td>
<td>$52.1_{-0.8}^{+0.9}$</td>
<td>$9.7_{-2.8}^{+3.8}$</td>
<td>$470_{-90}^{+110}$</td>
</tr>
<tr>
<td>$\Sigma_b^{*-}$</td>
<td>$72.8 \pm 0.7$</td>
<td>$11.5_{-2.2}^{+2.7}$</td>
<td>$800_{-100}^{+110}$</td>
</tr>
</tbody>
</table>
Augmenting the tracking

- A useful technique, can be improved by detecting low p tracks, only ~60 MeV Q for these decays about the same as for D*-D
- Examples of LHCb tracks
- Upstream tracks typically have $\Delta p/p \sim 15\%$, so not useful for most physics. So put detectors in the magnet

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Conclusions

- Flavor physics offers unique searches for high mass New Physics
- Hadron colliders provide enormous samples of b & c decays
- Several improvements are possible that could vastly improve the prospects of finding such new phenomena
- Good luck to Dave!
The End
Define Heavy Flavor Physics

- Flavor Physics: Study of interactions that differ among flavors: (quark flavors are u, d, c, s, b, t)
- Heavy: Not SM neutrino’s or u or d quarks, maybe s quarks, concentrate here on b quarks (some c), t too heavy

<table>
<thead>
<tr>
<th>u, d, (\nu)'s</th>
<th>s, (\mu)</th>
<th>c &amp; b, (\tau); (\nu_M)'s</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>too light</td>
<td>maybe</td>
<td>just right</td>
<td>too heavy</td>
</tr>
</tbody>
</table>
Luminosity Leveling

- Luminosity is maintained as at a constant value of $\sim 4 \times 10^{32} / \text{cm} \cdot \text{s}$ by displacing beams transversely.
- Integral $\mathcal{L}$ is 1/fb in 2011, collected 2/fb more in 2012.

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By definition

\[ a_{sl} = \frac{\Gamma(\bar{M} \rightarrow f) - \Gamma(M \rightarrow \bar{f})}{\Gamma(\bar{M} \rightarrow f) + \Gamma(M \rightarrow \bar{f})} \]

at \( t=0 \) \( \bar{M} \rightarrow f \) is zero as is \( M \rightarrow \bar{f} \)

Here \( f \) is by construction flavor specific, \( f \neq \bar{f} \)

Can measure eg. \( \bar{B}_s \rightarrow D_s^+ \mu^- \nu \), versus \( B_s \rightarrow D_s^- \mu^+ \nu \),

Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at \( \mu^+ \mu^+ \) vs \( \mu^- \mu^- \)

\( a_{sl} \) is expected to be very small in the SM,

\( a_{sl} = (\Delta \Gamma/\Delta M) \tan \phi_{12} \), where \( \tan \phi_{12} = \text{Arg}(-\Gamma_{12}/M_{12}) \)

In SM (\( B^0 \)) \( a_{sl}^d = -4.1 \times 10^{-4} \), (\( B_s \)) \( a_{sl}^s = +1.9 \times 10^{-5} \)
Using dimuons (3.9σ)

\[ A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\% \]

Indication from D0 that its \( B_S \)

Separate dimuons into \( B_d \) and \( B_S \) samples using muon impact parameter

Find \( a_{sl}^d = (-0.12 \pm 0.52)\% \)
\( a_{sl}^s = (-1.81 \pm 1.06)\% \)
New D0 Analysis

- Measure $a_{s\mu}^s$ using $D_s\mu^-\nu$ events, $D_s\rightarrow\phi\pi\pi^\pm$

- Detect a $\mu$ associated with a $D_s$ decay

- Find $a_{s\mu}^s=(-1.08\pm0.72\pm0.17)\%$

- Also measure $a_{s\mu}^d$ using $D^+\mu^-\nu$, $D^+\rightarrow K\pi^+\pi^+$

- $a_{s\mu}^d=(0.93\pm0.45\pm0.14)\%$

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$a_{\text{sl}}$ according to D0

- $a_{\text{sl}}^s = (-1.81 \pm 0.56)\%$
- $a_{\text{sl}}^d = (-0.22 \pm 0.30)\%$
- $3\sigma$ from SM
- arXiv:1208.5813

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LHCb measurement

- Use $D_s\mu^-\nu$, $D_s\rightarrow\phi\pi^\pm$, magnet is periodically reversed. For magnet down:

- Effect of $B_s$ production asymmetry is reduced to a negligible level by rapid mixing oscillations

- Calibration samples ($J/\psi$, $D^{*+}$) used to measure detector trigger, track & muon ID biases
LHCb finds

\[ a_{s_l}^s = \left( -0.24 \pm 0.54 \pm 0.33 \right) \%
\]

B-factor

\[ a_{s_l}^d = \left( -0.05 \pm 0.56 \right) \%
\]

Results consistent with SM

Expect \( \phi_s \) to grow as \( \sin[2|\beta_s| + \arg(M_{12})] \) for finite \( a_{s_l} \).

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Also $D^+$, $D_s$, $\Lambda_b$

$D^+ \rightarrow K^-\pi^+\pi^+$

$D_s \rightarrow K^-K^+\pi^+$

$LHCb$ Preliminary

$D^0$: 9406±110

$D^0$: 2446±60
Extract $B_s$ fractions

- Crucial to set absolute scale for $B_s$ rates, since not given by $e^+e^-$ machines.
- Must correct for $B_s \rightarrow D^0K^+X_{\mu\nu}$, also $\Lambda_b \rightarrow D^0pX_{\mu\nu}$

$$f_s / (f_u + f_d) = 0.136 \pm 0.004^{+0.012}_{-0.011}$$

$\sqrt{s} = 7$ TeV
LHCb Preliminary $\sim 3$ pb$^{-1}$

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\( B_s \) fraction - hadronic

- Also can use hadronic decays + theory ~35 pb\(^{-1}\)

Semileptonics:

\[ \frac{f_s}{f_d} = 0.272 \pm 0.008^{+0.024}_{-0.022} \]
Detector Requirements - General

Every modern heavy quark experiment needs:

- Vertexing: to measure decay points and reduce backgrounds, especially at hadron colliders
- Particle Identification: to eliminate insidious backgrounds from one mode to another where kinematical separation is not sufficient
- Muon & electron identification because of the importance of semileptonic & leptonic final states including J/ψ decay
- γ, π⁰ & η detection
- Triggering, especially at hadronic colliders
- High speed DAQ coupled to large computing for data processing
- An accelerator capable of producing a large rate of b’s
Consider

\[ a[f(t)] = \frac{\Gamma(M \rightarrow f) - \Gamma(M \rightarrow f)}{\Gamma(M \rightarrow f) + \Gamma(M \rightarrow f)} \]

Define

\[ A_f \equiv A(M \rightarrow f), \quad \bar{A}_f \equiv A(M \rightarrow f), \quad \lambda_f = \frac{p}{q} \frac{\bar{A}_f}{A_f} \]

Only 1 \( A_f \) & \( \Delta \Gamma = 0 \)

\[ \Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left( 1 - \text{Im} \lambda_f \sin (\Delta M t) \right) \]

Then \( a[f(t)] = -\text{Im} \lambda_f \), & \( \lambda_f \) is a function of \( V_{ij} \) in SM

For \( B^0 \), \( \Delta \Gamma \approx 0 \), but there can be multiple \( A_f \)

\[ \Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left( 1 - \frac{|\lambda_f|^2}{2} \cos \Delta M t - \text{Im} \lambda_f \sin (\Delta M t) \right) \]

If in addition \( \Delta \Gamma \neq 0 \), eg. \( B_s \)

\[ \Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left( \frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta \Gamma t}{2} + \frac{1 - |\lambda_f|^2}{2} \cos (\Delta M t) - \text{Re} \lambda_f \sinh \frac{\Delta \Gamma t}{2} - \text{Im} \lambda_f \sin (\Delta M t) \right) \]

See Nierste

Transversity

\[
\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi \phi)}{dt \, d\cos \theta \, d\varphi \, d\cos \psi} = \frac{d^4\Gamma}{dt \, d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)
\]

<table>
<thead>
<tr>
<th>(k)</th>
<th>(h_k(t))</th>
<th>(f_k(\theta, \psi, \varphi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(</td>
<td>A_0</td>
</tr>
<tr>
<td>2</td>
<td>(</td>
<td>A_\parallel(t)</td>
</tr>
<tr>
<td>3</td>
<td>(</td>
<td>A_\perp(t)</td>
</tr>
<tr>
<td>4</td>
<td>(\Im(A_\parallel(t)A_\perp(t)))</td>
<td>(-\sin^2 \psi \sin 2\theta \sin \phi) |</td>
</tr>
<tr>
<td>5</td>
<td>(\Re(A_0(t)A_\parallel(t)))</td>
<td>(\frac{1}{2} \sqrt{2} \sin 2\psi \sin^2 \theta \sin 2\phi) |</td>
</tr>
<tr>
<td>6</td>
<td>(\Im(A_0(t)A_\perp(t)))</td>
<td>(\frac{1}{2} \sqrt{2} \sin 2\psi \sin 2\theta \cos \phi) |</td>
</tr>
<tr>
<td>7</td>
<td>(</td>
<td>A_s(t)</td>
</tr>
<tr>
<td>8</td>
<td>(\Re(A_s^*(t)A_\parallel(t)))</td>
<td>(\frac{1}{3} \sqrt{6} \sin \psi \sin^2 \theta \sin 2\phi) |</td>
</tr>
<tr>
<td>9</td>
<td>(\Im(A_s^*(t)A_\perp(t)))</td>
<td>(\frac{1}{3} \sqrt{6} \sin \psi \sin 2\theta \cos \phi) |</td>
</tr>
<tr>
<td>10</td>
<td>(\Re(A_s^*(t)A_0(t)))</td>
<td>(\frac{4}{3} \sqrt{3} \cos \psi (1 - \sin^2 \theta \cos^2 \phi)) |</td>
</tr>
</tbody>
</table>

for S-wave under \(\phi\) predicted by Stone & Zhang PRD 79, 074024 (2009)
\[ |A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin (\Delta m t) \right], \]

\[ |A_{\parallel}(t)|^2 = |A_{\parallel}|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin (\Delta m t) \right], \]

\[ |A_{\perp}(t)|^2 = |A_{\perp}|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin (\Delta m t) \right], \]

\[ \Im(A_{\parallel}(t) A_{\perp}(t)) = |A_{\parallel}| |A_{\perp}| e^{-\Gamma_s t} \left[ - \cos (\delta_{\perp} - \delta_{\parallel}) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \cos (\delta_{\perp} - \delta_{\parallel}) \cos \phi_s \sin (\Delta m t) + \sin (\delta_{\perp} - \delta_{\parallel}) \cos (\Delta m t) \right], \]

\[ \Re(A_0(t) A_{\parallel}(t)) = |A_0| |A_{\parallel}| e^{-\Gamma_s t} \cos (\delta_{\parallel} - \delta_0) \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin (\Delta m t) \right], \]

\[ \Im(A_0(t) A_{\perp}(t)) = |A_0| |A_{\perp}| e^{-\Gamma_s t} \left[ - \cos (\delta_{\parallel} - \delta_0) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \cos (\delta_{\parallel} - \delta_0) \cos \phi_s \sin (\Delta m t) + \sin (\delta_{\parallel} - \delta_0) \cos (\Delta m t) \right], \]

\[ |A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin (\Delta m t) \right], \]

\[ \Re(A_s^*(t) A_{\parallel}(t)) = |A_s| |A_{\parallel}| e^{-\Gamma_s t} \left[ - \sin (\delta_{\parallel} - \delta_s) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin (\delta_{\parallel} - \delta_s) \cos \phi_s \sin (\Delta m t) + \cos (\delta_{\parallel} - \delta_s) \cos (\Delta m t) \right], \]

\[ \Im(A_s^*(t) A_{\perp}(t)) = |A_s| |A_{\perp}| e^{-\Gamma_s t} \sin (\delta_{\perp} - \delta_s) \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin (\Delta m t) \right], \]

\[ \Re(A_s^*(t) A_0(t)) = |A_s| |A_0| e^{-\Gamma_s t} \left[ - \sin (\delta_0 - \delta_s) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin (\delta_0 - \delta_s) \cos \phi_s \sin (\Delta m t) + \cos (\delta_0 - \delta_s) \cos (\Delta m t) \right]. \]
Systematic err

<table>
<thead>
<tr>
<th>Source</th>
<th>certain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial requirement</td>
<td>0.01%</td>
</tr>
<tr>
<td>Peaking background asymmetry</td>
<td>0.04%</td>
</tr>
<tr>
<td>Fit procedure</td>
<td>0.08%</td>
</tr>
<tr>
<td>Multiple candidates</td>
<td>0.06%</td>
</tr>
<tr>
<td>Kinematic binning</td>
<td>0.02%</td>
</tr>
<tr>
<td>Total</td>
<td>0.11%</td>
</tr>
</tbody>
</table>

\[ \Delta A_{CP} = [-0.82 \pm 0.21 \text{(stat.)} \pm 0.11 \text{(syst.)}] \% \]

Not definitive: only 3.5\(\sigma\), but is a nice hint, adding other experiments get (-0.65\(\pm\)0.18)\%
The Standard Model

<table>
<thead>
<tr>
<th>Charge</th>
<th>Quark</th>
<th>Lepton</th>
<th>Boson</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/3</td>
<td>u</td>
<td>e</td>
<td>H</td>
</tr>
<tr>
<td>-1/3</td>
<td>d</td>
<td>μ</td>
<td>Z</td>
</tr>
<tr>
<td>0</td>
<td>c</td>
<td>τ</td>
<td>±</td>
</tr>
<tr>
<td>-1</td>
<td>t</td>
<td>ν_e</td>
<td>H</td>
</tr>
</tbody>
</table>

No understanding of why 3 generations, but allows for CP violation in both quark & neutrino sectors.
Quark Mixing & CKM Matrix

- All 3 generations of -1/3 quarks (d, s, b) are mixed
- Described by CKM matrix (also ν are mixed)

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

- Unitary 3x3 matrix can be described by 4 parameters λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants of nature in the Standard Model
FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the $W$ mass

- $M_W$ changes due to $m_t$ 
  \[ \frac{dM_W}{dm_t} \alpha \frac{m_t}{M_W} \]

- $M_W$ changes due to $m_H$ 
  \[ \frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H} \]

- Gave predictions of $m_H$ prior to discovery

Nygren Symposium, May 2, 2014
B⁻ → J/ψ K⁻

LHCb Event Display
20 MHz of bunch crossing (in 2012, with 50 ns bunch spacing) with an average of 1.5 pp interactions per bunch crossing → this level of pileup not an issue for LHCb