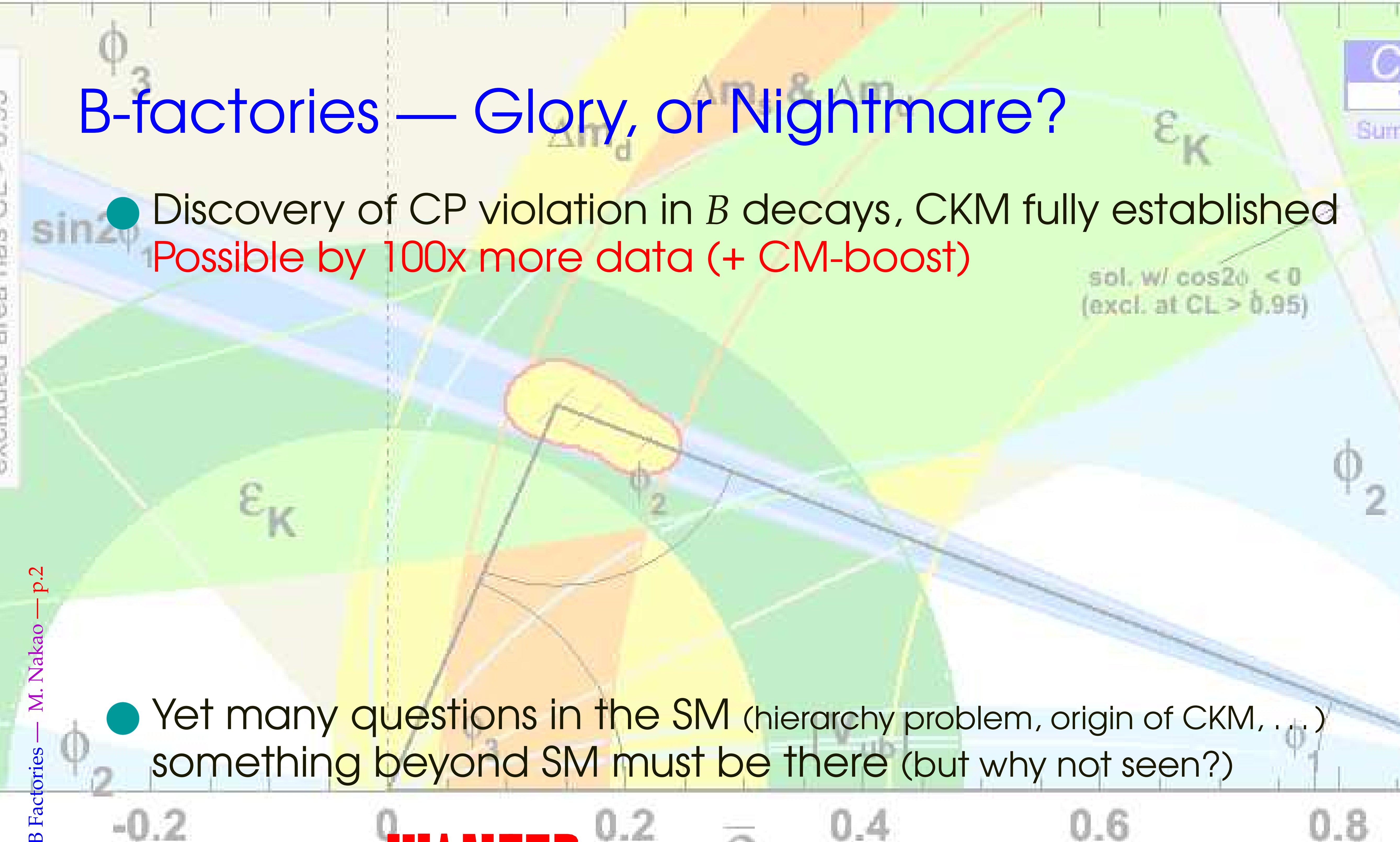
Super B Factories

Mikihiko Nakao (KEK, IPNS)
June 9, 2008
HQ&L 2008, Melbourne
mikihiko.nakao@kek.jp

Disclaimer: this talk is somewhat biased towards SuperKEKB

B-factories — Glory, or Nightmare?

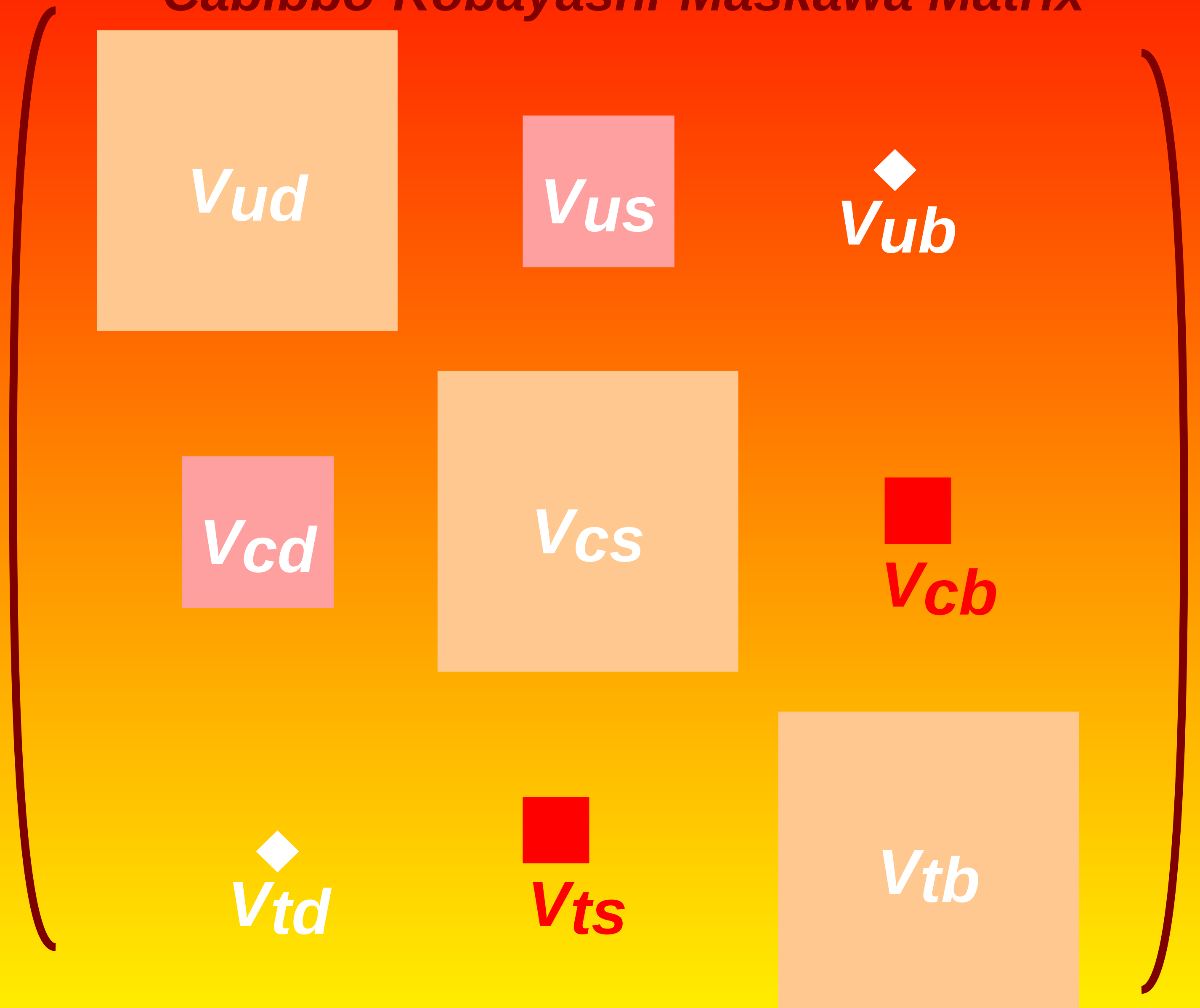
- Discovery of CP violation in B decays, CKM fully established
  Possible by 100x more data (+ CM-boost)



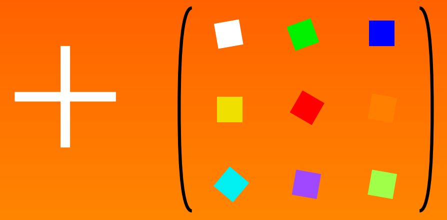
- Yet many questions in the SM (hierarchy problem, origin of CKM, . . .)
  something beyond SM must be there (but why not seen?)

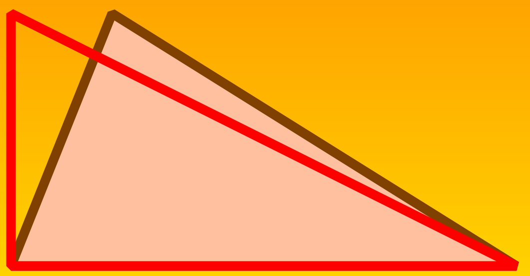
WANTED 100x more data, again

Cabibbo-Kobayashi-Maskawa Matrix



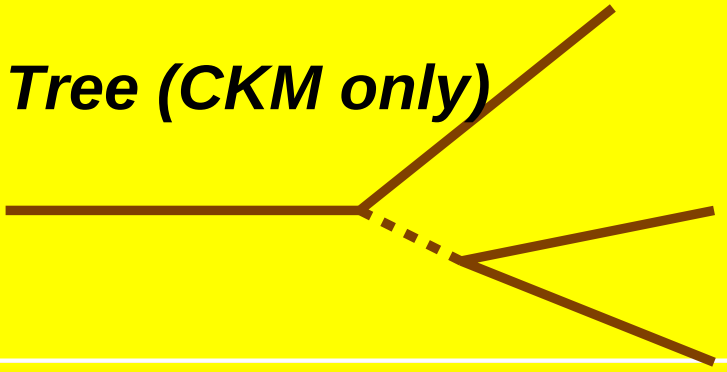
Effective BSM contribution?



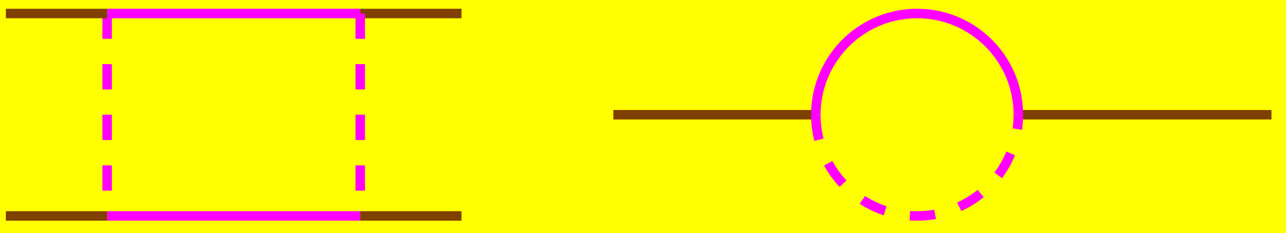


Unitarity triangle
CKM only and CKM+BSM

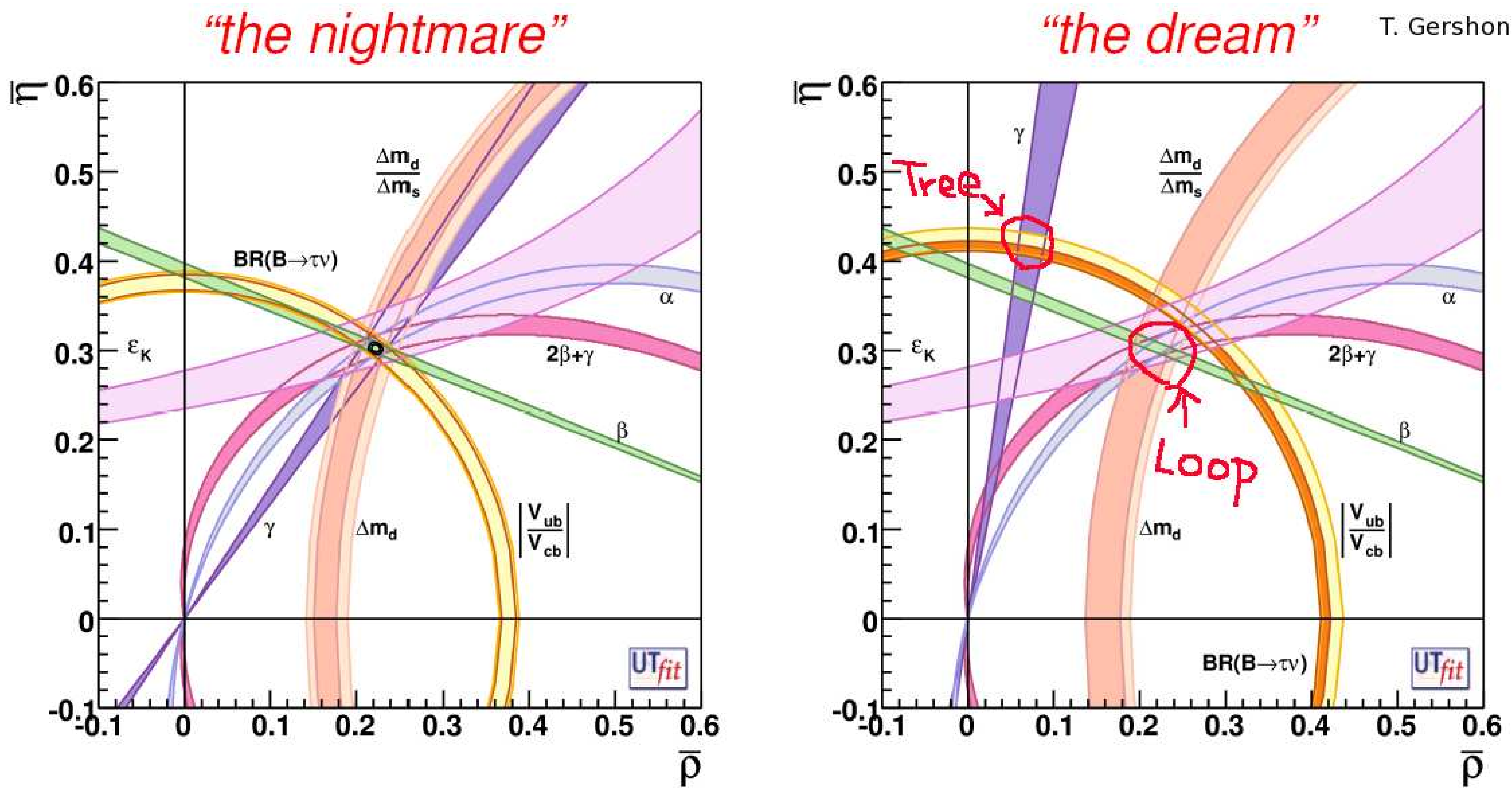
Tree (CKM only)



Box and Penguin (CKM + BSM)



Key measurements



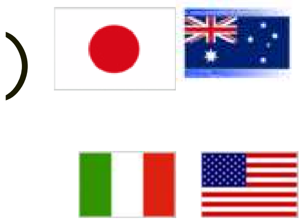
Need ultimate luminosity + theory improvements + some luck

(note: based on the ultimate optimistic error estimates)

More key measurements

- Precision CKM test: tree (ϕ_3 , V_{ub}) vs loop (ϕ_1, ϕ_2, V_{td})

  γ Maskawa β Cabibbo α Kobayashi

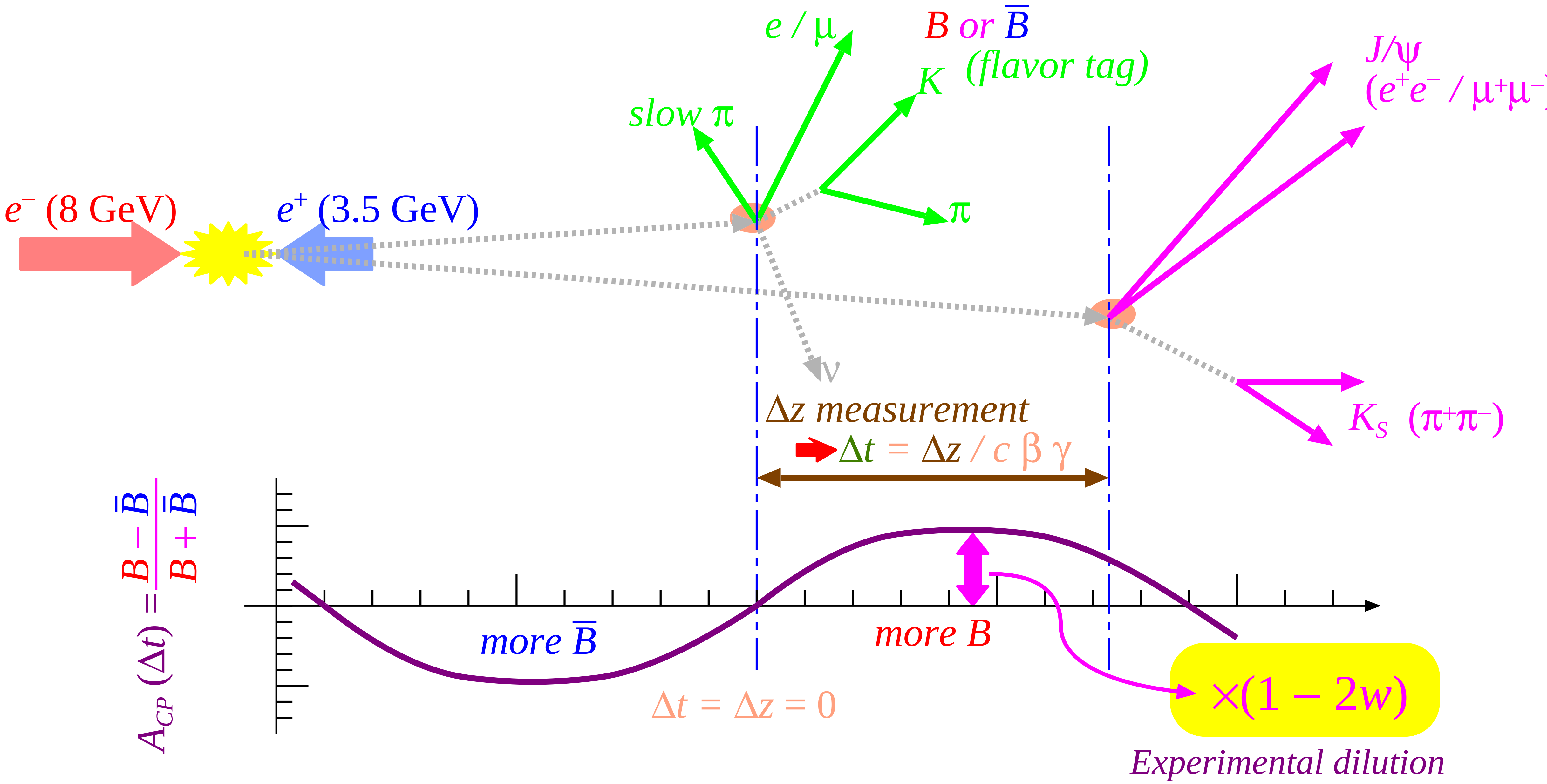


- Non-SM CP phase: tCPV in $b \to s$ penguin
  ($B \to \phi K^0_S$, $B \to \eta' K^0_S$ at Super B $\Leftrightarrow$ $B_s \to \phi\phi$ at LHCb)
- Non-SM right-handed current: $B \to K^* \gamma$ tCPV ($\Leftrightarrow$ $B_s \to \phi\gamma$)
- Charged Higgs: searches in $B^+ \to \tau^+ \nu$ and $B \to D^{(*)} \tau^+ \nu$
- Inclusive measurements: $b \to s\gamma$, $b \to d\gamma$, $b \to s\ell^+\ell^-$ (A_{FB}), V_{ub}
- Lepton flavor violation: searches in high statistics τ decays

(no counterpart at LHCb)

Modes with photon(s)
Modes with π^0
Modes with neutrino
} are crucial

Time-dependent CPV measurement

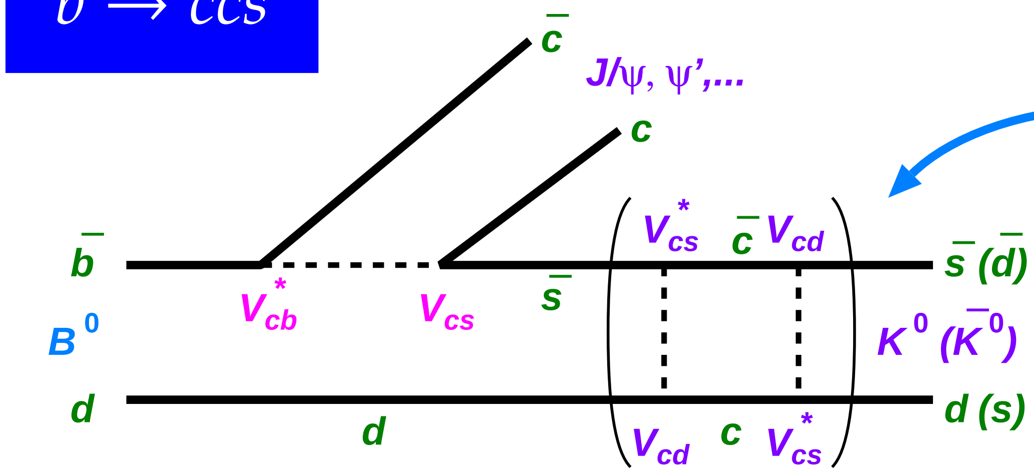


$$A_{CP}(\Delta t) = -\xi_f S \sin(\Delta m \Delta t) + \mathcal{A} \cos(\Delta m \Delta t)$$

$-C$

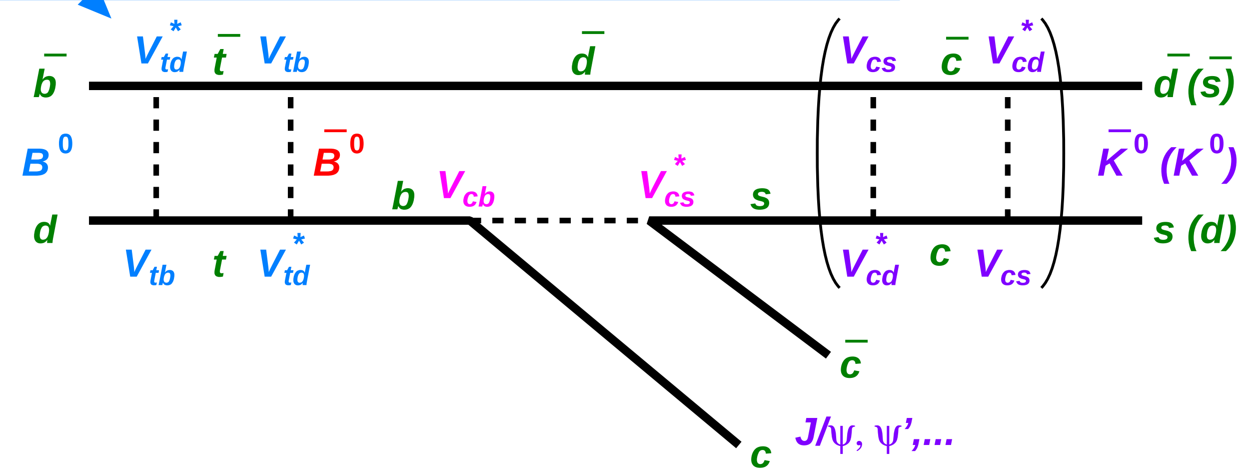
CPV in box + tree vs box + penguin

$b \to c\bar{c}s$

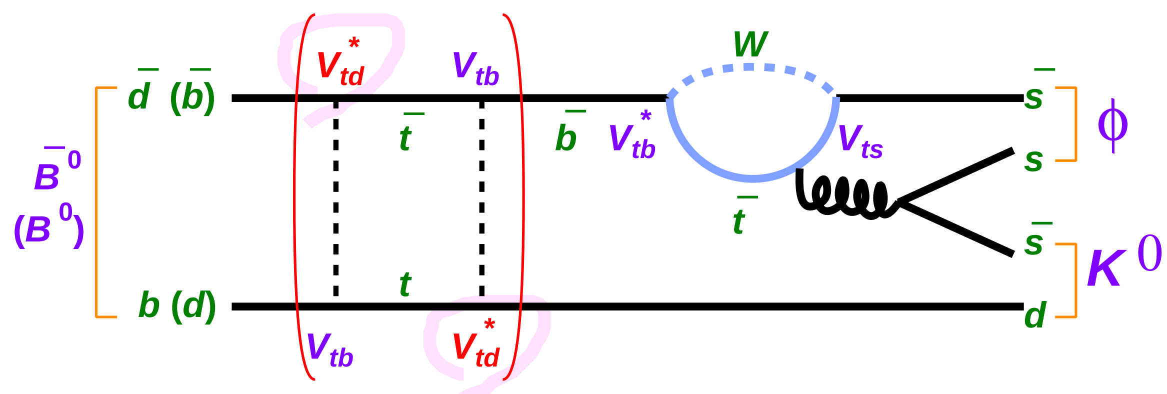


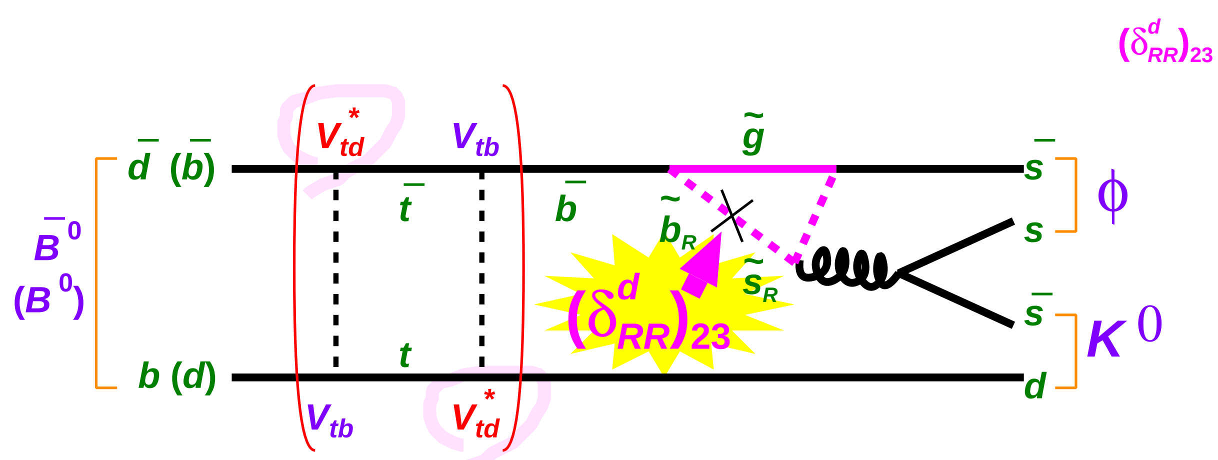
Complex interference term at $t \neq 0$
due to the weak phase difference,
$\phi_1 = \pi - \arg(V_{tb}^* V_{td} / V_{cb}^* V_{cd})$

⊕



$b \to s\bar{s}s$





Golden mode $B \to J/\psi K^0$

$\delta(\sin 2\phi_1) \sim 0.01$ (syst. limited)

with a few ab^{-1} $(\delta_{\mathrm{theo}} \sim 0.01)$

Platinum modes:

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

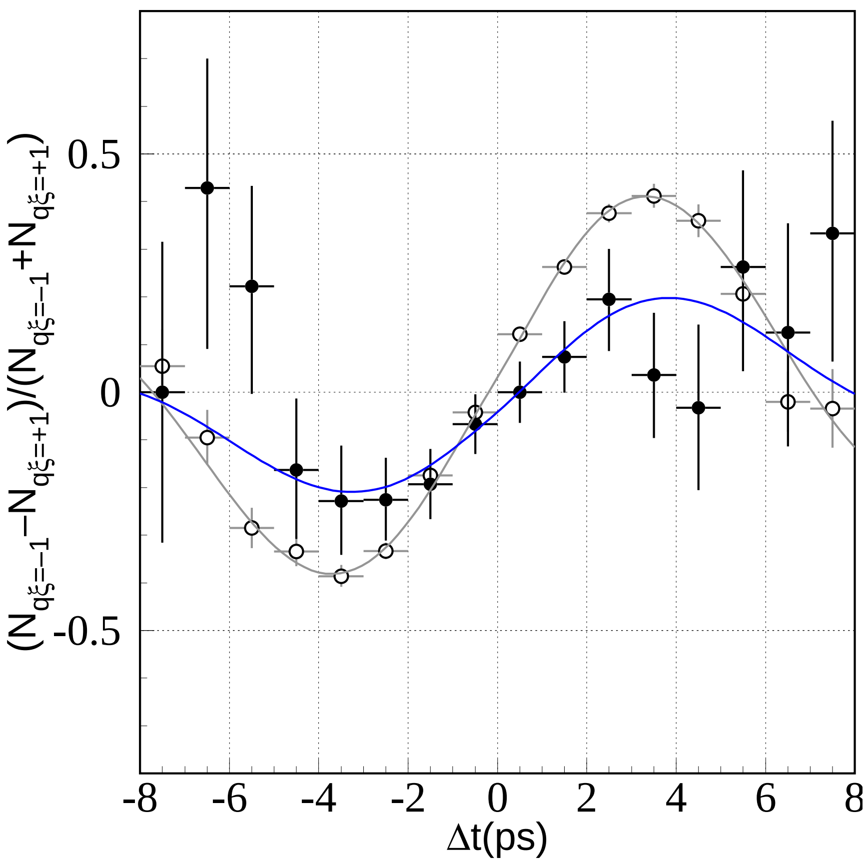
$B \to \eta' K^0$

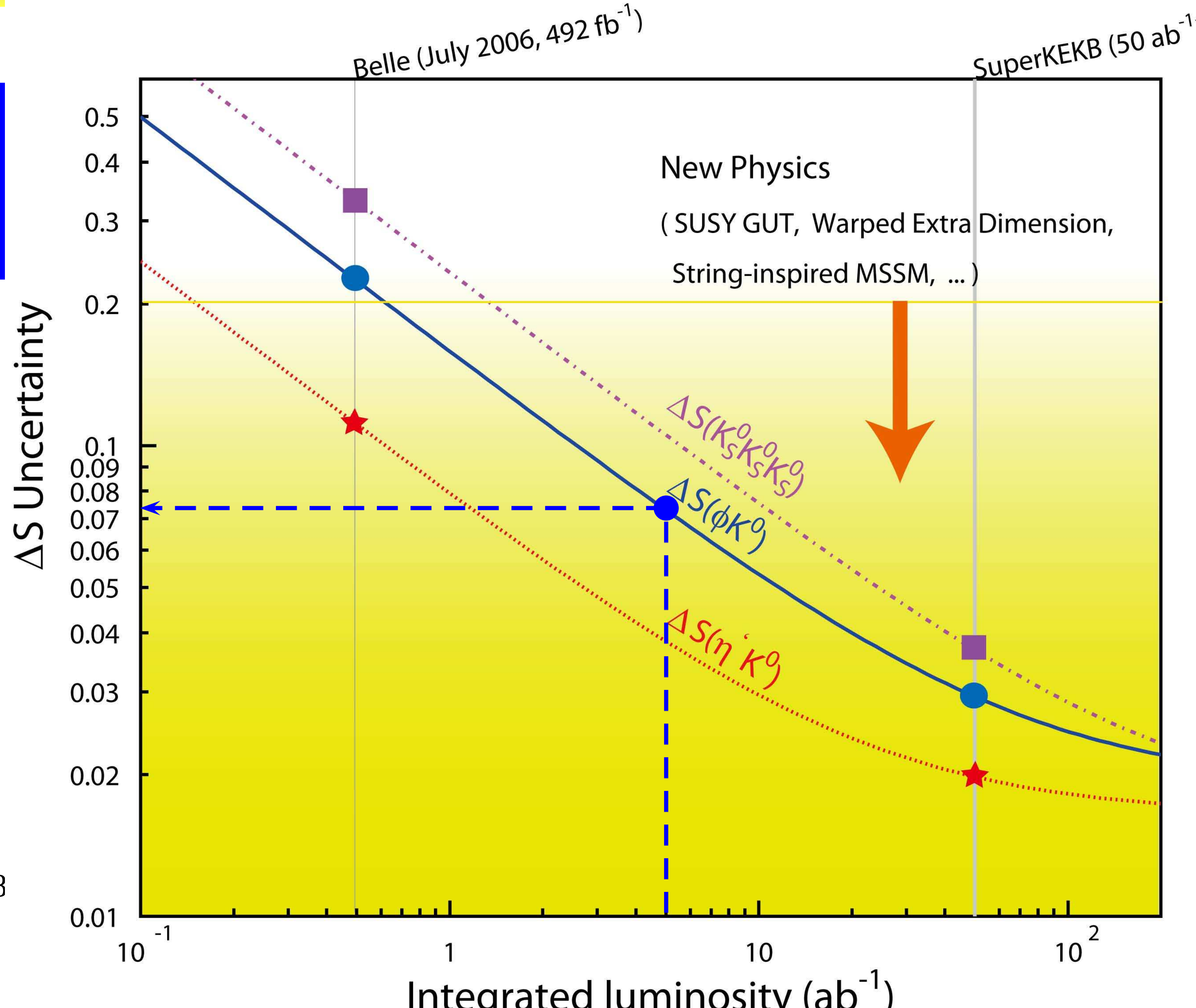
$B \to K_S^0 K_S^0 K_S^0$

$(\delta S_{\mathrm{theo}} \sim 0.02)$

$b \to s$ CPV Projection

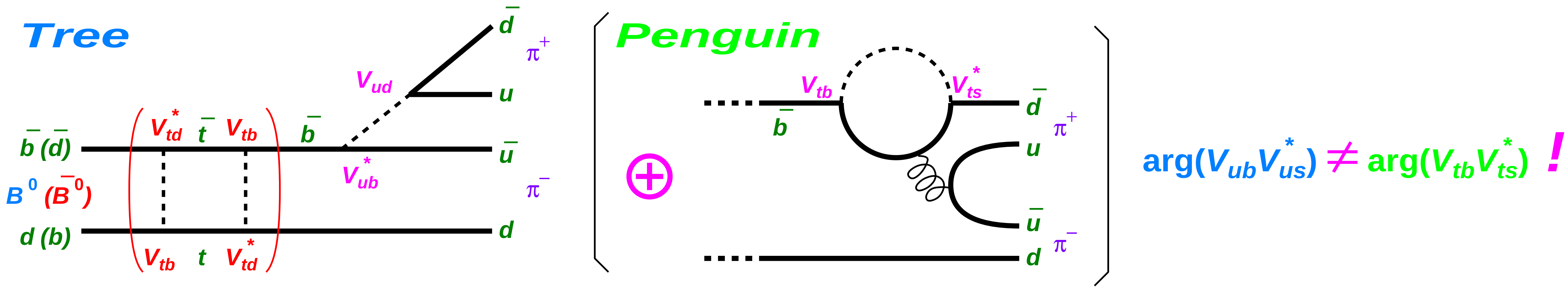
MC 5 ab^{-1} for $\mathcal{S}_{\phi K_S^0} = 0.39$, $\mathcal{A}_{\phi K_S^0} = 0$



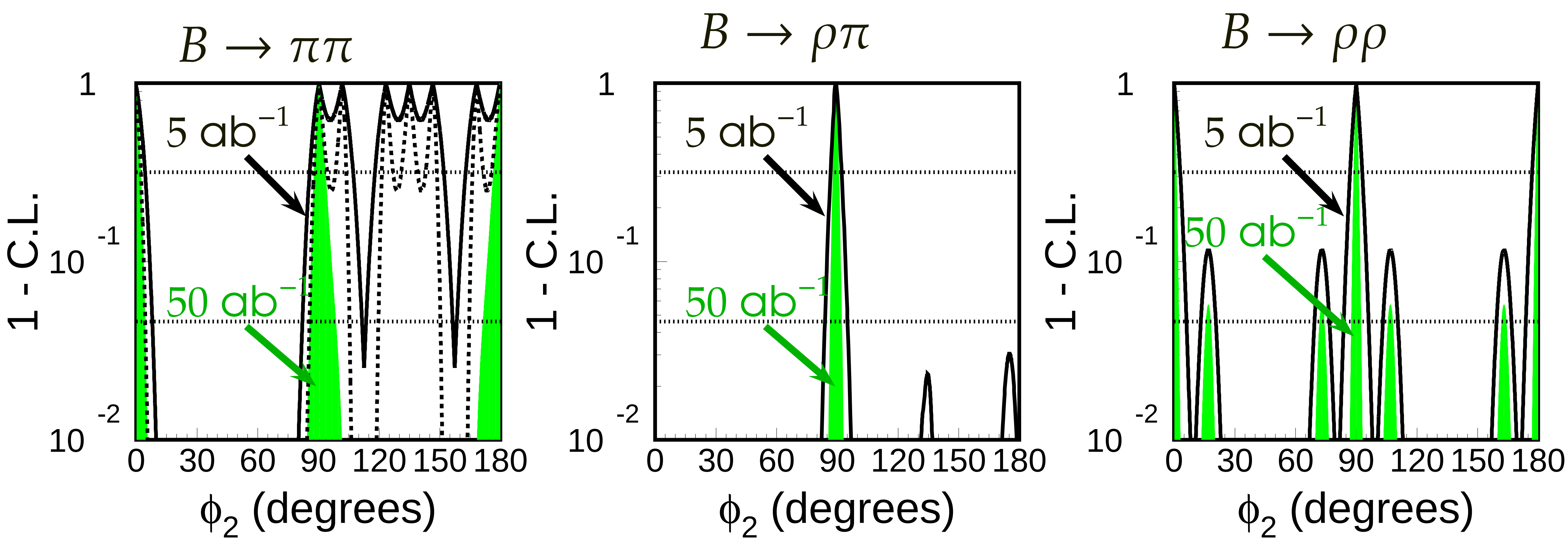


- $\mathcal{S}_{\phi K^0} \neq \sin 2\phi_1$ — easy to establish for current central values
- Statsitical error dominated till $\sim$ 50 ab^{-1}, final $\delta\mathcal{S} \sim$ 0.02–0.03

ϕ_2 from $B \to \pi\pi$, $\rho\pi$, $\rho\rho$

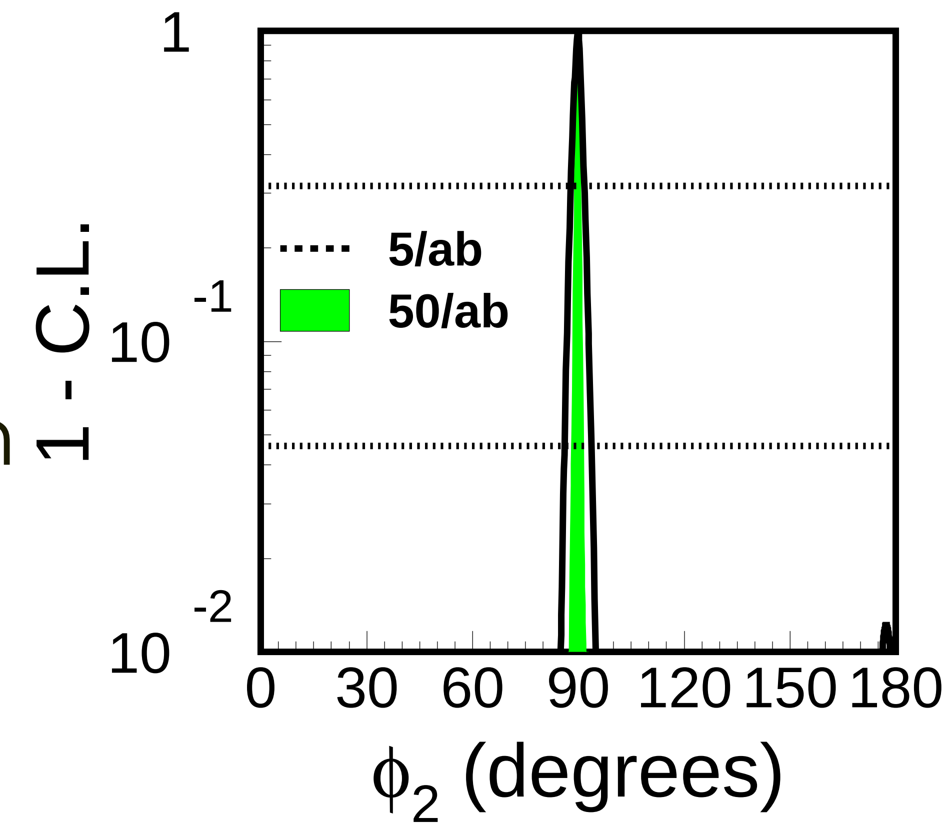


- $S = \sin 2\phi_2$ if no penguin pollution
- Isospin analysis — measure all branching fractions and A_{CP} for $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$ and $B^\pm \to \pi^\pm\pi^0$ (Dalitz for $B \to \rho\pi$)



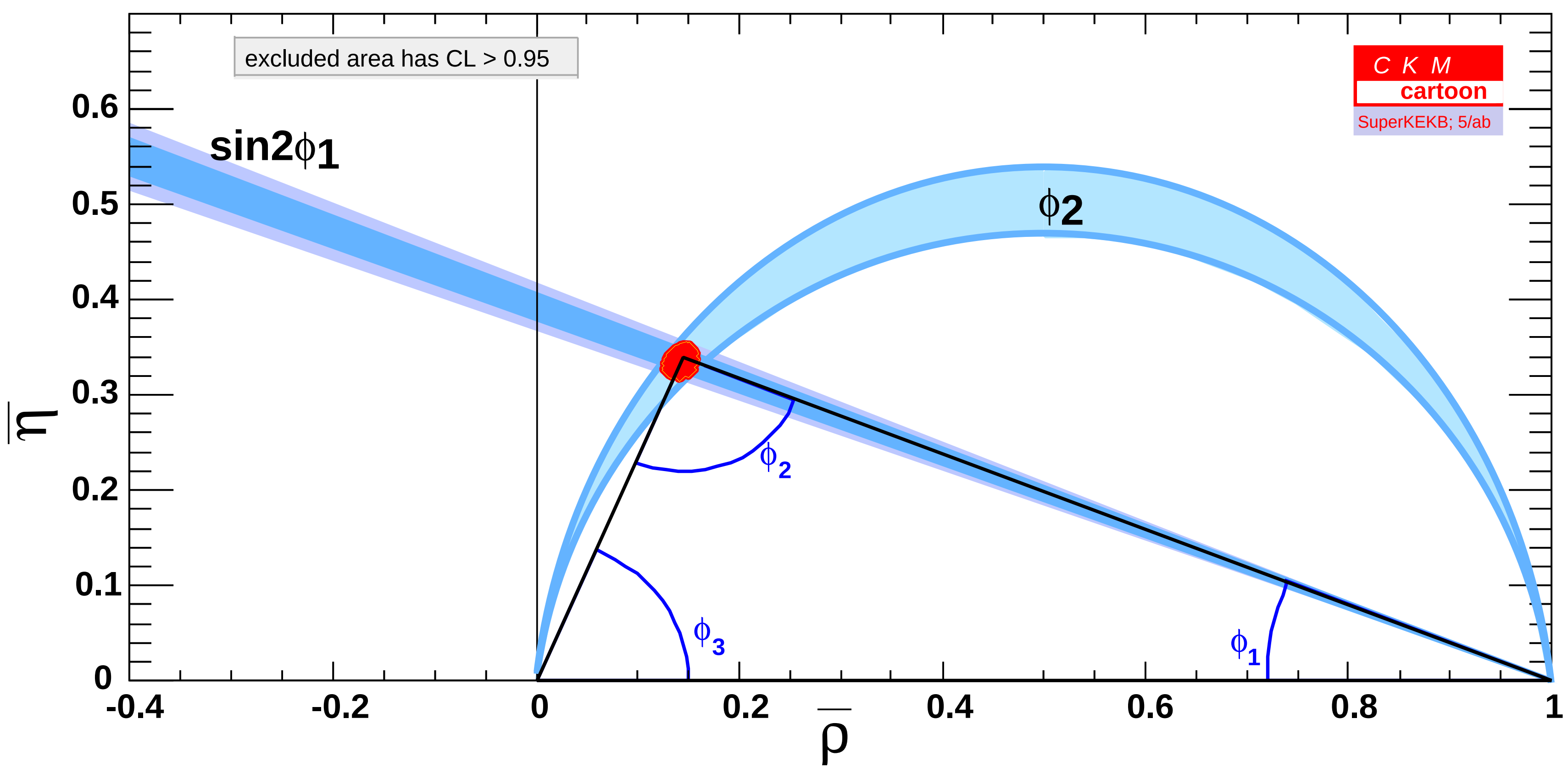
ϕ_1 and combined ϕ_2

- ϕ_2 combined: 2° error (5 ab^{-1})
  (1° error (50 ab^{-1}))
  if all results align
- Theory (isospin) error ~ 2° in addition



Reference point on $(\bar{\rho}, \bar{\eta})$!

$(\delta \sin 2\phi_1 = 0.016,\ \phi_1 = 21.4°,\ \phi_2 = 90°$ at 5 $ab^{-1})$



Free from LQCD!

ϕ_3

Methods

- tCPV of $B \to D^{*\pm}\pi^{\mp}$ ($\sin(2\phi_1 + \phi_3)$)
- $B^{\pm} \to D_{CP}K^{\pm}$ (GLW method)
- $B^{\pm} \to D_{\text{DCSD}}K^{\pm}$ (ADS method)
- $B^{\pm} \to D^0K^{\pm}$, $D^0 \to K^0_S\pi^+\pi^-$ Dalitz analysis

	5 ab^{-1}	50 ab^{-1}	
$B \to D^{*\pm}\pi^{\mp}$	18°	6°	(depends on the value of r)
GLW + ADS	16°	5°	
Dalitz	7°	2.5°	(need charm-factory data)
All combined	6°	2°	

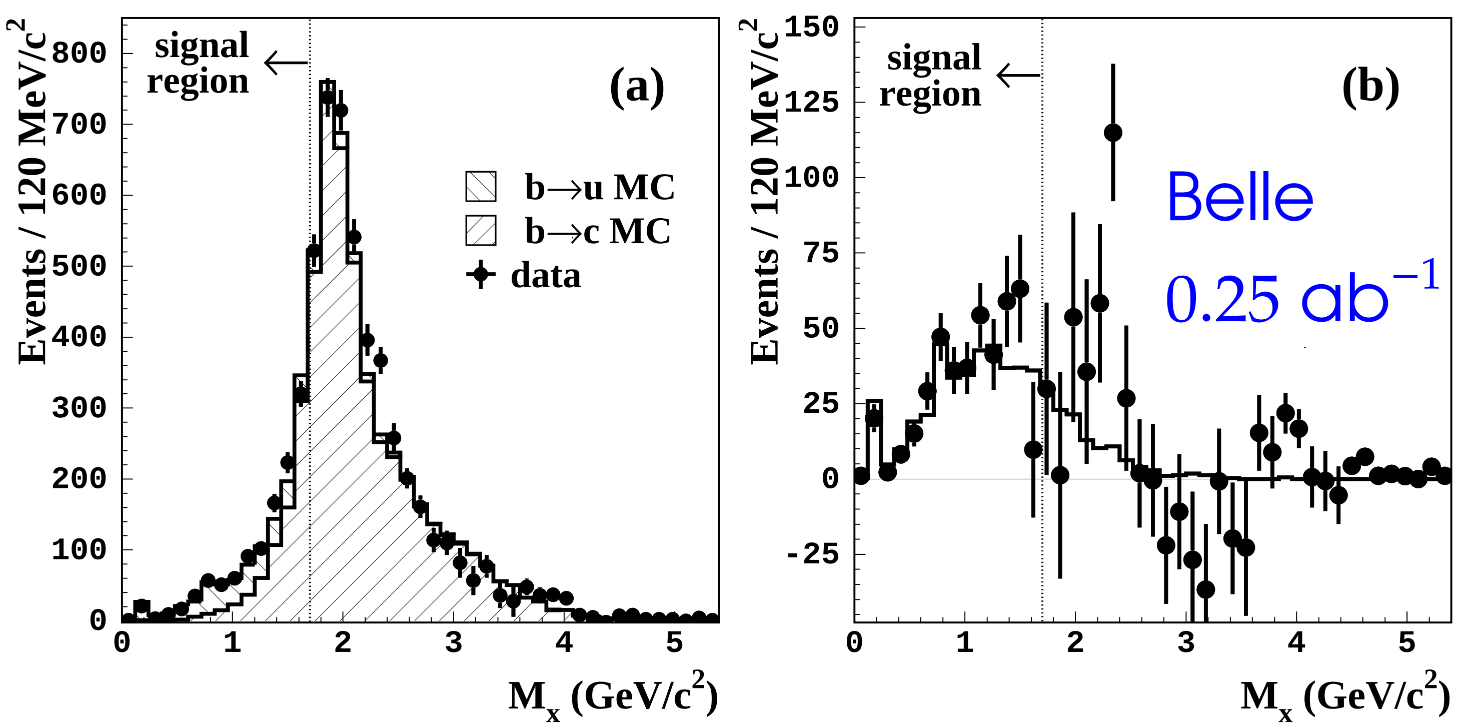
(cf. LHCb (10 fb^{-1} / 2013) — $\delta\phi_3 \sim 2°$ from D_sK (5°), ADS (4°), GLW (4°), Dalitz (5°))

V_{ub} (inclusive measurement)

$|V_{ub}| = (3.98 \pm 0.15_{\text{exp}} \pm 0.30_{\text{theo}}) \times 10^{-4}$ — (Jan.7,2008 HFAG)

$8.3\% = \pm 2.0_{\text{stat}} \pm 2.5_{\text{exp}} \pm 1.8_{\text{b2cmodel}} \pm 1.1_{\text{b2umodel}} \pm 6.3_{\text{HQEparam}} \pm 0.4_{\text{SFfunc}} \pm 0.7_{\text{subSF}} \pm 3.6_{\text{matching}} \pm 1.4_{\text{WA}}$

- HQE parameters to be reduced from $b \to c\ell^-\overline{\nu}$



Need to include higher M_X to reduce theory error

Not really stat. limited!

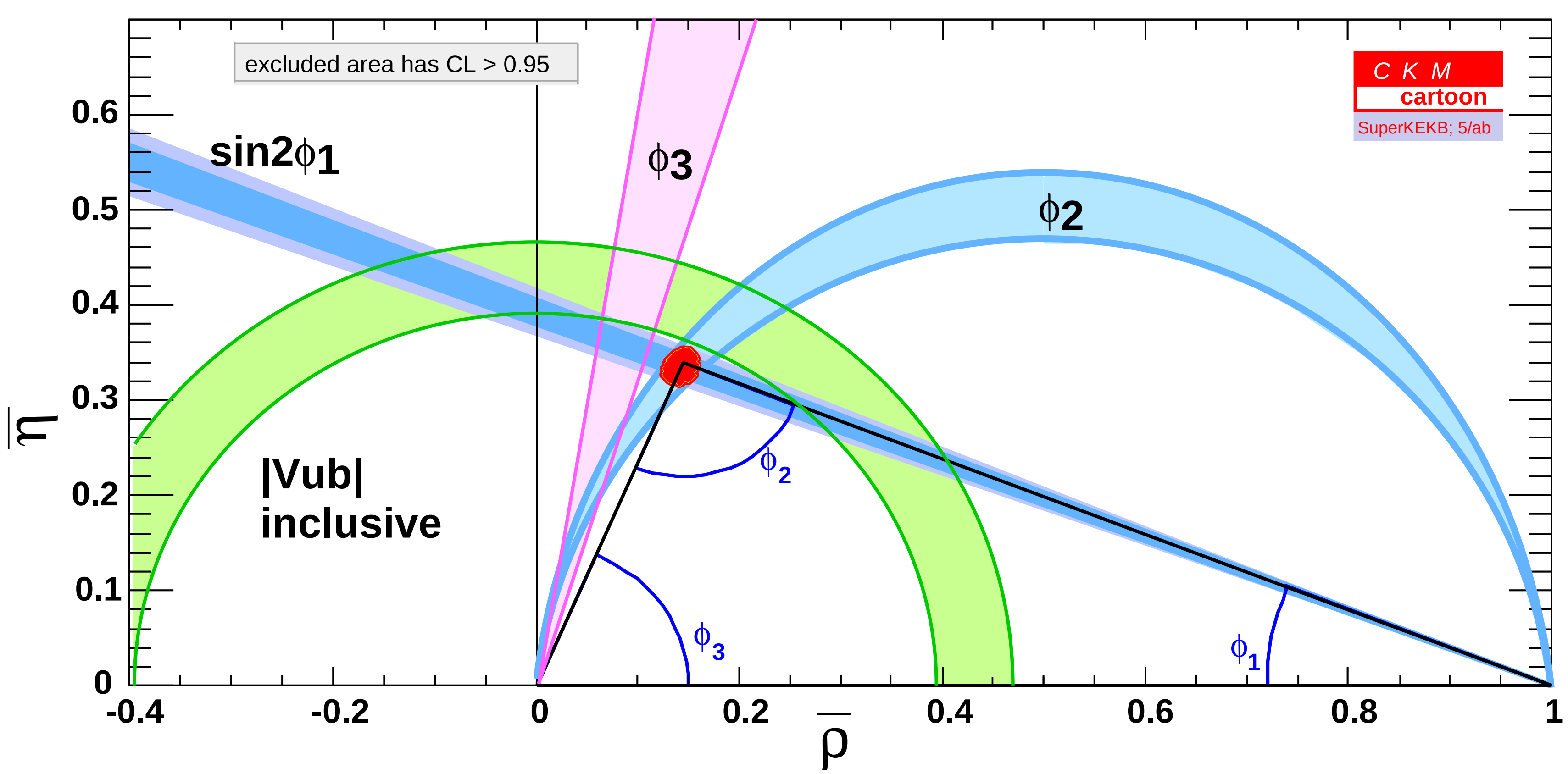
Larger dataset will help to study $b \to c$ background

(theory field is also VERY active)

V_{ub} from exclusive will improve, too, provided LQCD improves

Unitarity Triangle at $50\ \text{ab}^{-1}$

- V_{ub} from inclusive $b \to u\ell^-\overline{\nu} \Rightarrow \delta = 4\%$
- ϕ_3 from $B \to DK \Rightarrow \delta = 2^\circ$ with $50\ \text{ab}^{-1}$
- A super B-factory alone can discriminate tree vs loop
- Improvements in Lattice QCD will further reduce errors
  (V_{ub} from exclusive, V_{td} from $B \to \rho\gamma$)



Errors for $50\ \text{ab}^{-1}$
(with no LQCD info)

Central values
from 2007 averages

Next Generation B Factory

- Integrated luminosity of the order of 50 ab^{-1} is needed
  - ➡ Luminosity of the order of 10^{36} $cm^{-2}s^{-1}$ is needed
- Super Flavor factory — B, τ and charm physics at $\Upsilon(4S)$ (also option to run at different energies)
- To be operated in 2010s (synergy with LHCb and LHC)
- Two approaches pursued (desirable to have both, if ¥€$ allows)

SuperKEKB (Japan)
  Crab cavities for head-on collision
  Higher beam currents / higher power
  Straightforward upgrade of existing machine

SuperB (Italy)
  Radical new approach with a new machine
  Ultra-small beam spot (ILC damping-ring like)
  Large crossing angle and "crab waist"

The Master Formula

K.Oide

Beam current

1.7×1.4/3.2×2.1 (KEKB/PEP-II)
→ 9.4×4.1 A (SuperKEKB)
→ 1.85×1.85 A (SuperB)

Beam-beam parameter

0.059 (KEKB)
→ >0.24 (SuperKEKB)
→ 0.15 (SuperB)

Lorentz factor

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

Classical electron radius

Beam size ratio

Geometrical factors due to crossing angle and hour-glass effect

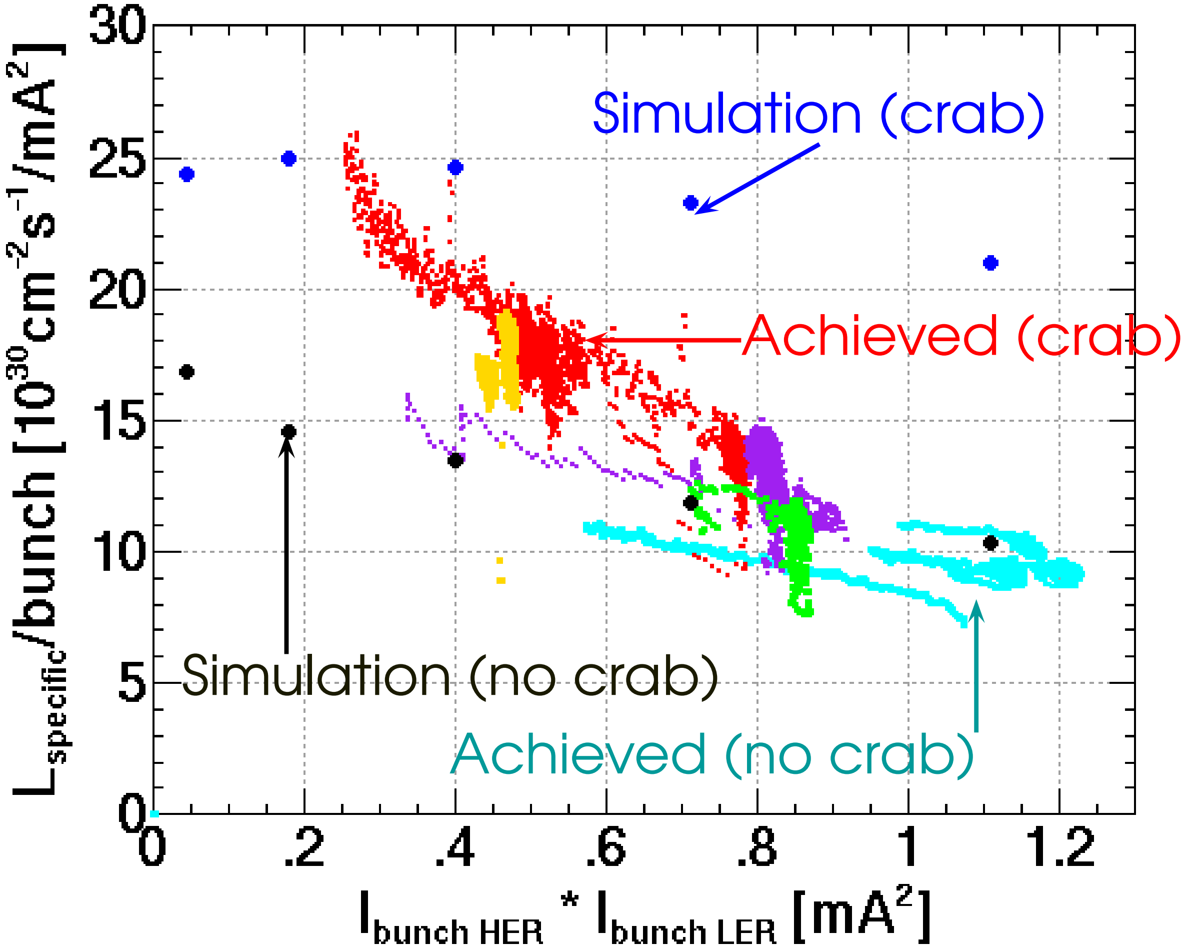
Luminosity

0.017×10^{36} cm^{-2}s^{-1} (KEKB)
→ 0.8×10^{36} cm^{-2}s^{-1} (SuperKEKB)
→ 1×10^{36} cm^{-2}s^{-1} (SuperB)

Vertical β at the IP

6.5/5.9 mm (KEKB)
→ 3.0/3.0 mm (SuperKEKB)
→ 0.22/0.39 mm (SuperB)

Crab cavity (KEKB/SuperKEKB)

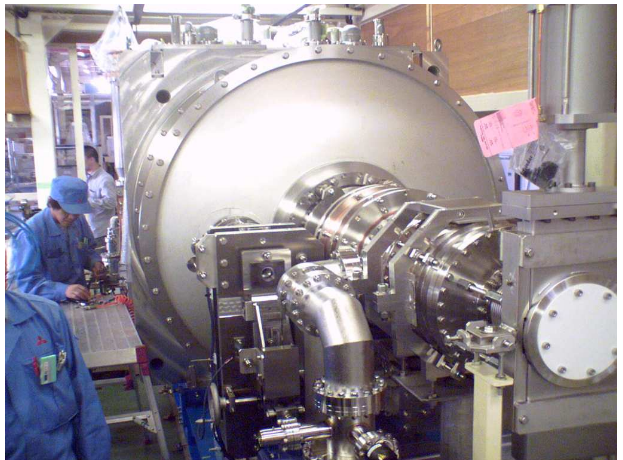


- Finite crossing (22 mrad) $\rightarrow$ effective head-on collision
- Beam-beam force become nearly independent on x at horizontal half integer tune

$\xi_y \sim 0.15$ for KEKB-crab
and twice more $\mathcal{L}$
($\xi_y > 0.24$ for SuperKEKB-crab)

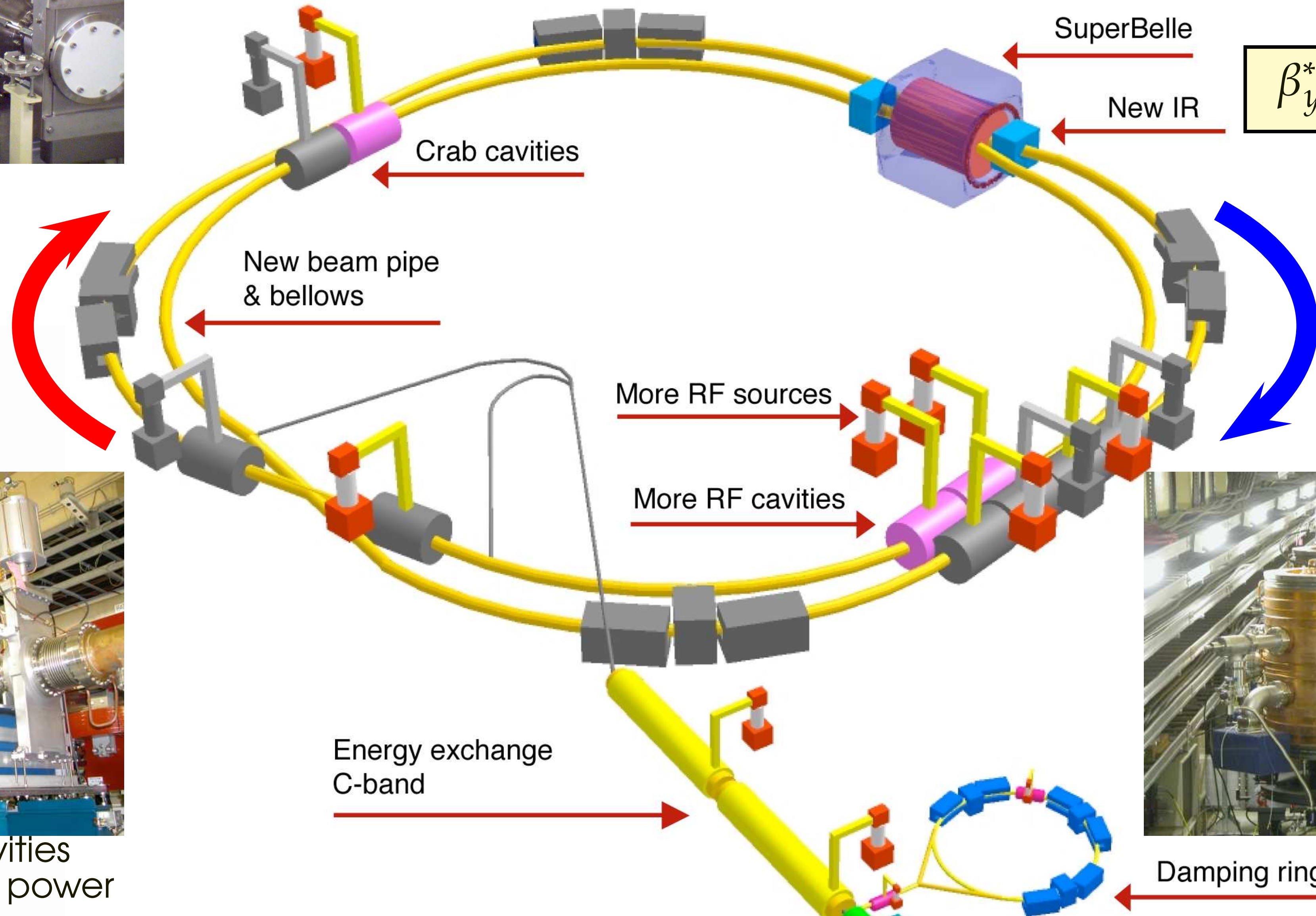
- Enhancement is seen, $\xi_y = 0.092$ (no crab: $\xi_y = 0.056$)
Luminosity drop for high current is being investigated

SuperKEKB Design



Crab cavities to be upgraded for a higher current

e^{+} 4.1 A

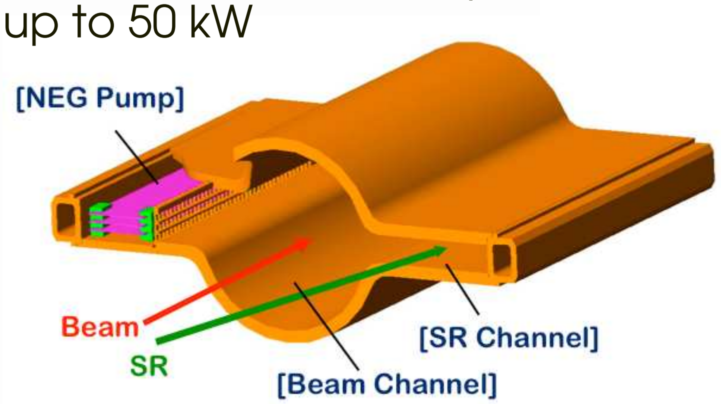


$\beta_y^* = \sigma_z = 3\text{mm}$

e^{-} 9.4 A

Superconducting cavities to absorb more HOM power up to 50 kW

ARES RF cavities with higher energy storage ratio



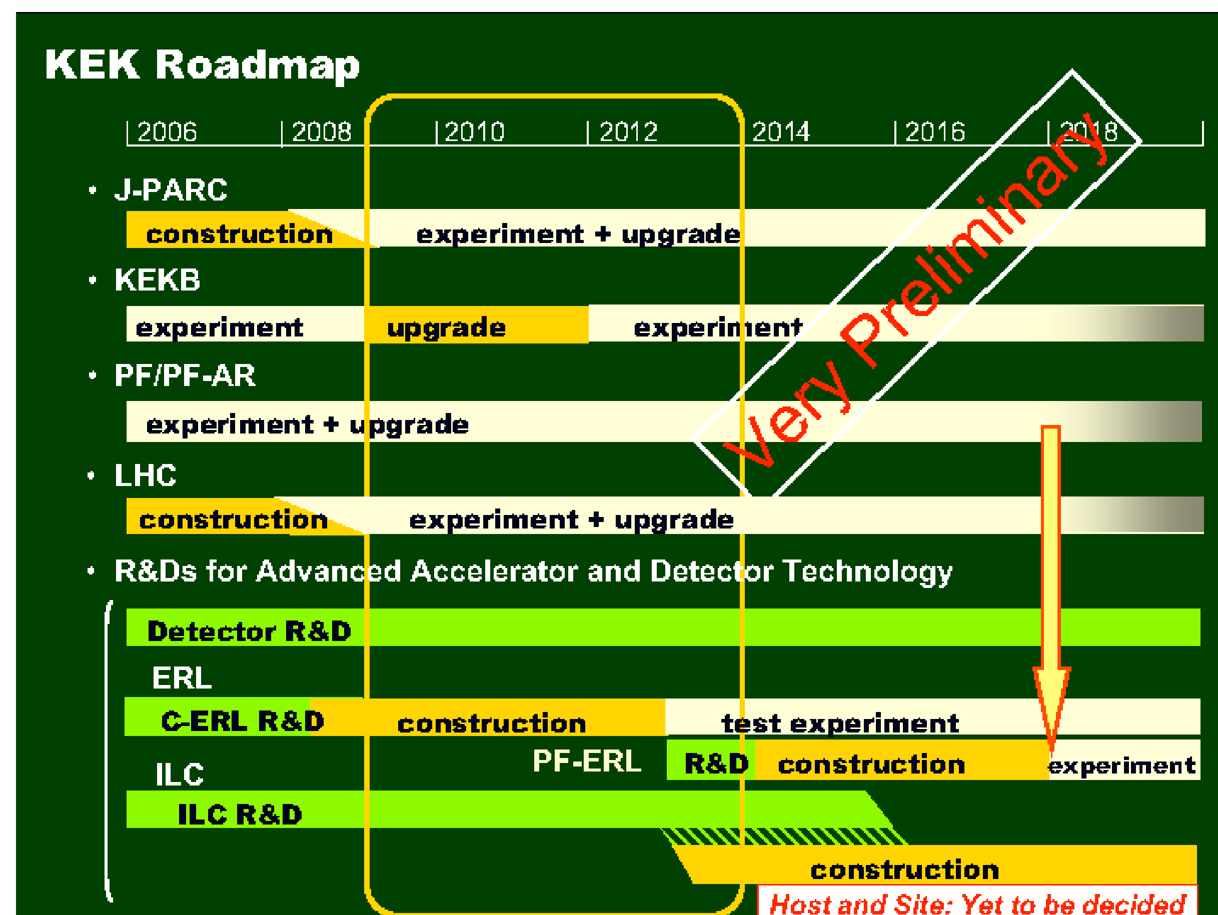
Antechamber beampipes and higher-current-proof bellows

for 8×10^{35} cm^{-2}s^{-1} (K.Oide)

KEK roadmap

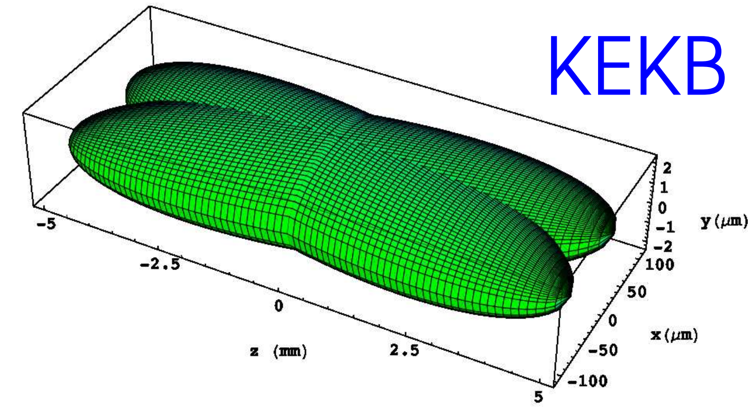
- KEK's 5-year roadmap,
  3-year KEKB upgrade ('09–'11) with constant annual budget
  (i.e., KEKB running cost → construction)
- Staging RF cavities and others, initial $\mathcal{L} \sim 2 \times 10^{35}$ cm^{-2}s^{-1}
- Not actually funded yet, KEK management in close contact with the funding agency (MEXT)

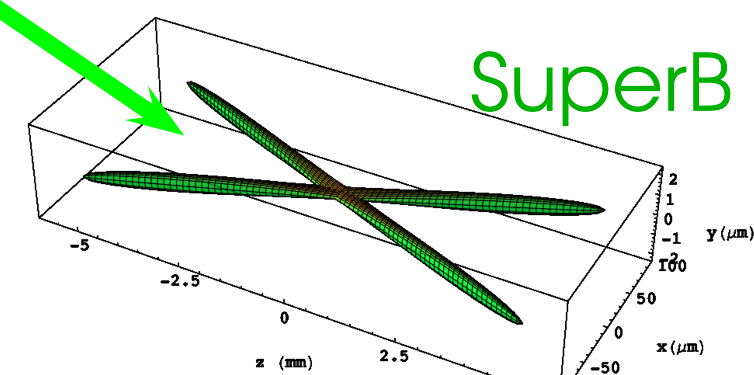
A very realistic scenario
with a 0.5–1 year delay
(KEKB will run in 2009)



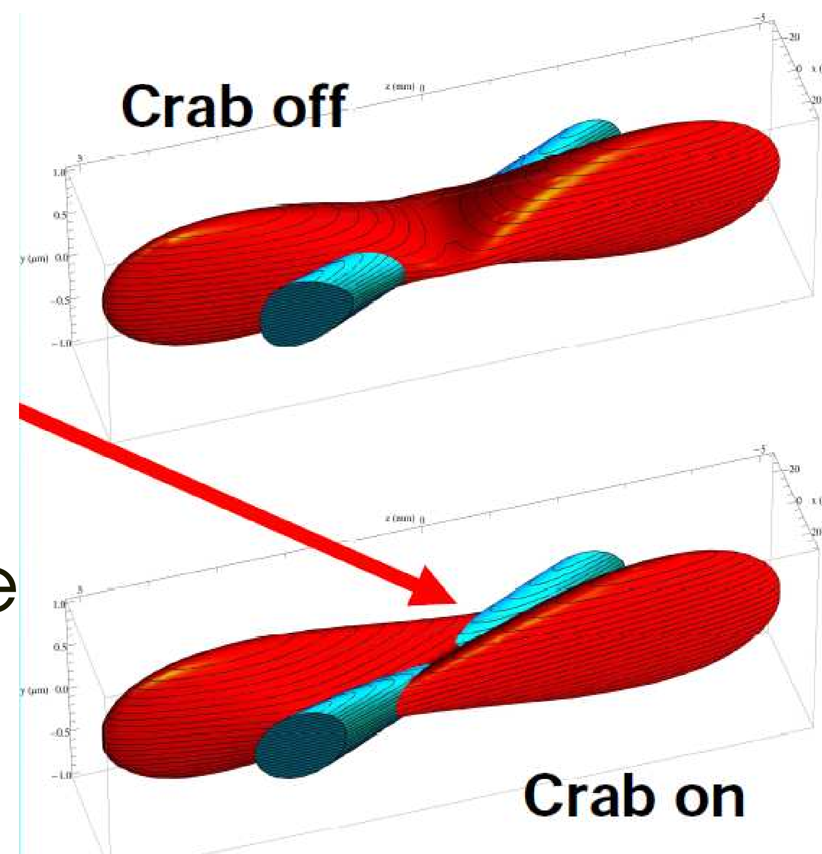
Crab waist (SuperB)

- Very small beam spot and β_y^* a la LC damping ring
- Very small $\beta_y^* \Rightarrow$ demands
  - a very short bunch length (hourglass effect)
  - or crab waist

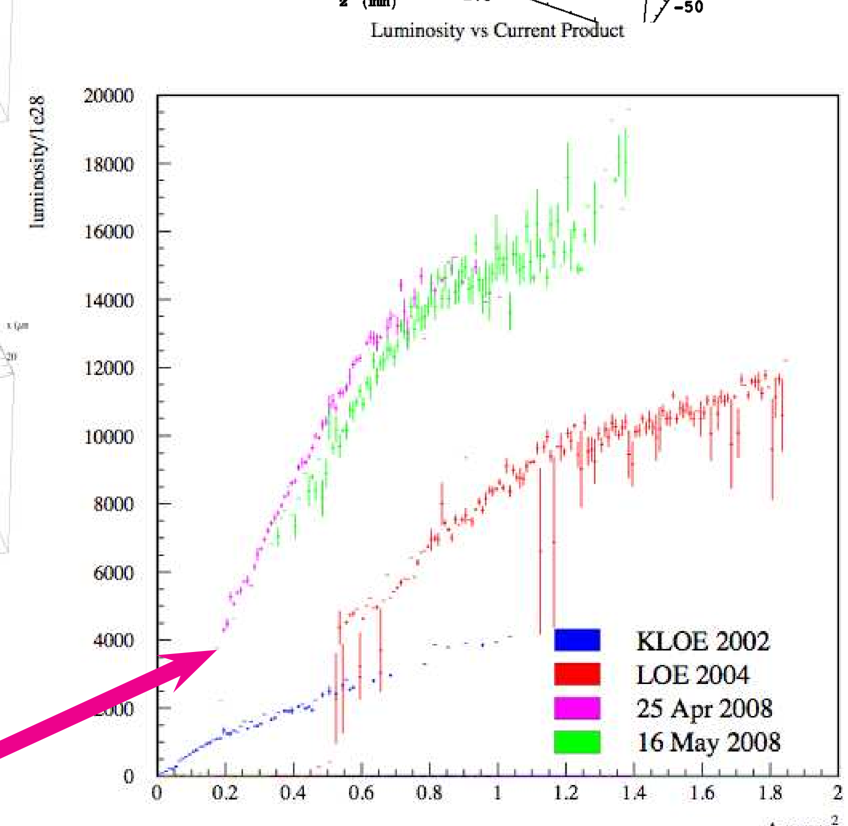




y waist can be moved along z with a sextupole on both sides at proper phase — "crab waist"

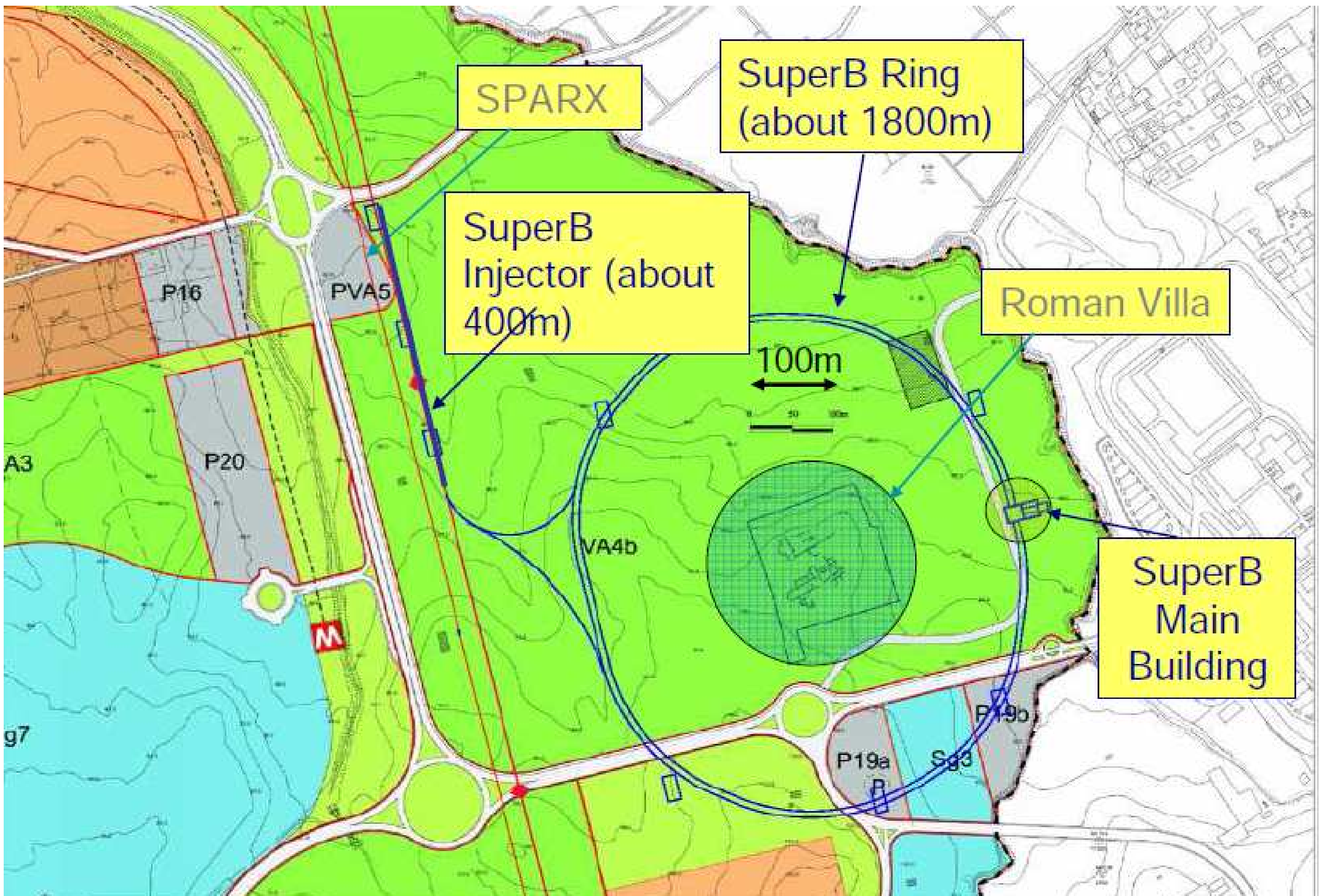


- Successful conceptual test at DAΦNE



SuperB site

- Site: INFN Rome Tor Vegarta campus
- Reuse: magnets will be brought from PEP-II



Detector Considerations

- Background issue
  - Much larger background is expected
  - Performance drop (esp. for photons) is not acceptable
- Beam energy asymmetry
  - Smaller asymmetry for lower electricity bill (for SuperB)
  - Also better for hermeticity, but worse for time-dep. CPV (unchaged for SuperKEKB)
- Existing detectors are excellent, no drastic performance difference after improving them to be capable for high background

Background issues

SuperBelle

- Higher beam current
  - ➡ large beam-gas background
- Moderate Touschek background
- Radiative-bhabha (luminosity term) is not dominant except KLM
- ×20 background at full spec

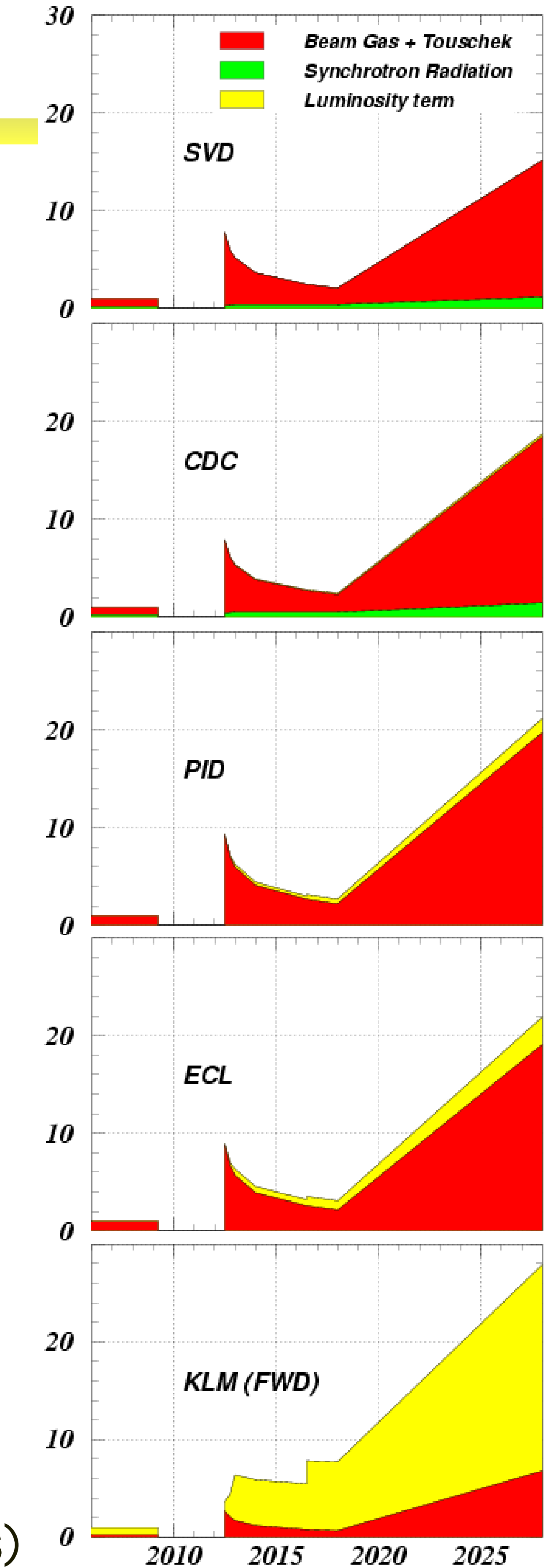
significant modification to Belle is needed

SuperB

- Beam-gas background is moderate
- Huge Touschek background
- Very short beam lifetime

small modification to BaBar is sufficient

(note: BaBar is already much immune to beam backgrounds)



SuperBelle

(baseline)

SVD: 6 layer (pixel?)

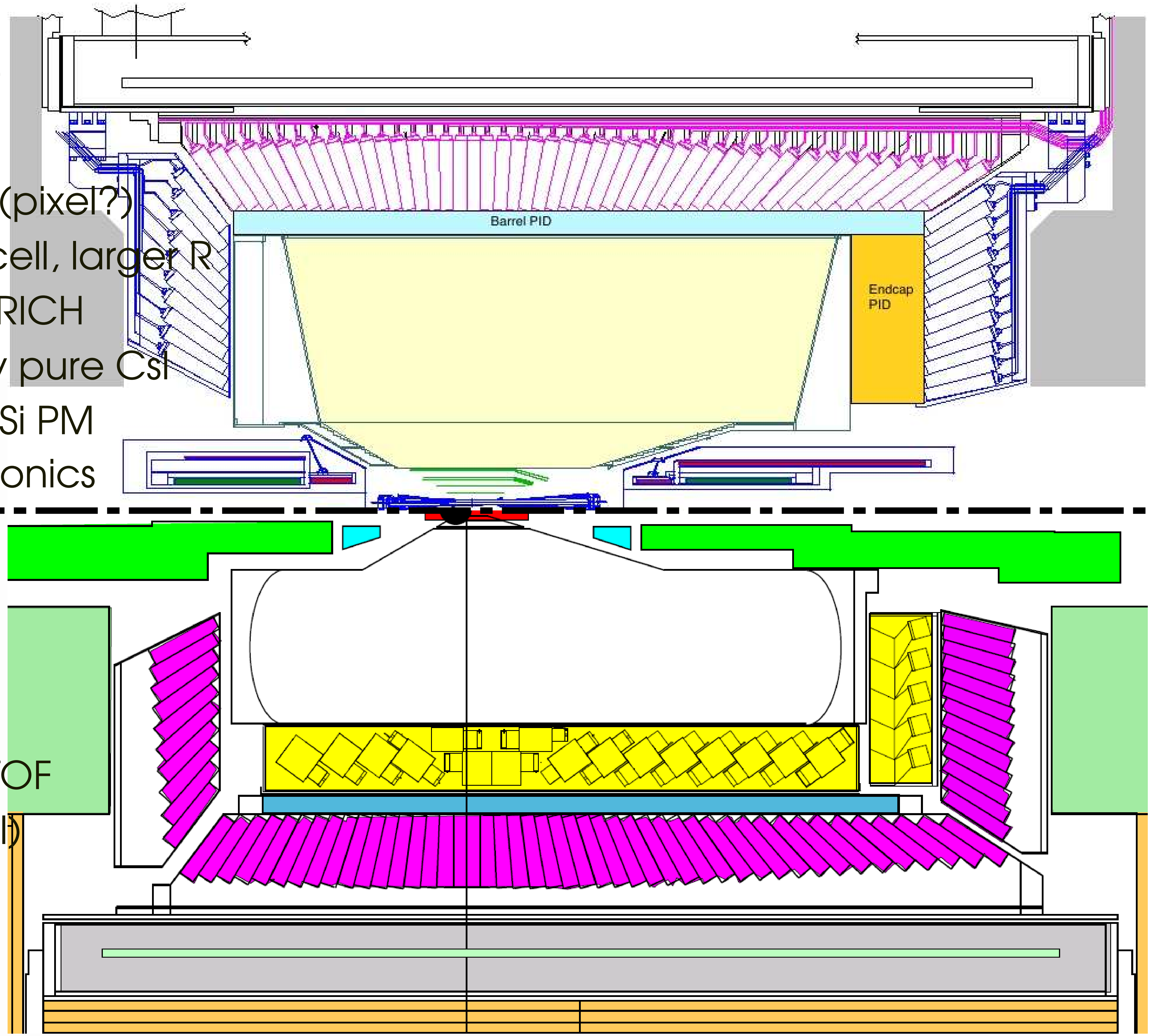
CDC: small cell, larger R

PID: TOP + ARICH

ECL: partially pure CsI

KLM: Scint.+ Si PM

+ new electronics



Current Belle

SVD: 4 layer

PID: ACC + TOF

ECL: All CsI(Tl)

KLM: RPC

SuperB detector

(baseline)

reuse of BaBar

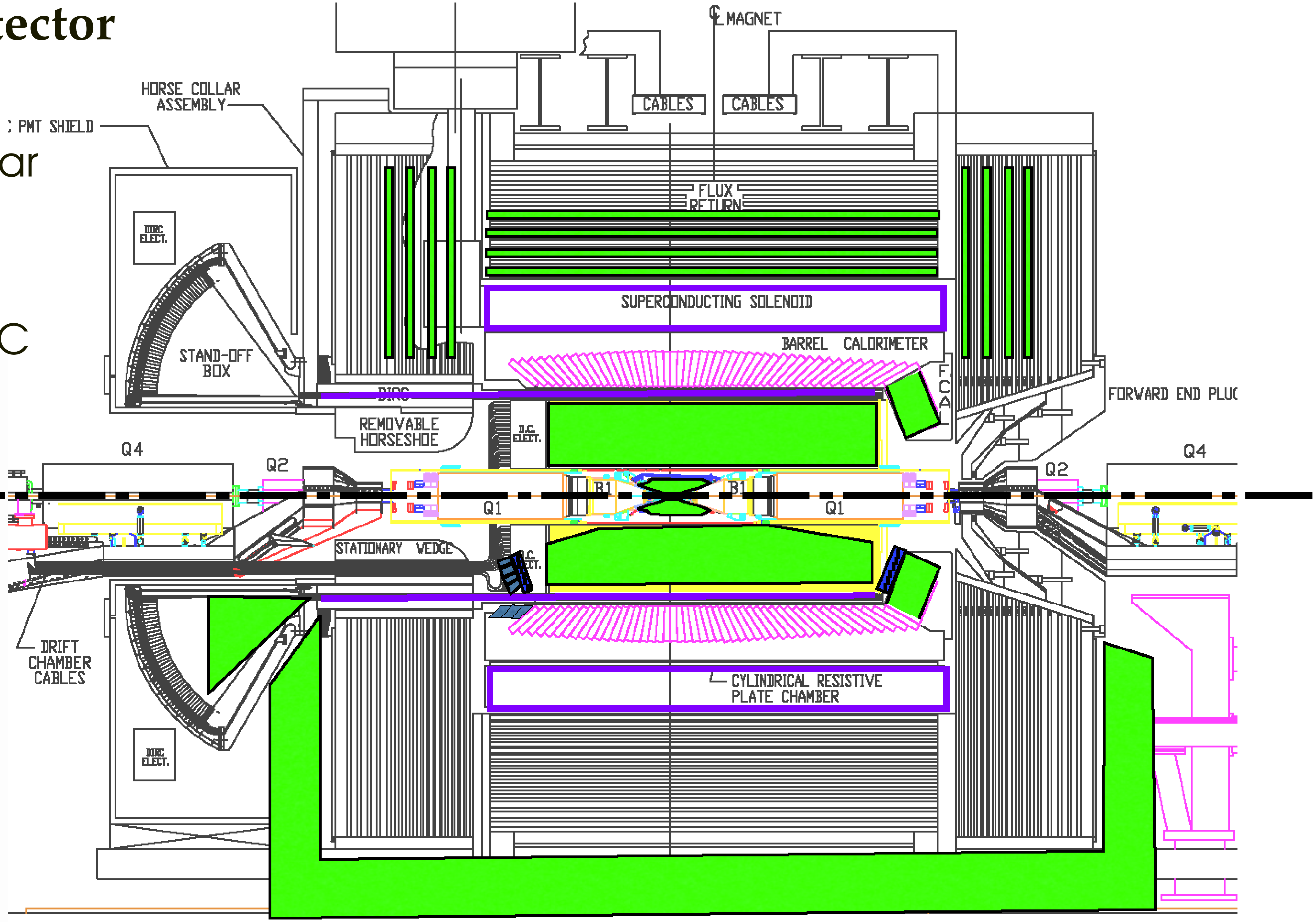
new SVT

new DCH

new fwd EMC

new IFR

(optional)



new components in green

Activities

SuperB group meeting last week
(http://www.pi.infn.it/bfactory/SuperB_elba2008/)

SuperKEKB meeting next month (http://superb.kek.jp/inaug/)

Summary

- Physics at super B-factories are very compelling, in the integrated luminosity range 5–50 ab^{-1}
  - Precise ϕ_2 ($\delta = 2^\circ$) provides a reference point ($\overline{\rho}, \overline{\eta}$), BSM from tree measurements and $b \to s$ penguin
  - Extensive searches for charged Higgs, RH current, LFV. . .
  - Many other physics not discussed here
- Will we have a super B factory?
  - Accelerator and detector R&D are very active
  - SuperKEKB finalizing for production
    SuperB design is getting converged
  - Probability for SuperKEKB is getting reasonably high
  - And, why don't you join us?

Backup

Parameter comparison

	SuperKEKB		SuperB	
	LER (e^+)	HER (e^-)	LER (e^+)	HER (e^-)
Energy (GeV)	3.5	8	4	7
Luminosity (10^{36})	0.55		1.0	
Number of bunches	5018		1251	
Beam current (A)	9.4	4.1	1.85	1.85
$\beta(y^*)$ (mm)	3		0.22	0.39
$\beta(x^*)$ (mm)	200		35	20
emittance $\epsilon(y)$ (pm.rad)	60	66	7	4
emittance $\epsilon(x)$ (nm.rad)	12	13	2.8	1.6
beam-size $\sigma(x^*)$ (μm)	37.5	39.8	0.039	0.039
beam-size $\sigma(y^*)$ (μm)	2.11	2.28	9.9	5.66
bunch length	3			
Damping time (trans/long) (ms)	84/–	47/–	40/20	40/20
Touschek lifetime (min)			20	40
Effective beam lifetime (min)			5.0	5.7
tune-shift $\xi(y)$ (from formula)	0.296		0.15	
tune-shift $\xi(x)$ (from formula)	0.153		0.0043	0.0025
RF power (MW)			17	

MSSM down-type squark mass matrix

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

measured at LHC/LC

mass insertion approximation (MIA): $(\delta^d_{ij})_{AB} = \dfrac{(\Delta^d_{ij})_{AB}}{\tilde{m}^2}$

$b \to s$ transition ($ij = 23$)

- CPV phase in $b \to s$
- $B \to X_s\gamma$ branching fraction
- B_s mixing

$b \to d$ transition ($ij = 13$)

- CPV phase in $b \to d$
- $B \to X_d\gamma$ branching fraction
- B_d mixing

Inclusive $b \to s\gamma$

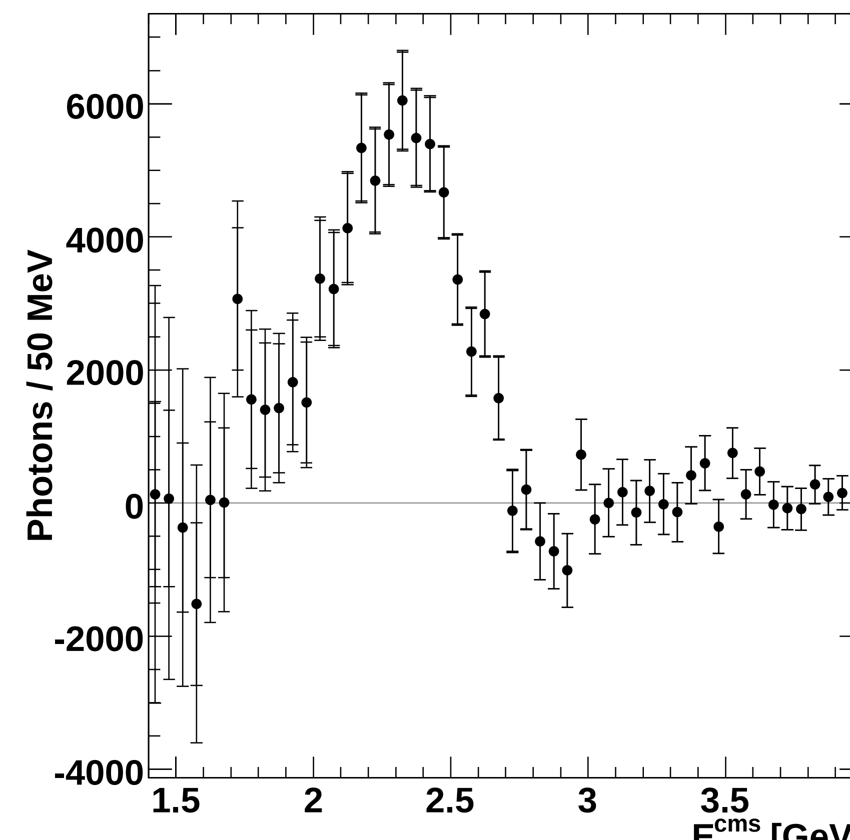
Most stringent BSM constraints — $\delta(\text{exp}) \sim \delta(\text{theo}) \sim 7\%$

$\mathcal{B}(B \to X_s\gamma; 1.6\ \text{GeV}) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$ (new HFAG average)

$\mathcal{B}(B \to X_s\gamma; 1.6\ \text{GeV}) = (3.15 \pm 0.23) \times 10^{-4}$ (SM NNLO Misiak et al)

- We've just learned that the full B-factory dataset is still statistical error limited
  - Fully inclusive $B \to X_s\gamma$
  - Full Belle dataset (605 fb^{-1})
  - $E_\gamma^{\text{min}} = 1.7$ GeV

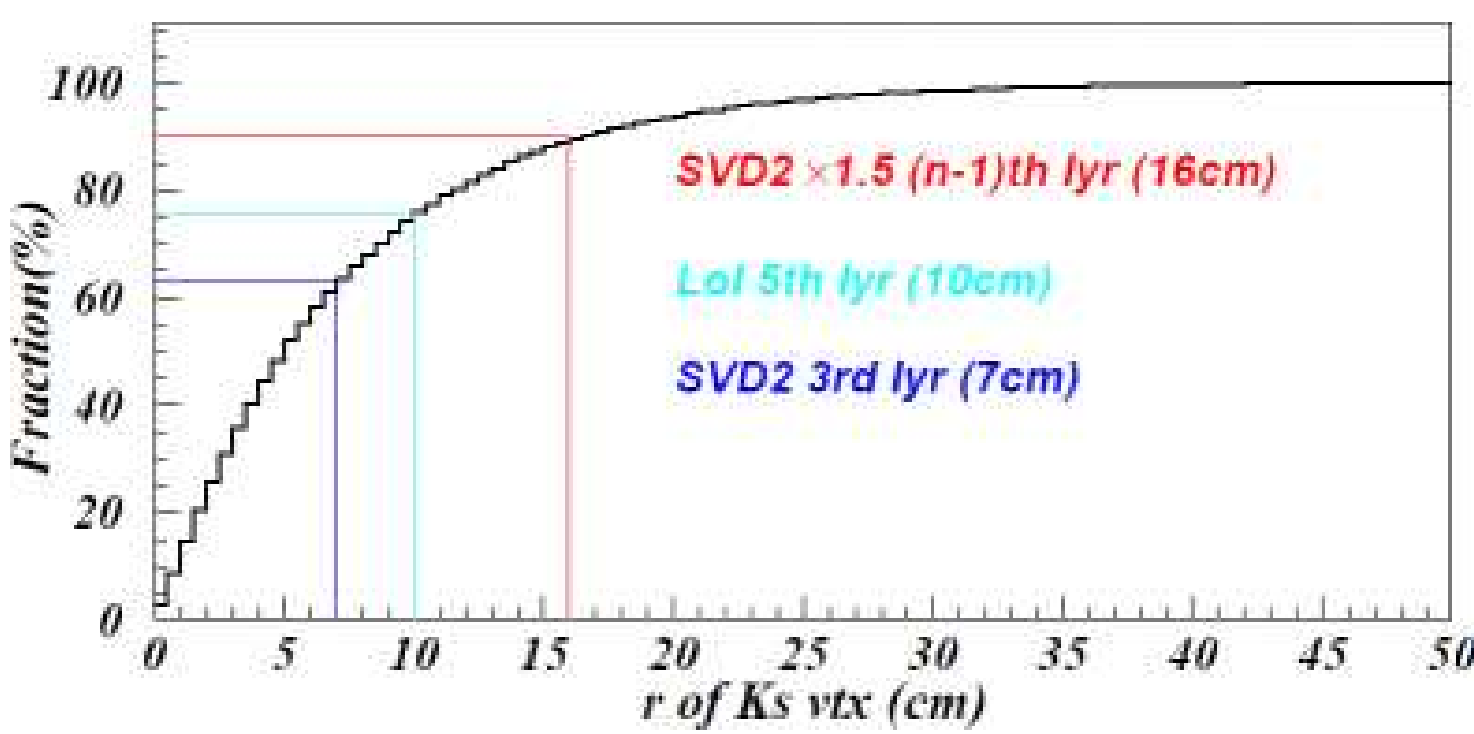
  Still a super B-factory topic if we'd like to go down to lower E_γ

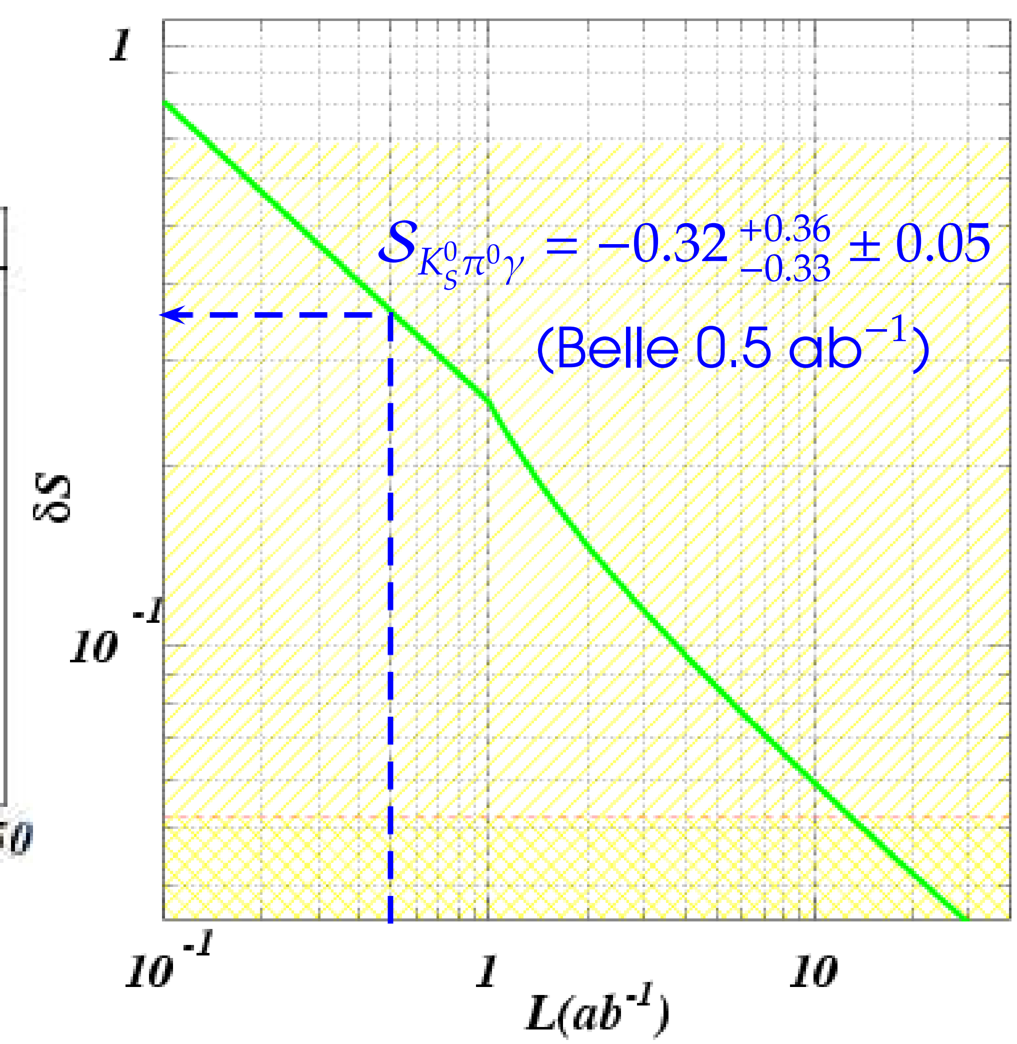


- Direct CPV in $B \to X_s\gamma$ — 0.4% in SM, can reach this sensitivity
- Direct CPV in $B \to X_{s+d}\gamma$ — even small in SM, SUSY, . . .

Exclusive $b \to s\gamma$

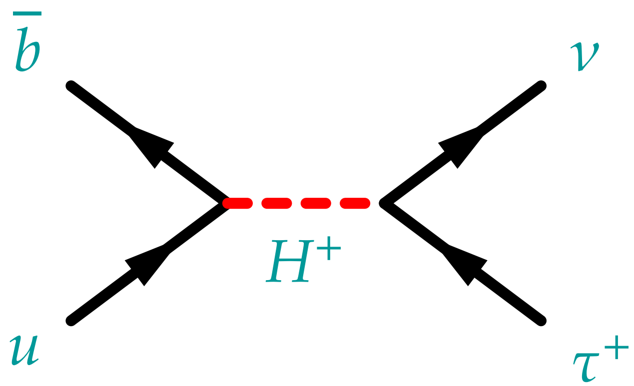
- CPV: sensitive to the non-SM right handed current
- SM CPV is suppressed ($S \sim -\frac{2m_s}{m_b} \sin 2\phi_1$ = a few %), while e.g., δ^d_{RL} and δ^d_{RR} in MSSM will enhance it
- $B \to K^0_S \pi^0 \gamma$ — extrapolate $K^0_S \to \pi^+\pi^-$ vertex to IP for Δz (larger vertex detector volume helps)
- Stat. error dominant

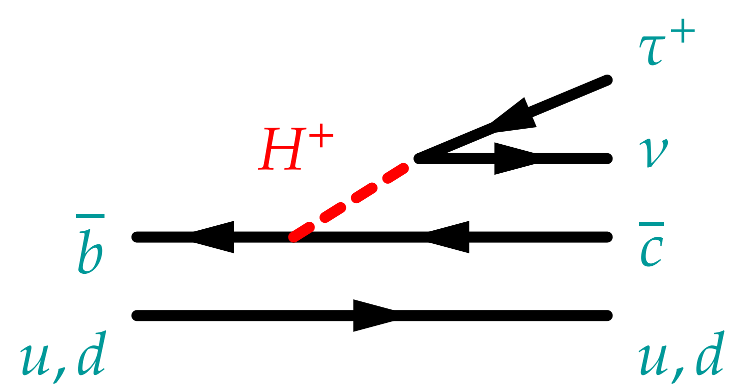


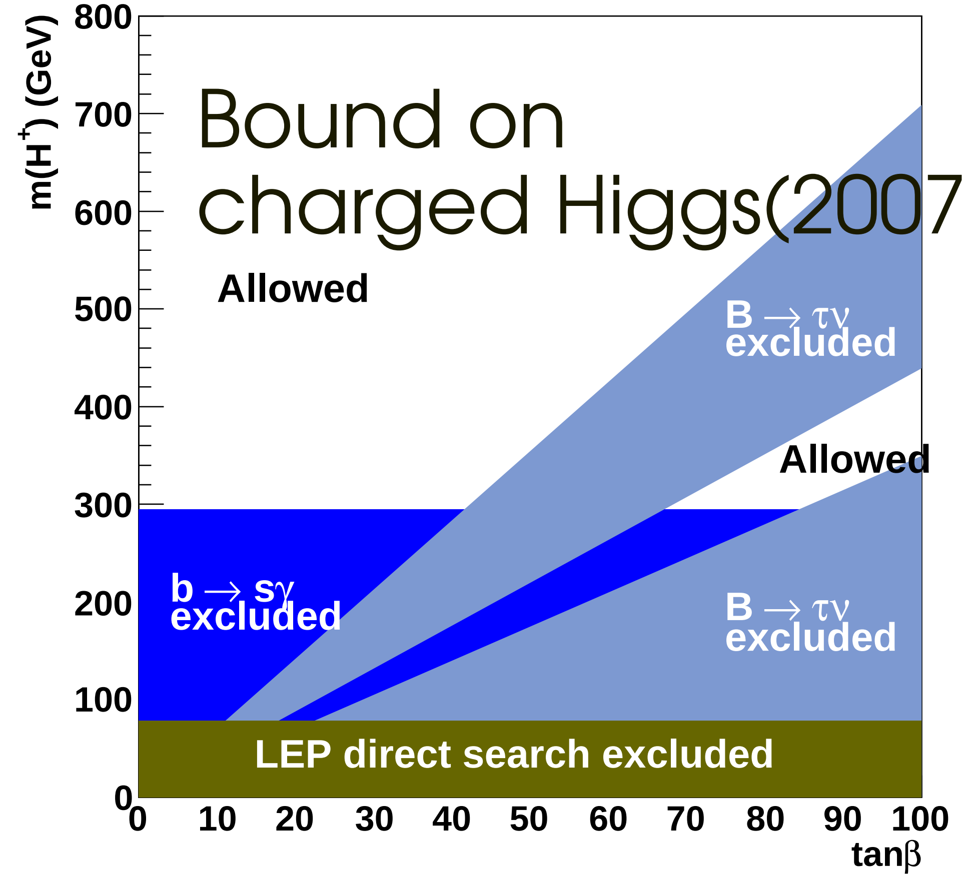


Charged Higgs

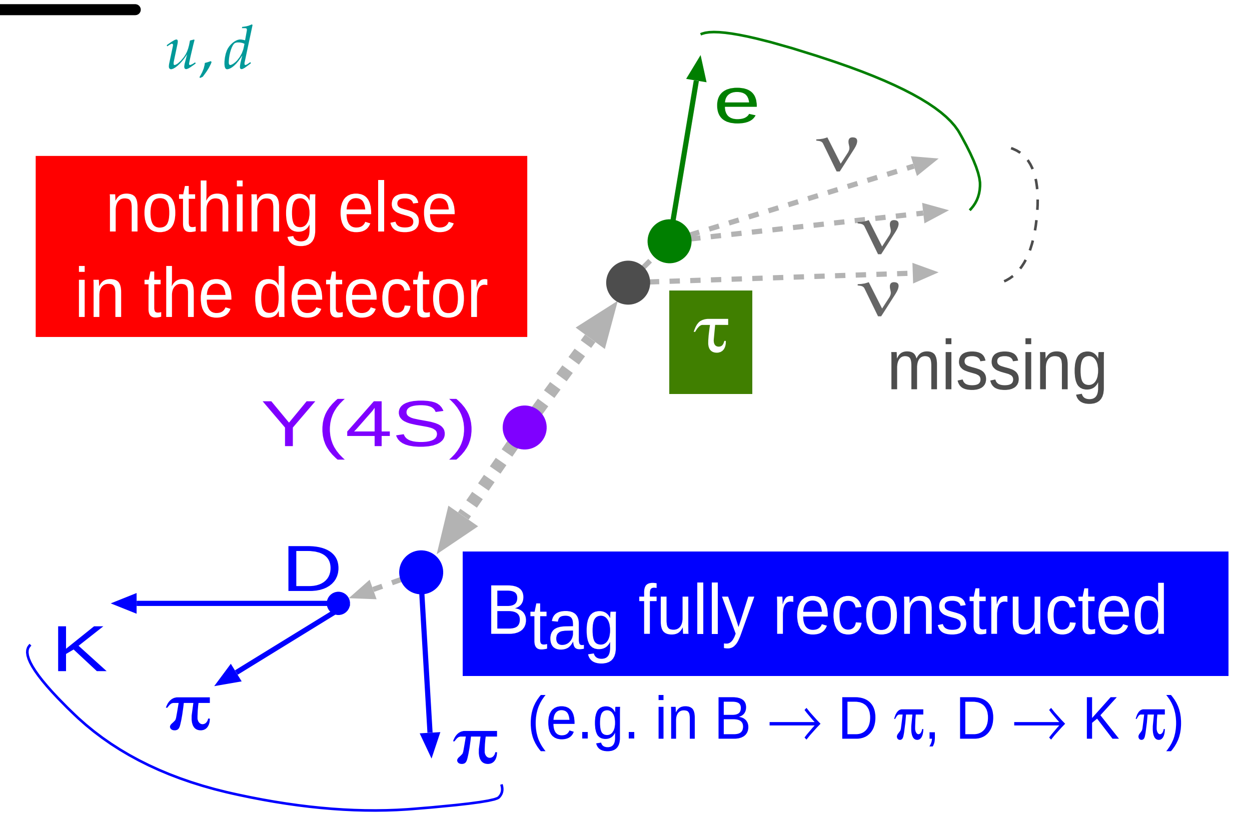
- Needed in many BSM
- Appears in a tree diagrams:
  $B^+ \to \tau^+\nu,\, B \to D\tau^+\nu,\, B^+ \to \mu^+\nu$
  (also in loops: $b \to s\gamma$)
- Universality tests: $\tau \leftrightarrow \mu,\, c\tau\nu \leftrightarrow u\tau\nu$





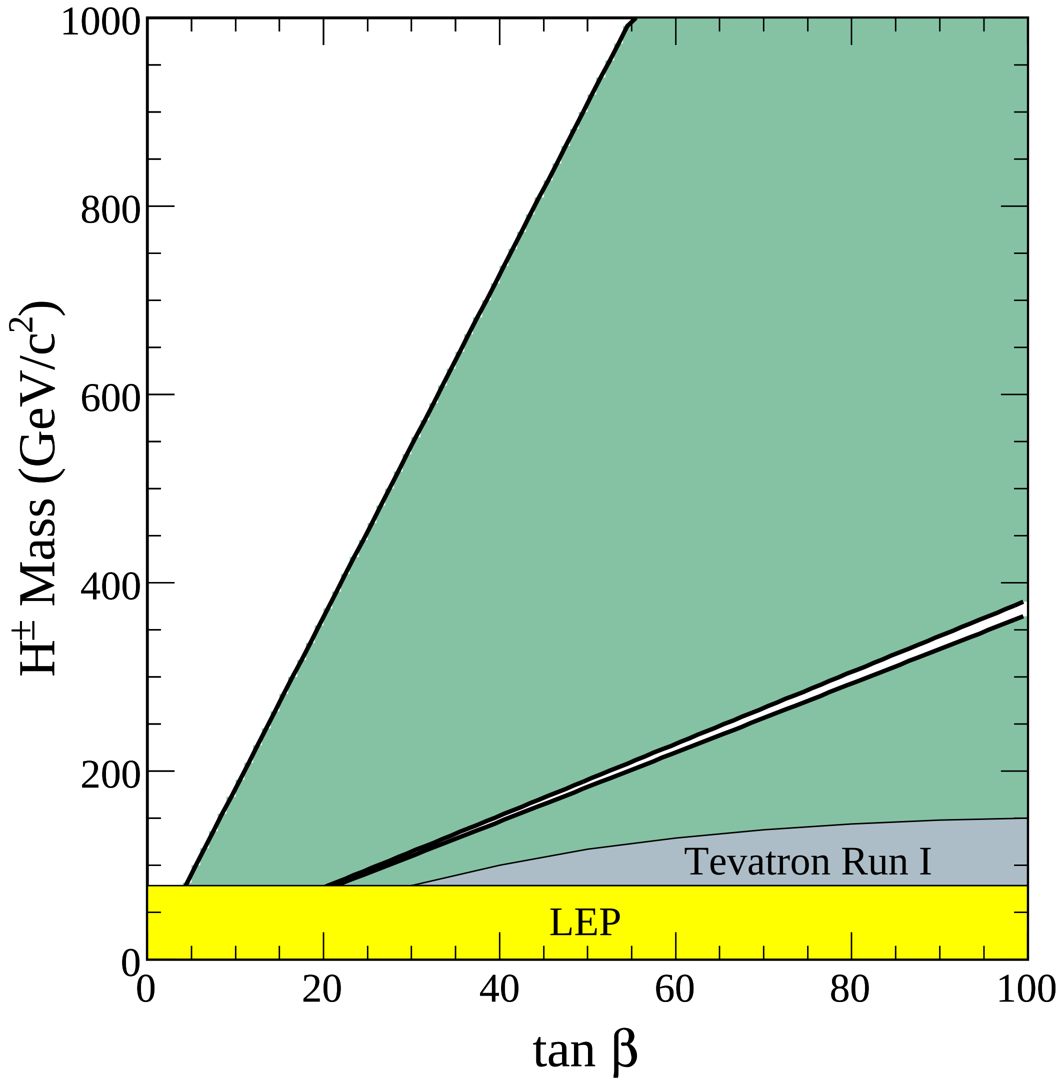


- More than one neutrino, full reconstruction of other B
- Hermeticity
- Small calorimeter noise hits, good neutral E resolution

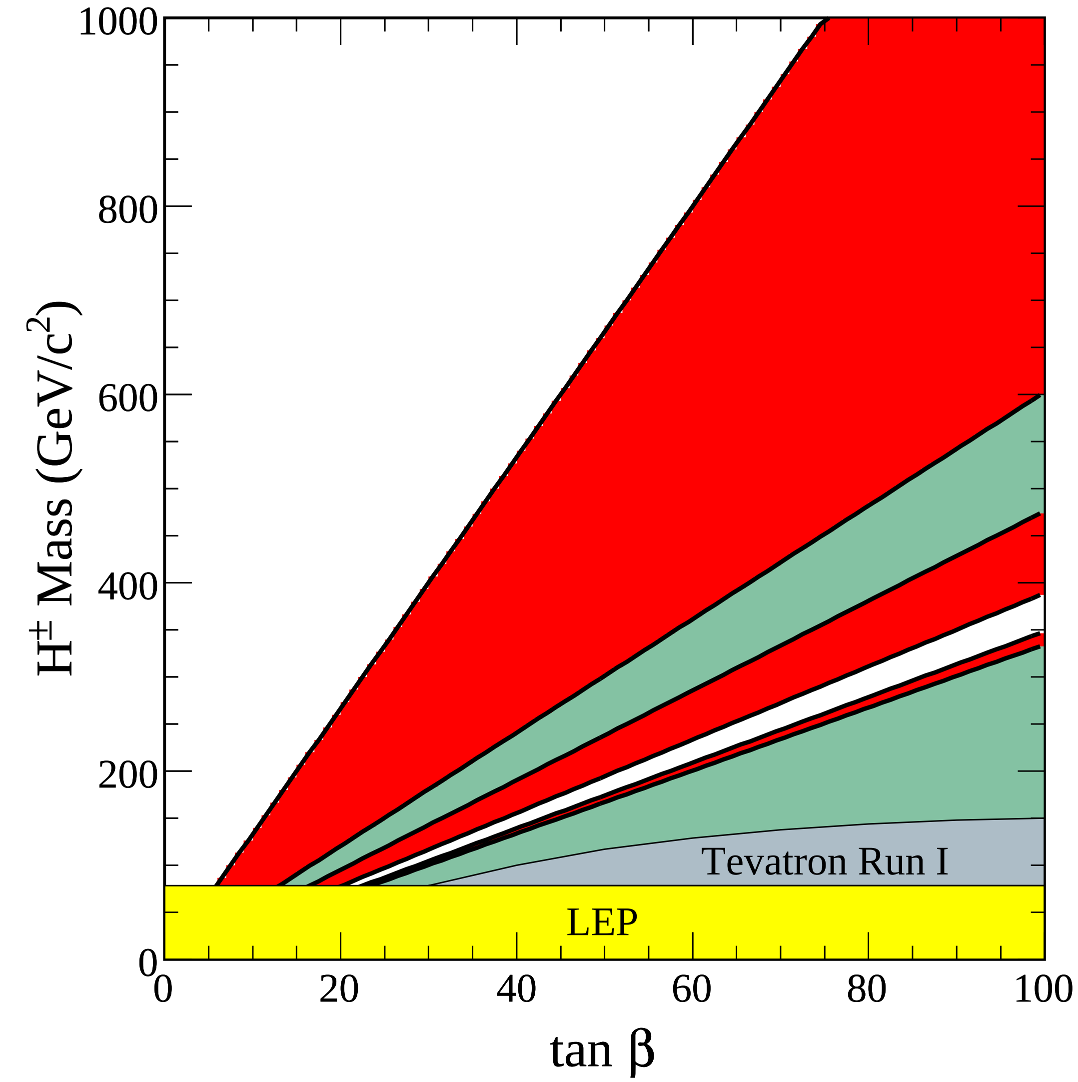


$B^+ \to \tau^+\nu$ at 50 ab^{-1}

Excluded region

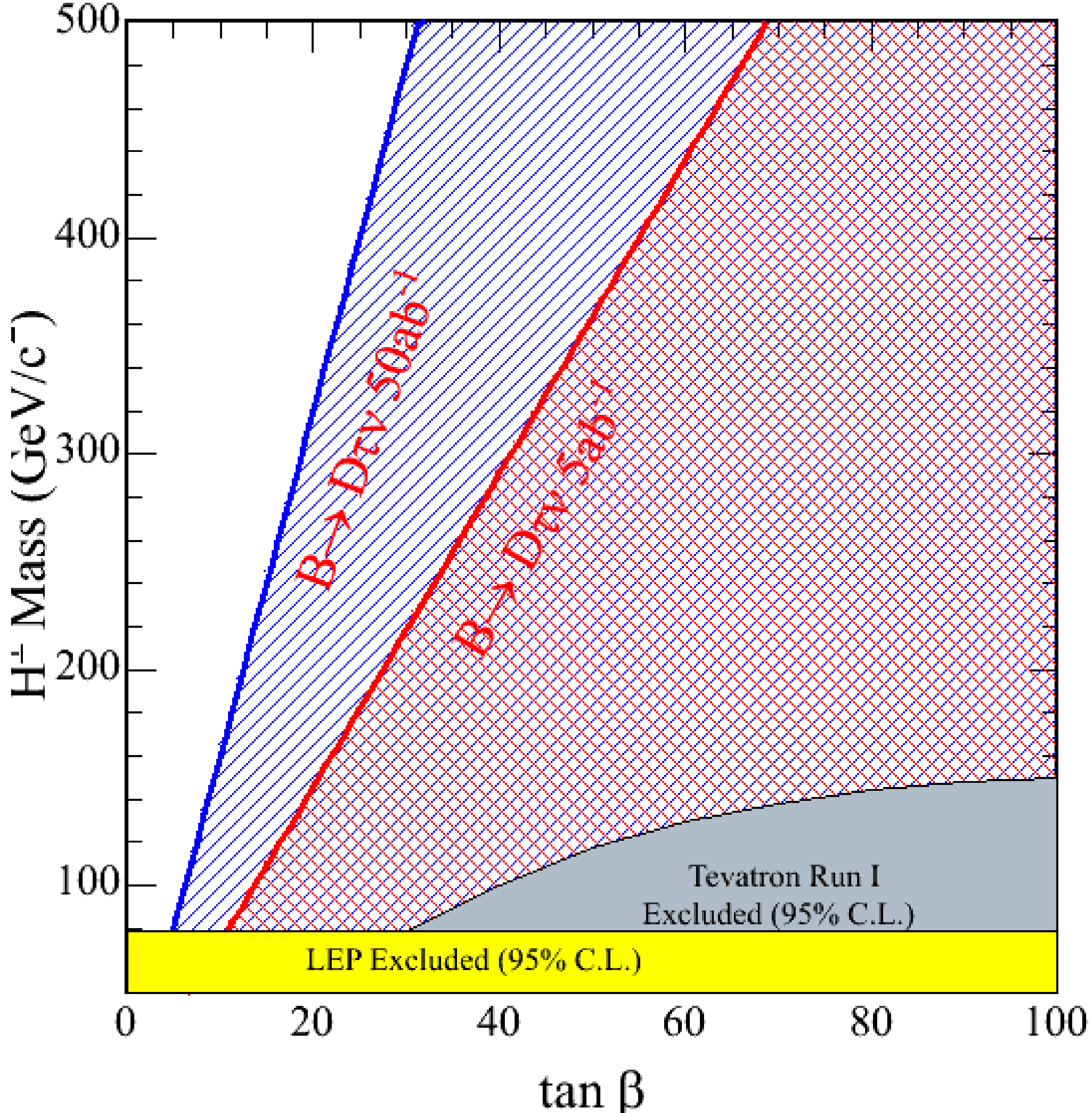


or, Discovery region
(outside the current excluded region)

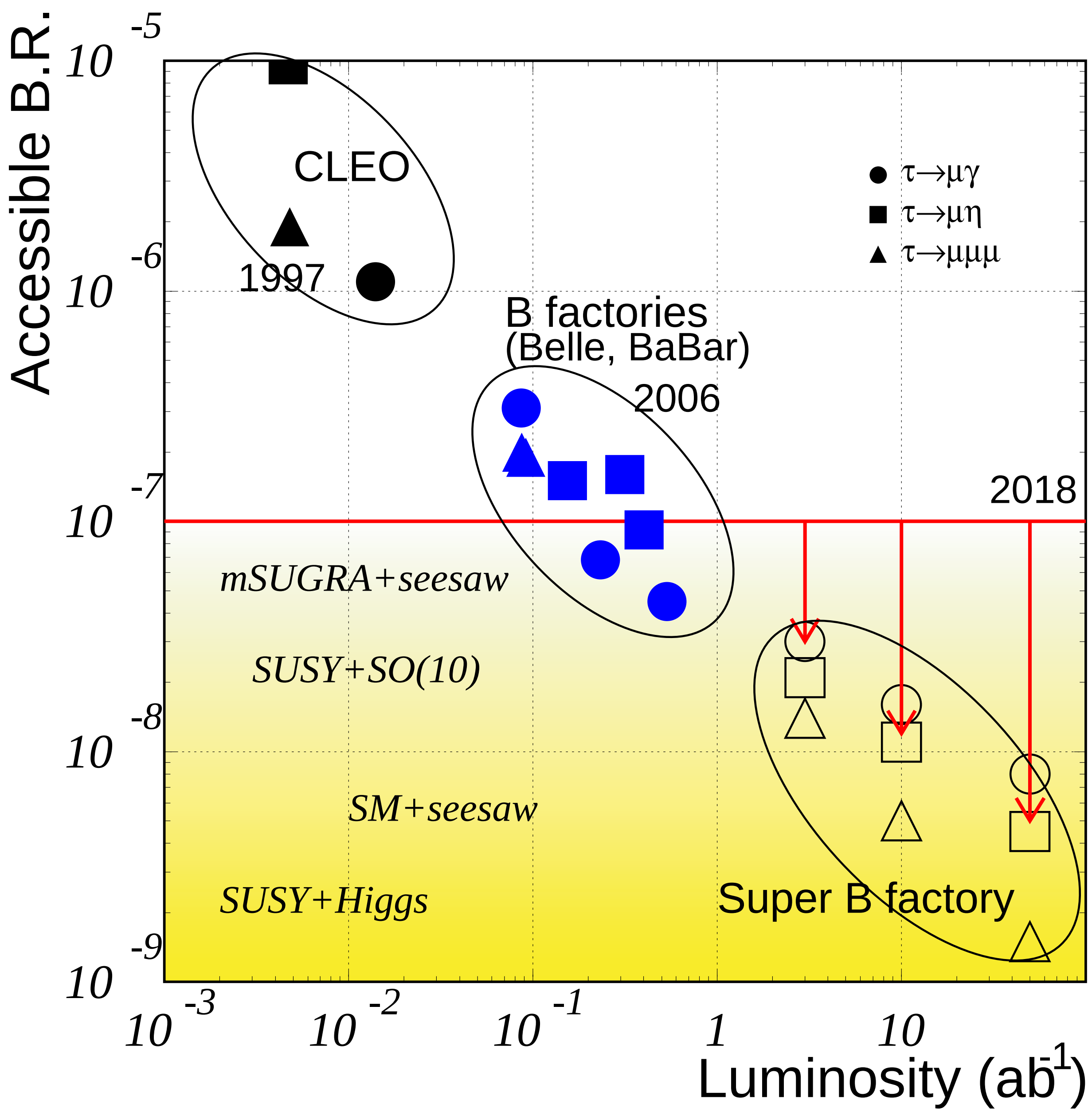


- Similar limit from $B \to D^{(*)}\tau^+\nu$
- Searches up to $m_{H^+} \sim$ several 100 GeV for large $\tan\beta$

$B \to D\tau^+\nu$ at 5 and 50 ab^{-1}

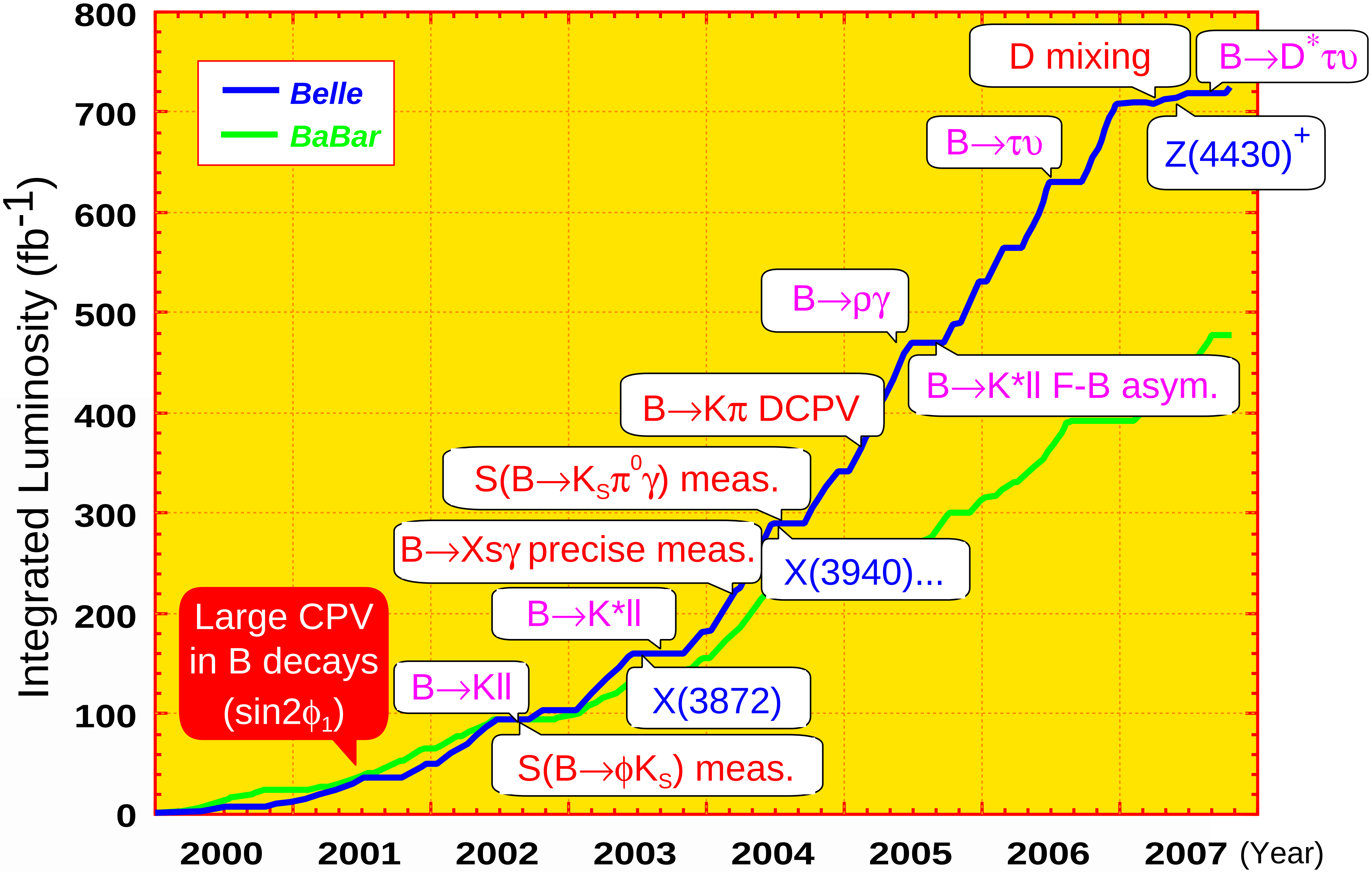


τ lepton flavor violation (LFV)



- Quark mixing ➡ KM
- Neutrino mixing ➡ MNS
- Charged lepton — LFV?
  - LFV through neutrino mixing is extremely small: e.g. $\mathcal{B}(\tau \to \mu\gamma) \sim 10^{-54}$
  - BSM scenarios (SUSY, etc) generates LFV: SUSY SO(10) $\sim 10^{-8}$, sSUGRA + seesaw $\sim 10^{-7}$
- Many modes to search (those including lepton number violation with and without $B - L$)

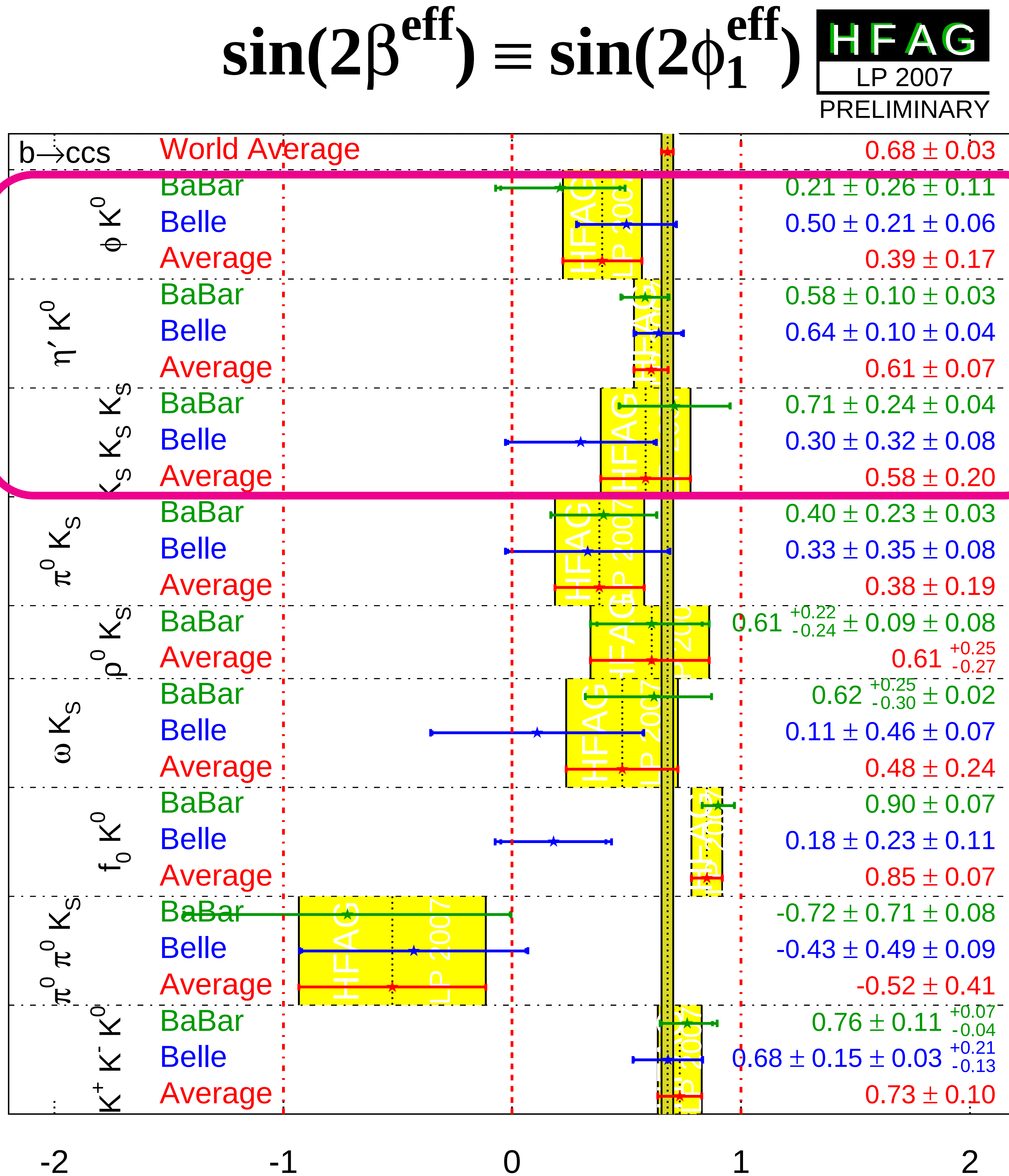
Searches down to $O(\sim 10^{-9})$

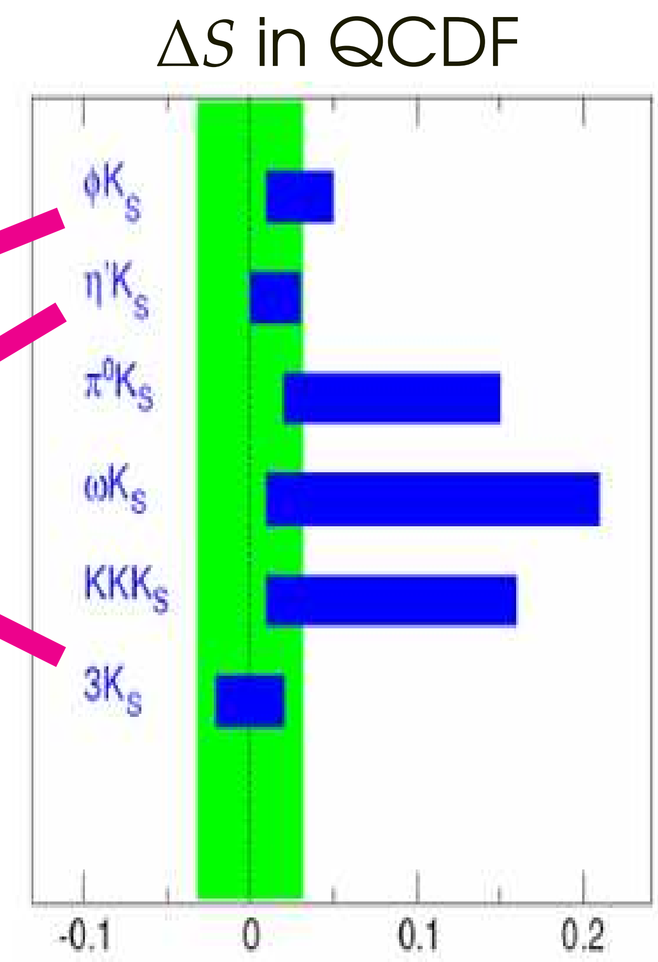


Belle has established the needed decays/techniques

- Decay modes: $b \to s\ell^+\ell^-$, $b \to d\gamma$, $B^+ \to \tau^+\nu$, $B \to D^*\tau^+\nu$
- Phases: time-dependent CPV in $b \to s$, $b \to s\gamma$

$b \to s$ CPV: now





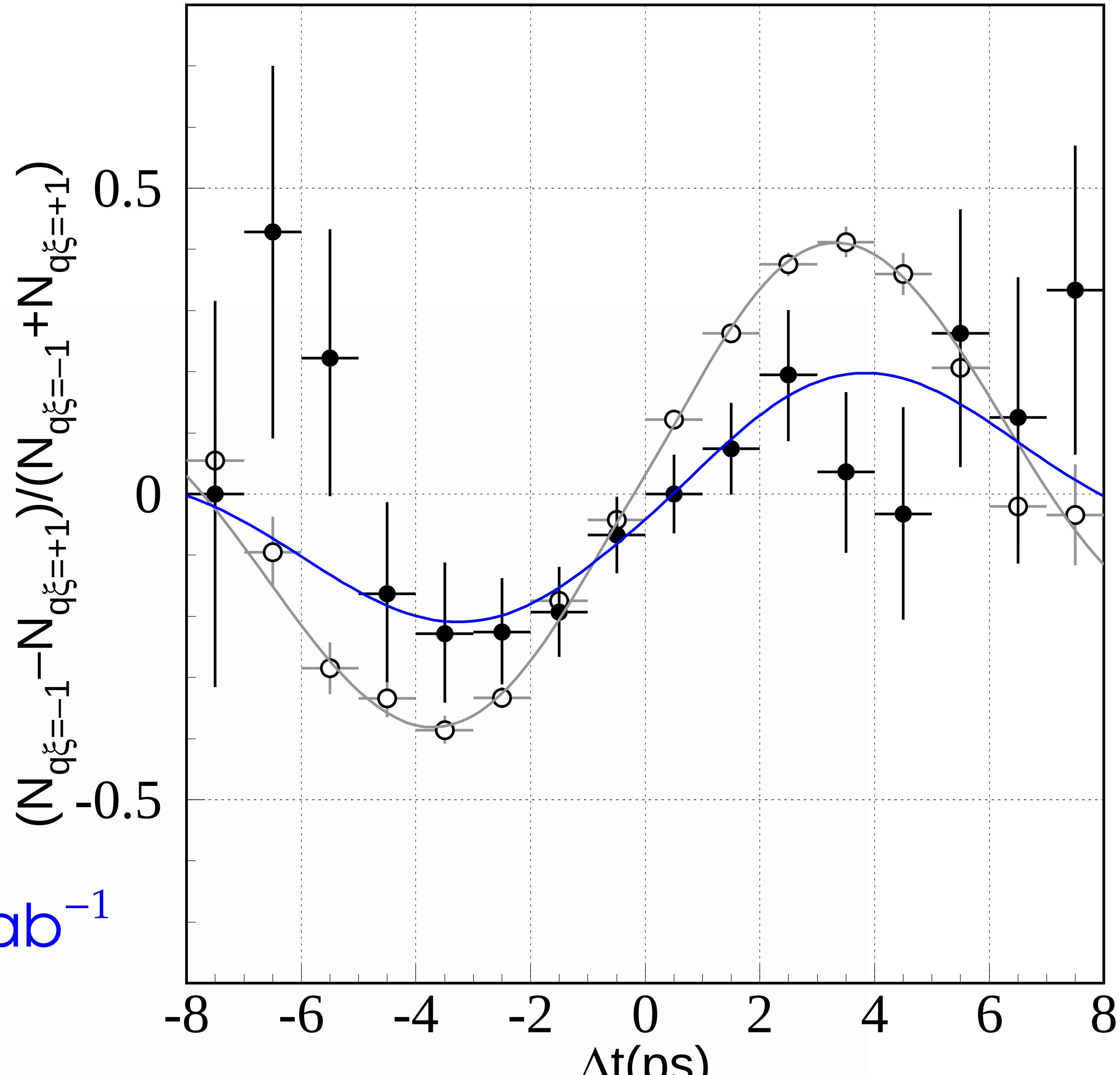
Three golden modes
$\delta S_{\rm theo} \sim 0.02$

Definitely need more data to pin down the difference mode by mode.

For 3 ab^{-1}

	N(event)	$\sigma_{stat}(S)$
ϕK^0_S	1860	0.094
ϕK^0_L	720	0.230
ϕK^0	2580	0.086
$\eta' K^0_S$	8640	0.043
$\eta' K^0_L$	2760	0.097
$\eta' K^0$	11400	0.039
$K^0_S K^0_S K^0_S$	1140	0.129

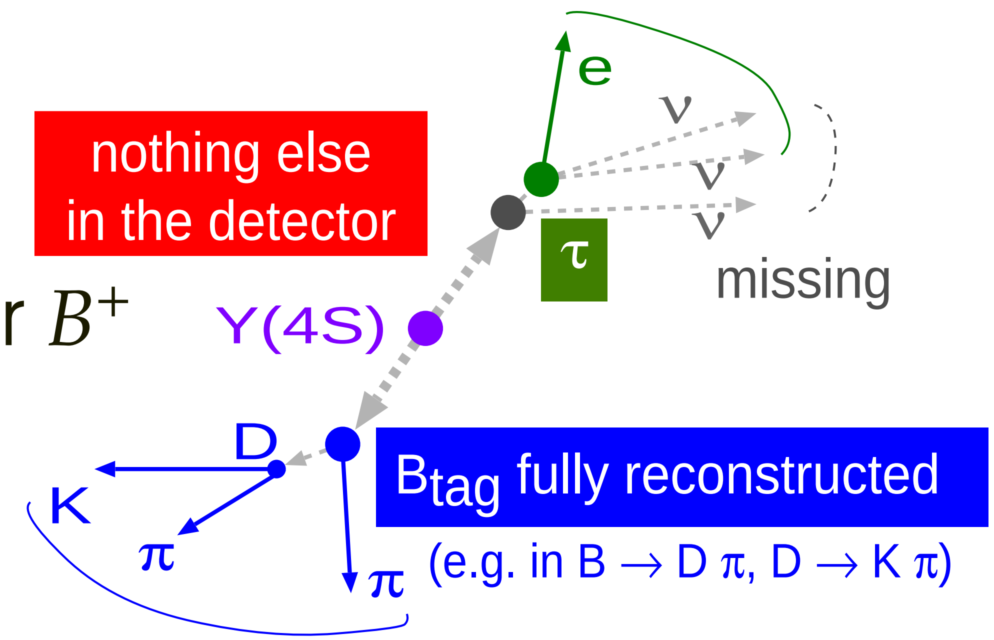
$\Delta\mathcal{S} > 3\sigma$ already with 3 ab^{-1}
for the current $\mathcal{S}_{\phi K^0} = 0.39$



MC 5 ab^{-1} for $\mathcal{S}_{\phi K^0_S} = 0.39$, $\mathcal{A}_{\phi K^0_S} = 0$

Prospects on full reconstruction

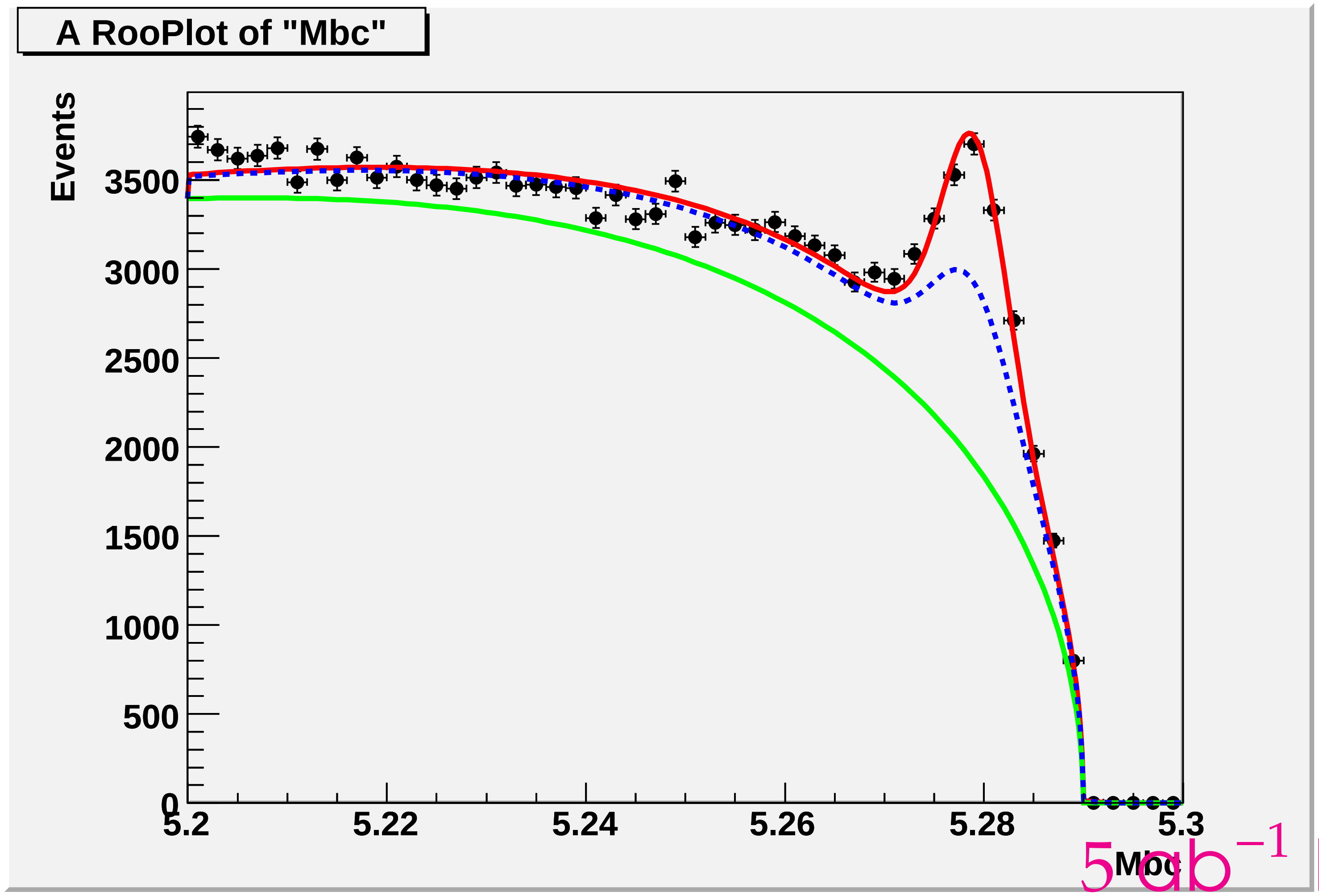
- Latest Belle code
  - Modes: $D^{(*)}(\pi^+, \rho^+, a_1^+, D_s^{(*)+})$
  - Efficiency: 0.09% for B^0, 0.15% for B^+
- Problems
  - Not an ultimate approach
    (χ^2 based best-candidate selection)
  - Slow $\pi^\pm$ recovery with SVD tracker
- At upgraded KEKB
  - Beam background: worries in soft photon, π^0, $\pi^\pm$
  - Soft photon reconstruction:
    — Less material in front of CsI
    — More beam background pile-up



Full reconstruction code is now being revisited

$B \to X_d\gamma$ at 5 ab^{-1}

- Efficiency 2.9%
- A fit result:
  $\Rightarrow Y = 4249 \pm 224 \pm 888$
- $b \to s\gamma$ component
  ±20% uncertainty
- Error sources:
  Stat.: 5%
  Fit.: 21%
  Model: 10% (not in Y)
  Total: 24%



5 ab^{-1} MC

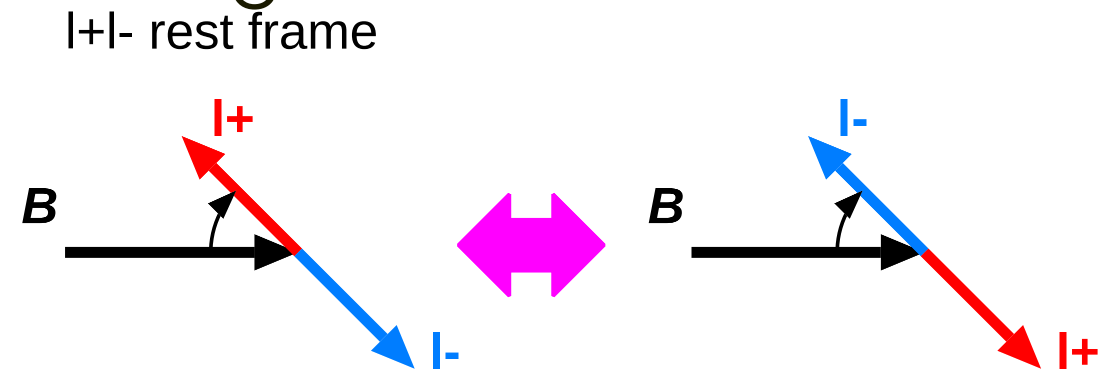
$B \to X_d\gamma$ seems to be possible with 5 ab^{-1}!

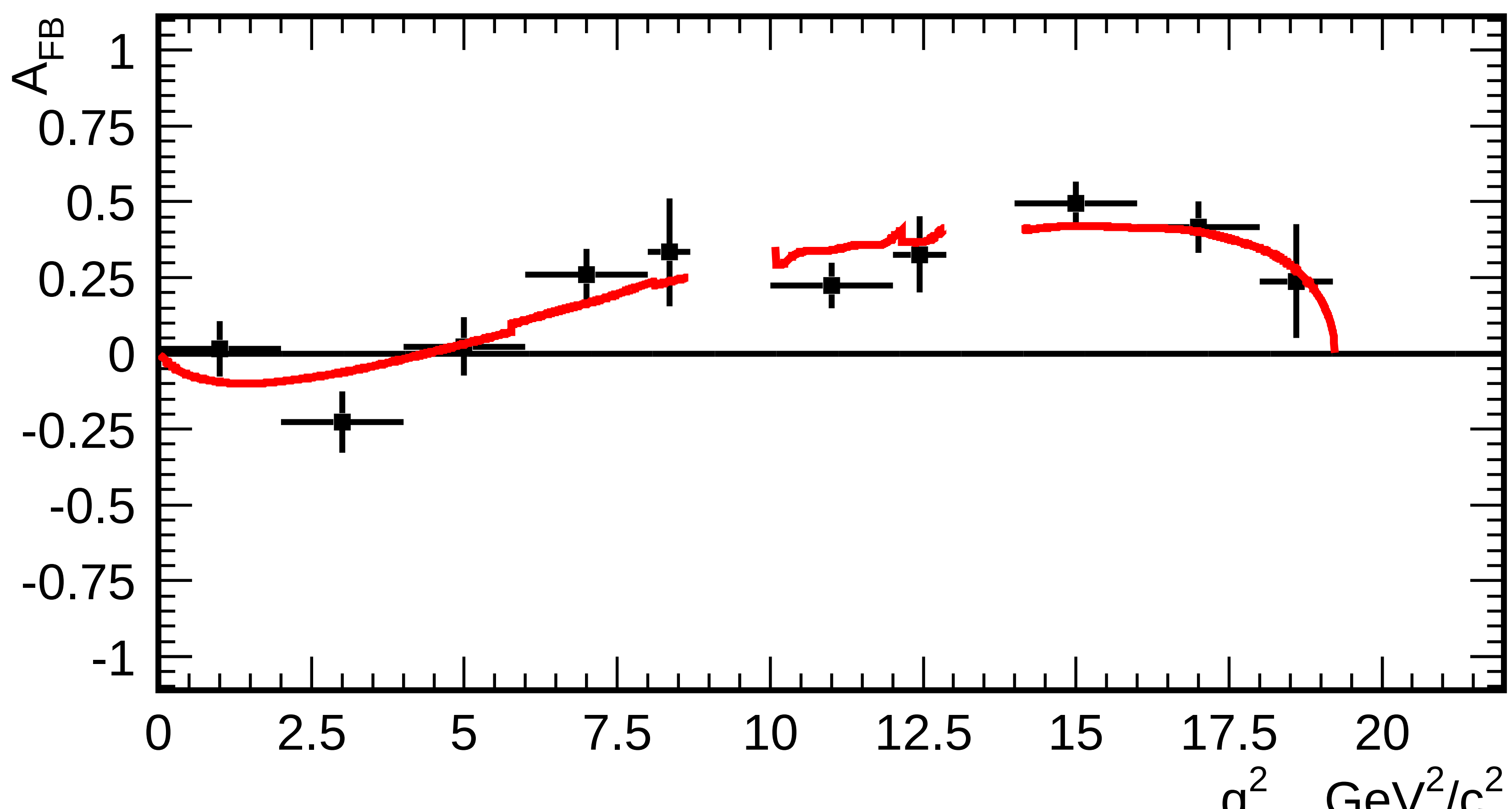
(still challenging, systematic error could be quite different in reality)

$A_{FB}(B \to K^* \ell^+ \ell^-)$ at 5 ab^{-1}

- Sensitive to C_9 and C_{10} Wilson coefficients
- Full (q^2, θ) fit with SM q^2 dist with leading coefficients only (A_9 and A_{10})
- $\delta A_9 / A_9 \sim 11\%$, $\delta A_{10}/A_{10} \sim 13\%$ at 5 ab^{-1}

  (i.e., $\delta A_9/A_9 \sim \delta A_{10}/A_{10} \sim 4\%$ at 50 ab^{-1})





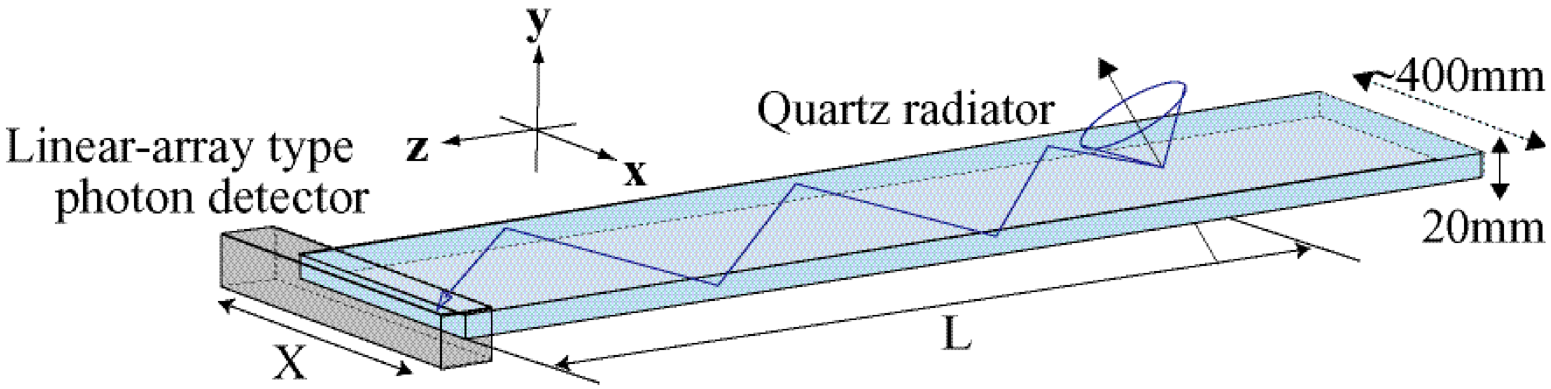
Beam-background

- Vertex (SVD)
  - Fast readout chip (APV25)
  - Eventually monolithic pixel
- Drift chamber (CDC)
  - Larger SVD radius
  - small cell to shorten drift time
- Calorimeter (ECL)
  - Sampling readout + wave form analysis
  - Pure CsI (endcap only, costly. . .)
- Muon, K_L^0 (KLM)
  - RPC to scintillator tile

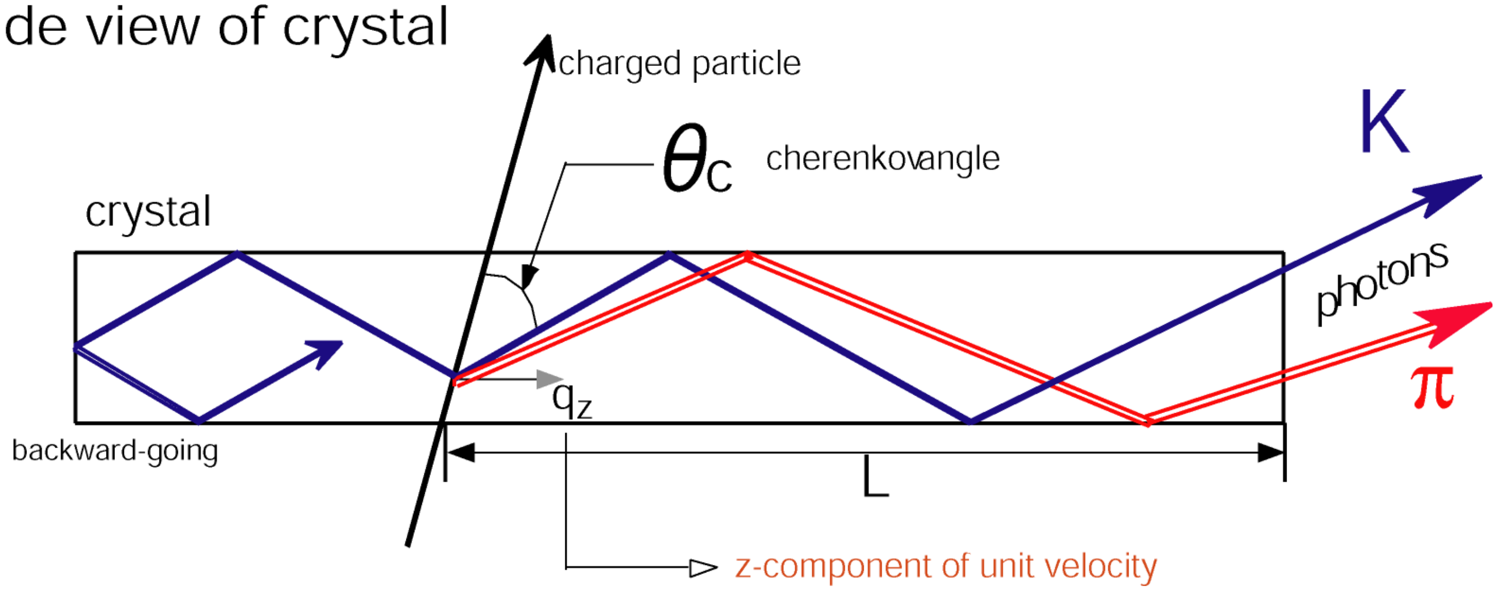
All these efforts just to compensate

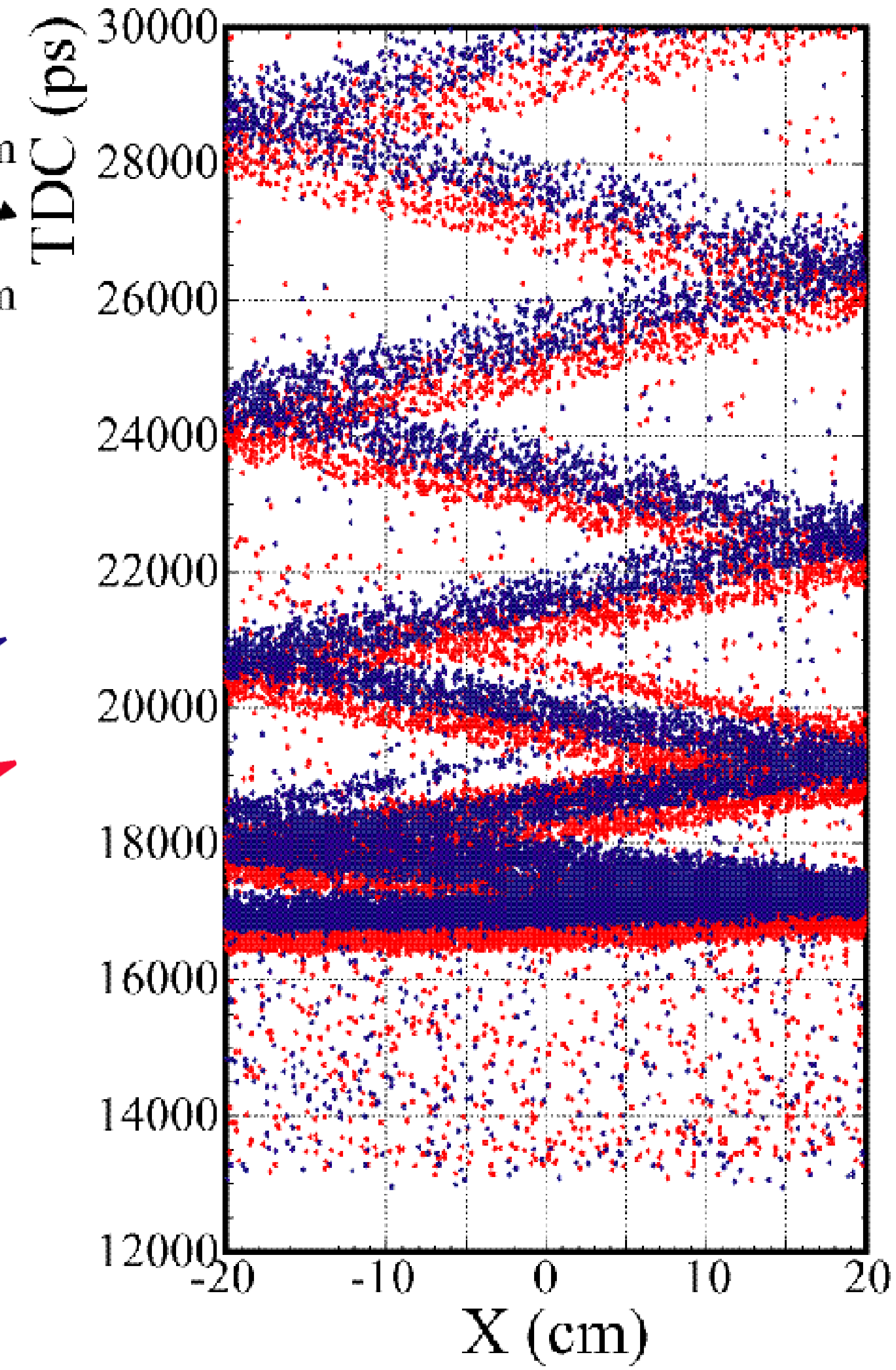
TOP — Time of projection counter

Cherenkov angle ➡ time difference



Side view of crystal

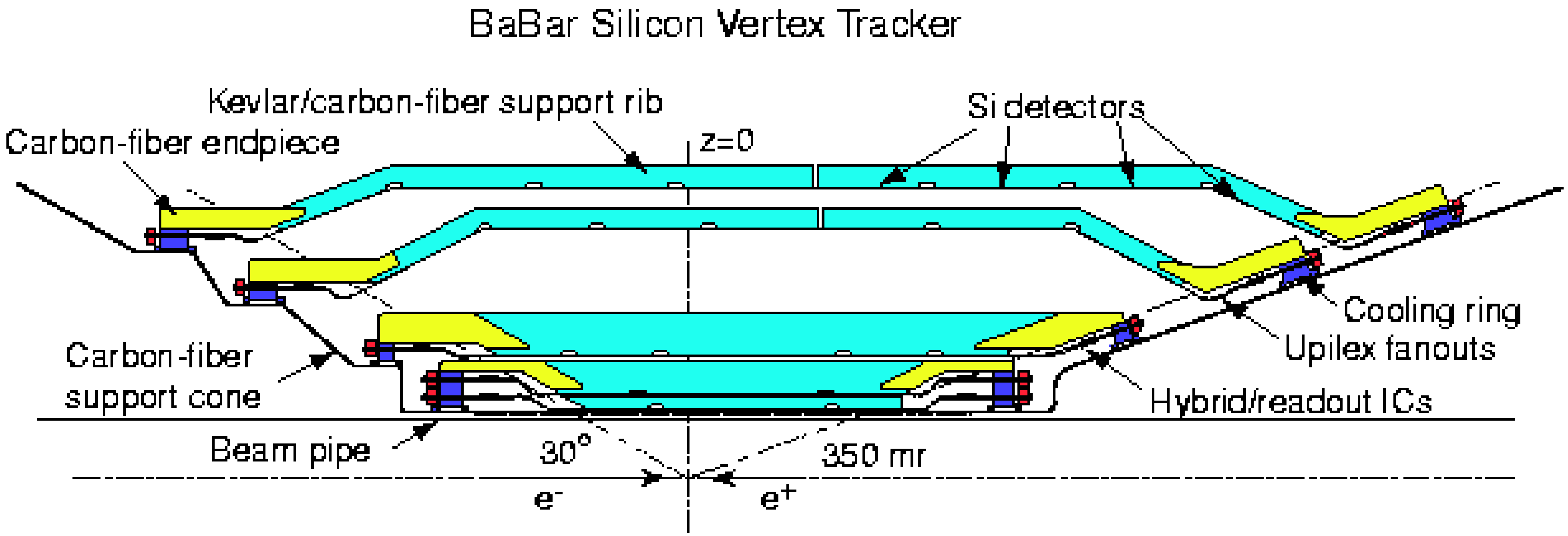




- Compact, no need of 2-d readout
- Time-resolution ~40 ps for $>4\sigma$ K/π separation
- Best candidate for SuperBelle Barrel PID

SuperB SVT

B.Ratcliff



- Very similar to that of the 5 layer BaBar SVT, supplemented by a new layer 0 to measure the first hit (Goal is coverage to 300 mrad both forward and backward)
- BaBar SVT cannot be re-used because of radiation damage and modest changes in geometry.
- Beam pipe radius and thickness are crucial to obtain adequate resolution in vertex separation.

LHCb?

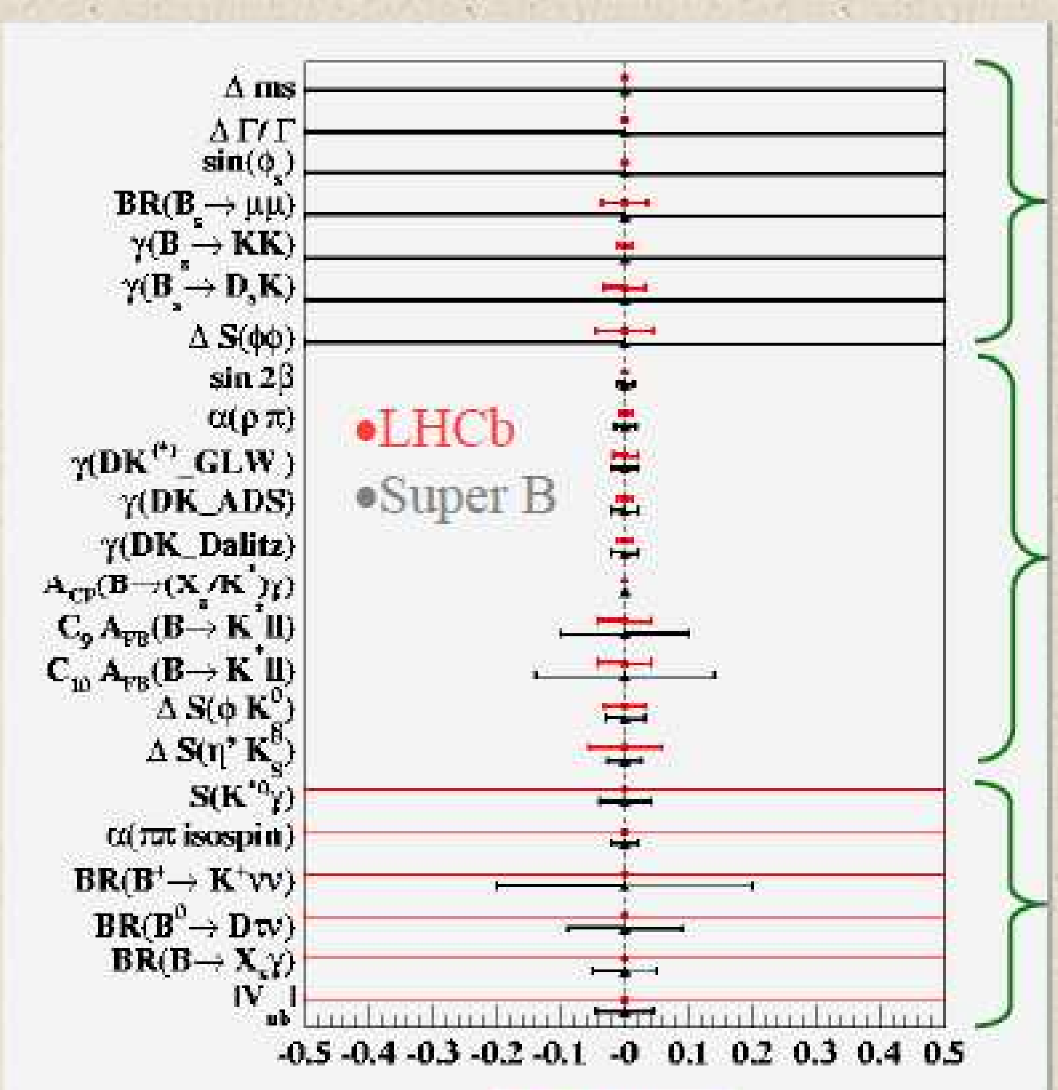
S. Stone

Super B factory and Super-LHCb

Sensitivity Comparison ~2020

Super-LHCb 100 fb^{-1} vs Super-B factory 50 ab^{-1}

SuperB numbers from M Hazumi - Flavour in LHC era workshop; LHCb numbers from Muheim



Bs

Common

No IP Neutrals, ν

- This plot is made by our LHCb friend. LHCb: 10/fb Super-LHCb: 100/fb

Quite complementary to each other !

56