Exploring Matter-Antimatter Asymmetries with B mesons

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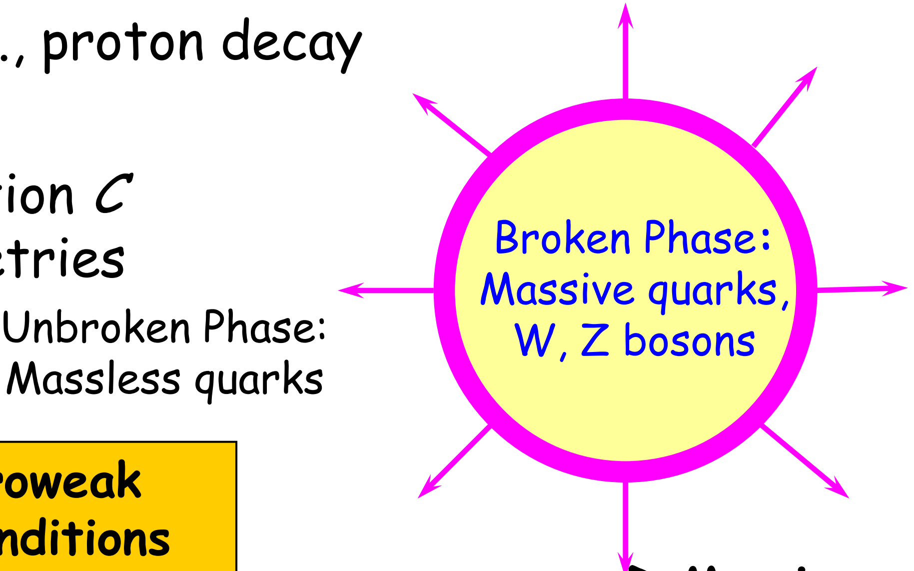
U.S. DEPARTMENT OF
ENERGY

A fundamental cosmological question

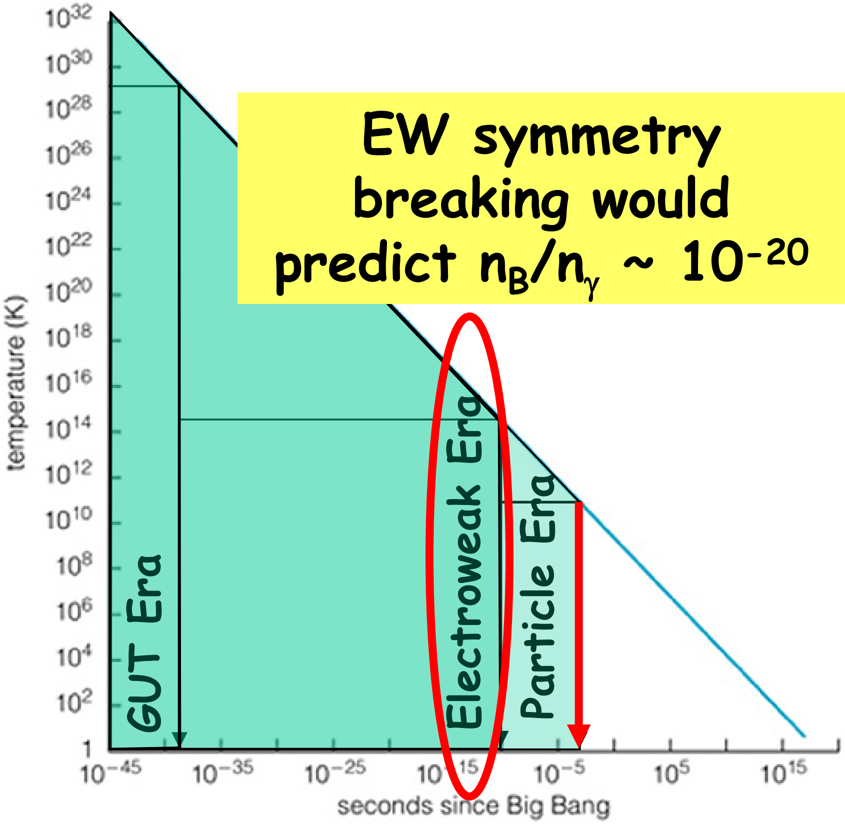
- ***The universe is now matter dominated: how did this matter-antimatter imbalance arise?***
  - Anti-proton/proton ratio ~10^{-4} in cosmic rays; no evidence for annihilation photons from intergalactic clouds
- ***Cosmological generation of asymmetry: Sakharov conditions (1967)***
  - Baryon number violation, e.g., proton decay
  - Thermal non-equilibrium
  - Violation of charge conjugation *C* and parity *P* discrete symmetries



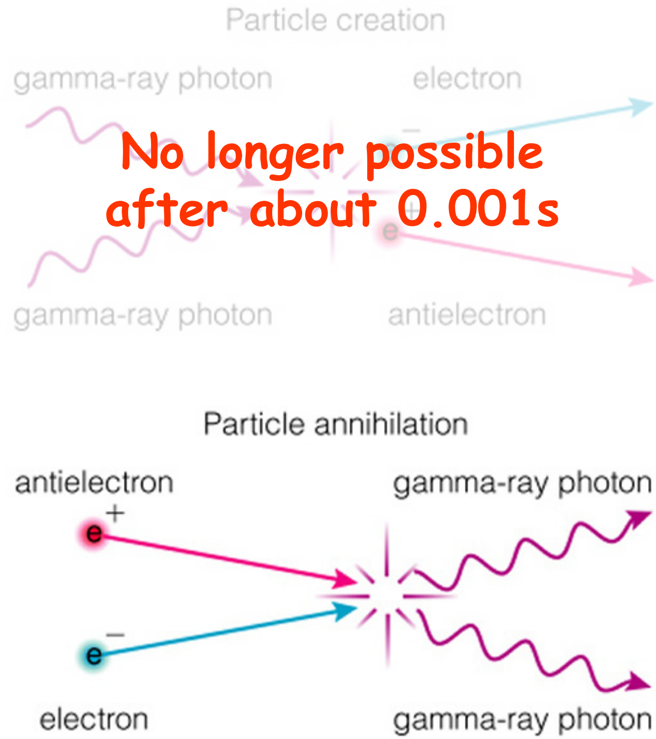
Transition to broken electroweak symmetry provides these conditions

D.Morrissey

Matter- Antimatter annihilation



EW symmetry breaking would predict $n_B/n_\gamma \sim 10^{-20}$

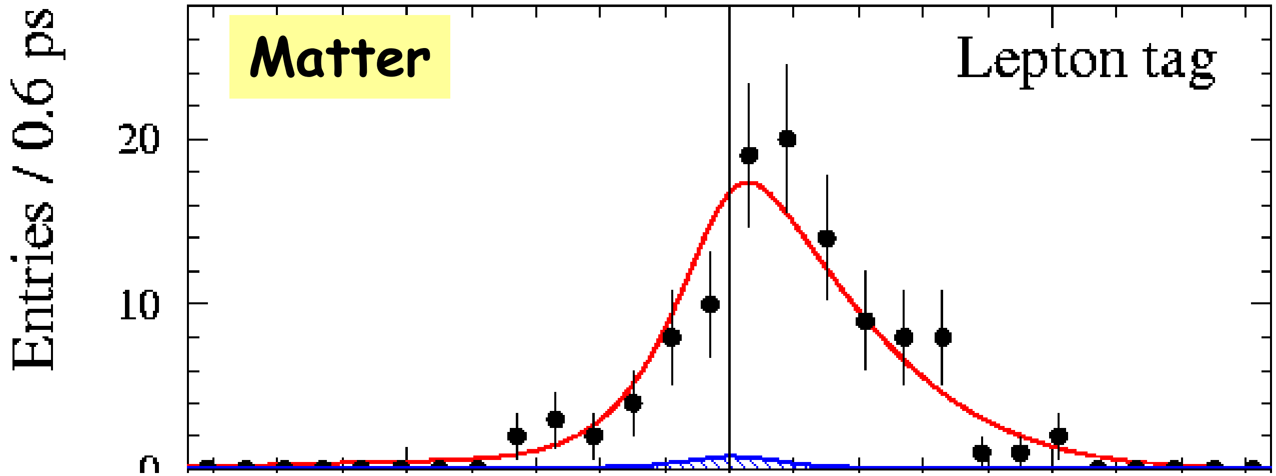


No longer possible after about 0.001s

Temperature too low to produce nucleon pairs

Observed $n_B/n_\gamma \sim 10^{-10}$

Implies 10^{-10} matter-antimatter asymmetry at 0.001s after big bang

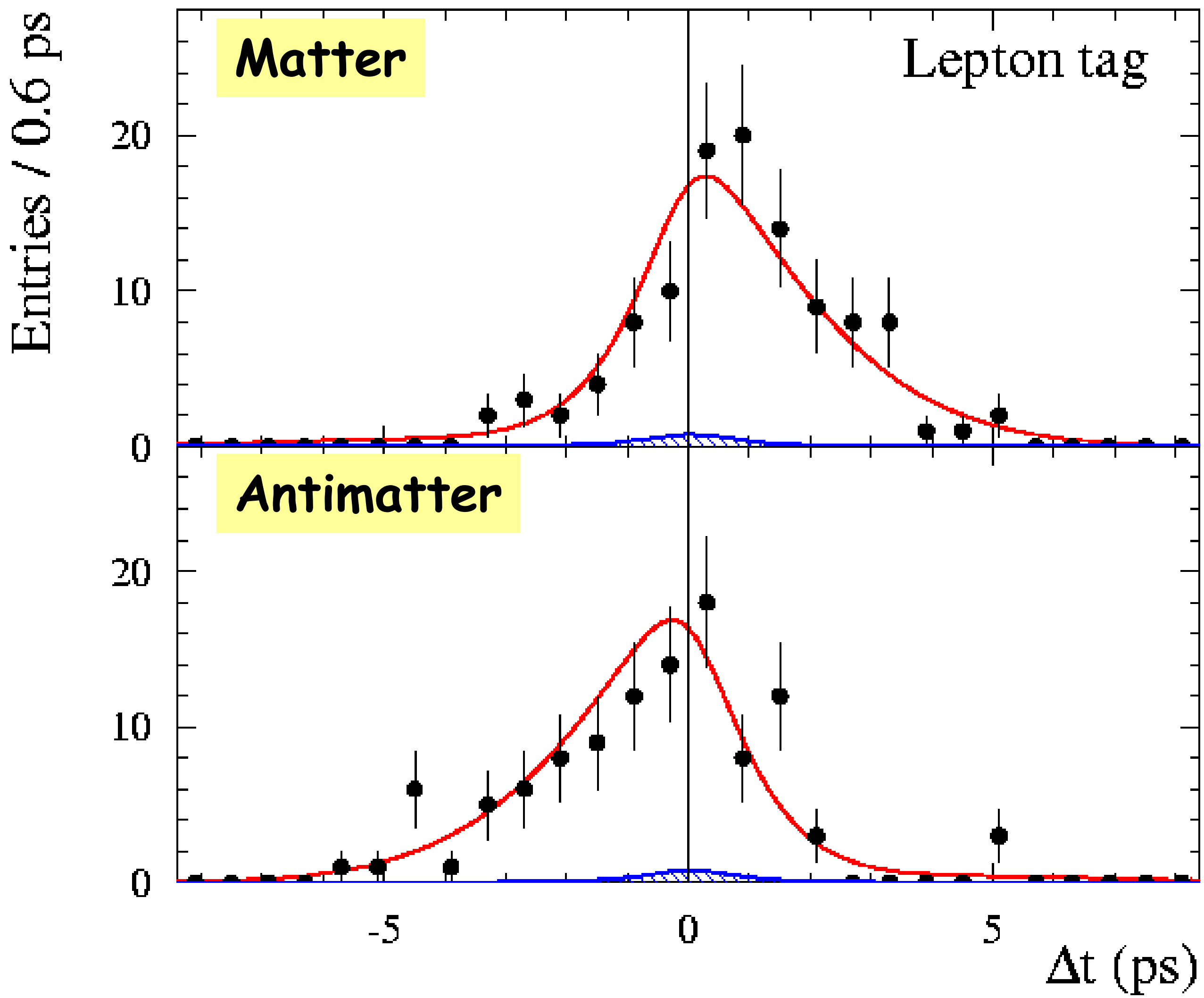


BABAR, summer 2002

($b\bar{d}$) mesons

Proper time

Matter- Antimatter asymmetry!



BABAR, summer 2002

$(b\bar{d})$ mesons

$(\bar{b}d)$ mesons

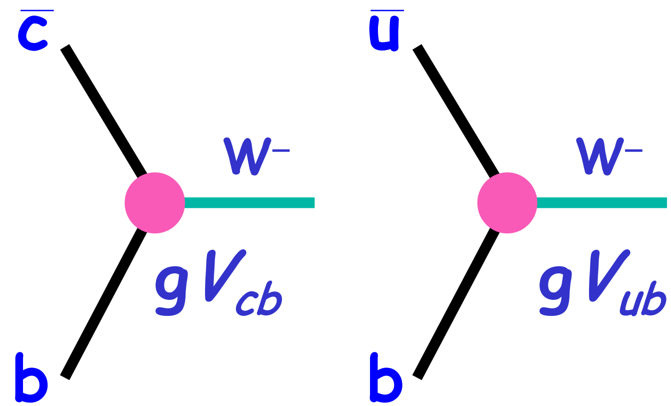
Proper time

Brief review of Standard Model weak interactions for quarks and *CP* violation

Quark couplings: CKM matrix

Mass Eigenstates ≠ Weak Eigenstates ⇒ Quark Mixing

Flavor changes through mixed couplings to quarks



Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Unitary matrix described for 3 generations of quarks by 3 rotation angles and 1 non-trivial phase

CKM matrix: a source of CP violation

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

CKM elements & quark masses are fundamental constants emerging from EW symmetry breaking

Wolfenstein parameterization:

Observed experimental hierarchy

$\lambda \sim 0.22$

$\sin\theta_C$

Cabibbo angle

$$V_{CKM} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$2 \to 1$ $\sim\lambda$

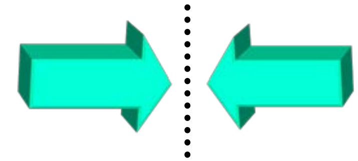
$3 \to 2$ $\sim\lambda^2$

$3 \to 1$ $\sim\lambda^3$

Phase: changes sign under CP

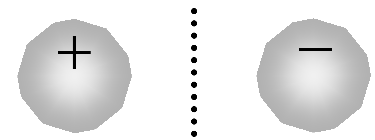
Important discrete symmetries

- ## Parity, P
  - Reflection a system through the origin, thereby converting right-handed into left-handed coordinate systems
  - Vectors (momentum) change sign but axial vectors (spin) remain unchanged



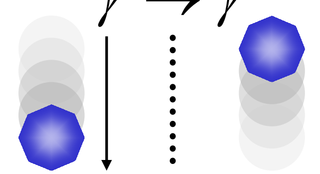
$$\mathbf{r} \rightarrow -\mathbf{r}$$
$$\mathbf{p} \rightarrow -\mathbf{p}$$
$$\mathbf{L} \rightarrow \mathbf{L}$$

- ## Charge Conjugation, C
  - Change all particles into anti-particles and vice versa



$$e^- \rightarrow e^+$$
$$\gamma \rightarrow \gamma$$

- ## Time Reversal, T
  - Reverse the arrow of time, reversing all time-dependent quantities, e.g. momentum



$$t \rightarrow -t$$

Good symmetries of strong and electromagnetic forces, but C & P are violated in the weak interaction

Is CP a good symmetry of Nature?

Not Quite!

Dominant decay modes for neutral kaons:

$$K_S^0 \to \pi^+\pi^- \qquad CP = +1$$

$$K_L^0 \to \pi^+\pi^-\pi^0 \qquad CP = -1 \qquad \left|K_L^0\right\rangle \sim \left|K_{CP=-1}^0\right\rangle + \varepsilon\left|K_{CP=+1}^0\right\rangle$$

In 1964, Christenson *et al.* observed:

$$K_L^0 \to \pi^+\pi^- \text{ with } \frac{\Gamma\left(K_L^0 \to \pi^+\pi^-\right)}{\Gamma\left(K_S^0 \to \pi^+\pi^-\right)} = 2.3x10^{-3}$$

CP symmetry is violated at a tiny rate in the decays of neutral kaons!

More recently, direct *CP* violation also observed

CKM Predicts: $\varepsilon = 3x10^{-3} B_K A^2 \eta\left[1 + A^2(1-\rho)\left(\frac{m_t}{94}\right)^2\right] \neq 0$

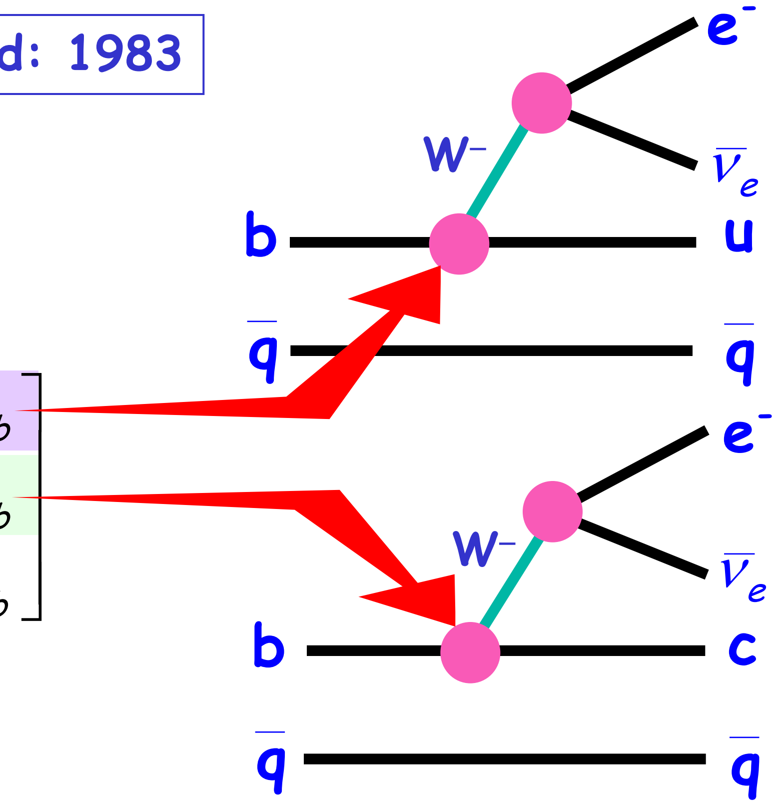
Is this the origin?

Difficult to interpret due to complications of hadronic physics

Weak decays of B mesons

B meson discovered: 1983

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



Rare: B decays to non-charm

$V_{ub} \sim A\lambda^3$

Dominant: B decays to charm

$V_{cb} \sim A\lambda^2$

1986: *B* meson long lived

ARGUS at DESY, 1987

Produce matter-antimatter pairs

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0$$

ARGUS at DESY, 1987

Produce matter-antimatter pairs

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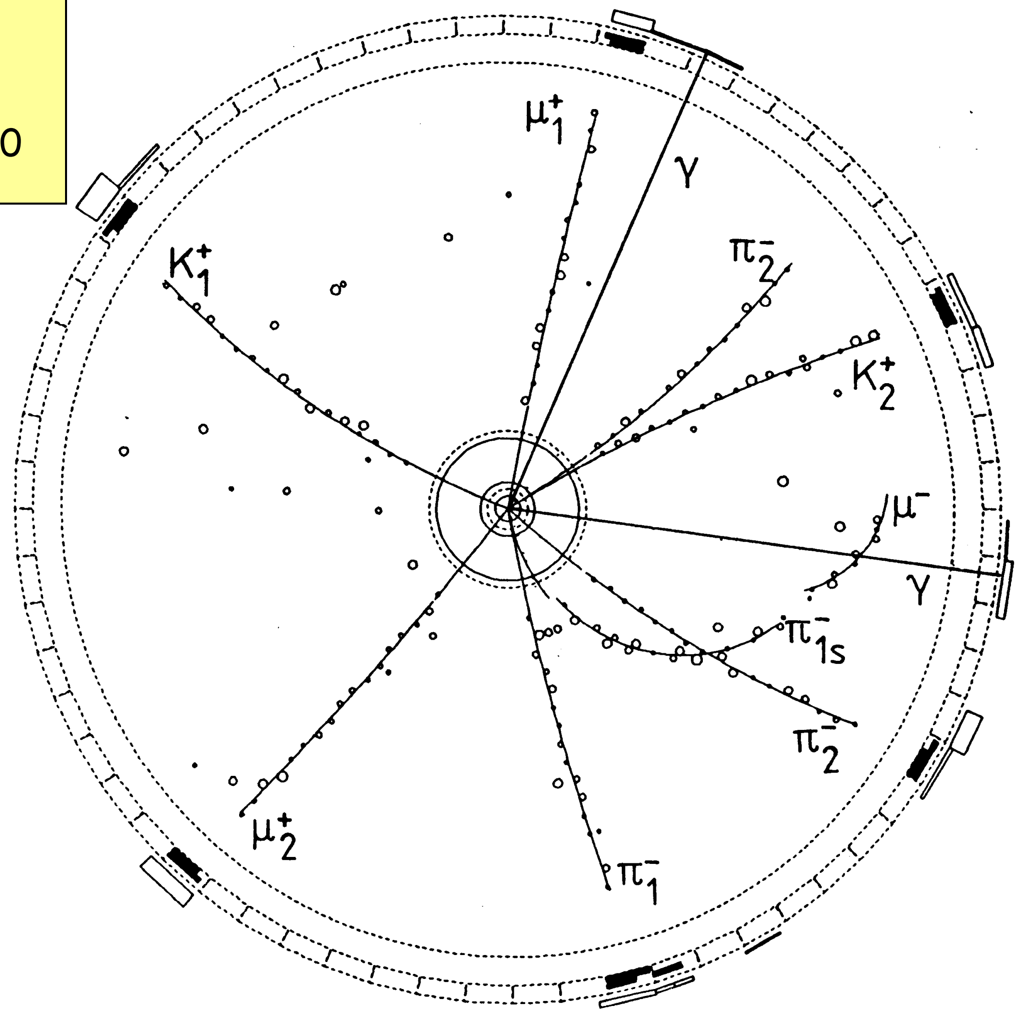
By the time of decay

$$B^0\overline{B}^0 \rightarrow B_1^0 B_2^0$$

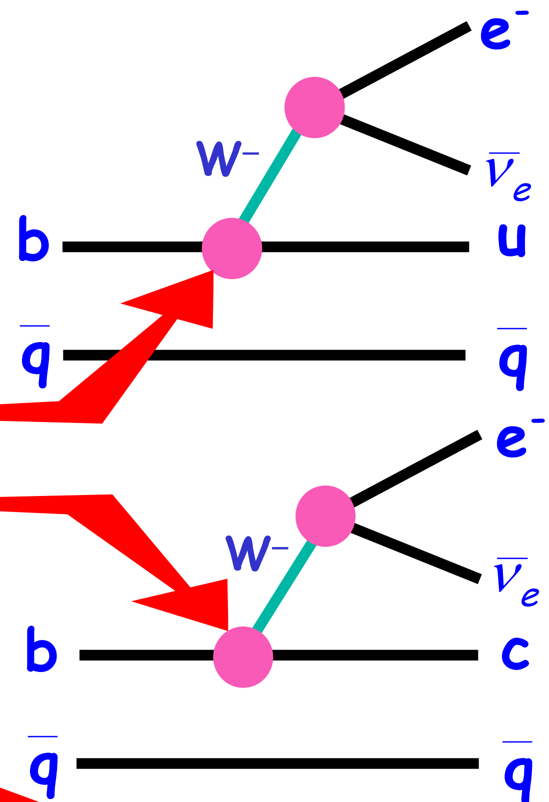
Matter-Antimatter oscillations!



Weak decays of B mesons

B Meson =
($\bar{b}$u) or ($\bar{b}$d) state

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



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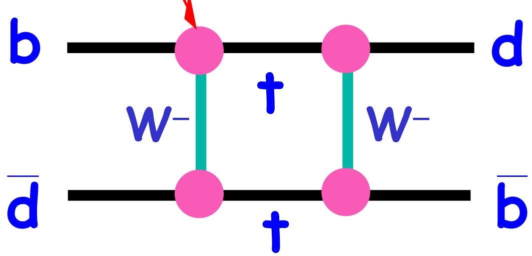
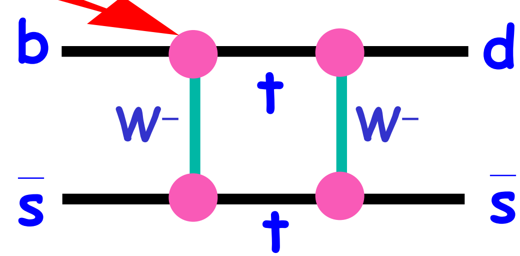




Matter-Antimatter oscillations

$V_{tb}V_{td}^{*} \sim A\lambda^3$

Weak interaction in Standard Model

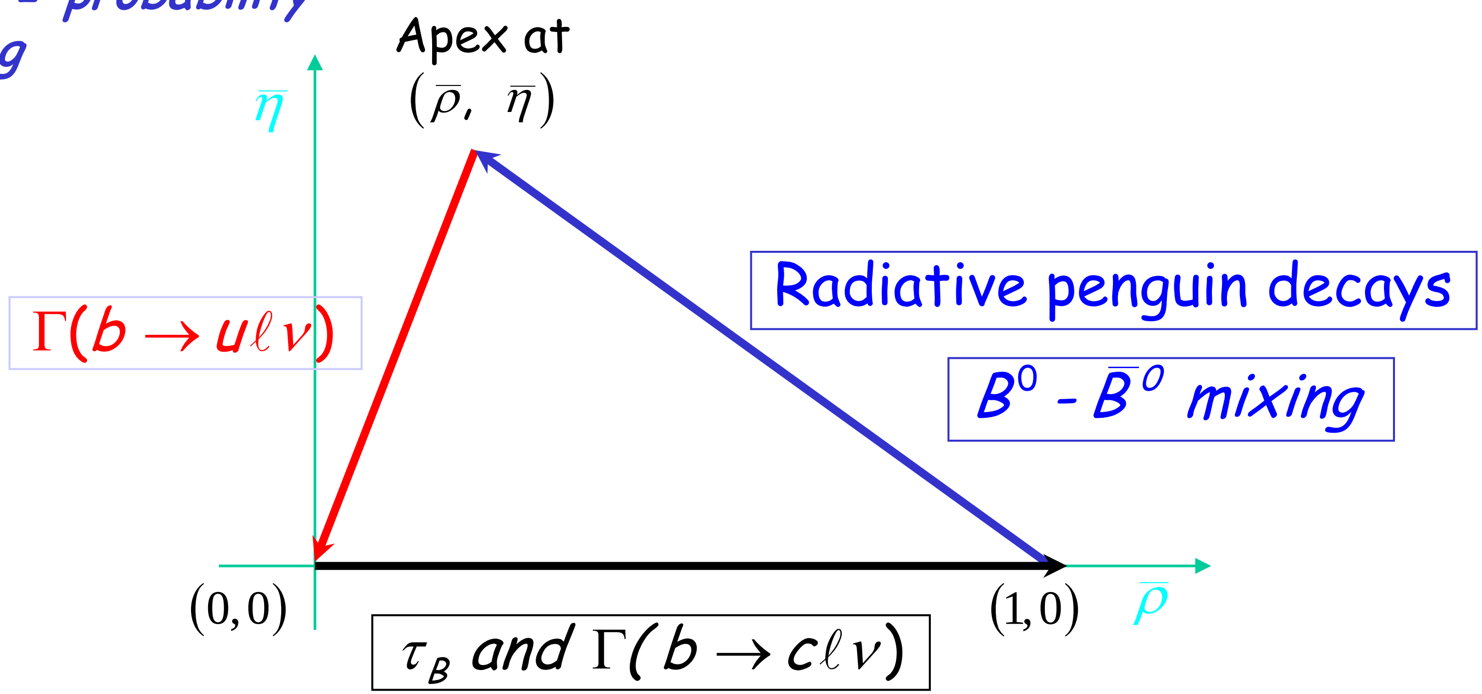
Unitarity Triangle as a summary of Standard Model b physics

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

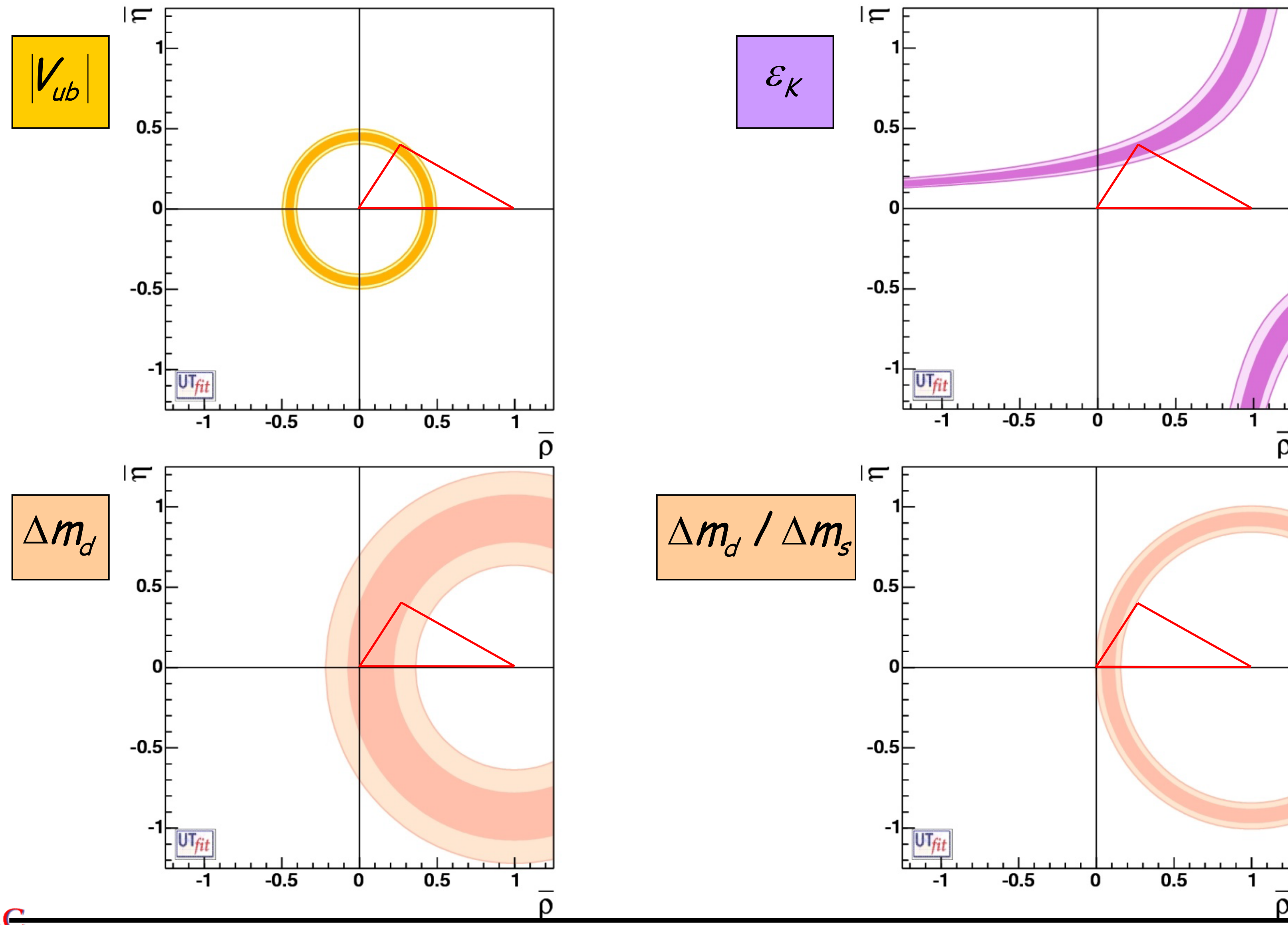
+ phases

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

Unitarity = probability preserving



Existing constraints



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Unitarity Triangle as a summary of Standard Model *b* physics

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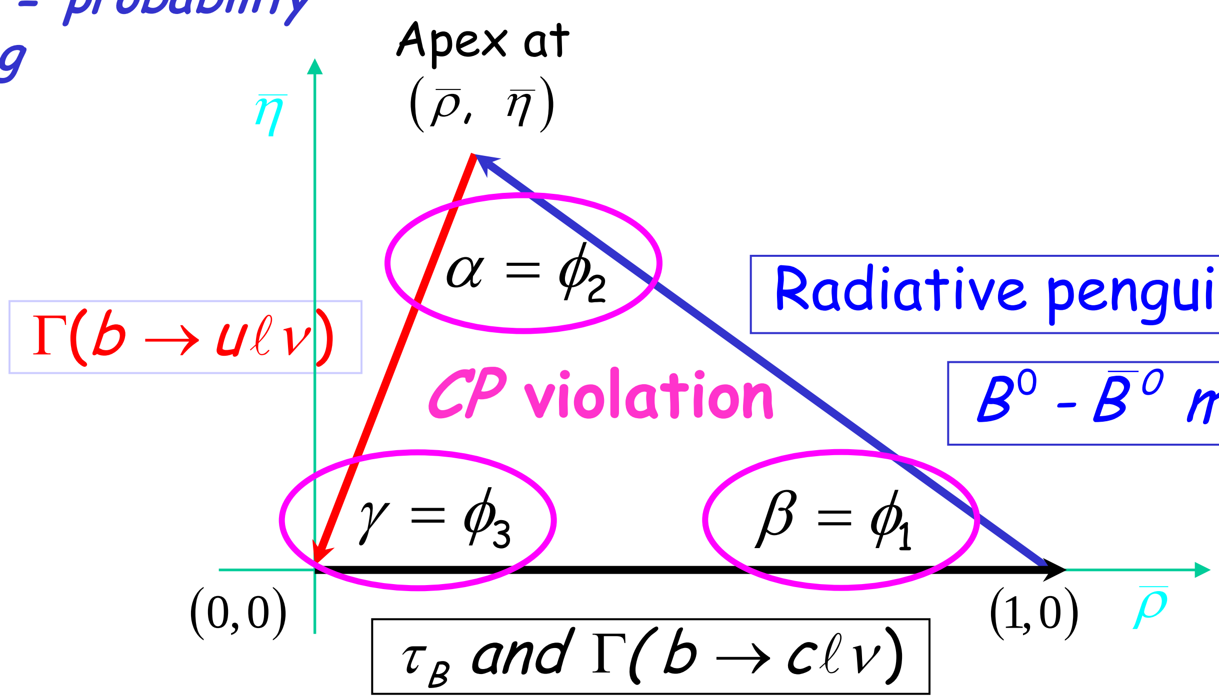
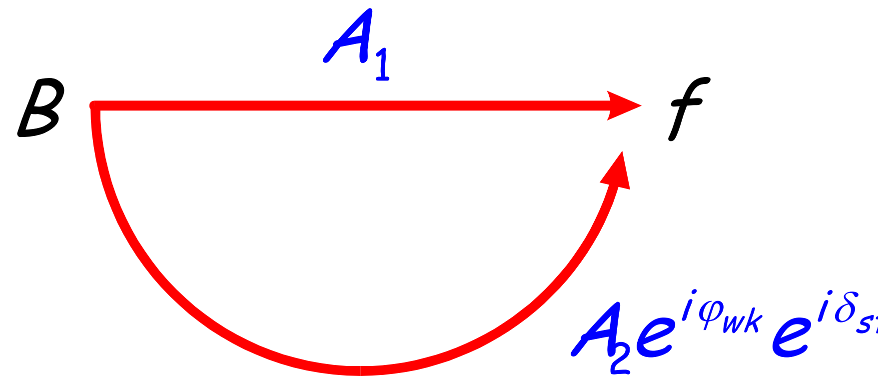
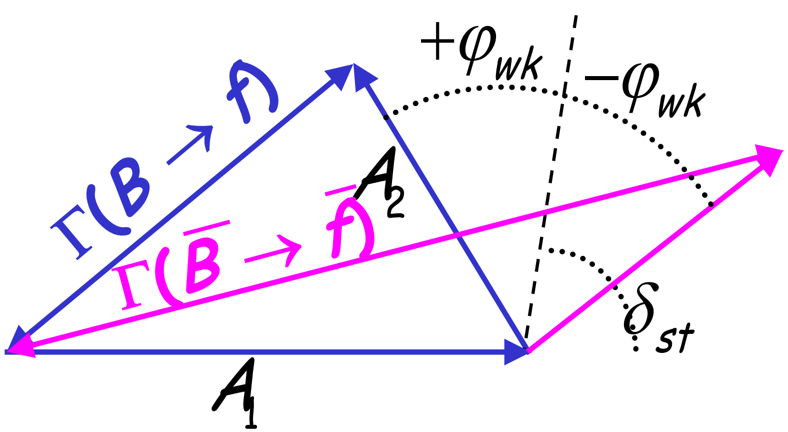


CP violation in the B system

Analogous to a two-slit quantum interference experiment!

- CPV through interference of decay amplitudes





$$\Gamma(B \to f) = \left| A_1 + A_2 e^{i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

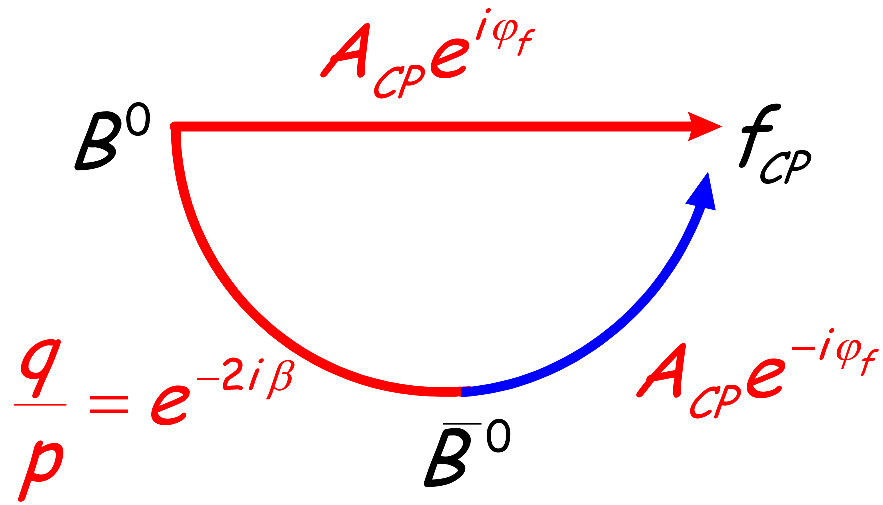
$$\Gamma(\overline{B} \to \overline{f}) = \left| A_1 + A_2 e^{-i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f})$$
for $\varphi_{wk} \neq 0$ and $\delta_{st} \neq 0$

CP violation in the B system

- CPV through interference between mixing and decay amplitudes

Directly related to CKM angles for single decay amplitude



Time-dependent asymmetry

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})} = S_{f_{CP}} \sin \Delta m_d t - C_{f_{CP}} \cos \Delta m_d t$$

$$S_{f_{CP}} = \frac{2 \operatorname{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \qquad C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \qquad \lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

CP violation in the B system

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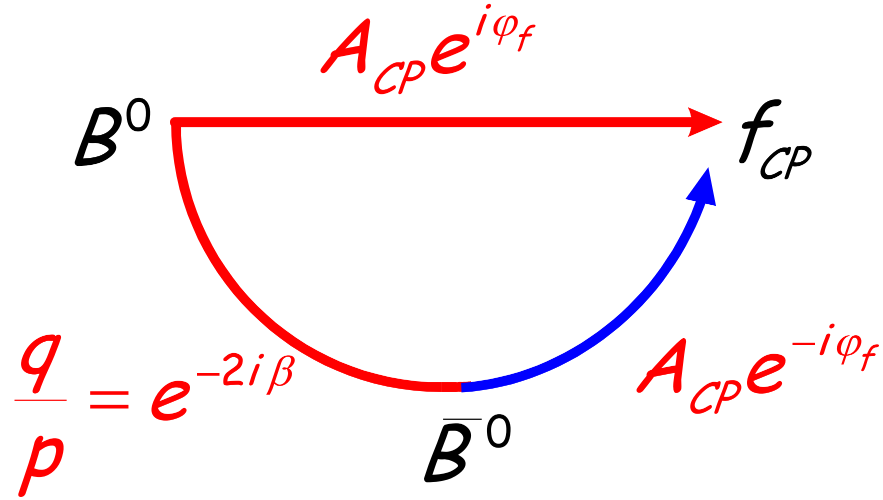

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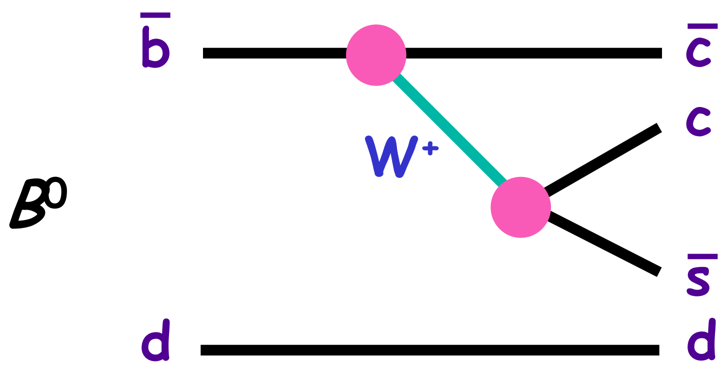
$$S_{f_{CP}} = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} = \mathrm{Im}\,\lambda_{f_{CP}} \qquad C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} = 0 \qquad \lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

For simple case shown with single decay mechanism

But how big are the CP asymmetries?



J/ψ

$K^0 \rightarrow K_S^0$

Golden Channel

CP Eigenstate:
η_{CP} = -1

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \rightarrow f_{CP}) - \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \rightarrow f_{CP}) + \Gamma(B^0_{phys}(t) \rightarrow f_{CP})} = S_{J/\psi K_S^0} \sin \Delta m_d t$$

Amplitude of *CP* asymmetry

$$\mathrm{Im}\,\lambda_{J/\psi K_S^0} = -\eta_{f_{CP}}\,\mathrm{Im}\left\{ \frac{V_{cs}V_{cb}^*}{V_{cs}^*V_{cb}} \times \frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}} \times \frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}} \right\} = \mathrm{Im}\frac{V_{td}^*}{V_{td}} = \sin 2\beta$$

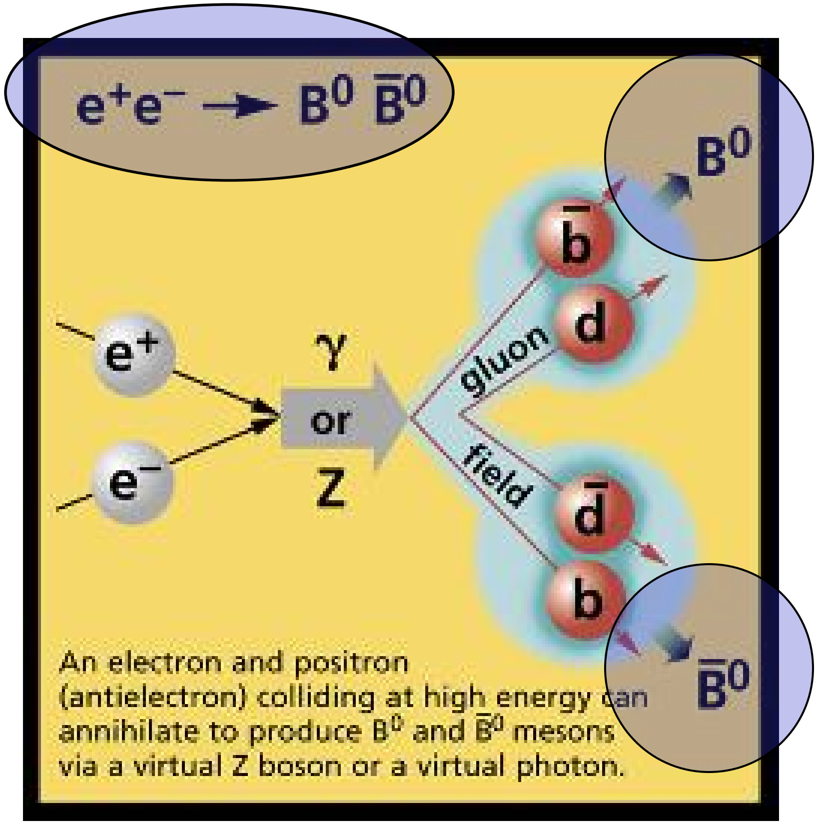
Quark subprocess | B^0 mixing | K^0 mixing

~0.7 instead of 2×10^{-3}!

Experimental approach to *CP* violation in the *B* meson system

Some reality…

Cross Section: 1nb = 10^{-33}cm^{-2}



Reconstruct *CP* eigenstate
with probability ~10^{-5}

Was it a B^0 or anti-B^0?
tagging probability ~30%

Luminosity target: 3 x 10^{33} cm^{-2}s^{-1}

3 Hz of $B\bar{B}$ events

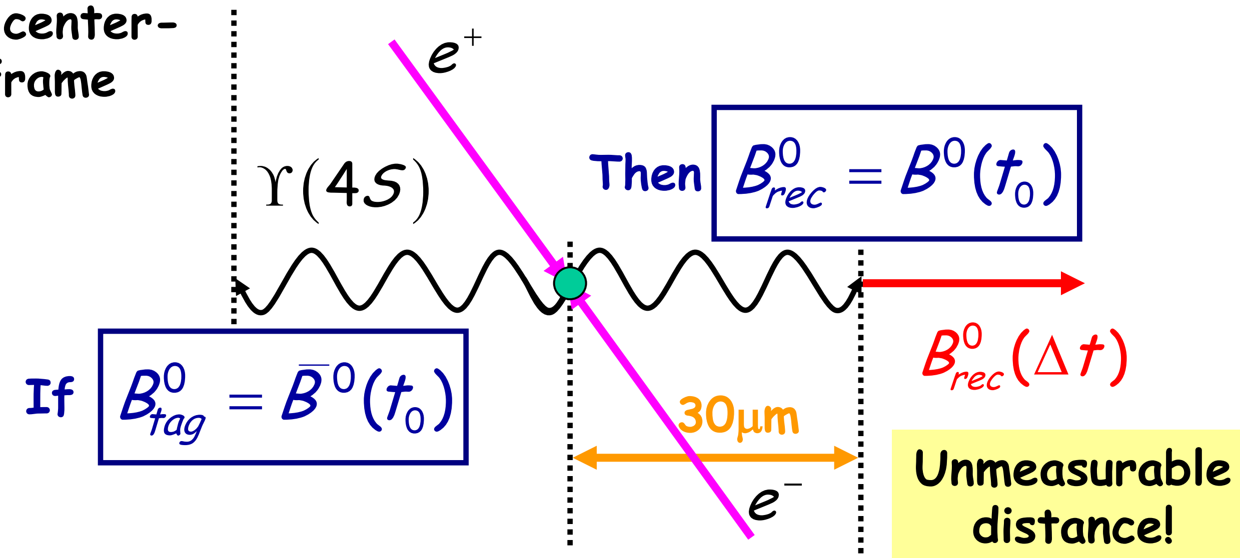
1 year of data logging = 300 tagged and reconstructed *CP* events

Complications from Quantum Mechanics

$$\Upsilon(4S) \to B^0\bar{B}^0$$
$$1^- \to 0^- + 0^-$$

Initial state: prepared <u>antisymmetric</u> wave function

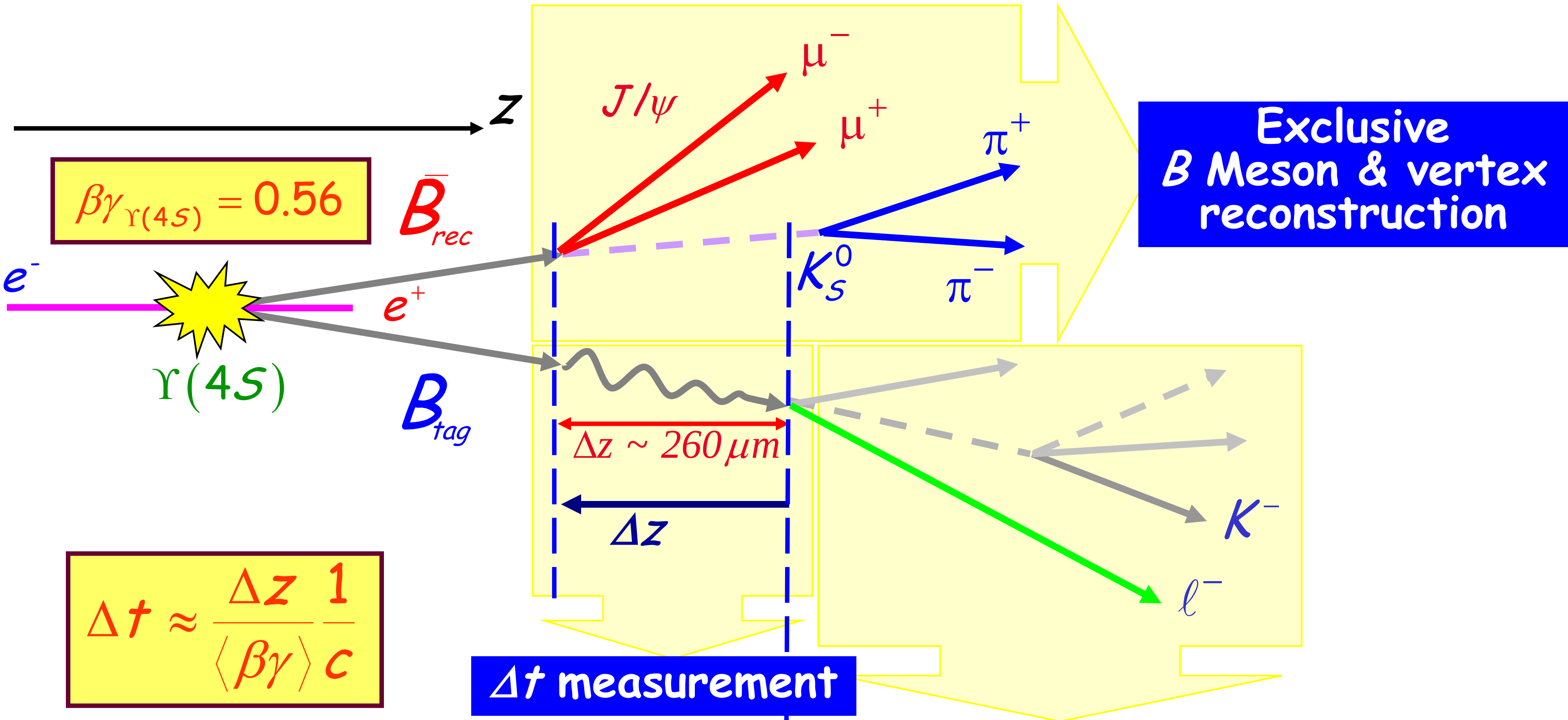
View in e^+e^- center-of-mass frame



Consequence

B^0_{rec} evolves independently as a function of $\Delta t = t - t_0$

Use asymmetric-energy collisions!



Δt is a signed quantity

$\sigma_{\Delta t} \sim 1$ ps $\Leftrightarrow$ 170 μm

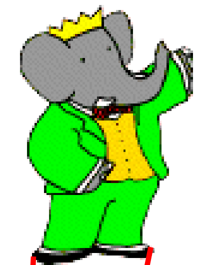
Start the clock

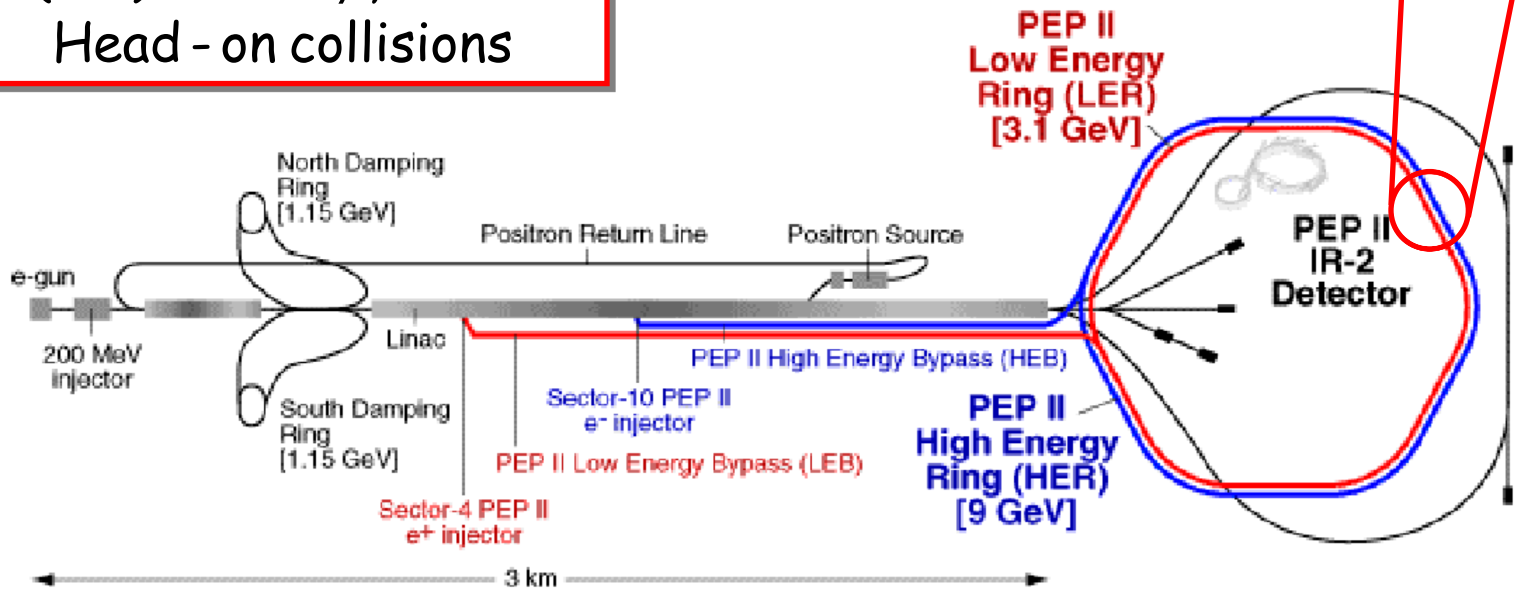
$\tau_B \sim 1.6$ ps $\Leftrightarrow$ 250 μm

Tagging performance: Q = 30.5%

PEP-II B Factory at SLAC

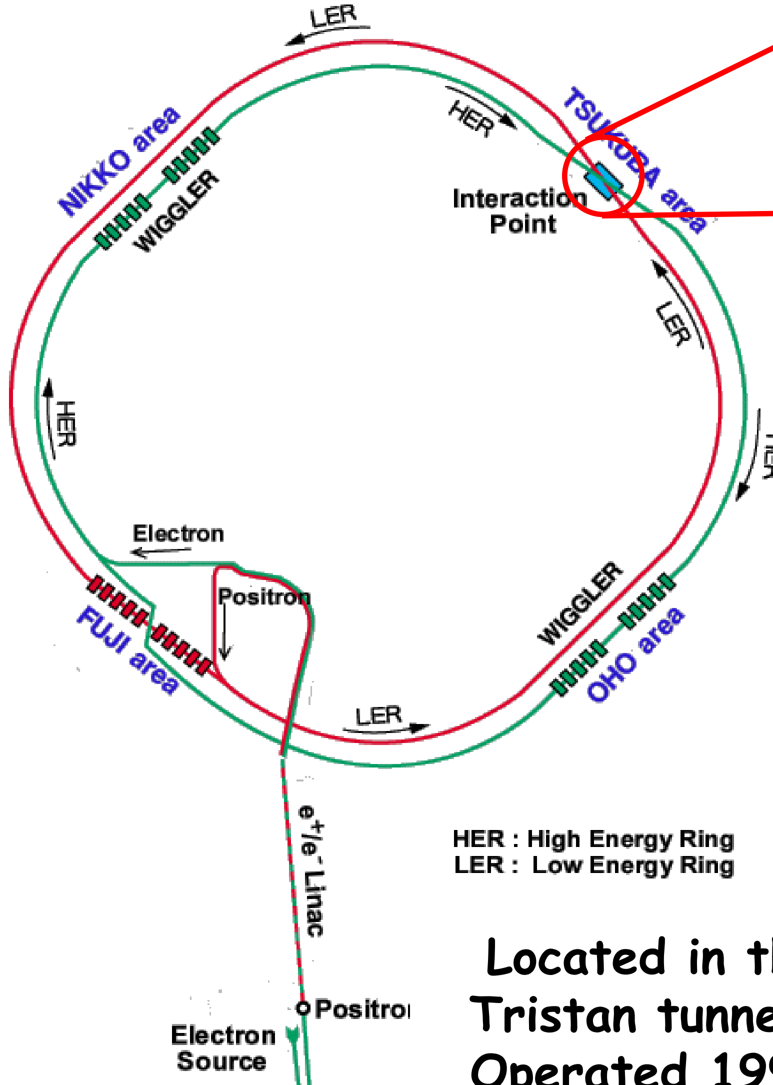
$9\ \text{GeV}\ e^- \times\ 3.1\ \text{GeV}\ e^+$
$\Upsilon(4S)$ boost: $\beta\gamma = 0.55$
Head-on collisions





Located at the SLAC National Accelerator Laboratory
Operated from 1999-2008

KEKB Factory at KEK



8 GeV $e^- \times$ 3.5 GeV e^+

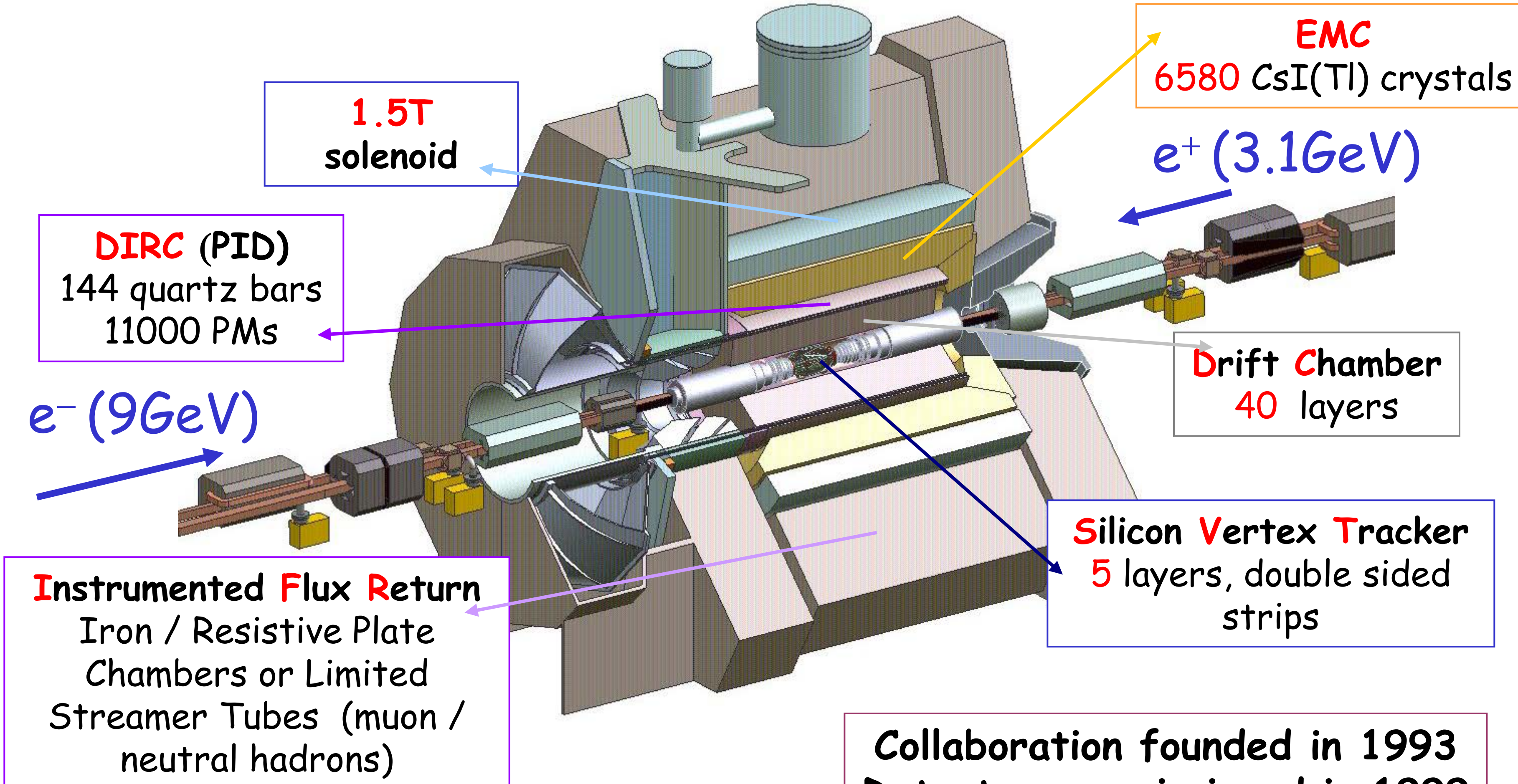
$\Upsilon(4S)$ boost: $\beta\gamma = 0.425$

$\pm 11\,\mathrm{mrad}$ crossing angle

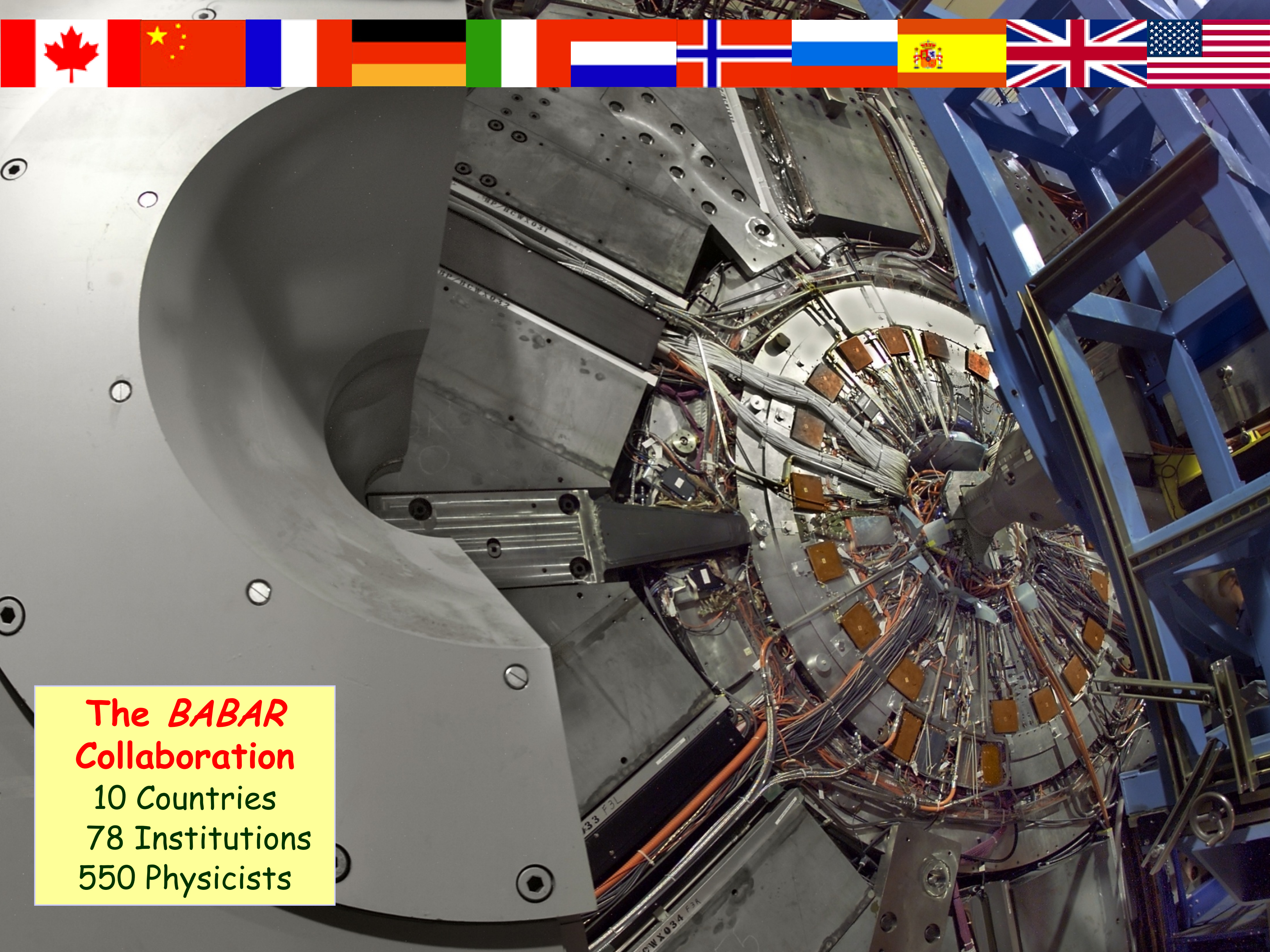
Located in the 3 km Tristan tunnel at KEK
Operated 1999-2010


PEP-II Collider
KEKB Collider

BABAR detector



Collaboration founded in 1993
Detector commissioned in 1999



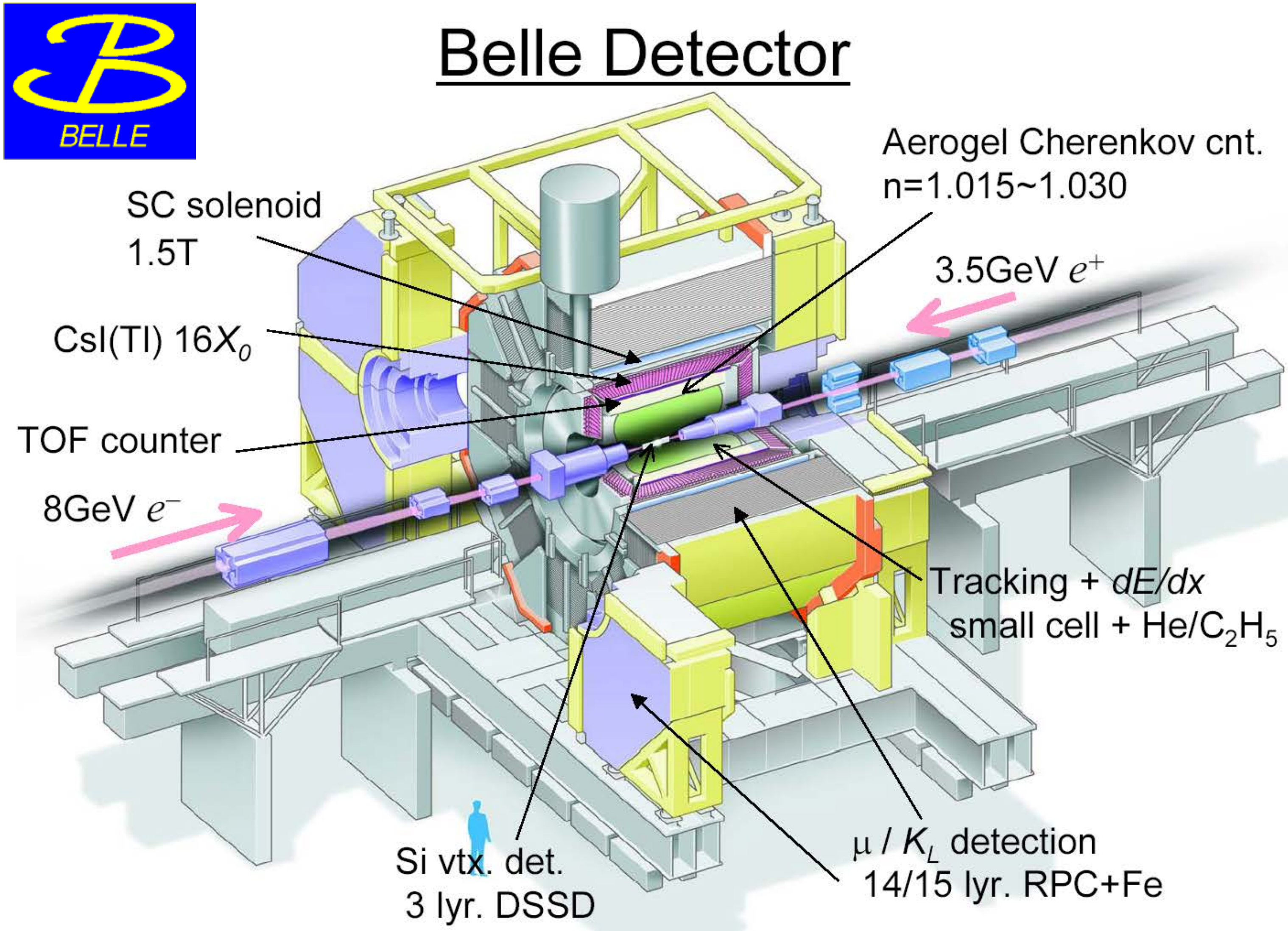
The *BABAR* Collaboration

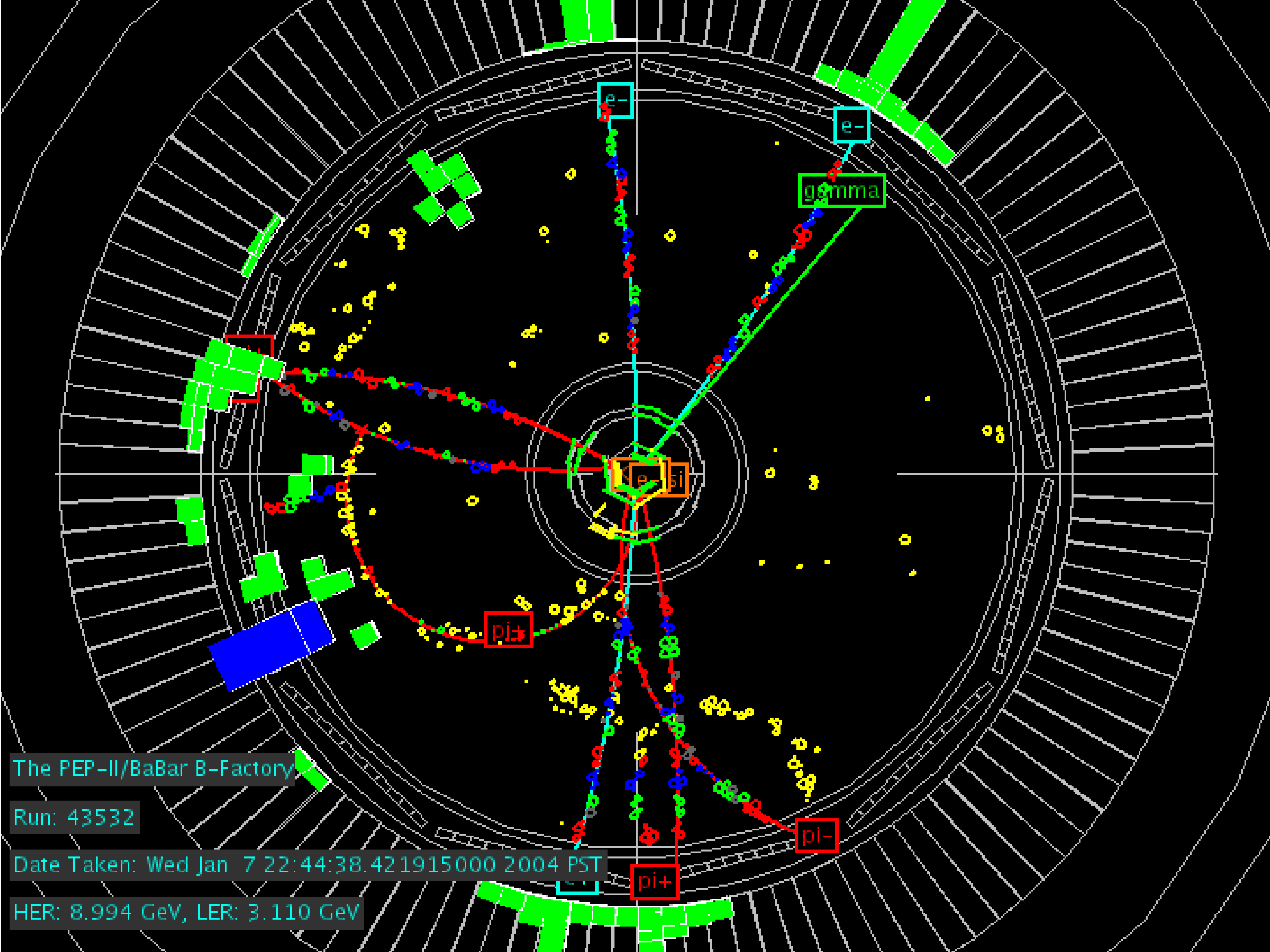
10 Countries

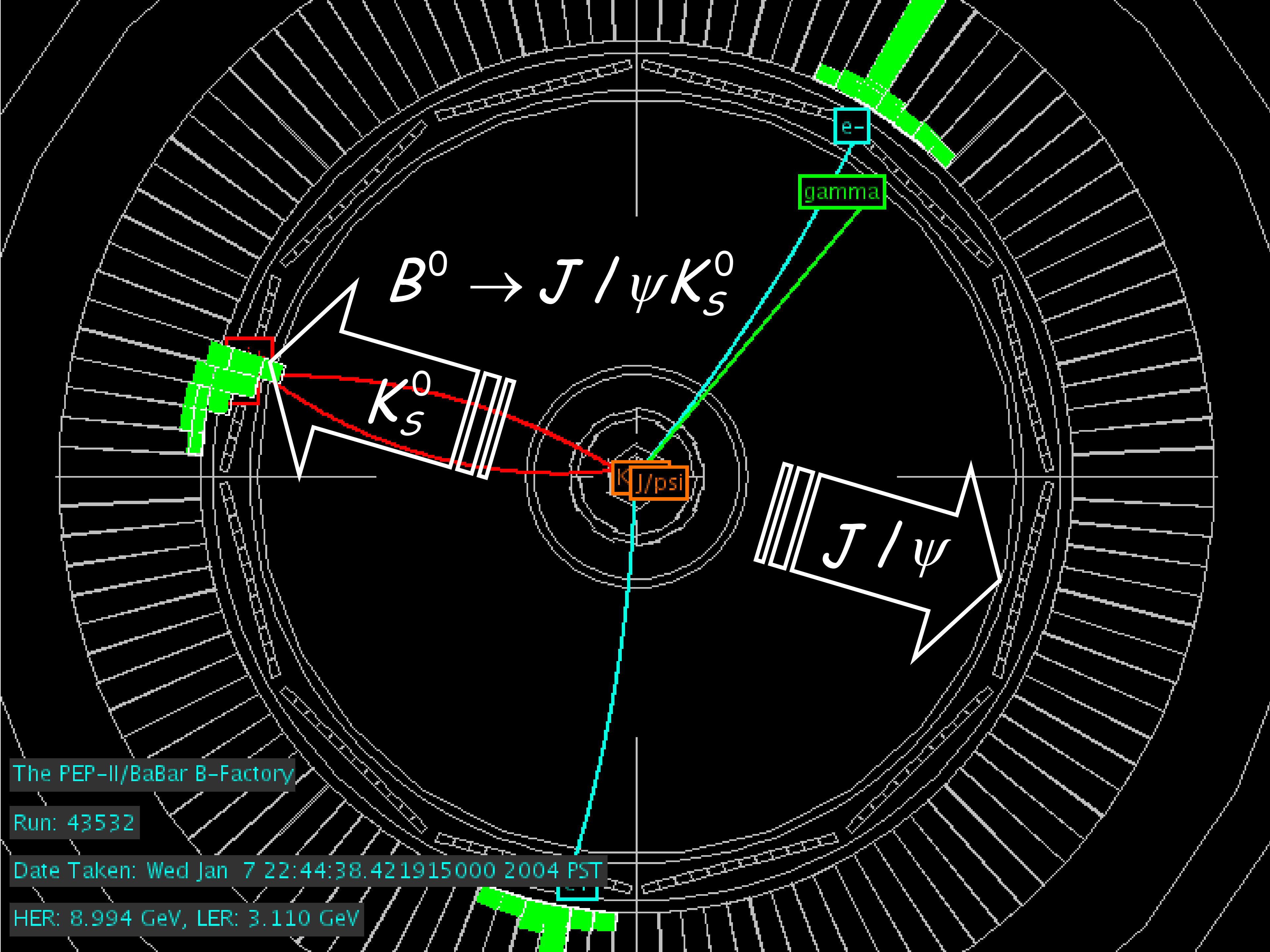
78 Institutions

550 Physicists

Belle Detector




e-
e-
gamma
pi+
pi-
pi+
The PEP-II/BaBar B-Factory
Run: 43532
Date Taken: Wed Jan 7 22:44:38.421915000 2004 PST
HER: 8.994 GeV, LER: 3.110 GeV


e-
gamma
$B^0 \to J/\psi K_S^0$
K_S^0
J/psi
J/ψ
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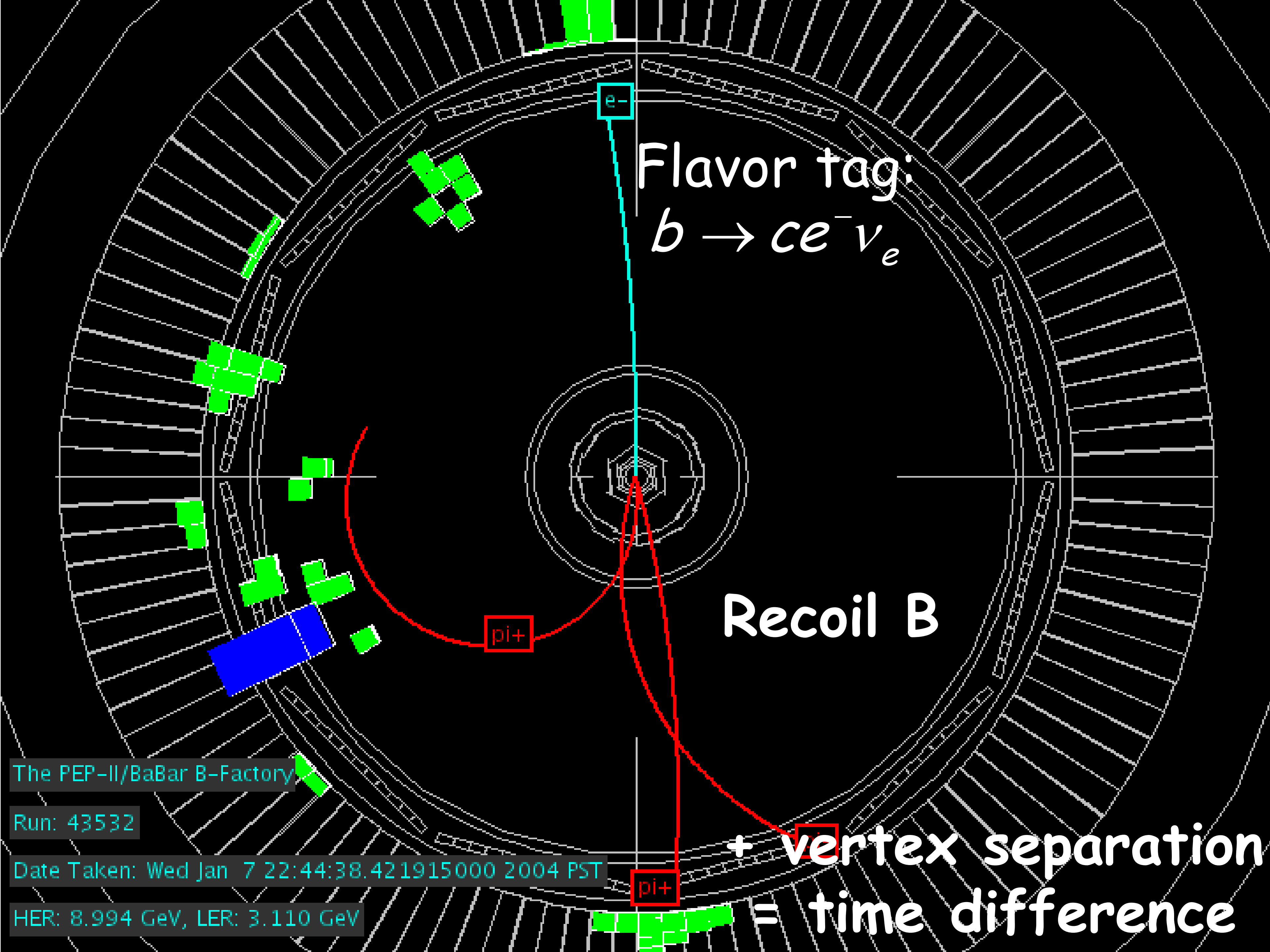
e-
Flavor tag:
$b \to c e^- \nu_e$
pi+
Recoil B
pi+
+ vertex separation
= time difference
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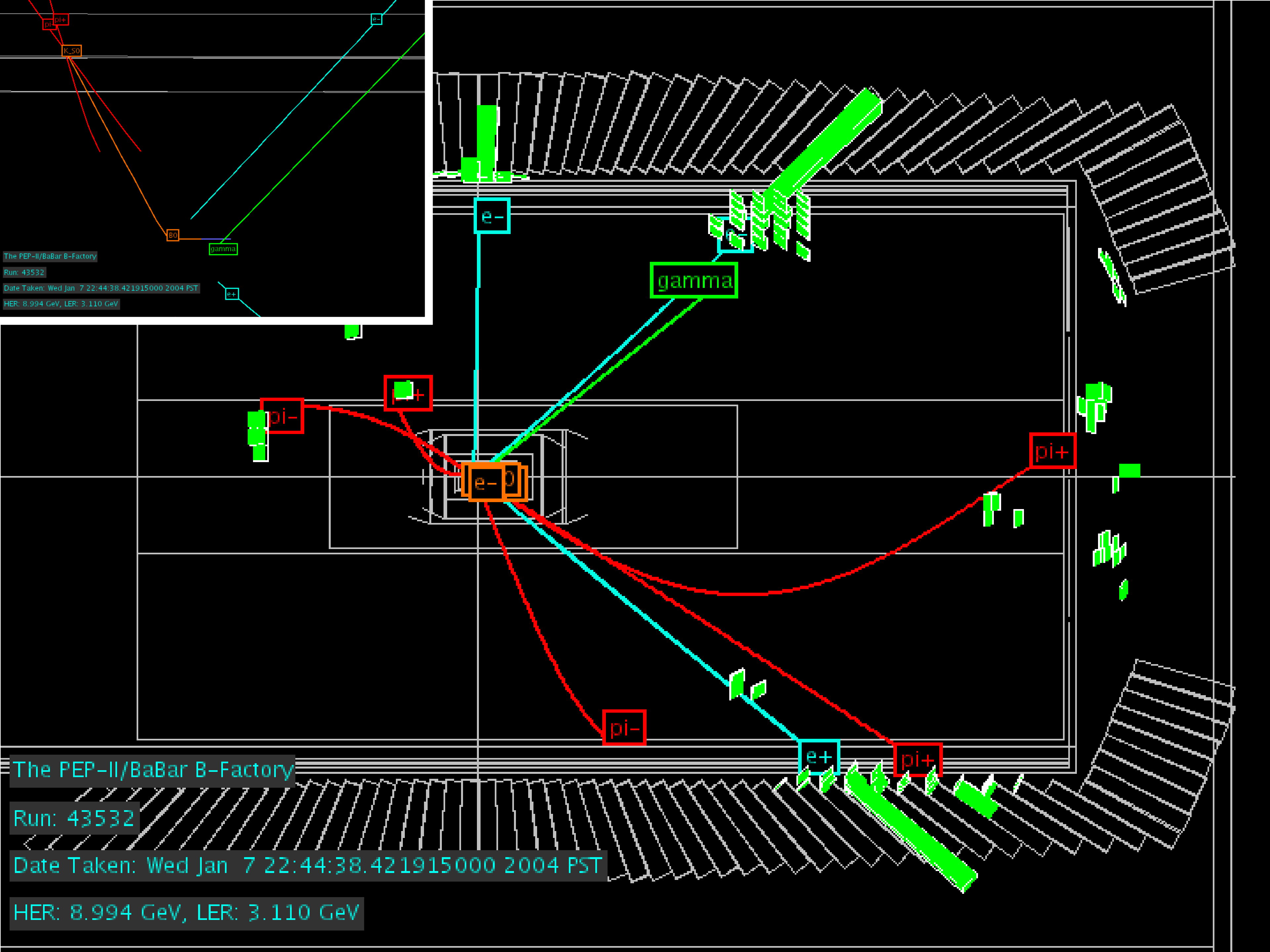
pi-
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Main Variables for B Reconstruction

For exclusive B reconstruction, two nearly uncorrelated* kinematic variables are used:

$$\Delta E = E_B^* - E_{beam}^*$$

Signal at $\Delta E \sim 0$

"Energy-substituted mass"

$$m_{ES} = \sqrt{\left(E_{beam}^*\right)^2 - \left(\mathbf{p}_B^*\right)^2}$$

Signal at $m_{ES} \sim m_B$

$(E_B^*, \mathbf{p}_B^*), E_{beam}^*$ — B candidate (energy, 3-momentum) and beam energy in $\Upsilon(4S)$ frame

Resolutions

$$\sigma_{\Delta E}^2 = \sigma_{beam}^2 + \sigma_E^2 \sim \sigma_E^2$$

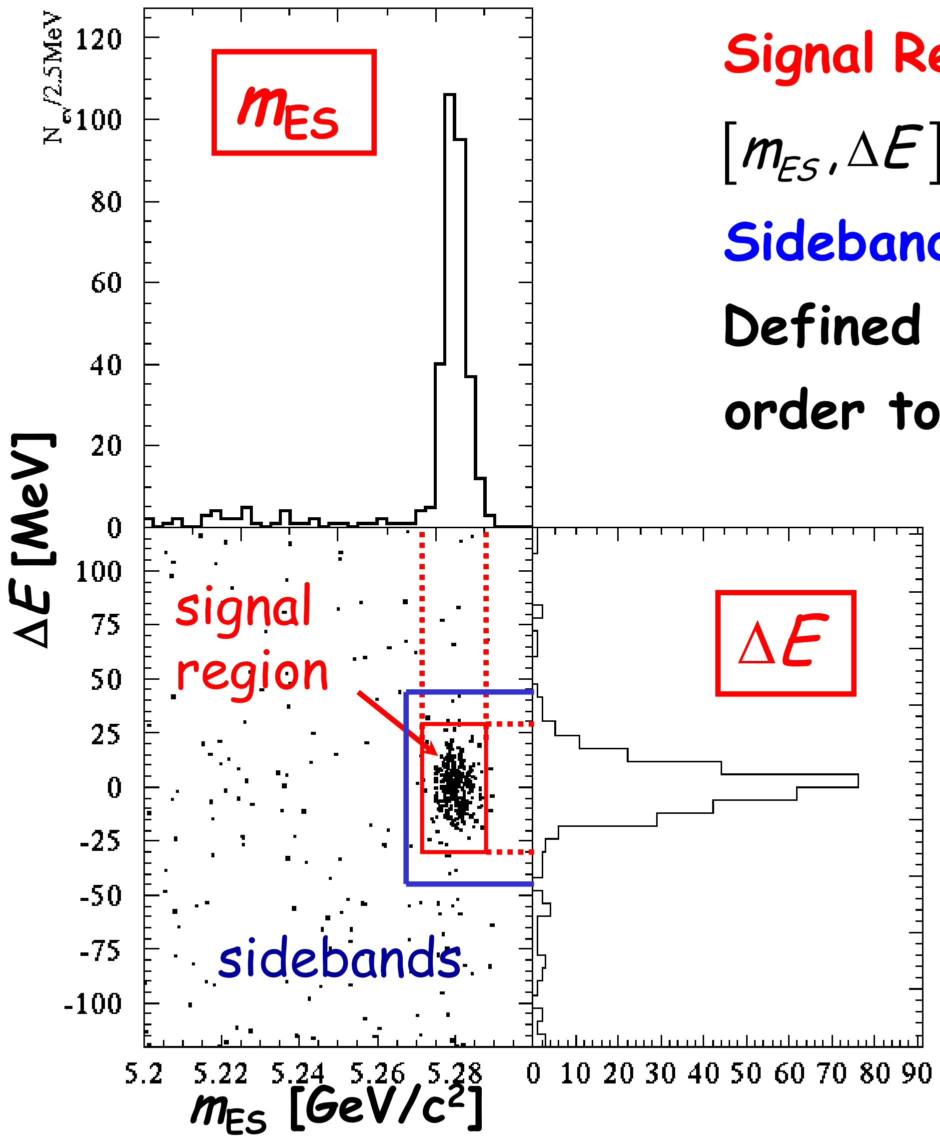
$$\sigma_{\Delta E} \sim 10 - 40 \text{ MeV}$$

$$\sigma_{m_{ES}}^2 = \sigma_{beam}^2 + \left[\frac{p}{m_B}\right]^2 \sigma_p^2 \sim \sigma_{beam}^2$$

$$\sigma_{m_{ES}} \sim 2.6 \text{ MeV}/c^2$$

* If σ_E were zero, the variables would be fully correlated; however, σ_E is typically at least 5 times larger than σ_{beam} and so dominates ΔE

Example for Hadronic B Decays



Signal Region :

$$[m_{ES}, \Delta E] = [m_B \pm 3\sigma_{m_{ES}}, 0 \pm 3\sigma_{\Delta E}]$$

Sideband Region :

Defined outside signal region in order to estimate backgrounds

$B^0 \to J/\psi K_S$

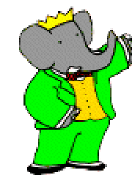
Flavor Eigenstate Neutral B Sample

Charm decay modes $\sum BF(\bar{D}^0) \sim 28\% \quad \sum BF(D^-) \sim 12\%$

Self-Tagging Modes

$D^{*-} \rightarrow \bar{D}^0\pi^-, \bar{D}^0 \rightarrow K^+\pi^-, K^+\rho^-, K^+\pi^+\pi^-\pi^-, K_S^0\pi^+\pi^-$

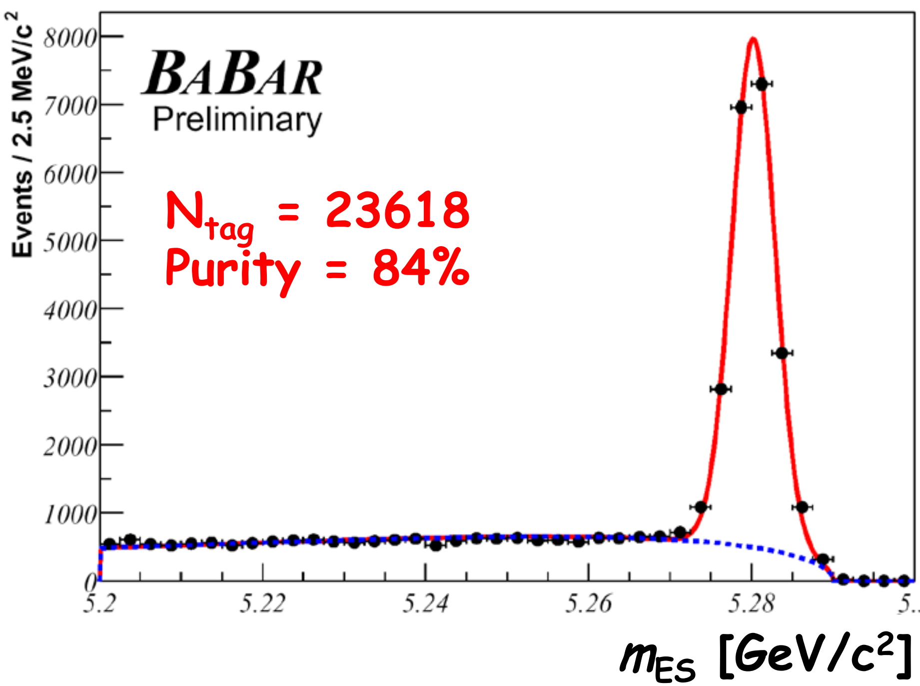
$D^- \rightarrow K^-\pi^+\pi^+, K_S^0\pi^-$



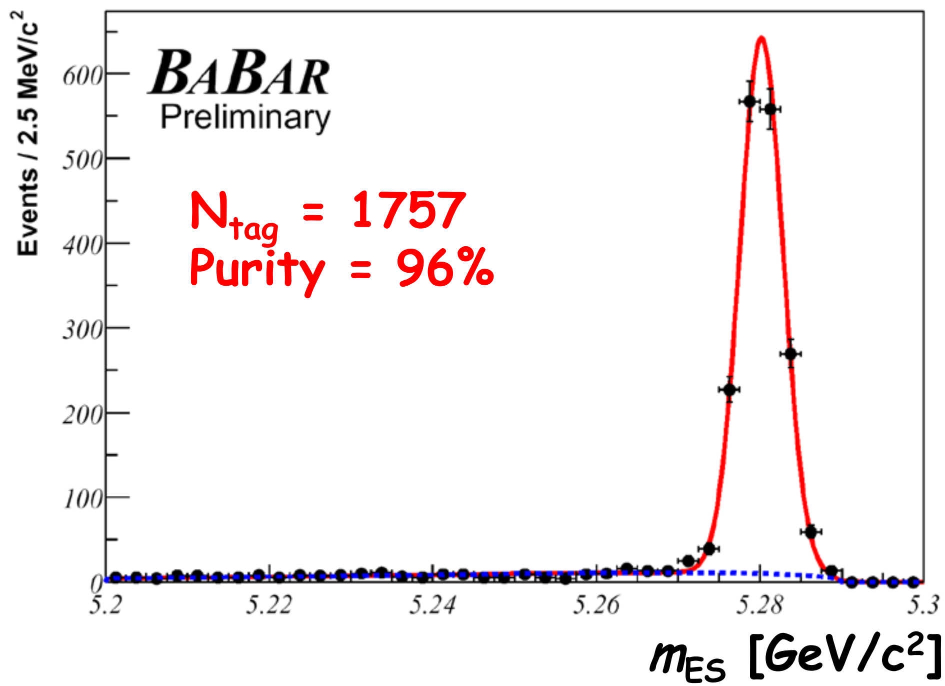
BABAR
81.3 fb^{-1}

B decay modes $\sum BF(B^0) \sim 4.1\%$

$B^0 \rightarrow D^{(*)-}h^+(h^+ = \pi^+, \rho^+, a_1^+)$

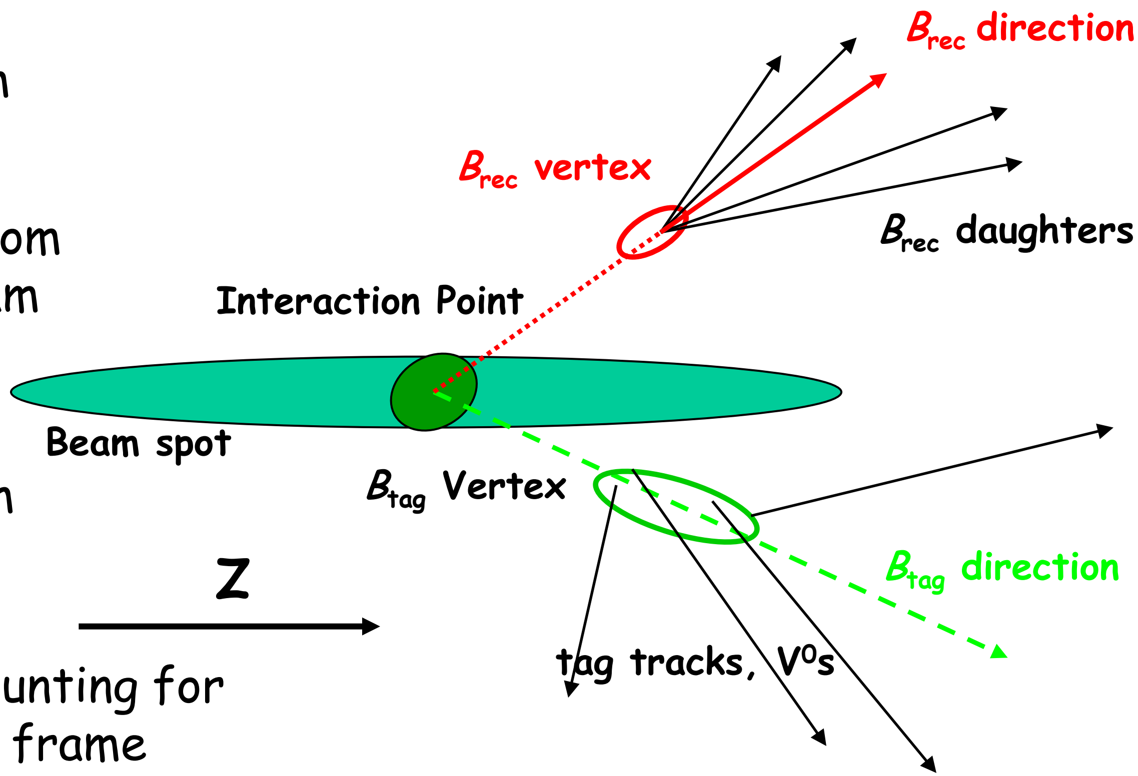


$B^0 \rightarrow J/\psi K^{*0}(\rightarrow K^+\pi^-)$



Vertex and Δz Reconstruction

1. Reconstruct B_{rec} vertex from B_{rec} daughters
2. Reconstruct B_{tag} direction from B_{rec} vertex & momentum, beam spot, and $\Upsilon(4S)$ momentum = pseudotrack
3. Reconstruct B_{tag} vertex from pseudotrack plus consistent set of tag tracks
4. Convert from Δz to Δt, accounting for (small) B momentum in $\Upsilon(4S)$ frame

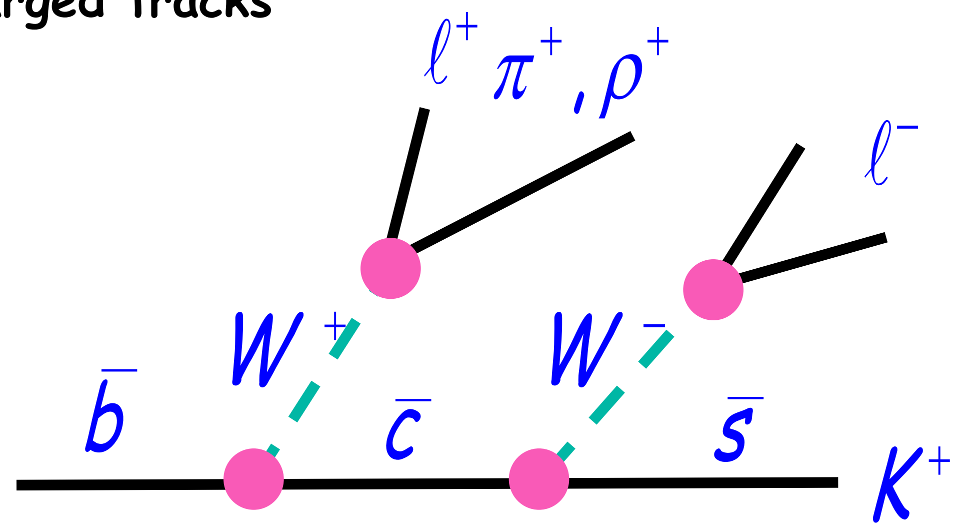


Result: High efficiency (97%) and $\sigma(\Delta z)_{rms} \sim 180\mu m$ versus $\langle|\Delta z|\rangle \sim \beta\gamma c\tau = 260\mu m$

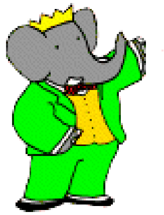
Methods for B Flavor Tagging

Many different physics processes can be used

Primary lepton	$B^0 \to D^{*-}\ell^+\nu$
Secondary lepton	$B^0 \to D^-\pi^+, D^- \to K^{*+}\ell^-\bar{\nu}$
Kaon(s)	$B^0 \to \bar{D}X, \bar{D} \to K^+X$
Soft pions from D^* decays	$B^0 \to D^{*-}X^+, D^{*-} \to \bar{D}^0\pi_s^-$
Fast charged tracks	



Tagging at BABAR



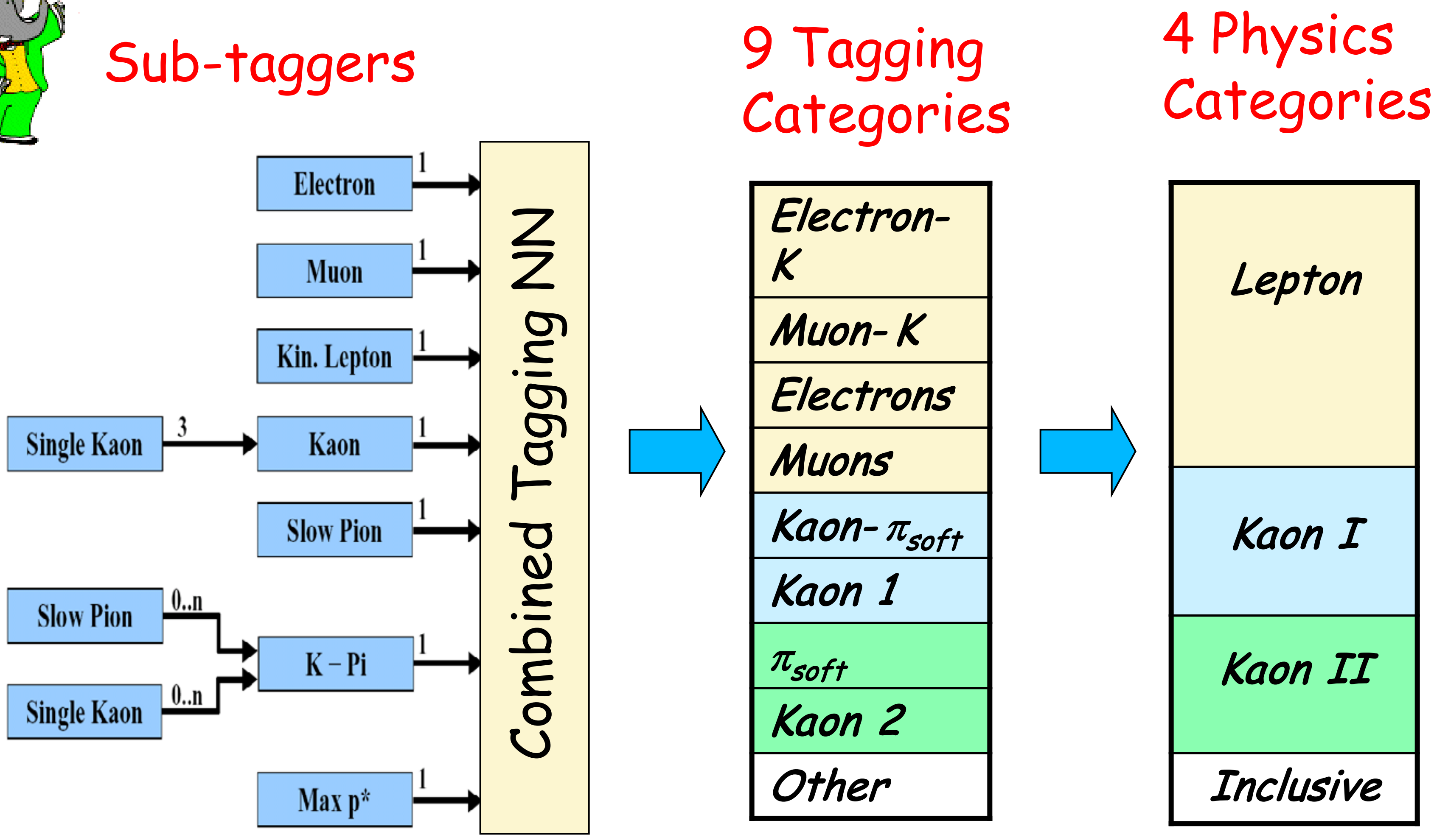


Figure of merit for tagging $Q = \varepsilon D^2$

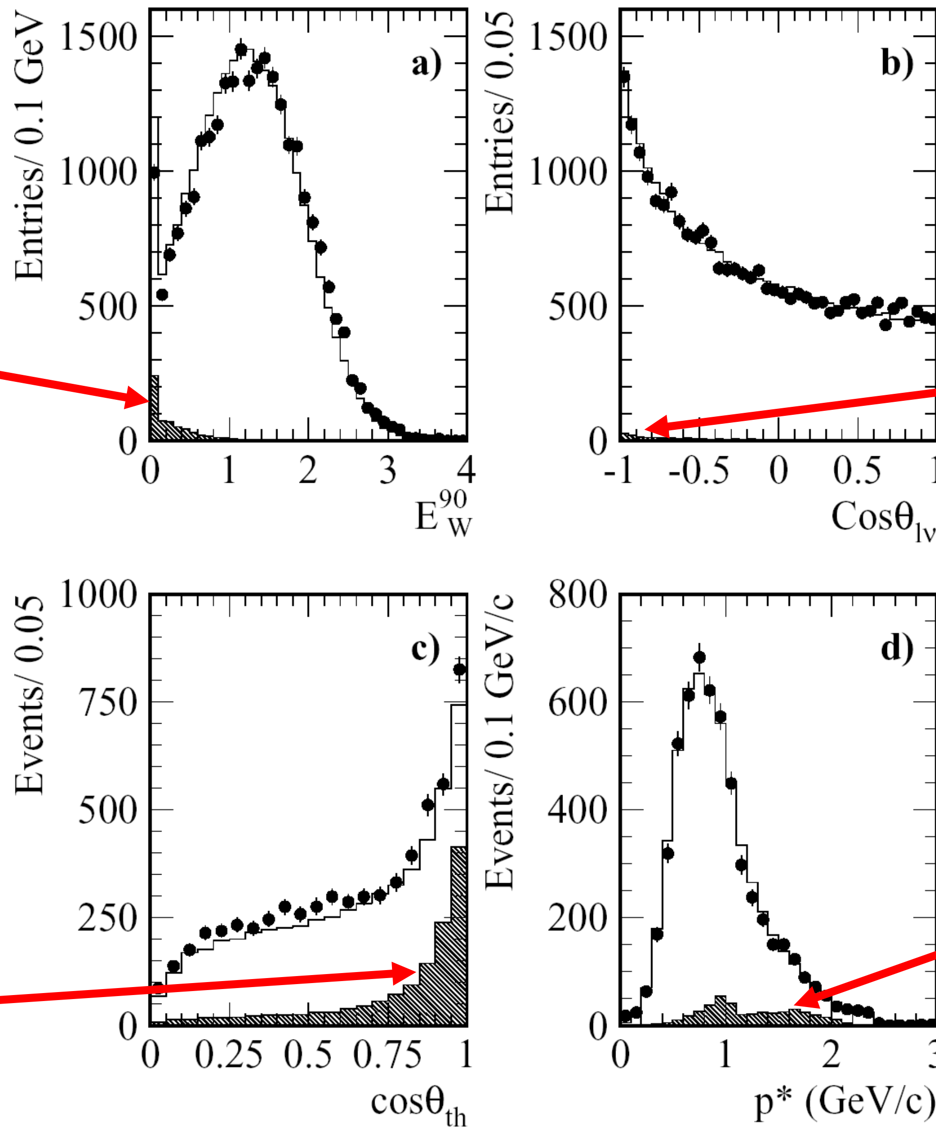
Some Inputs to NN Tagger

Sum of energy within 90° of estimated W direction

$B^0 \to D^{*-}\ell^+\nu$

Opening angle between input track and missing momentum vector

$B^0 \to D^{*-}\ell^+\nu$



Opening angle between input track and thrust axis of recoil B

$B^0 \to D^{*-}X^+,$

$D^{*-} \to \bar{D}^0\pi_s^-$

CMS momentum of input track

$B^0 \to D^{*-}\ell^+\nu$

Flavor Tagging Performance in Data

The large sample of fully reconstructed events provides the precise determination of the tagging parameters required in the *CP* fit

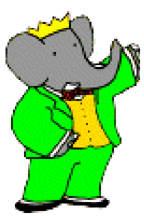
Tagging category	Fraction of tagged events ε (%)	Wrong tag fraction w (%)	Mistag fraction difference Δw (%)	Q = ε(1-2w)² (%)
Lepton	9.1 ± 0.2	3.3 ± 0.6	-0.9 ± 0.5	7.9 ± 0.3
Kaon I	16.7 ± 0.2	9.9 ± 0.7	-0.2 ± 0.5	10.7 ± 0.4
Kaon II	19.8 ± 0.3	20.9 ± 0.8	-2.7 ± 0.6	6.7 ± 0.4
Inclusive	20.0 ± 0.3	31.6 ± 0.9	-3.2 ± 0.6	0.9 ± 0.2
ALL	65.6 ± 0.5			28.1 ± 0.7

Highest "efficiency"

Error on sin2β and Δm_d depend on the "quality factor" Q approx. as:

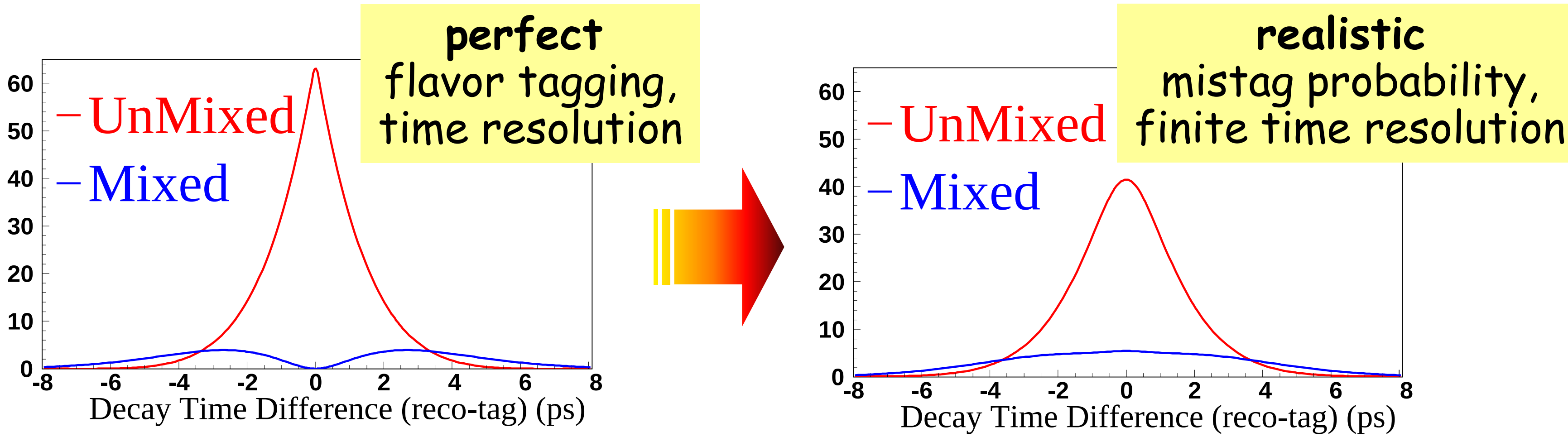
$$\sigma(\sin 2\beta) \sim \frac{1}{\sqrt{Q}}$$

Smallest mistag fraction



BABAR
$81.3\ \text{fb}^{-1}$

B-Mixing Analysis: Time Distributions



$$f_{mixing,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left(1 \pm (1-2w)\cos \Delta m_d \Delta t\right) \right\} \otimes R(\Delta t)$$

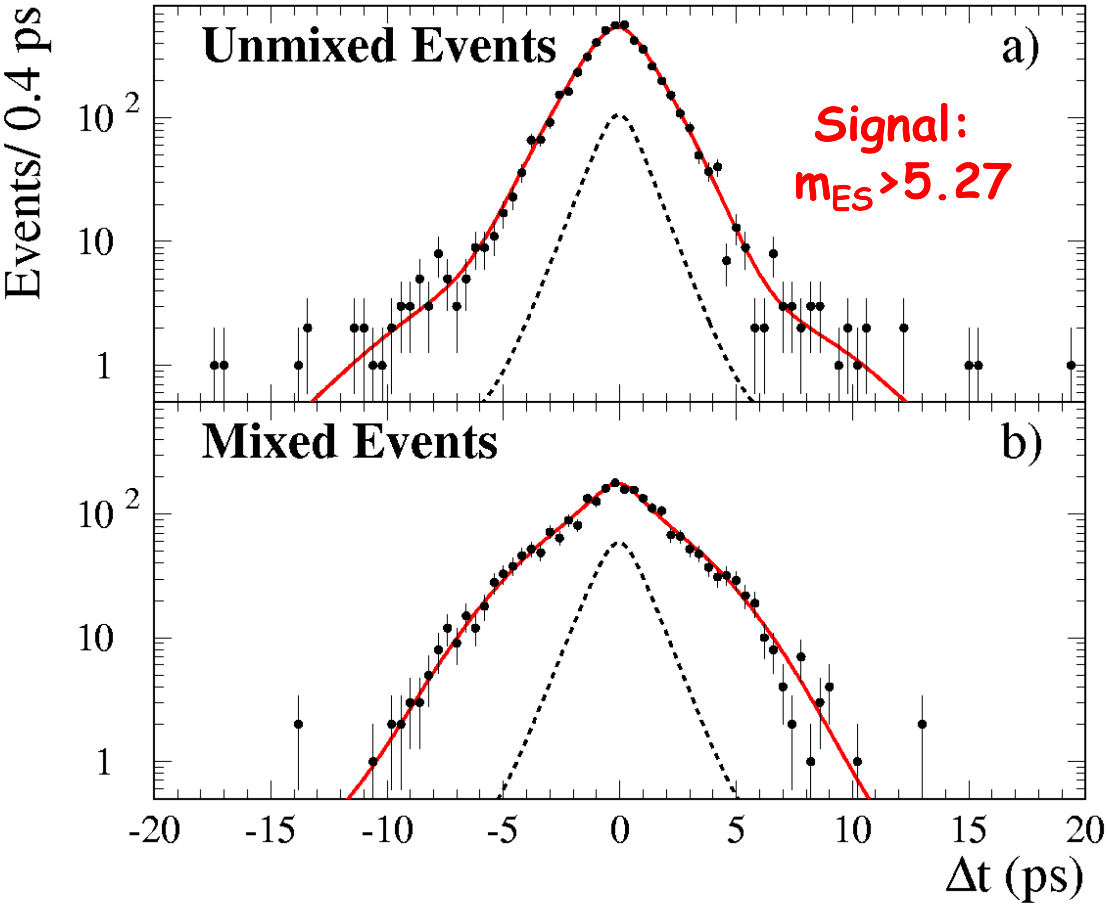
"$f_{mixing,+}$" $\Leftrightarrow$ unmixed $(B^0_{flav}\bar{B}^0_{tag}$ or $\bar{B}^0_{flav}B^0_{tag})$

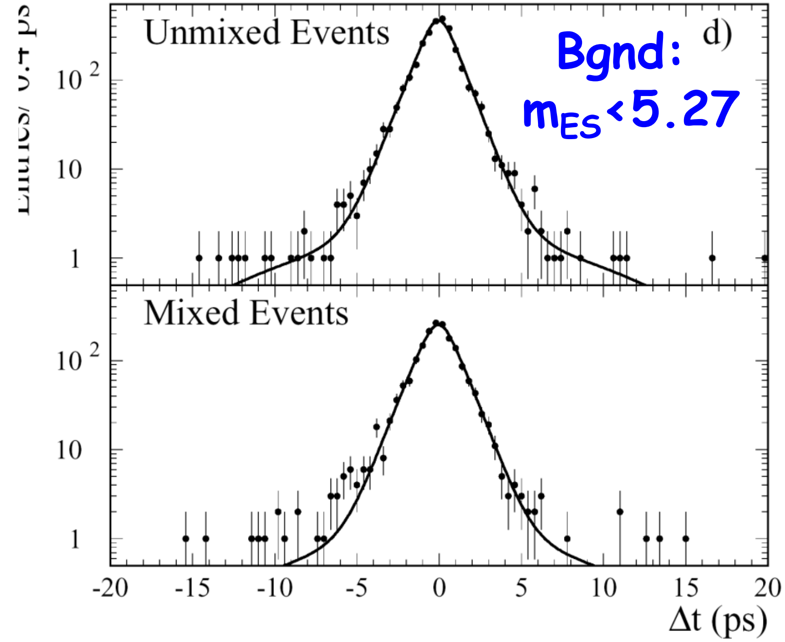
"$f_{mixing,-}$" $\Leftrightarrow$ mixed $(B^0_{flav}B^0_{tag}$ or $\bar{B}^0_{flav}\bar{B}^0_{tag})$

ω is the flavor mistag probability

$R(\Delta t)$ is the time resolution function

Mixing with Hadronic Sample





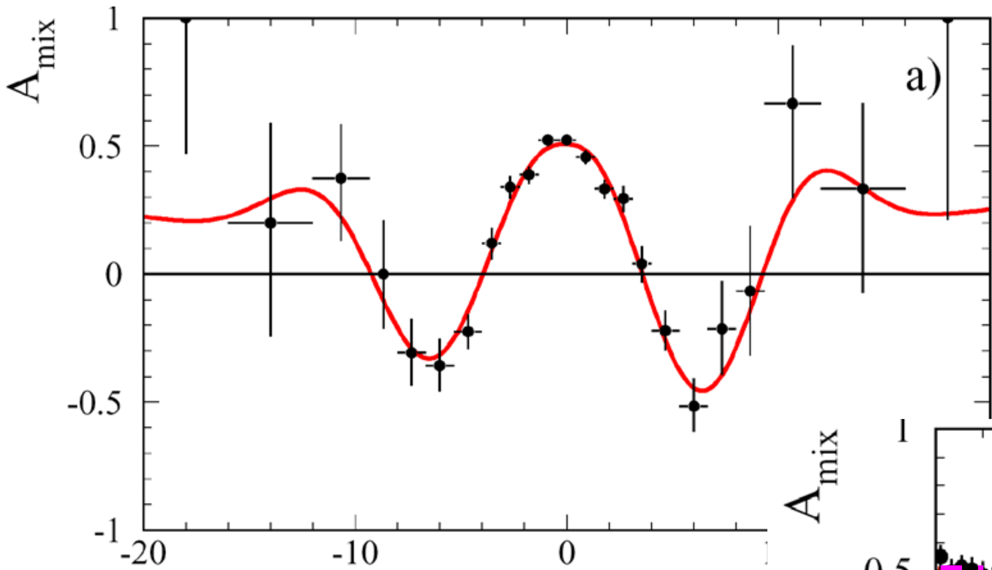
BABAR
29.7 fb^{-1}

Precision measurement consistent with world average

$$\Delta m_d = (0.516 \pm 0.016_{(stat)} \pm 0.010_{(syst)})\ \ ps^{-1}$$

BABAR PRL **88**, 221802 (2002)

Mixing Asymmetry with Hadronic Sample

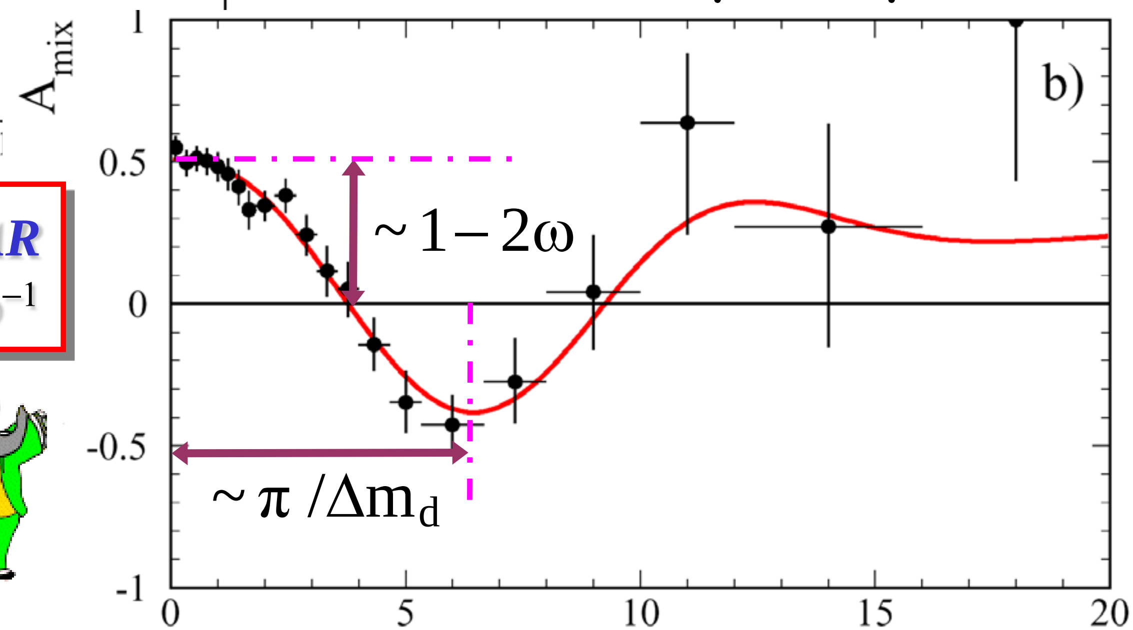


Δt [ps]

Unfolded raw asymmetry

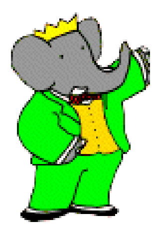
$$A_{mixing}(\Delta t) \approx (1-2\omega)\cos \Delta m_{B_d} \Delta t$$

Folded raw asymmetry

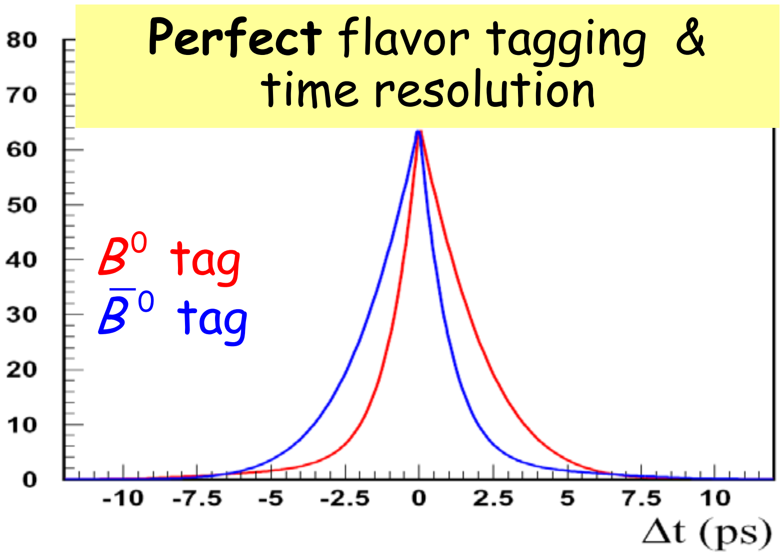


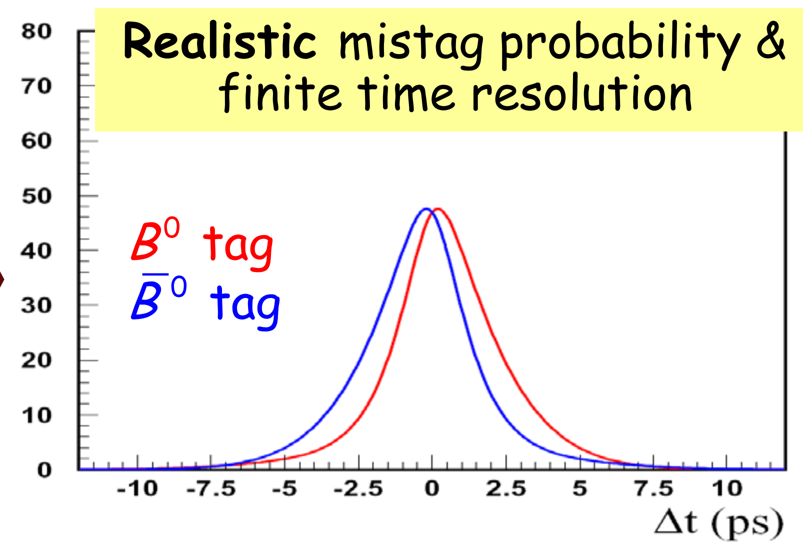
$|\Delta t|$ [ps]

BABAR
29.7 fb^{-1}



CP analysis: time distributions





$$f_{CP,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{2\tau_{B_d}} \left(1 \mp \eta_f \,(1-2\omega)\sin 2\beta \sin \Delta m_{B_d} \Delta t\right) \right\} \otimes R(\Delta t)$$

$$\text{"}f_{CP,+}\text{"} \Leftrightarrow B^0_{tag} = B^0$$

$$\text{"}f_{CP,-}\text{"} \Leftrightarrow B^0_{tag} = \bar{B}^0$$

same mistag probability ω
and time-resolution function $R(\Delta t)$

Time-Dependent CP Asymmetries

Time-dependence of
B^0-$\bar{B}^0$ mixing

$$A_{mixing}(\Delta t) = \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)} \approx (1-2w)\cos\Delta m_d \Delta t$$

Time-dependence of
CP-violating asymmetry in
$B^0_{CP} \to J/\psi K^0_S$

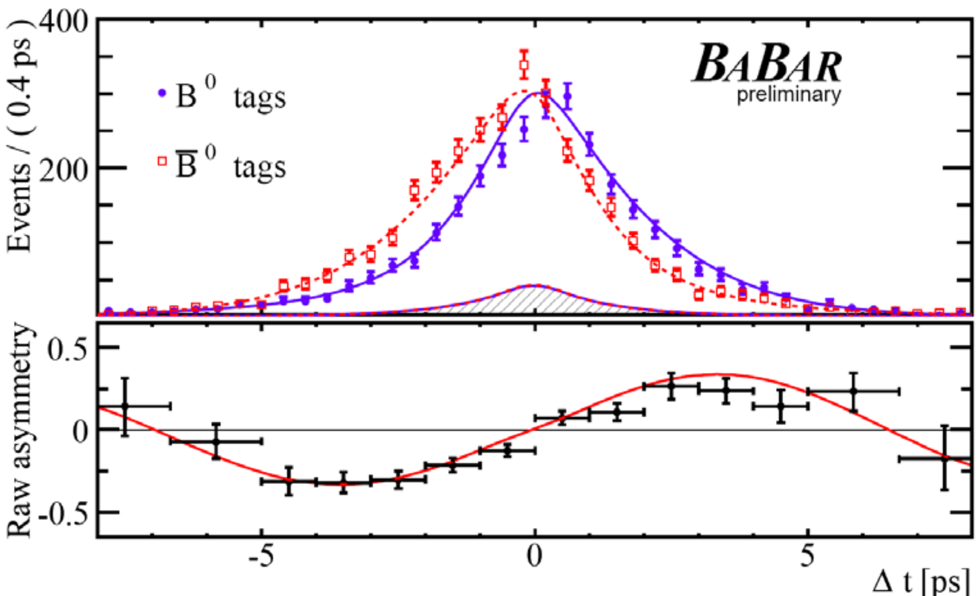
(Assuming no confusion of B_{rec} state)

$$A_{CP}(\Delta t) = \frac{N(B_{tag} = B^0) - N(B_{tag} = \bar{B}^0)}{N(B_{tag} = B^0) + N(B_{tag} = \bar{B}^0)} \approx (1-2w)\sin 2\beta \sin\Delta m_d \Delta t$$

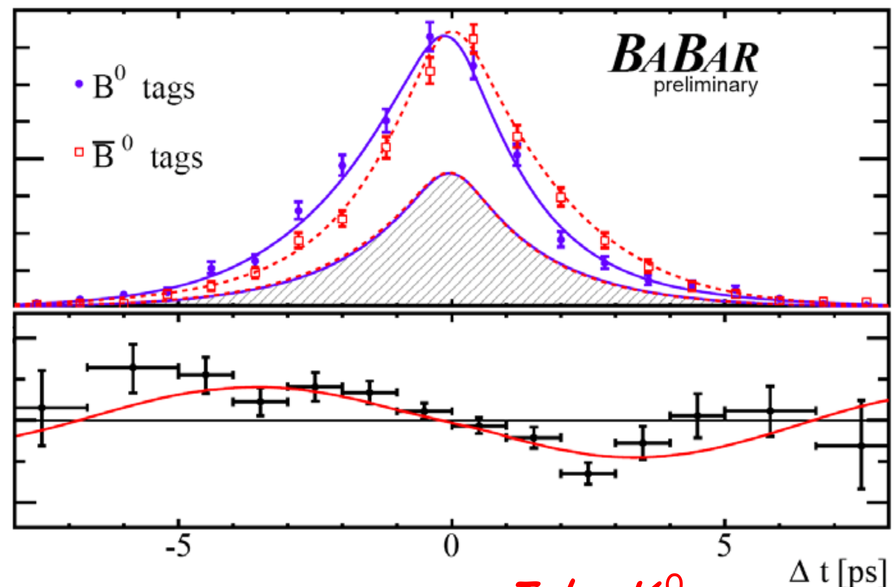
Use the large statistics B_{flav} data sample to determine the **mistag probabilities** and the parameters of the **time-resolution function**

Now classic results for sin2β

$(c\bar{c})K_S^0$ (CP odd) modes



$(c\bar{c})K_L^0$ (CP even) modes



BABAR CONF-06/036

$(c\bar{c})K_S^0$ + $(c\bar{c})K_L^0$

$\sin 2\beta = 0.710 \pm 0.034 \pm 0.019$
$C = -A = 0.070 \pm 0.028 \pm 0.018$

$316 fb^{-1}$ on peak or $348M$ $B\bar{B}$ pairs
11496 CP events (tagged signal)

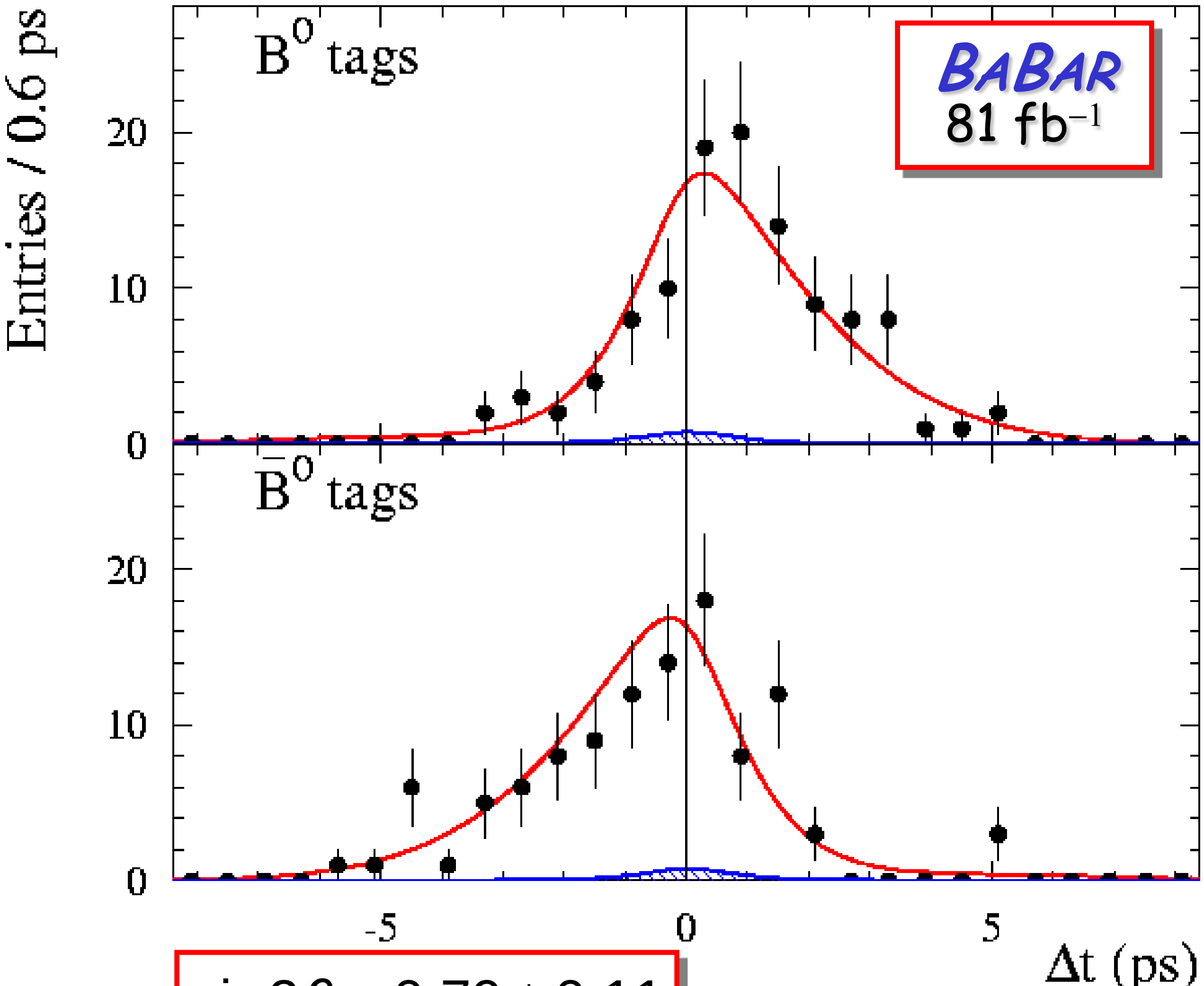
BELLE-CONF-0647

$J/\psi K_S^0$ + $J/\psi K_L^0$ only

$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$
$C = -A = -0.018 \pm 0.021 \pm 0.014$

$492 fb^{-1}$ on peak or $532M$ $B\bar{B}$ pairs
13994 CP events (tagged signal)

Pure Gold: Lepton Tags Alone

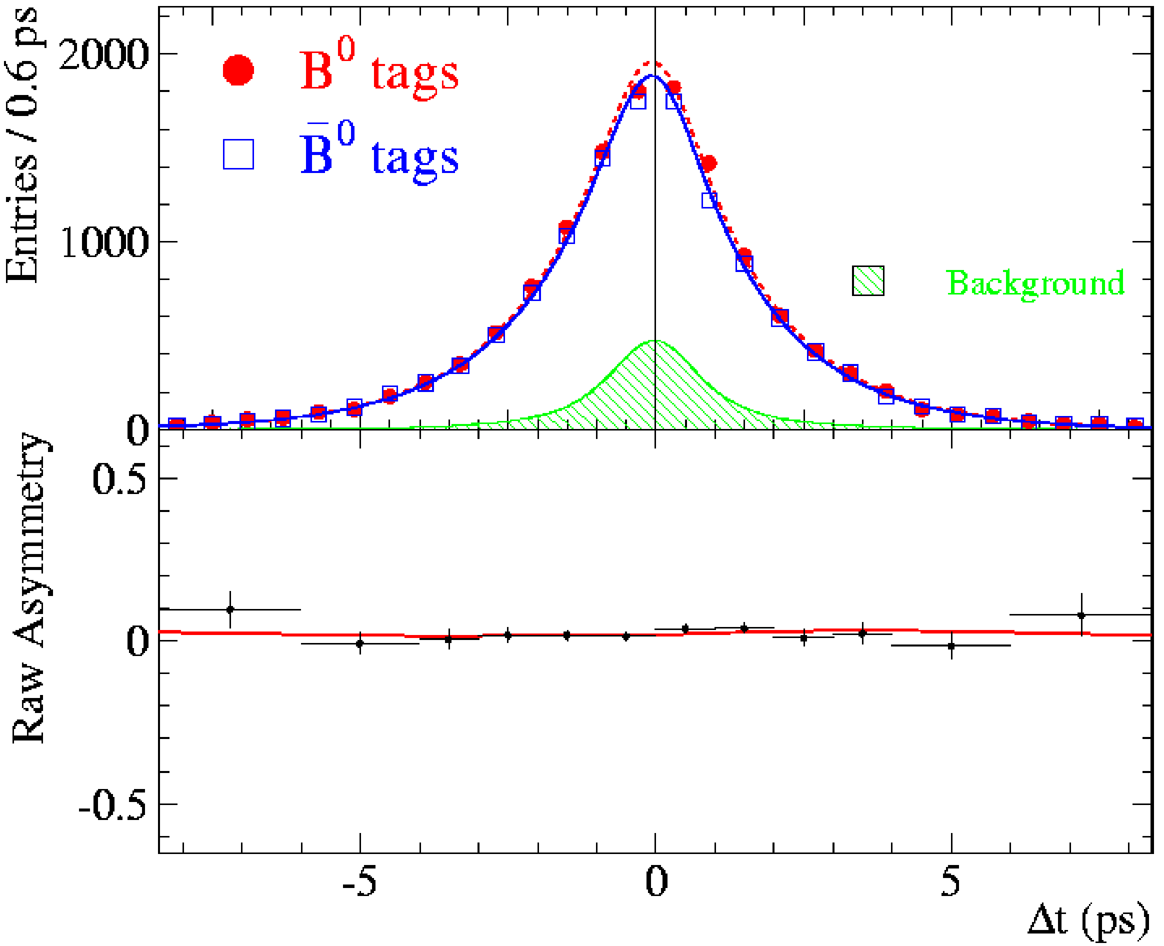


$\sin 2\beta = 0.79 \pm 0.11$

220 tagged η_f = -1 events

98% purity
3.3% mistag rate
20% better Δt resolution

Check "null" Control Sample at BABAR

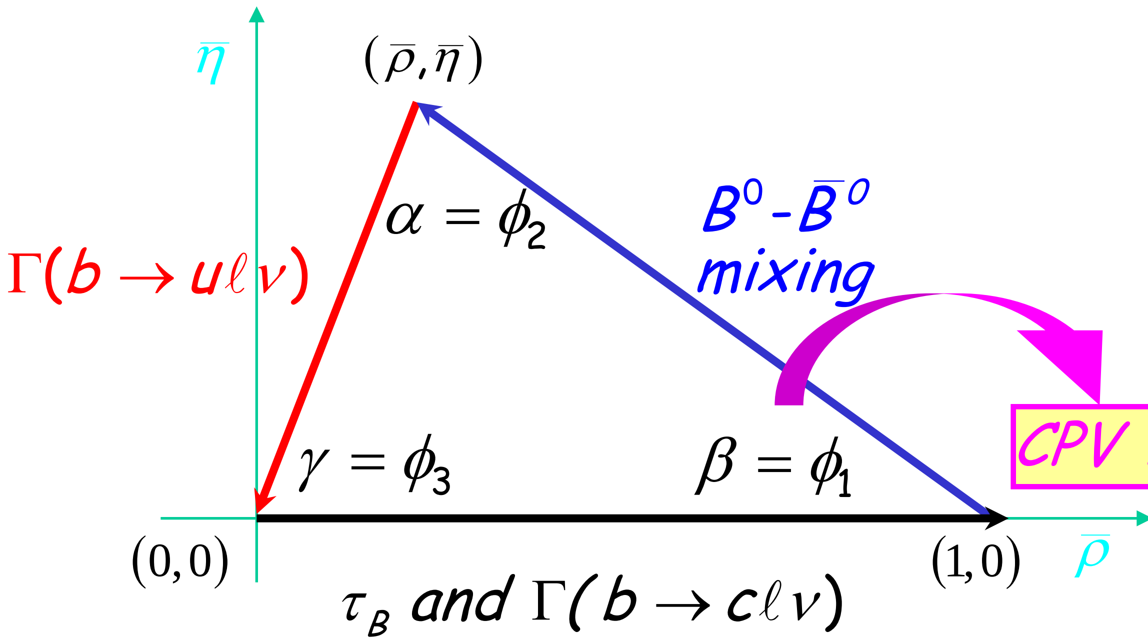


Input B_{flav} sample to *CP* fit

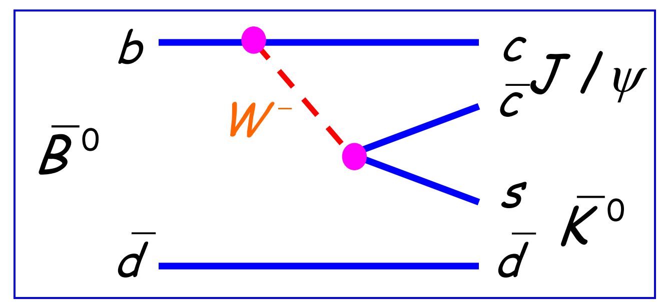
No asymmetry expected

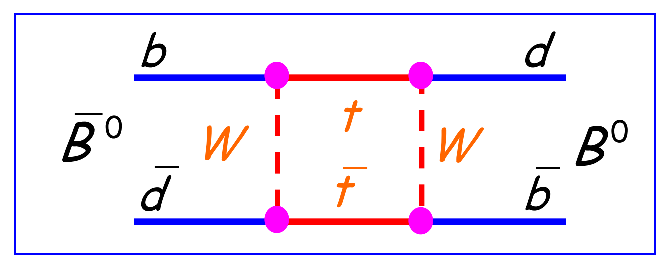
Sample	*"sin2β"*
B_{flav}	0.021 ± 0.022
B^{+}	0.017 ± 0.025

CPV in charmonium modes



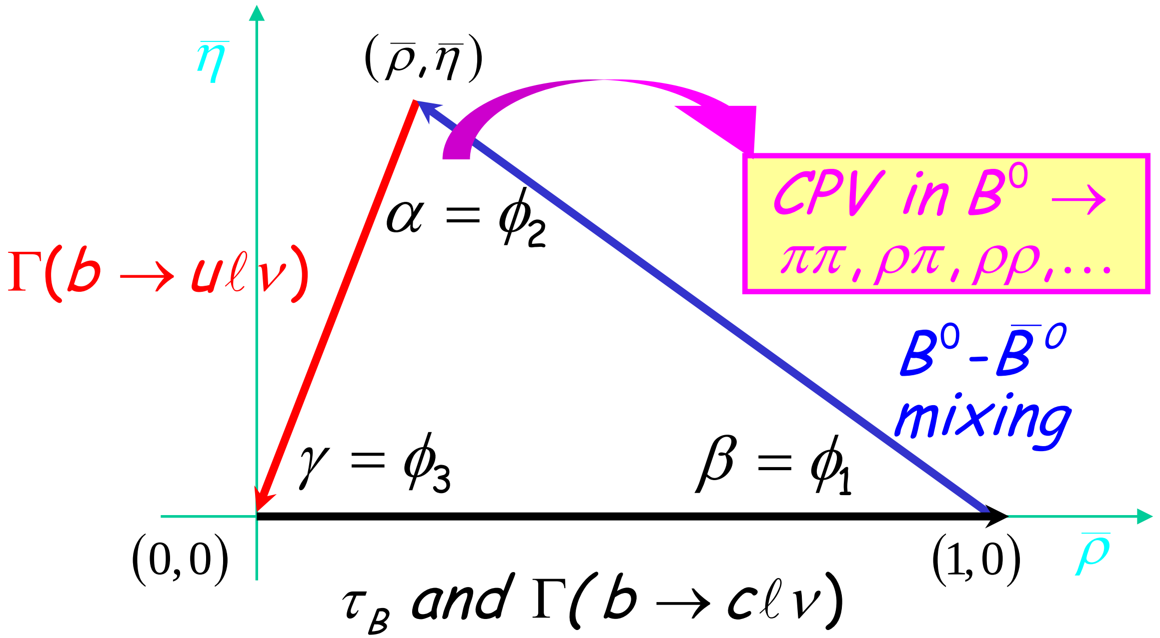
CPV in $B^0 \to J/\psi K_S^0$





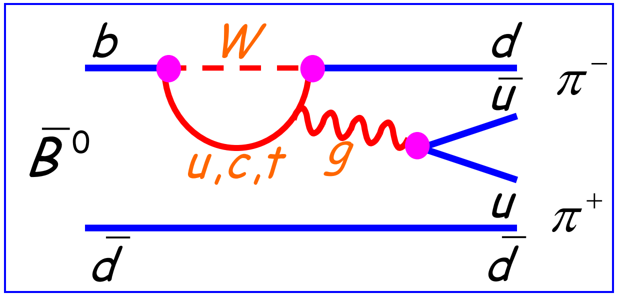
Interference of $b \to c$ tree decay with mixing

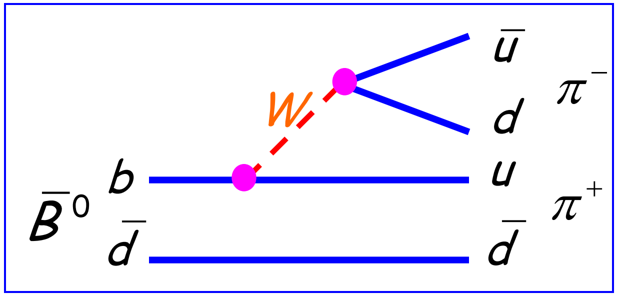
CPV in charmless modes

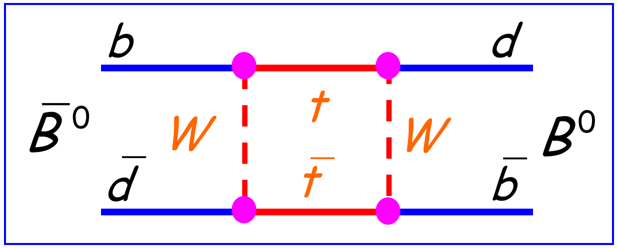


Interference of suppressed $b \to u$ tree decay with mixing

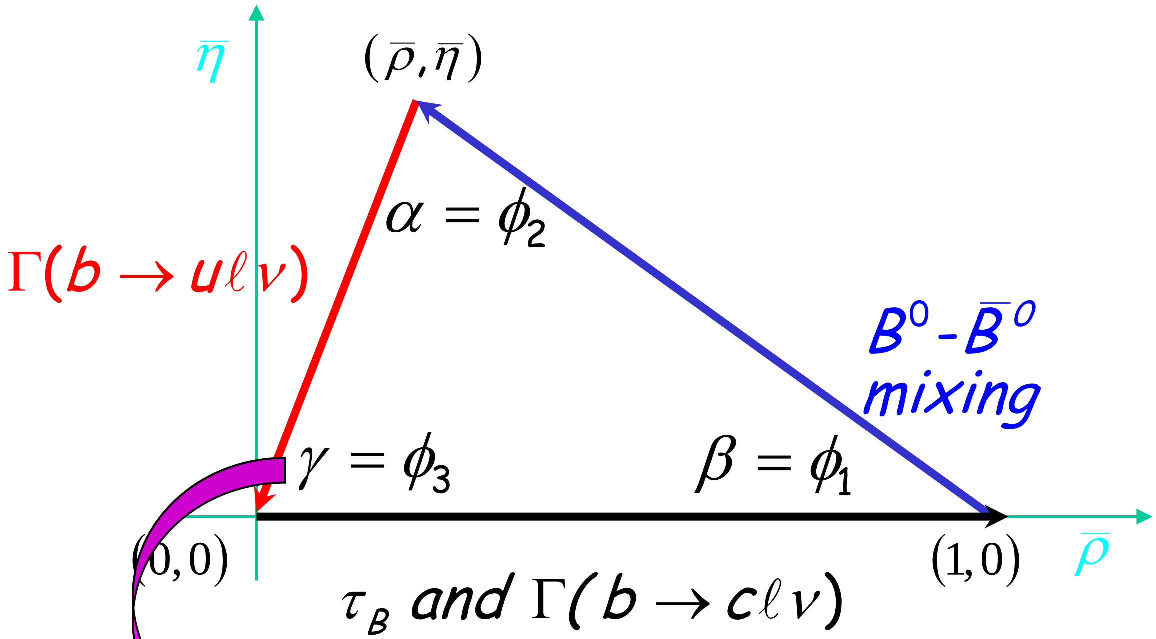
3rd component: sizable Penguin diagram







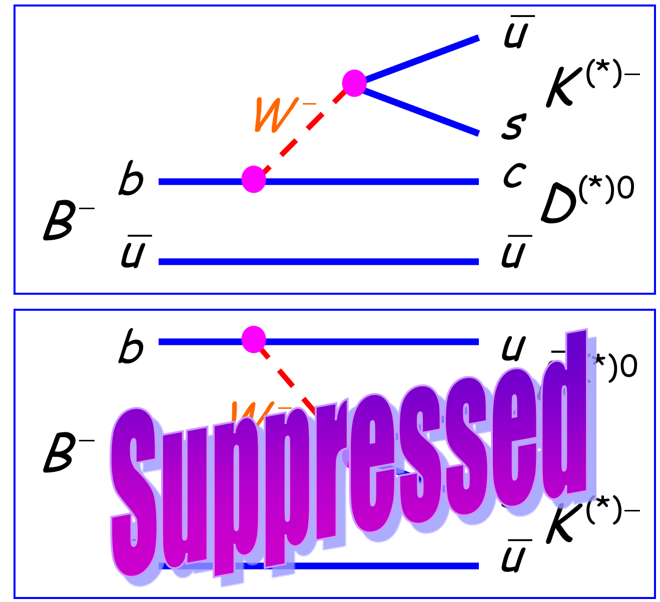
Remarkably good progress on gamma!



γ : CPV in $B^0 \to D_{CP}K, D_{DCS}K, \ldots$

Interference of color-allowed and color-suppressed tree decays

Effect depends on ratio of two diagrams

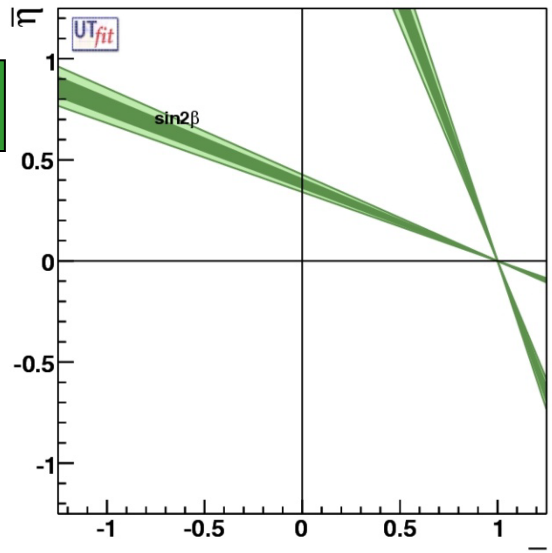


$+D(\bar{D})$ decay to common final state

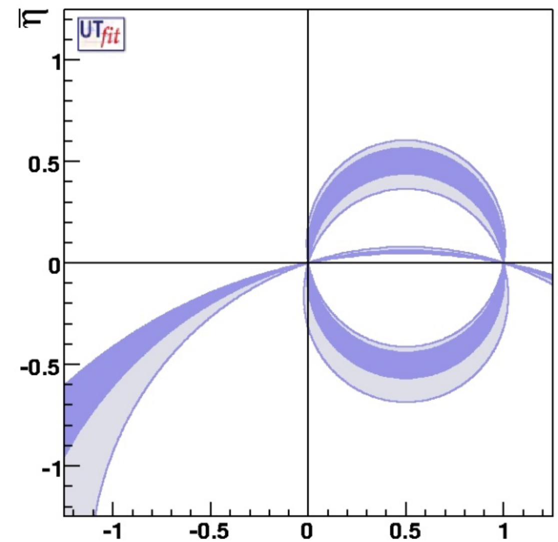
$D_{CP}, D_{DCS}, D^0 \to K_S^0\pi^+\pi^-$

Direct CP violation measurements

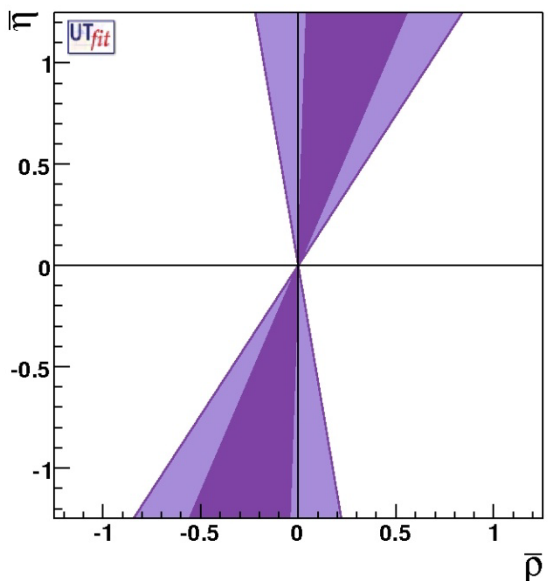
$\sin 2\beta$



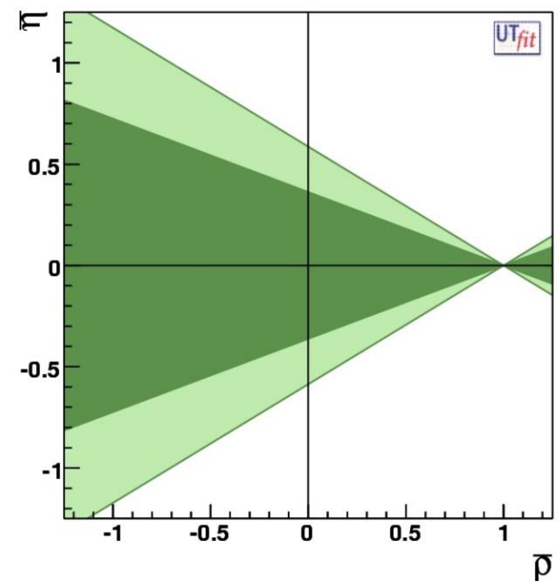
α



γ



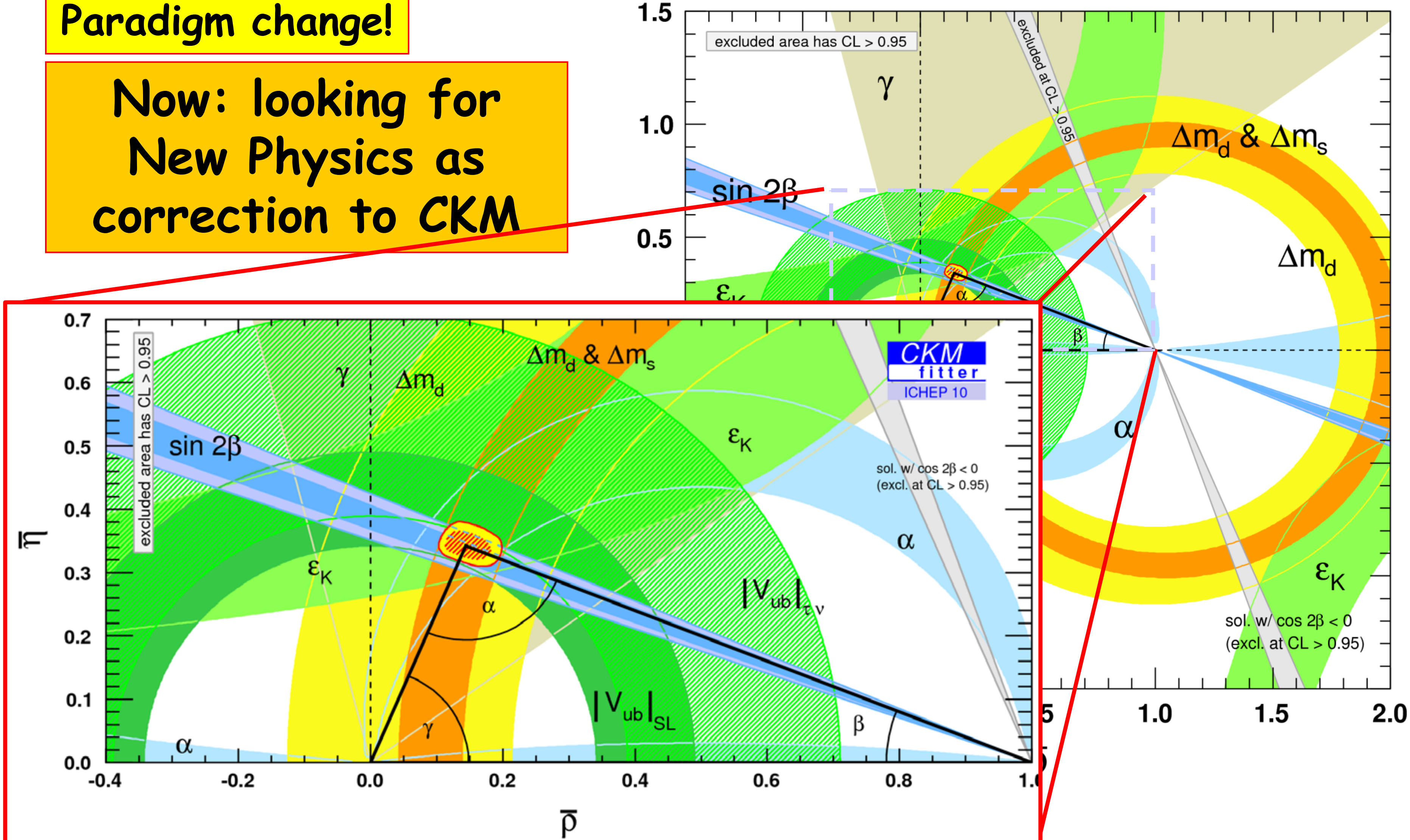
$\cos 2\beta$



Summary of UT triangle constraints

Paradigm change!

Now: looking for New Physics as correction to CKM

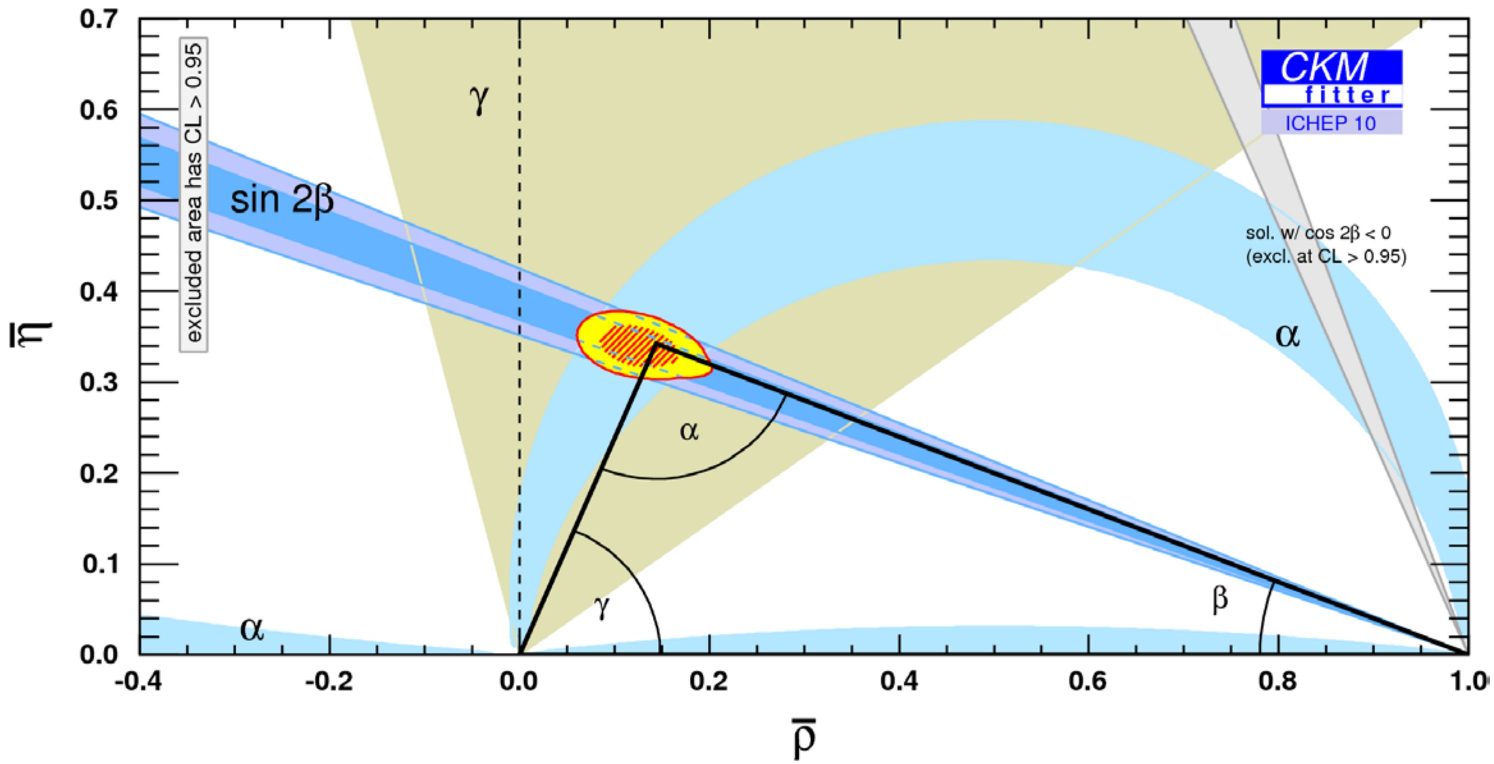


Continuing the hunt for new sources of CP violation

UT from CP violation measurements alone

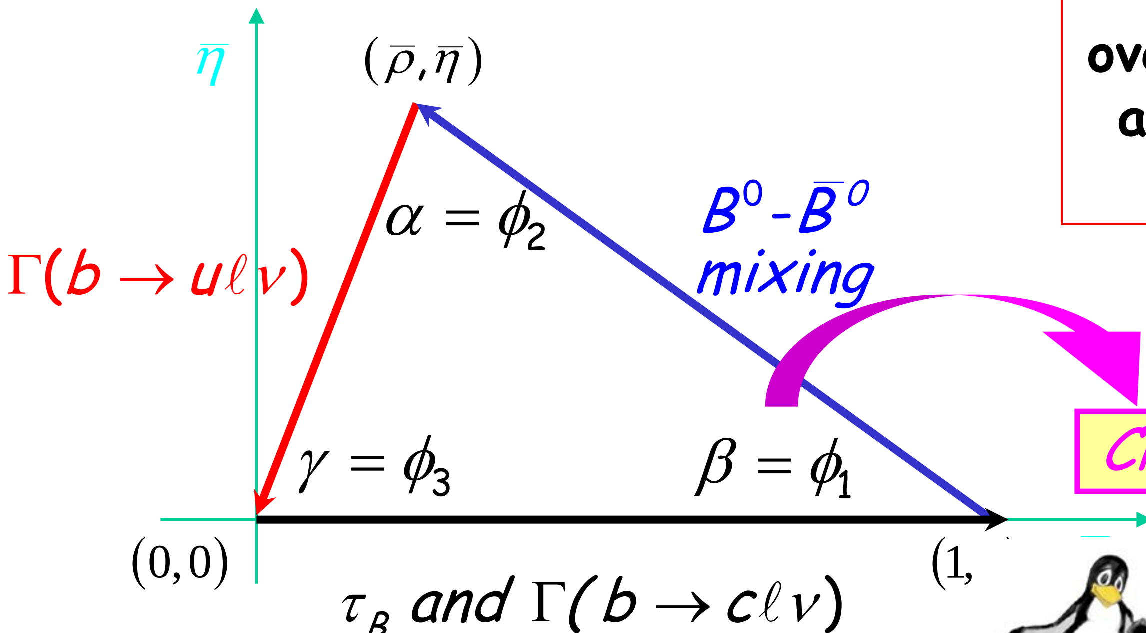
***B* Factory milestone: Comparable UT precision from *CPV* in *B* decays alone**

Overconstrained: subsets of measurements can be used to test for new physics

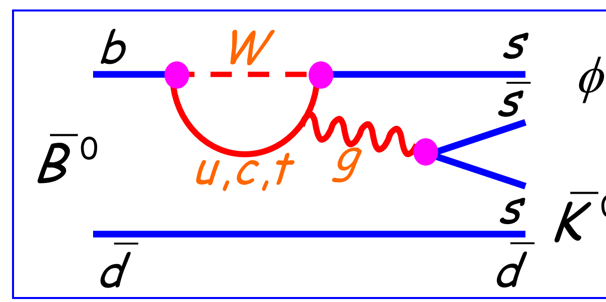


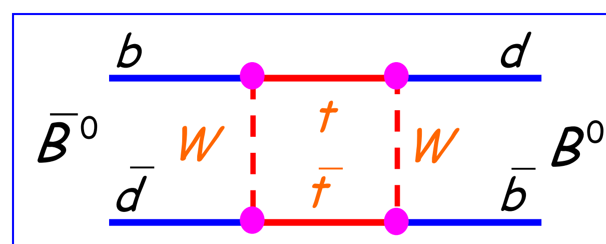
CPV in Penguin Modes

Another implication of overconstrained: redundant approaches to same CKM parameter



CPV in $B^0 \to \phi K_S^0, \eta' K_S^0, \ldots$

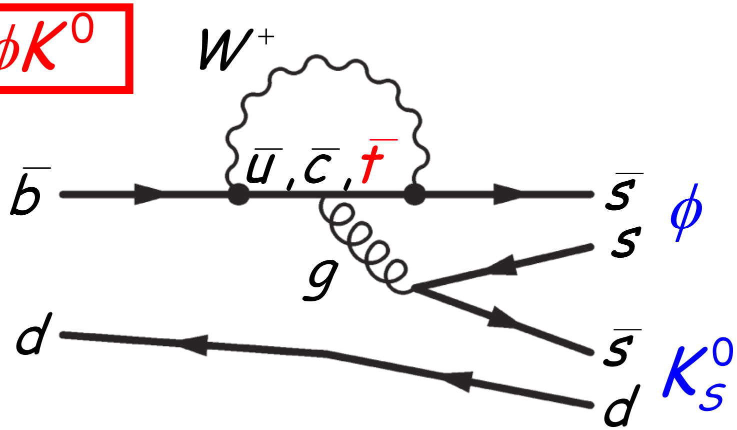




Interference of suppressed $b \to s$ Penguin decay with mixing

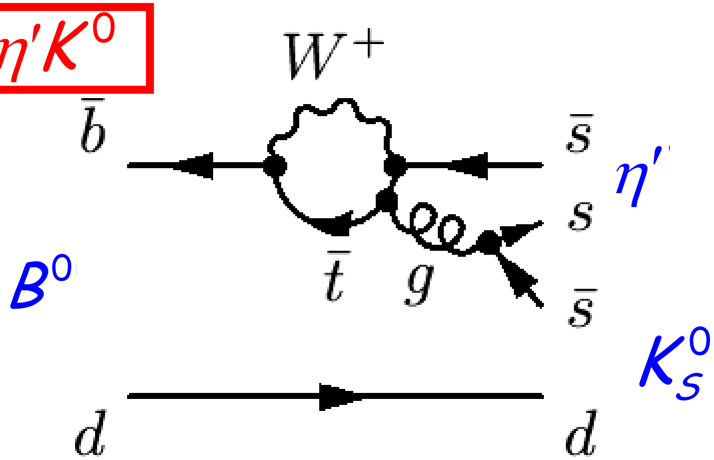
Potential New Physics contributions

$B^0 \to \phi K^0$

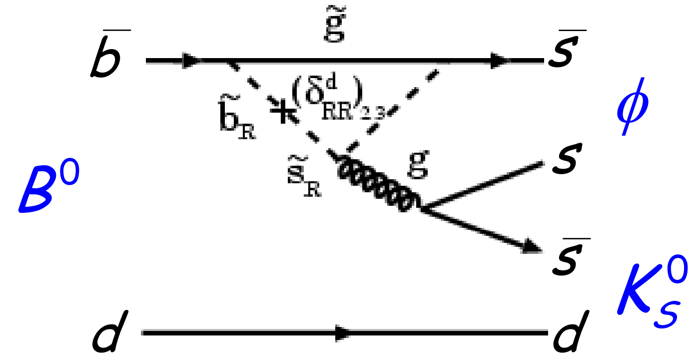


"Internal Penguin"

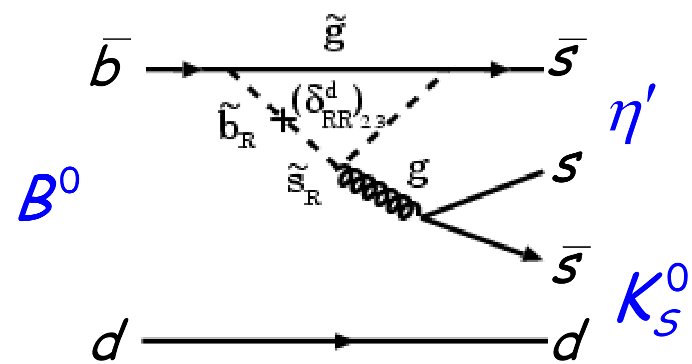
$B^0 \to \eta' K^0$



New physics in loops?



SUSY contribution with new phases



Is there New Physics in mixing?

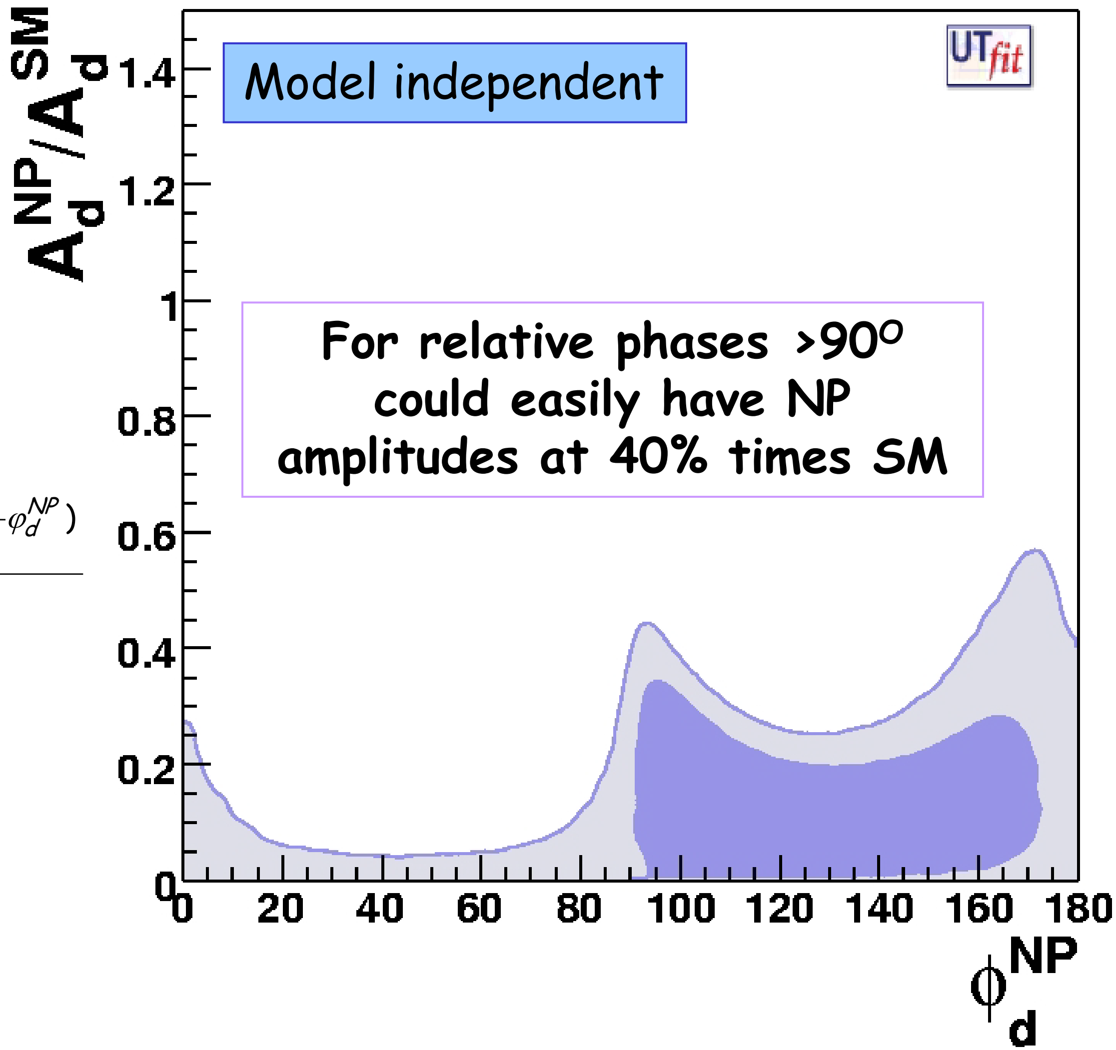
Introduce new physics in $b \to d$ mixing diagram

$$\left(\Delta M_{B_d}\right) = C_{B_d}\left(\Delta M_{B_d}\right)^{SM}$$

$$A_{CP}\left(J/\psi K_S^0\right) = \sin 2\left(\beta + \phi_{B_d}\right)$$

$$C_{B_d} e^{2i\varphi_{B_d}} = \frac{A_d^{SM} e^{2i\varphi_d^{SM}} + A_d^{NP} e^{2i(\varphi_d^{SM}+\varphi_d^{NP})}}{A_d^{SM} e^{2i\varphi_d^{SM}}}$$

Mass scale being probed for unit coupling:
Λ(now) ~ 5 TeV
Λ(2008) ~ 10 TeV

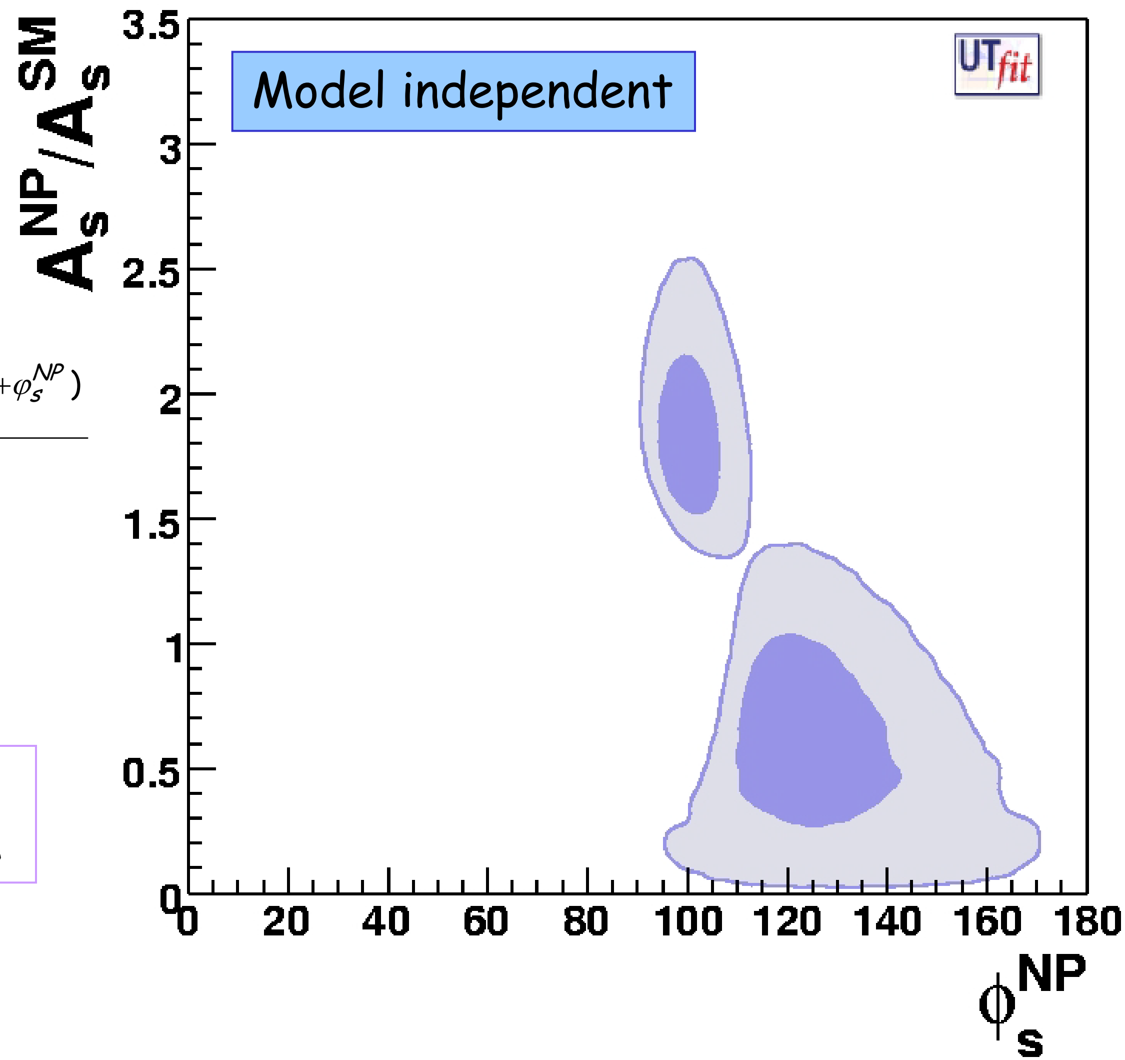


For relative phases >90° could easily have NP amplitudes at 40% times SM

Further bounds on New Physics

Introduce new physics in $b \to s$ mixing diagram

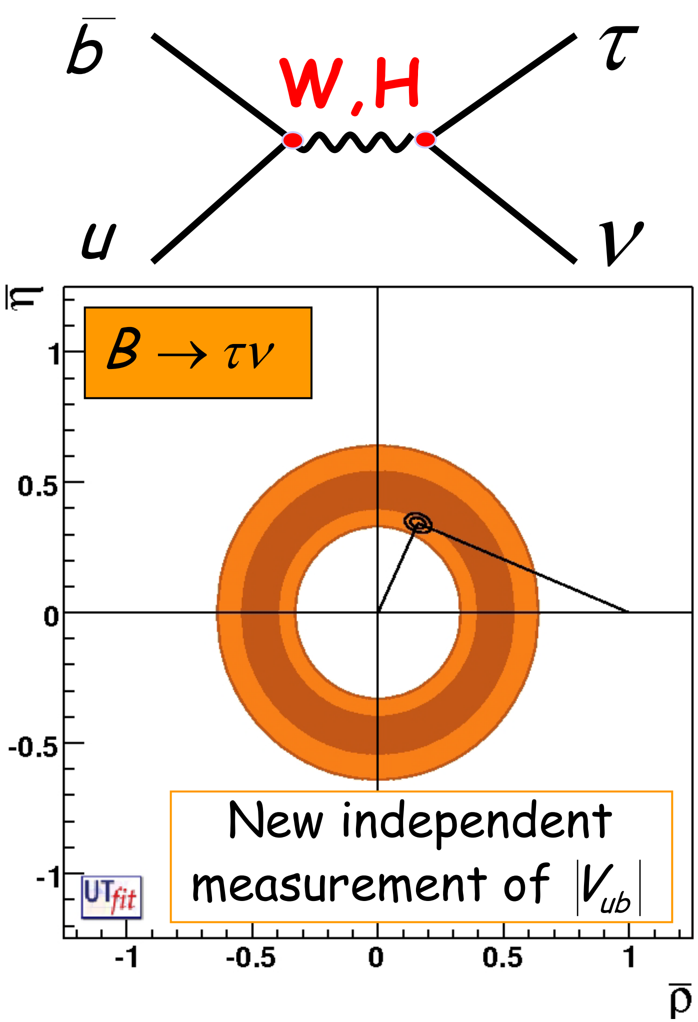
$$C_{B_s} e^{2i\varphi_{B_s}} = \frac{A_s^{SM} e^{2i\varphi_s^{SM}} + A_s^{NP} e^{2i(\varphi_s^{SM}+\varphi_s^{NP})}}{A_s^{SM} e^{2i\varphi_s^{SM}}}$$

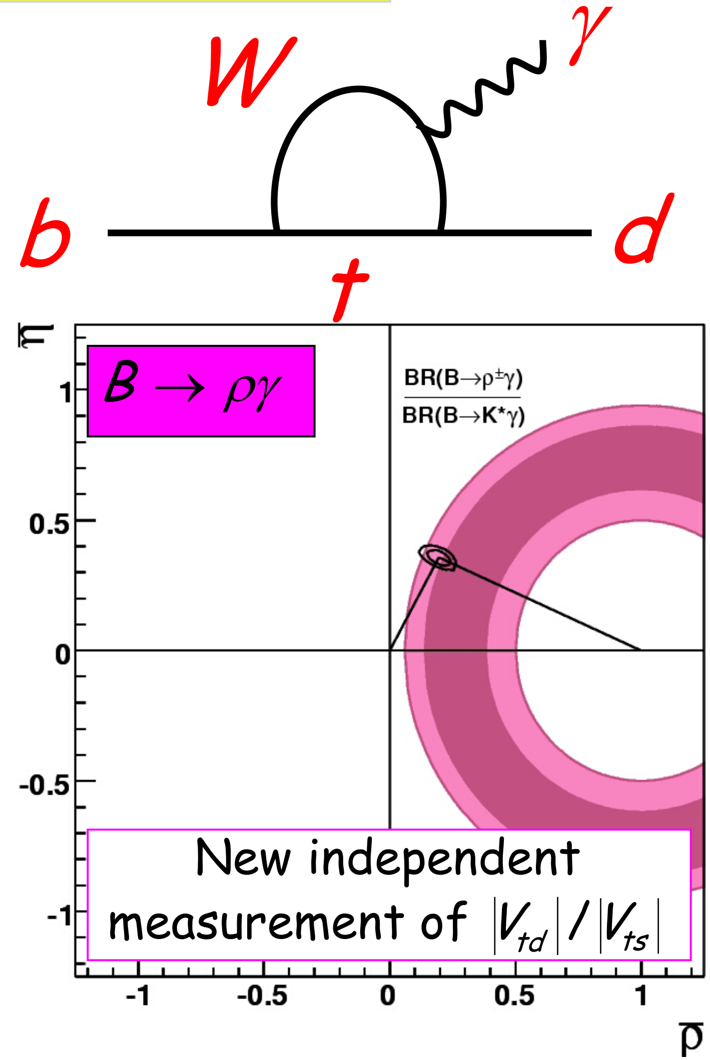


Could easily have NP amplitudes up to 3 times SM

Other windows on New Physics

Examples of rare decays with sensitivity to New Physics

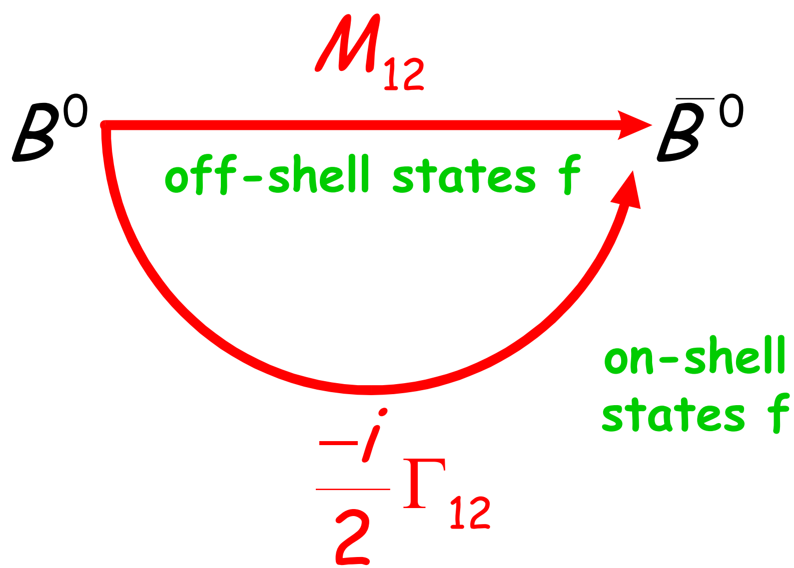




CP Violation in mixing diagram

- CPV through interference of decay amplitudes
- CPV through interference between mixing and decay amplitudes
- **CPV through interference of mixing diagram**

Expected to be very small



Resulting semileptonc charge asymmetry:

$$a_{Sl}^q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

where $\Delta M_q, \Delta\Gamma_q$ are mass & width differences for propagation matrices of neutral eigenstates

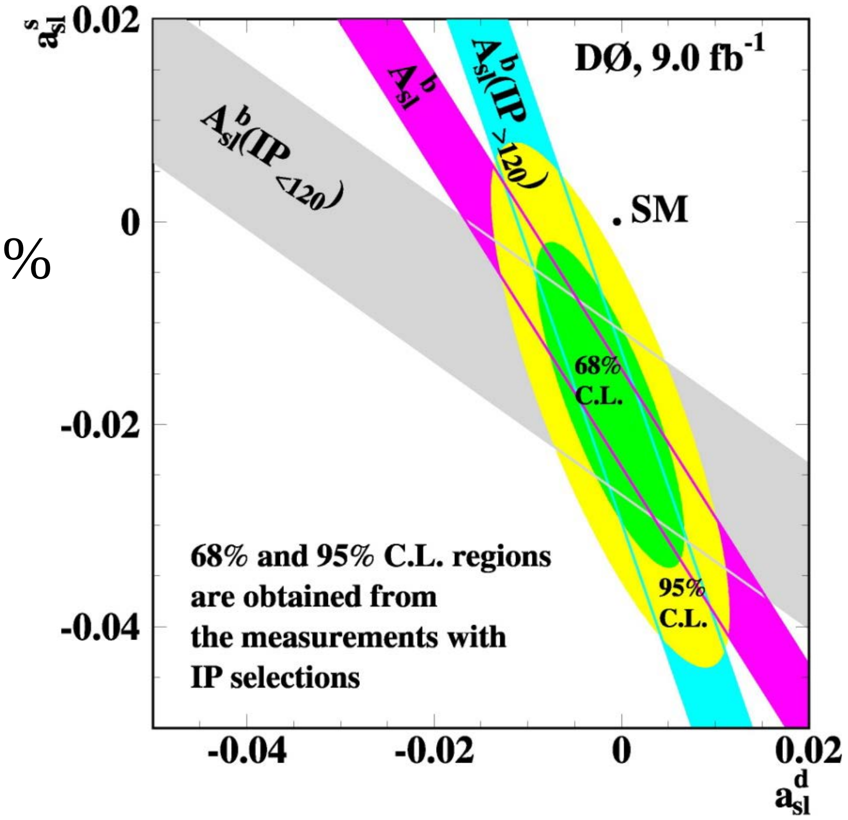
ϕ_q CP violating phase

Asymmetry measurement from D0

Measurable: Like-sign dimuon charge asymmetry:

$$A_{Sl}^{b} = \frac{N_{b\bar{b}}^{++} - N_{b\bar{b}}^{--}}{N_{b\bar{b}}^{++} + N_{b\bar{b}}^{--}} = C_d a_{Sl}^{d} + C_s a_{Sl}^{s}$$

Coefficients C_d, C_s depend on impact parameter



D0 observes:

$$A_{Sl}^{b} = (-0.787 \pm 0.172(stat) \pm 0.093(syst))\%$$

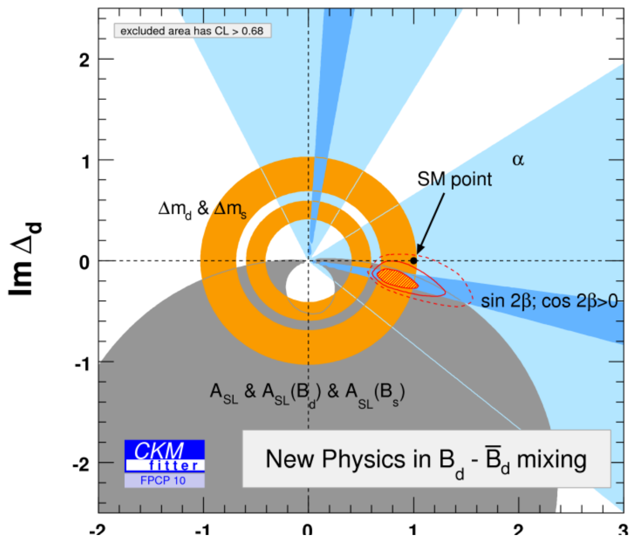
versus Standard Model expectation:

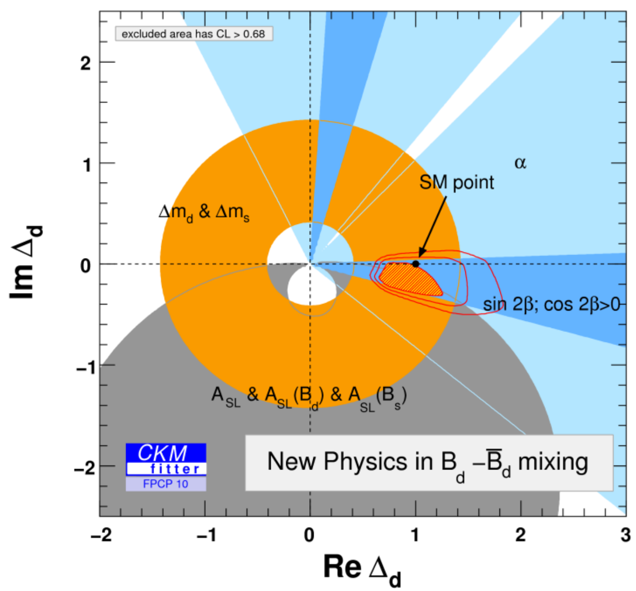
$$A_{Sl}^{b}(SM) = (-0.028^{+0.005}_{-0.006})\%$$

(3.9σ difference)

V.M.Abazov, et al. (D0 Collab), FERMILAB-PUB-11-307-E

Implications for new physics in mixing





2 rings ↔ 2 ρ-η-sols.
($a_{SL}(B_d)$ disf. 2nd sol.)

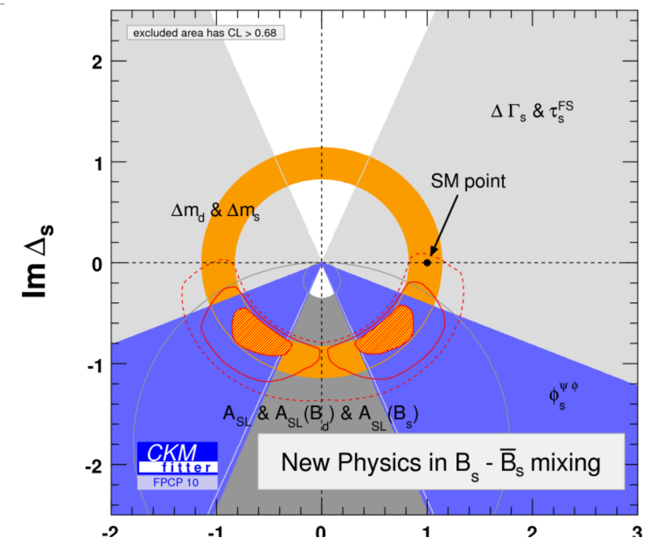
$\sigma(|\Delta_s|) < \sigma(|\Delta_d|)$:
*$\sigma(f_{Bs}^2 B_{Bs}) < \sigma(f_{Bd}^2 B_{Bd})$
*$|\Delta_d|$: ρ–η dependent
(→ $|V_{ub}|$ & γ(α))

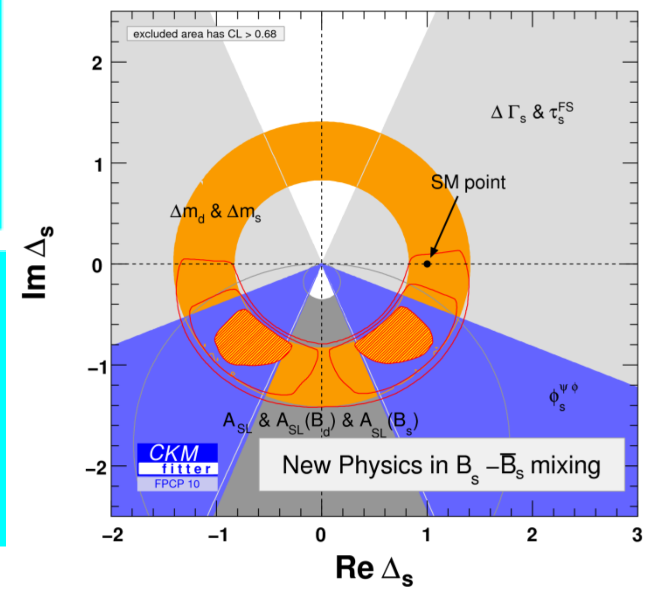
NP contributions can be as large as 40%

ϕ^{Δ}_s(3.3σ): A_{SL} & $B_s \to \psi\phi$ (Tevatron)
ϕ^{Δ}_d(2.8σ): sin2β – $B \to \tau\nu$ (B-factories)

$B \to \tau\nu$:
*$\sigma(|\Delta_d|)\downarrow$ by removing f_{Bd}
*$\sigma(|\Delta_s|)\downarrow$ thanks to ξ:

$$\frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}} f_{B_d}^2 B_{B_d} = \xi^2 f_{B_d}^2 B_{B_d}$$

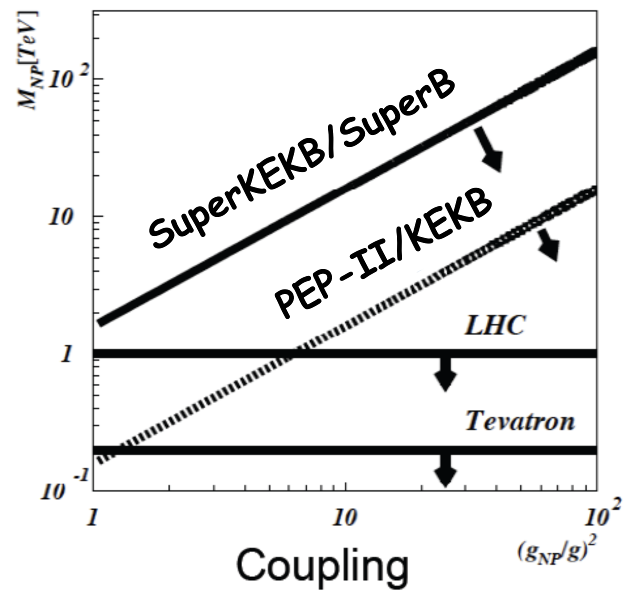




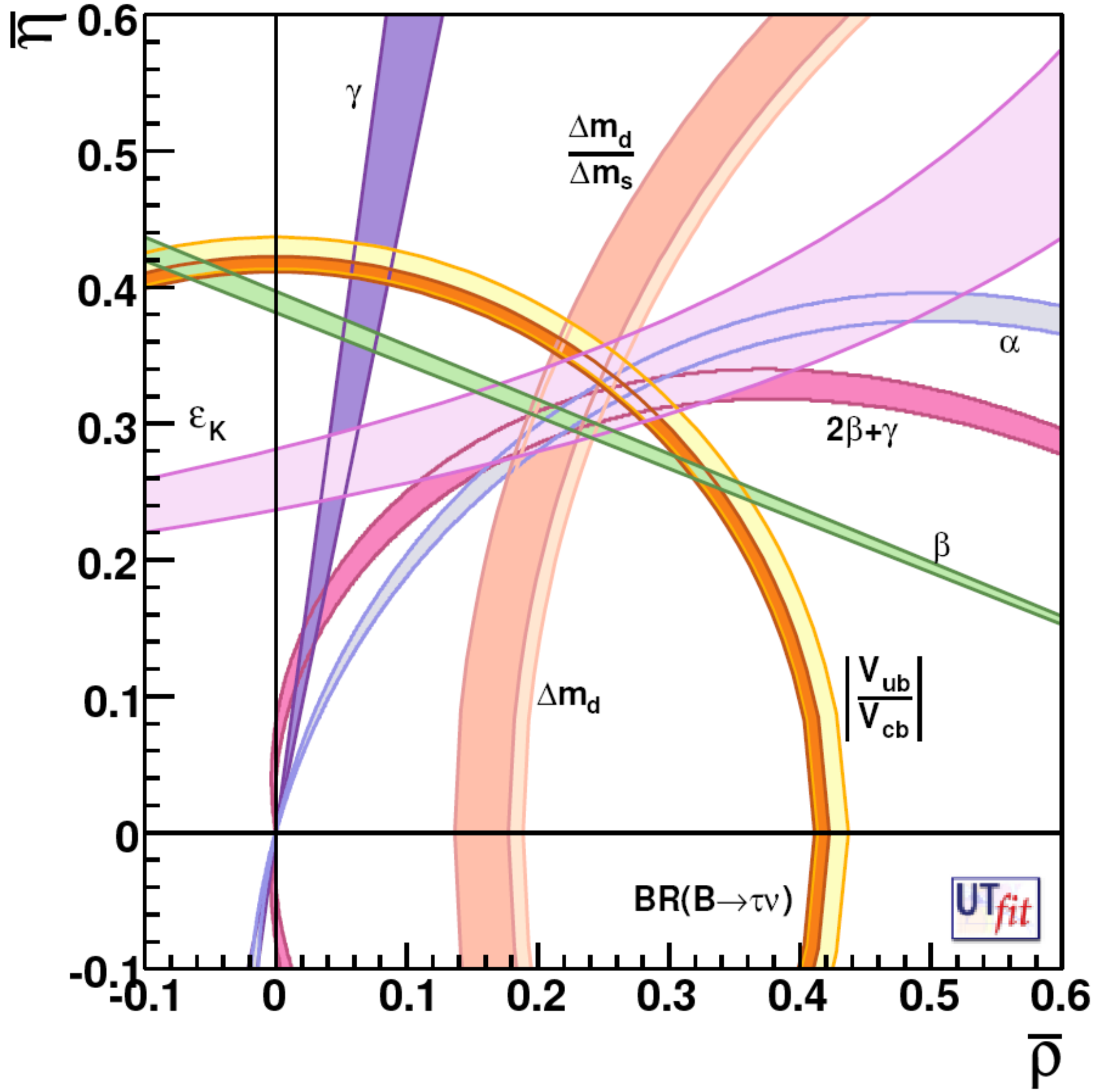
A new era with Super *B* Factories

Physics case for new Flavor Factories

- *Flavor physics sensitive to processes that are one-loop in SM but could be O(1) for NP*
  - FCNC, mixing, CPV
- *Current experimental bound is O(10-100 TeV) depending on NP coupling.*
  - If the LHC finds NP at O(1 TeV) it must have a non-trivial flavor structure
- *Even if no NP is discovered at the LHC, current SM couplings provide sensitivity to NP at high mass scales*



Physics opportunity with Super Flavor Factory

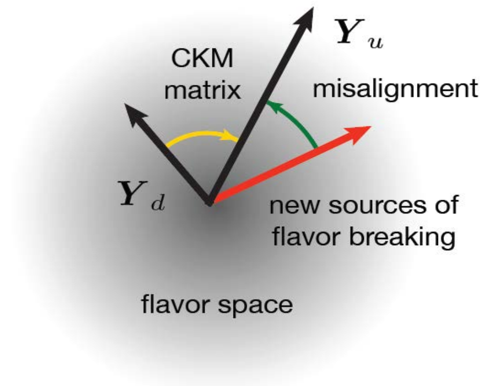


2020

×50-75 sample size

Revealing new physics effects in the flavor sector

- *CKM matrix measures the relative orientation of the u and d sector Yukawa couplings in the Standard Model*
- *In SUSY there are a new set of (model-dependent) Yukawa couplings describing the* ***squark*** *and* ***slepton*** *sectors*
- *Minimal Flavor Violation (MFV), for example, is the assumption that the old and new Yukawa couplings are aligned*



Mass insertion approximation allows us to set a model-independent scale for effects

$$\left(\delta_{ij}^{d}\right)_{AB} = \frac{\left(\Delta_{ij}^{d}\right)_{AB}}{\tilde{m}^2}$$

$$\begin{array}{cccccc} d_L & d_R & s_L & s_R & b_L & b_R \end{array}$$

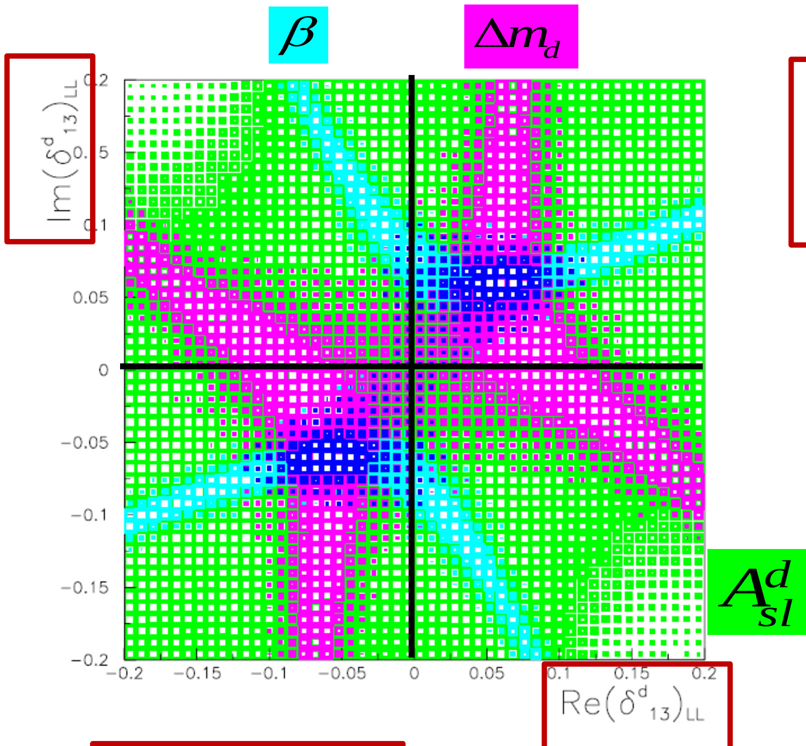
$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d - \mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s - \mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & [\tilde{m}^2_D]_{ij} & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b - \mu\tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

LHC

Flavor studies determine the off-diagonal (mixing) elements

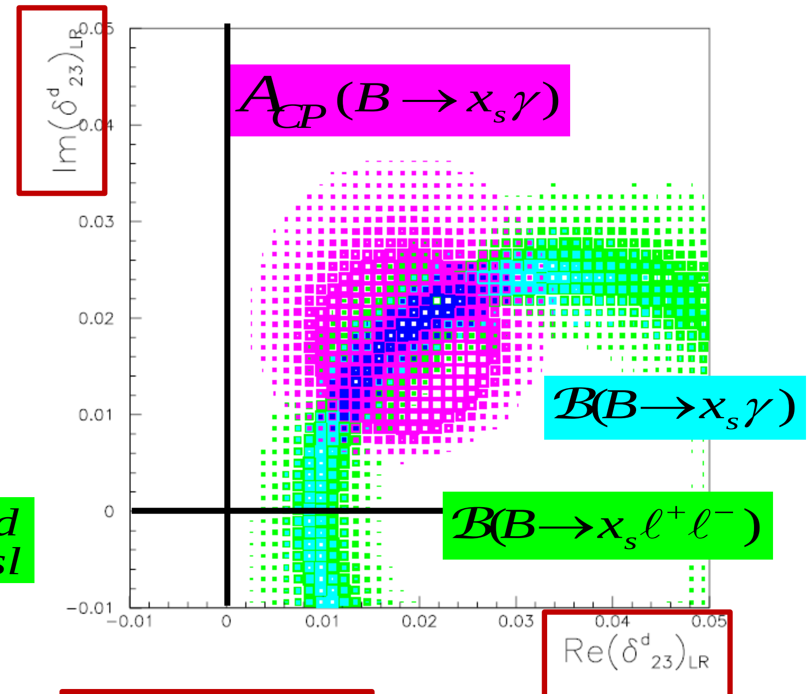
Super Flavor Factory with 75 ab^{-1}

1-3 transitions



$m_{\tilde{q}} = m_{\tilde{g}} = 1$ TeV, $(\delta^d_{13})_{LL} = 0.085 e^{i\pi/4}$

2-3 transitions



$m_{\tilde{q}} = m_{\tilde{g}} = 1$ TeV, $(\delta^d_{23})_{LR} = 0.028 e^{i\pi/4}$

Complementary to discovery opportunity with the LHC

Unraveling the nature of New Physics

- Need to combine measurements to elucidate structure of new physics

	Observable/mode	H^+ high $\tan\beta$	MFV	non-MFV	NP Z penguins	Right-handed currents	LTH	SUSY AC	SUSY RVV2	SUSY AKM	SUSY δLL	SUSY FBMSSM
✓	$\tau \to \mu\gamma$							★★★	★★★	★	★★★	★★★
✓	$\tau \to \ell\ell\ell$						★★★					
✓	$B \to \tau\nu, \mu\nu$	★★★(CKM)										
✓	$B \to K^{(*)+}\nu\overline{\nu}$			★	★★★			★	★	★	★	★
✓	S in $B \to K_S^0\pi^0\gamma$					★★★						
✓	S in other penguin modes			★★★(CKM)		★★★		★★★	★★	★	★★★	★★★
✓	$A_{CP}(B \to X_s\gamma)$			★★★		★★		★	★	★	★★★	★★★
✓	$BR(B \to X_s\gamma)$		★★★	★		★						
✓	$BR(B \to X_s\ell\ell)$			★	★	★						
✓	$B \to K^{(*)}\ell\ell$ (FB Asym)							★	★	★	★★★	★★★
	$B_s \to \mu\mu$							★★★	★★★	★★★	★★★	★★★
	β_s from $B_s \to J/\psi\phi$							★★★	★★★	★★★	★	★
✓	a_{sl}						★★★					
✓	Charm mixing							★★★	★	★	★	★
✓	CPV in Charm	★★									★★★	

✓ = SuperB can measure these modes

More information on the golden matrix can be found in arXiv:1008.1541, arXiv:0909.1333, and arXiv:0810.1312.

Next generation Super Factories

Strong physics case for a 10^{36} facility (x50): improve sensitivity by more than order of magnitude

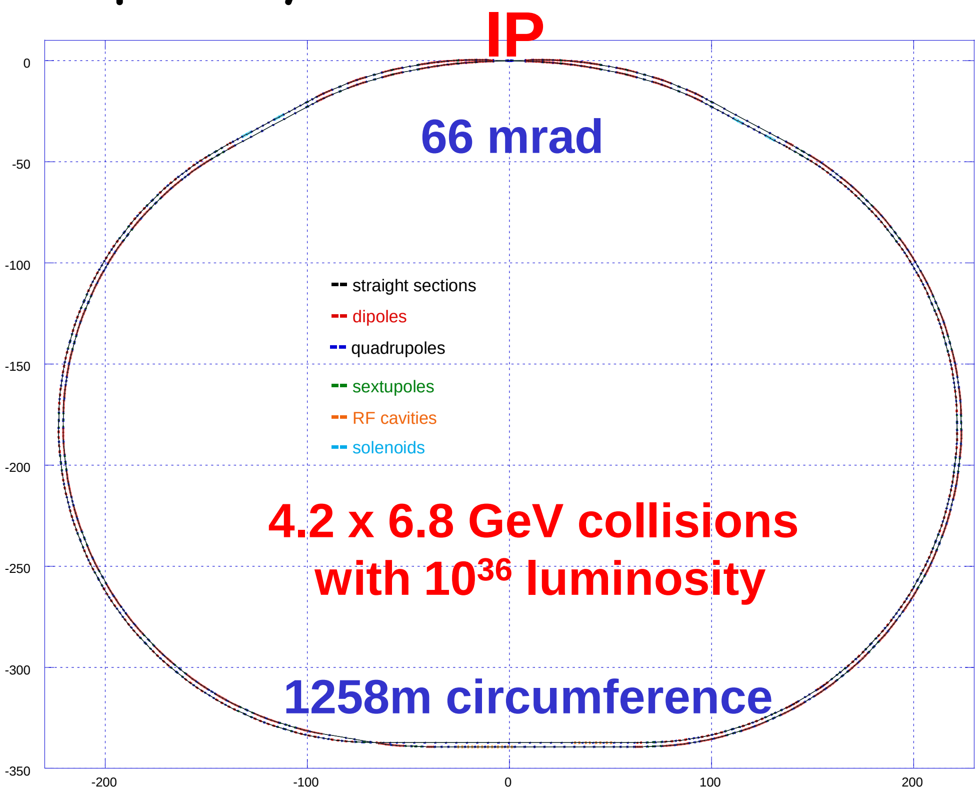
New ideas:

- Ultra low-emittance, similar to ILC damping rings
- Scaled version ILC final focus
- Large crossing angle and crabbed waist

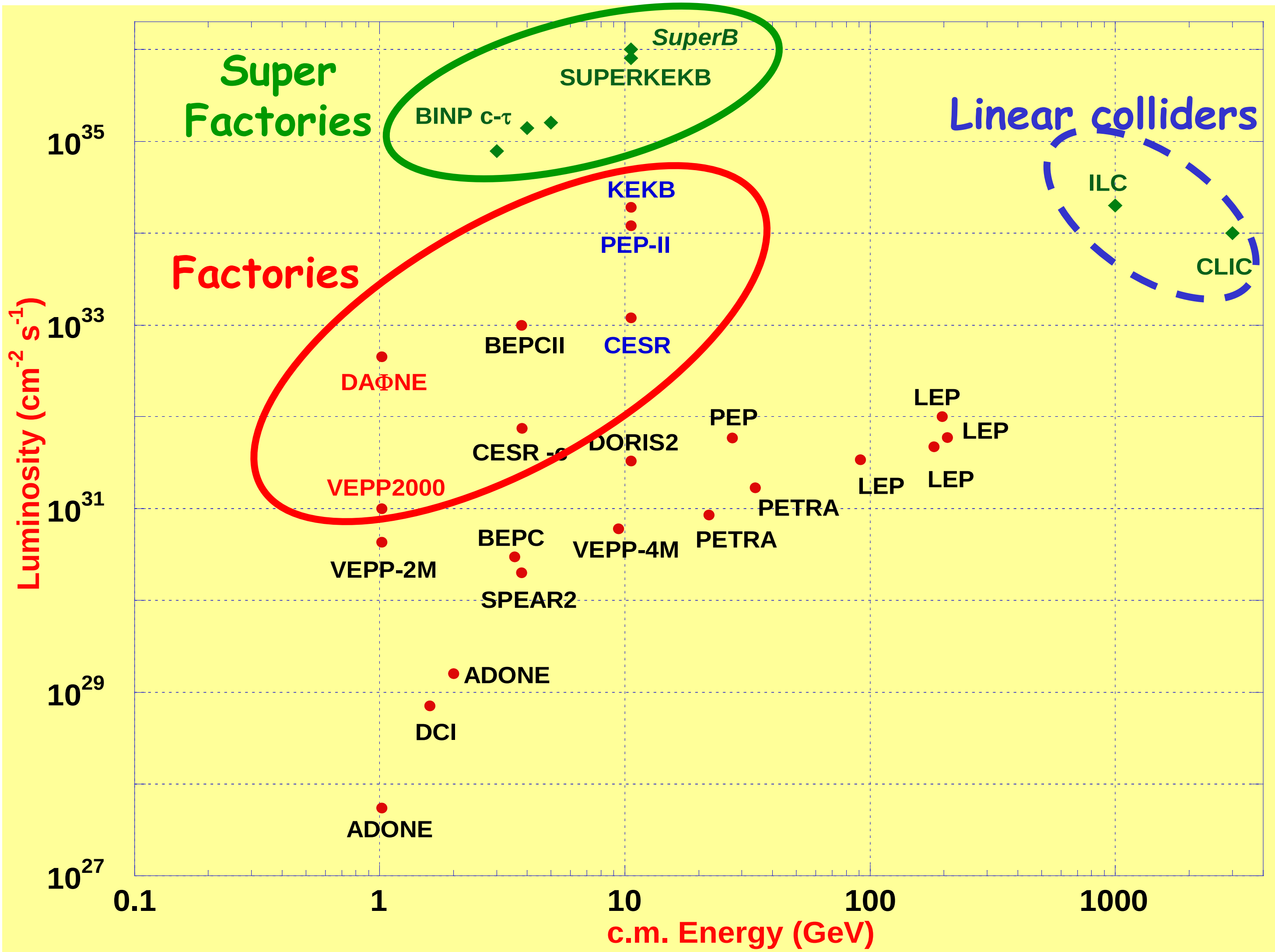
Features:

- Machine has significant technical overlap with ILC
- Possible to reach 10^{36} luminosity with beam currents comparable to present *B* Factories allowing (re-)use of existing detectors and machine components

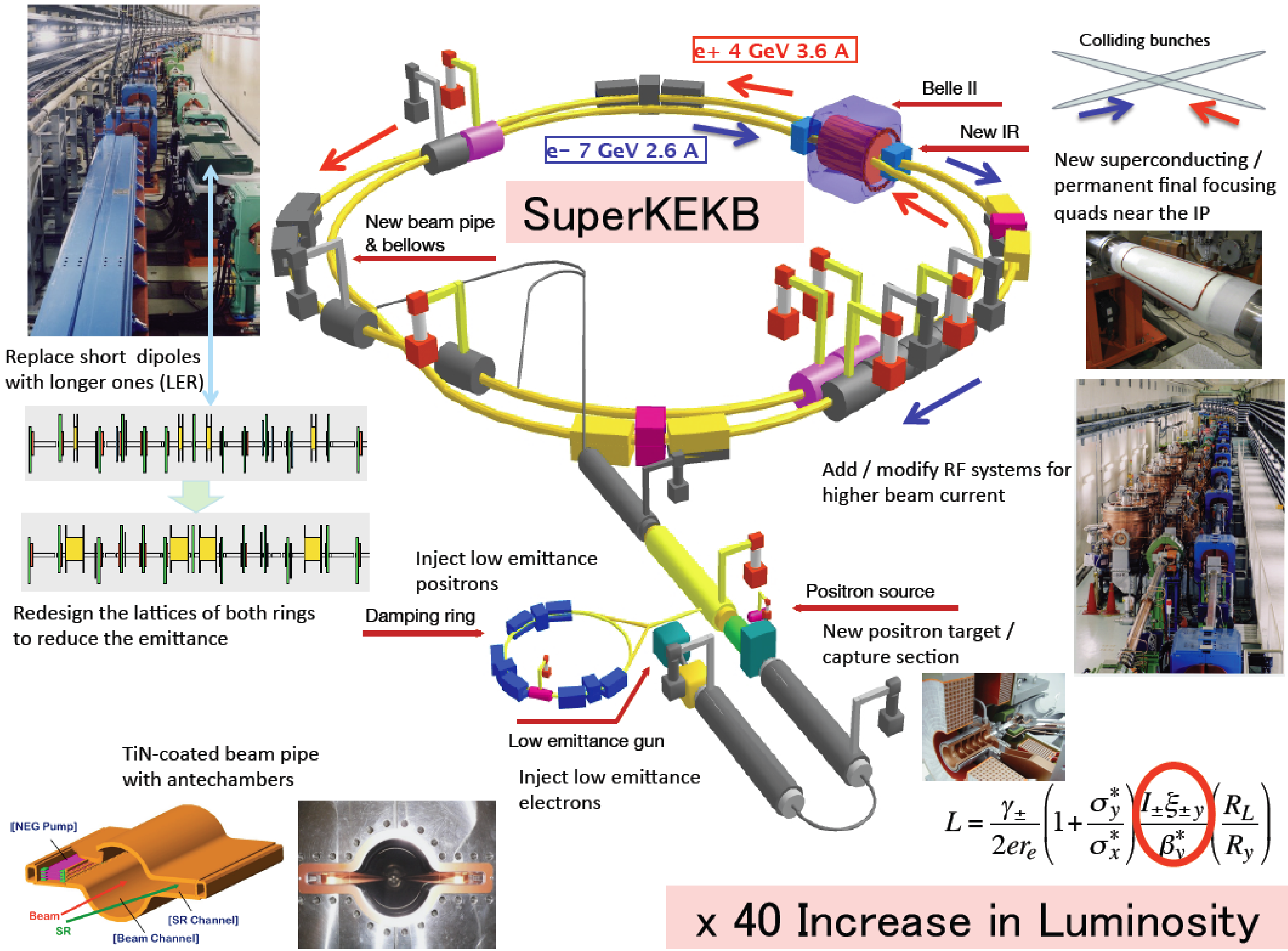
SuperB layout



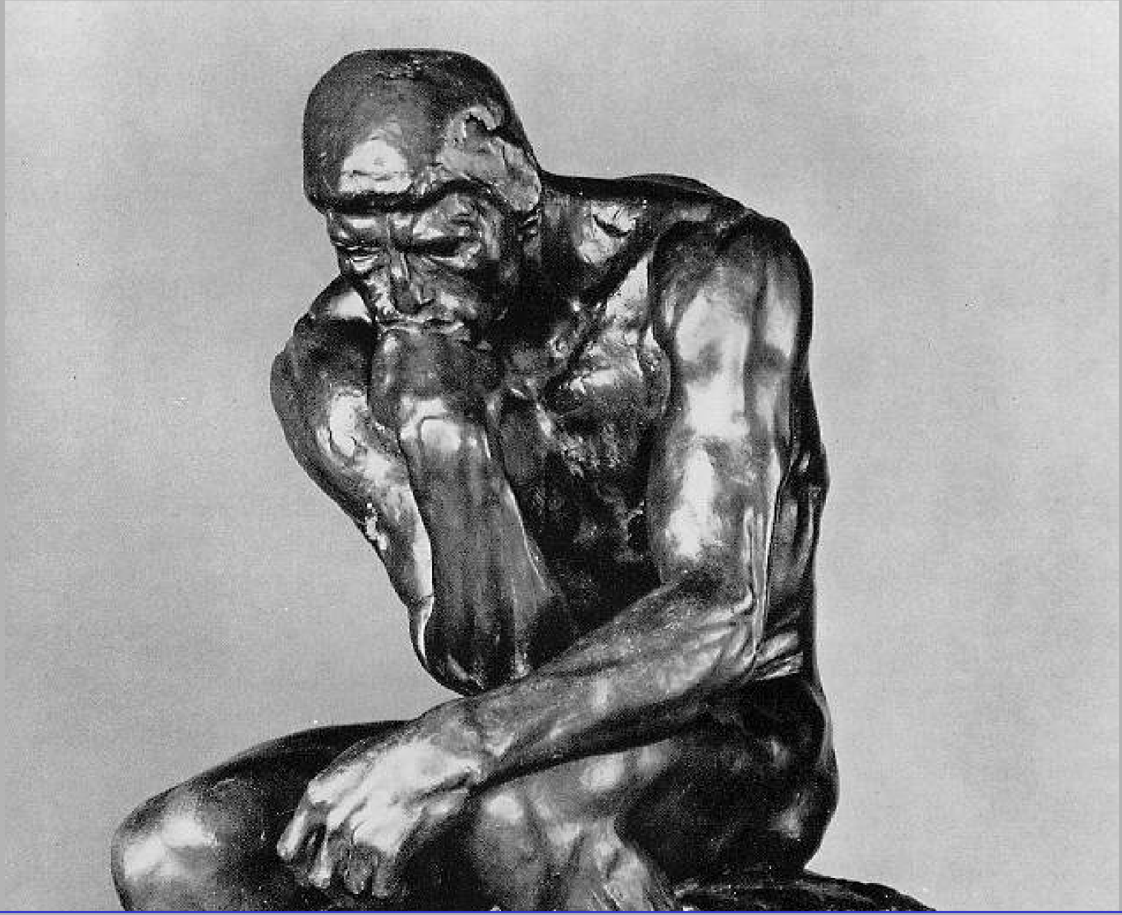
History of e^+e^- collider luminosity



SuperB at Tor Vergata, Italy


SuperKEKB
e+ 4 GeV 3.6 A
e− 7 GeV 2.6 A
Colliding bunches
Belle II
New IR
New superconducting / permanent final focusing quads near the IP
New beam pipe & bellows
Replace short dipoles with longer ones (LER)
Add / modify RF systems for higher beam current
Redesign the lattices of both rings to reduce the emittance
Inject low emittance positrons
Damping ring
Positron source
New positron target / capture section
Low emittance gun
Inject low emittance electrons
TiN-coated beam pipe with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$
x 40 Increase in Luminosity

SuperKEKB luminosity upgrade projection



Origin of matter-antimatter asymmetry remains a fundamental mystery: New round of Super B Factories is essential for exploring this frontier