

Observation of orbitally excited (L=1) B
mesons in $B^+ \rightarrow J/\psi K^+$ decays



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Graduate Board Oral Exam

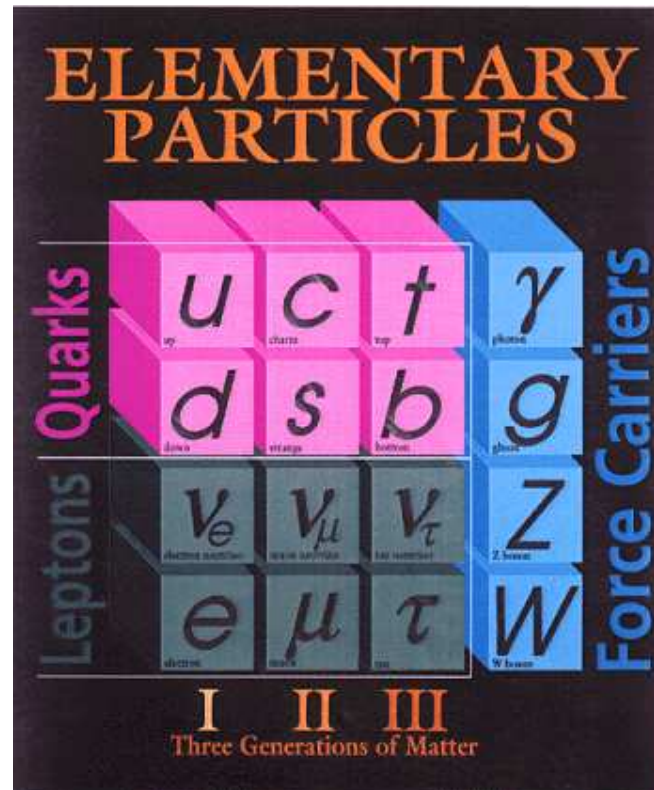
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Outline

- Review Standard Model
- B^{**} Motivation:
 - Heavy Quark Effective Theory
 - Same Side Tagging
- B^{**} Theoretical Predictions
- Run II Collider Detector at Fermilab
- Preliminary Results
- Future Research

Standard Model

- Standard Model (SM) extremely successful
 - to date, all measurements in agreement with SM predictions.



Standard Model Forces

- **QCD** = Quantum Chromodynamics - theory of strong interactions
- **QED** = Quantum Electrodynamics - theory of electromagnetic interactions
- **Electroweak** - unification of QED and weak interactions at high energy
- **Gravity** - not included in SM

Problems with SM

- Still incomplete (no Higgs boson).
 - Too many free parameters (e.g. particle masses, number of quark/lepton generations).
 - Unwieldy explanations of CP violation, quark mixing, neutrino masses...
 - No solution to matter/anti-matter asymmetry.
 - Dark energy and dark matter hint at physics beyond SM.
- ⇒ We hope SM is not the complete picture.

B^{**} Motivation: the CKM Matrix

- Cabibbo-Kobayashi-Maskawa (CKM) Matrix relates quark flavor states to weak interaction states.

Wolfenstein parameterization:

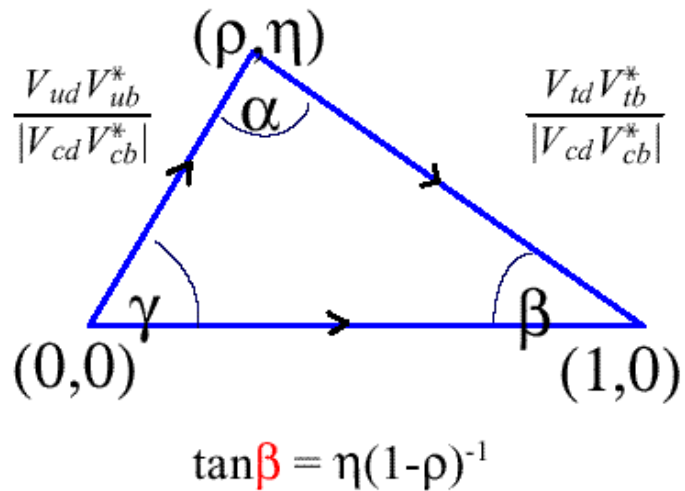
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 &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

- Non-zero elements \rightarrow quarks change flavor through weak interactions.
- Probability conservation requires V_{CKM} unitary.

One example: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

CKM Matrix \Rightarrow Unitarity Triangle

Unitarity of V_{CKM} described by triangles in the complex plane:



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

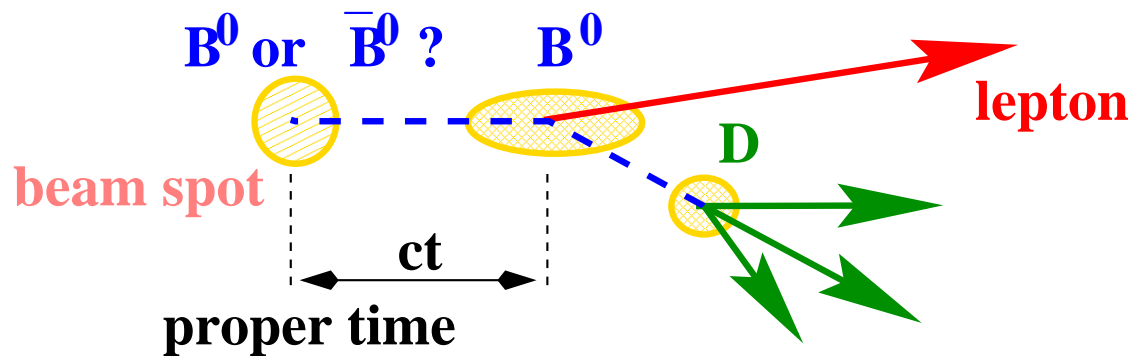
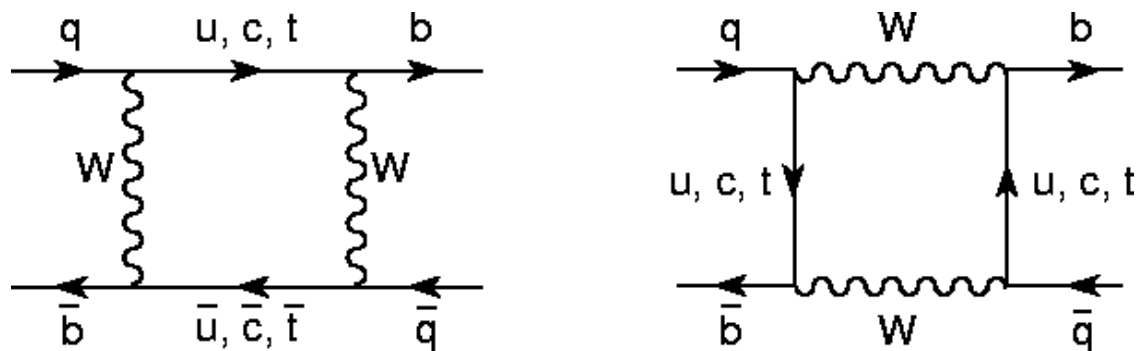
Use B physics measurements to measure sides and angles of triangle.

Heavy Quark Effective Theory

- Heavy Quark Symmetry simplifies QCD calculations for mesons with heavy quarks.
- Corrections scale as $\frac{1}{m_Q}$, where m_Q = mass of heavy quark.
- Add dynamical models of light quark for quantitative predictions -
e.g. non-relativistic or relativistic light quark models.
- Model heavy-light quark bound systems to measure V_{ub} and V_{cb} .

B^{**} Motivation: B^0 Mixing

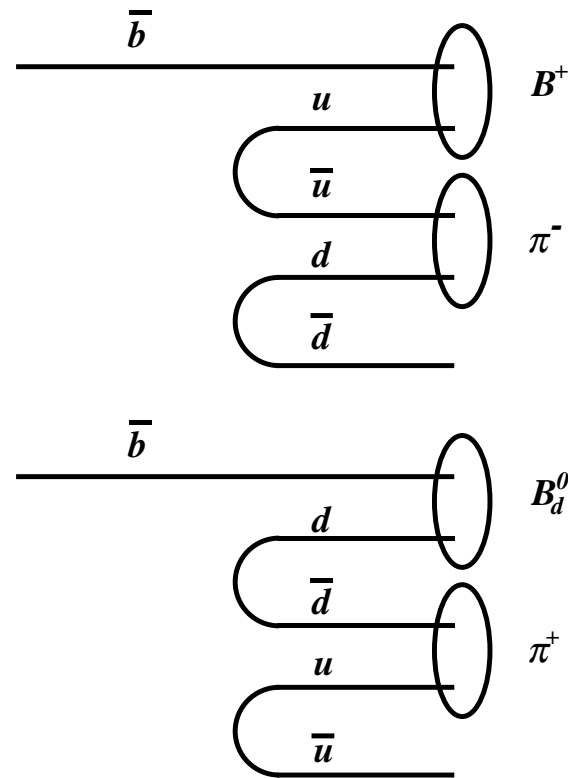
- Weak interactions $\rightarrow B^0$ oscillation (mixing)



\Rightarrow Need flavor of B^0 both at decay and production (flavor tagging).

Example: Same Side Tagging

- Search for pions produced along with B mesons:



- $\sim 30\%$ of B mesons produced from B^{**} decays.

B^{**} : Theory

- $\bar{b}d$ meson - two ground states for $L=0$:

Quark spins	State
$\uparrow\downarrow$	B^0
$\uparrow\uparrow$ <i>or</i> $\downarrow\downarrow$	B^{0*}

- excited radial and orbital states of light quark's wavefunction

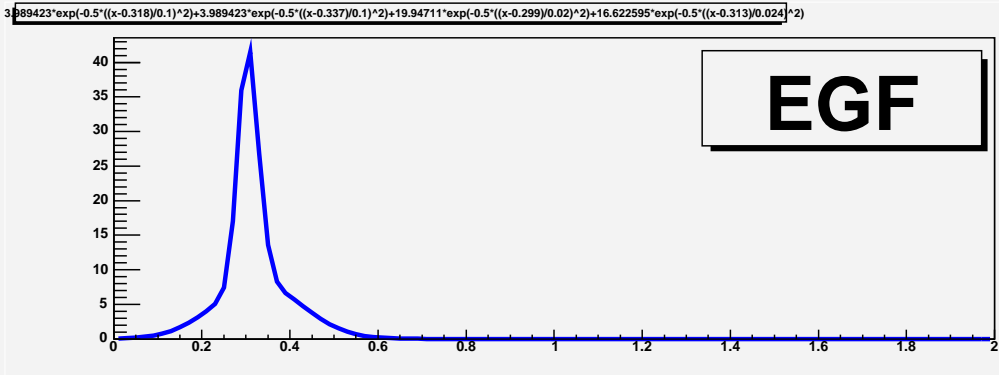
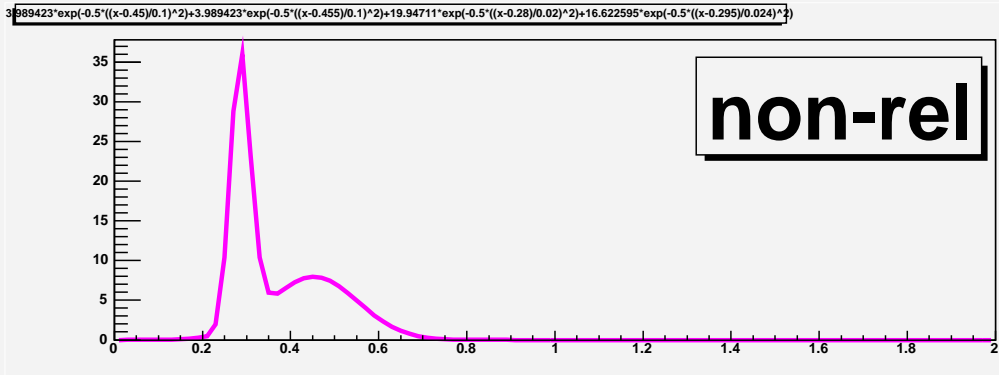
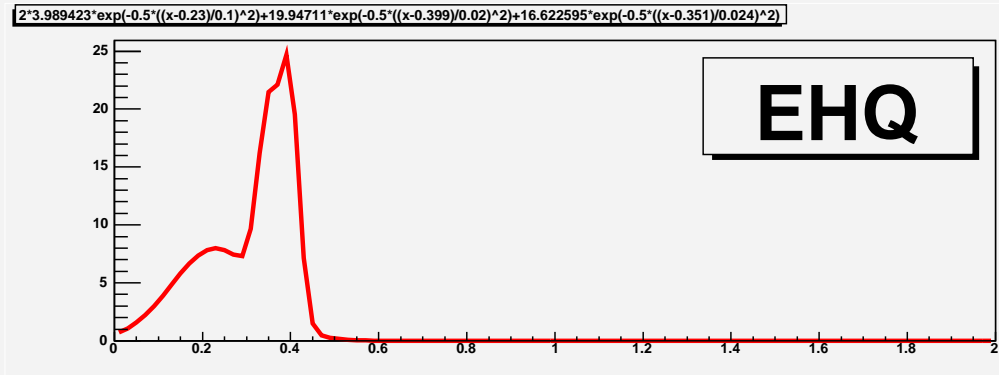
- First orbitally excited states ($L=1$) energetically lower than first radially excited states.

⇒ Lowest excited states are four $L=1$ (collectively labelled " B^{**} ").

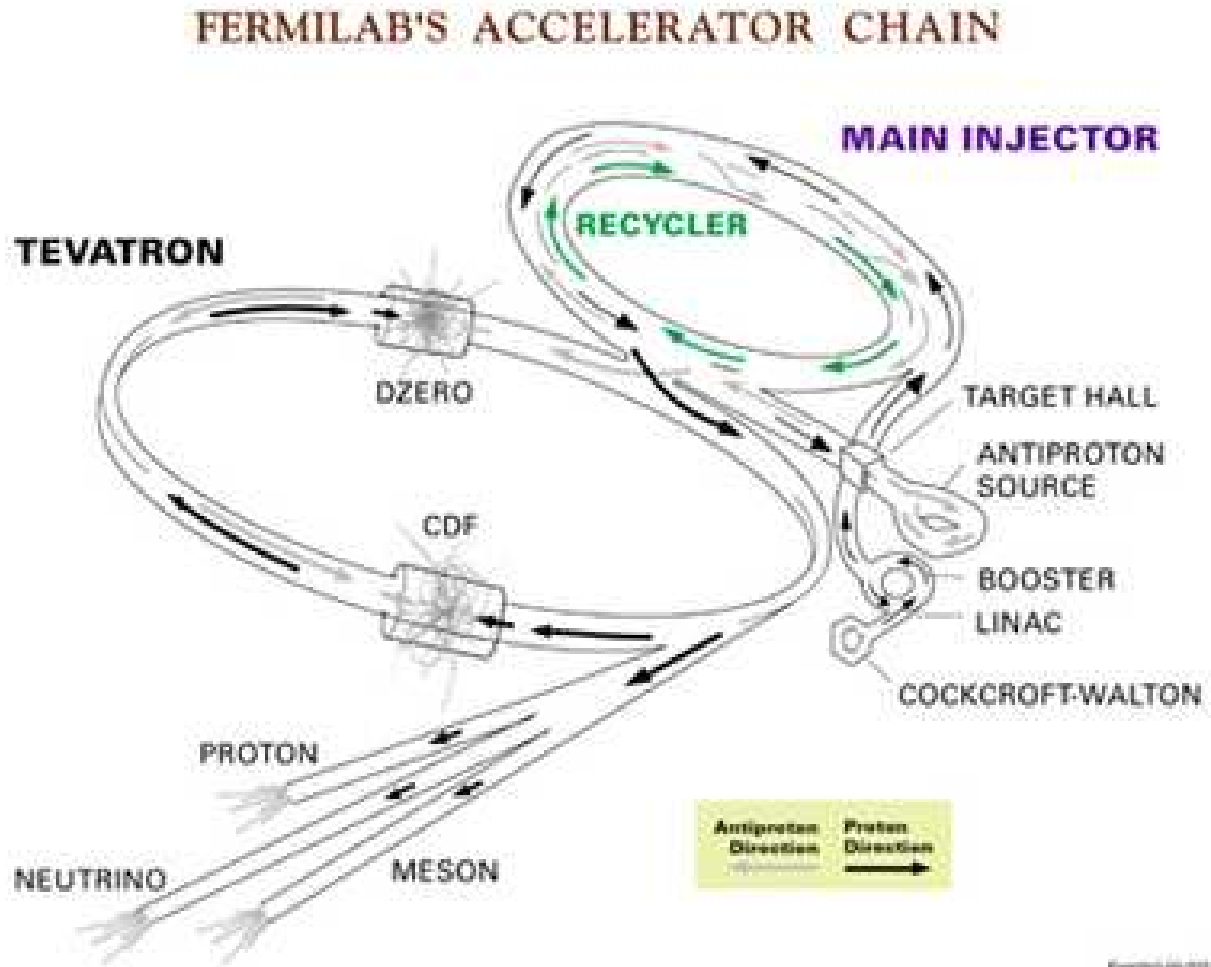
B^{**} : Theory 2

Name	\mathbf{J}	J_q	Mass (GeV/c^2)			Width MeV/c^2	Decays
			EHQ	non-rel	EGF		
B_0^*	0	$\frac{1}{2}$	5.650	5.870	5.738	100	$(B\pi)_{L=0}$
B_1^*	1	$\frac{1}{2}$	5.650	5.875	5.757	100	$(B^*\pi)_{L=0}$
B_1^*	1	$\frac{3}{2}$	5.759	5.700	5.719	20	$(B^*\pi)_{L=2}$
B_2^*	2	$\frac{3}{2}$	5.771	5.715	5.733	24	$(B\pi, B^*\pi)_{L=2}$

Widths may be narrower: scaling from D^{**} measurements by $\frac{1}{3}$ (width scales as $\frac{1}{m_Q}$ and $m_b \sim 3m_c$).

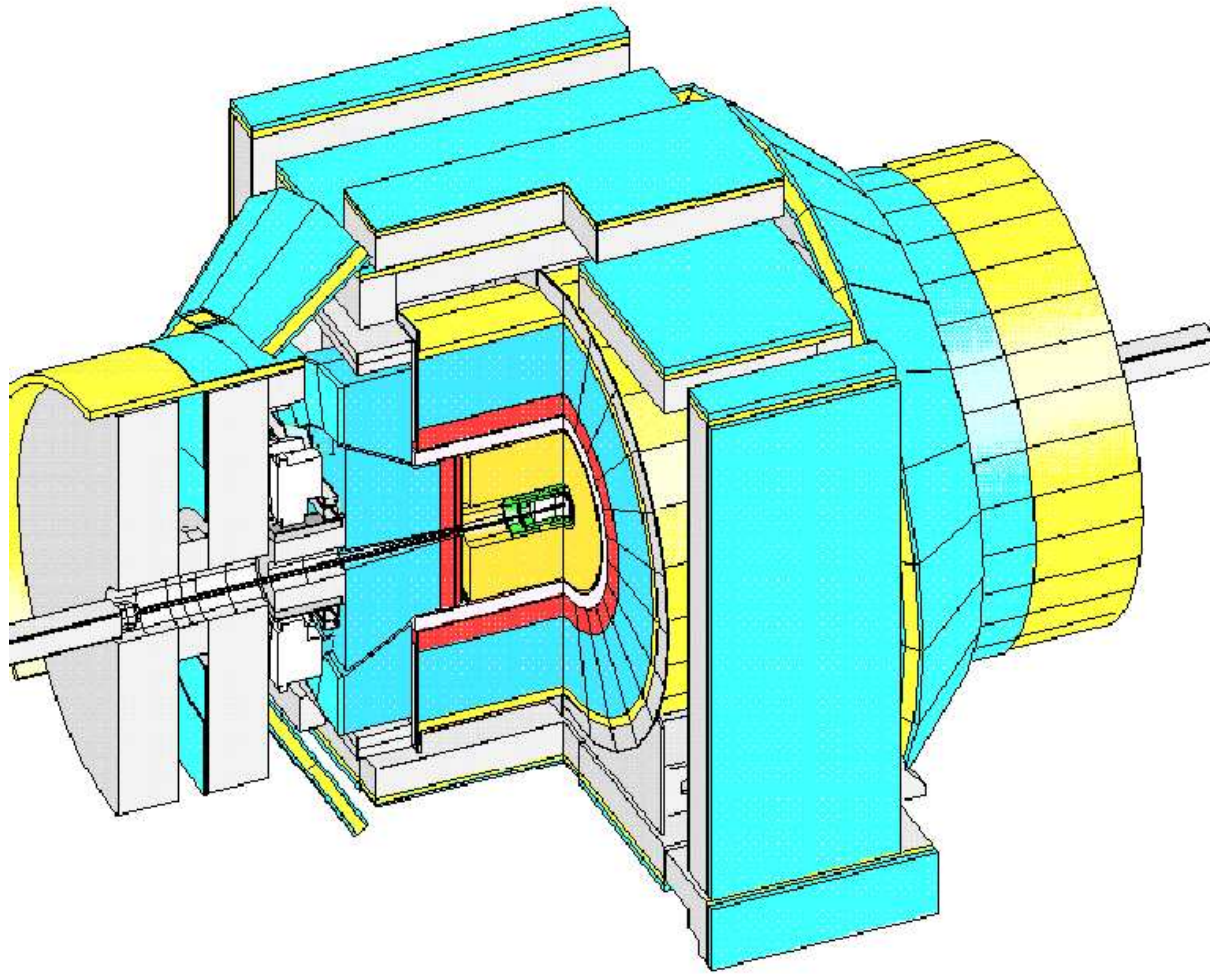


Fermilab: Accelerator Chain



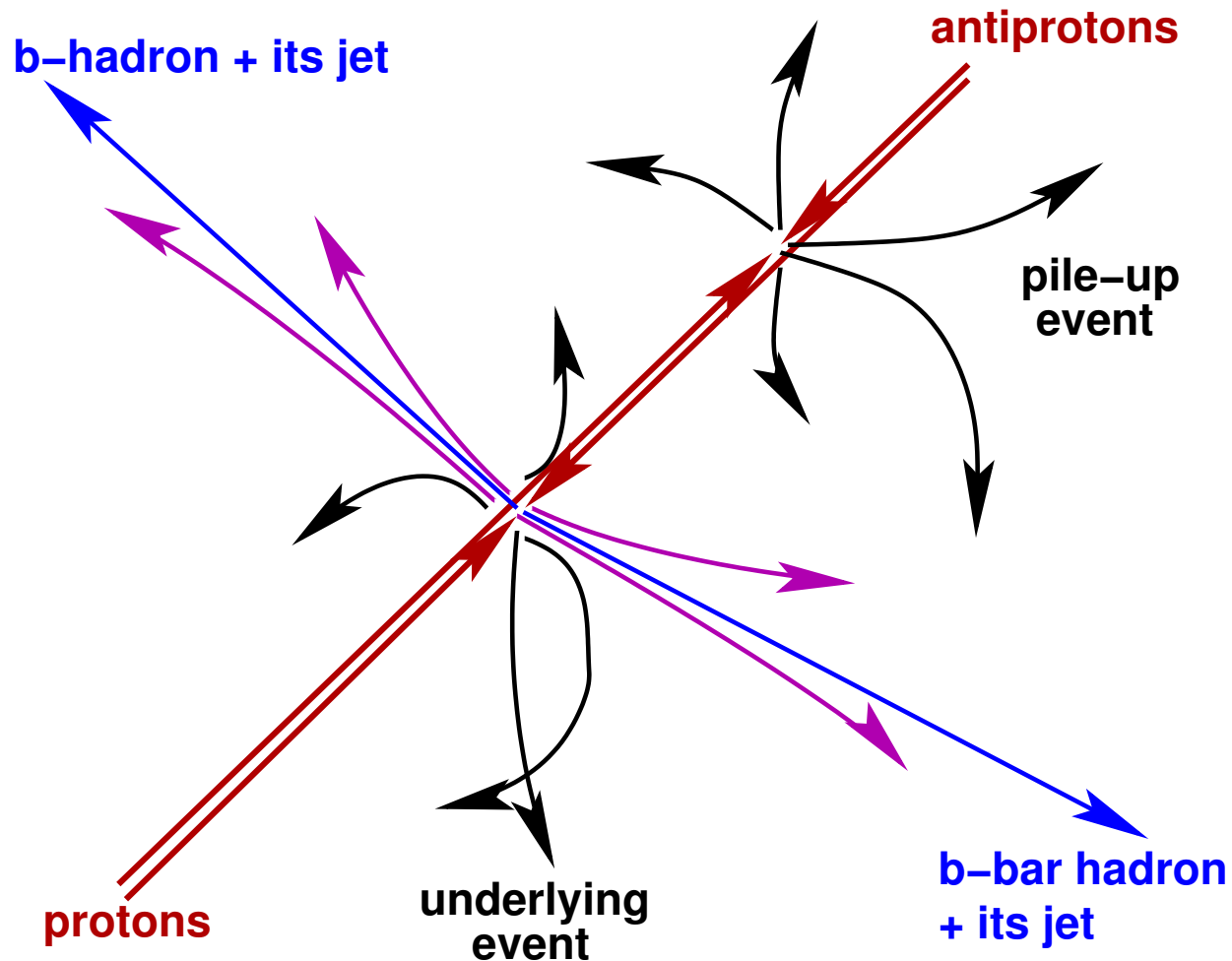
The Experiment: CDF II

Tevatron collides $p\bar{p}$ at center of mass energy $S = 1.96$ TeV



B Background:

- Fragmentation, Underlying event, Pileup event

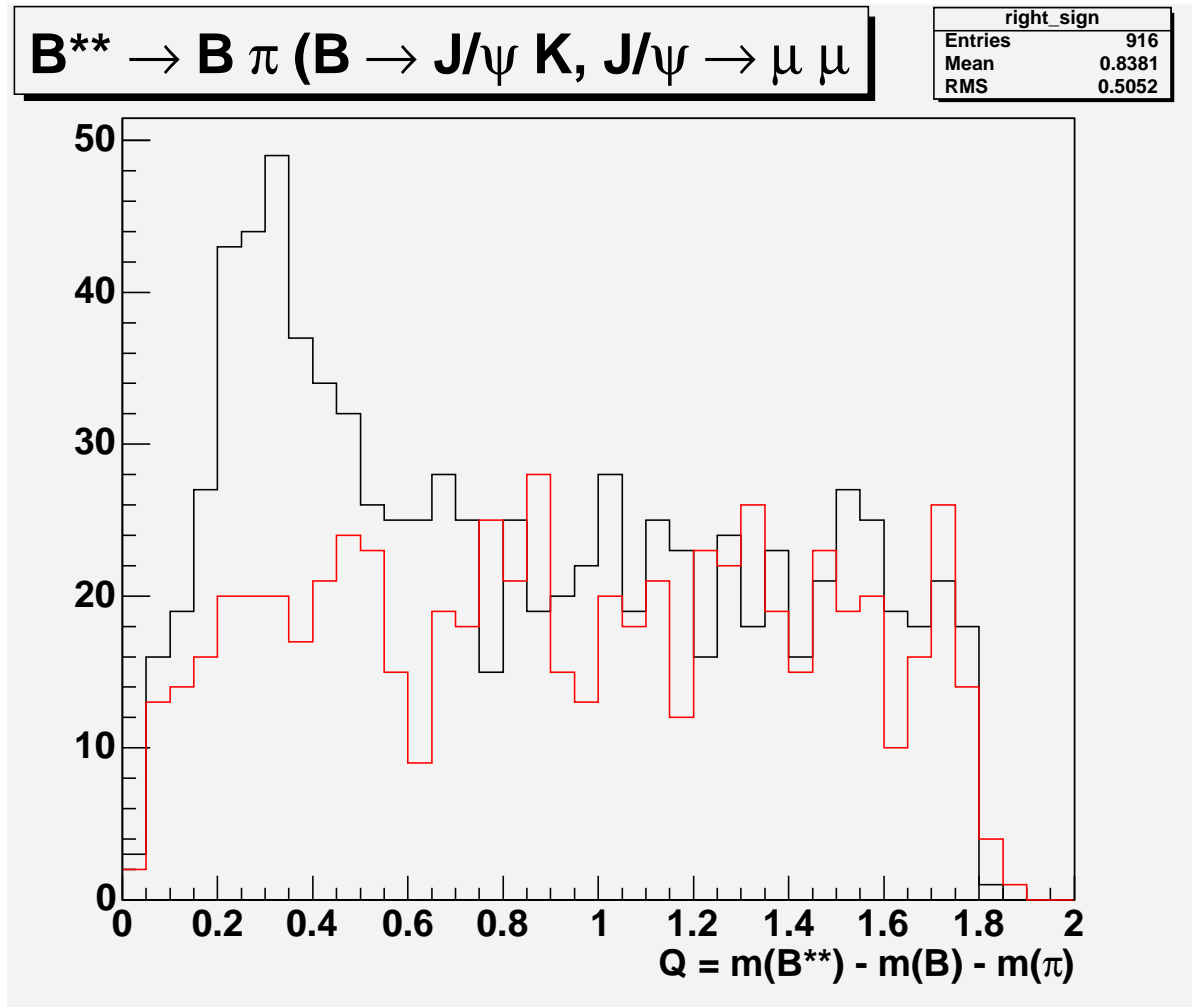


The Search for B^{**}

- Look for orbitally excited B mesons using fully reconstructed B decays (all decay products observed).
- First decay mode analyzed:

$$B^{**} \rightarrow B^+ \pi^- (B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu^+ \mu^-)$$

- Use all CDF II data collected from March 2001 to Sept. 2003.



Black: $B^{\pm} \pi^{\mp}$

Red: $B^{\pm} \pi^{\pm}$

Preliminary results show indications of peak in signal region.

Future Research

- Continue analysis of B^{**} :
 - Perform efficiency studies using Monte Carlo
 - Optimize event selection
 - Extract masses of 2 wide and 2 narrow states
- Increase statistics by exploring other decay modes:

$$B^{**} \rightarrow B^+ \pi^- (B^+ \rightarrow D^0 \pi^+, D^0 \rightarrow K^+ \pi^-)$$

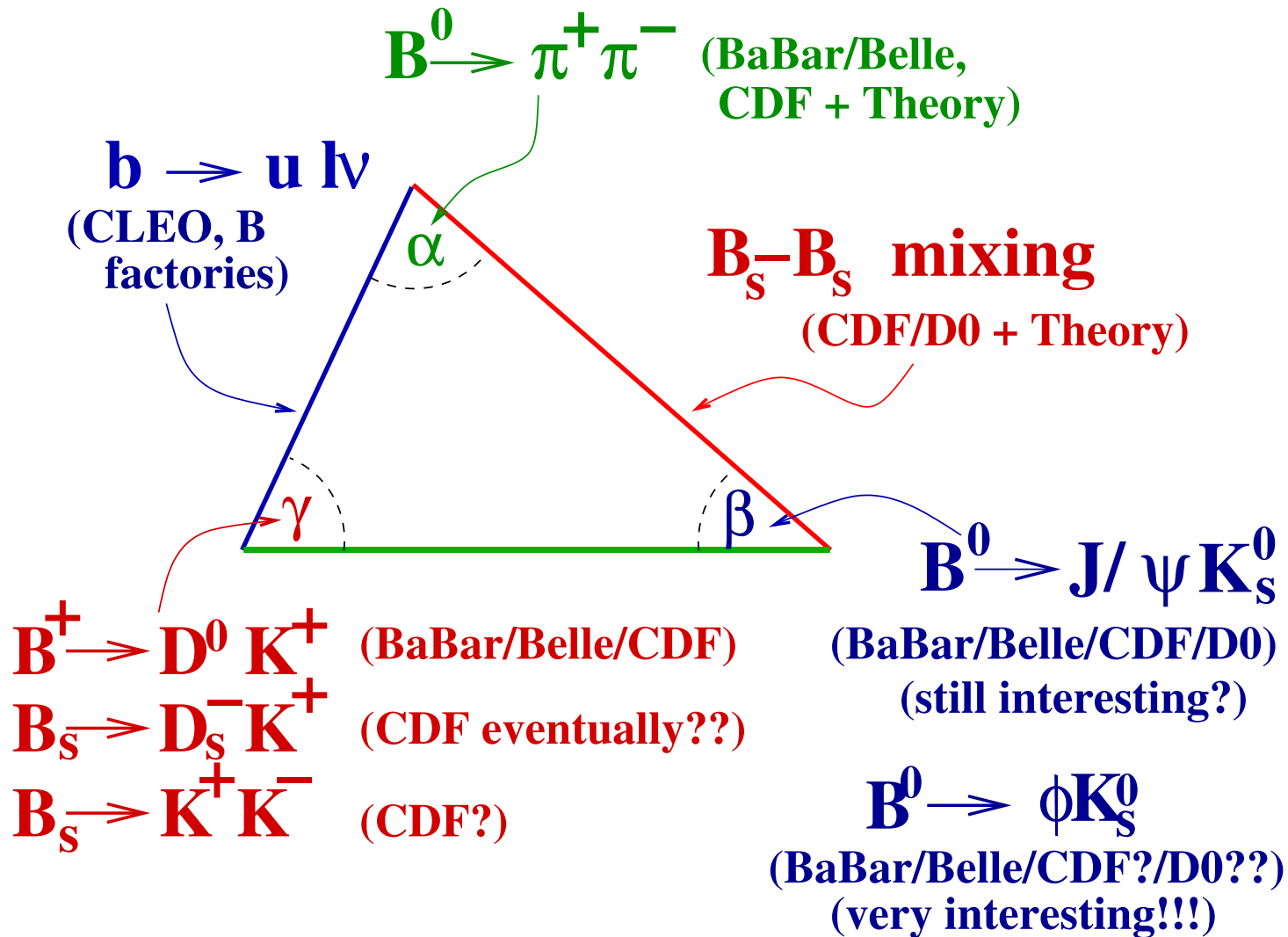
- Extend search to include $B^{**\pm}$ to study B^0 mixing:

$$B^{**+} \rightarrow B^0 \pi^+ (B^0 \rightarrow D^+ \pi^-, D^+ \rightarrow \pi^+ K^- \pi^+)$$

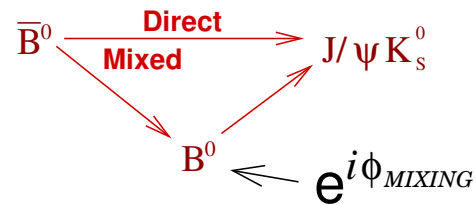
Conclusions

- Results of B^{**} measurement will add to B physics knowledge and assist other measurements designed to constrain CKM Matrix elements.
- See indications of narrow B^{**} mass peak (possibly even wide peaks)
 - more work needed to make results conclusive.
- Goal: be ready for B^{**} publication by the fall.

More on Unitarity Triangle



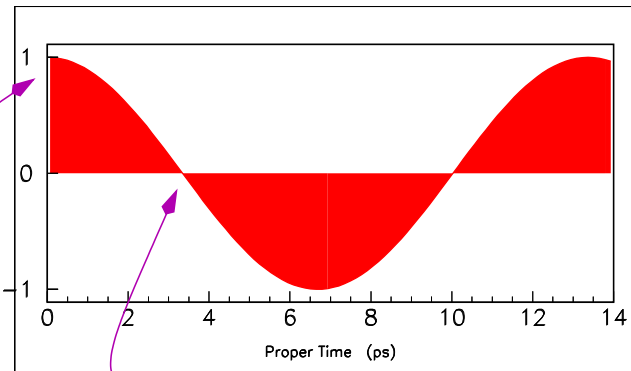
More on B^0 Mixing



Flavor Asymmetry:

$$\frac{N(\bar{B}^0 \rightarrow \bar{B}^0) - N(\bar{B}^0 \rightarrow B^0)}{N(\bar{B}^0 \rightarrow \bar{B}^0) + N(\bar{B}^0 \rightarrow B^0)}$$

Pure \bar{B}^0
No Interference



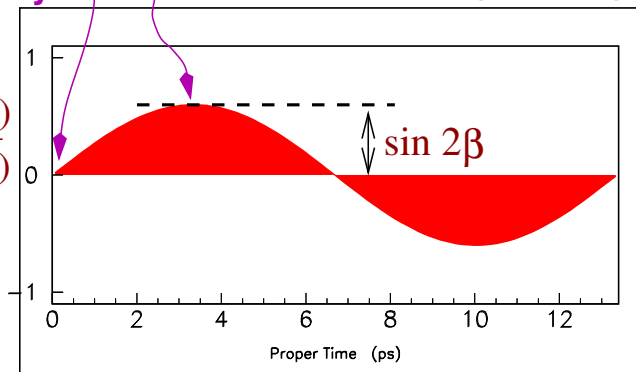
Equal B^0 - \bar{B}^0 Mixture

No CP Asymmetry

Maximal CP Asymmetry

CP Asymmetry:

$$\frac{N(\bar{B}^0 \rightarrow J/\psi K_s^0) - N(B^0 \rightarrow J/\psi K_s^0)}{N(\bar{B}^0 \rightarrow J/\psi K_s^0) + N(B^0 \rightarrow J/\psi K_s^0)}$$



More on Tagging

