B物理 未解決の課題

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2007年3月16日

特定領域「フレーバー物理の新展開」研究会

@京都

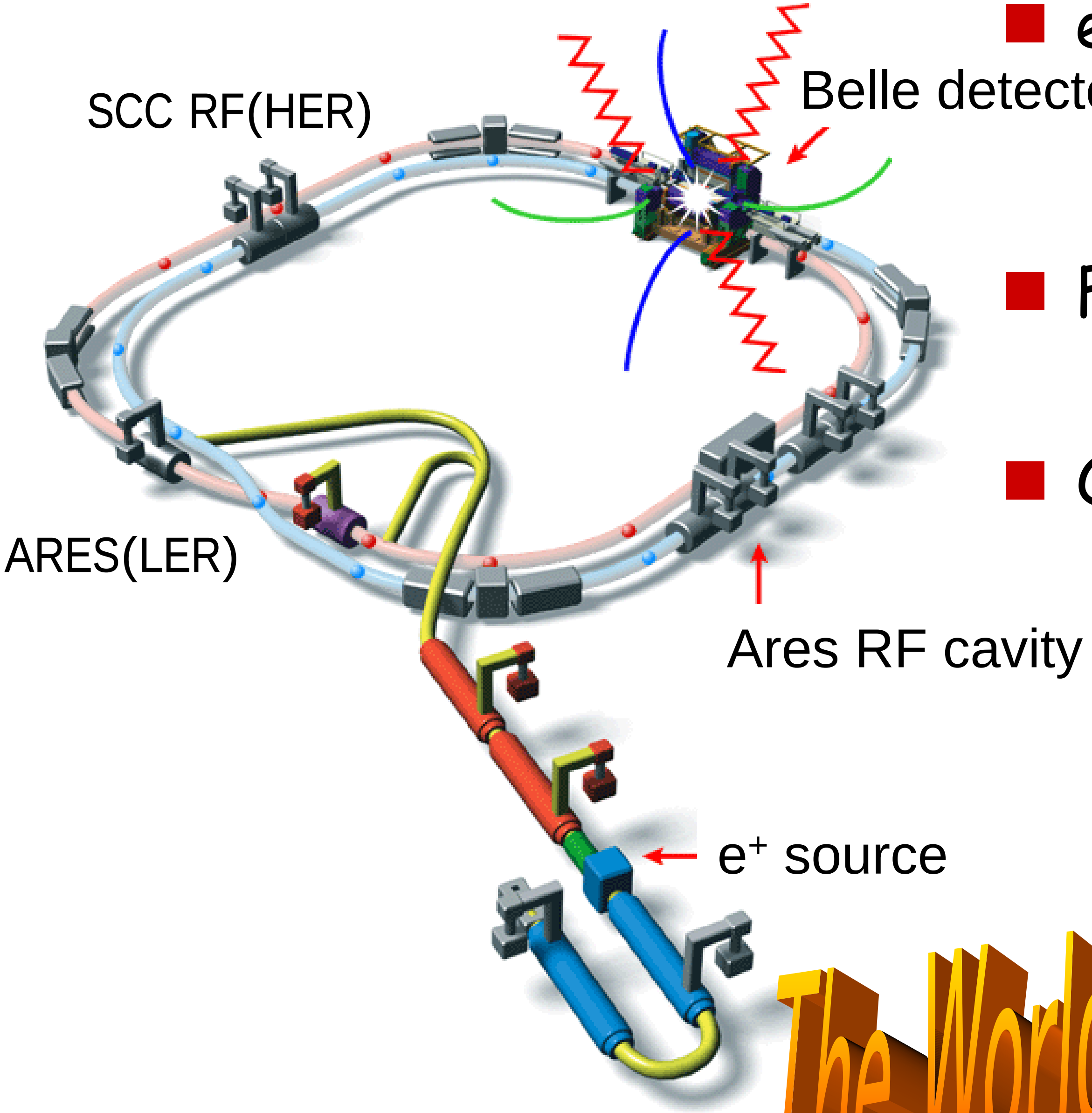
内容

- KEKB の状況
- これまでの成果
- これからの展望

今後数年間→ 数ab-1のデータ

何が注目されるか？

The KEKB Collider

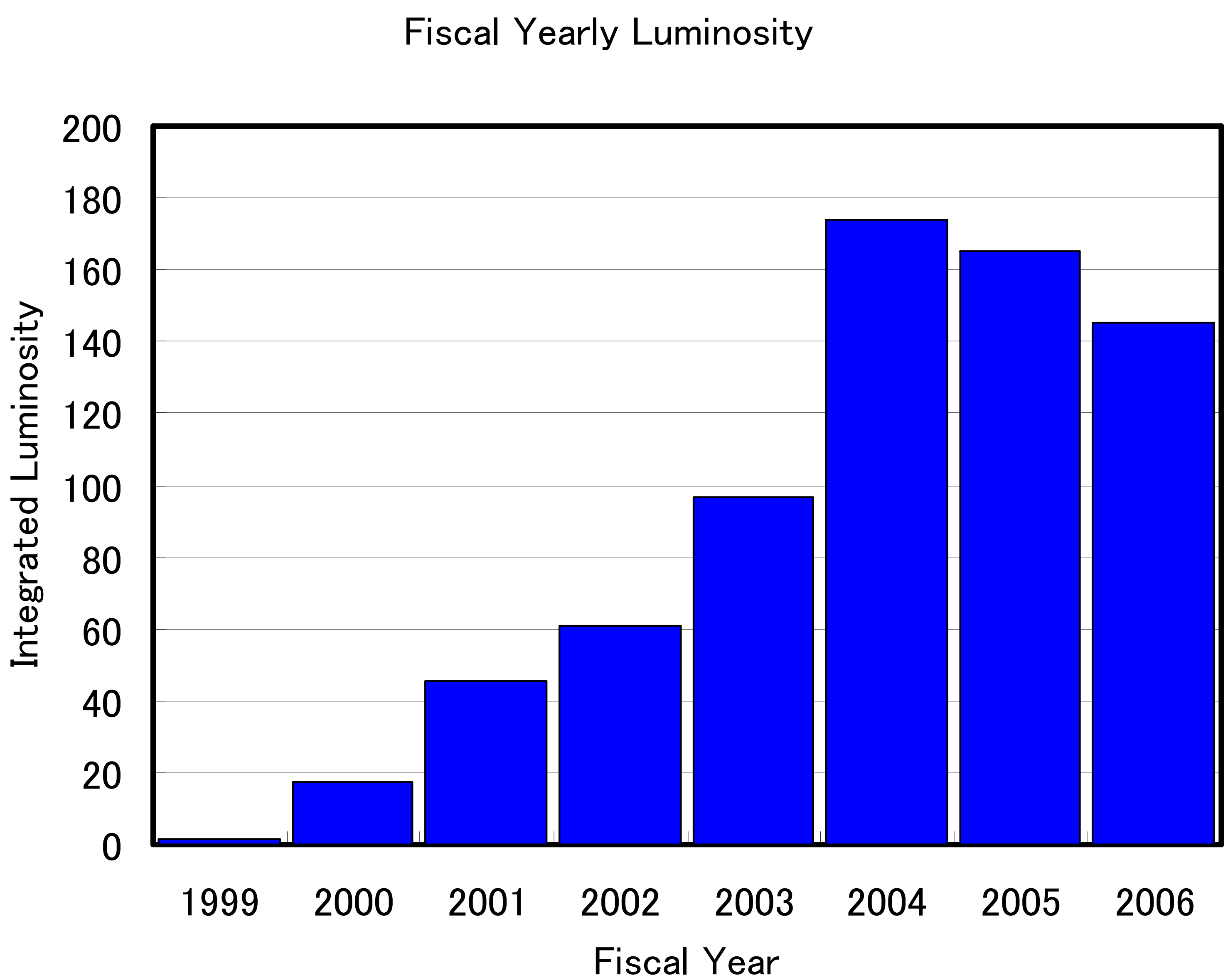


- e^- (8.0GeV) × e^+ (3.5GeV)
  - ⇒ϒ(4S) →BB
  - ⇒Lorentz boost: $\beta\gamma$ = 0.425
- Finite crossing angle
  - 11mrad ×2
- Operation since 1999.

Peak luminosity
1.71 x 10^{34} cm^{-2}s^{-1} !

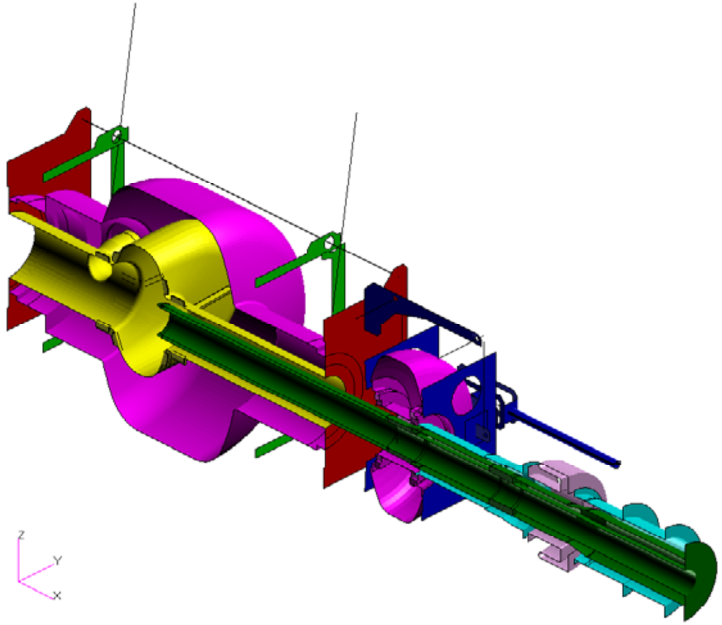
The World Highest Luminosity

Fiscal Yearly Luminosity

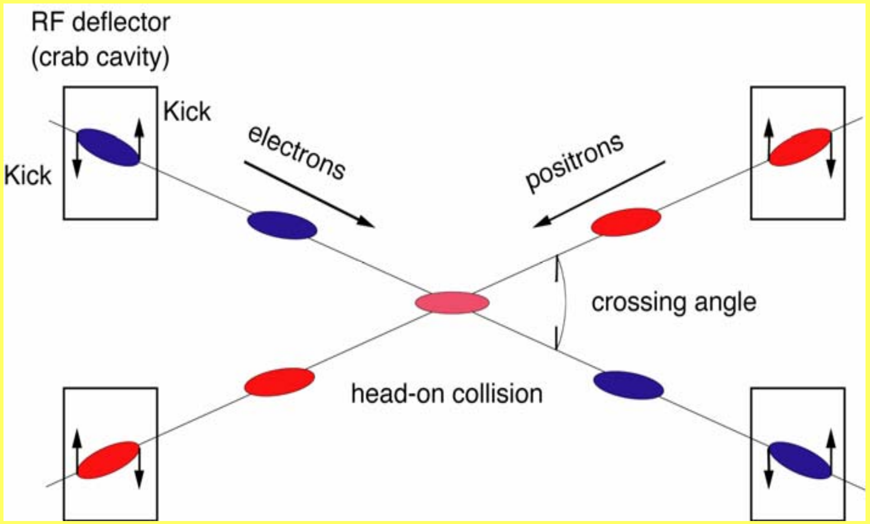


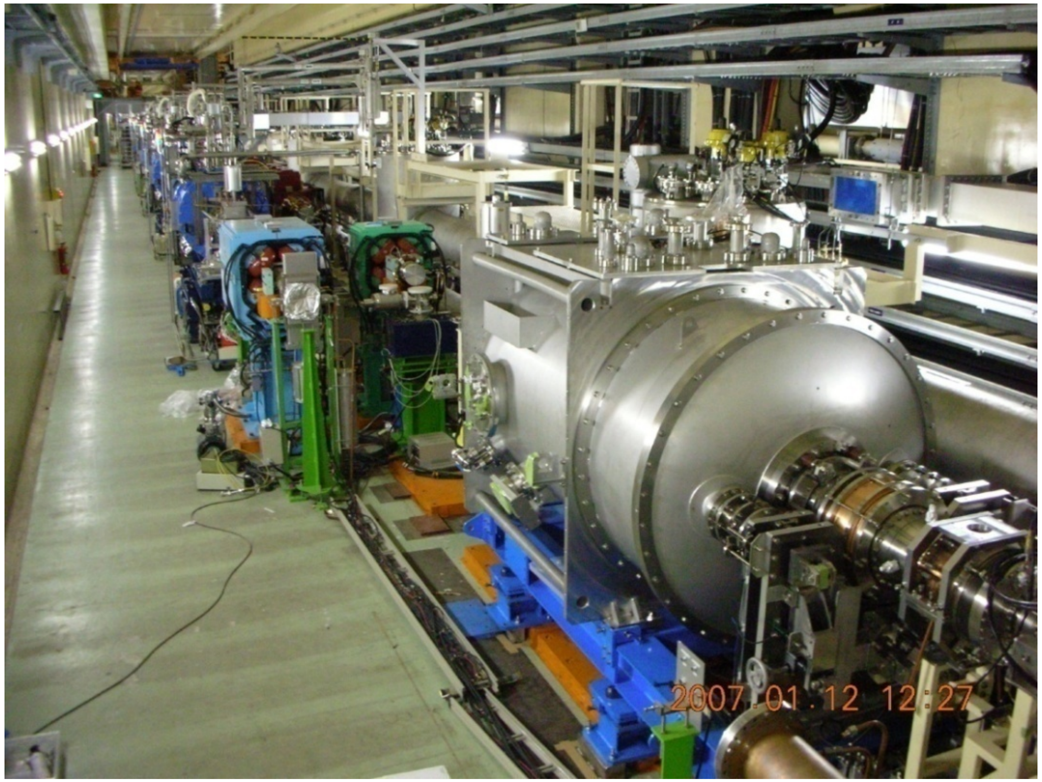
Crab Cavity

- Superconducting crab cavities (1LER and 1HER) have been installed, and being tested at KEKB.

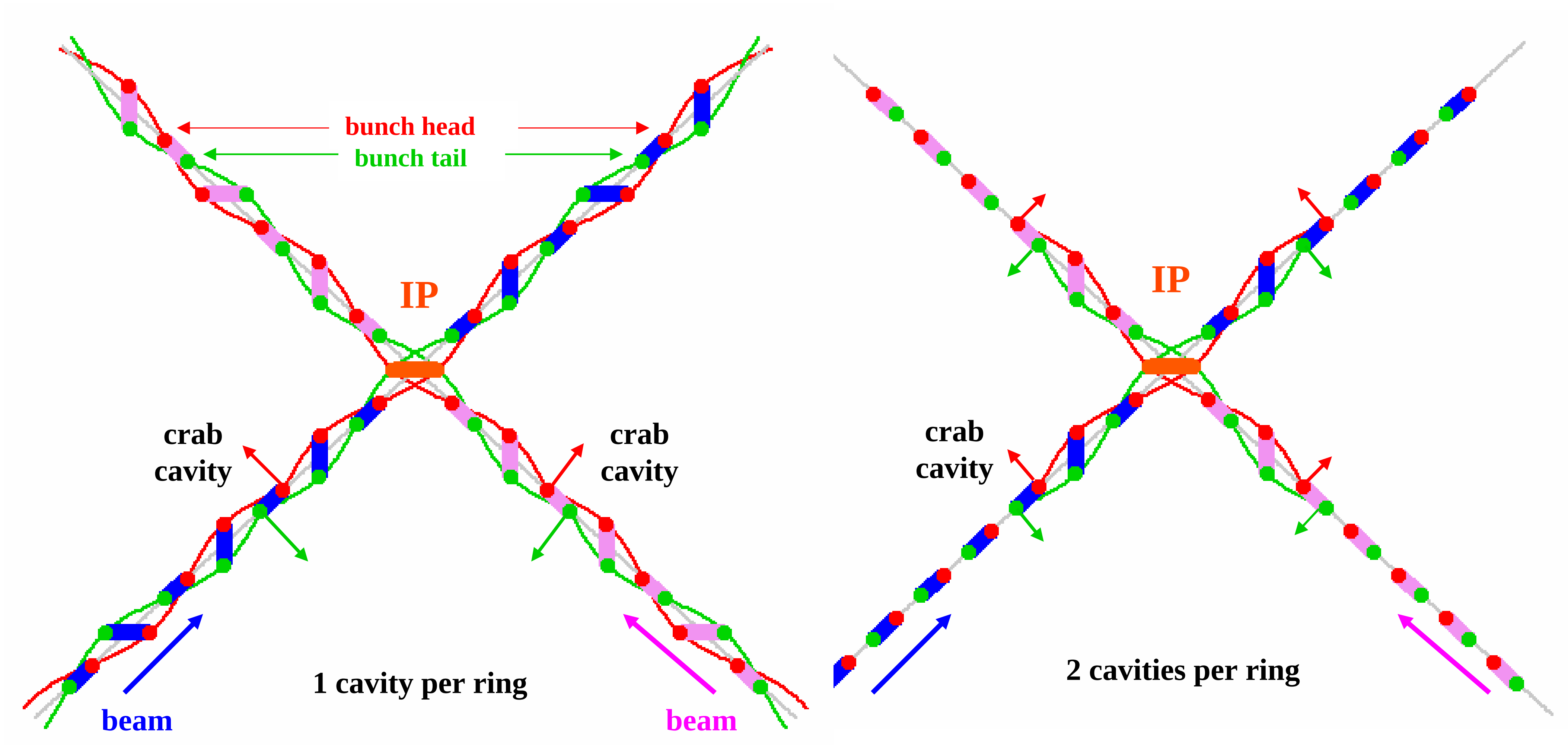


$$L \approx \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{\pm y}}{\beta_y^*}$$

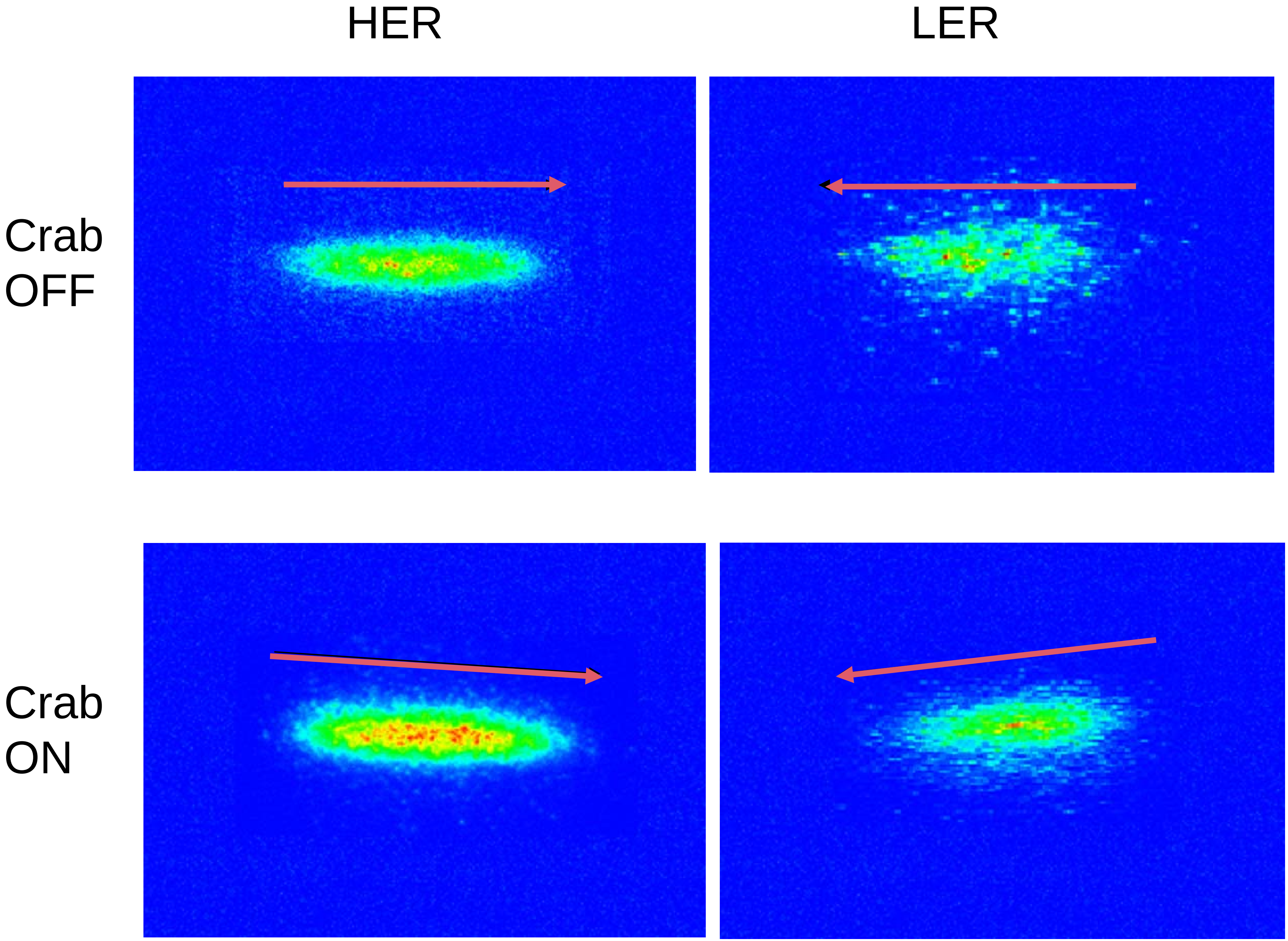




Crab Crossing

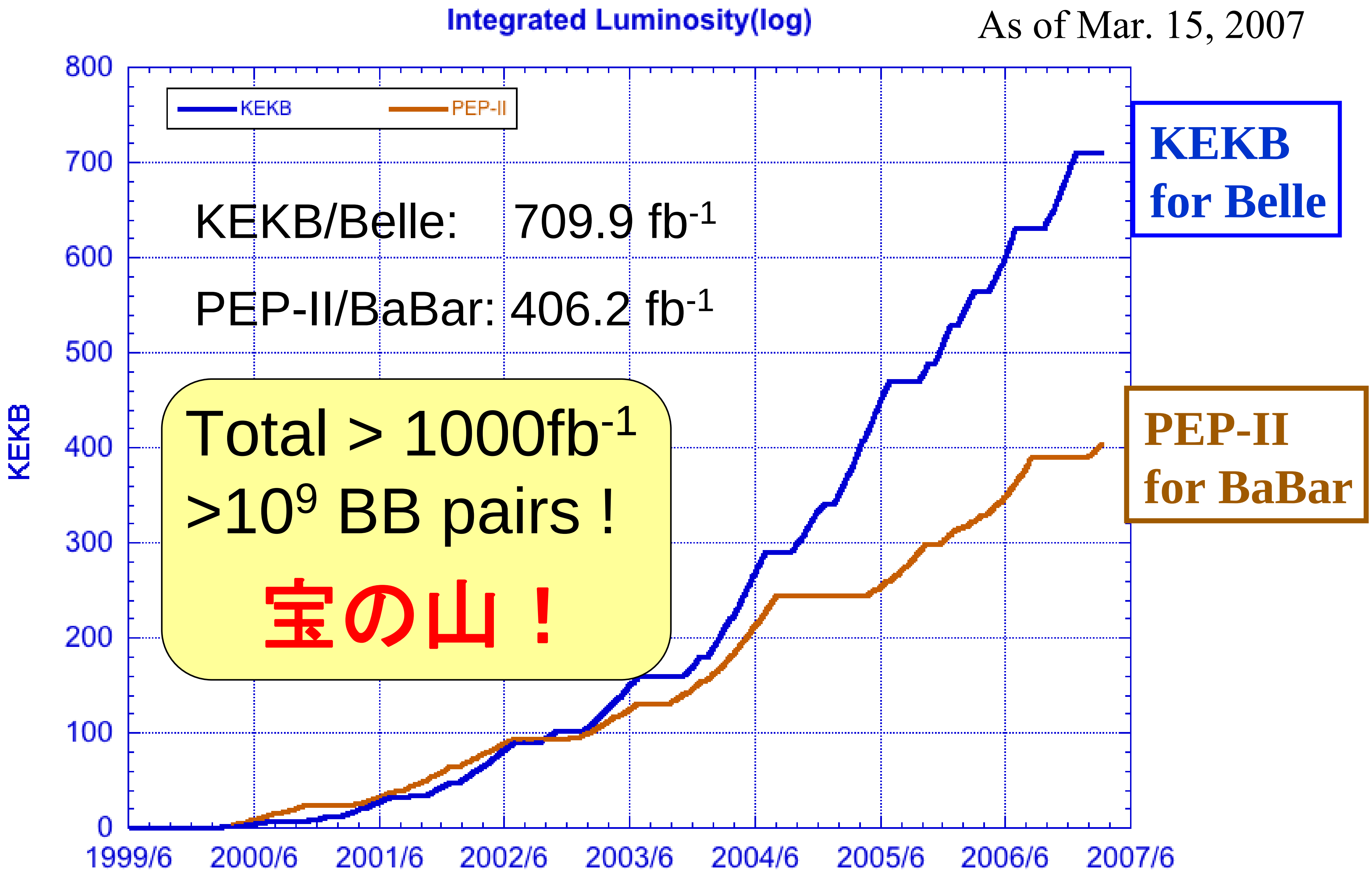


orbits of bunch head and tail



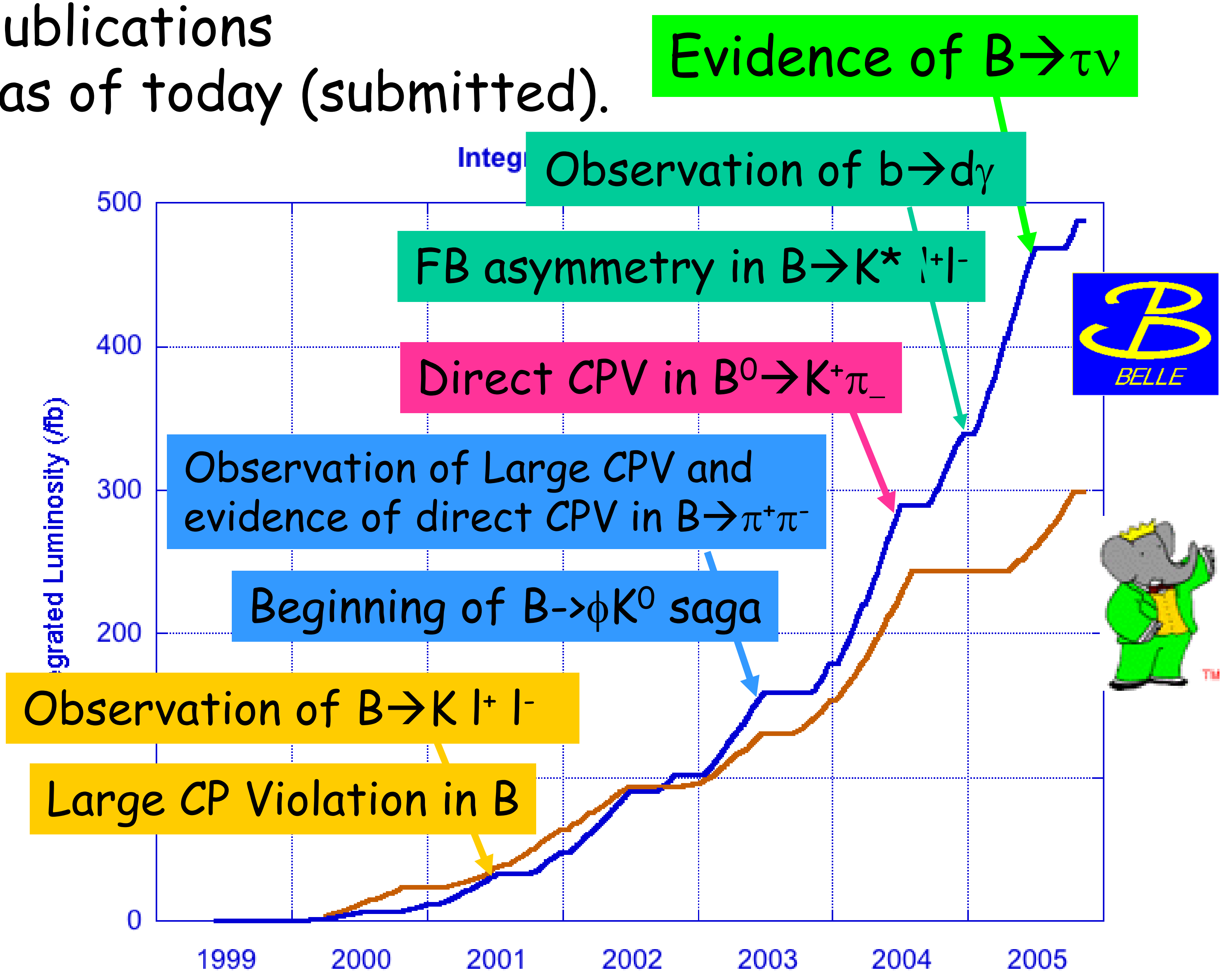
H. Ikeda, et al.

Integrated Luminosity



Belle Physics Milestone

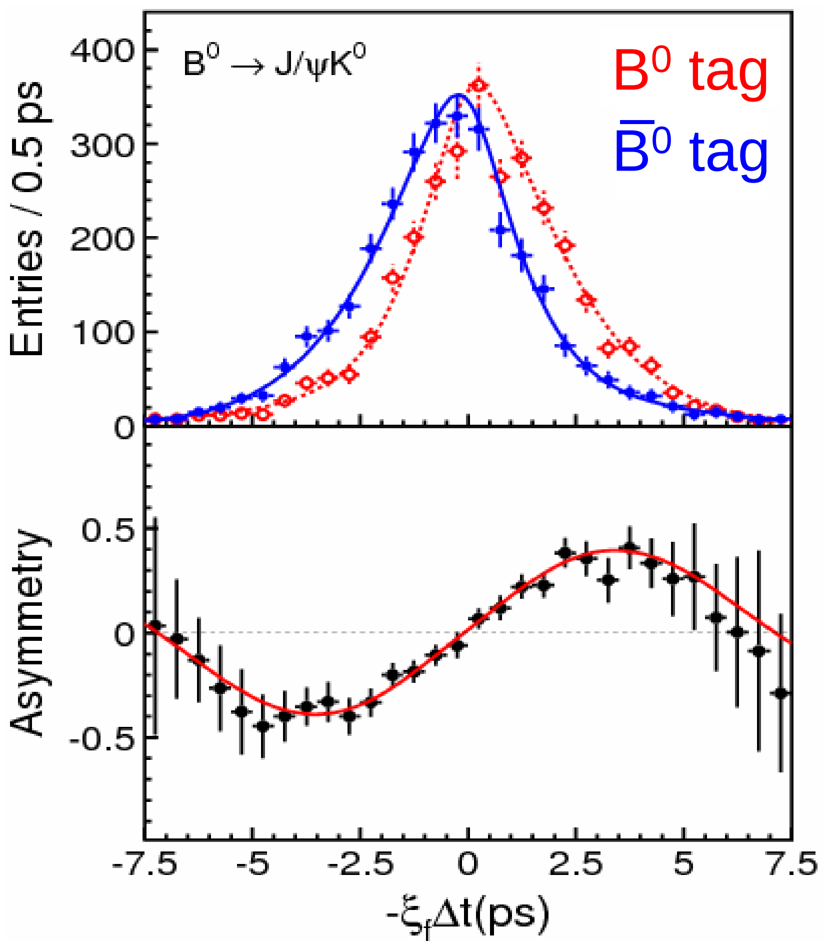
of publications
= 206 as of today (submitted).



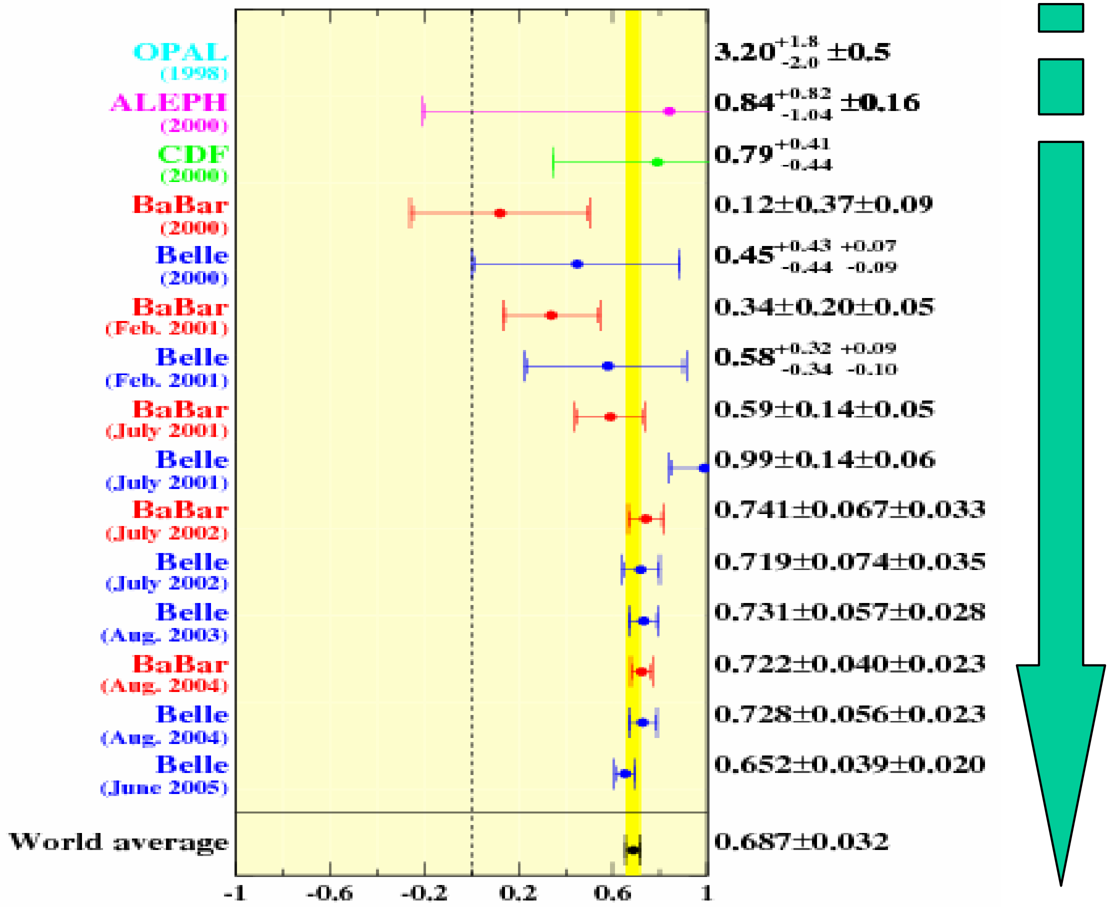
Sin2ϕ1 (Summer 2006)

Belle($B \to J/\psi$ K0): $\sin 2\phi_1 = 0.642 \pm 0.031$ (sta) ± 0.017 (sys)

W.A.: $\sin 2\phi_1 = 0.674 \pm 0.026$



sin2ϕ1 history
(1998-2005)



Success of B Factories

First precise test of CKM picture for CPV.

- $\sin 2\phi_1 = +0.674 \pm 0.026$ is now a precise measurement (~4%).
- The other angles are becoming interesting.
  - ϕ_2 from $\rho\rho\,/\rho\pi\,/\pi\pi$
  - $2\phi_1+\phi_3$ from $B \to D^{(*)}\pi$
  - $\phi 3$ from $B \to DK$ (w/ D Dalitz)

  + side measurements too.

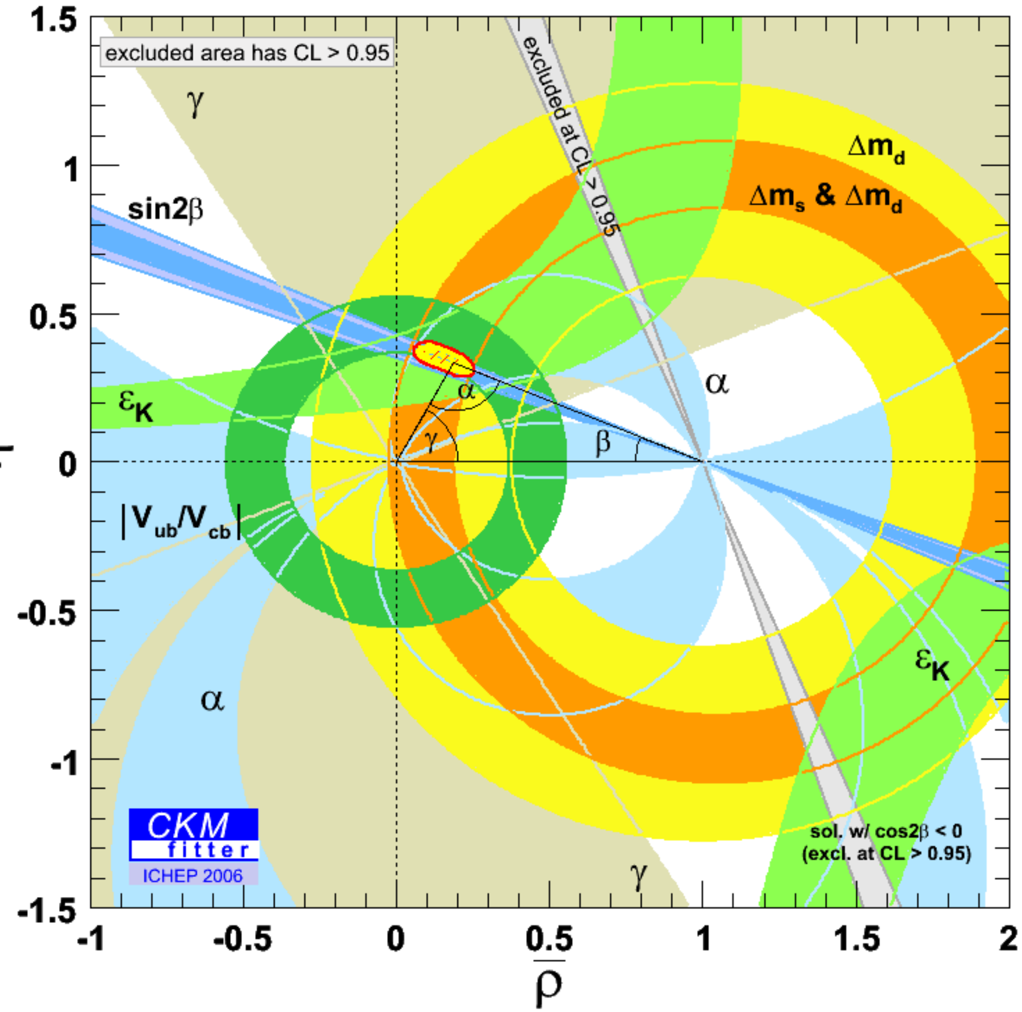
  $|V_{cb}|$, $|V_{ub}|$. Δm_d , Δm_s

Paradigm change: look for Alternatives to CKM

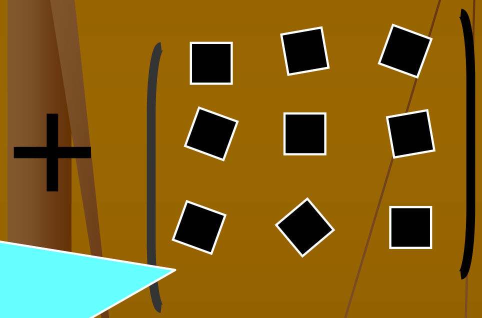
↓

Corrections by NP

Need far precise tests



Quark Flavor Physics



Open Questions

- Are there new CP-violating phases ?
- Are there new right-handed currents ?
- Are there effects from new Higgs fields ?
- Are there new flavor violation ?

Beyond CKM

dark flavor ?

Cabibbo-Kobayashi-Maskawa matrix

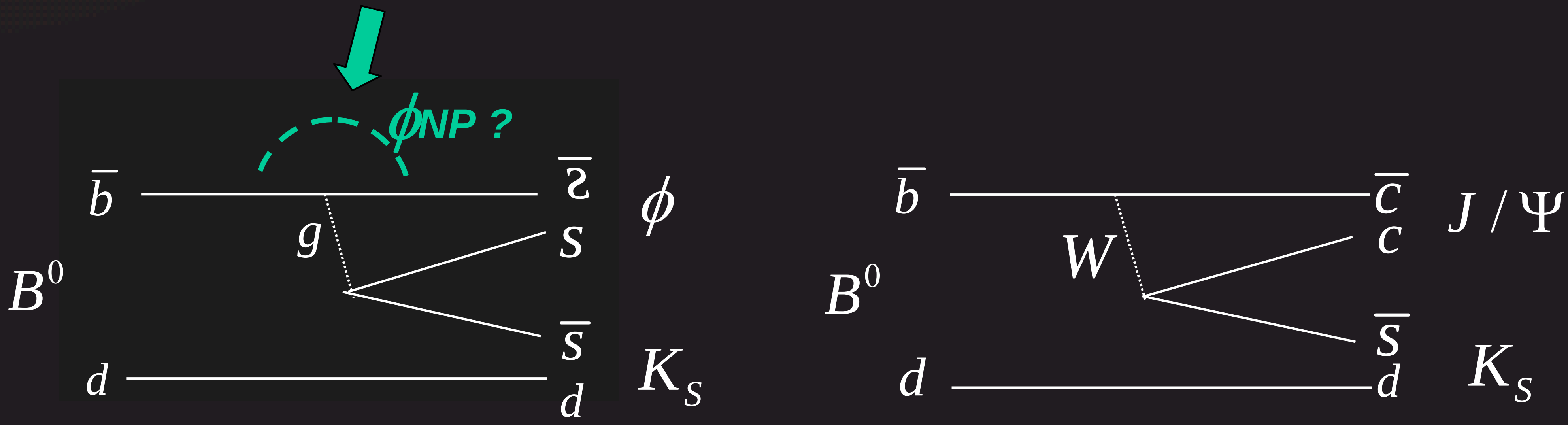
Key Measurements

1) t*CP*V in $B^0 \rightarrow \phi K^0$, $\eta' K^0$, $K_s K_s K_s$
2) t*CP*V in $B^0 \rightarrow K_s \pi^0 \gamma$
3) $B \rightarrow \tau\nu$, $\mu\nu$, $D\tau\nu$
4) FCNC: $B \rightarrow Kll$, $K\nu\nu$ (+ distribution)
5) $\tau \rightarrow \mu\gamma$
6) Unitarity triangle with O(1)% precision
   $|V_{ub}|$, $\phi 3$

These are also theoretically clean.

CPV in b→s Penguin Processes

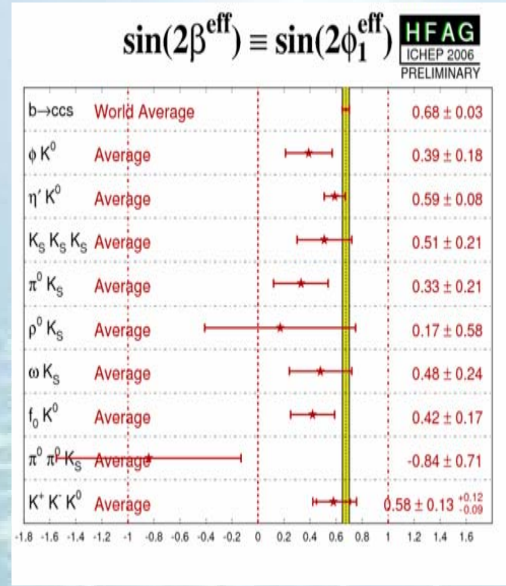
- Heavy particles may be mediated in the quantum loop.
- In SM, CPV($B^0 \rightarrow \phi$Ks) = CPV($B^0 \rightarrow J/\psi$Ks)
- If a new particle carries a quantum new phase
  CPV($B^0 \rightarrow \phi$Ks) ≠ CPV($B^0 \rightarrow J/\psi$Ks)



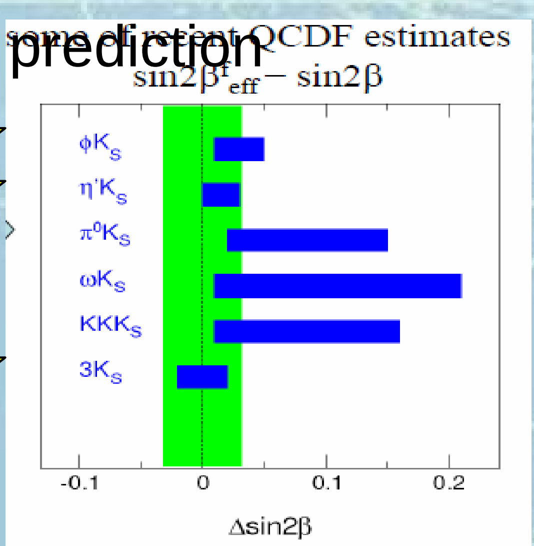
$$A_{CP}(t) = \sin 2(\phi_1 + \phi_{NP}) \times \sin(\Delta m_d t)$$

New CP Violation in b → s

2.6σ (2006) from $\sin 2\phi_1$

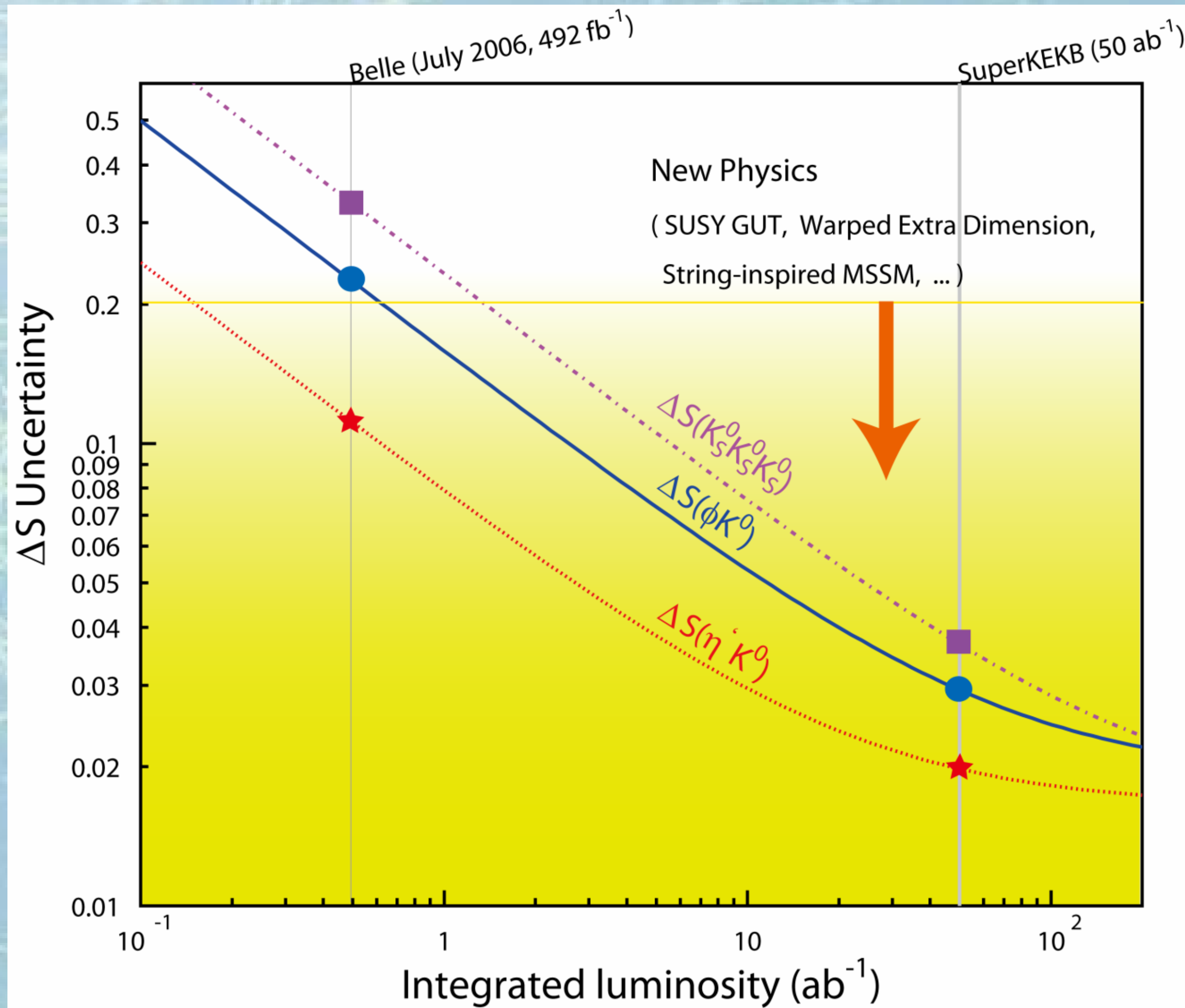


SM prediction



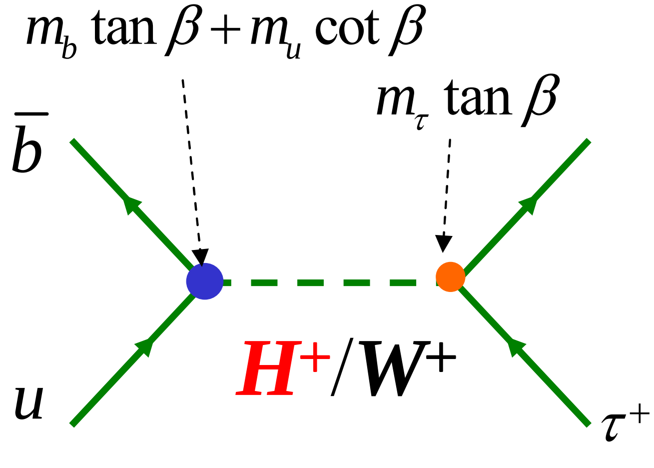
B → φK⁰, η′K⁰, KsKsKs projection for SuperKEKB

total errors (incl. systematic errors)



B→τ ν

- Proceed via W annihilation in the SM.



- SM Branching fraction is given by

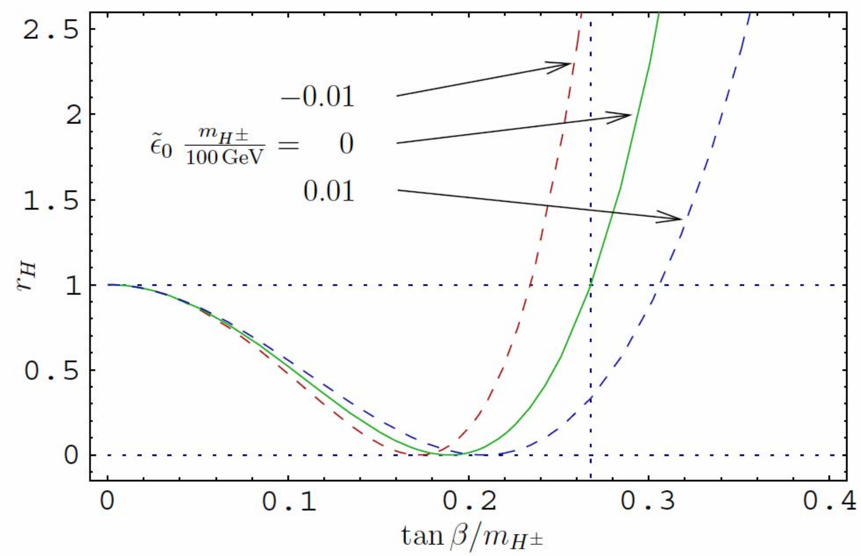
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

➡ f_B determination

- Sensitive to the charged Higgs

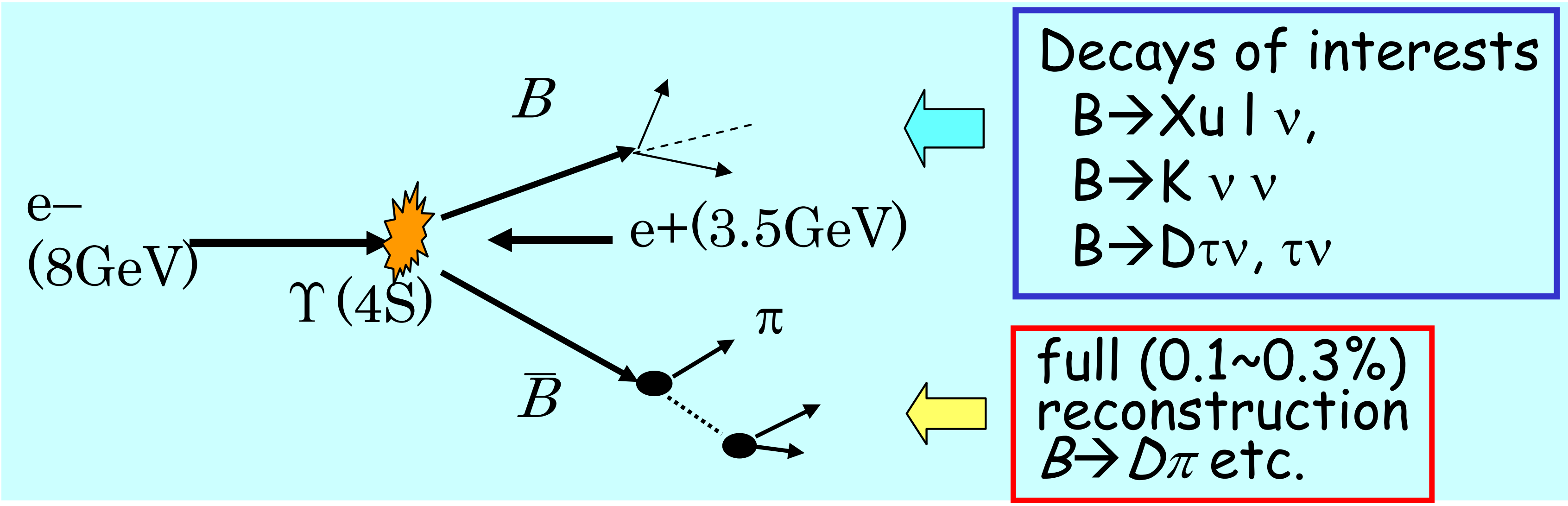
$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H$$

$$r_H = (1 - \frac{m_B^2}{m_H^2}\tan^2\beta)^2$$



Full Reconstruction Method

- Fully reconstruct one of the B's to tag
  - B production
  - B flavor/charge
  - B momentum



Single B meson beam in offline !

Powerful tools for B decays w/ neutrinos

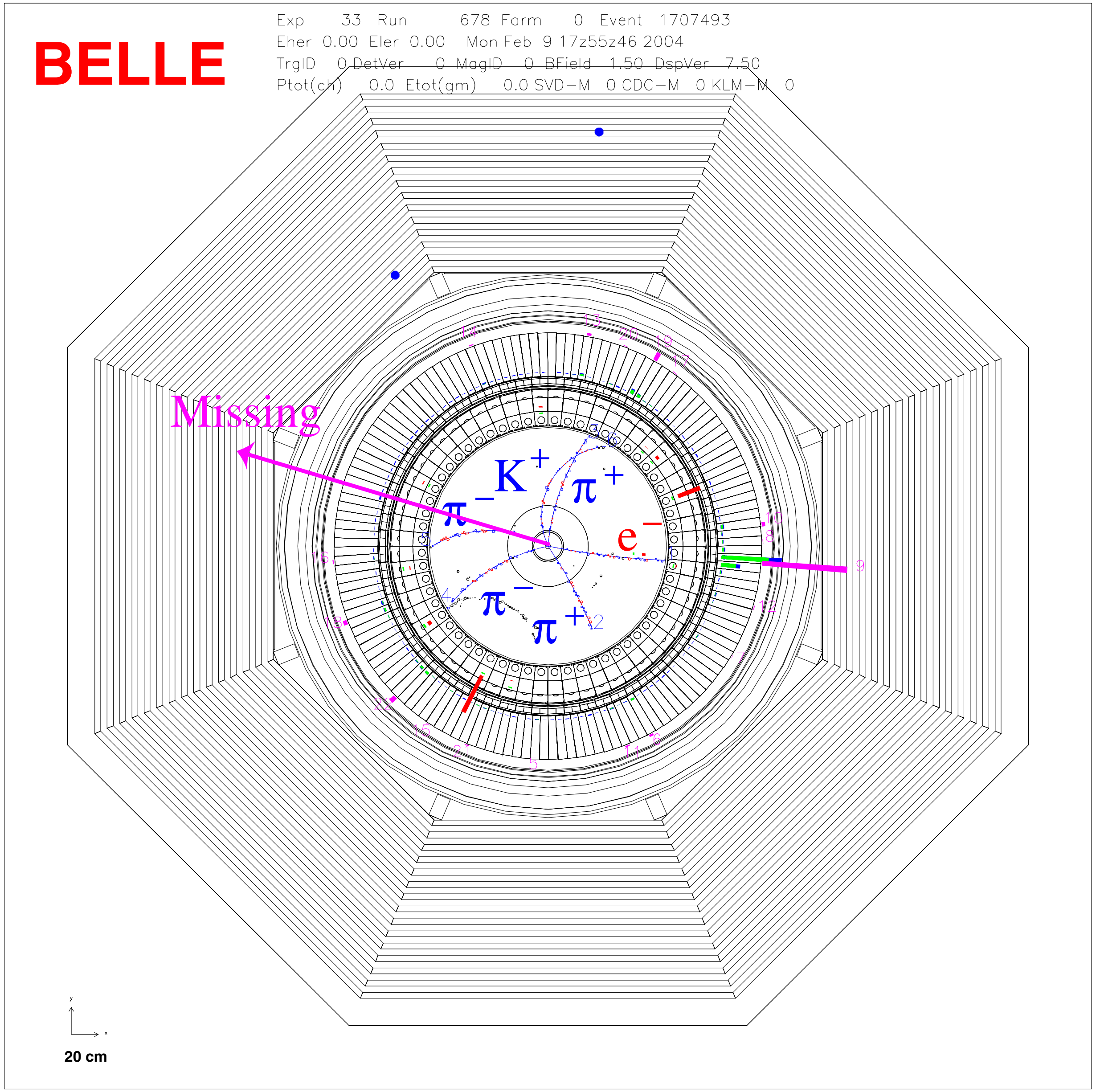
B→τν Candidate Event

$B^+ \rightarrow \overline{D}^0 \pi^+$

└→ $K^+ \pi^- \pi^+ \pi^-$

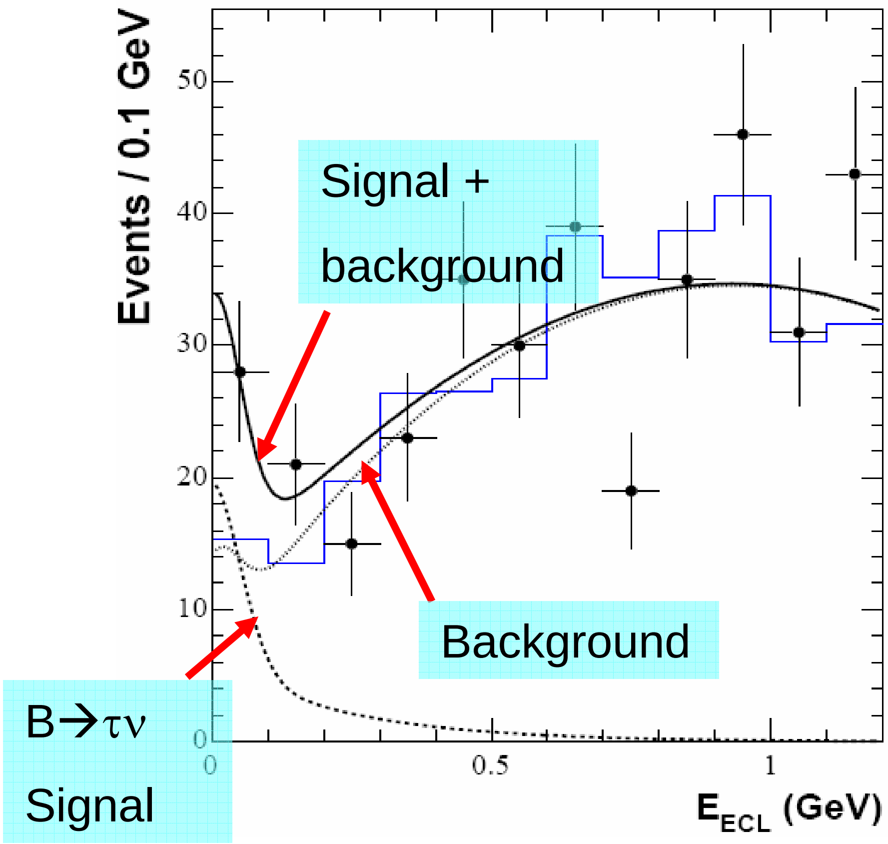
$B^- \rightarrow \tau^- \nu$

└→ $e^- \nu \nu$



The 1st Evidence of B→τ ν

- The final results are deduced by unbinned likelihood fit to the obtained E_{ECL} distributions.



	N_{obs}	N_s	N_b	Σ
$\mu^-\bar{\nu}_\mu\nu_\tau$	13	$5.6^{+3.1}_{-2.8}$	$8.8^{+0.1}_{-0.1}$	2.7σ
$e^-\bar{\nu}_e\nu_\tau$	12	$4.1^{+3.3}_{-2.6}$	$9.0^{+0.1}_{-0.1}$	1.8σ
$\pi^-\nu_\tau$	9	$3.8^{+2.7}_{-2.1}$	$3.9^{+0.1}_{-0.1}$	2.4σ
$\pi^-\pi^0\nu_\tau$	11	$5.4^{+3.9}_{-3.3}$	$5.4^{+0.6}_{-0.6}$	1.7σ
$\pi^-\pi^+\pi^-\nu_\tau$	9	$3.0^{+3.5}_{-2.5}$	$4.8^{+0.4}_{-0.4}$	1.1σ
Combined	54	$17.2^{+5.3}_{-4.7}$	$32.0^{+0.7}_{-0.7}$	4.6σ

Σ : Statistical Significance

Observe 17.2 $^{+5.3}_{-4.7}$ events.
Significance decreased to 3.5 σ after including systematics

Signal shape : Gauss + exponential
Background shape : second-order polynomial + Gauss (peaking component)

PRL97, 251802 (2006)

f_B Extraction

- Product of B meson decay constant f_B and CKM matrix element $|V_{ub}|$

$$f_B \times V_{ub} = (10.1^{+1.6+1.1}_{-1.4-1.3}) \times 10^{-4}\, GeV$$

- Using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ from HFAG

$$f_B = 229^{+36+30}_{-31-34}\, MeV$$

15% 14% = 12%(exp.) + 8%(V_{ub})

$f_B = 216 \pm 22$ MeV

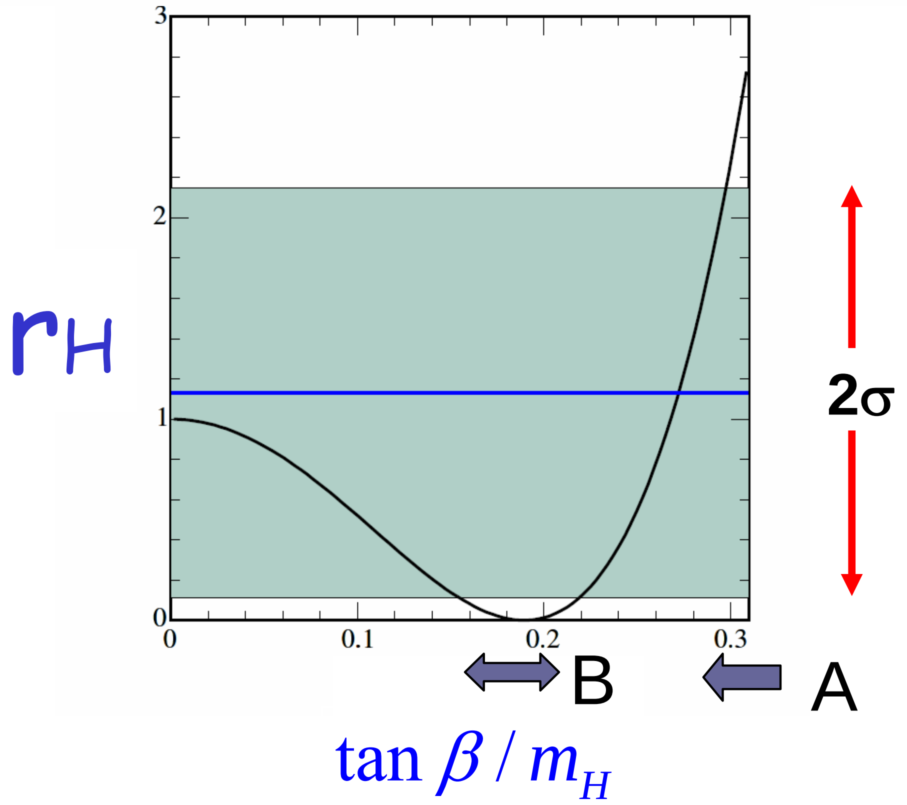
[HPQCD, Phys. Rev. Lett. 95, 212001 (2005)]

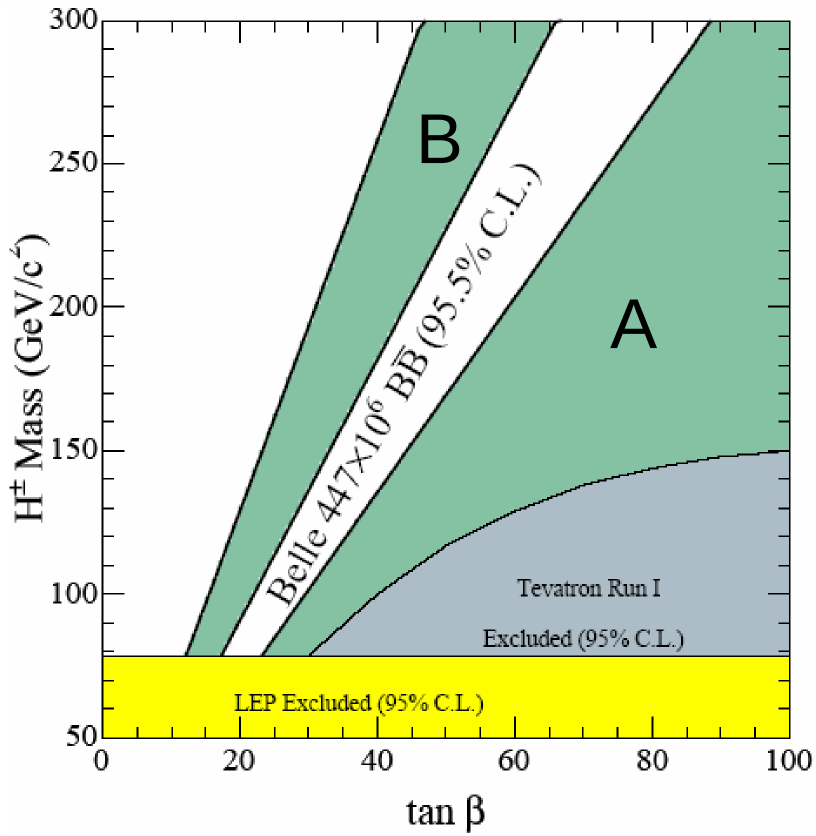
Constraints on Charged Higgs

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\rm SM} \times r_H$$

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2 \quad \to \quad r_H = 1.13 \pm 0.51$$

- ◇ Experimental result : $\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49}(\text{stat})^{+0.39}_{-0.46}(\text{syst})) \times 10^{-4}$
- ◇ SM prediction : $\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = (1.59 \pm 0.40) \times 10^{-4}$





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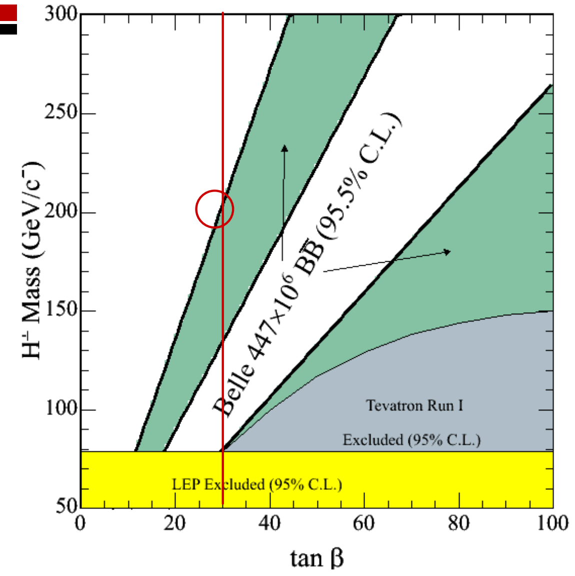
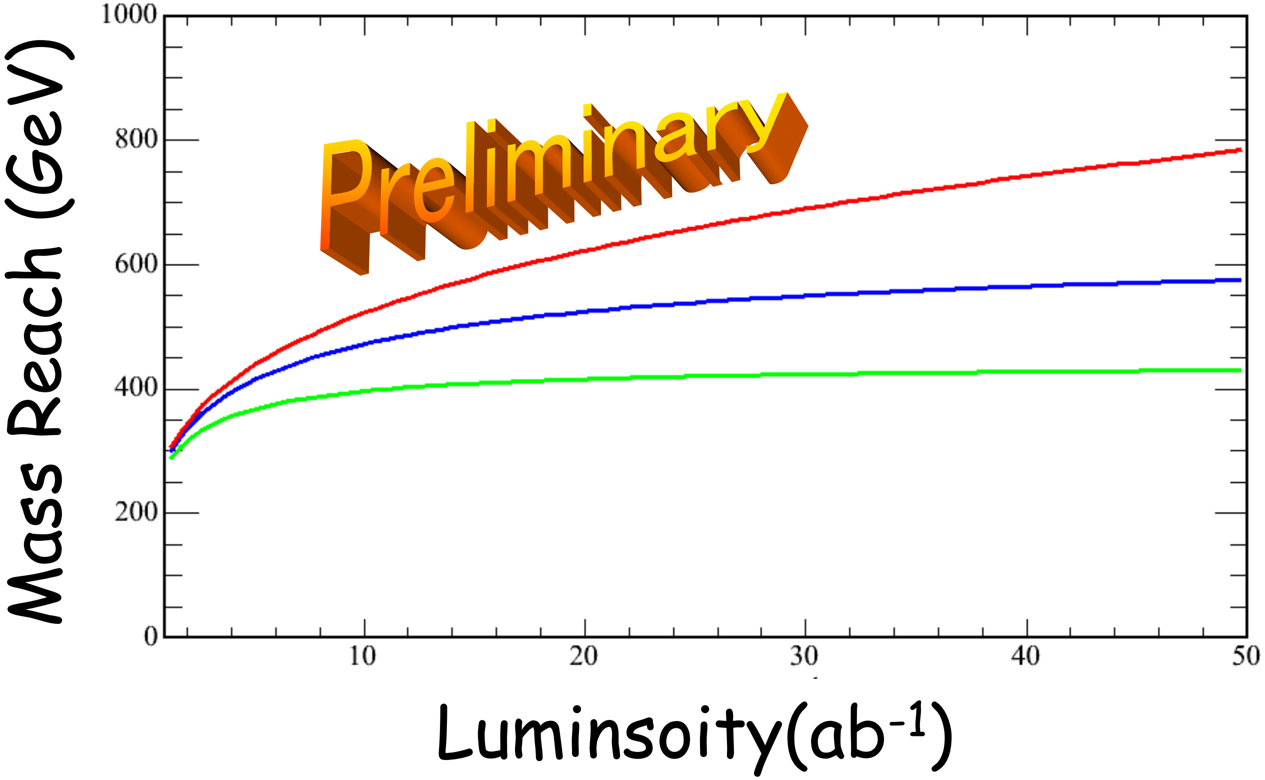


Charged Higgs Mass Reach
(95.5%CL exclusion @ tanβ=30)



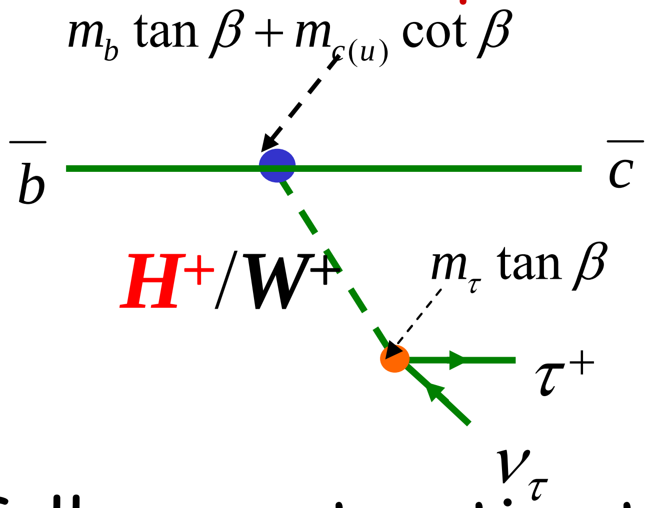
Only exp. error
(ΔV_{ub}=0%, Δf_B=0%)

ΔV_{ub}=2.5%, Δf_B=2.5%

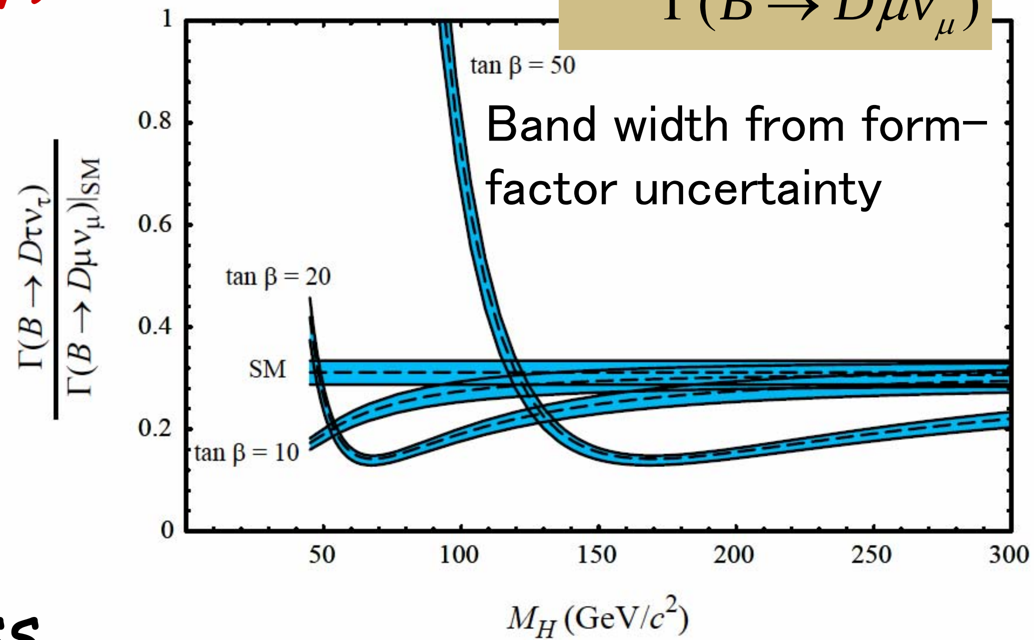
ΔV_{ub}=5%, Δf_B=5%

Search for Charged Higgs

- $B \to D\tau\nu$ (semileptonic decay)

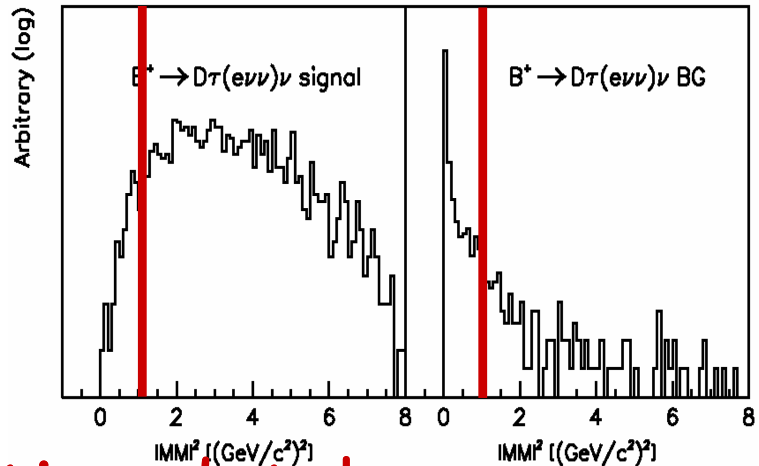


$$B = \frac{\Gamma(B \to \bar{D}\tau\nu_\tau)}{\Gamma(B \to \bar{D}\mu\nu_\mu)}$$



- Full reconstruction tag
- Signal → large missing mass
- Expected at $1/5ab^{-1}$

Mode	Nsig	Nbkg	dB/B
$D^0\tau^+(\ell^+\bar{\nu}_\tau\nu_\ell)\nu_\tau$	56/280	110/550	17/7.9%
$D^0\tau^+(h^+\bar{\nu}_\tau)\nu_\tau$	124/620	720/3600	



Good chance to find in the existing data!

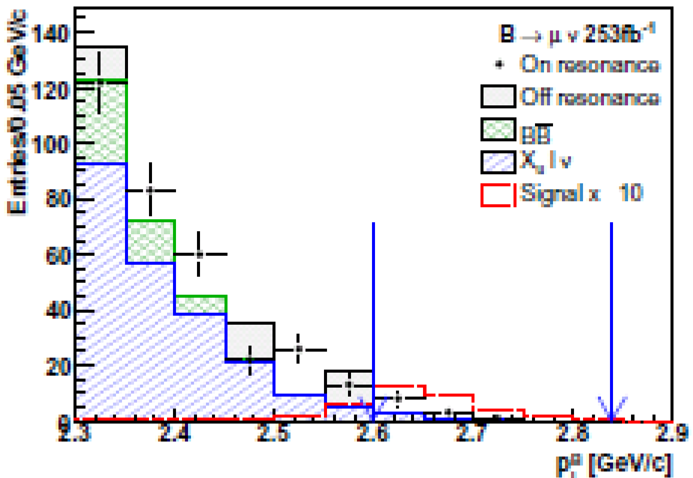
B→μν (eν)

SM prediction.
Br(τν)=1.6x10^{-4}
Br(μν)=7.1x10^{-7}
Br(eν)=1.7x10^{-11}

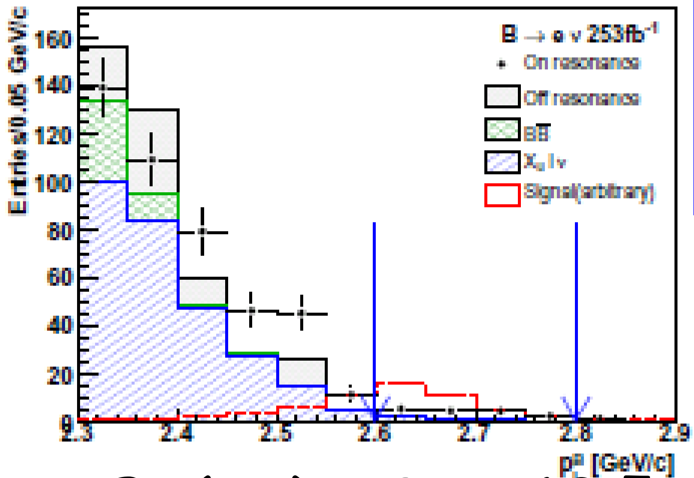
- Signal = monoenegetic charged lepton
- Inclusive reconstruction employed.
  - Reconstruct the accompanying B via a 4-vector sum of everything else in the event.
  - Efficiency: 2.18±0.06% (μν), 2.39±0.06% (eν)
  - N_{SM}: 2.8±0.2 (μν), (7.3±1.4)x10^{-5} (eν)

253fb $^{-1}$

μν



eν



@90%CL Br(μν) < 1.7x10^{-6} Br(eν) < 9.8x10^{-7}

hep-ex/0611045, to appear in Phys. Lett. B

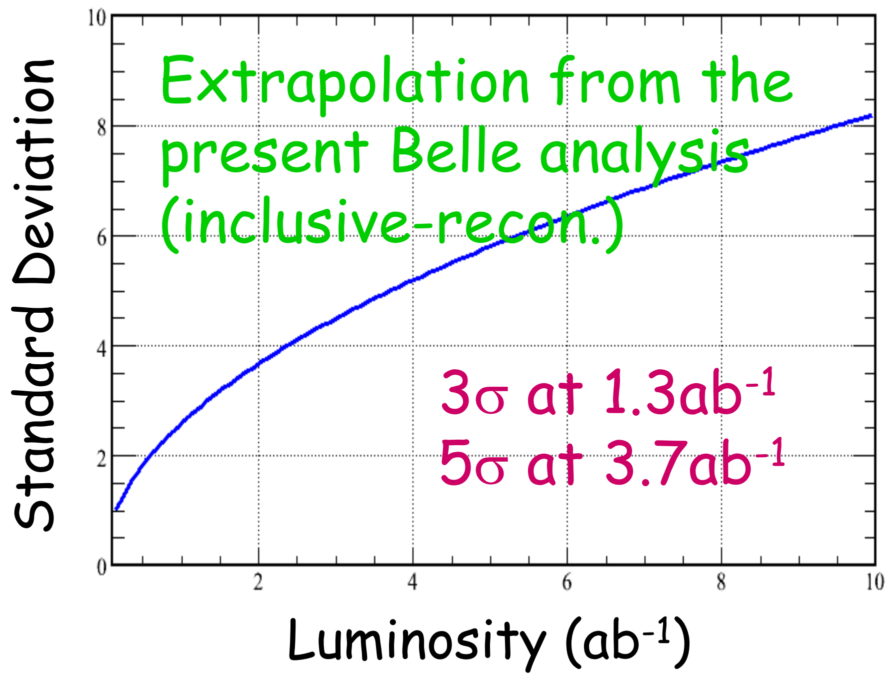
B→μν (eν)

Preliminary

- B→μν is the next milestone decay.

We may start to see by adding more data.

~50 events @ 5ab-1
~500 events @ 50ab-1

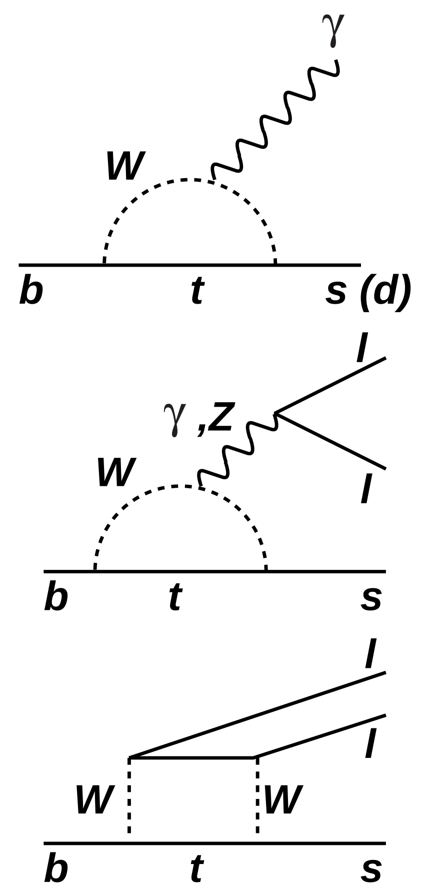


- Precise B→τ ν/μ ν data provide lepton universality test.
  - Higgs effect itself is universal.

    $R_H^{\tau\nu} = R_H^{\mu\nu}$
  - Good probe to distinguish NP models.

FCNC Decays

- FCNC processes: $b \to s\gamma$, $b \to sll$ decays
  - Forbidden in SM at tree level.
  - Occur via box diagrams or penguin loops.



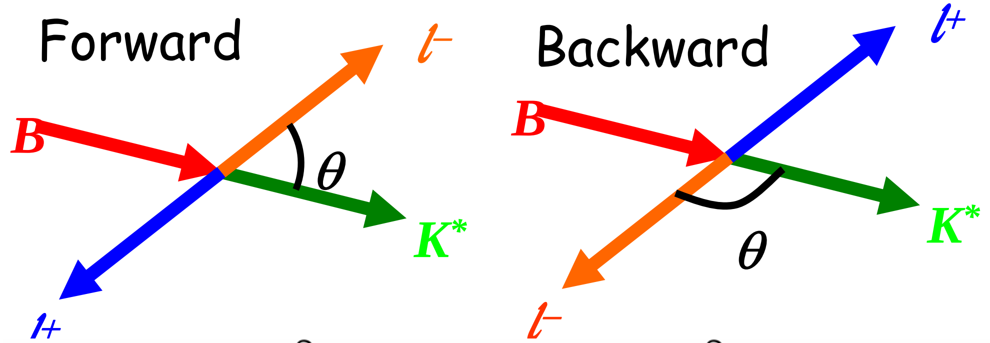
- Sensitive to non-SM physics (charged Higgs, SUSY,…).
  - $B \to K^*(892)\gamma$
    - Rate difference bet. charged and neutral decays
    - Charge asymmetry (Acp < 1% in SM)
  - $B \to \rho\gamma$, $B \to \omega\gamma$
    - $|Vtd/Vts|^2$
  - $B \to K^{(*)}ll$, $B \to Xsll$
    - Branching fractions, dilepton mass spectrum, F-B asymmetry

Clean low energy tool to probe high energy scale !

B→K*ll FB Asymmetry

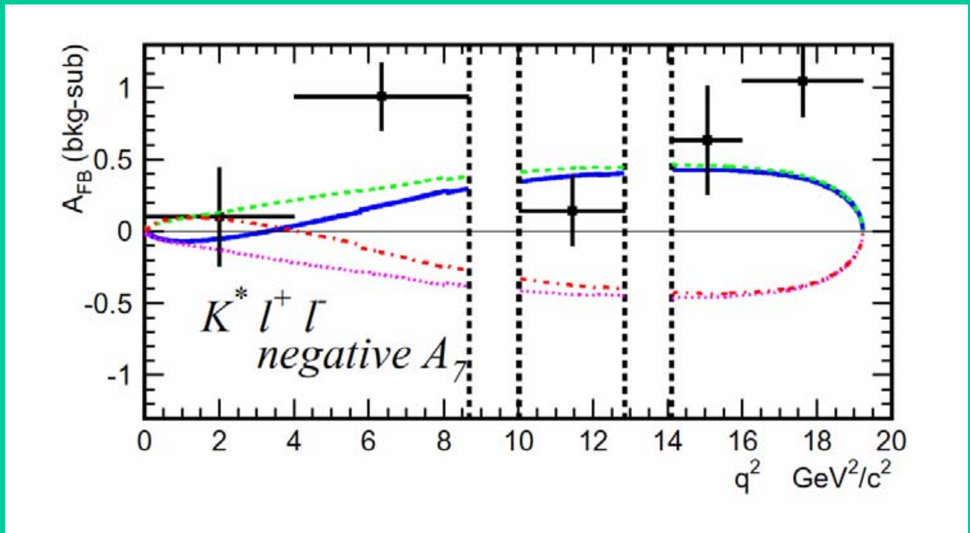
- q^2 distribution has different pattern depending on sign(C_7).

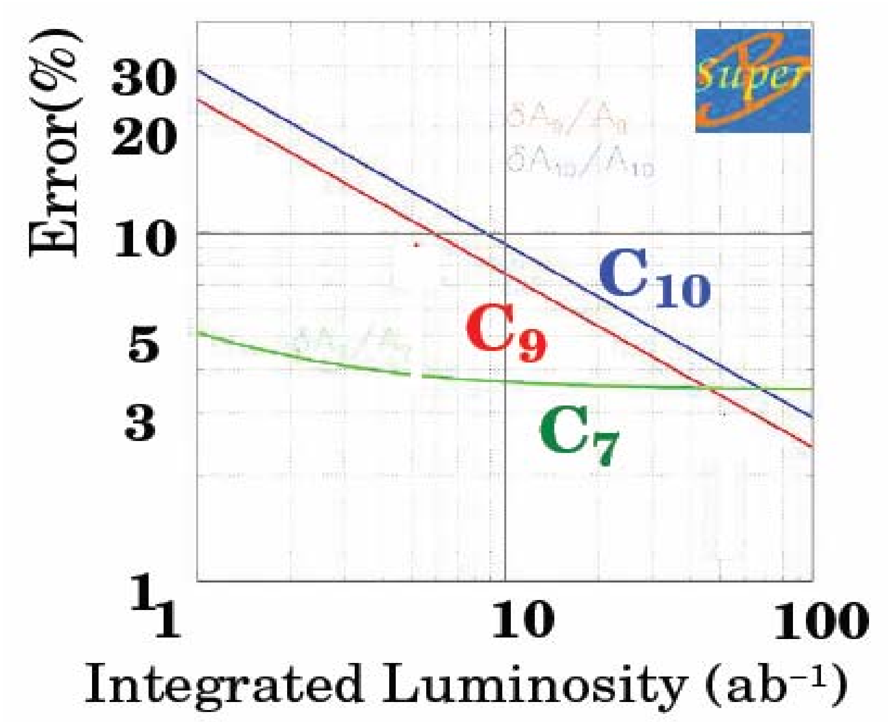
$$A_{FB} \propto \Re\left[C_{10}^{*}\left(sC_9^{eff}(s) + r(s)C_7\right)\right]$$



$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) - \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) + \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}$$

Belle (386MBB), PRL96,251801(2006)





q_0(the point w/ A_{FB}=0) is sensitive for New Physics

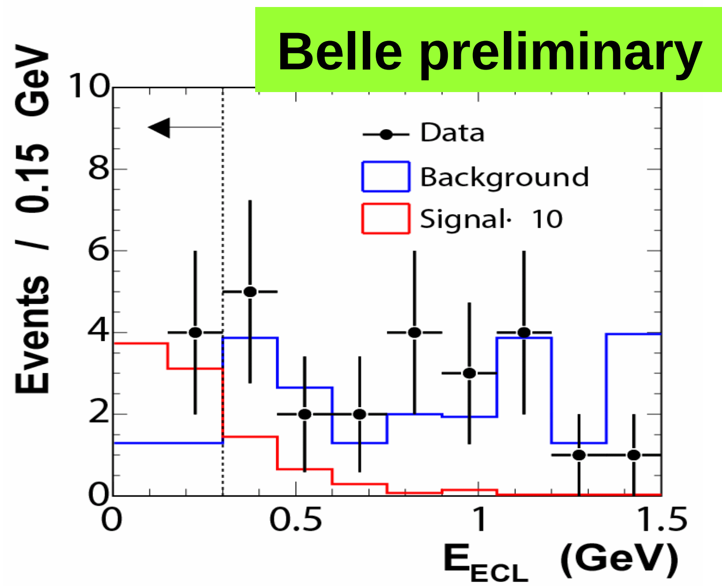
SM; $q_0^2=(4.2\pm0.6)\mathrm{GeV}^2$

Future Prospect: B→Kνν

- Belle @ 250fb^{-1} (preliminary)

cf.) K.Ikado @ BNM2006

Fully reconstructed tag (by modifying the PID criteria used in B→τν analysis).



Efficiency(%)	42.8 ± 1.8
Signal expected	0.70 ± 0.03
Background expected	2.6 ± 1.6
Observed Events	4

Consistent with BG expected

$$\mathcal{B}(B^+ \to K\nu\bar{\nu}) < 3.6 \times 10^{-5} (90\% \text{C.L.})$$

Signif.	Lum (ab^{-1})
3σ	12
5σ	33

Need Super-B !

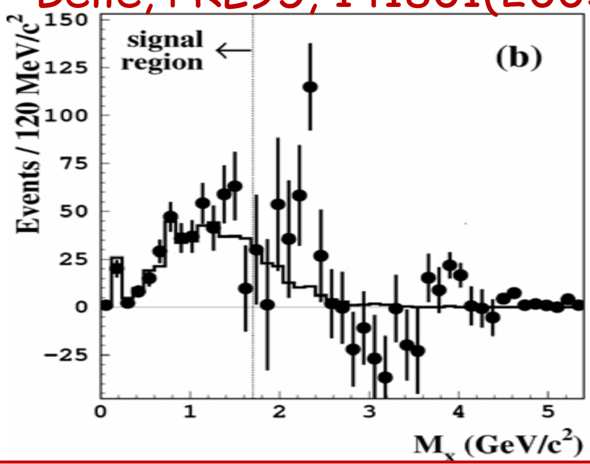
$|V_{ub}|$ Measurement

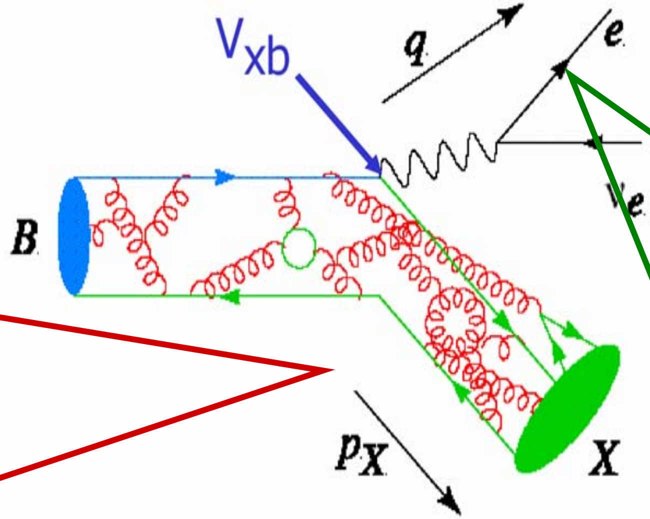
- Semileptonic decays are the most common utilities.
- Measurement of $b \to ul\nu$ suffer from $O(10^3)$ larger $b \to cl\nu$ background, and need introduce a cut → extrapolation error.
- In B factory era, tagging allows us to measure not only Pl, but also Mx and q2, by which the extrapolation error can be reduced.

$M_X < M_D$ ~80%

Mx (hadron mass)

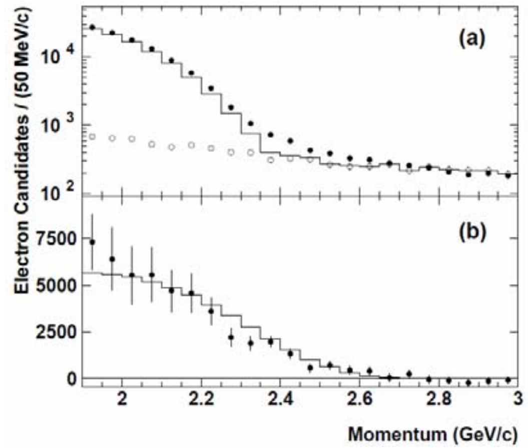
Belle, PRL95, 141801(2005)





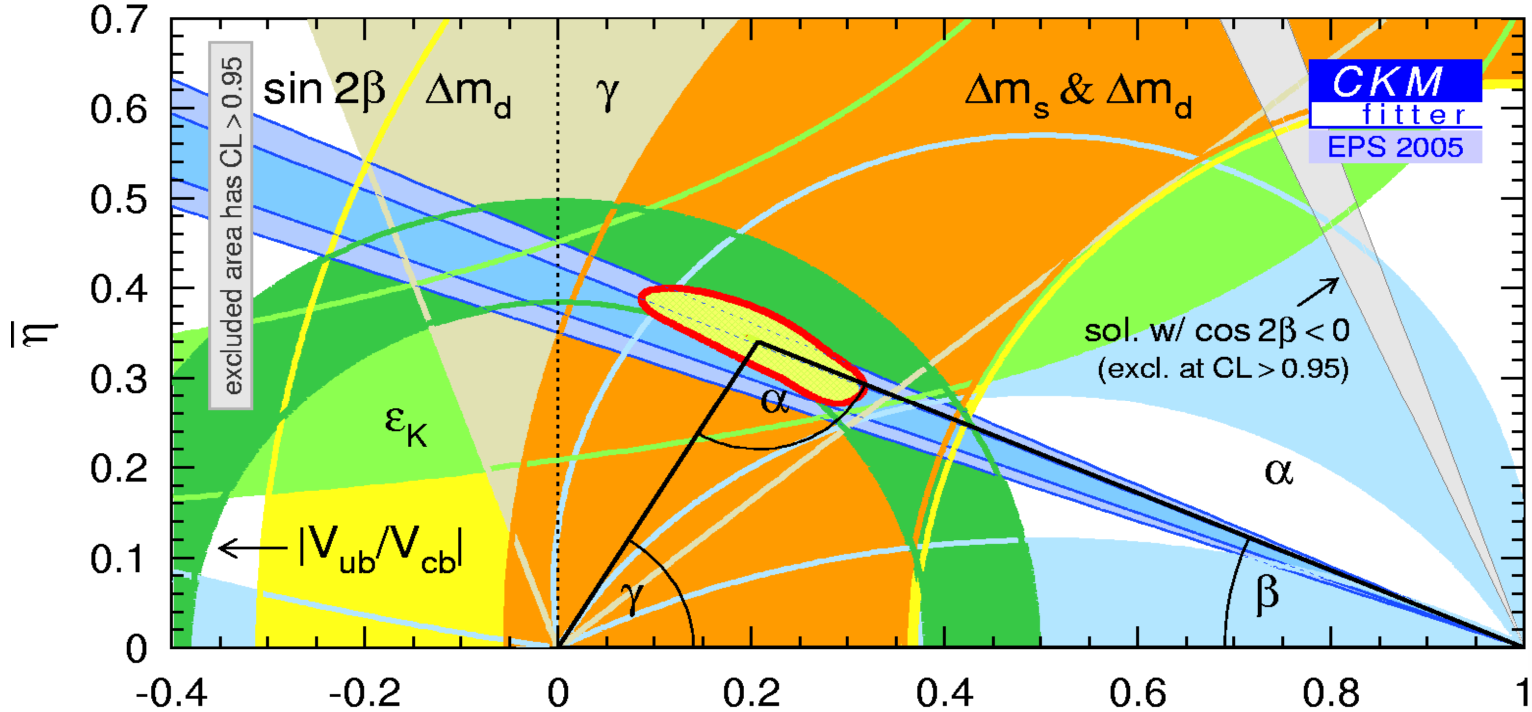
Pl at endpoint

Belle, PLB621, 28(2005)



$$E_\ell > \frac{m_B^2 - m_D^2}{2m_B}$$ ~10%

CKM at Summer02 → 05



GOAL w/ 500-1000 fb^{-1} data

$\Delta|V_{ub}|$ < 5% with both inclusive and exclusive

(the two approaches will cross check each other)

$|V_{ub}|$ tension & $B \to \tau\nu$

- $|V_{ub}|$ tension problem: measured $|V_{ub}|$ is larger than that from the CKM fit.
- $\tau\nu$ tension? : measured $Br(\tau\nu)$ is larger than that from the CKM fit.
- Something may be wrong with the measured $|V_{ub}|$?

  But, it cannot solve the two at the same time.

$|Vub|_{fit}=(3.68 +0.11-0.08)\times 10^{-3}$

$|Vub|_{HFAG}=(4.49 \pm 0.19 \pm 0.27)\times 10^{-3}$

"Vub tension"?

$Br(\tau\nu)_{fit}=(0.87 +0.13-0.20)\times 10^{-4}$

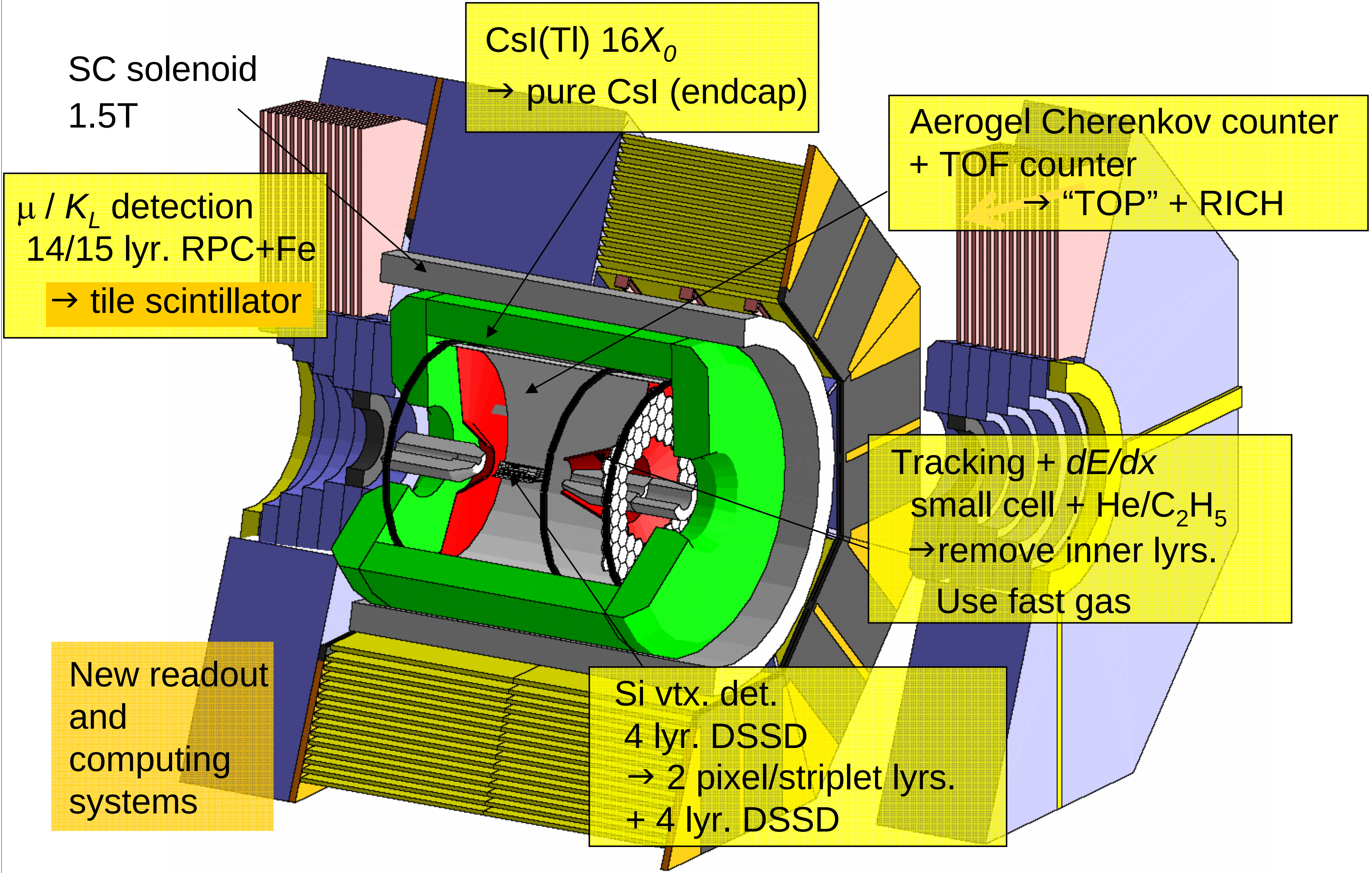
$Br(\tau\nu)_{belle}=$
$(1.79 +0.56-0.49 +0.46-0.51)\times 10^{-4}$

"$B \to \tau\nu$ tension"?

f_B lattice ?

- It would be very interesting to see this comparison with improved $B \to \tau\nu$ measurement.
- It is important to cross check $|V_{ub}|$ with exclusive.

Belle Upgrade



まとめ

- 世界最強のKEKBを crab cavity でさらに増強。
  - 150fb-1/年 →300fb-1/年
  - 2~3 ab-1 by 2009.

- B物理で注目すべきところ
  - ペンギン崩壊におけるCPV → 新しいCPV位相
  - FCNC: forward-backward asymmetry in Kll
  - Higgs effect
    - B→τν,　観測済。精度向上
    - Dτν, μν,　まず観測。
  - |Vub| + φ3

他にもたくさん

⇒ Super-B へ

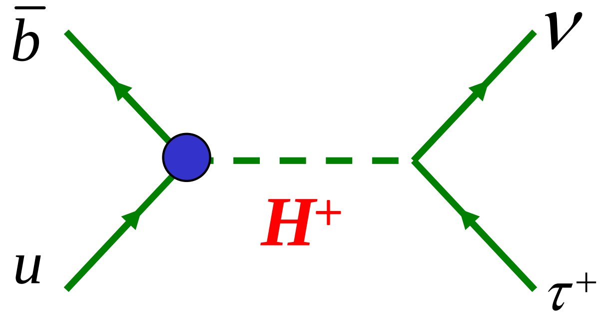
Backup Slides

New Physics in large tanβ

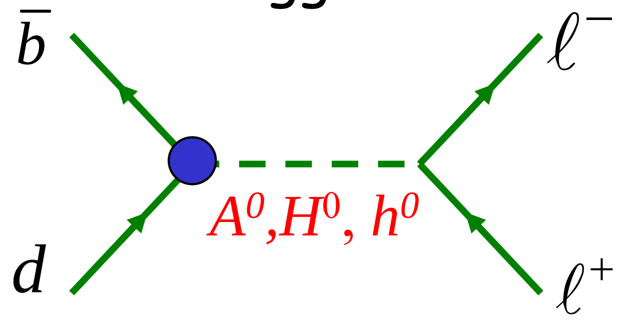
- Leptonic decays ($B\to l\nu$, ll) are theoretically clean, free from hadronic uncertainty.
- In particular, they are good probes in large tanβ region, together with other measurements; Δm_{BS}, $B_s\to\mu\mu$, $B\to X_s\gamma$ and also τ decays ($\tau\to\mu\eta$, $\tau\to\mu\gamma$).

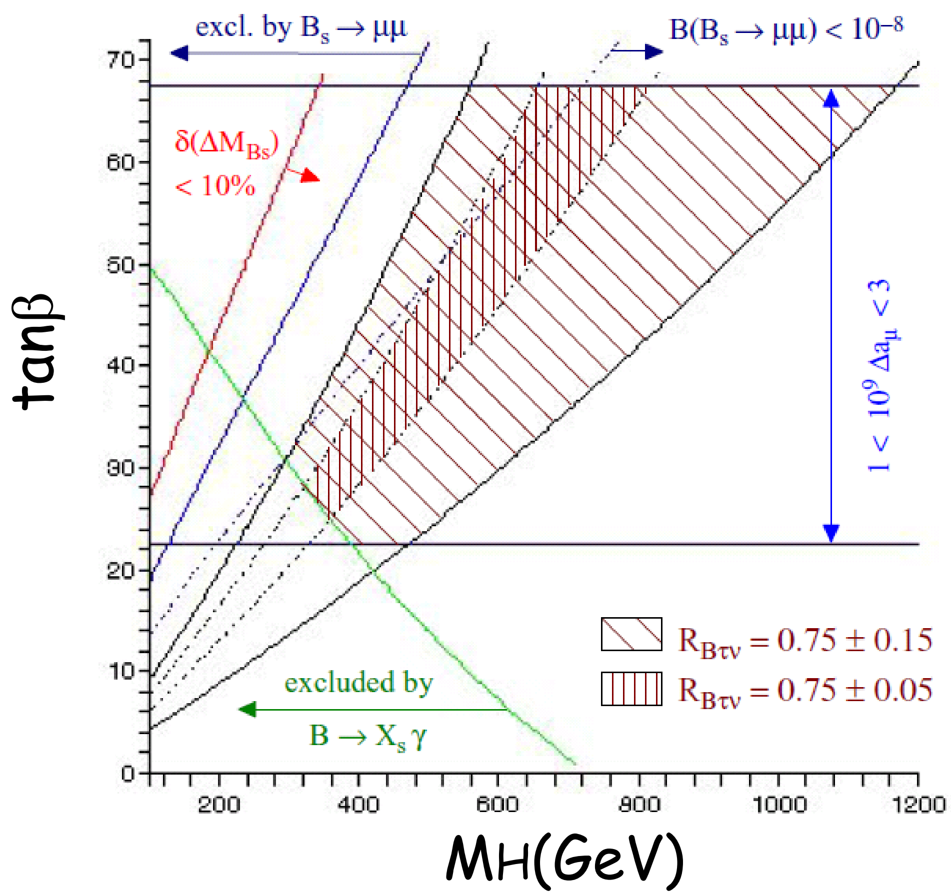
Ex.) G.Isidori & P.Paradisi, hep-ph/0605012

Charged Higgs



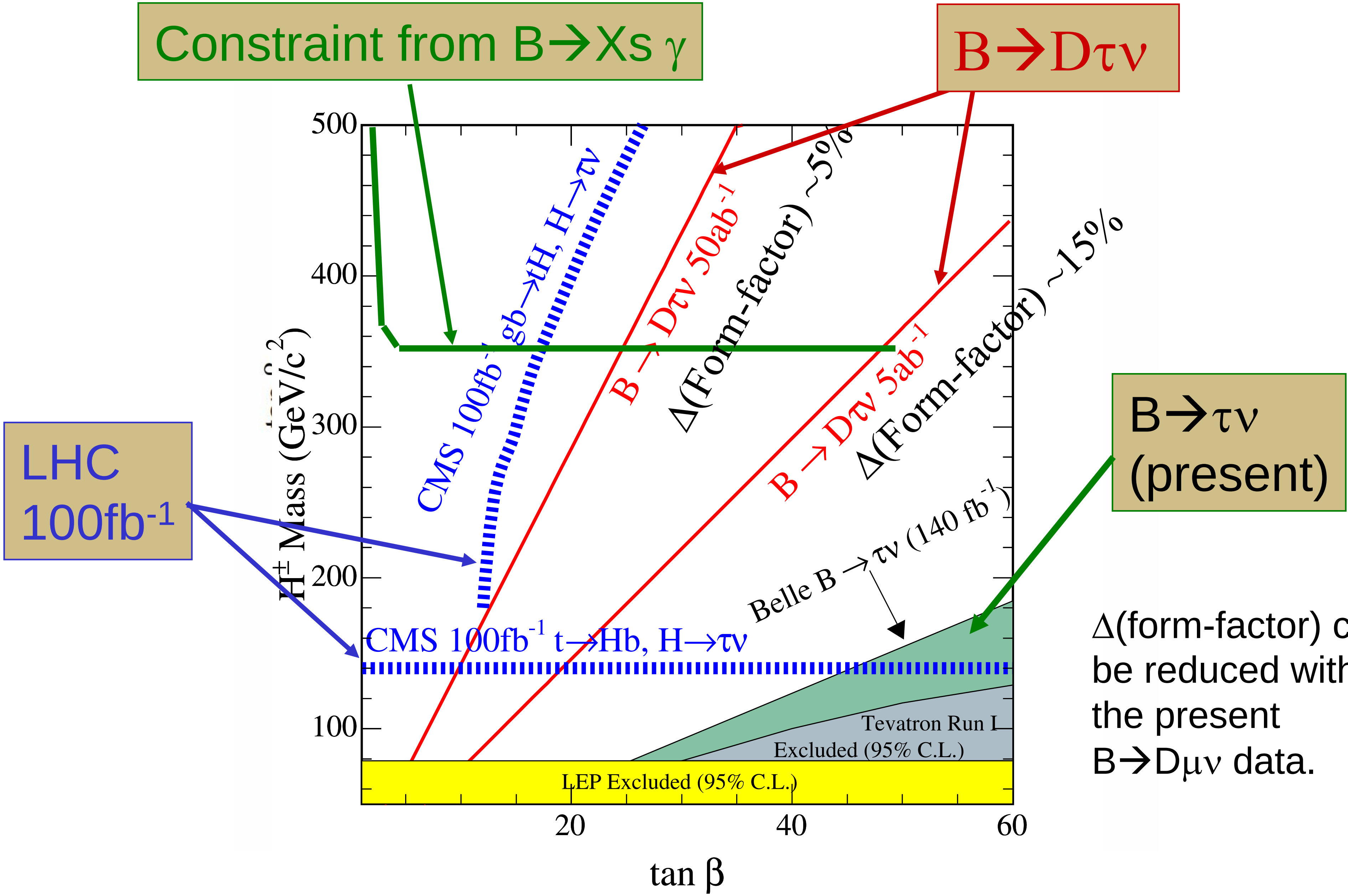
Neutral Higgs





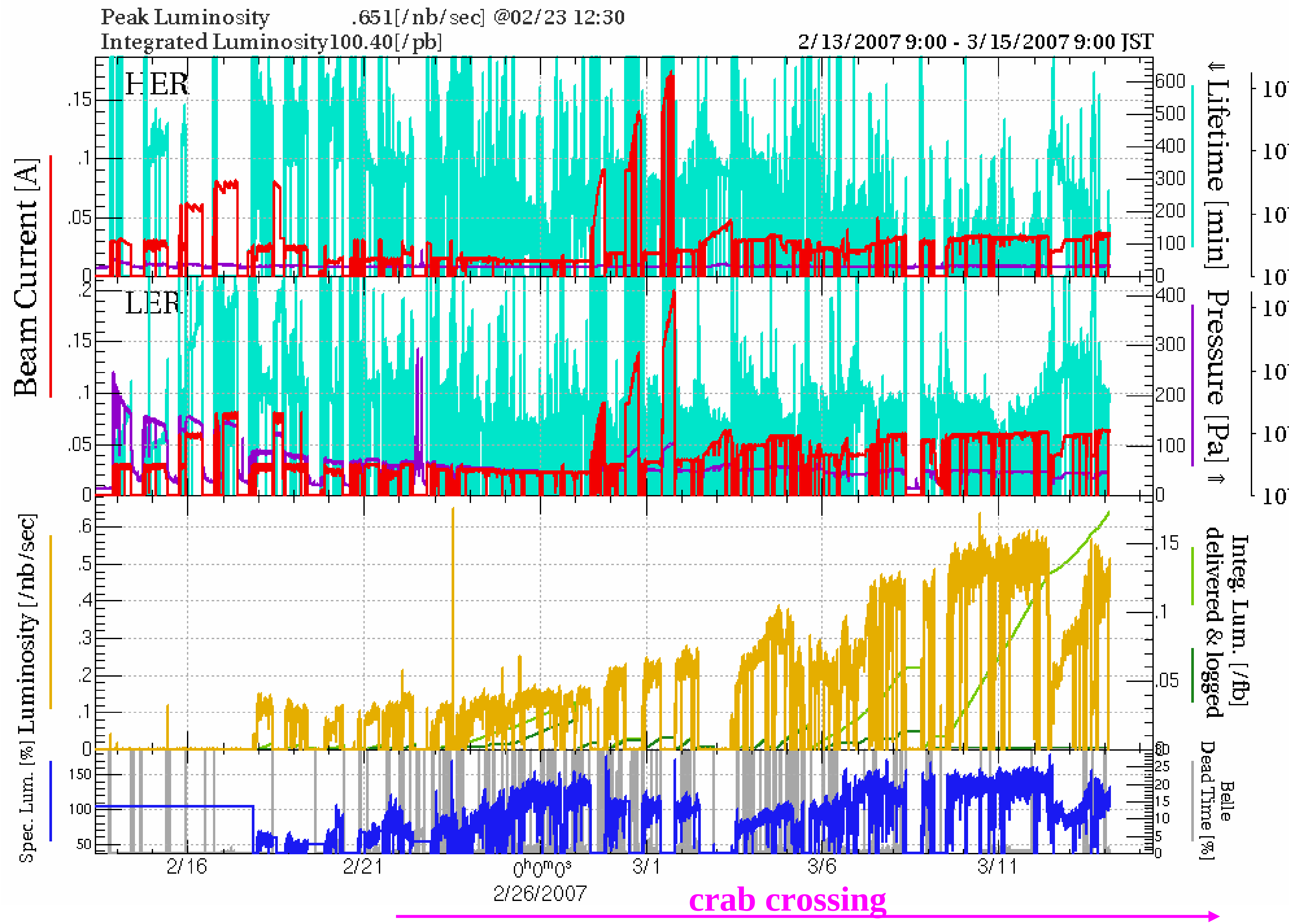
See talk by A.Weiler

Sensitivity for Charged Higgs



Δ(form-factor) can be reduced with the present B→Dμν data.

2007.2.13 – 3.14



Peak Luminosity .651[/nb/sec] @02/23 12:30
Integrated Luminosity100.40[/pb]
2/13/2007 9:00 - 3/15/2007 9:00 JST
HER
LER
Beam Current [A]
⇐ Lifetime [min]
Pressure [Pa] ⇒
Luminosity [/nb/sec]
Integ. Lum. [/fb]
delivered & logged
Spec. Lum. [%]
Belle Dead Time [%]
2/16
2/21
0h0m0s
2/26/2007
3/1
3/6
3/11
crab crossing

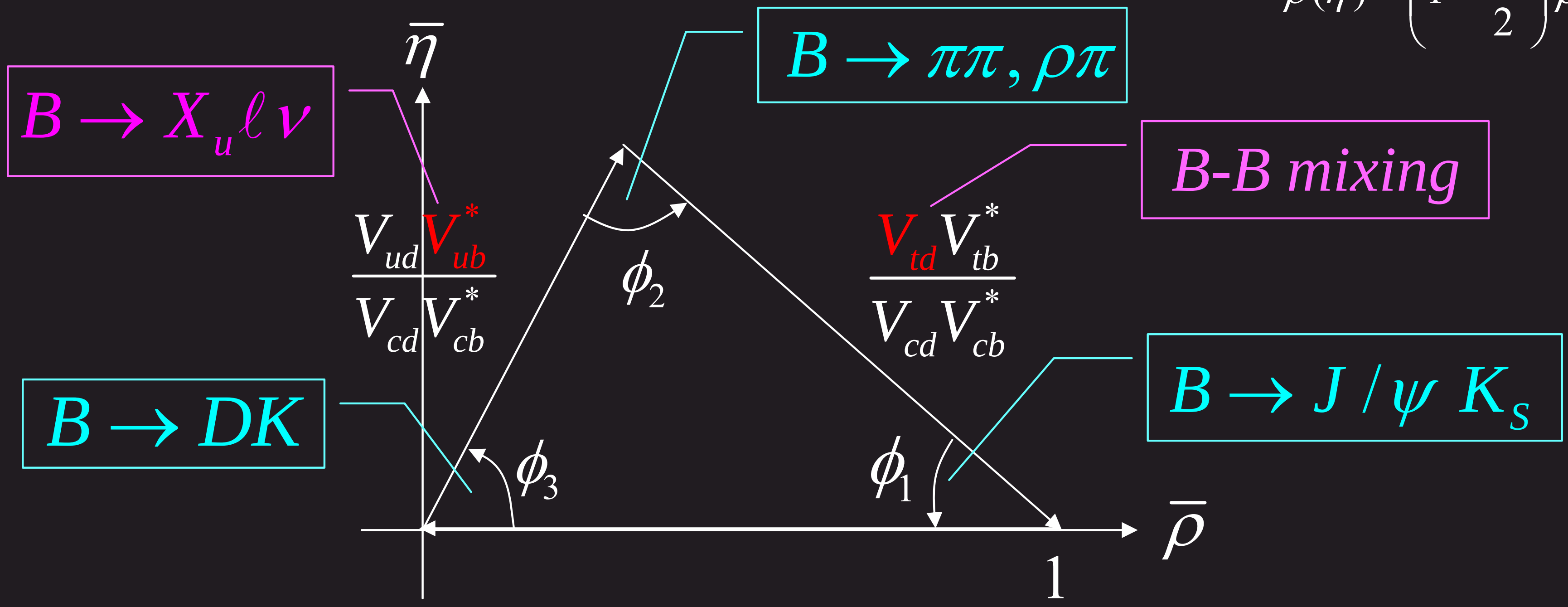
The Unitarity Triangle

$$\begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix}_{KM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

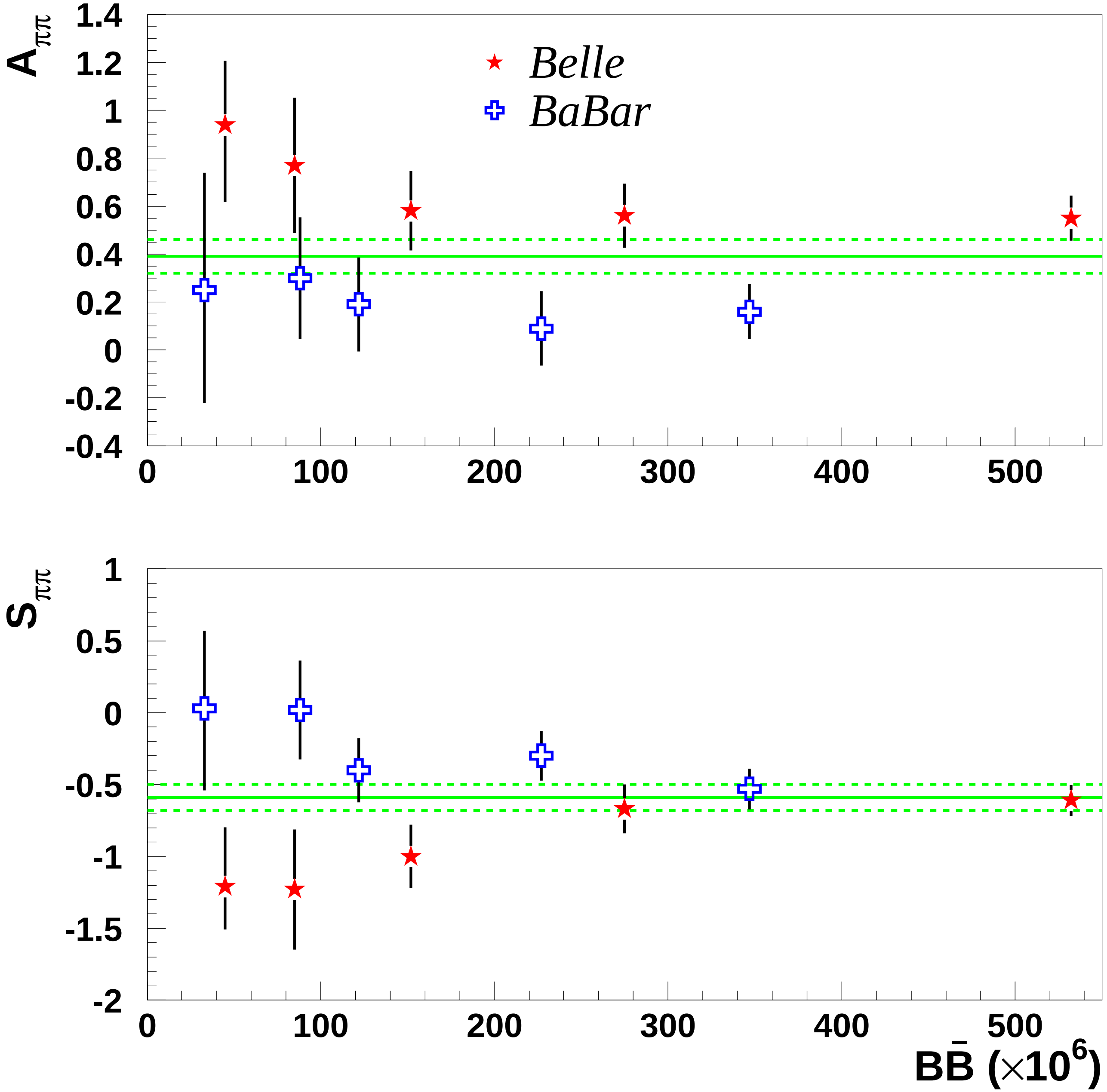
Wolfenstein

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

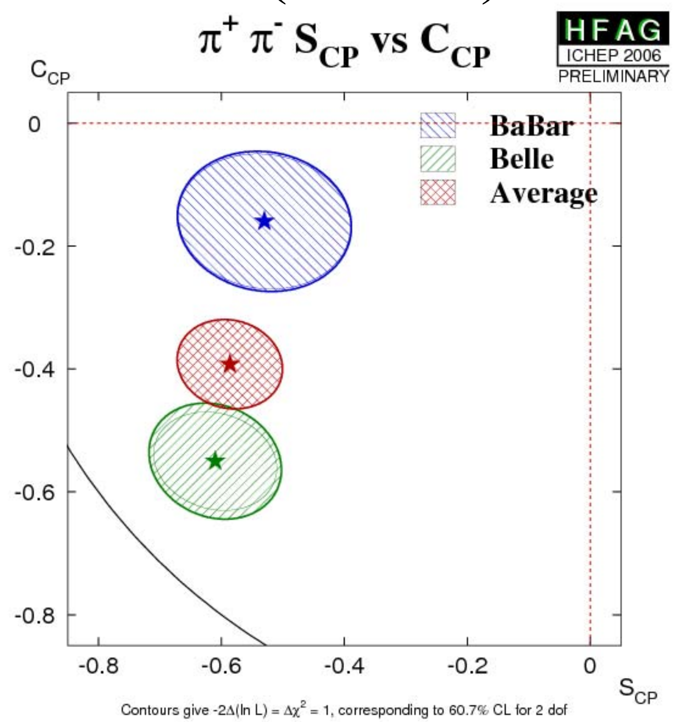
$$\bar{\rho}(\bar{\eta}) = \left(1 - \frac{\lambda^2}{2}\right)\rho(\eta)$$



History of $B^0 \to \pi^+\pi^-$ decay

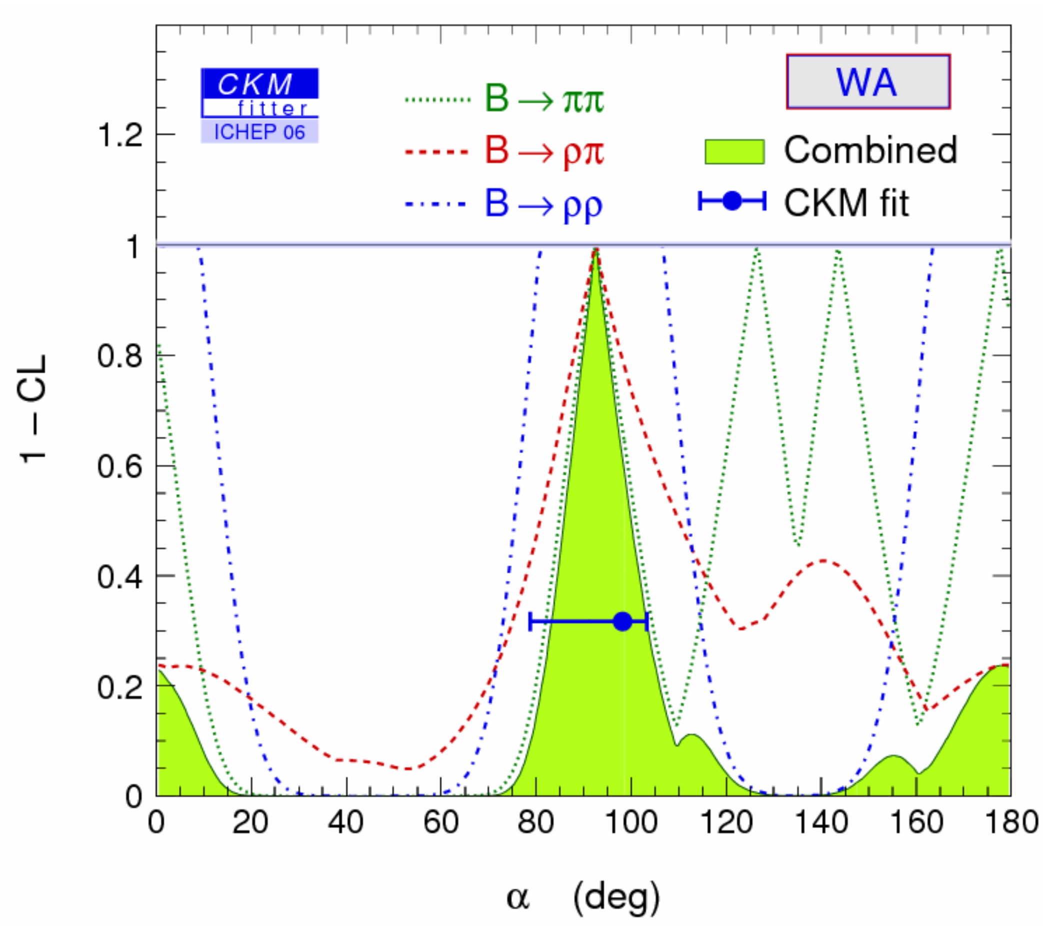


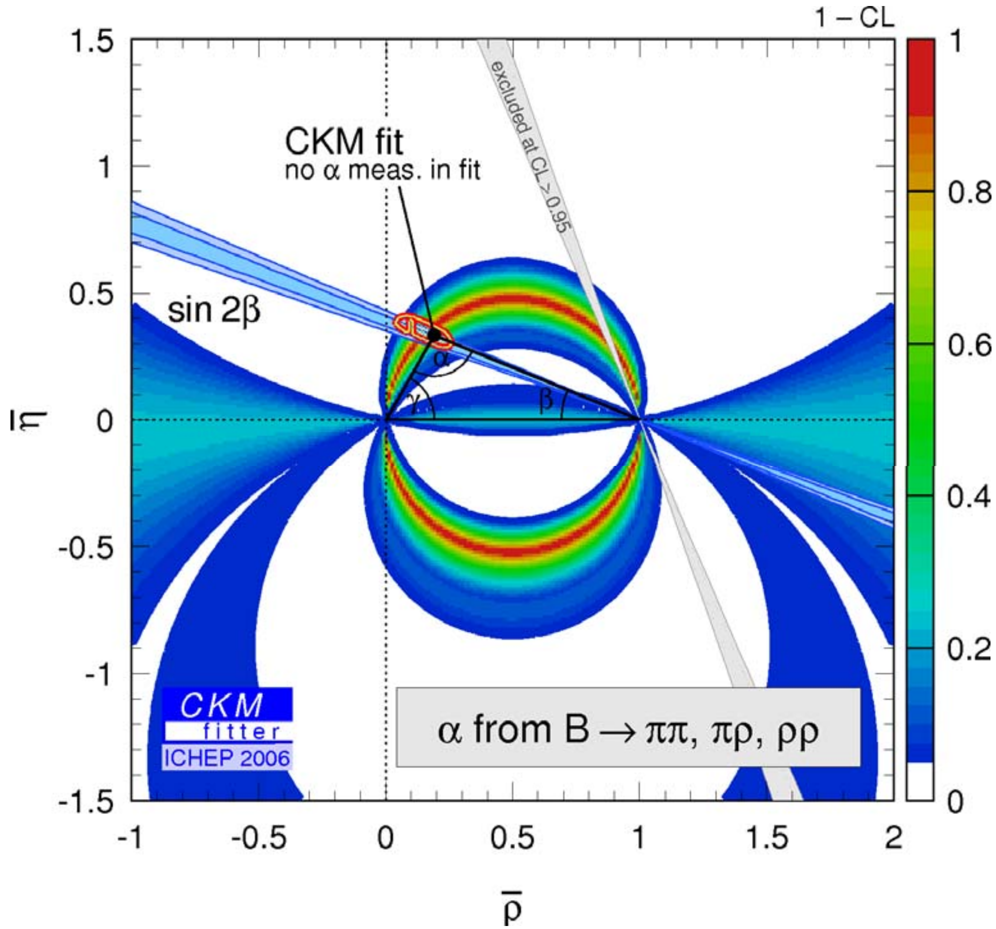
$(\mathcal{C} = -\mathcal{A})$



2.3σ diff.
btw. Belle
and BaBar

ICHEP2006: BaBar(ππ/ρπ/ρρ) + Belle(ππ/ρρ)





$$\alpha/\phi_2 = [93^{+11}_{-9}]^\circ$$

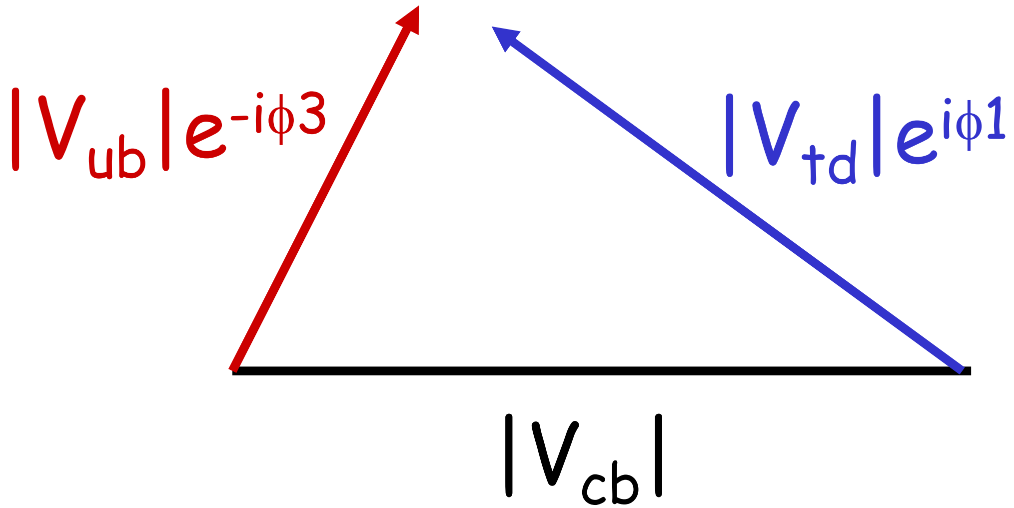
consistent with a global fit w/o α/ϕ_2

$\alpha_{\text{Global Fit}} = [\,98\,^{+5}_{-19}]^{\circ}$

Is this enough ?

No,

- A little tension between $|V_{ub}|$ and ϕ_1.
- Need improvement of ϕ_3
  - We should first determine the apex by tree-level processes; $|V_{ub}| + \phi_3$
  - Then compare it to others;
    - Bd mixing and CPV
    - Bs mixing and CPV
    - εK and $B(K \rightarrow \pi\nu\nu)$

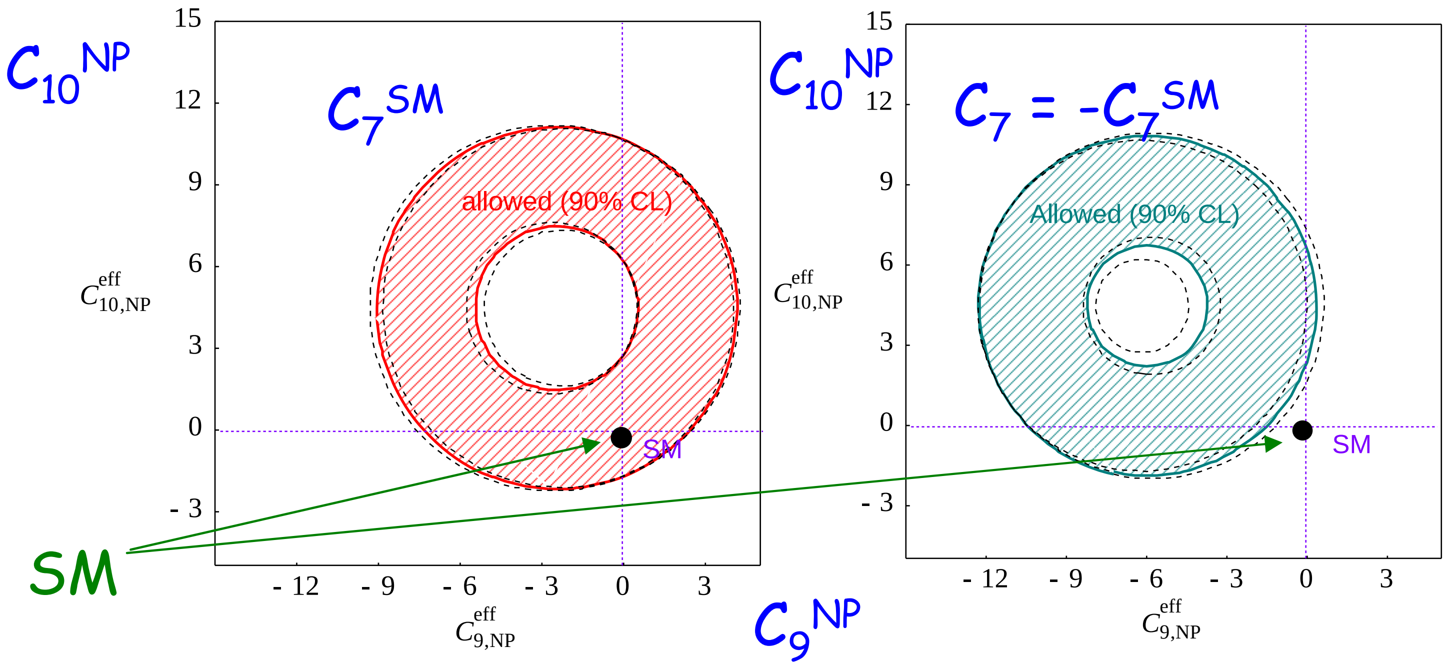


Constraints on C_i from $B(B \to X_s l^+ l^-)$

P.Gambino, U.Haisch and M.Misiak PRL 94 061803 (2005)

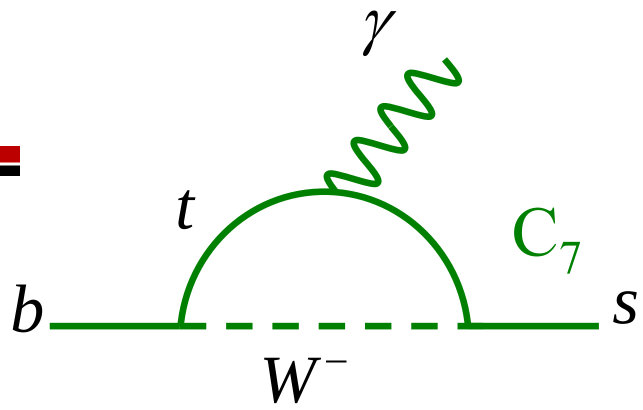
- Clean prediction for $B(B \to X_s ll)$ with $1<q^2<6GeV^2$ is available.
  - Combine Belle and Babar results
  - Sign of C_7 flipped case with SM C_9 and C_{10} value is unlikely.

BF	Belle	Babar	WA	SM	$C_7 = -C_7^{SM}$
$q^2>(2m_\mu)^2$	4.11±1.1	5.6±2.0	4.5±1.0	4.4±0.7	8.8±0.7
$1<q^2<6GeV^2$	1.5±0.6	1.8±0.9	1.60±0.5	1.57±0.16	3.30±0.25

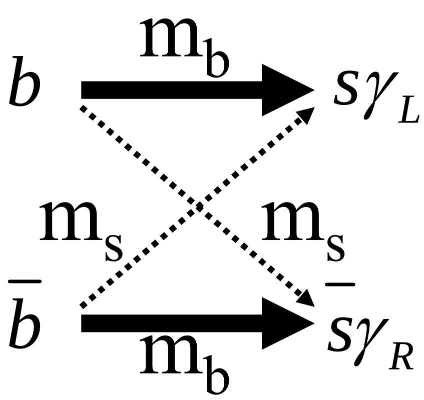


Donut : 90% CL allowed region

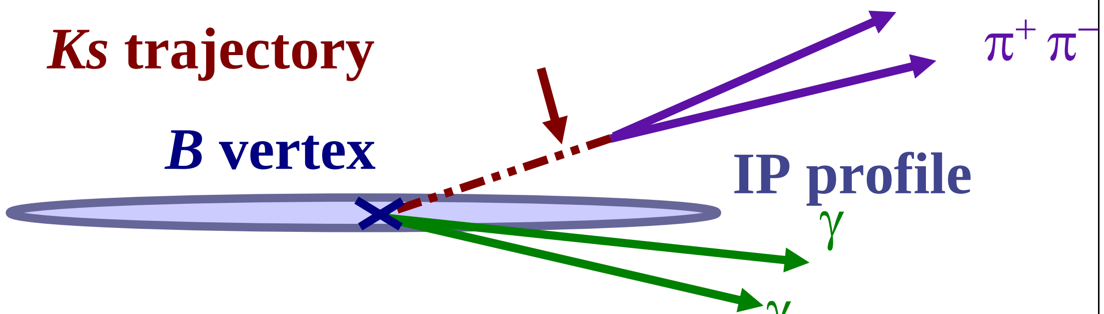
B→X$_s$γ CP Asymmetry



- Sensitive to NP.
- Theoretically clean.
- Standard Model "~Zero".
  - Gamma is polarized, and the final state is almost flavor specific.
  - Helicity flip of γ suppressed by ~m_s/m_b



- Time dependent CPV requires vertex reconstruction with Ks →π+π-



$$\sigma_x = 100\mu m, \sigma_y = 5\mu m, \sigma_z = 3mm,$$

Vertex recon. Eff.
51% (SVD2)
40% (SVD1)

Possible at e$^+$e$^-$ B-factory