Lecture 3

Classification of CP-violating effects

CPV in decay:

$\left|\overline{A}_{\bar{f}}/A_f\right| \neq 1$

$$\mathrm{A}_{CP,f^{\pm}} \equiv \frac{\Gamma\left(P^- \to f^-\right) - \Gamma\left(P^+ \to f^+\right)}{\Gamma\left(P^- \to f^-\right) + \Gamma\left(P^+ \to f^+\right)} = \frac{\left|\overline{A}_{f^-}/A_{f^+}\right|^2 - 1}{\left|\overline{A}_{f^-}/A_{f^+}\right|^2 + 1}$$

CPV in mixing:

$|q/p| \neq 1$

$$\mathrm{A}_{SL}(t) \equiv \frac{d\Gamma/dt\left(\overline{P}^0_{phys} \to l^+ X\right) - d\Gamma/dt\left(P^0_{phys} \to l^- X\right)}{d\Gamma/dt\left(\overline{P}^0_{phys} \to l^+ X\right) + d\Gamma/dt\left(P^0_{phys} \to l^- X\right)} =$$

$$= \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

CPV in the interference decay-mixing:

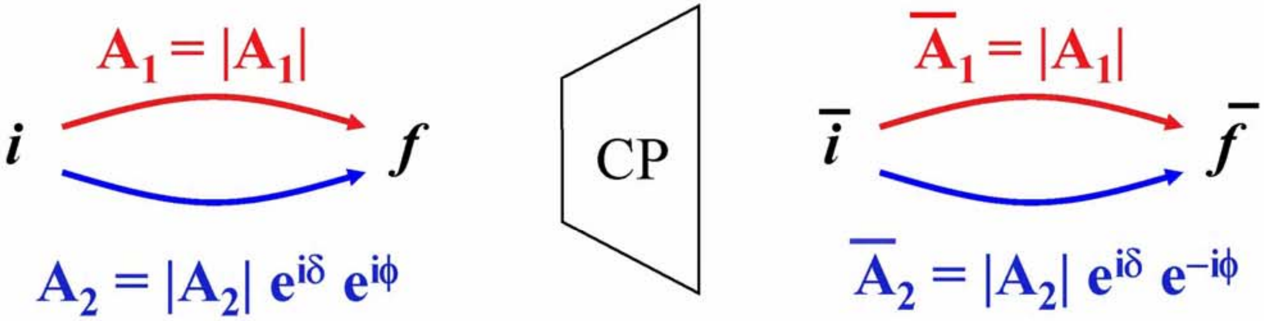
$\Im\mathrm{m}\left(\lambda_f\right) \neq 0$

$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$

For example: decays to CP eigenstates f_{CP}

$$\mathrm{A}_{f_{CP}}(t) \equiv \frac{d\Gamma/dt\left(\overline{P}^0_{phys} \to f_{CP}\right) - d\Gamma/dt\left(P^0_{phys} \to f_{CP}\right)}{d\Gamma/dt\left(\overline{P}^0_{phys} \to f_{CP}\right) + d\Gamma/dt\left(P^0_{phys} \to f_{CP}\right)}$$

Observables: “direct” CP asymmetry - 1



$A_1 = |A_1|$

$A_2 = |A_2|\, e^{i\delta}\, e^{i\phi}$

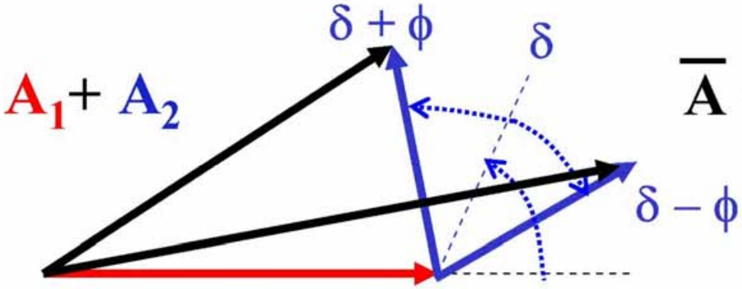
$\bar{A}_1 = |A_1|$

$\bar{A}_2 = |A_2|\, e^{i\delta}\, e^{-i\phi}$

$\delta \to \delta$ (CP-conserving)
$\phi \to -\phi$ (CP-violating)

Time-integrated “direct” CP asymmetry requires two amplitudes and $\delta \neq 0$:

$A = A_1 + A_2$



$\bar{A} = \bar{A}_1 + \bar{A}_2 \neq A$

Observables: “direct” CP asymmetry - 2

Time-integrated “direct” CP asymmetry (“CP violation in decay”):

$$A_{CP} \equiv \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} = \frac{2|A_1||A_2|\sin\delta\sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos\delta\cos\phi}$$

- the only possibile CPV effect for *charged* mesons decays !
- requires at least two amplitudes *and* $\delta \neq 0$

Time evolution of neutral *B* mesons - 3

(assuming CPT as a good symmetry, for simplicity)…

Time-dependent decay rate for $B^0_{phys} \to f$:

$$\frac{d\Gamma\left(B^0_{phys}(t) \to f\right)}{dt} = \left|\left\langle f \left| H \right| B^0_{phys}(t)\right\rangle\right|^2 =$$

$$= \frac{e^{-\Gamma t}}{2}\left[\begin{array}{l} \left(1+\cos(\Delta m\, t)\right)\left|A_f\right|^2 + \\ +\left(1-\cos(\Delta m\, t)\right)\left|\frac{q}{p}\right|^2\left|\overline{A}_f\right|^2 - \\ -2\Im\mathrm{m}\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(\Delta m\, t) \end{array}\right] = \frac{e^{-\Gamma t}}{2}\left|A_f\right|^2\left[\begin{array}{l} \left(1+\cos(\Delta m\, t)\right) + \\ +\left(1-\cos(\Delta m\, t)\right)\left|\lambda_f\right|^2 - \\ -2\Im\mathrm{m}(\lambda_f)\sin(\Delta m\, t) \end{array}\right]$$

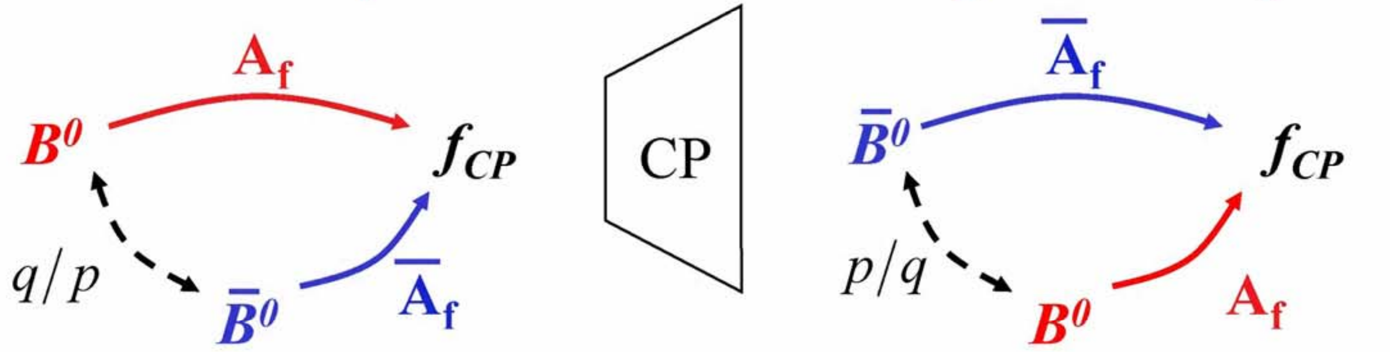
"decay"

"oscillation, then decay"

"interference"

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

Time-dependent CP asymmetry - 1



Interference between mixing and decay to a CP eigenstate f_{CP}

$$\Rightarrow \quad \Gamma\left(B^0_{phys}(t) \to f_{CP}\right) \neq \Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right)$$

Flavor-tagged time-dependent decay rates are different!
they are governed by the "CP parameter":

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

CP eigenvalue

$\approx e^{-i2\beta}$ from mixing

Amplitude ratio

Time-dependent CP asymmetry - 2

Decay distributions $f_+(f_-)$ when tag = $B^0(\bar{B}^0)$, pair-produced at $\Upsilon(4S)$

$$f_{CP,\pm}(\Delta t) = \frac{\Gamma}{4} e^{-\Gamma \Delta t}[1 \pm S_{f_{CP}} \sin \Delta m_d \Delta t \mp C_{f_{CP}} \cos \Delta m_d \Delta t]$$

Asymmetry

$$A_{f_{CP}}(\Delta t) = C_{f_{CP}} \cos(\Delta m_d \Delta t) - S_{f_{CP}} \sin(\Delta m_d \Delta t)$$

CP parameter

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

$$\boxed{\begin{aligned} C_{f_{CP}} &= \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \\ S_{f_{CP}} &= \frac{-2 \mathrm{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \end{aligned}}$$

For single decay amplitude

$$= 0$$

$$= -\mathrm{Im} \lambda_{f_{CP}}$$

CPV in the B sector: CKM angles

$V_{td} = |V_{td}|e^{-i\phi_1}$ (B^0-$\bar{B}^0$ mixing) $V_{td} = |V_{td}|e^{-i\beta}$

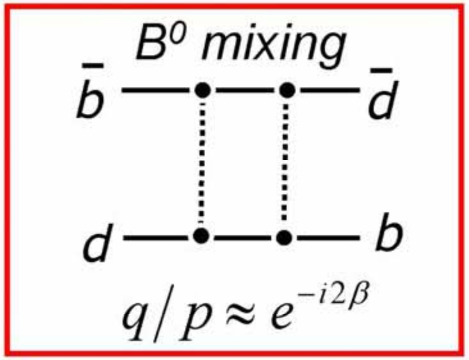
- Mixing-assisted CPV
  - Observation in $B^0 \to J/\psi K^0$ BaBar & Belle (2001)
- CPV in B^0-$\bar{B}^0$ mixing itself
  - Not seen yet

$V_{ub} = |V_{ub}|e^{-i\phi_3}$ ($b \to u$ decays) $V_{ub} = |V_{ub}|e^{-i\gamma}$

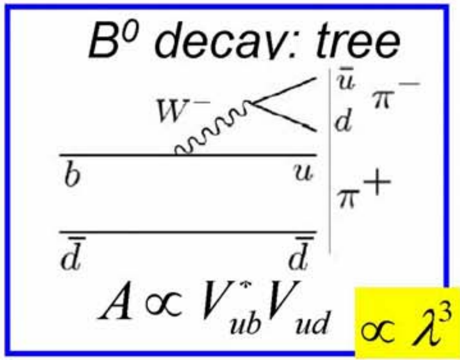
- Direct CPV (Interference with other diagrams)
  - Evidence in $B^0 \to \pi^+\pi^-$ Belle (2003), not seen by BaBar
  - Evidence in $B^0 \to K^+\pi^-$ BaBar & Belle (2004)

Both V_{td} and V_{ub} are involved

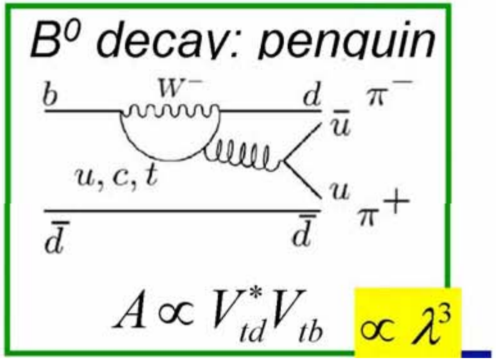
- Mixing-assisted CPV for final states containing V_{ub}
  - Evidence in $B^0 \to \pi^+\pi^-$ Belle (2003), not seen by BaBar


B^0 mixing

$q/p \approx e^{-i2\beta}$


B^0 decay: tree

$A \propto V_{ub}^* V_{ud}$ $\propto \lambda^3$


B^0 decay: penguin

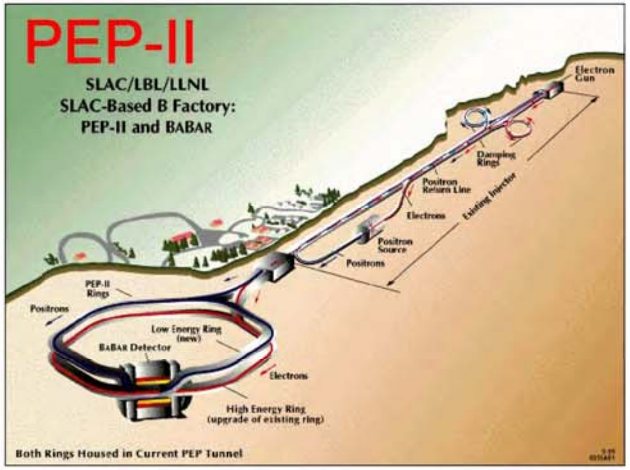
$A \propto V_{td}^* V_{tb}$ $\propto \lambda^3$

Experimental facilities

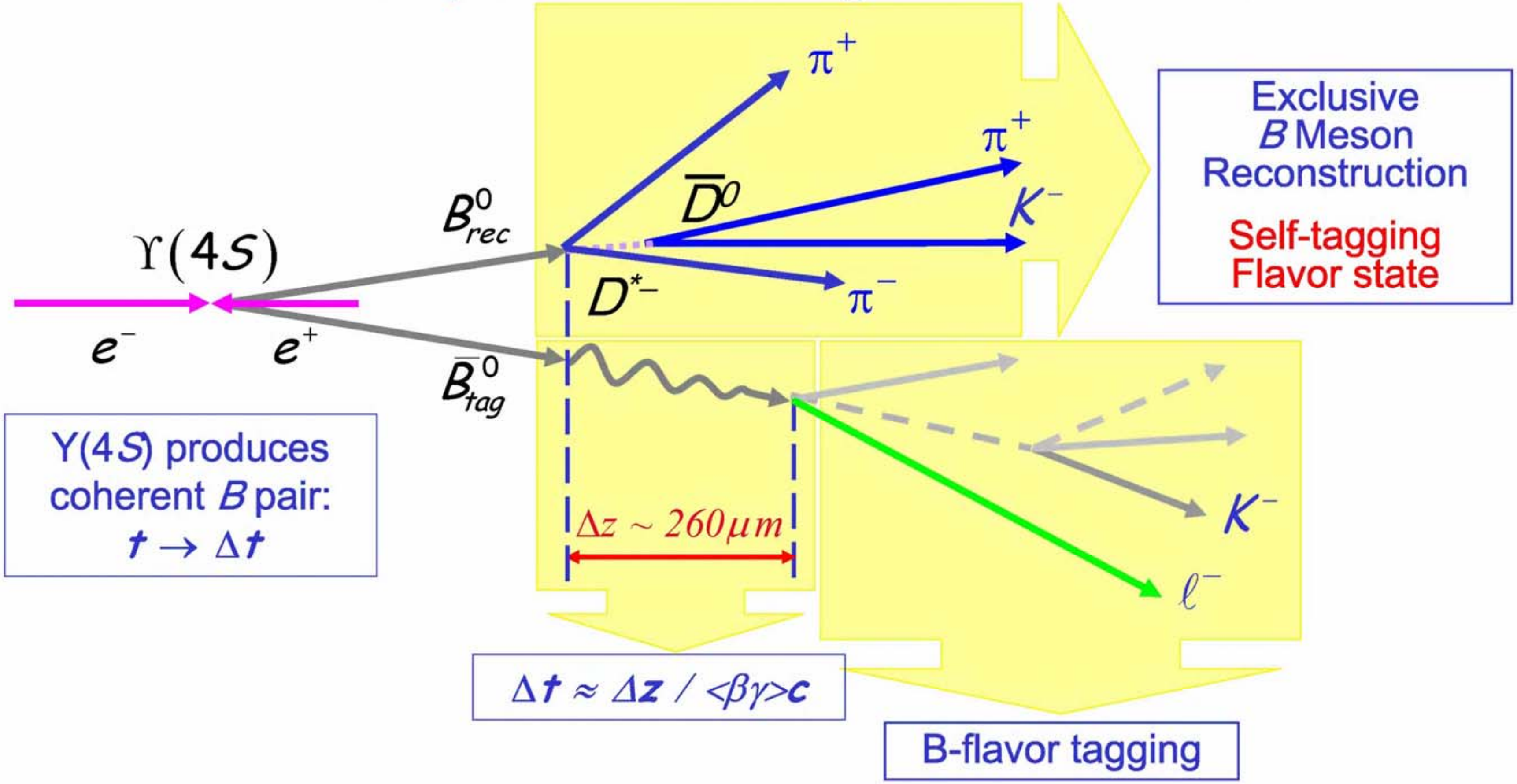
Past: DORIS, CESR, LEP

Present: Tevatron, KEK-B, PEP-II

Future: LHC, Super B-Factory



Time-Dependent Mixing Measurement



Exclusive *B* Meson Reconstruction

Self-tagging Flavor state

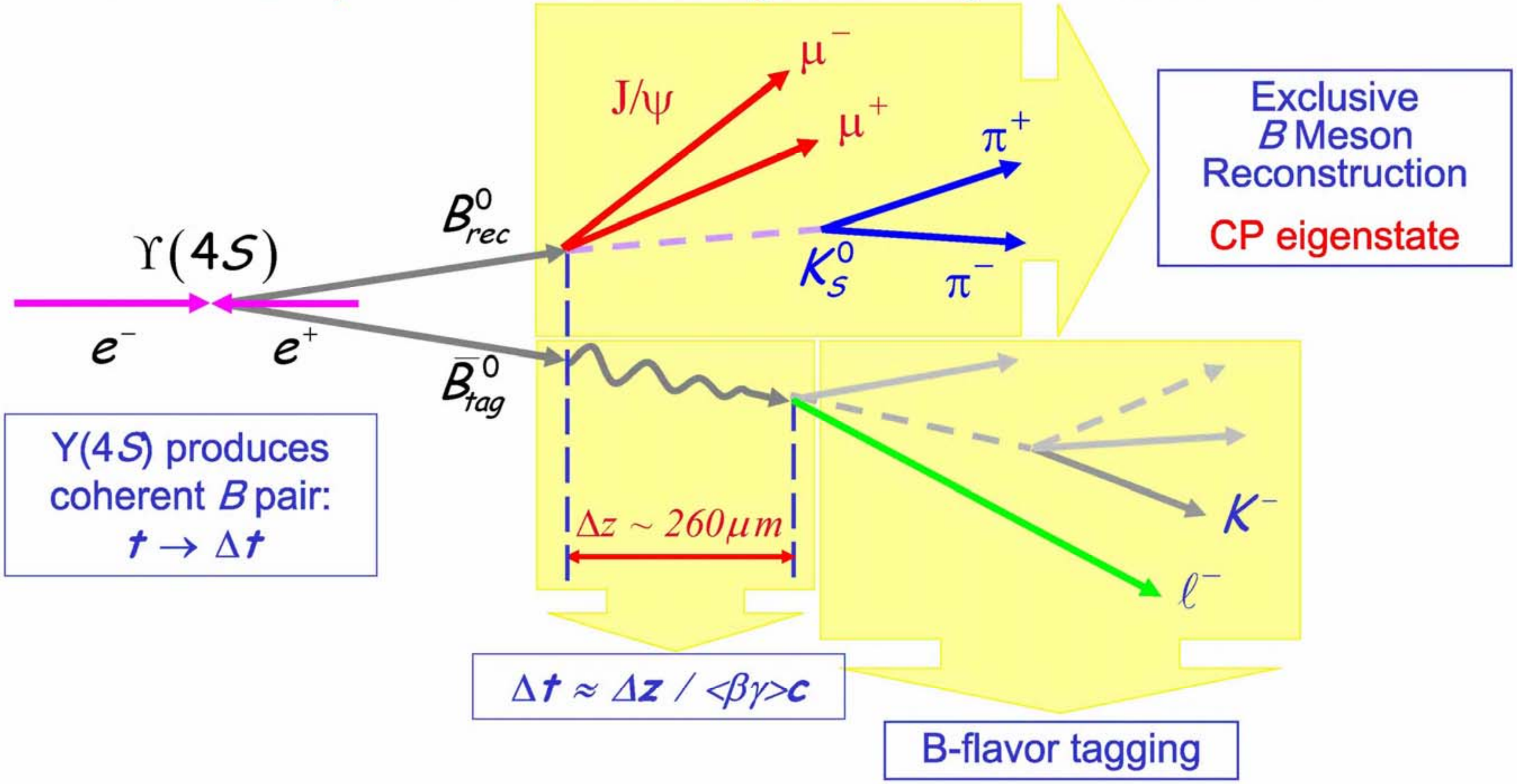
Y(4*S*) produces coherent *B* pair: $t \rightarrow \Delta t$

$\Delta t \approx \Delta z \, / <\beta\gamma> c$

B-flavor tagging

B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging flavor states)

Time-Dependent CP Asymmetry Measurement



Exclusive
B Meson
Reconstruction

CP eigenstate

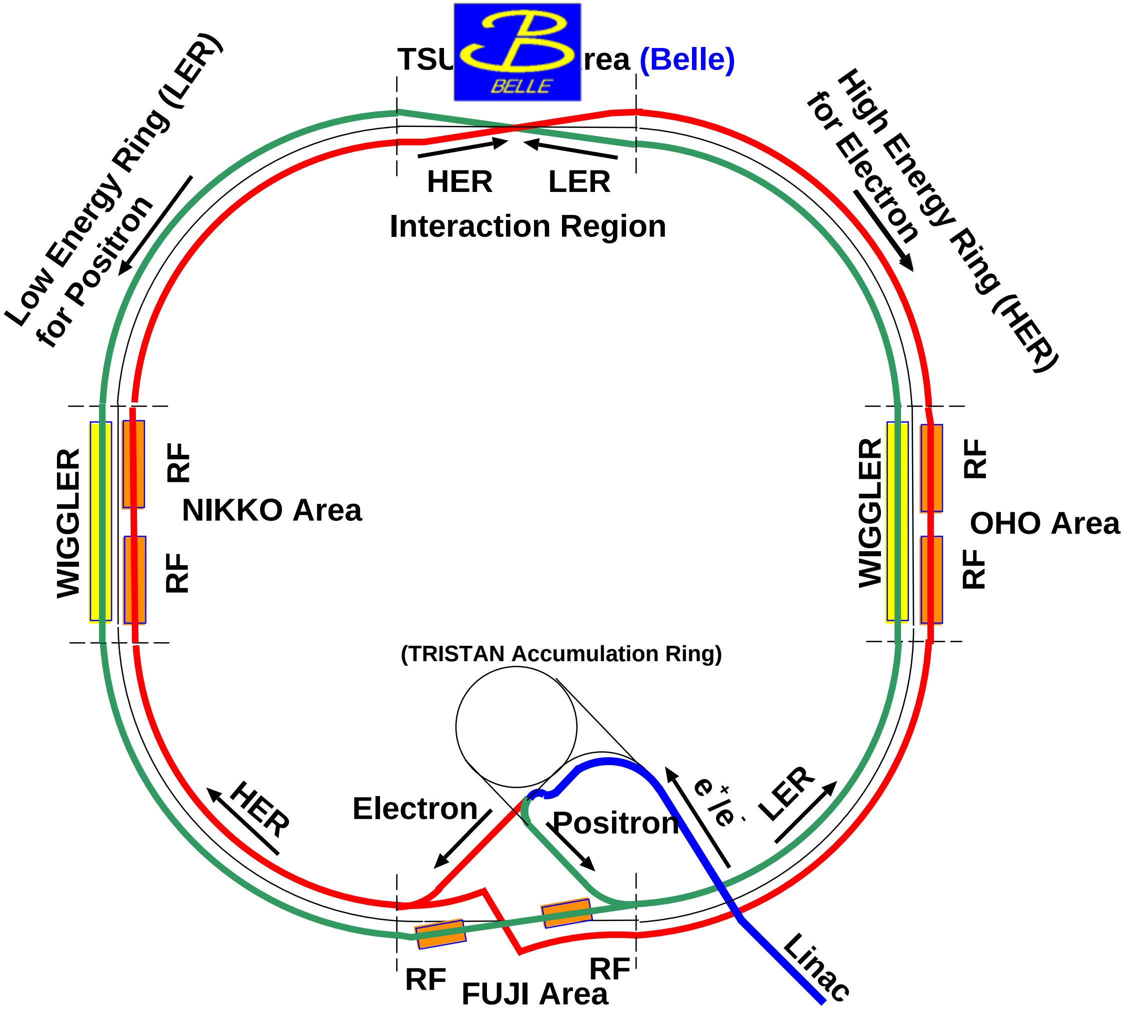
Y(4*S*) produces
coherent *B* pair:
$t \rightarrow \Delta t$

$\Delta t \approx \Delta z \,/\, <\beta\gamma>c$

B-flavor tagging

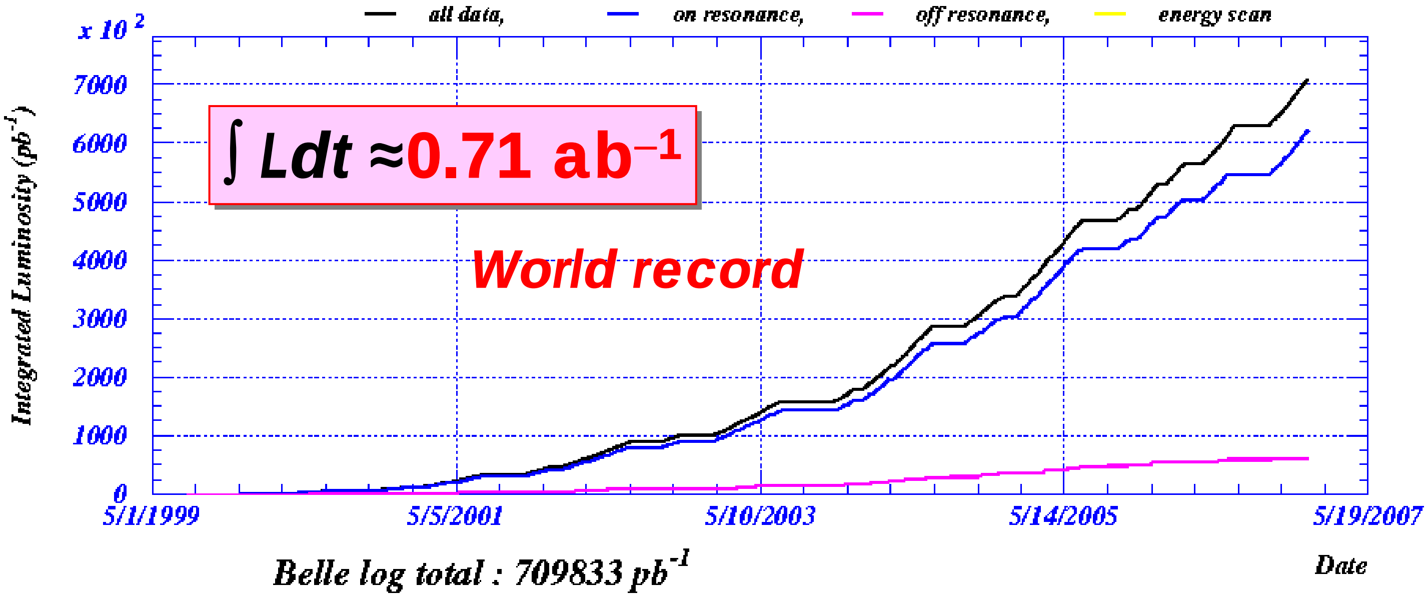
B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging flavor states)

KEKB asymmetric e^+e^- collider



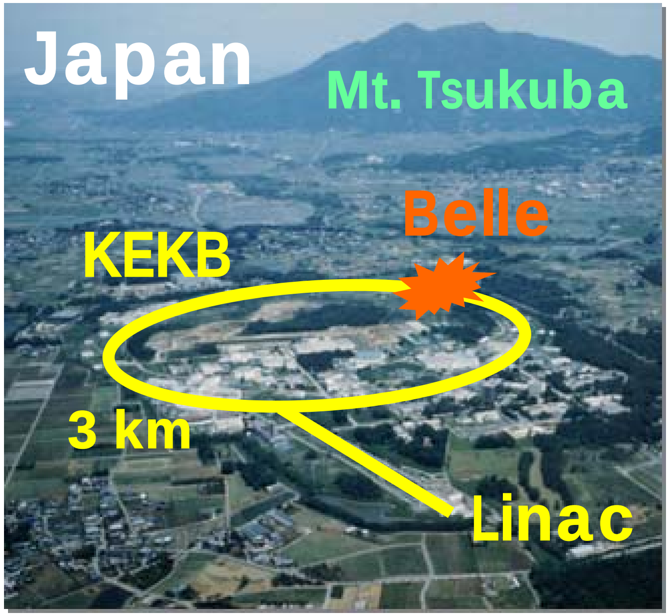
- Two separate rings
  - e^+ (LER) : 3.5 GeV
  - e^- (HER) : 8.0 GeV
  - $\beta\gamma = 0.425$
- E_{CM} : 10.58 GeV at Υ(4S)
- Design:
  - Luminosity: 10^{34} cm^{-2}s^{-1}
  - Current: 2.6 / 1.1A
    (LER HER)
- Beam size: $\sigma_y \approx 3$ µm
  $\sigma_x \approx 100$ µm
- ±11 mrad crossing angle

KEKB asymmetric e^+e^- collider



$\int Ldt \approx 0.71\ ab^{-1}$

World record



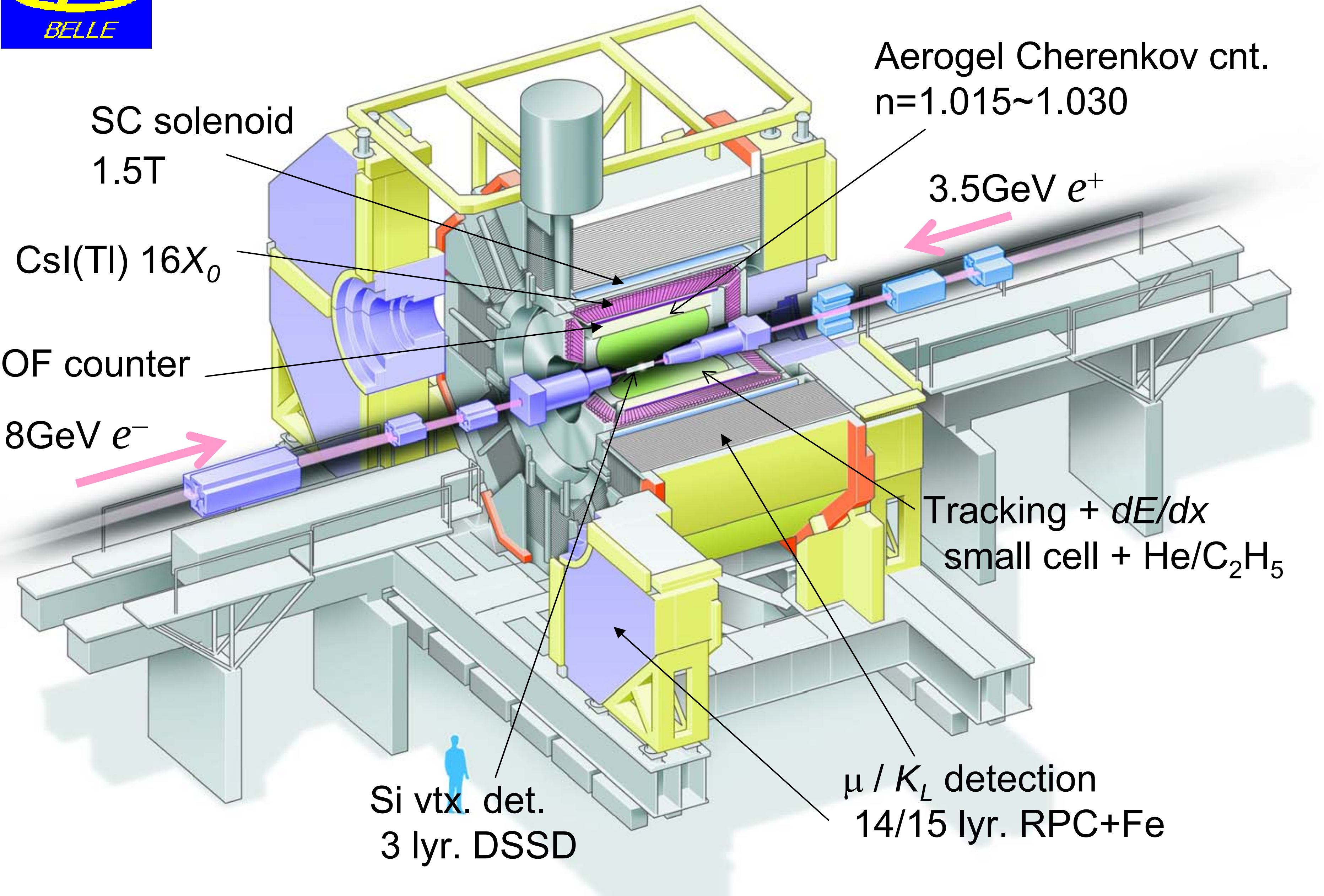
- Peak luminosity

$$L_{peak} = 1.71 \times 10^{34}\ cm^2/s$$

World record

Results based on 535M $\bar{B}B$ pairs

Belle Detector



SC solenoid
1.5T

CsI(Tl) 16X_0

TOF counter

8GeV e^-

Aerogel Cherenkov cnt.
n=1.015~1.030

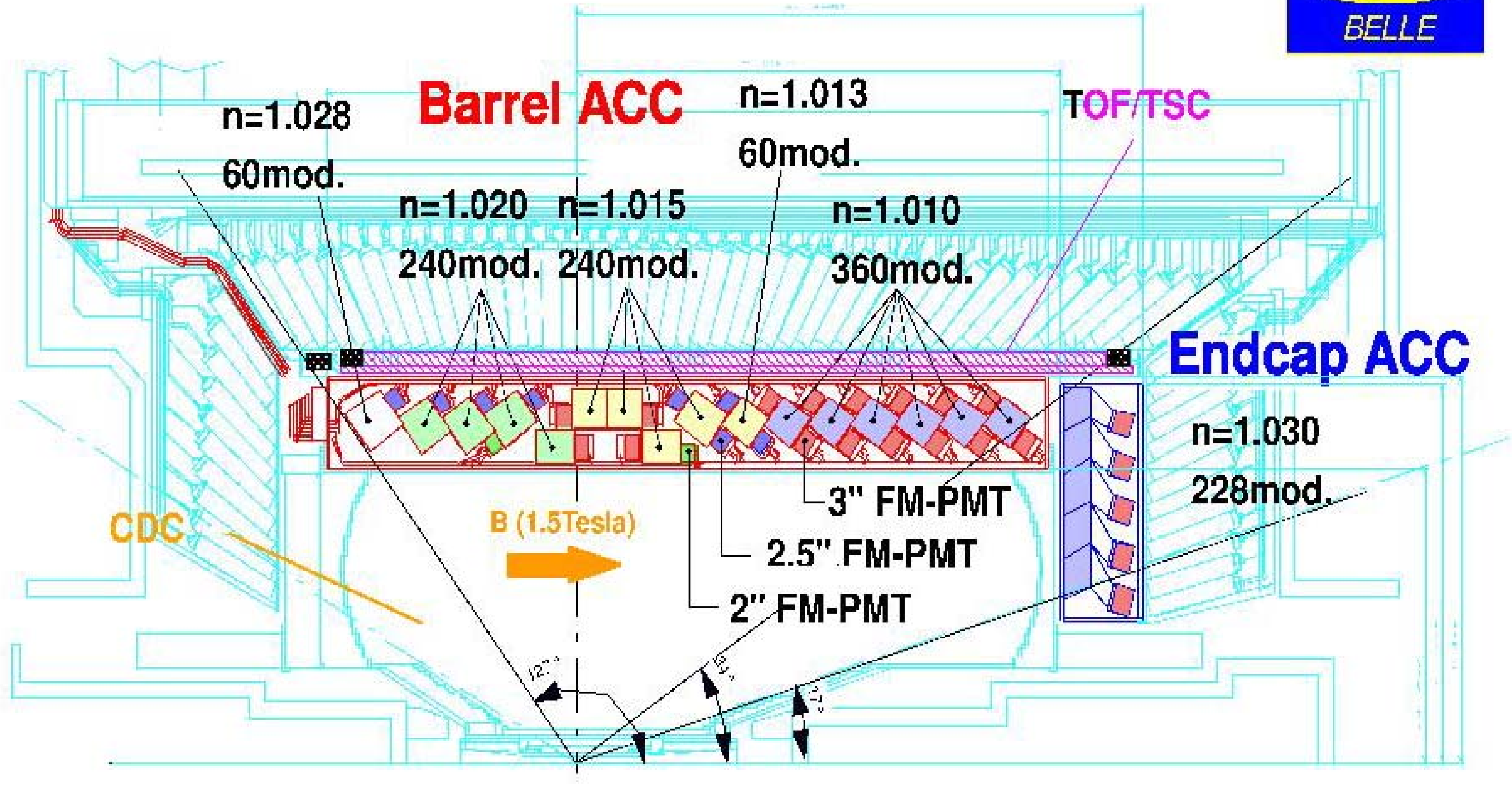
3.5GeV e^+

Tracking + *dE/dx*
small cell + He/C_2H_5

Si vtx. det.
3 lyr. DSSD

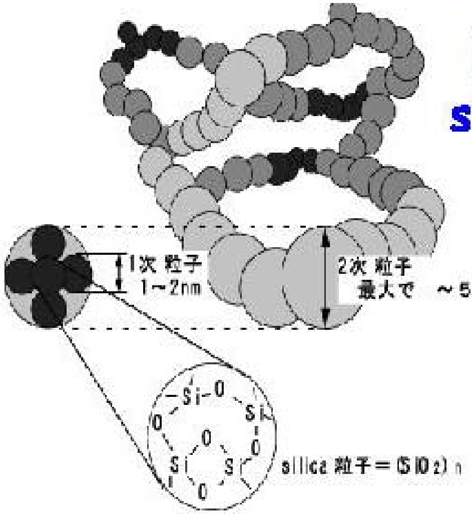
μ / K_L detection
14/15 lyr. RPC+Fe

PID System at Belle



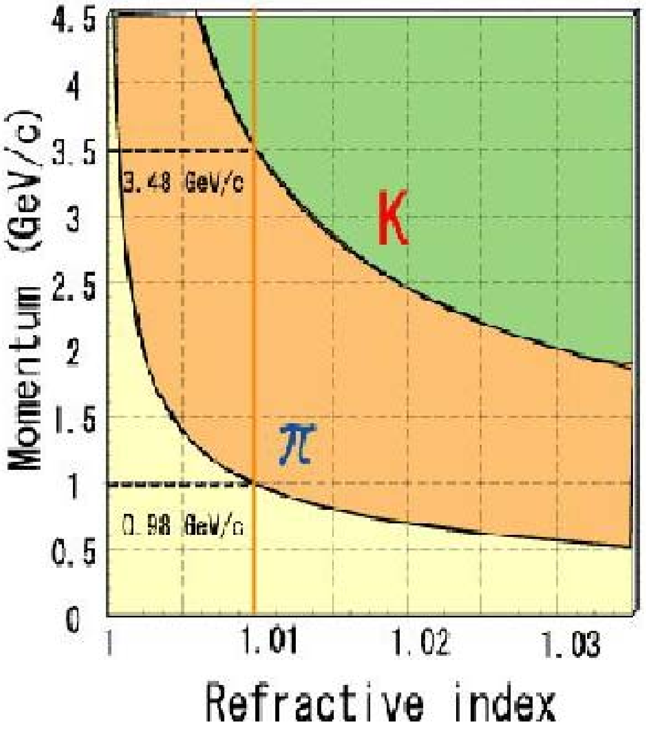
Aerogel Cherenkov Counters

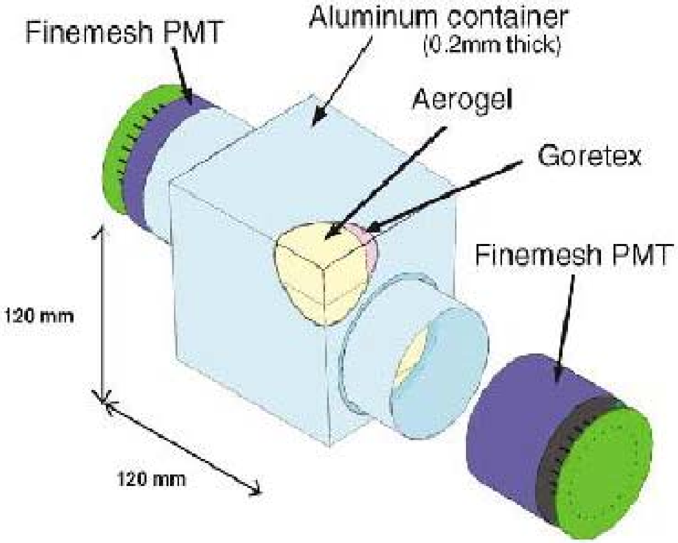
- Hydrophobic silica-aerogels
- n = 1.01~1.028 (barrel), 1.03 (endcap)
- 960 modules (barrel) ->1560 PMTs
- 228 modules (endcap) -> 228 PMTs



Fractal structure

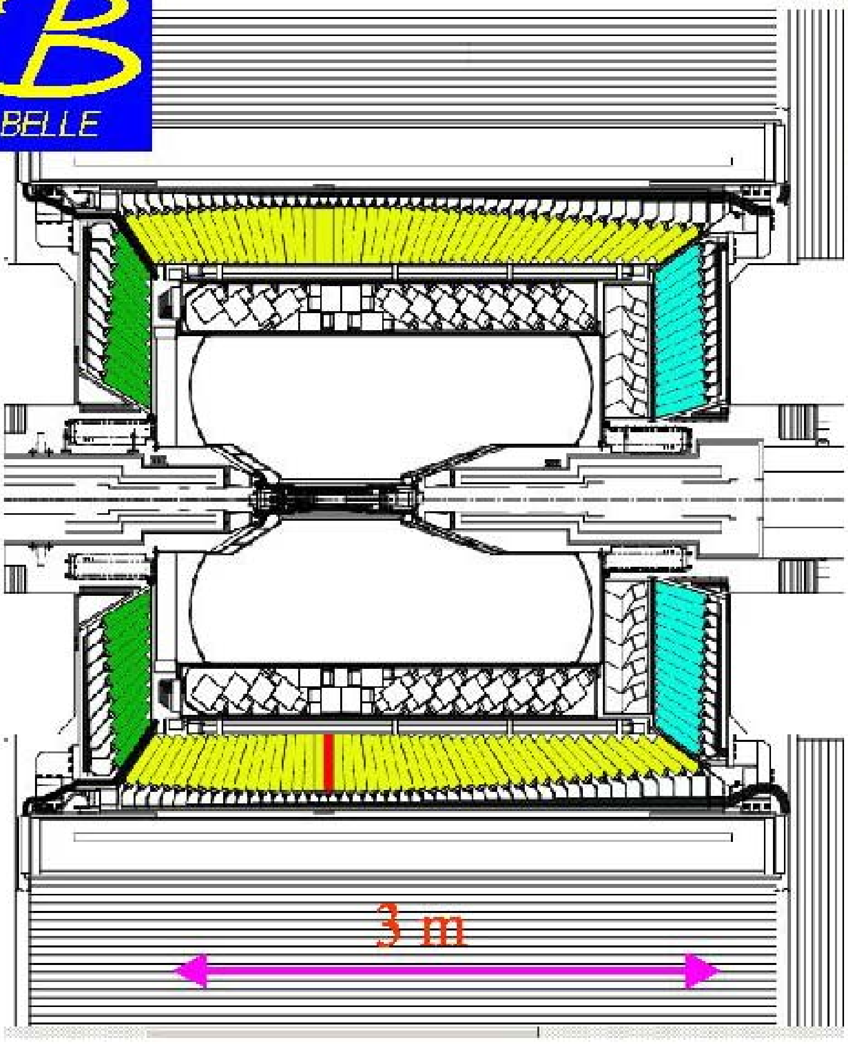
Cherenkov light thresholds





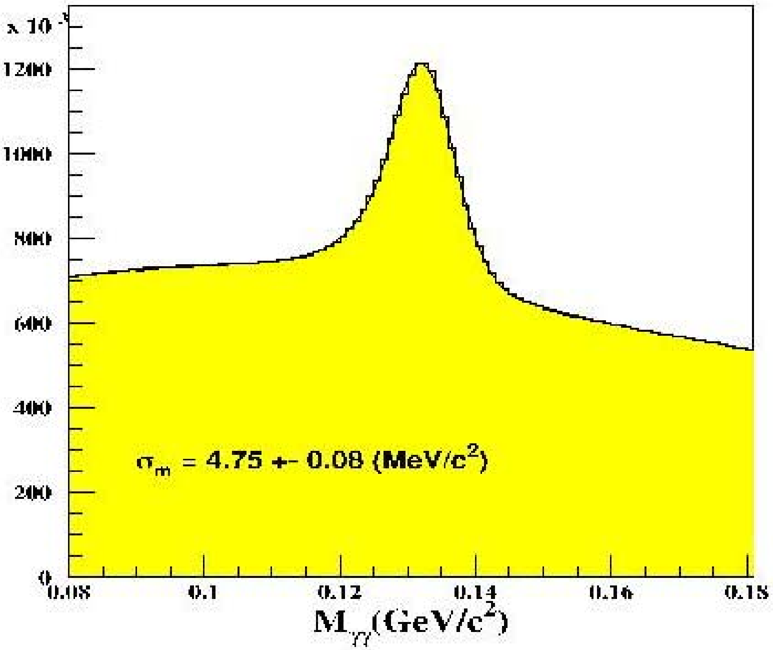
BELLE

Electromagnetic Calorimeter at Belle

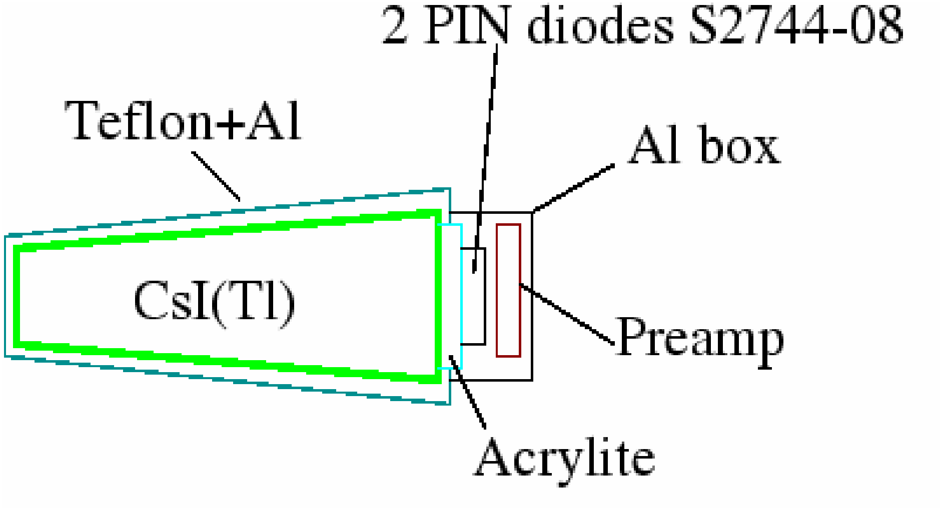


- *8736 CsI(Tl) crystals with photodiode readout*
- *About 16.2 X0, inside solenoid*
- *Coverage from 12 to 155°*

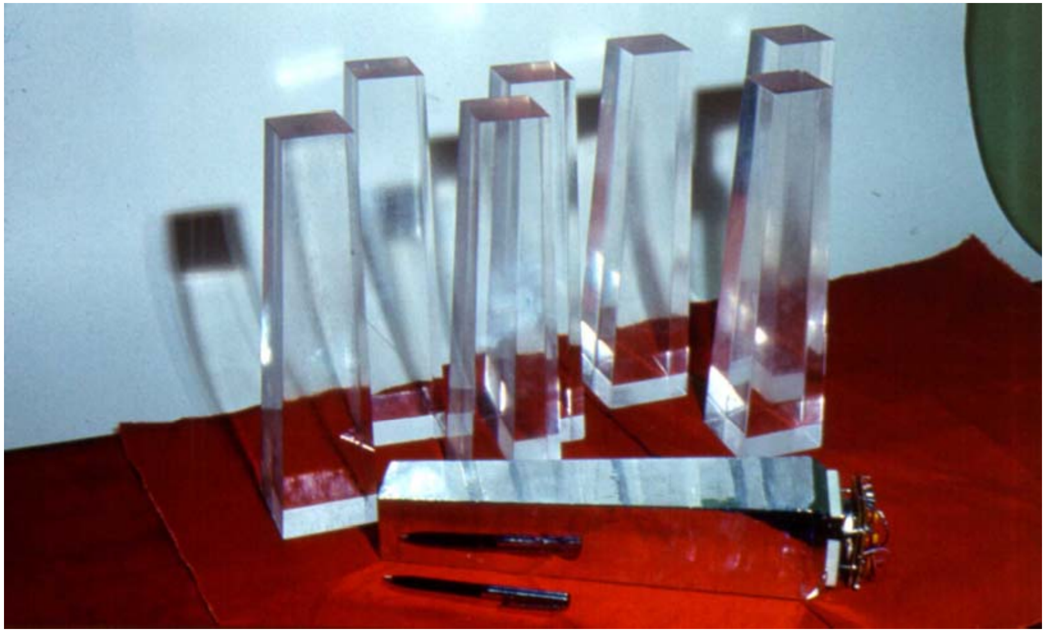
$\pi^0 \rightarrow \gamma\gamma$ in hadronic events



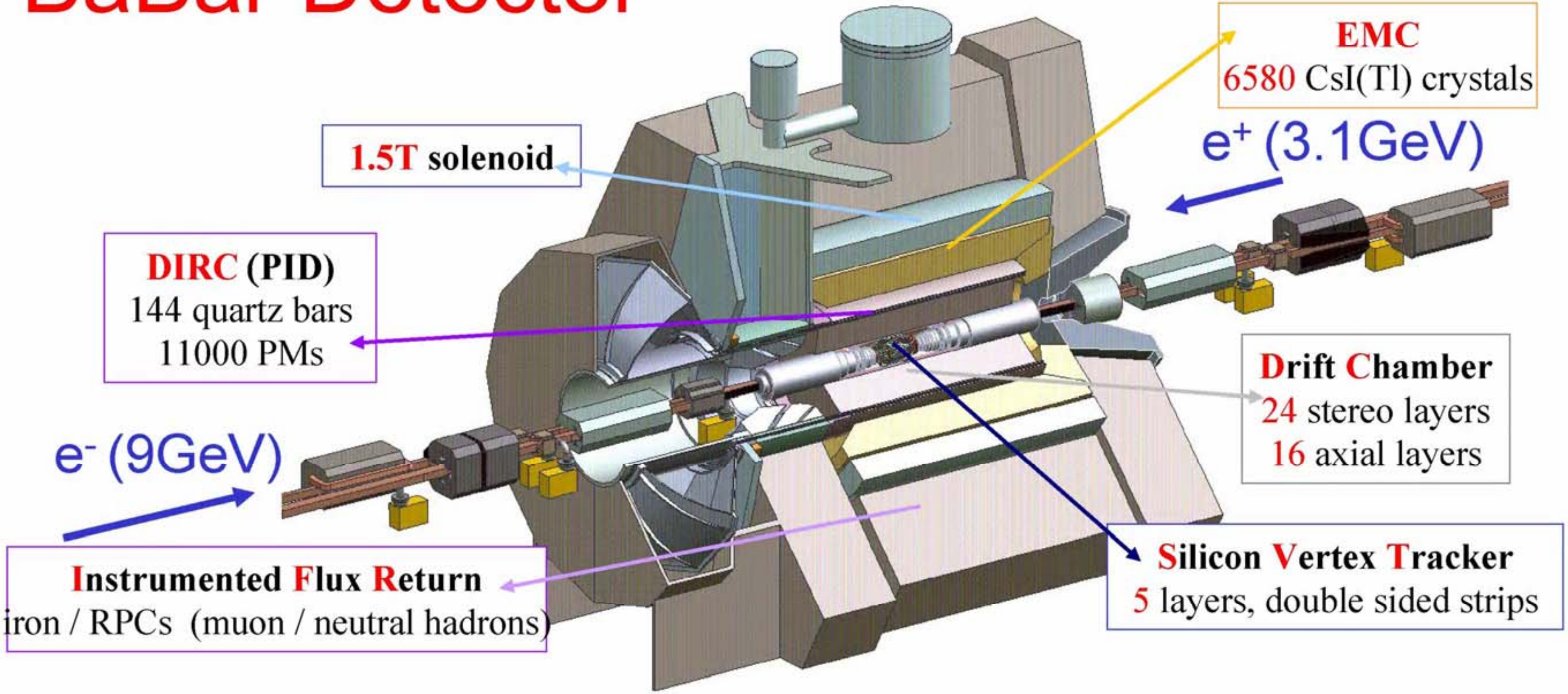
CsI(Tl) crystals for Belle



Light output – 5000 ph.el./MeV
Electronics noise σ~200 KeV



BaBar Detector



EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
24 stereo layers
16 axial layers

e^- (9GeV)

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

Silicon Vertex Tracker
5 layers, double sided strips

SVT: vertexing and tracking: crucial for Δt and low p_T tracks

DCH: main tracking device, also dE/dx for particle ID

DIRC: K-π separation > 3.4σ for P < 3.5GeV/c

EMC: very good energy resolution; electron ID, π^0 and γ reco.

IFR: Muon and neutral hadrons (K^0_L) ID

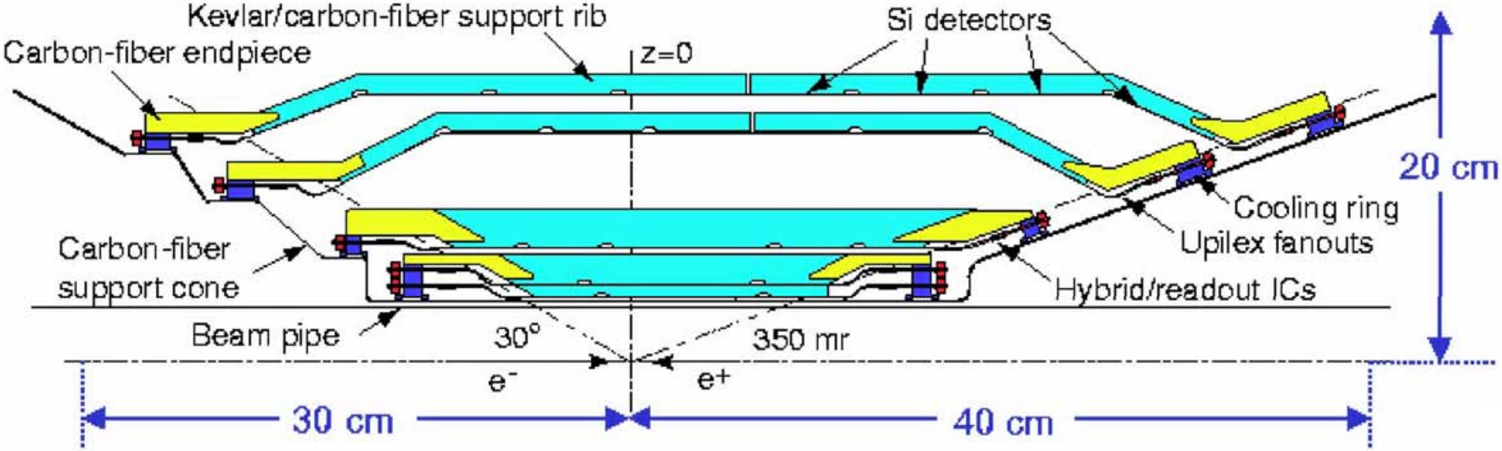
BaBar: the Silicon Vertex Tracker

double-sided Si microstrip detectors

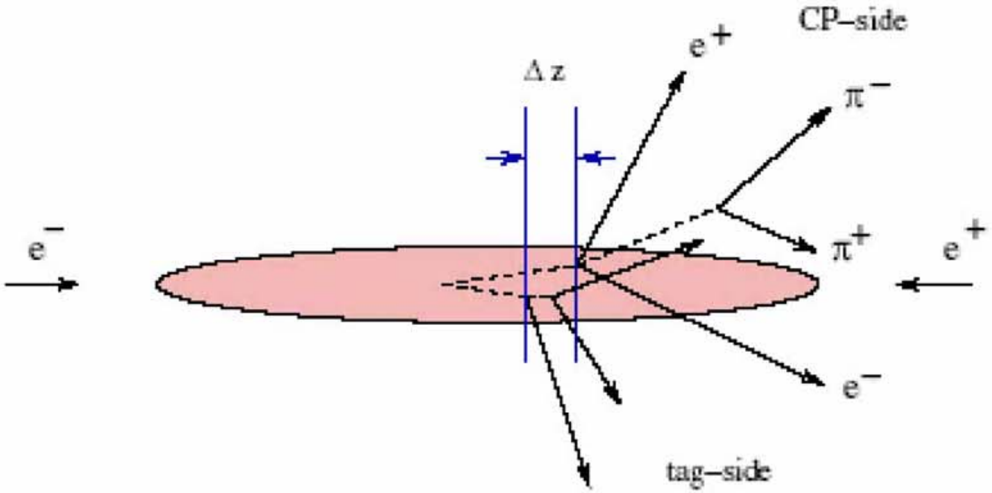
5 layers: 340 wafers, 150000 readout channels

$20^o < \theta < 150^o$

$\sigma_{point} \approx$ 10-15 μm for the inner layers



Δt from $(\Delta z)_{\mathrm{LAB}}$



- $\Delta z = z_{cp} - z_{\mathrm{tag}}$

  $\Delta t \simeq \Delta z/(\gamma\beta c)$
- Interaction Point $\gg \Delta z$

  B flight-length in x-y: only $\sim 30\mu$
- C conservation in $\Upsilon(4S) \to BB$

  $\psi(t) = |B_1^0 > |\bar{B}_2^0 > -|\bar{B}_1^0 > |B_2^0 >$

  (one is B^0 and other is $\bar{B}^0$ at any time)

The other B provides time reference and flavor tagging at $\Delta t = 0$

Parameters	BaBar	Belle
e^+e^- energy	$3.1 \times 9\,\mathrm{GeV}$	$3.5 \times 8.5\,\mathrm{GeV}$
$\gamma\beta$	0.56	0.425
Interaction point ($h \times v \times l$)	$120\,\mu\mathrm{m} \times 5\,\mu\mathrm{m} \times 8.5\,\mathrm{mm}$	$80\,\mu\mathrm{m} \times 2\,\mu\mathrm{m} \times 3.4\,\mathrm{mm}$
Typical Δz	$260\mu\mathrm{m}$	$200\mu\mathrm{m}$
σ_z (CP-side)	$50\,\mu\mathrm{m}$	$75\,\mu\mathrm{m}$
σ_z (tag-side)	$100 \sim 150\,\mu\mathrm{m}$	$140\,\mu\mathrm{m}$

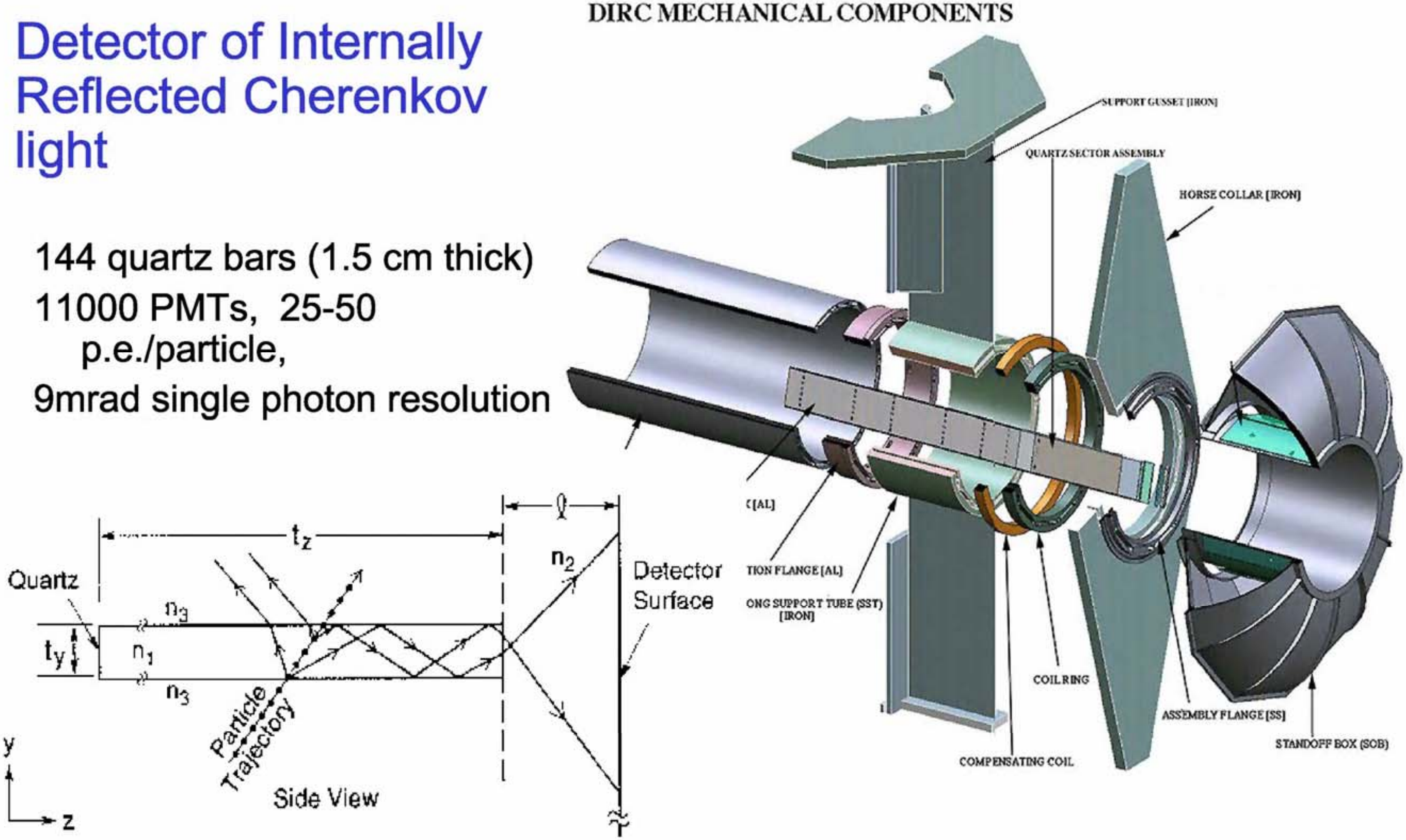
Particle identification: the DIRC

- Detector of Internally Reflected Cherenkov light

144 quartz bars (1.5 cm thick)

11000 PMTs, 25-50 p.e./particle,

9mrad single photon resolution



K identification performance

Charged K identified by

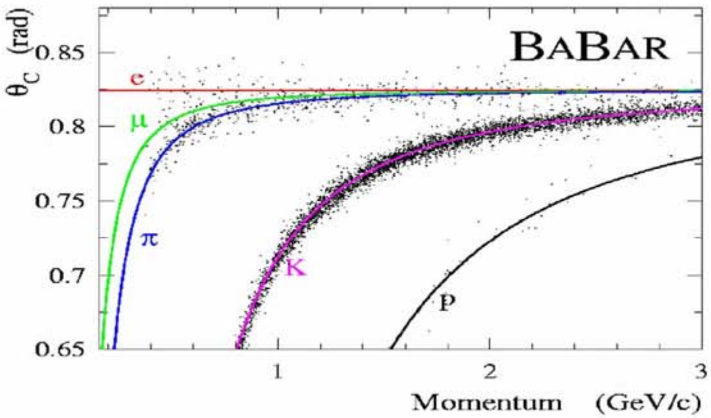
DIRC: Cerenkov angle

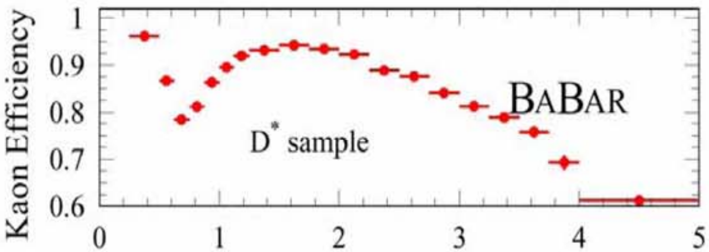
DCH: dE/dx ($p < 0.7$ GeV/c)

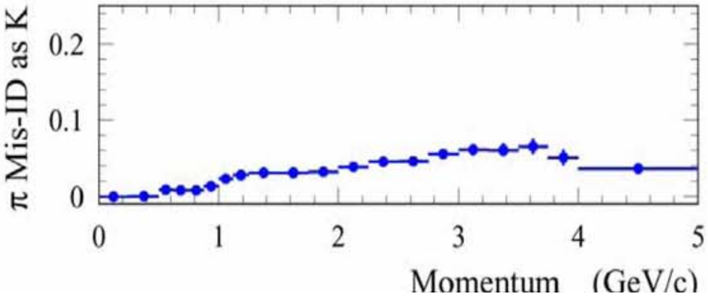
Efficiency and purity measured on control samples (soft pion tag)

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

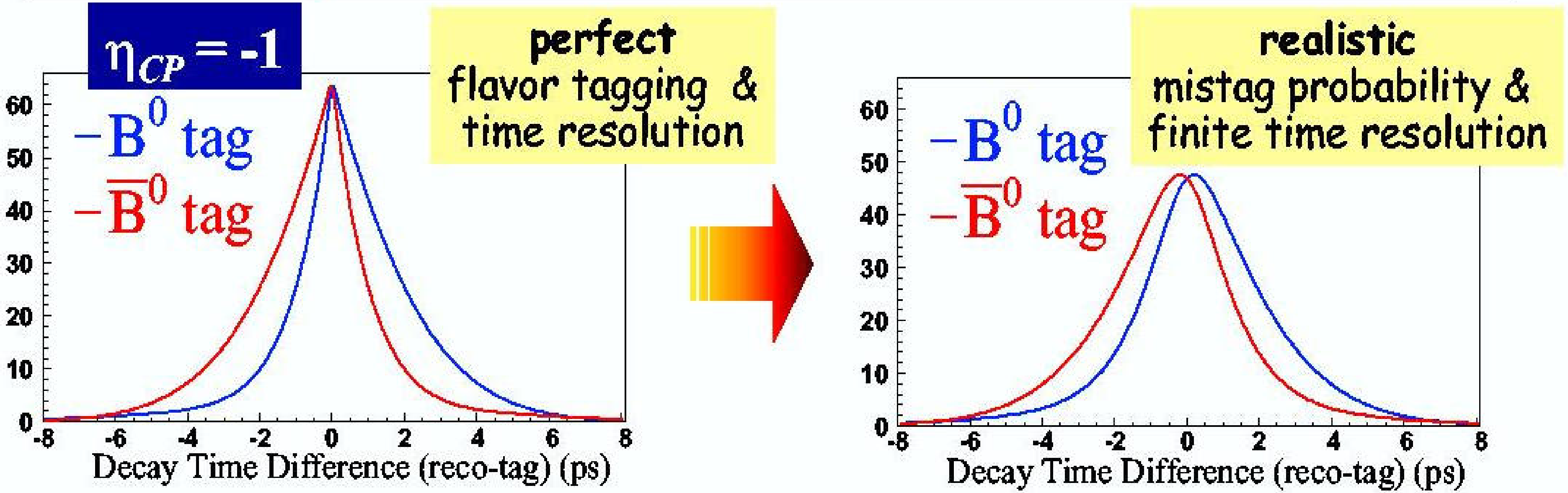
$> 3.4\sigma$ π/K separation up to ≈ 3.5 GeV/c







CP Analysis: Time Distribution



perfect
flavor tagging &
time resolution

realistic
mistag probability &
finite time resolution

$$f_{CP,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left(1 \mp \eta_f \,(1-2\omega)\, \sin 2\beta \sin \Delta m_d \Delta t \right) \right\} \otimes R(\Delta t)$$

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

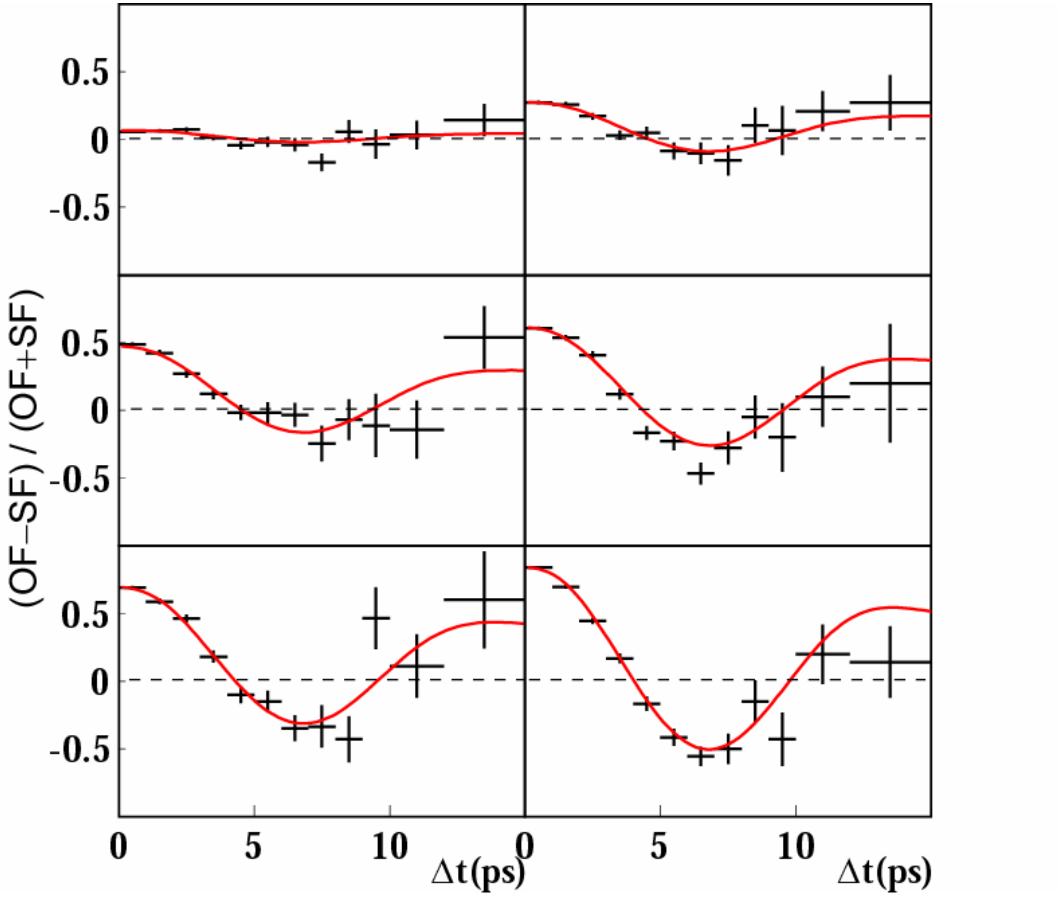
$$\text{"}f_{CP,-}\text{"} \Leftrightarrow B^0_{tag} = \overline{B}^0$$

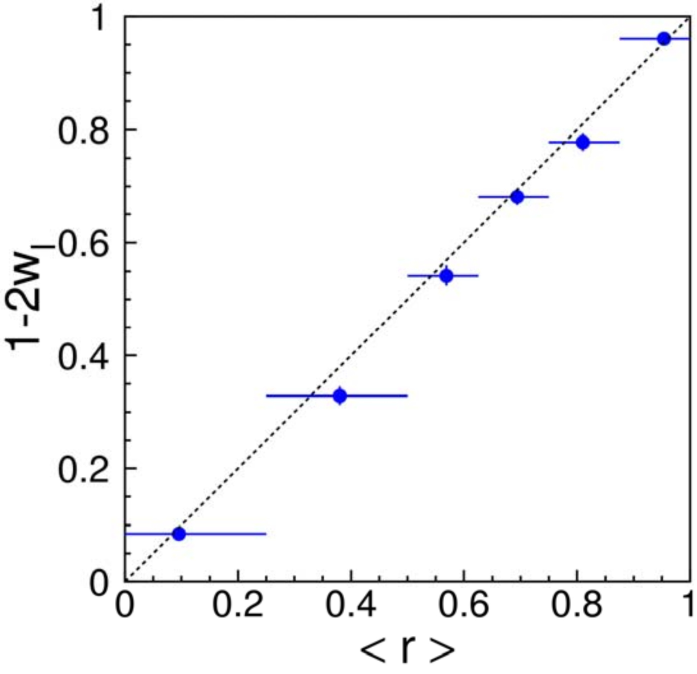
same mistag probability ω
and time-resolution function $R(\Delta t)$

Flavor tagging – dilution factor

Classify the events into six classes and measure
D = (1-2w) for each. (*w* : wrong tag prob.)

$B^0B^0 \to D^*l\nu$: reconstruction
↳ tag

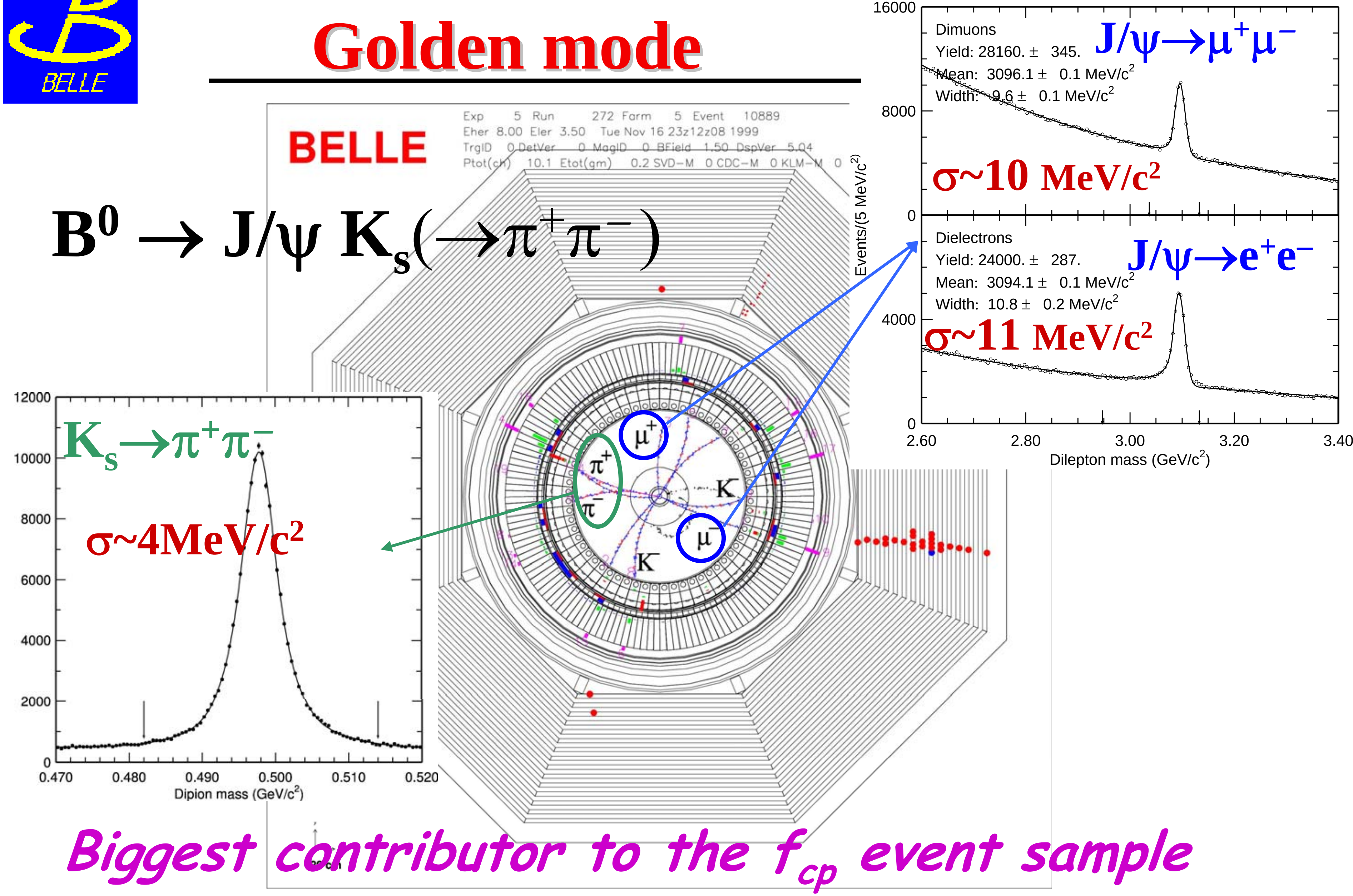




Efficiency > 99.5%
$\varepsilon_{\text{effective}}$ = 28.8±0.5%

Golden mode

$$B^0 \rightarrow J/\psi\ K_s(\rightarrow \pi^+\pi^-)$$



$K_s \rightarrow \pi^+\pi^-$

$\sigma \sim 4 MeV/c^2$

$J/\psi \rightarrow \mu^+\mu^-$

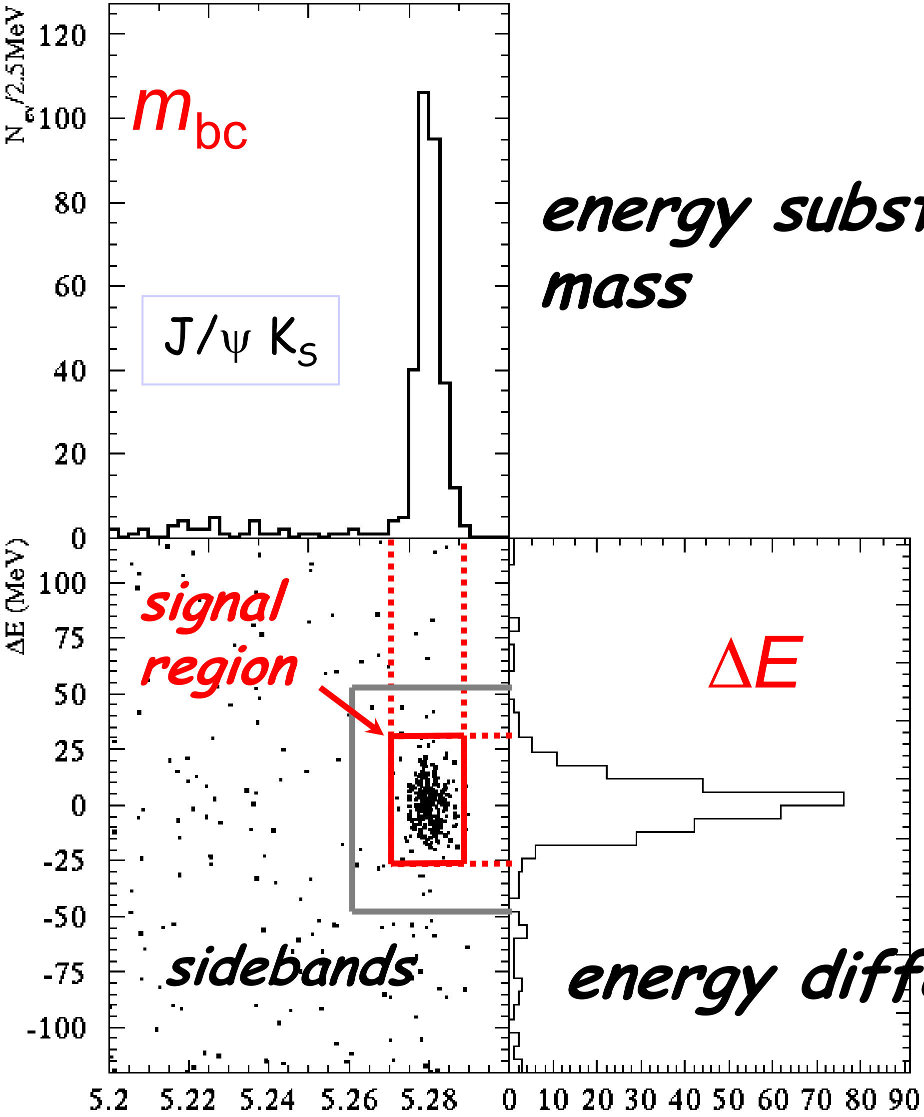
$\sigma \sim 10$ MeV/c²

$J/\psi \rightarrow e^+e^-$

$\sigma \sim 11$ MeV/c²

Biggest contributor to the f_{cp} event sample

Reconstruction of B mesons



energy substituted mass

Initial state kinematic constraint

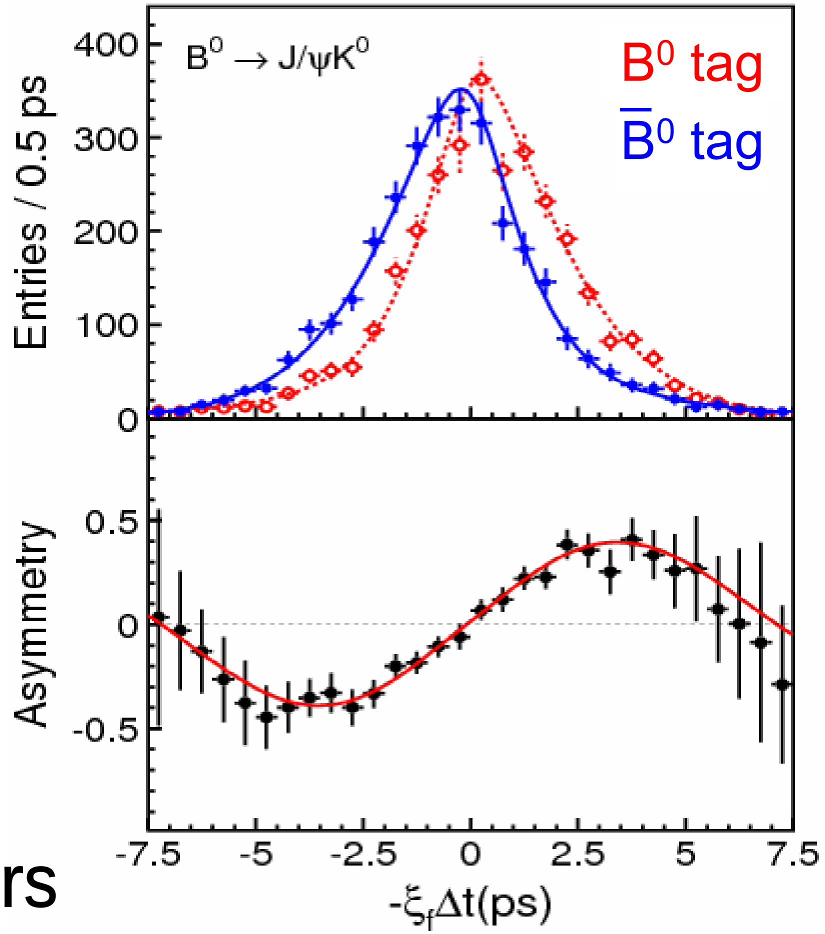
$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$

$$m_{bc} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$$

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

energy difference

$B^0 \rightarrow J/\psi\ K^0$: combined result



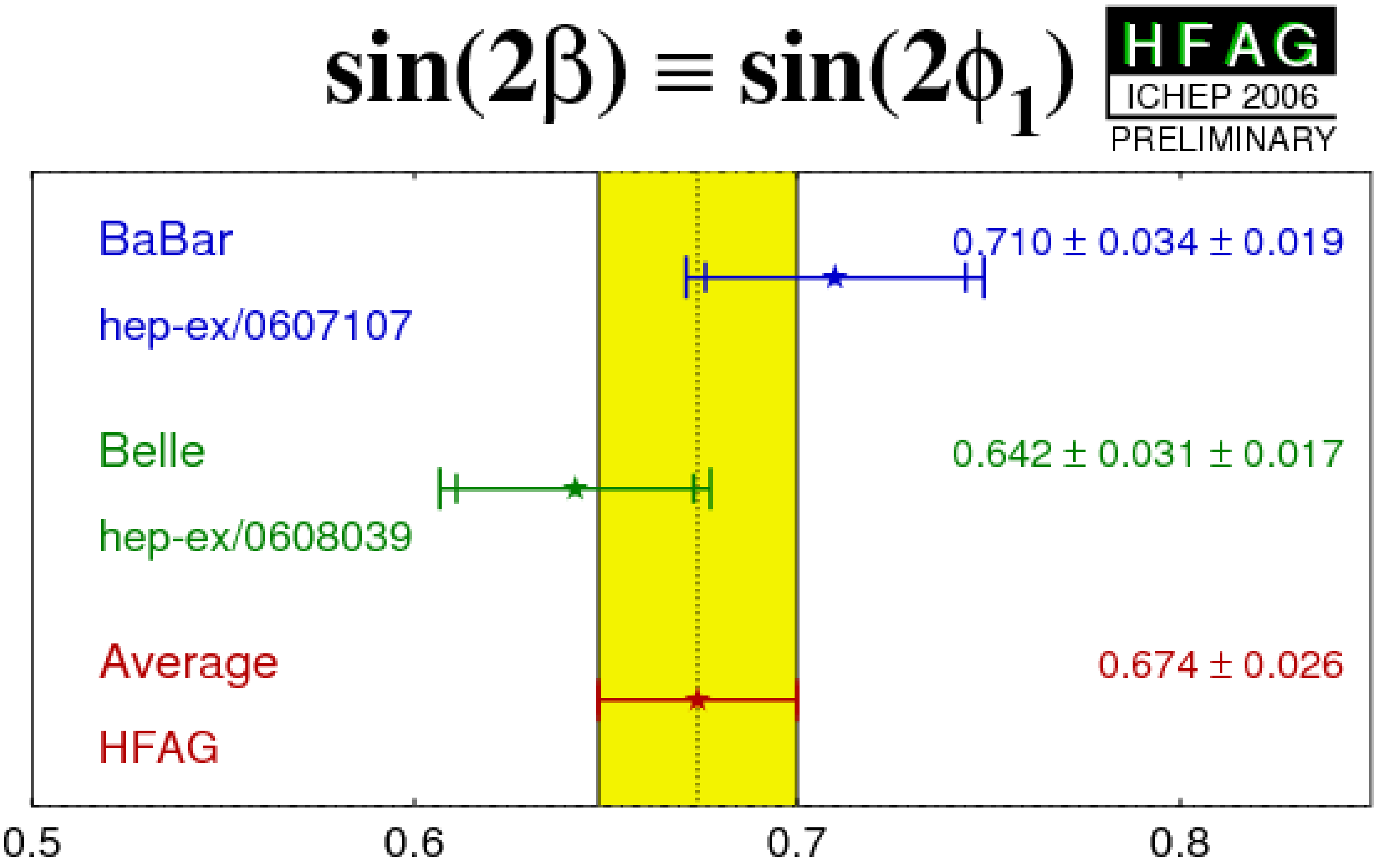
- background subtracted
- good tags

535 M $B\overline{B}$ pairs

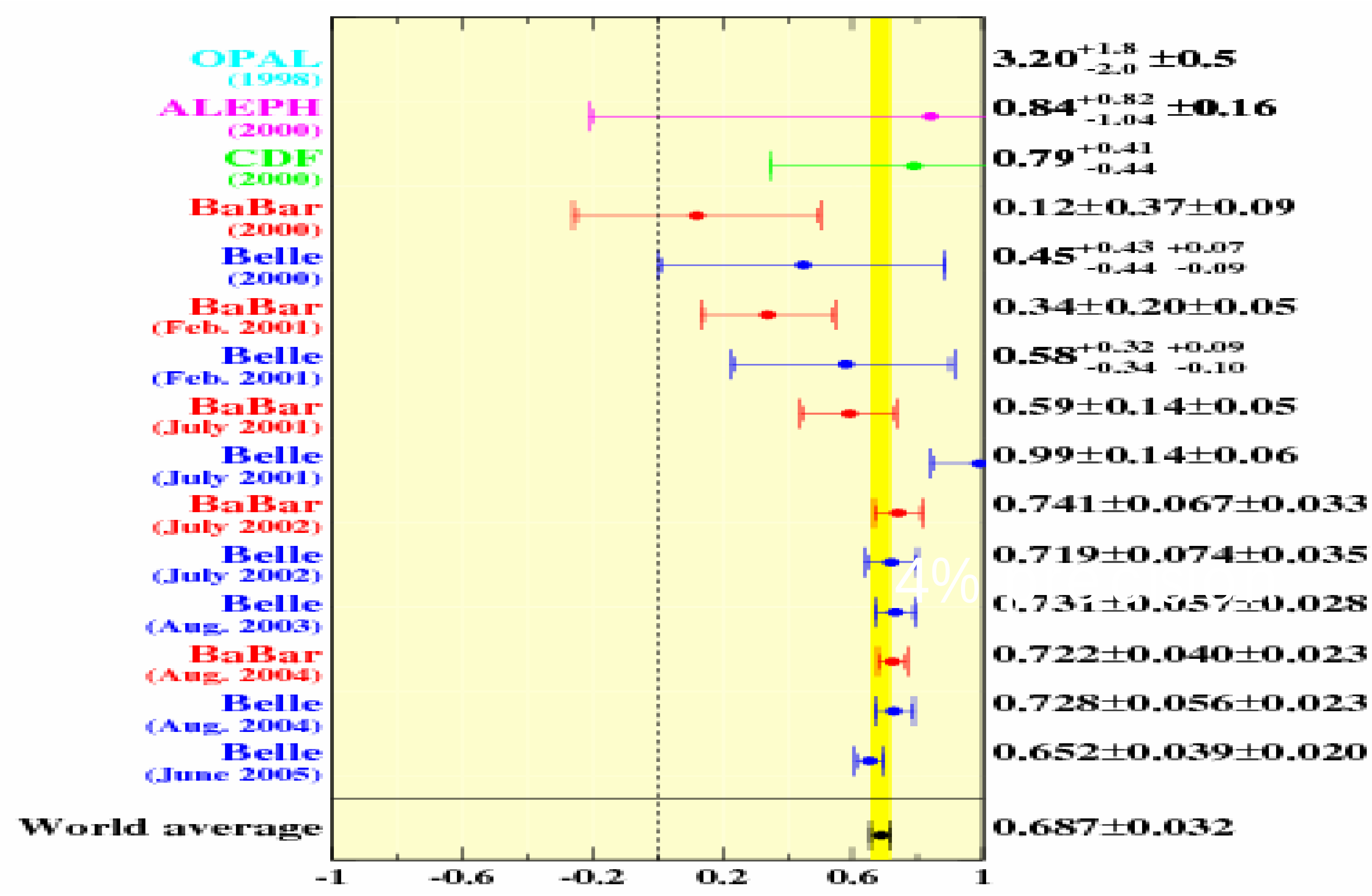
previous measurement
$\sin2\phi_1 = 0.652 \pm 0.044$
(386 M $B\overline{B}$ pairs)

$\sin2\phi_1 = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)
$\mathcal{A} = 0.018 \pm 0.021$ (stat) ± 0.014 (syst)

2006: BaBar + Belle

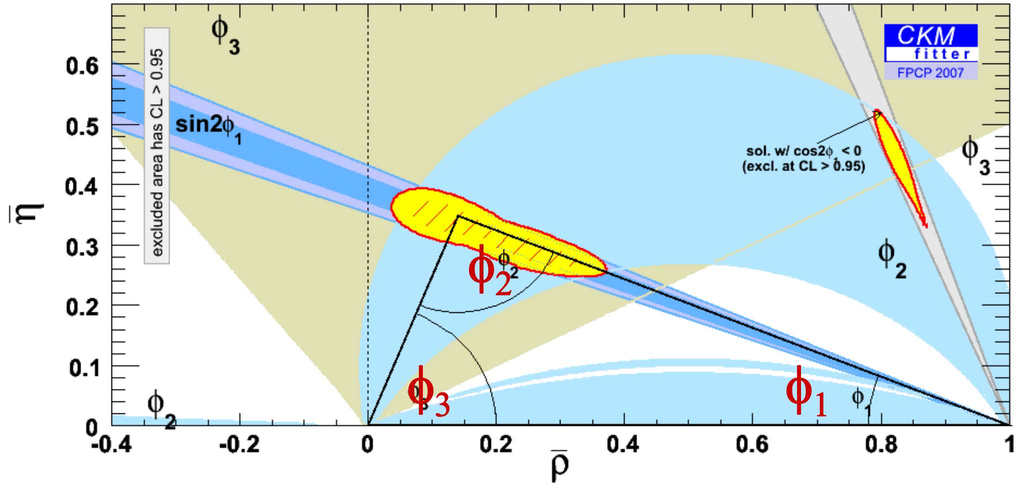


$\sin 2\phi_1$ history (1998-2005)

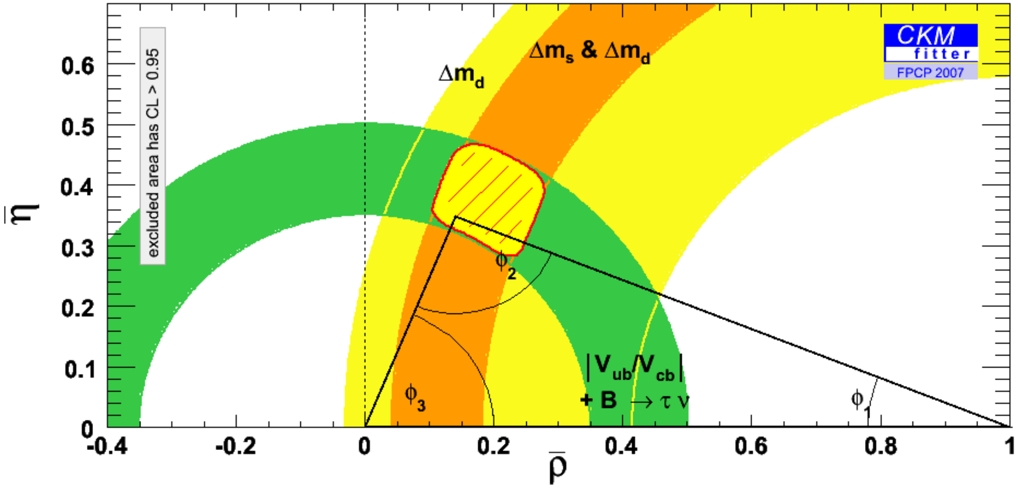


Summary

Unitary triangle from CPV angles



UT from CP-conserving quantities



Summary

- Large CP violations seen in B decays
- Excellent agreement with KM ansatz
  - $\sin 2\phi_1$ → a new "gold standard" for New Physics searches
- Room for New Physics is pretty small
  - either the NP mass scale is very high
  - or NP is somehow hidden from the flavor sector

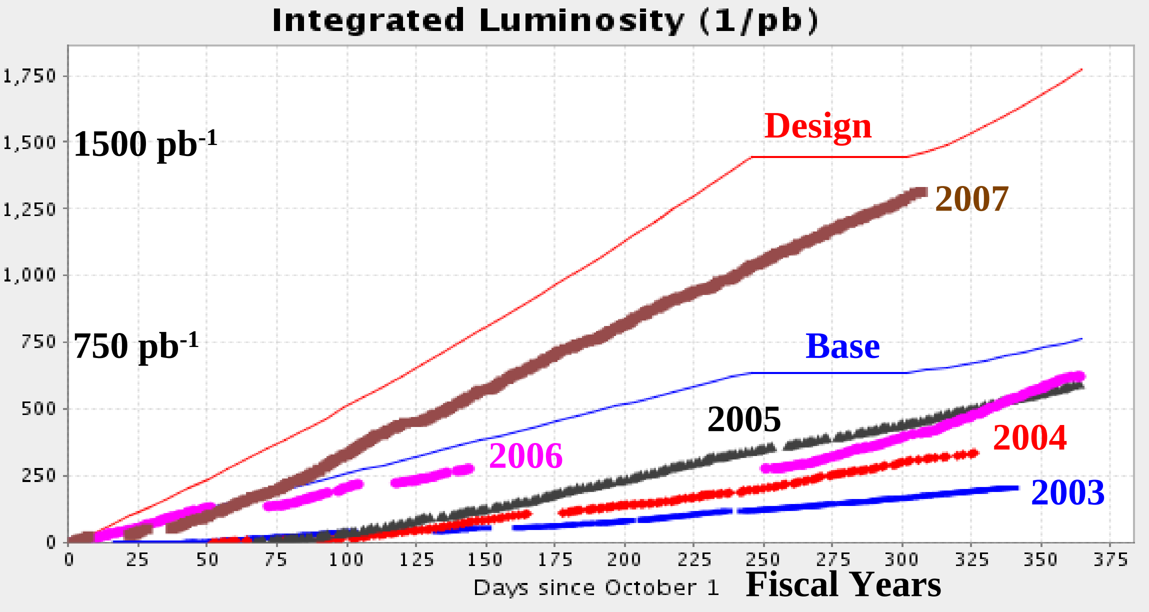
- But the strength of CP violation in SM is not sufficient to explain Baryon Asymmetry in the Universe

- NP searches with B's have another order-of-magnitude of reach (at least).
  - A phased approach to Super-KEKB/Belle seems likely
  - An announcement from the KEK DG Suzuki soon?!

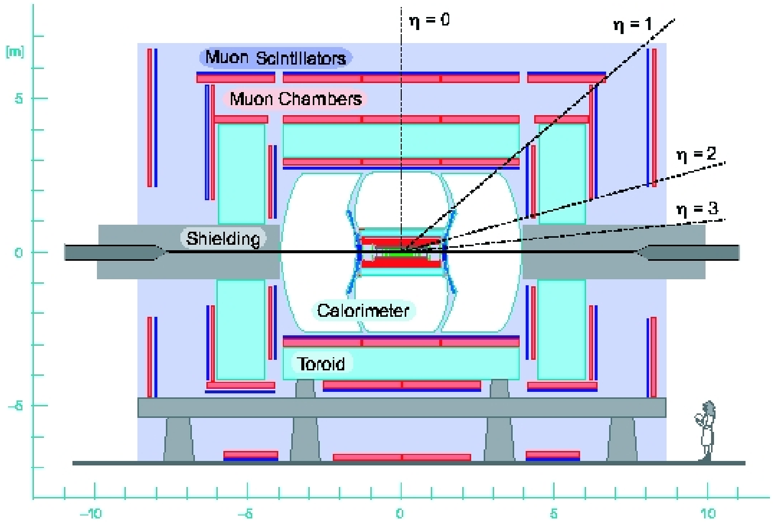
What’s next?

Tevatron Performance

- **Many improvements over last year**
  - **More pbars, more reliable**
    - **Monthly int. lum. increased 25 → 45 pb^{-1}**
    - **Peak lum. increased 180 10^{30} → 286 10^{30} cm^{-2} s^{-1}**
- **Expect ~6-7 fb^{-1} by Oct. ‘09**

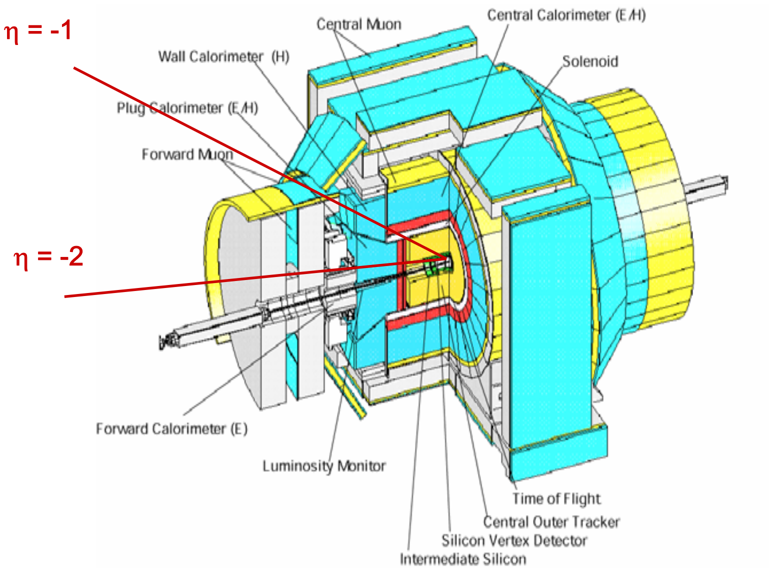


Tevatron Detectors



DZero Run II upgrades

2T solenoid
inner tracking
Preshower
extended μ coverage
and shielding
Trigger, DAQ

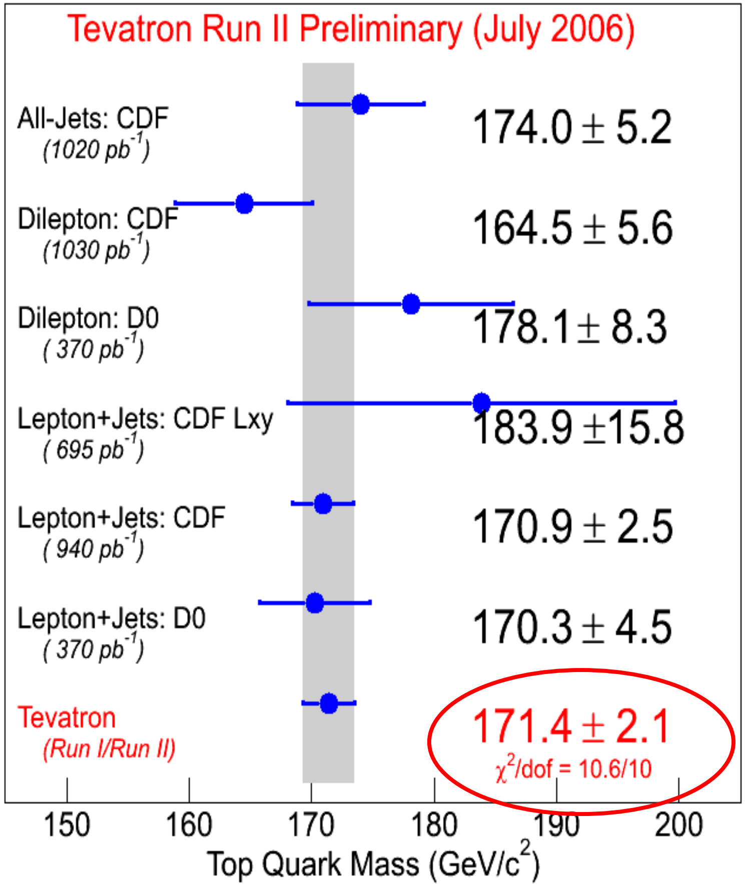


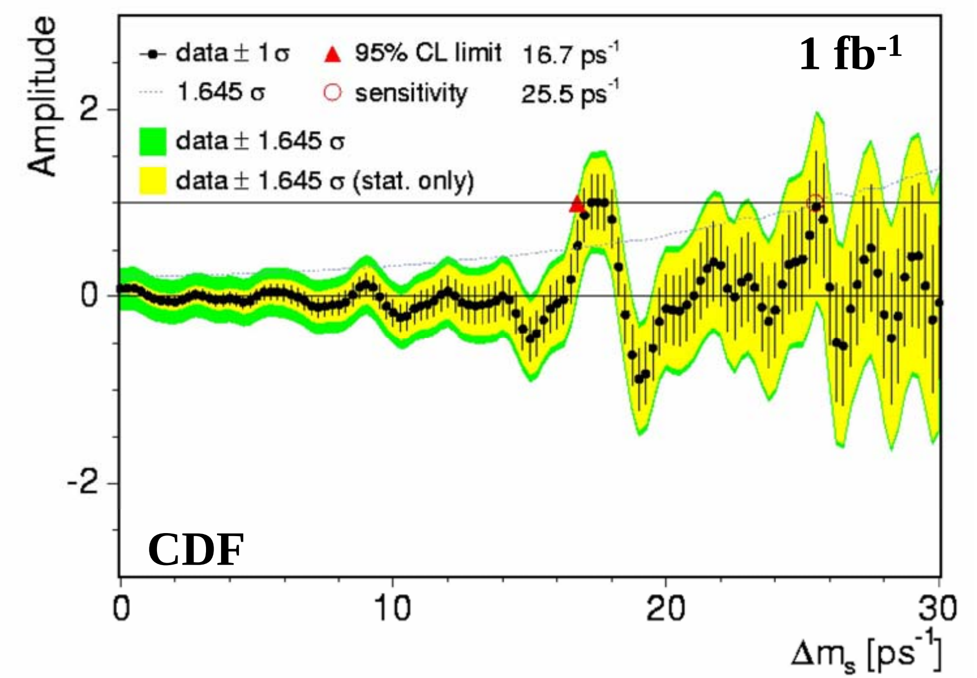
CDF Run II upgrades

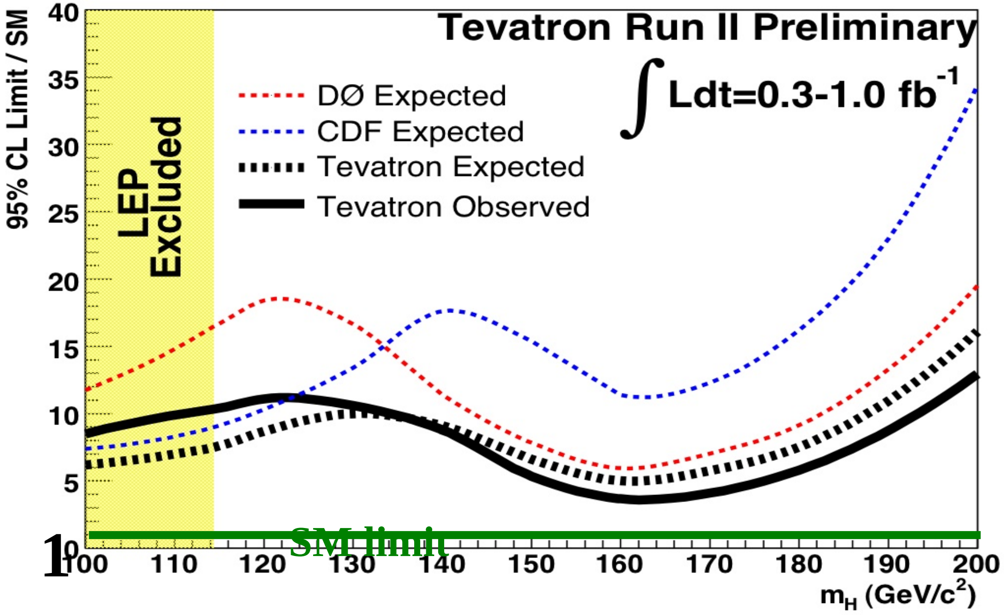
Inner tracking
Forward calorimeter
extended μ coverage
Trigger, DAQ

recorded 3 fb^{-1}

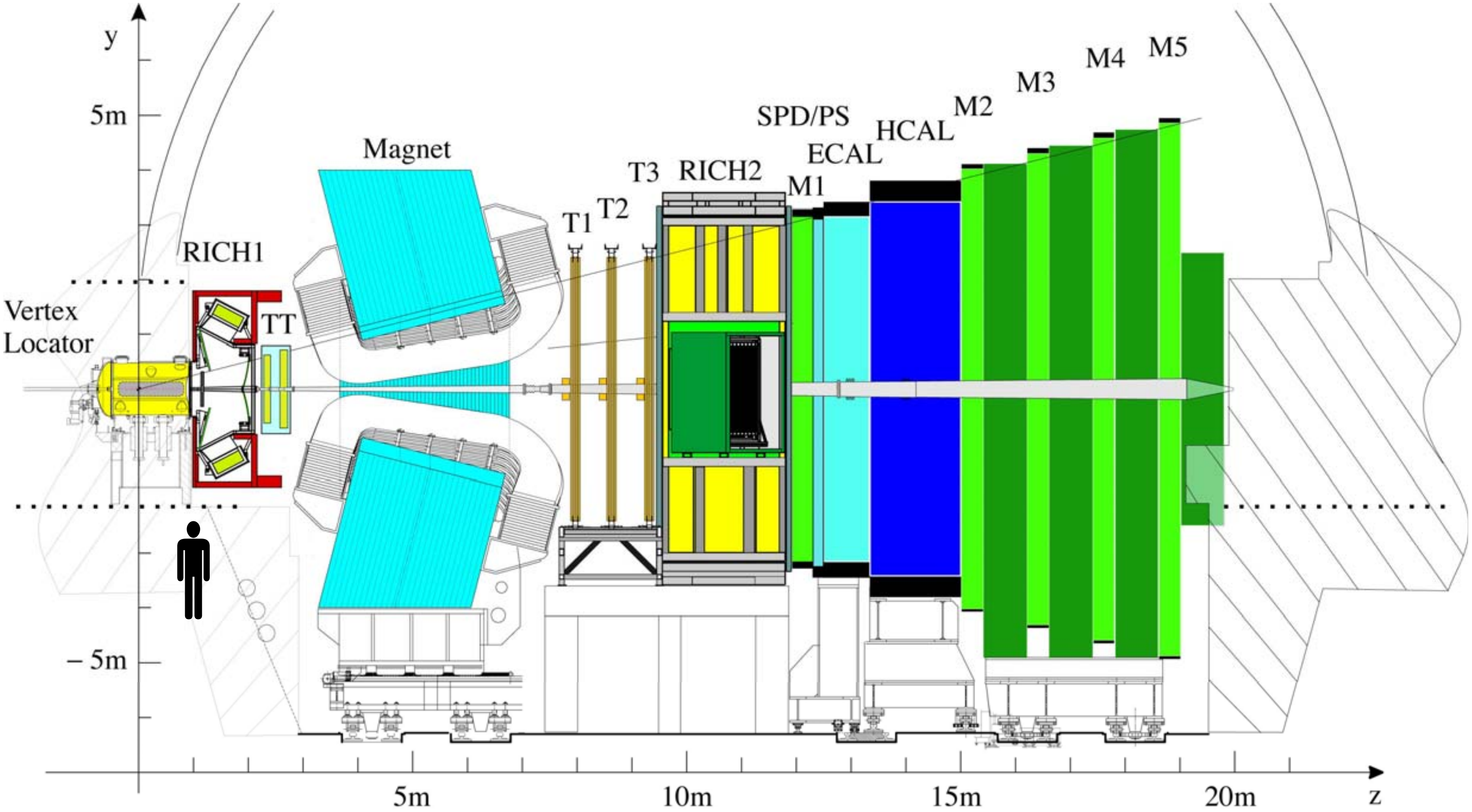
data taking efficiency ~ 85%


Tevatron Run II Preliminary (July 2006)
All-Jets: CDF
(1020 pb^{-1})
174.0 ± 5.2
Dilepton: CDF
(1030 pb^{-1})
164.5 ± 5.6
Dilepton: D0
(370 pb^{-1})
178.1 ± 8.3
Lepton+Jets: CDF Lxy
(695 pb^{-1})
183.9 ±15.8
Lepton+Jets: CDF
(940 pb^{-1})
170.9 ± 2.5
Lepton+Jets: D0
(370 pb^{-1})
170.3 ± 4.5
Tevatron
(Run I/Run II)
171.4 ± 2.1
χ^2/dof = 10.6/10
150
160
170
180
190
200
Top Quark Mass (GeV/c^2)


1 fb^{-1}
Amplitude
data ± 1σ
95% CL limit 16.7 ps^{-1}
1.645 σ
sensitivity 25.5 ps^{-1}
data ± 1.645 σ
data ± 1.645 σ (stat. only)
2
0
-2
CDF
0
10
20
30
Δm_s [ps^{-1}]


Tevatron Run II Preliminary
$\int$Ldt=0.3-1.0 fb^{-1}
95% CL Limit / SM
40
35
30
25
20
15
10
5
1
0
LEP Excluded
DØ Expected
CDF Expected
Tevatron Expected
Tevatron Observed
SM limit
100
110
120
130
140
150
160
170
180
190
200
m_H (GeV/c^2)

LHCb detector



Flavor Physics at LHCb

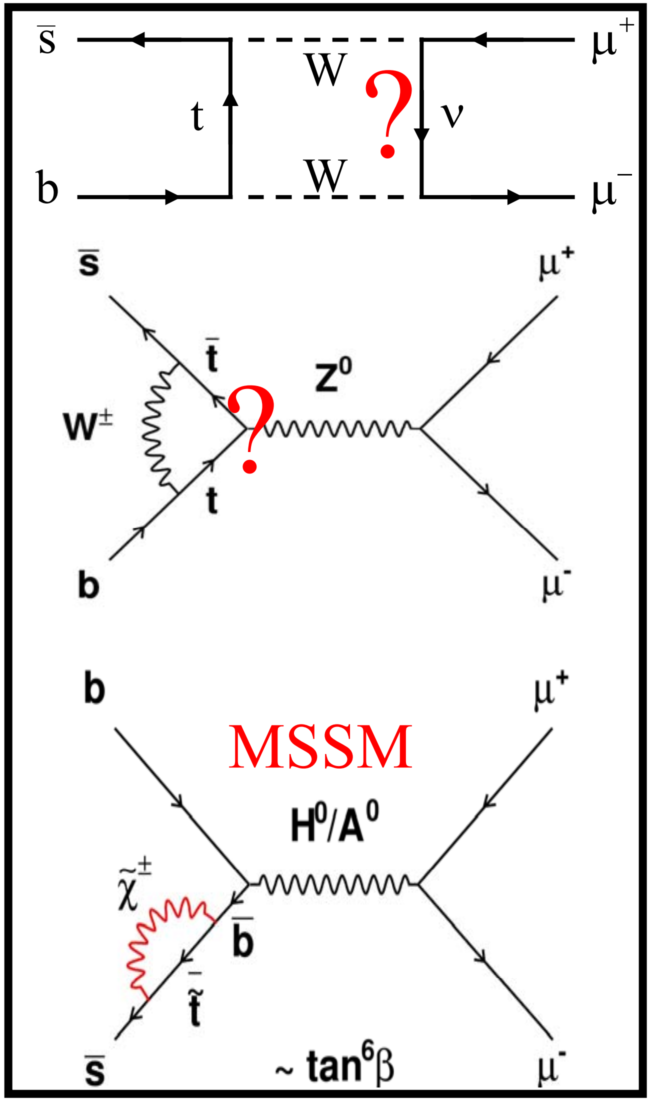
- At LHCb huge xsection (.5 mb), long decay length (1 cm)
- ….but high backgrounds, high performance trigger fundamental.
- Systematics will be more important than statistics, at the startup at least.
- Rich program possible, even at modest luminosities

A few examples……

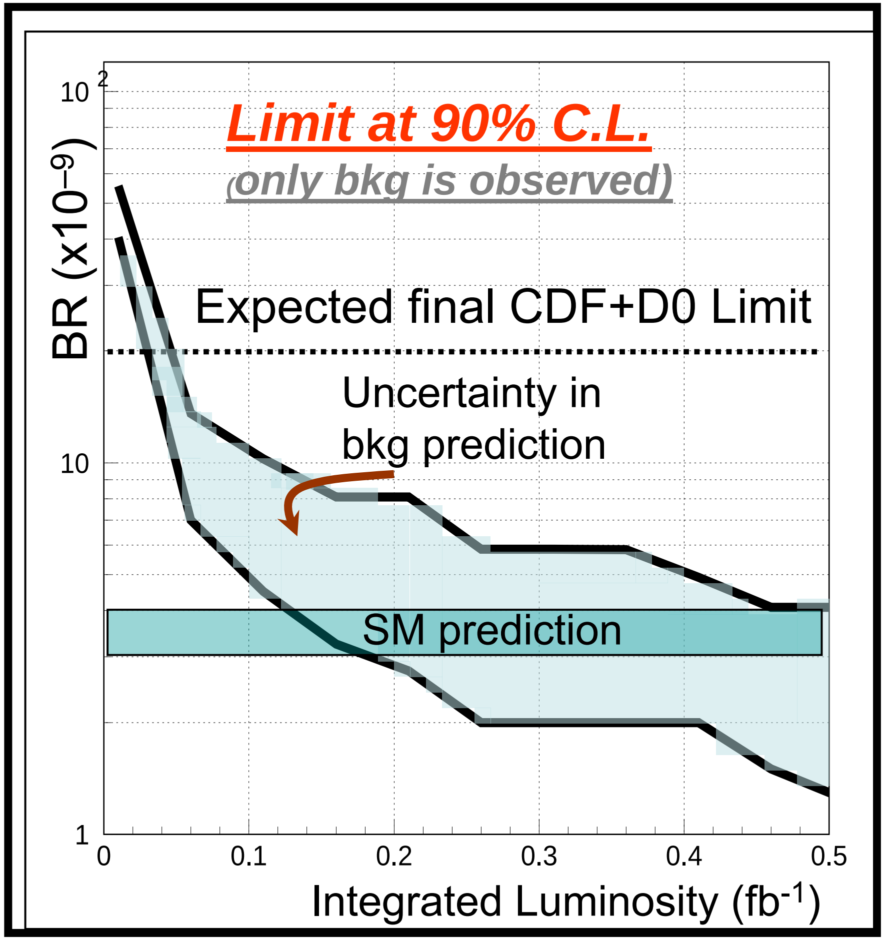
Very Rare B Decays: $B_s \rightarrow \mu^+\mu^-$

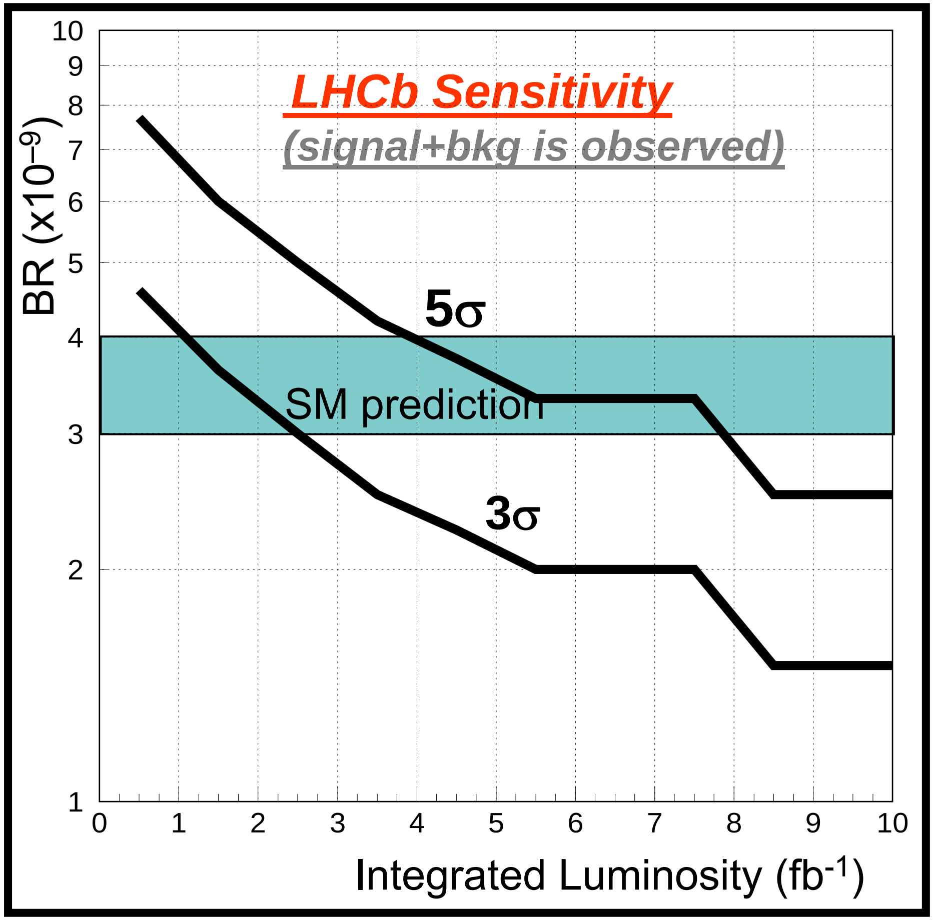
- **Very rare loop decay, sensitive to New Physics:**
  - BR ~3.5×10^{-9} in SM, can be strongly enhanced in SUSY
  - Current 90% CL limit from
  - CDF+D0 with 1 fb–1 is
  - ~20 times SM

- **Main issue is background rejection**
  - With limited MC statistics, indication that main background is $b \rightarrow \mu$, $b \rightarrow \mu$



Very Rare B Decays: $B_s \to \mu^+\mu^-$



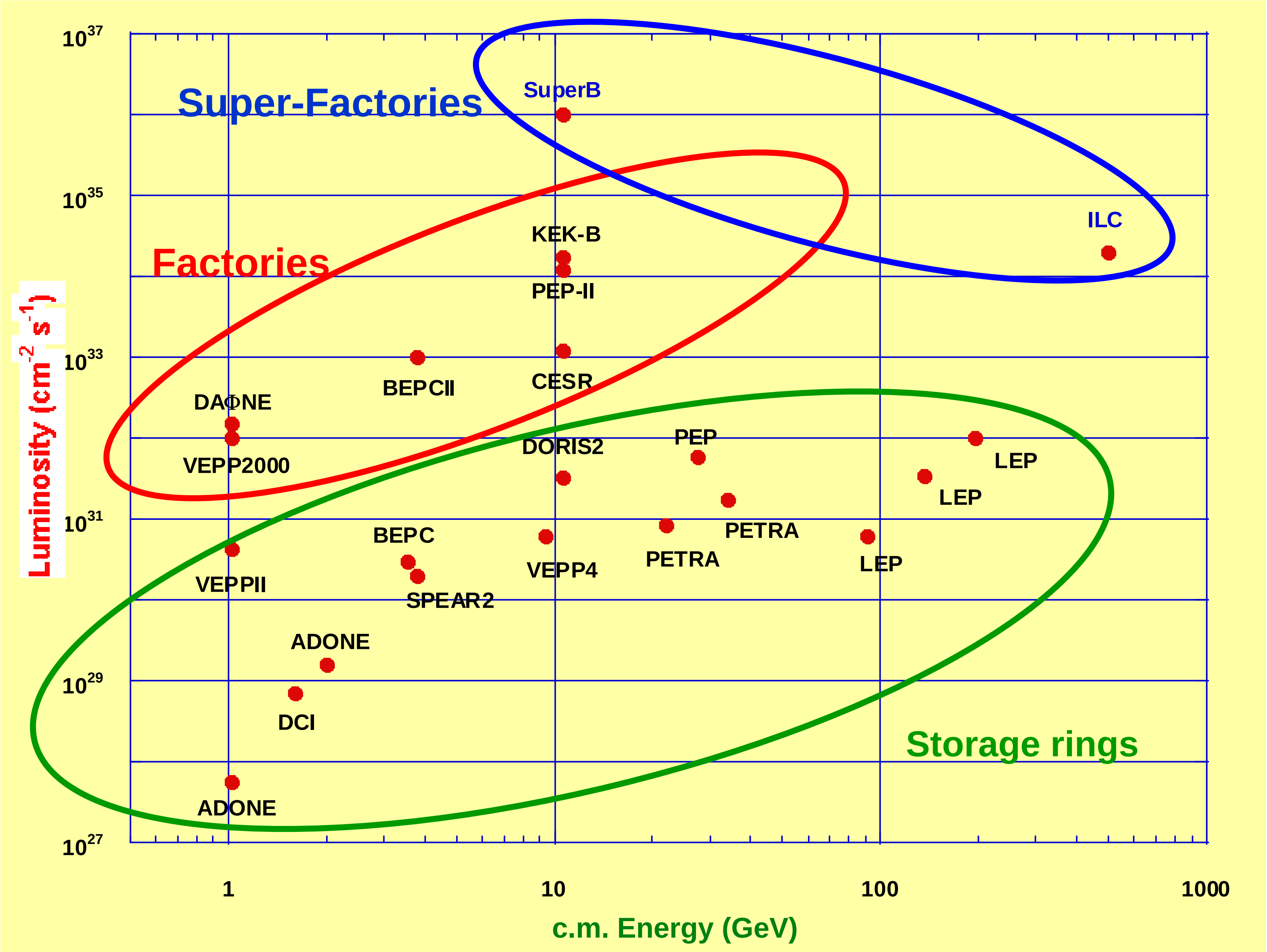


0.05 fb⁻¹ ⇒competitive with CDF+D0
0.5 fb⁻¹ ⇒ exclude BR values down to SM

2 fb⁻¹ ⇒ 3σ evidence of SM signal
10 fb⁻¹ ⇒ >5σ observation of SM signal

e+e- colliders

M.Biagini EPS 07

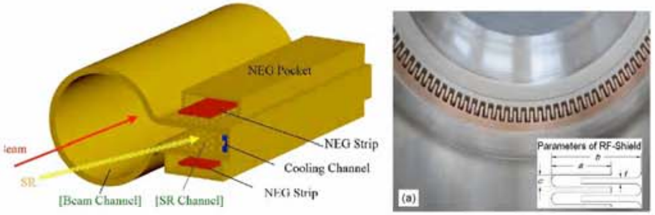


Super B factory at KEK

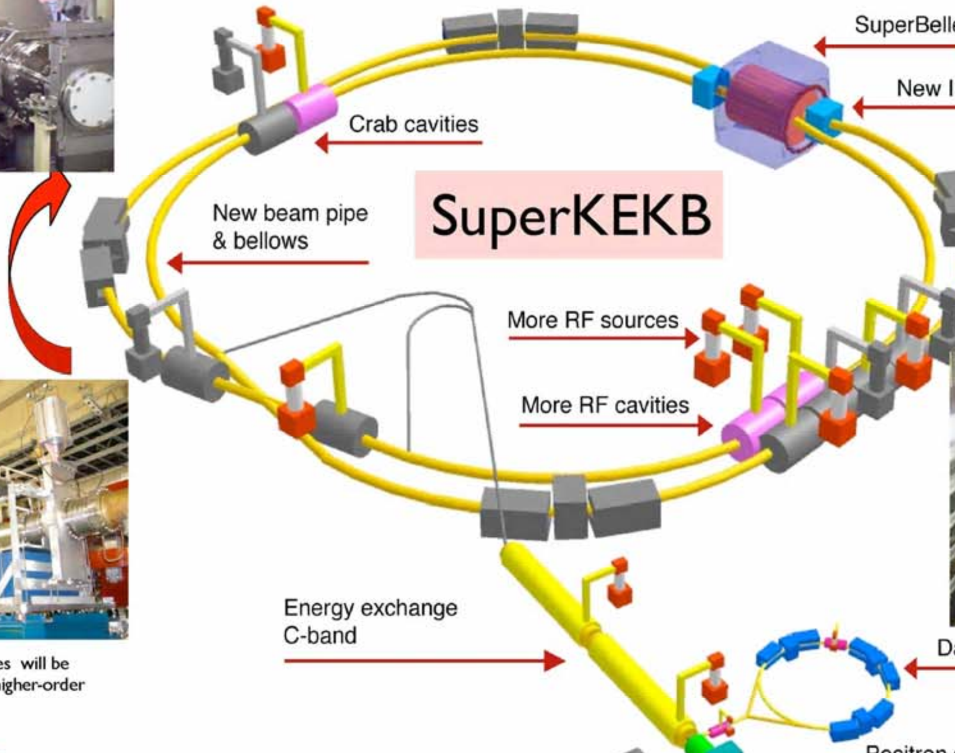
Crab cavities will be installed and tested with beam in 2006.

e+ 4.1 A

The superconducting cavities will be upgraded to absorb more higher-order mode power up to 50 kW.



The beam pipes and all vacuum components will be replaced with higher-current-proof design.



$\beta^*_y = \sigma_z = 3$ mm

e- 9.4 A

The state-of-art ARES copper cavities will be upgraded with higher energy storage ratio to support higher current.

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

will reach 8 × 10^{35} $\mathrm{cm^{-2}s^{-1}}$.