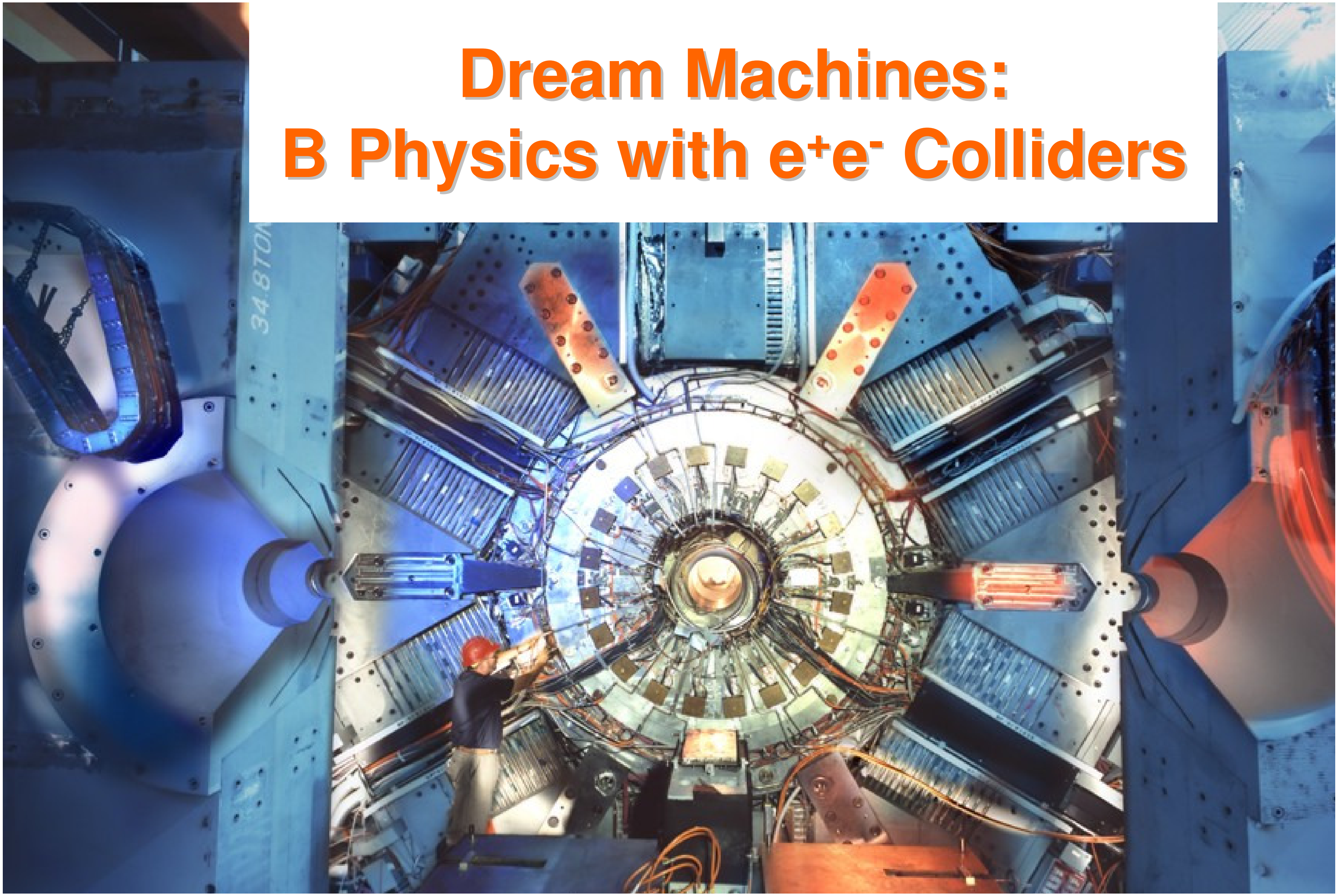
Dream Machines: B Physics with e^+e^- Colliders



2007 Fermilab Academic Lecture Series: Flavor Physics

Jeffrey Berryhill (FNAL)

Outline

An Introduction to Υ(4S) Experiments and Measurement Techniques

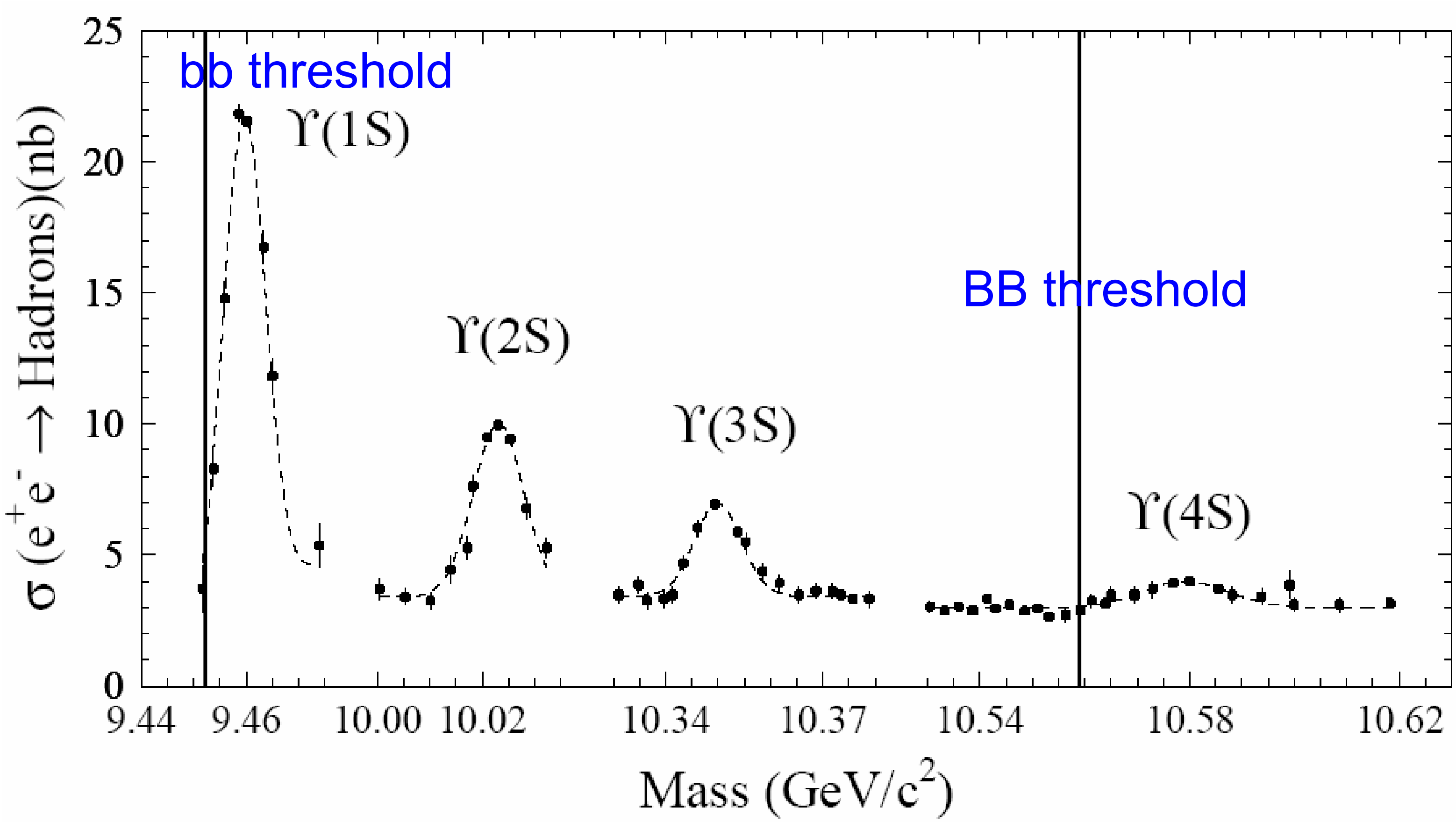
•**Dream Machines: Accelerators, Detectors, and the Υ(4S) environs**

•**Exclusive B branching fractions and direct CP violation**
Kinematic constraints
Multivariate background discrimination
Case Study: $B^0 \rightarrow K^+ \pi^-$

•**Time dependent CP violation of exclusive B decays**
B decay length difference
B flavor tagging
Case Study: $B^0 \rightarrow \psi K_s$

•**B branching fractions to inclusive or neutrino-ful final states**
Recoil side reconstruction
Case Study: $B^- \rightarrow \tau^- \nu$

B meson production with e^+e^- collisions



Y(4S) lightest bb bound state decaying to B mesons

Mass = 10.58 GeV (B meson mass = 5.279 GeV)

Peak production xsec = 1.1 nb

Decays exclusively to B^+B^- (50%) and $B^0\overline{B}^0$ (50%)

B pair produced nearly at rest in Y(4S) frame ($\beta\gamma = 0.06$)

Other production at 10.58 GeV

Final State	Xsec (nb)	Events/fb^{-1}
$\Upsilon(4S) \rightarrow B\bar{B}$	1.1	1.1 M
$u\bar{u}$, $d\bar{d}$, and $s\bar{s}$	2.0	2.0 M
$c\bar{c}$	1.4	1.4 M
$\tau^+\tau^-$	1.0	1.0 M

~2.2 million b quarks per fb^{-1} =

0.55M B^+B^- +
0.55M $B^0\bar{B}^0$

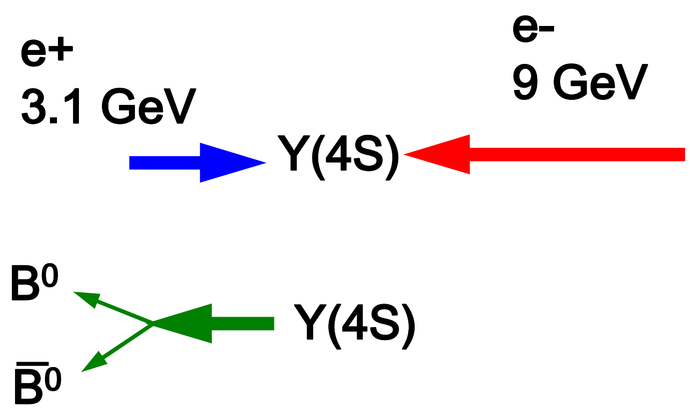
Y(4S) signal/bkg
= 1:4

Also (very low multiplicity):
QED ($ee(\gamma)$, $\mu\mu(\gamma)$)
Two-photon collisions

A B factory at Y(4S) is also a charm and tau factory!

At 10.54 GeV, "off-resonance" events collected to study or measure background

Asymmetric-energy B Factories



B Meson $\beta\gamma$ = 0.56

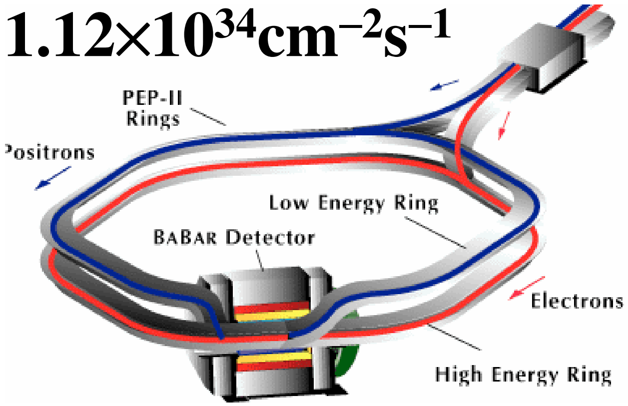
Asymmetric-energy B Factories

PEP-II at SLAC

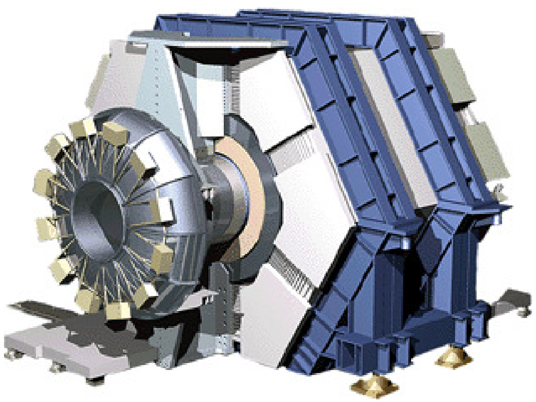
9GeV (e^-) × 3.1GeV (e^+)
peak luminosity:

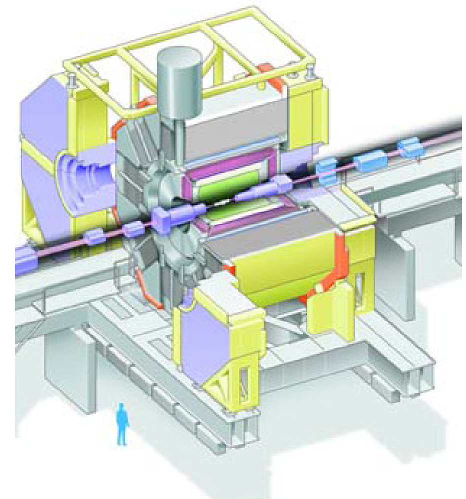
1.12×10^{34}cm^{-2}s^{-1}

B Meson $\beta\gamma$ = 0.56
No crossing angle,
dipole separates beams

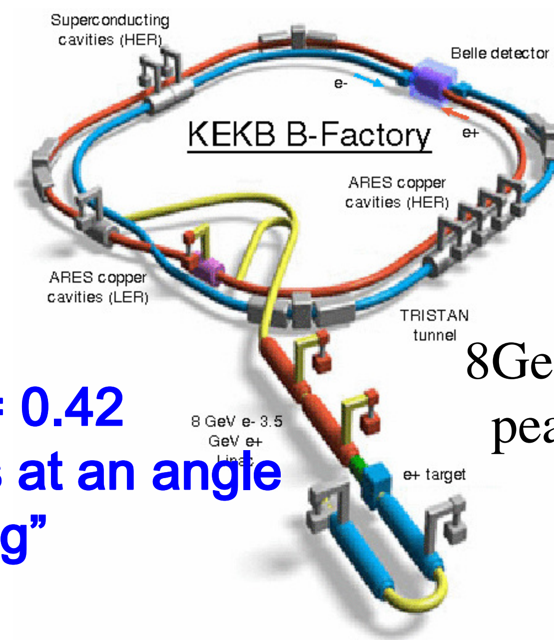


BaBar





Belle



KEKB at KEK

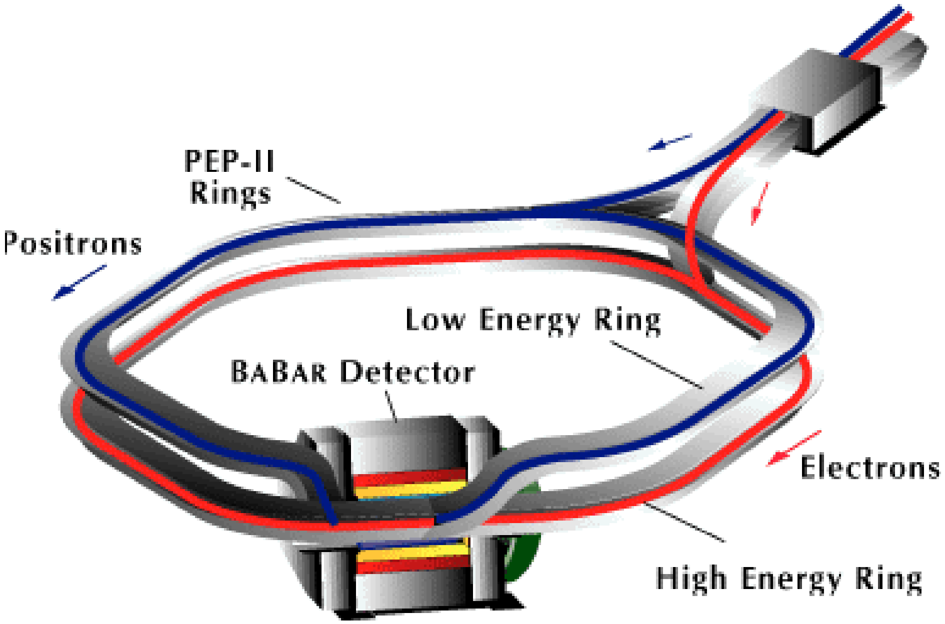
8GeV (e^-) × 3.5GeV (e^+)
peak luminosity:

1.65×10^{34}cm^{-2}s^{-1}

B Meson $\beta\gamma$ = 0.42
Beams cross at an angle
"crab crossing"

PEP-II at the Stanford Linear Accelerator Center

PEP-II performance



Int. Lum. = 391 fb^{-1}
Off resonance = 37 fb^{-1}

780 million b quarks produced!

Operated continuously since 1999

PEP-II top luminosity:
$11.2 \times 10^{33} cm^{-2}s^{-1}$
(more than 3x design goal 3.0×10^{33})

Beams carry >1 Amp of current each, injected continuously

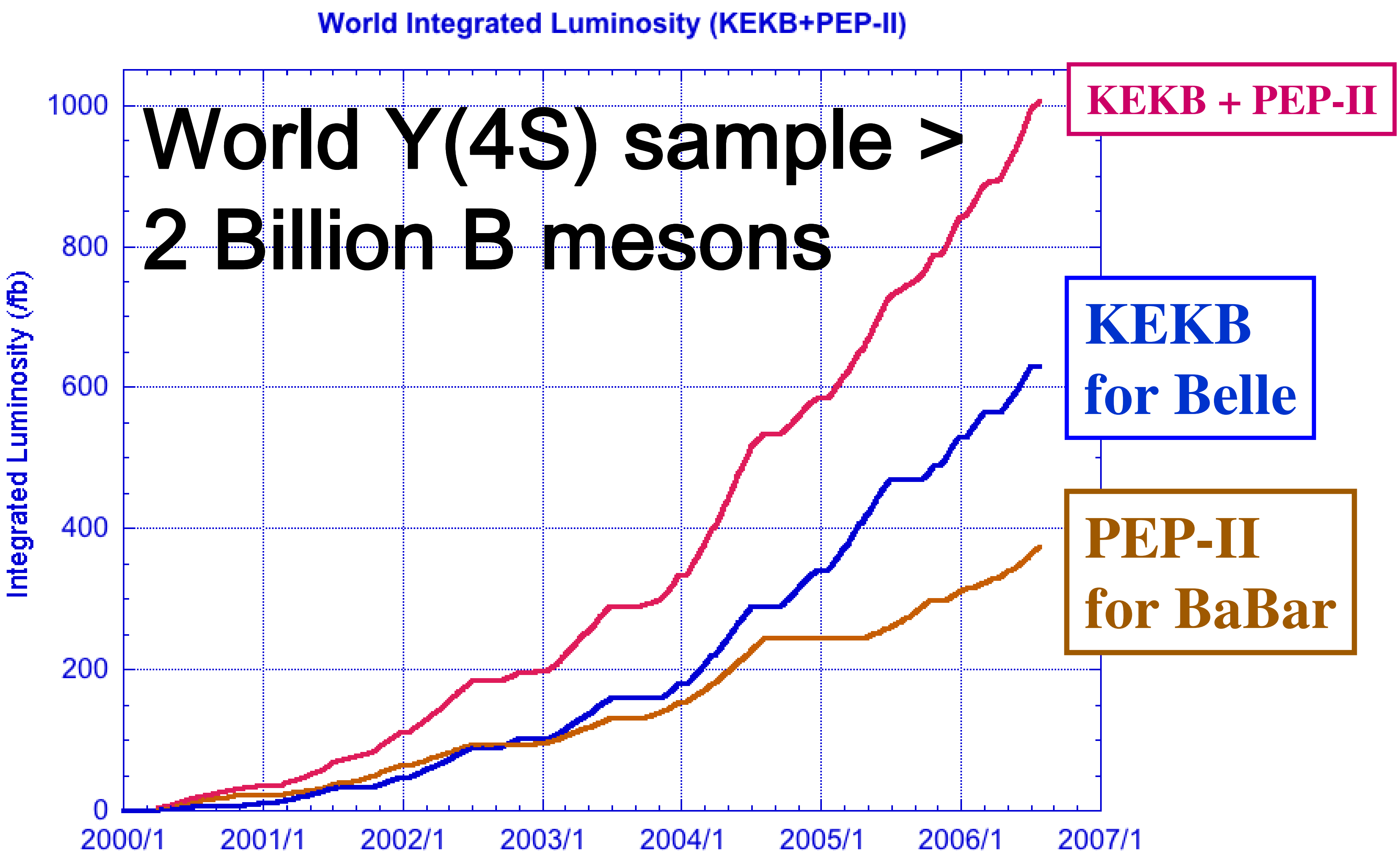
Beams collide in a small area of about

100 µm X 6 µm

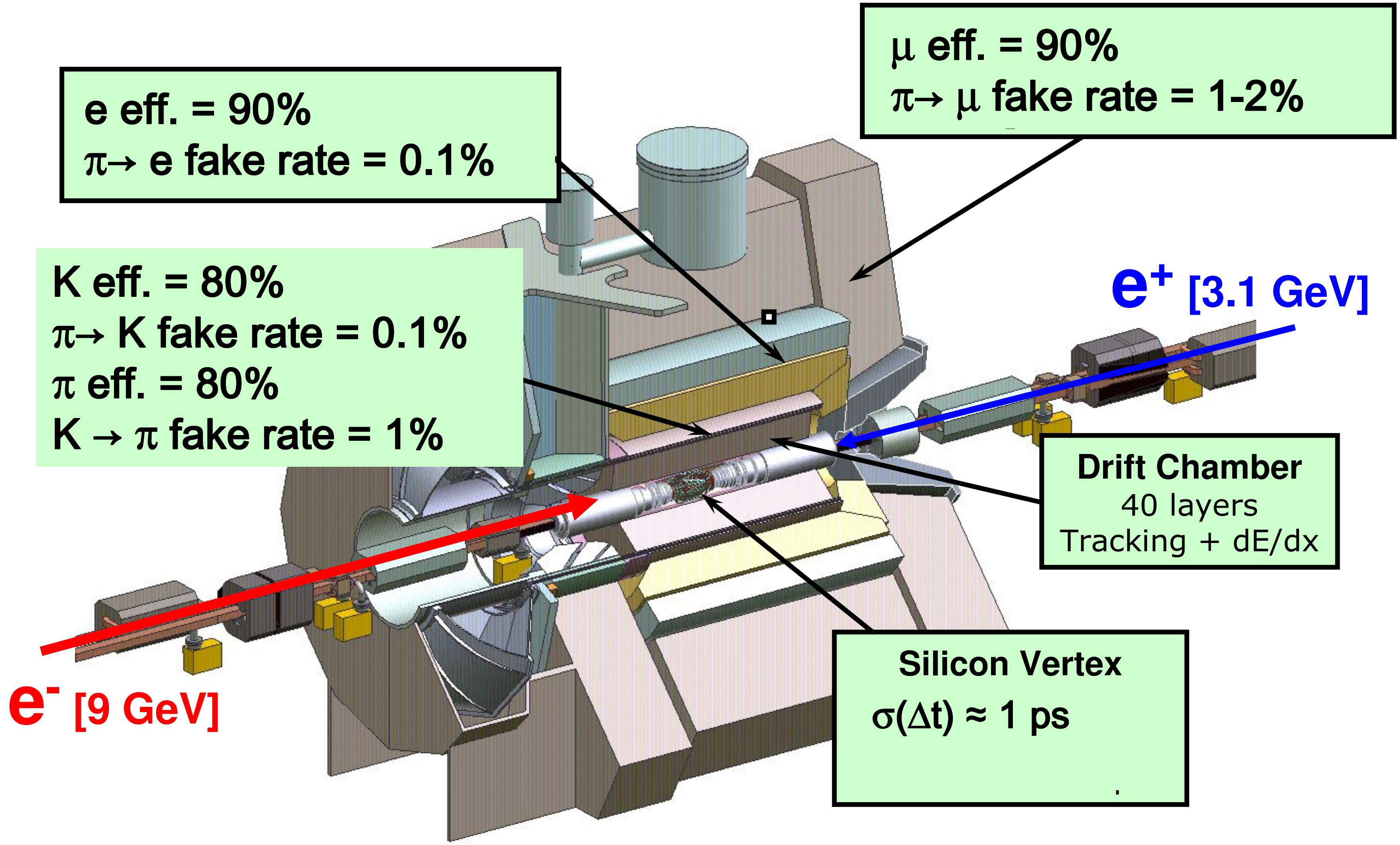
In 1 day : created 1.5 million b quarks !

Also hundreds of millions each of u, d, s, c, and τ!

Integrated Luminosity



The BaBar detector



Particles produced

(Quasi) stable detectable "building blocks"

Mesons			Leptons			Baryons
$\pi+$	π^0 (γ pair)		e	μ	γ	p
K+	K_S (π pair)	K_L				n

Charmed mesons

D^+ ($K-\pi+\pi+$, $K_S\pi+$)
D^0 ($K-\pi+$, $K-\pi+\pi^0$, $K-\pi+\pi+\pi-$, $K_S\pi+\pi-$)
D^{*0} ($D^0\pi^0$, $D^0\gamma$)
D^{*+} ($D^0\pi^+$, $D^+\pi^0$)
D_s^+ ($\phi\pi^+$, K^+K_S)
D_s^{+*} ($D_s^+\gamma$)
J/ψ ($e+e-$, $\mu+\mu-$)

Light mesons

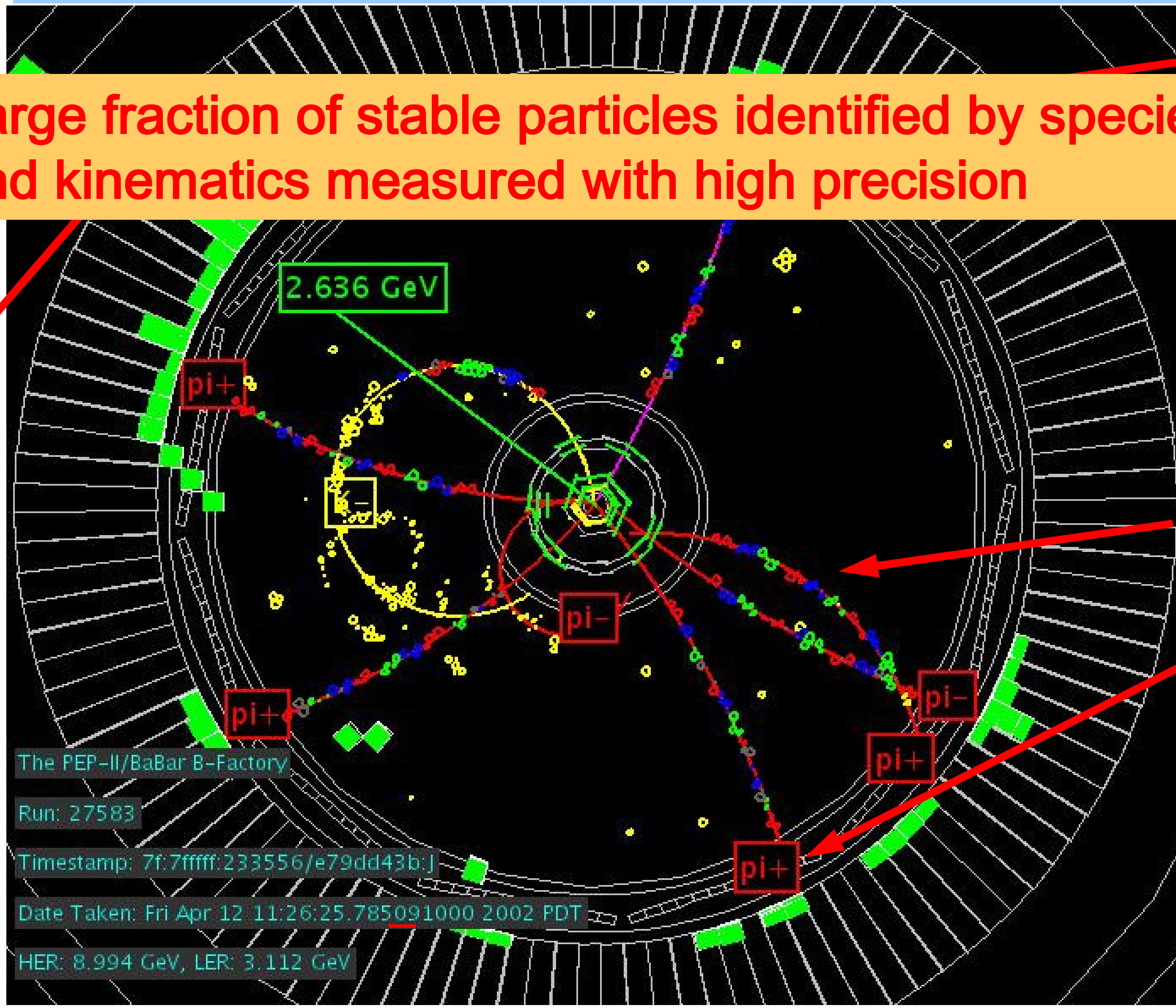
ρ ($\pi+\pi-$, $\pi+\pi^0$)
ω ($\pi+\pi-\pi^0$)
η ($\gamma\gamma$, $\pi+\pi-\pi^0$)
η' ($\eta\pi+\pi-$, $\rho\gamma$)

K^* ($K\pi$)
ϕ ($K+K-$, $K_S K_L$)

Others: $\psi(2S)$, χ_c, η_c, $K_2^*(1430)$, Λ, Λ_C, $f_0(980)$, $a_{0,1,2}$

$B^+ \to K^{*+}\gamma$ Candidate

Large fraction of stable particles identified by species and kinematics measured with high precision



High energy photon absorbed by ECAL

Muon
om
her
decay

$K_s \to \pi^+\pi^-$

and π+

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Anatomy of a Branching Fraction Measurement

•Signal candidate reconstruction: Collect sample of events with exclusive final state X (particle ID and kinematic constraints)

•Background rejection: Cuts which exploit event shape differences to reduce continuum and other backgrounds

•Signal yield extraction: Estimator of N_X for selected events using multi-dimensional likelihood fit over kinematic and background rejection variables

•Efficiency estimation: Fraction ε_X of produced events selected (checked against numerous control samples)

•B counting: Total number of B pairs N_{BB} produced in collisions

•Putting it all together:

$BF(B^0 \rightarrow X) = N_X \;/\; \varepsilon_X N_{BB}$

Kinematic Constraints

- For rare decay studies or high precision, eliminating random combinations of particles as possible B candidates is essential

- For a completely reconstructed B meson candidate with daughters (p_i, m_i), two uncorrelated kinematic constraints:

Beam-constrained mass:

Candidate should have mass $m_B^2 = (5.279\ \text{GeV})^2 = E^2 - p^2$

AND, Y(4S) decays exclusively to a B pair, so E = E(beam) in Y(4S) frame

$$M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$$

p_B, E(beam) in Y(4S) frame

p_B and E(beam) precisely known, so M_{bc} should agree with m_B to within 3 MeV! **Independent of mass hypotheses for daughters**

Kinematic Constraints

Energy difference:

Candidate energy should coincide with beam energy in Y(4S) frame

$$\Delta E = \sum_{\alpha=1}^{n} \sqrt{m_\alpha^2 + |\mathbf{p}_\alpha|^2} - E_{\text{beam}} \approx 0$$

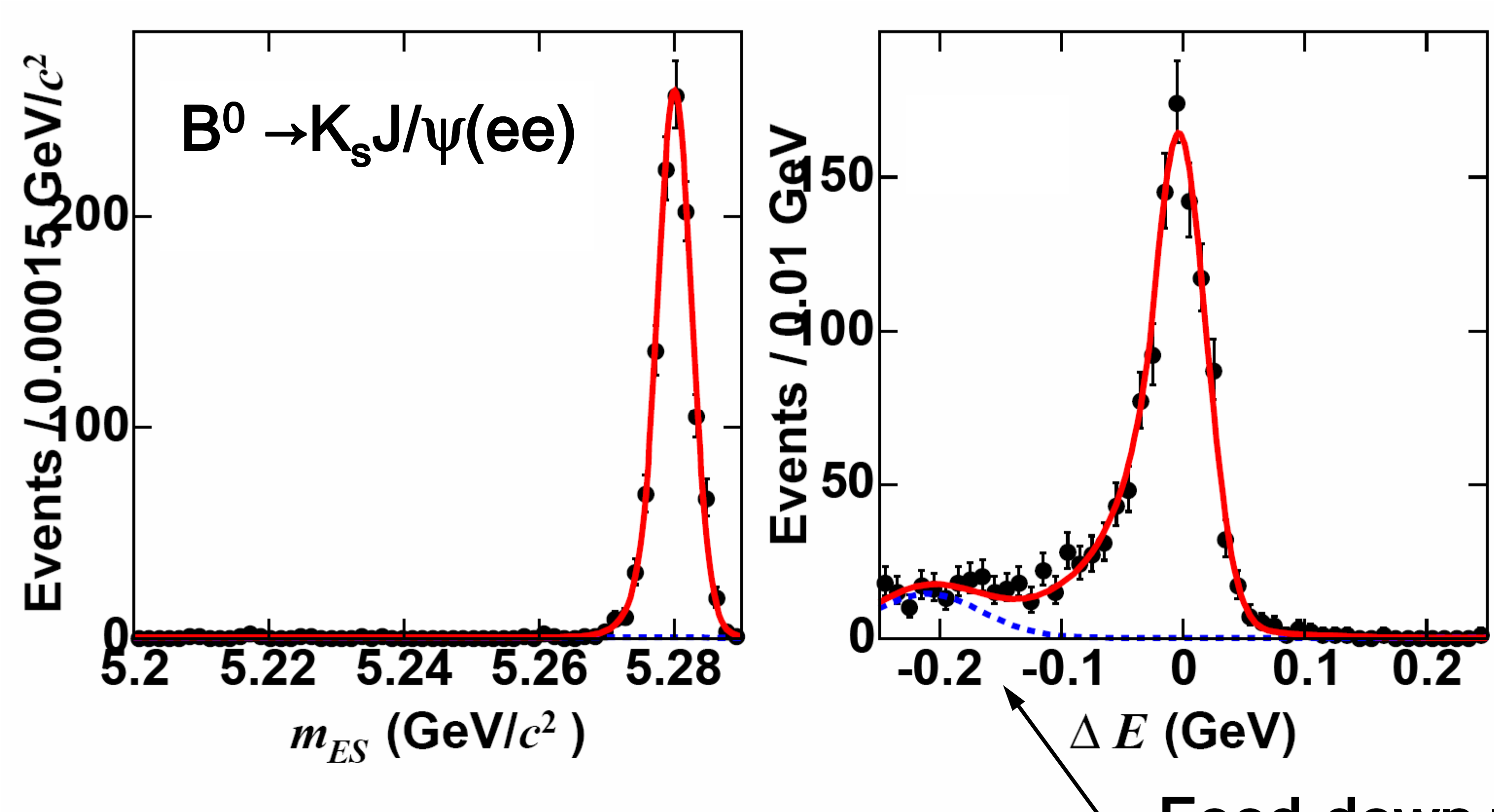
p, E(beam)
in Y(4S) frame

Resolution typically 10-30 MeV

Depends explicitly on mass hypotheses for daughters

Incorrect particle ID or missing particles will shift ΔE from 0
(suppresses backgrounds from other B decays: false ID or “cross-feed”)

Kinematic Constraints



Feed-down from $J/\psi\ K^{*+}$

Also: Intermediate particle masses (e.g. composites listed previously) and decay helicity angles can provide additional rejection

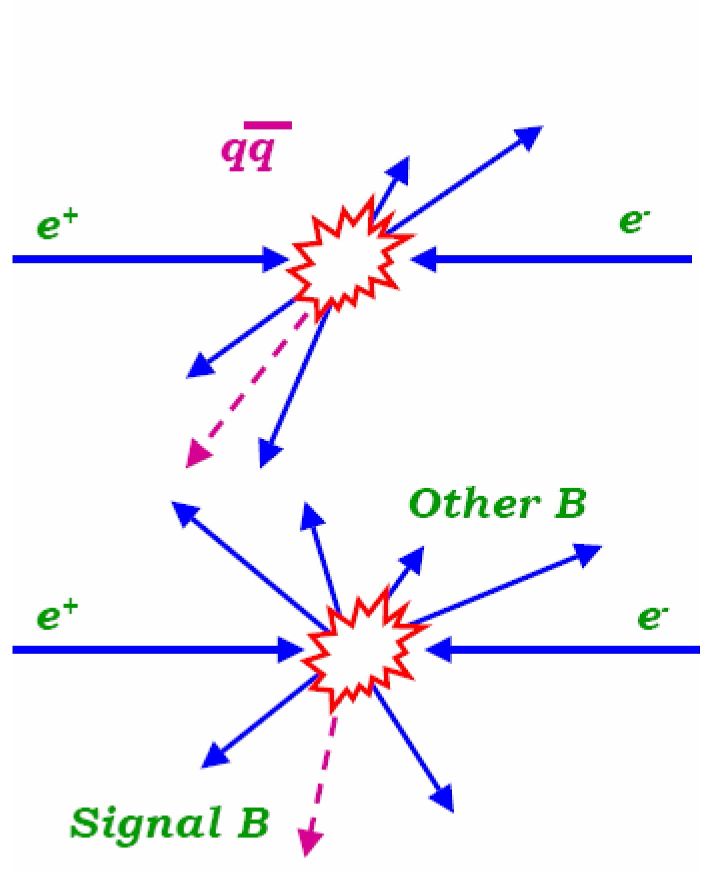
Background Suppression

Exploit fact that continuum events are more jet-like than BB events

•Event shape variables: spherical B vs. jet-like continuum (Fox-Wolfram moments, Legendre moments, sphericity, thrust angle)

•B flavor tagging variables: kaons and leptons in the rest of the event
•B candidate vertex separation from rest of the event

Sometimes combined into a single Fisher discriminant or neural net variable



Signal Extraction

Unbinned maximum likelihood fit of (m_{ES}, ΔE, et al.): maximizes LH function

$$\mathcal{L} = \frac{1}{N!} \exp\left(-\sum_i N_i\right) \prod_j \left[\sum_i N_i \mathcal{P}_i(\vec{x}_j;\vec{\alpha}_i)\right]$$

i components: signal, peaking backgrounds, combinatorial background, with normalization N_i and shape parameters α_i
j events: each event with a vector of variables x_j

P_i typically multidimensional: $P_i = P_i(m_{ES})*P_i(\Delta E)*$….. (usually uncorrelated)

Signal yield, background yield and background shape parameters are typically free parameters in fit (background systematics absorbed into statistical error on signal yield)

Signal yield or other parameters of key interest are BLIND until all analysis techniques finalized

B counting

•Select all on-resonance multi-track events satisfying very loose event shape cuts ($N^{on}(MH)$)

•Use same selection on off-resonance data ($N^{off}(MH)$)

•Select ee → μμ events as an estimator of luminosity in on and off resonance samples ($N^{on}(\mu\mu)$ and $N^{off}(\mu\mu)$)

$$N_{BB} = N_{MH}^{On} - N_{MH}^{Off} \cdot \frac{N_{\mu\mu}^{On}}{N_{\mu\mu}^{Off}} \cdot \frac{\sigma_{\mu\mu}(s_1)}{\sigma_{\mu\mu}(s_0)} \cdot \frac{\varepsilon_{\mu\mu}(s_1)}{\varepsilon_{\mu\mu}(s_0)} \cdot \frac{\sigma_X(s_0)}{\sigma_X(s_1)} \cdot \frac{\varepsilon_X(s_0)}{\varepsilon_X(s_1)}$$

$$= N_{MH}^{On} - N_{\mu\mu}^{On} \cdot \frac{N_{MH}^{Off}}{N_{\mu\mu}^{Off}} \cdot \kappa$$

In practice, κ is very close to 1

B counting systematic uncertainty is typically 1%

Case Study: $B^0 \to K^+\pi^-$ BF and A_{CP}

BaBar preliminary BF, hep-ex/0608003 227M BB
BaBar preliminary ACP, hep-ex/0607106 347M BB

Measurement of rare $b \to s$ penguin decay and its direct CP asymmetry

$$\mathcal{A}_{K\pi} \equiv \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}}$$

Simultaneous study of $K\pi$, $\pi\pi$, KK (pion hypothesis for all tracks)

5D likelihood fit of $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-\}$

F = event shape Fisher discriminant, θ_C = Cherenkov angle in DIRC

$\pi\pi$ background at few % level

θ_C PDFs and asymmetry in efficiencies from large (400k) $D^{*+} \to D\pi$ control sample

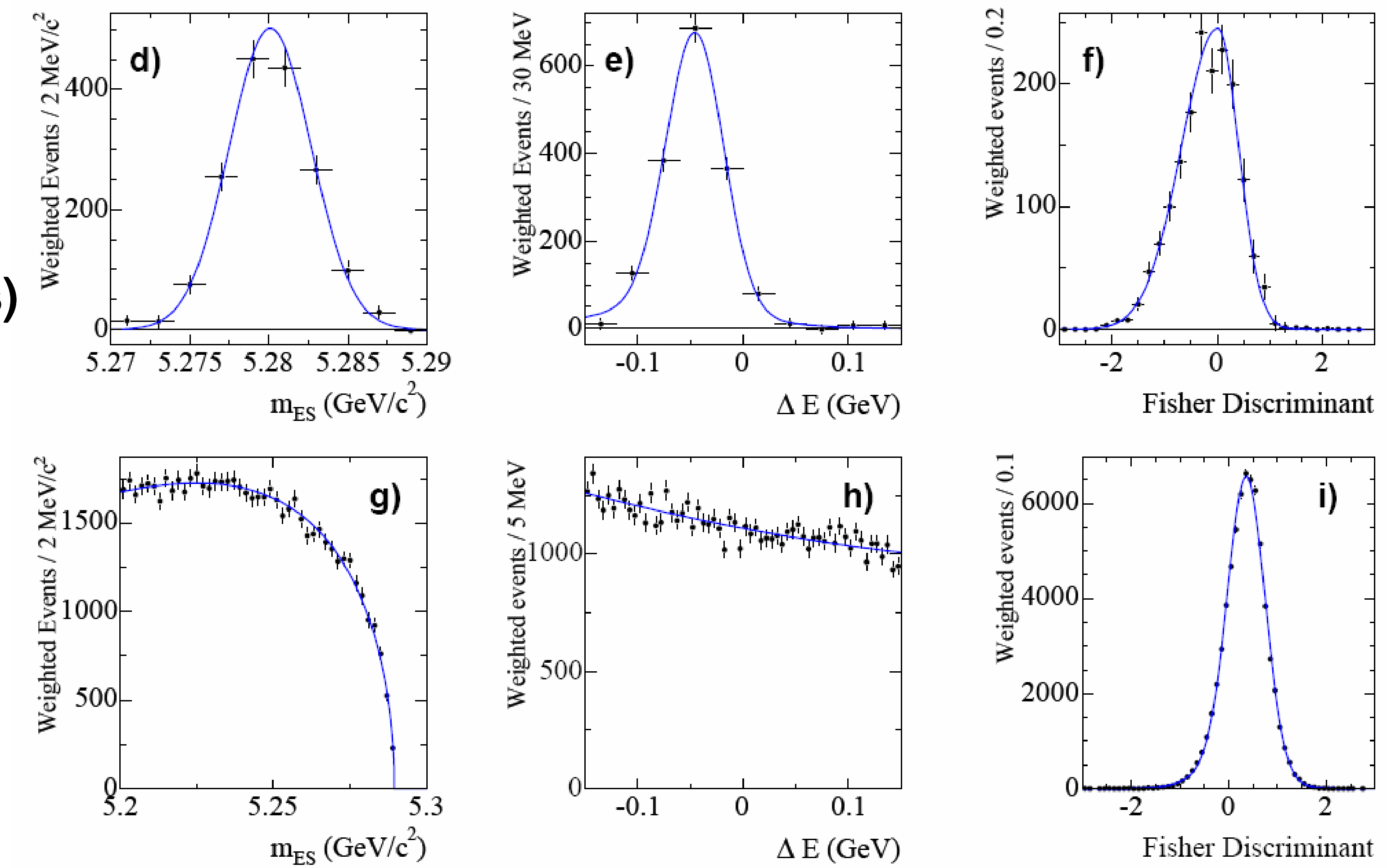
Case Study: $B^0 \rightarrow K^+\pi^-$ BF and A_{CP}

Signal
fit PDFs
vs. data

(1660 events)

qq Bkg
fit PDFs
vs. data

(65000)

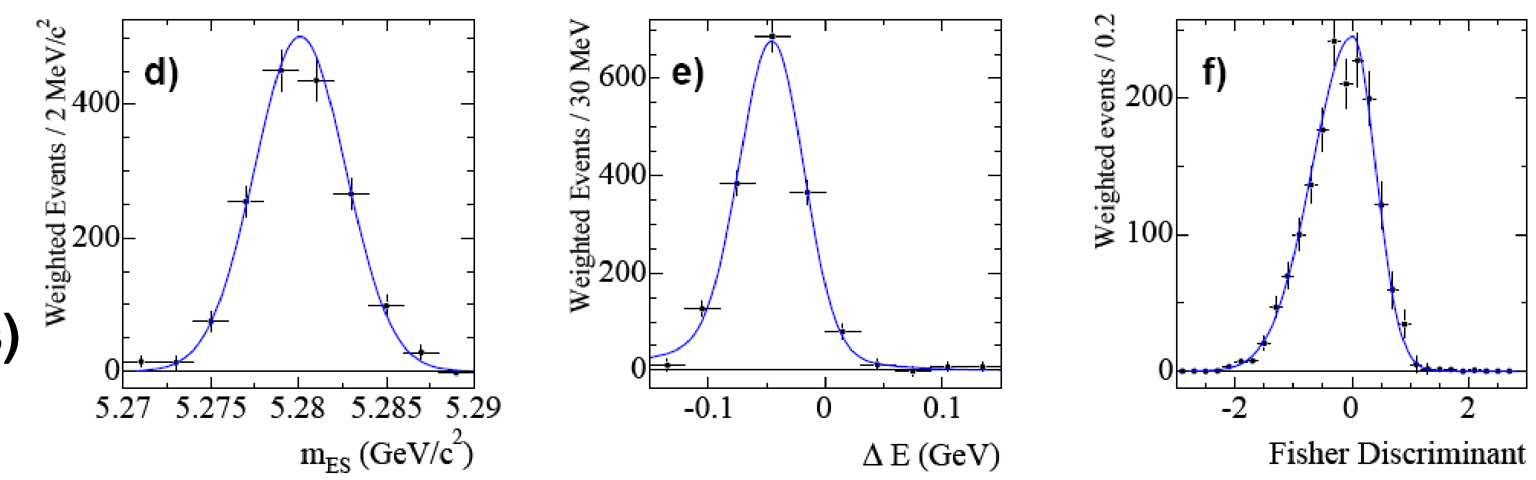


"sPlot" method of projecting out of the data each PDF component
(a fancy background subtraction using LH function)

Case Study: $B^0 \to K^+\pi^-$ BF and A_{CP}

Signal
fit PDFs
vs. data

(1660 events)



qq Bl
fit PD
vs. d

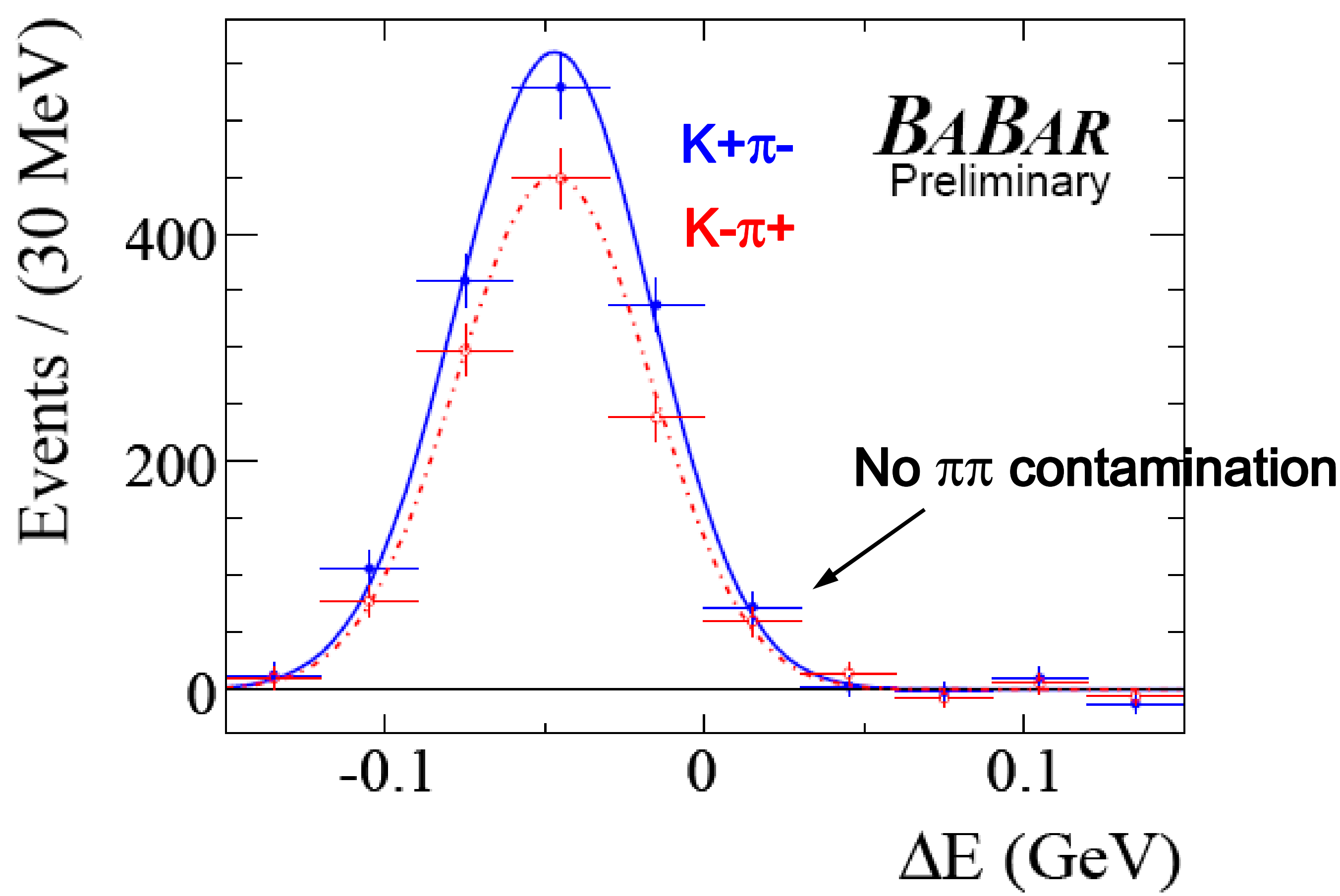
(650

Mode	N_S	ϵ (%)	$\mathcal{B}_{E_\gamma}$ (10^{-6})
$\pi^+\pi^-$	$489 \pm 35 \pm 11$	$40.3 \pm 0.2 \pm 1.2$	$5.4 \pm 0.4 \pm 0.3$
$K^+\pi^-$	$1660 \pm 52 \pm 15$	$39.3 \pm 0.2 \pm 1.0$	$18.6 \pm 0.6 \pm 0.6$
K^+K^-	$3.3 \pm 13.1 \pm 6.8$	$38.5 \pm 0.3 \pm 0.8$	< 0.40 (90% C.L.)

m_ES (GeV/c²) Δ E (GeV) Fisher Discriminant

"sPlot" method of projecting out of the data each PDF component
(a fancy background subtraction using LH function)

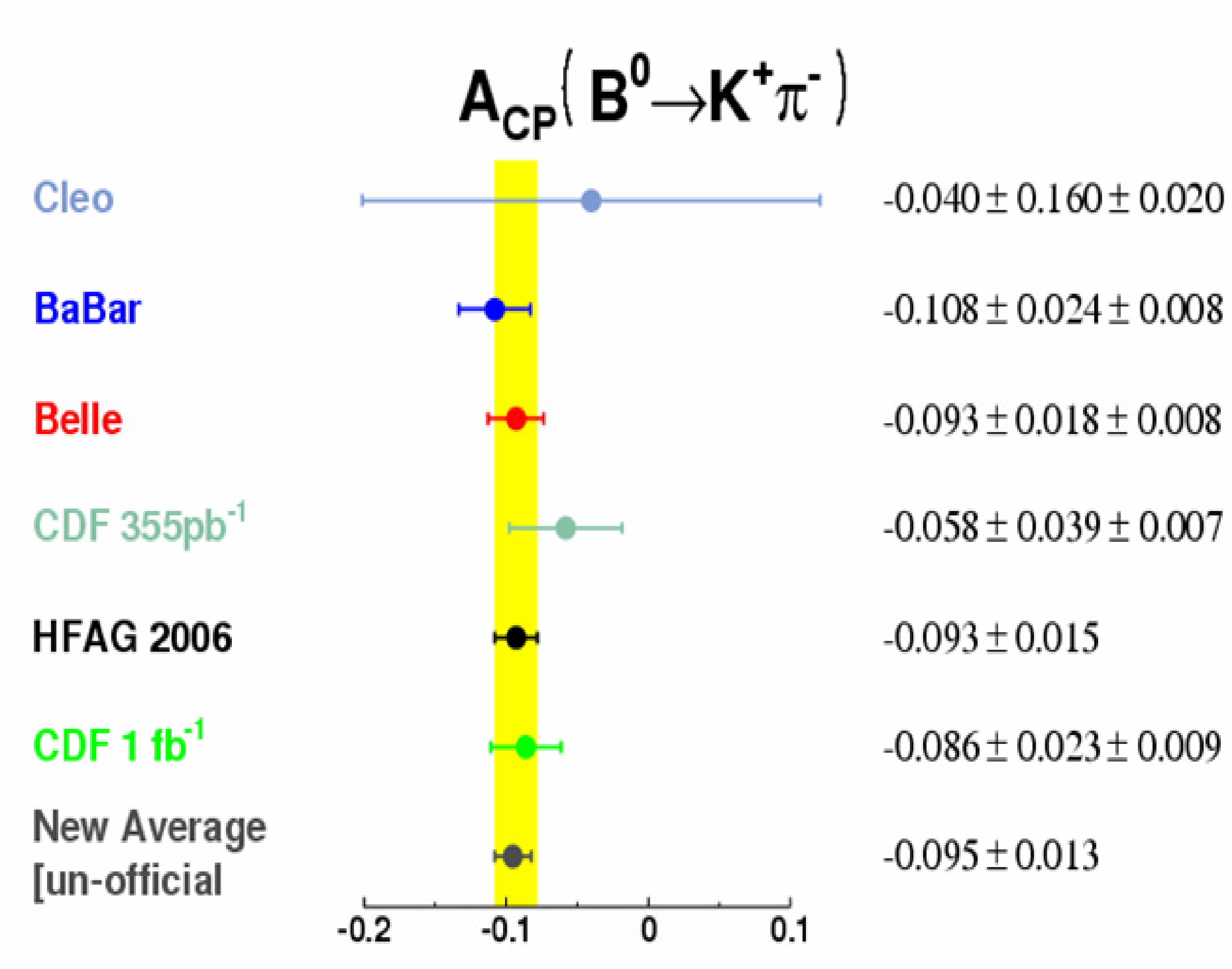
Case Study: $B^0 \rightarrow K^+\pi^-$ BF and A_{CP}



$$\mathcal{A}_{K\pi} = -0.108 \pm 0.024 \pm 0.008$$

4.5 σ evidence for direct CP violation!

Case Study: $B^0 \rightarrow K^+\pi^-$ BF and A_{CP}



CDF is now an even competitor

Hard to reconcile with null result in $K^+\pi^0$

(4.9σ difference in world average)

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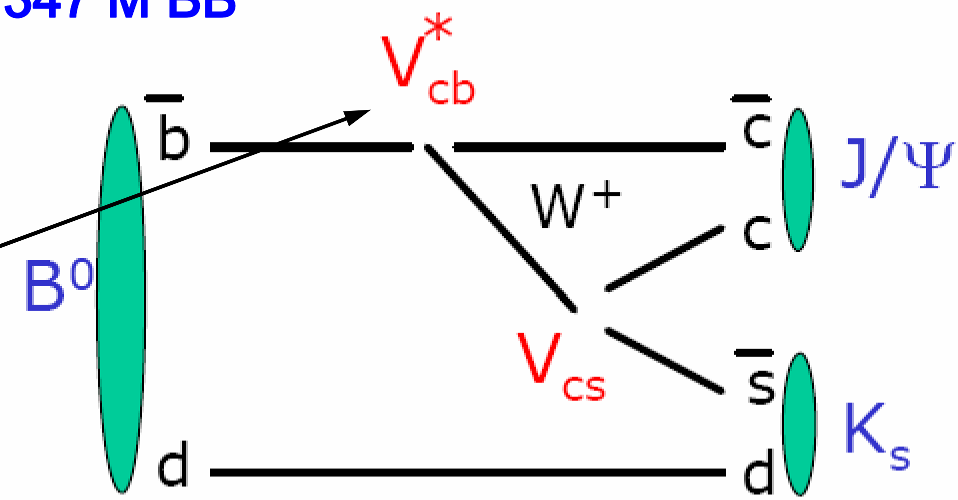
$B^0 \to J/\psi\, K_S^0$ and sin 2β

BaBar preliminary: hep-ex/0607107, 347 M BB

Decay dominated by a single "tree-level" Feynman diagram: $b \to c\bar{c}s$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



J/ψ identified cleanly by decay to a lepton pair;
K_S identified cleanly by decay to pion pair.
Both particles are CP eigenstates → both B^0 and $\bar{B}^0$ decay to them

Time-dependent CP violation has amplitude sin 2β and frequency Δm

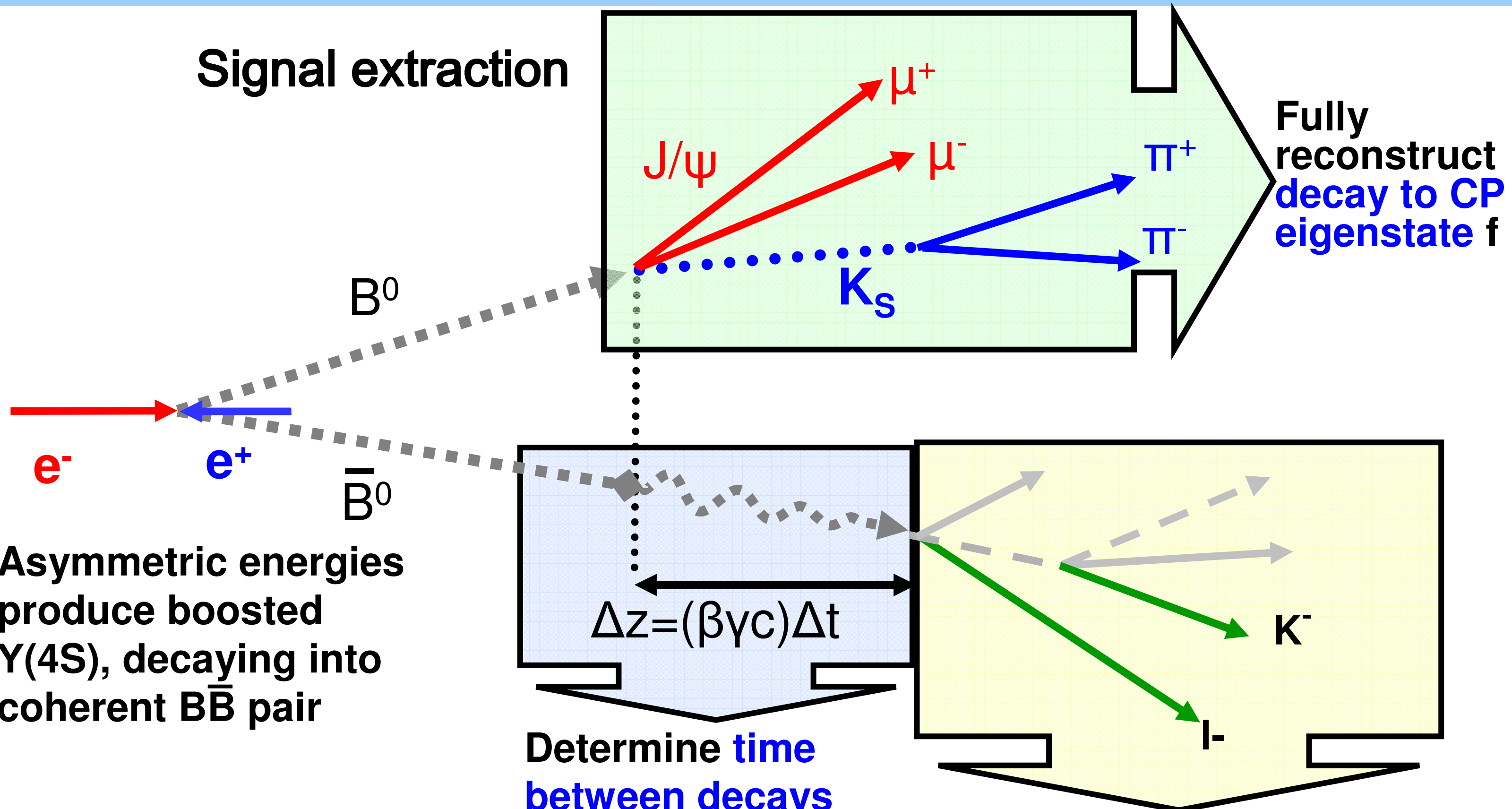
$$A_{CP}(J/\psi K_s; t) = S\sin(\Delta m_d t) - C\cos(\Delta m_d t)$$

Works for several other $b \to c\bar{c}s$ decays as well; results can be combined

$$S = -\eta_f \sin 2\beta \qquad \eta_f \text{ is } -1 \text{ for } (c\bar{c})K_S^0$$

Time-Dependent CP Violation: Experimental technique

Signal extraction



Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

$\sigma(\Delta t) \approx 1$ ps

Determine flavor and vertex position of other B decay

Naively: compute CP violating asymmetry $A(\Delta t) = \dfrac{N(\bar{f}\,;\Delta t) - N(f\,;\Delta t)}{N(\bar{f}\,;\Delta t) + N(f\,;\Delta t)}$

In reality, extract A from unbinned LH fit over signal & control samples

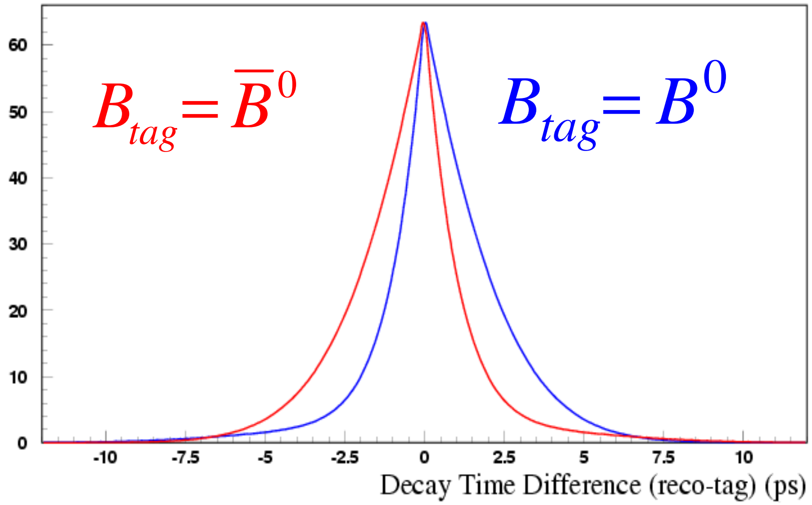
Δt Measurement

Time diff. distributions of CP B decays with a B ($\bar{B}$) tag

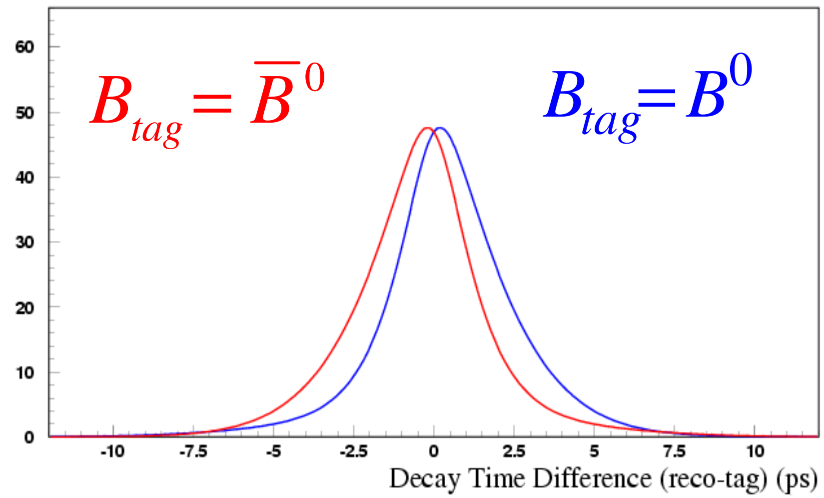
$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ (1 \mp \Delta\omega) \pm (1-2\omega) \times \left[\frac{2\mathcal{I}m\,\lambda}{1+|\lambda|^2} \sin(\Delta m_d \Delta t) - \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m_d \Delta t) \right] \right\}$$

ω is average mistag rate (3-40%)
Δω is mistag difference between B and $\bar{B}$ tag (~1%)
Observed f's are convolved with resolution functions

f±(Δt), ω = Δω = 0



fobs = f±(Δt) ⊗ R(Δt)



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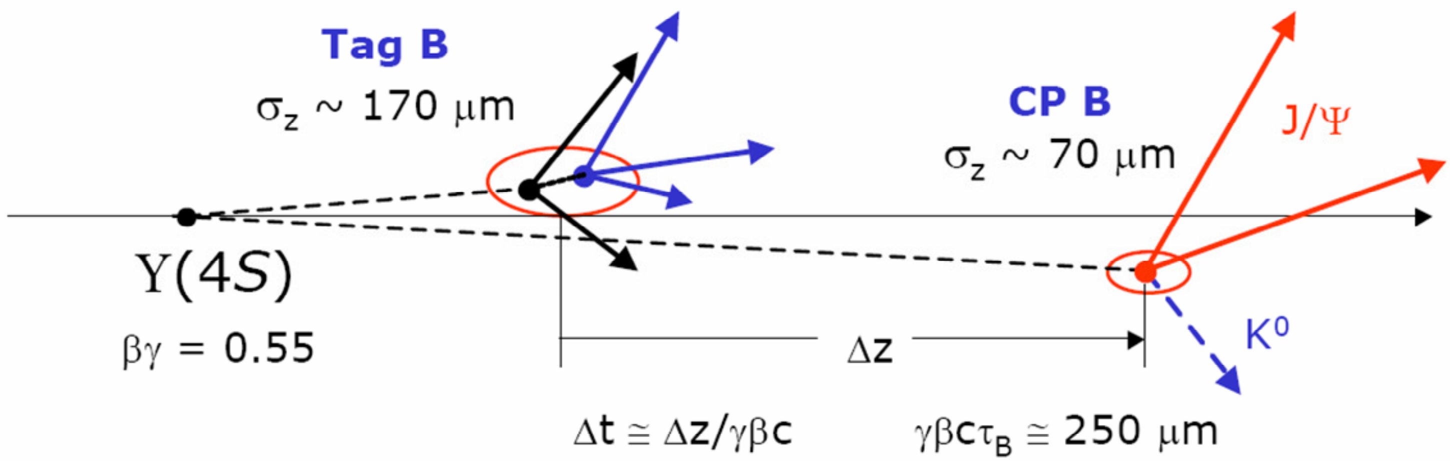
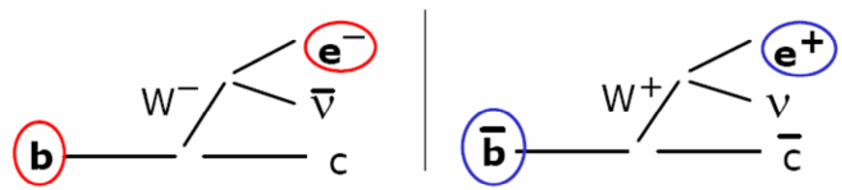
- $J/\Psi \to l^+l^-$ dominates in determination of CP vertex.
- Tracks not from CP B combined to form tag vertex.
  - Tracks with large χ^2 iteratively removed.
  - Long-lived particles (K_s, Λ) explicitly reconstructed.
  - Photon conversions ($\gamma \to e^+e^-$) removed.
- Vertex incorporates constraint from average beam position.
- Efficiency for CP sample 97 % (95% after $|\Delta t|<20$ ps, $\sigma_{\Delta t}<2.5$ ps)



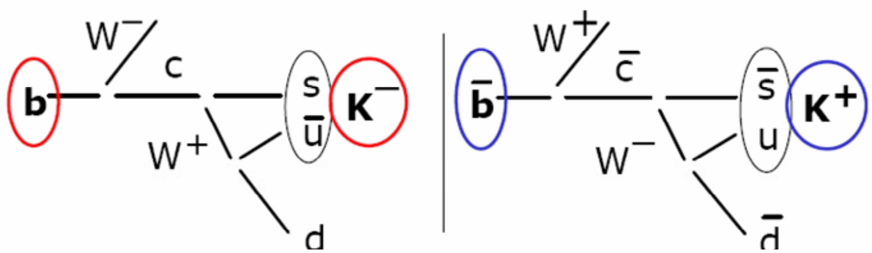
Flavor Tagging

Use decay products of *other* (tag) B.

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Full tagging algorithm combines all in neural network

Six categories based on particle content and NN output.

Tagging performance

$$\sum_i \epsilon_i (1 - 2\omega_i)^2$$

Q = 30.4 %!

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.67 ± 0.08	3.0 ± 0.3	-0.2 ± 0.6	7.67 ± 0.13
Kaon I	10.96 ± 0.09	5.3 ± 0.4	-0.6 ± 0.7	8.74 ± 0.16
Kaon II	17.21 ± 0.11	15.5 ± 0.4	-0.4 ± 0.7	8.21 ± 0.19
Kaon-Pion	13.77 ± 0.10	23.5 ± 0.5	-2.4 ± 0.8	3.87 ± 0.14
Pion	14.38 ± 0.10	33.0 ± 0.5	5.2 ± 0.8	1.67 ± 0.10
Other	9.61 ± 0.08	41.9 ± 0.6	4.6 ± 0.9	0.25 ± 0.04
All	74.60 ± 0.12			30.4 ± 0.3

$$\sigma(\sin(2\beta)) \propto \frac{1}{\sqrt{NQ}}$$

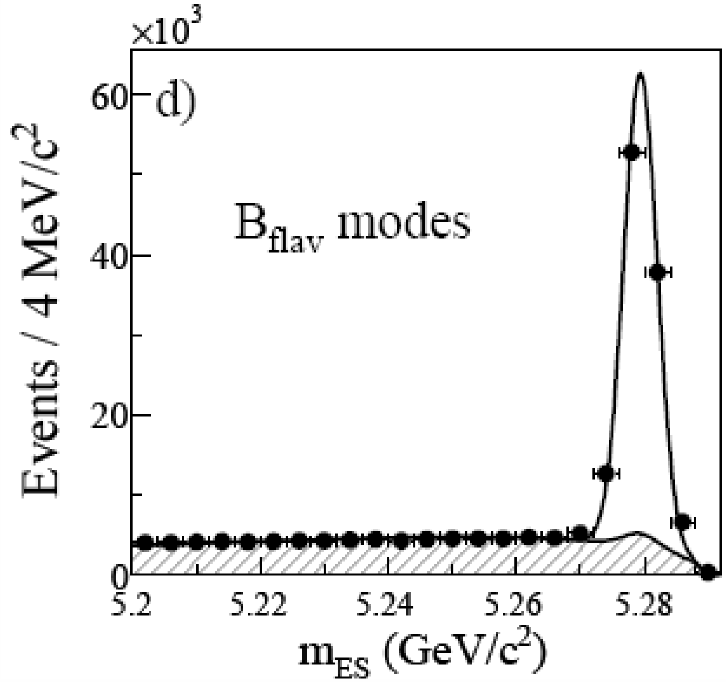
B Candidate Samples

Extract control sample of hadronic B decays that are self-tagging and negligible CPV

B → D(*)- h+, h+ = π+, ρ+, a_1+

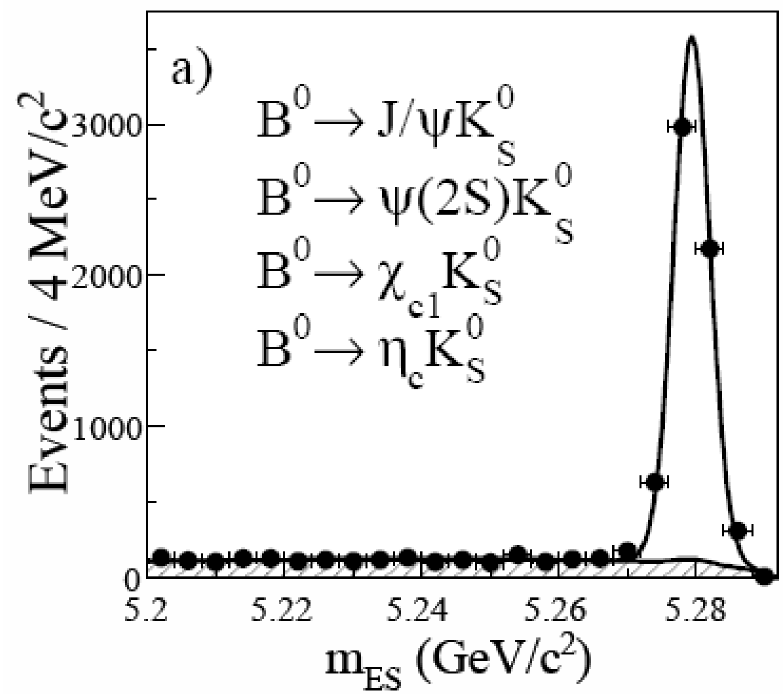
➢100,000 events!

For each flavor tagging category, measure ω, Δω, and resolution functions.



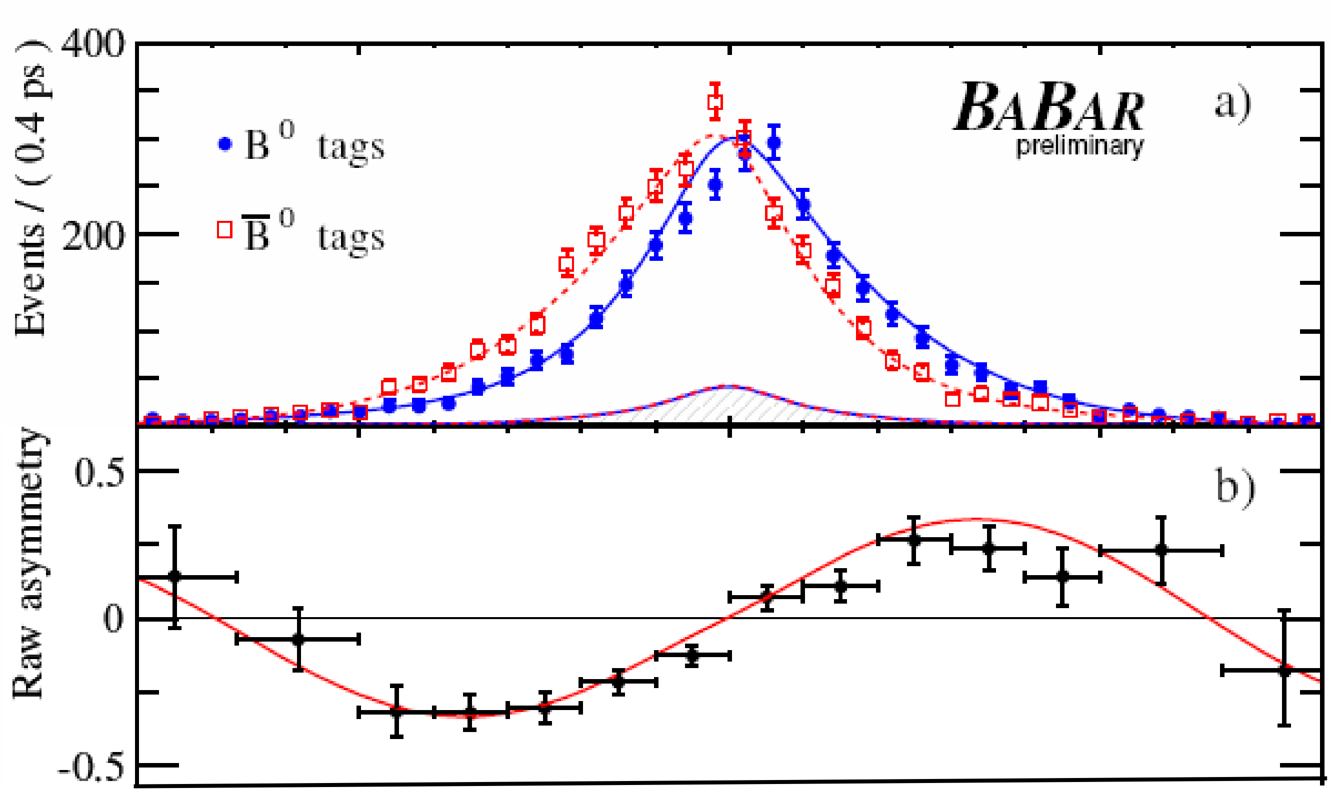
Extract signal of CP B decays

➢11,000 events



Asymmetry Extraction

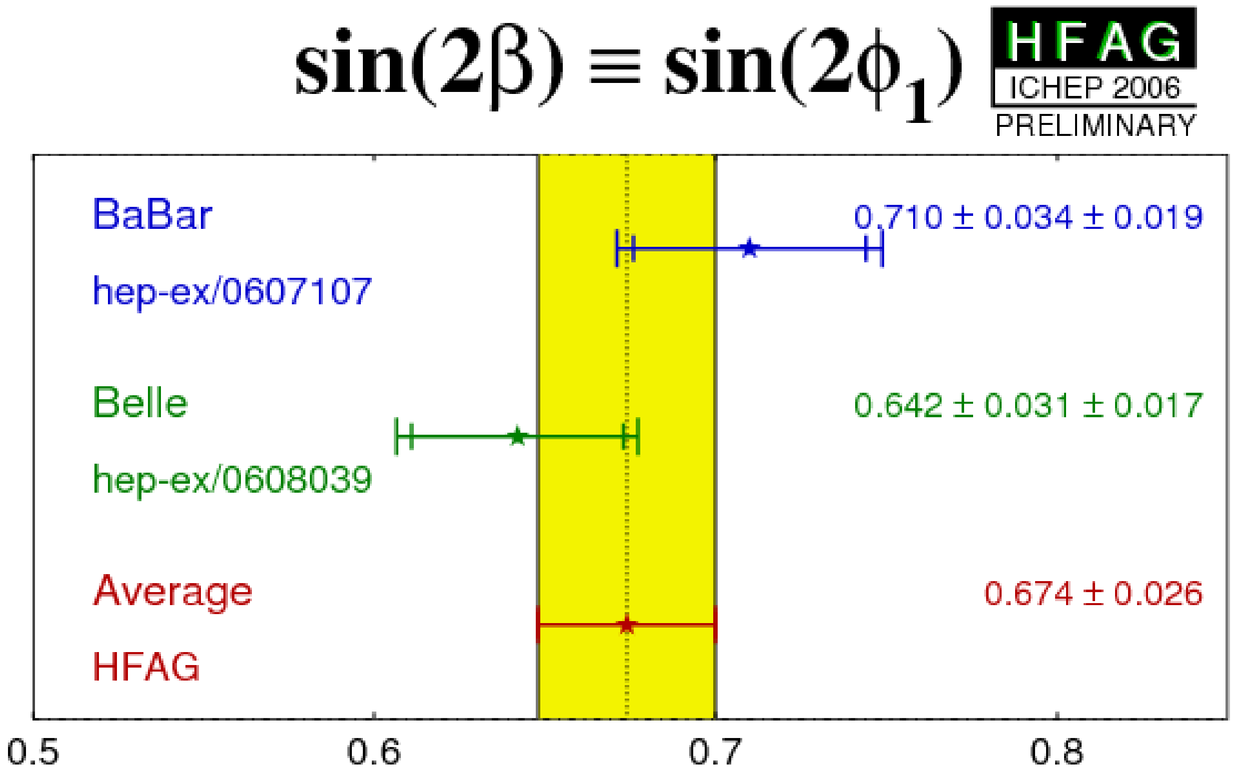
Simultaneous fit to Δt distributions of CP events and hadronic events over six tagging categories and six decay modes



$$\sin 2\beta = 0.715 \pm 0.034 \pm 0.019$$

$$|\lambda| = 0.932 \pm 0.026 \pm 0.017$$

CKM Global Fit (Sep.2006)



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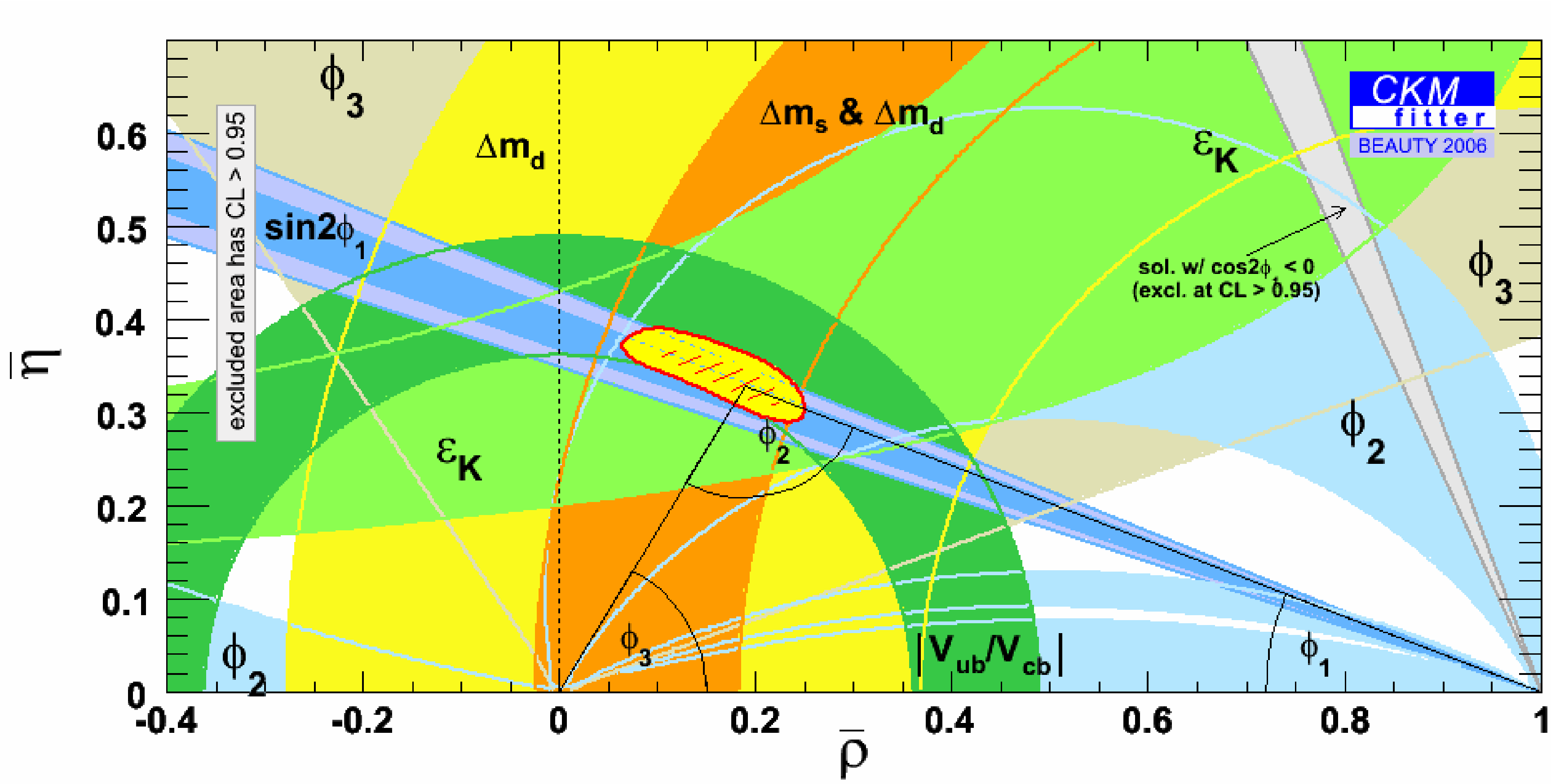
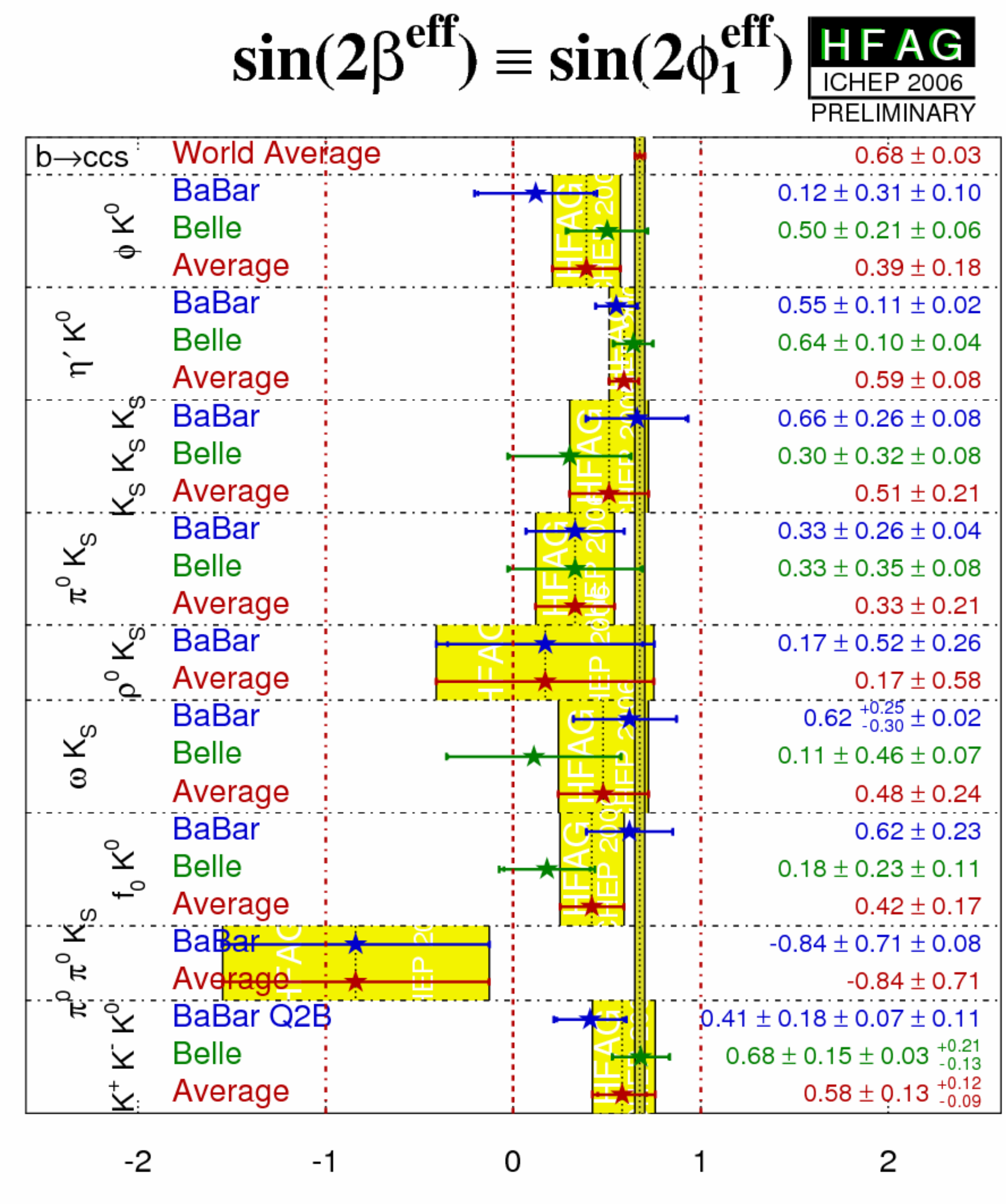


Time-Dependent CPV in b →ss̄s Decays



Smaller than b→cc̄s in all of 9 modes

Naïve average of all b → s modes

$\sin 2\beta^{eff} = 0.52 \pm 0.05$

2.6 σ deviation between penguin and tree

(b → s) (b → c)

Hazumi, ICHEP 2006

Outline

•**Dream Machines: Accelerators, Detectors, and the Υ(4S) environs**

•**Exclusive B branching fractions and direct CP violation**
Kinematic constraints
Multivariate background discrimination
Case Study: $B^0 \rightarrow K^+ \pi^-$

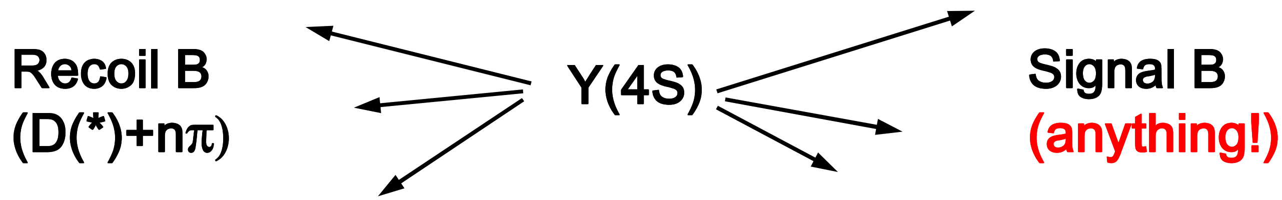
•**Time dependent CP violation of exclusive B decays**
B decay length difference
B flavor tagging
Case Study: $B^0 \rightarrow \psi K_s$

•**B branching fractions to inclusive or neutrino-ful final states**
Recoil side reconstruction
Case Study: $B^- \rightarrow \tau^- \nu$

Recoil Side Reconstruction

Lesson from sin 2β: To gain precise control over one of the B mesons, reconstruct the other B meson in high-purity, high-efficiency modes

Efficiency penalty is at least 1%, so signal B process cannot be too rare (BF >10^{-6}) and backgrounds must be large for this to be optimal



Use cases:

Inclusive B decay rates and distributions: large rates, but fewer kinematic constraints on the signal decays, due to neutrinos ($b \to cl\nu$ or $ul\nu$) or numerous final states ($b \to s\gamma$)

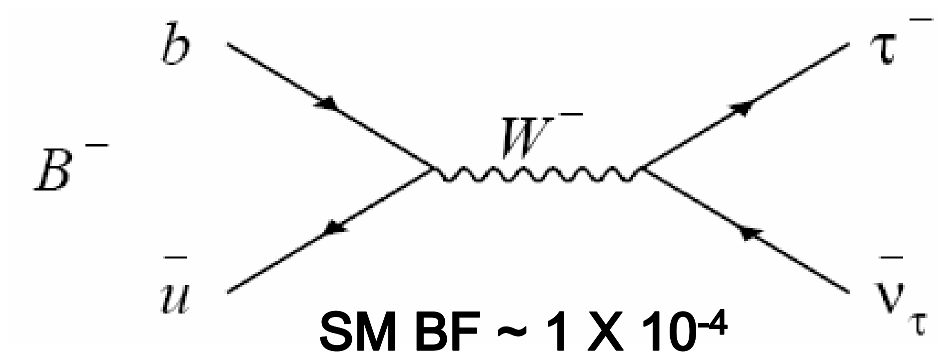
Exclusive B decays to one or more neutrinos: lack of kinematic constraints on the signal side means recoil side is the only recourse for background rejection ($B \to \tau\nu$, $B \to \mu\nu$, $B \to K(*)\nu\nu$, $B \to$ invisible)

Case Study: B+ → $\tau^+\nu$

Belle PRL 97 (2006) 251802, 449M BB

Simple decay through weak annihilation

Sensitive to B decay constant f_B or to charged Higgs boson



SM BF ~ 1 X 10^{-4}

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

Up to 3 neutrinos in the final state requires recoil reconstruction sample

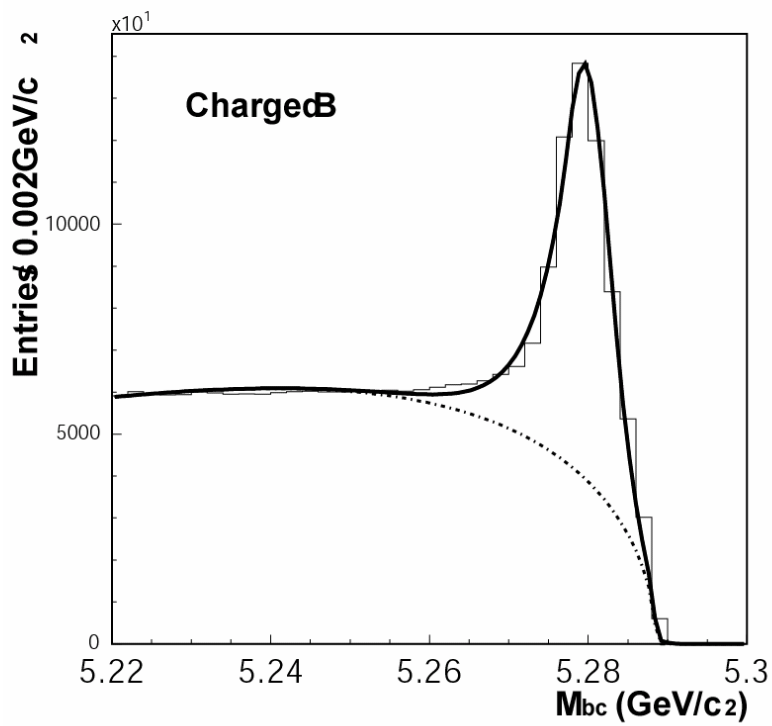
Case Study: B+ → $\tau^+\nu$

Total Event Reconstruction

On recoil side, require charged B decays to high purity, high rate hadronic decays using previously described signal extraction methods

$$B^+ \rightarrow \overline{D}^{(*)0}\pi^+,\ \overline{D}^{(*)0}\rho^+,\ \overline{D}^{(*)0}a_1^+ \text{ and } \overline{D}^{(*)0}D_s^{(*)+}$$

180 modes, 680k events, Recoil side efficiency = 0.13%



Case Study: B+ → $\tau^+\nu$

Total Event Reconstruction

On signal side, require simplest τ decay modes and no other tracks

$$\tau^- \rightarrow \mu^-\nu\bar{\nu},\ e^-\nu\bar{\nu},\ \pi^-\nu,\ \pi^-\pi^0\nu,\ \pi^-\pi^+\pi^-\nu$$

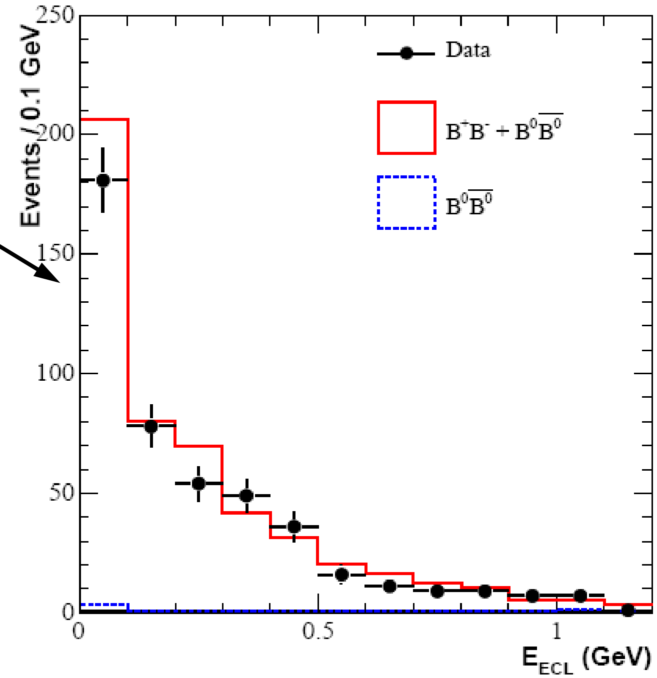
5 modes, 300 events, recoil side efficiency = 15%

$q\bar{q}$ background eliminated!

Remaining background from B decays to neutrals (π^0, n, K_L)

Extra neutral energy (ECL) peaked at 0 for signal

Background broad in (ECL) (shape from MC)



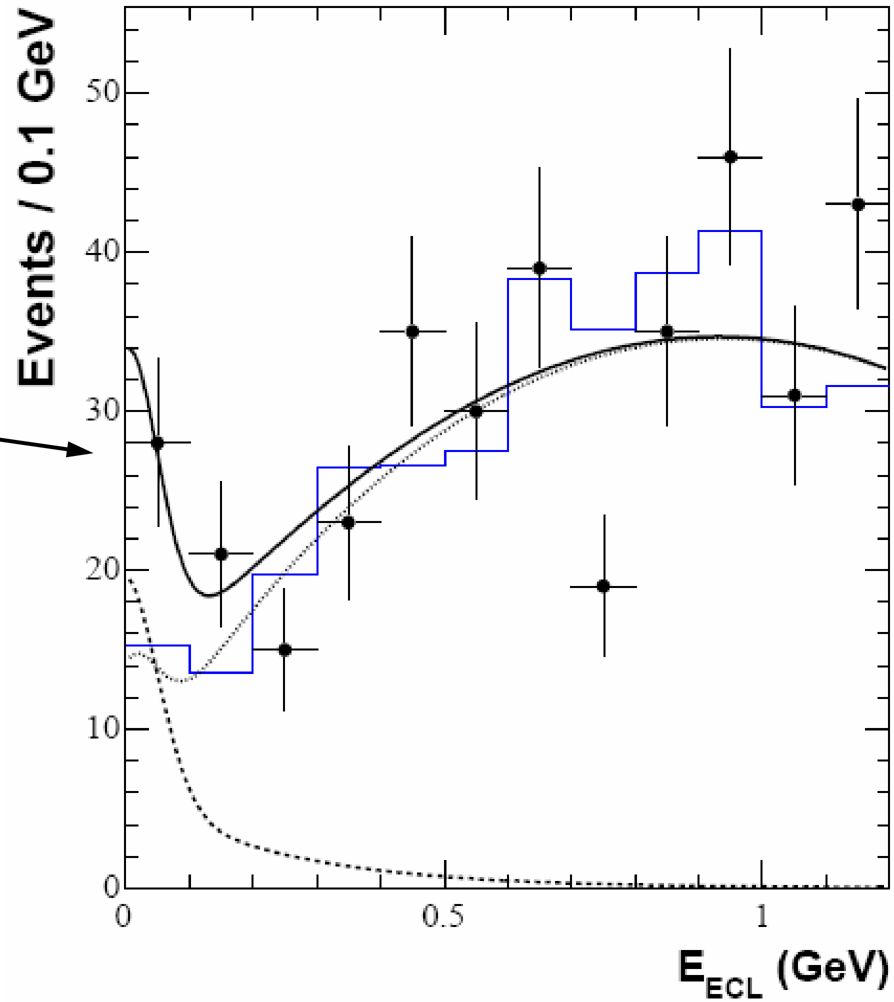
Case Study: B+ → $\tau^+\nu$

Signal extracted from 1D likelihood fit to ECL

24+\- 7 signal events observed!

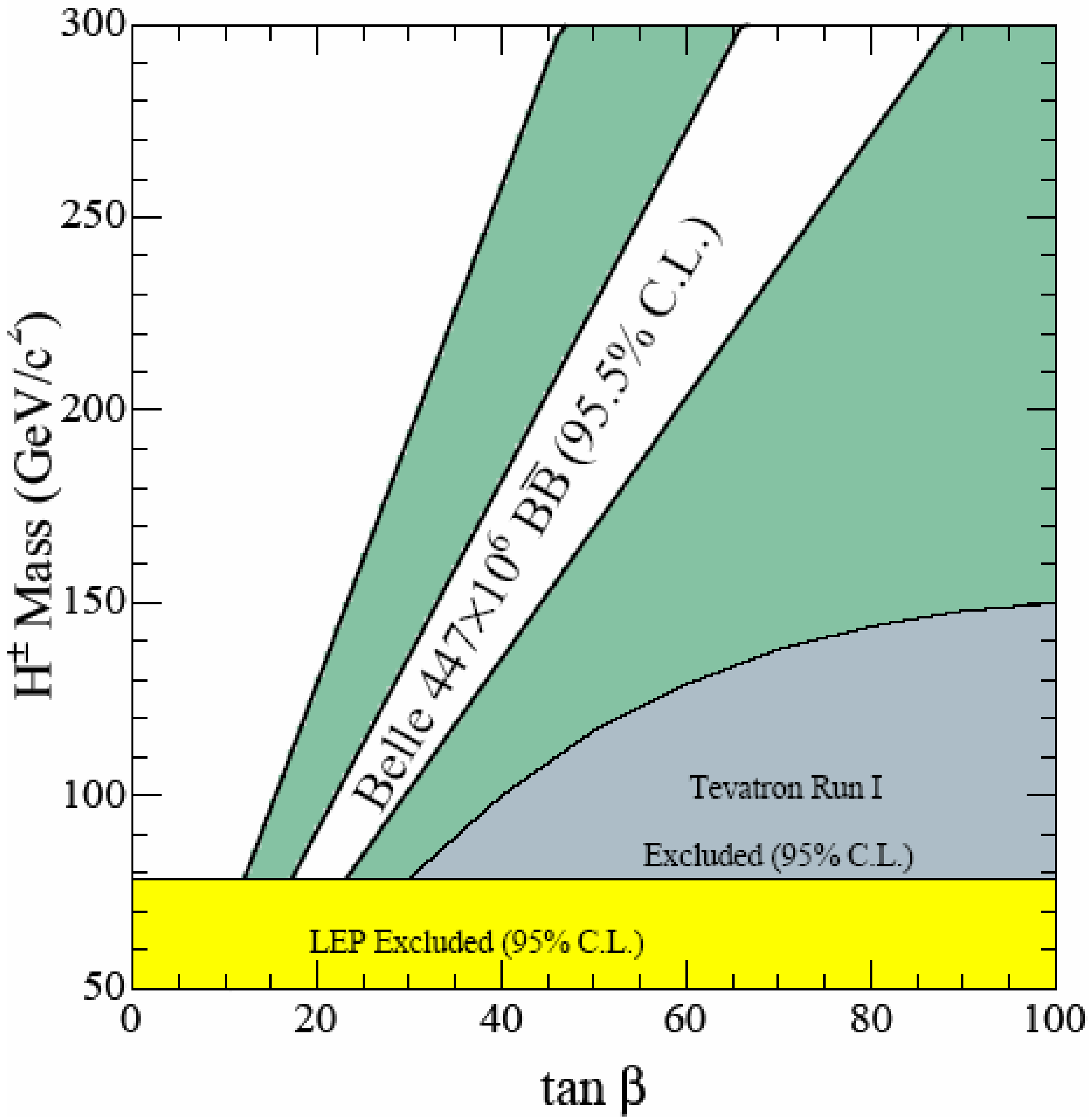
Significance = 3.5σ

Consistent excess in all τ decay modes



$$\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49}(\mathrm{stat})^{+0.46}_{-0.51}(\mathrm{syst})) \times 10^{-4}$$

Case Study: B+ → $\tau^+\nu$



BF sensitive to H^+ in Type II 2HDM at large tan β

Sensitivity comparable to recent MSSM Higgs search at Tevatron

For MSSM, there are significant SUSY radiative corrections which complicates interpretation

Summary

<u>Highlights of B physics capability at Y(4S)</u>

•Awesome accelerator performance results in Giga-B samples

•Unique kinematic constraints and control samples allow for precise/rare studies of exclusive B decays and direct CPV

•Highly efficient flavor tagging makes for world's best time-dependent CPV

•Recoil side reconstruction allows for detection of B decays to virtually anything

•Can be extended in the future to a Super-B factory (100X) or B_s physics at the Y(5S)