Flavorful Ways to New Physics
Waldhotel Zollernblick, Oct 28-31, 2014

Flavor Physics at Belle and Belle II

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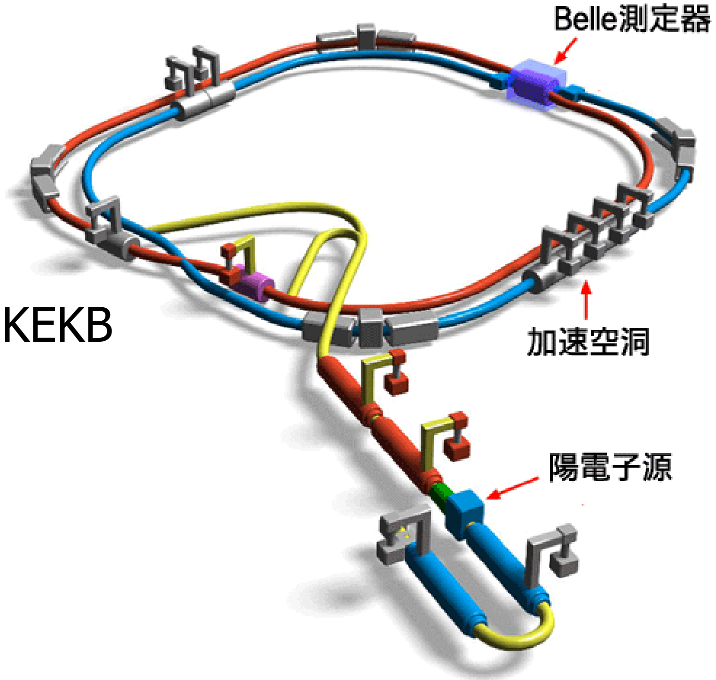
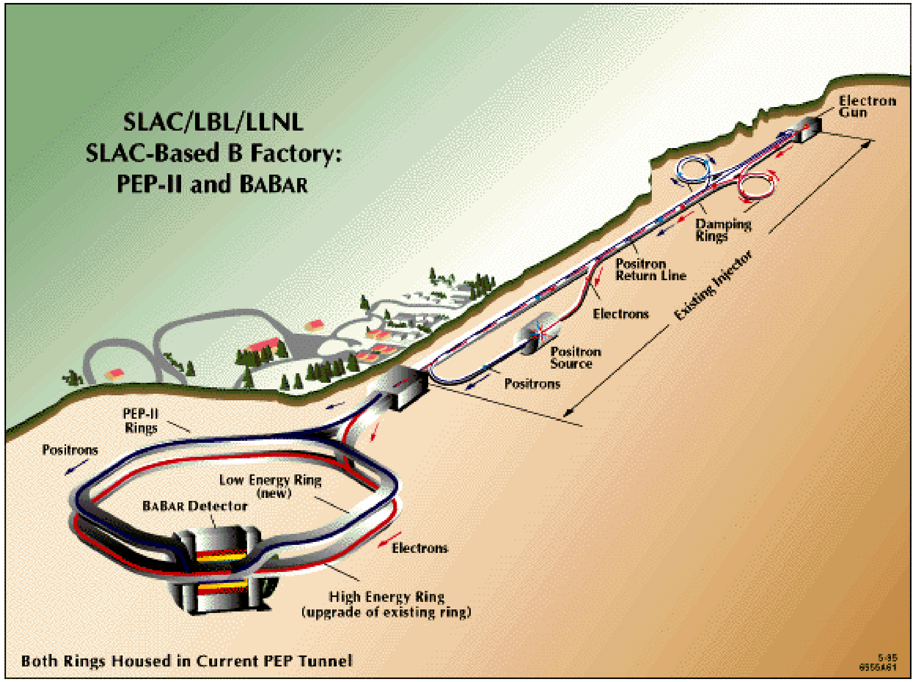
Contents

- Introduction with a little bit of B factory primer
- B factories: recent results
- Super B factory: status and outlook
- Summary

Flavour physics at the luminosity frontier with asymmetric B factories





$\sqrt{s}=10.58$ GeV

$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

$\Upsilon(4s) \rightarrow B\,\bar{B}$

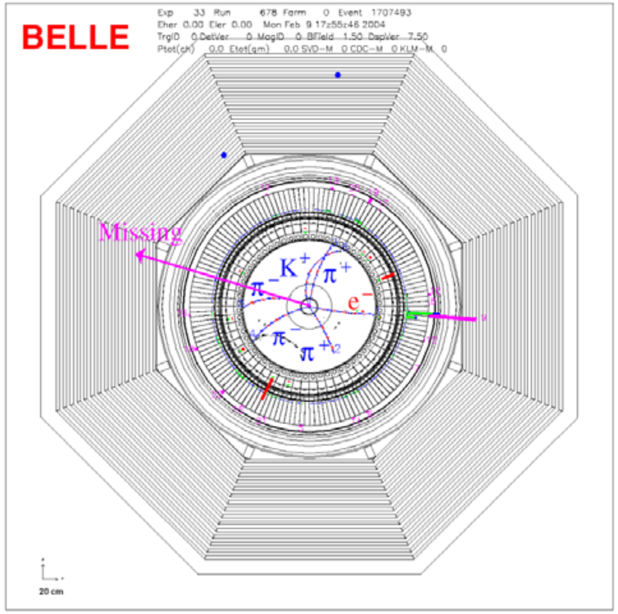
$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

To a large degree shaped flavour physics in the previous decade

Advantages of B factories in the LHC era

$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



Unique capabilities of B factories:

→ Exactly two B mesons produced (at $\Upsilon(4S)$)

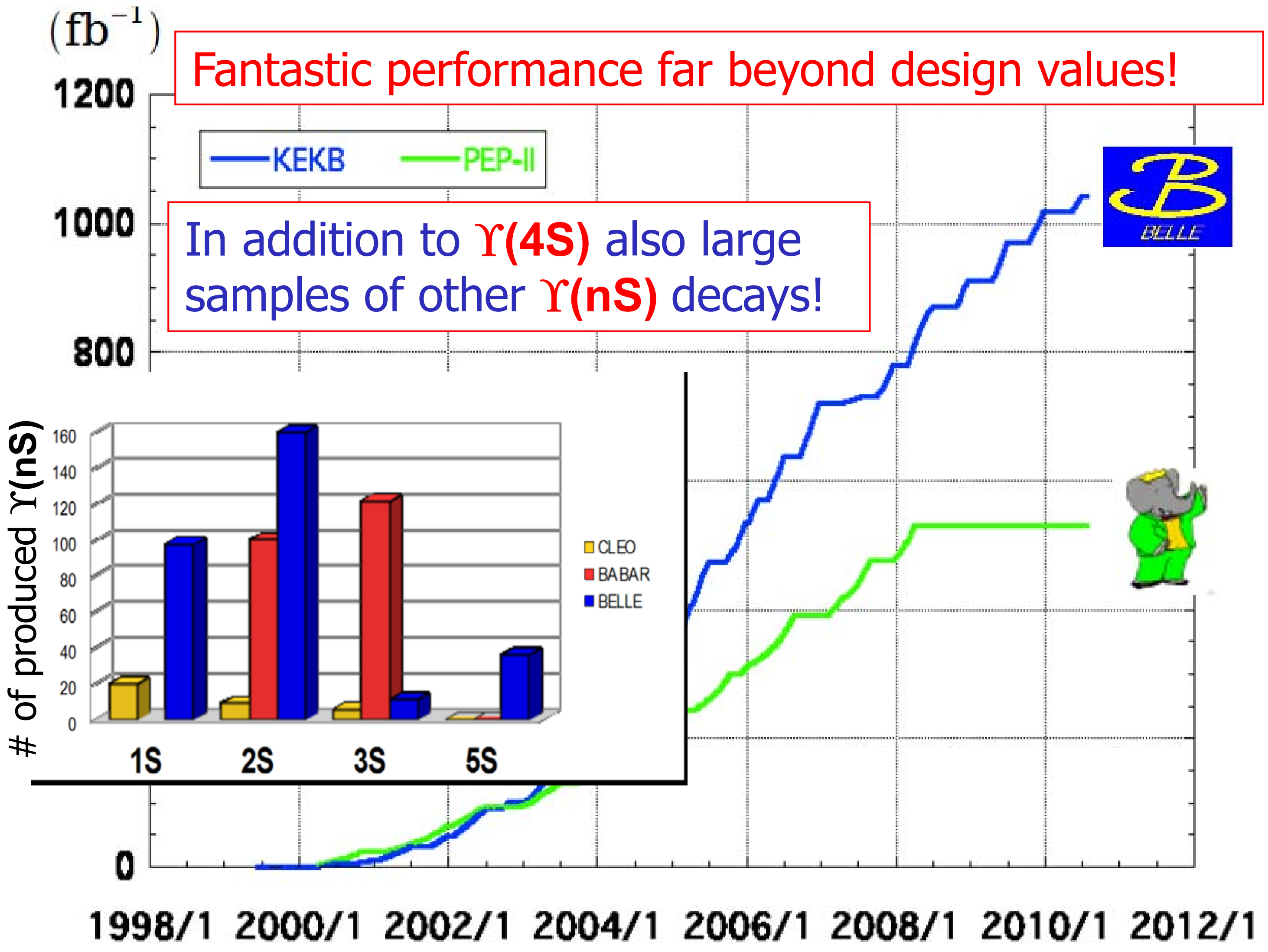
→ High flavour tagging efficiency

→ Detection of gammas, π^0s, K_Ls

→ Very clean detector environment (can observe decays with several neutrinos in the final state!)

→ Well understood apparatus, with known systematics, checked on control channels

Integrated luminosity at B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

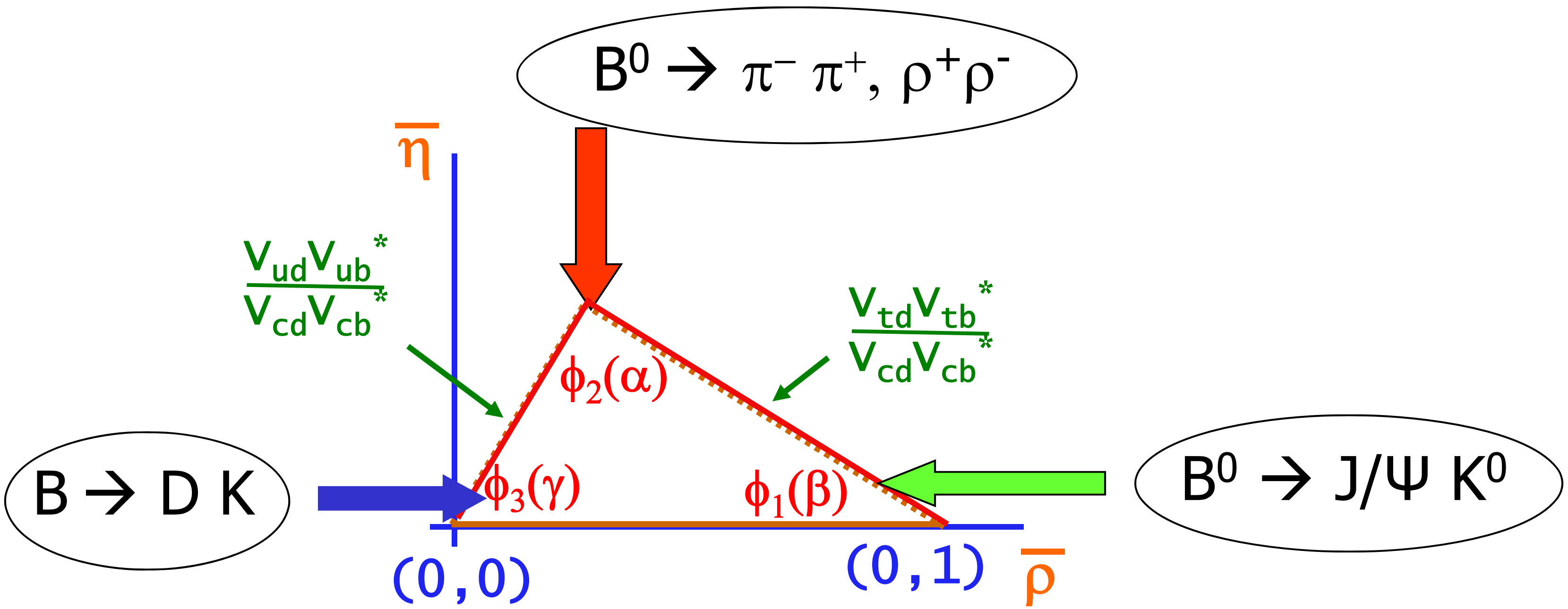
$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

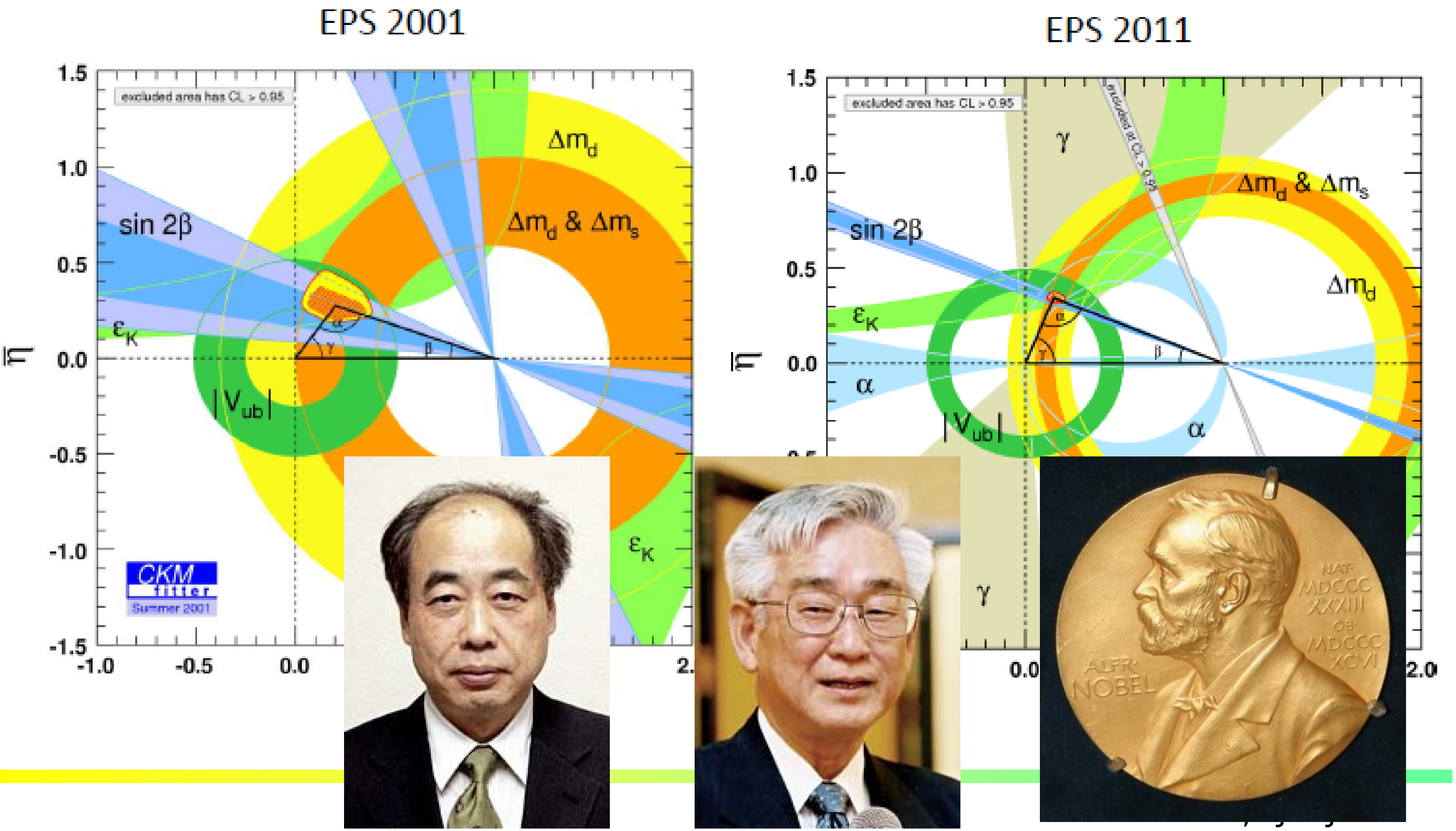
~ 54 fb^{-1}

CP violation in the B system and unitarity triangle



B factories: CP violation in the B system

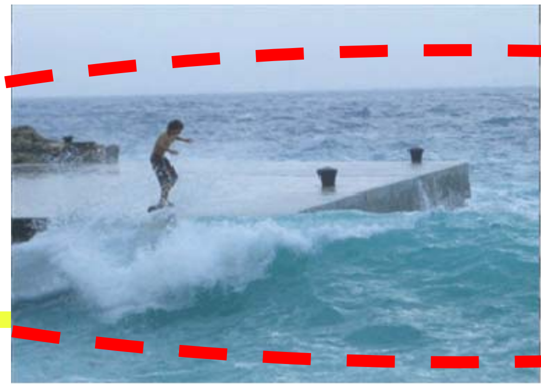
CP violation in the B system: from the discovery (2001) to a precision measurement (2011).



Comparison of **energy** /**intensity** frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

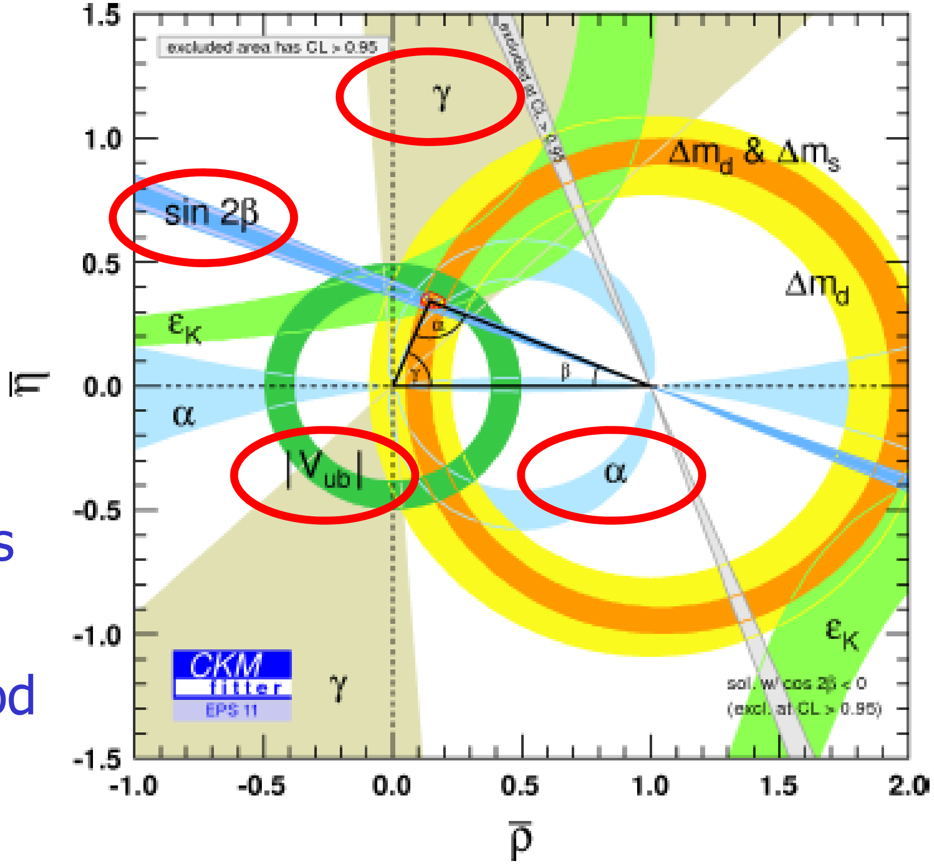
Energy frontier (LHC)



Luminosity frontier - (super) B factories

The unitarity triangle – new/final measurements

Constraints from measurements of angles and sides of the unitarity triangle → Remarkable agreement, but still 10-20% NP allowed



Selected results:

→ $\sin 2\phi_1$ (=$\sin 2\beta$): final measurements

→ ϕ_2 (=α): final measurements

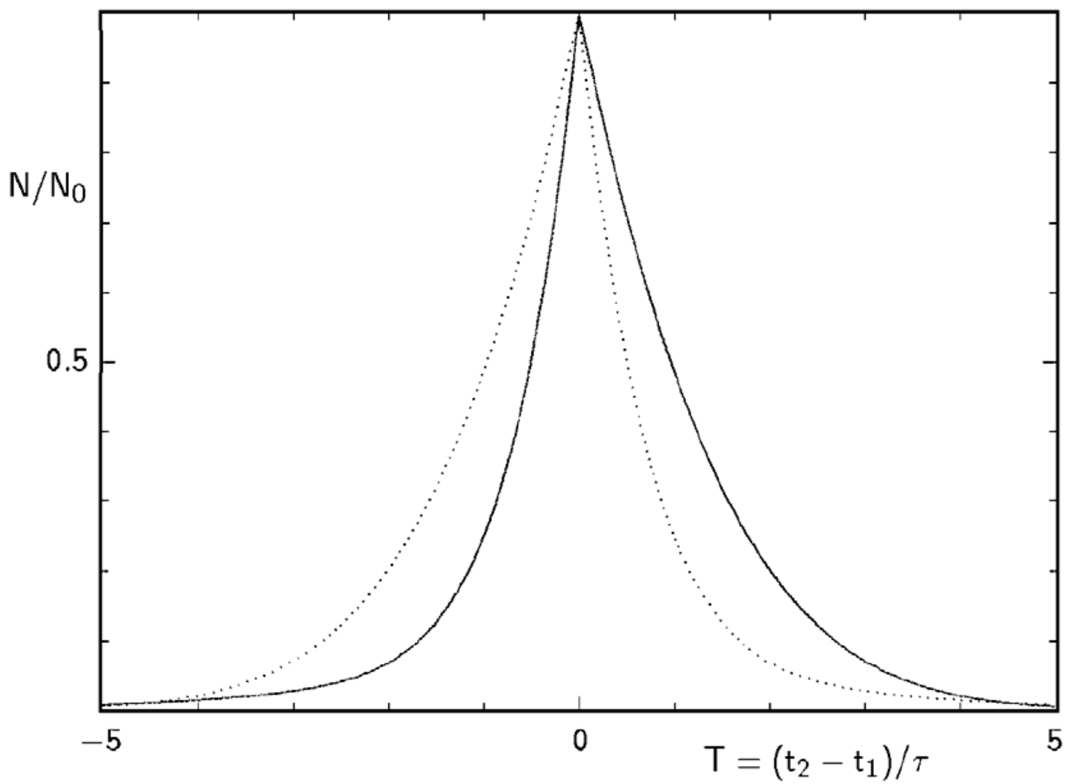
→ ϕ_3 (=γ): new model-independ. method

→ Rare decays

CP violation measurement

Want to measure the asymmetry between B and anti-B mesons,

$$P(B^0(\overline{B}^0) \rightarrow f_{CP}, t) = e^{-\Gamma t}\left(1 \mp \sin(2\phi_1)\sin(\Delta m t)\right)$$

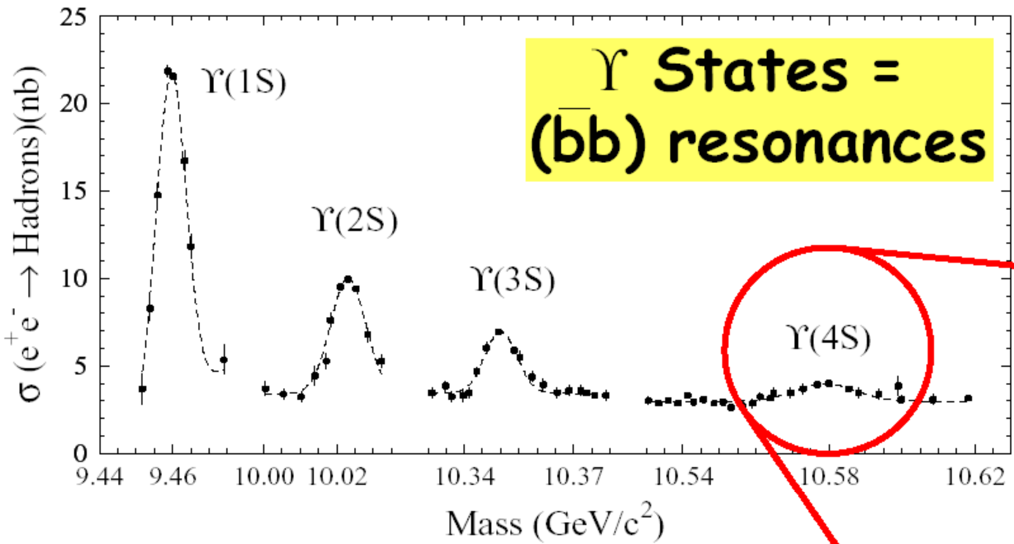


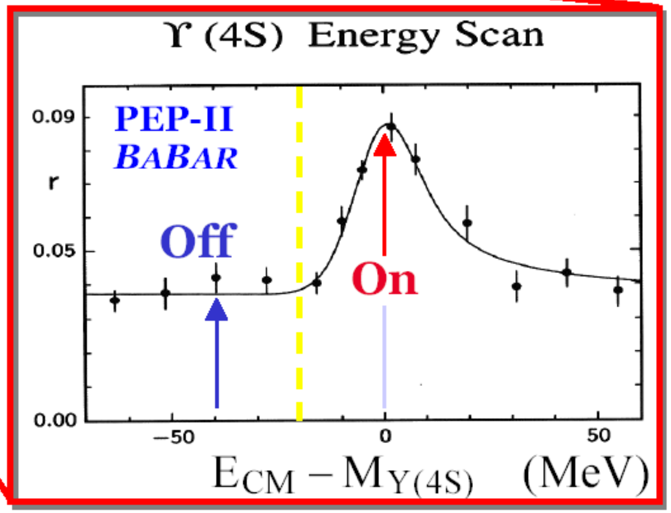
→Want to distinguish the decay rate of B (dotted) from the decay rate of anti-B (full).

Integrals are equal, time information mandatory! (true at Y(4s), but not for incoherent production)

Resolution ~B lifetime

B meson production at Υ(4s)





Cross Sections at Υ(4S):

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

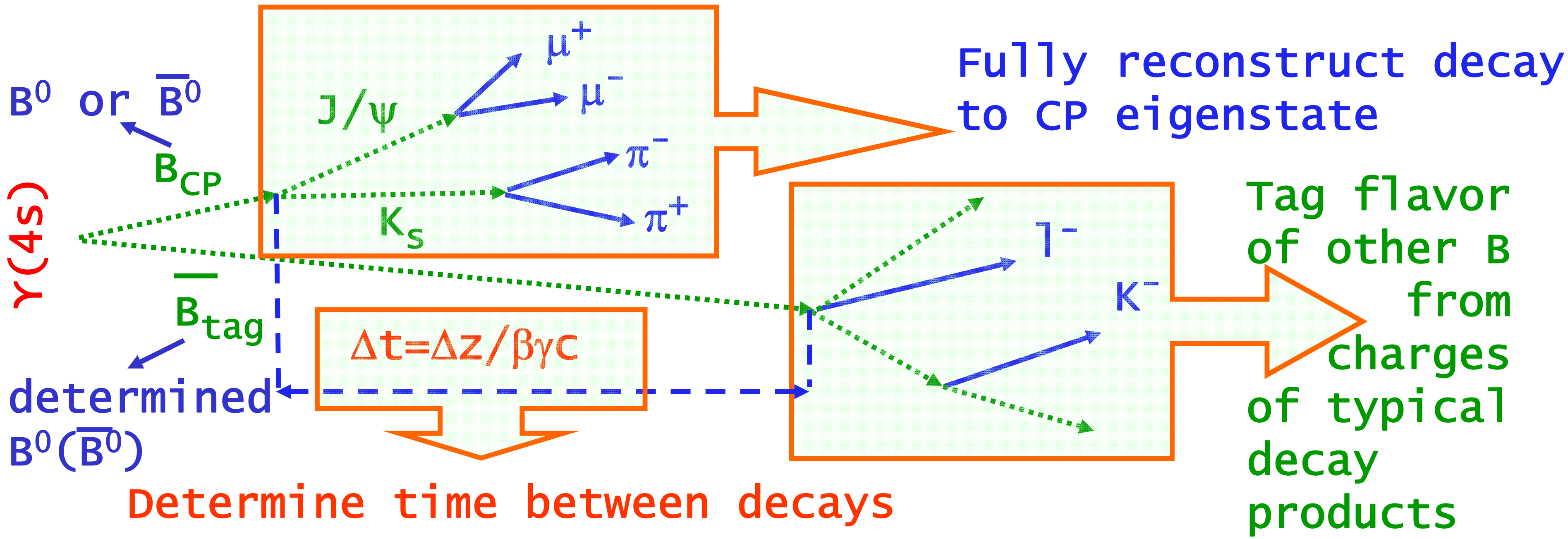
$u\bar{u} \sim 1.4$ nb

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

$L = 1$ state

CP violation measurement

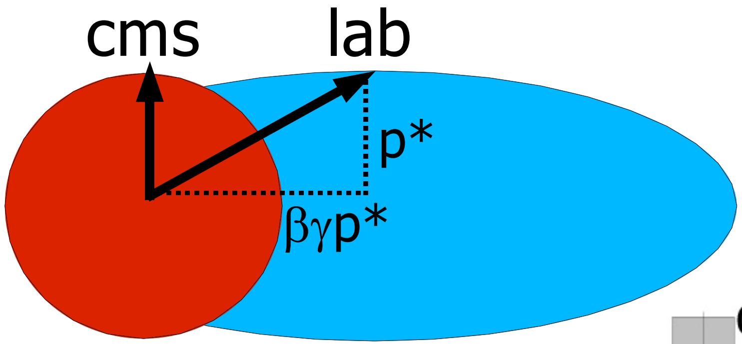
Measure the difference in time evolution in B^0 and anti-B^0 decays to a CP eigenstate



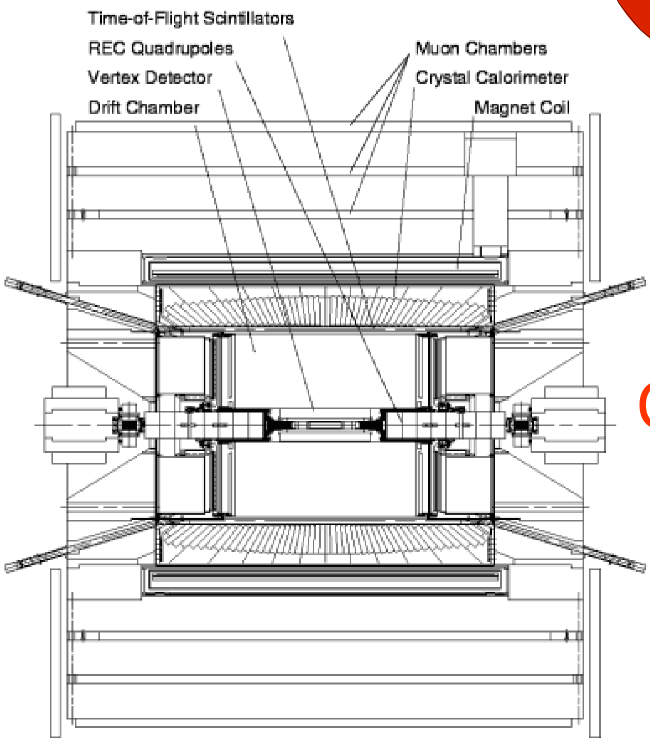
CMS should be boosted!

Experimental considerations

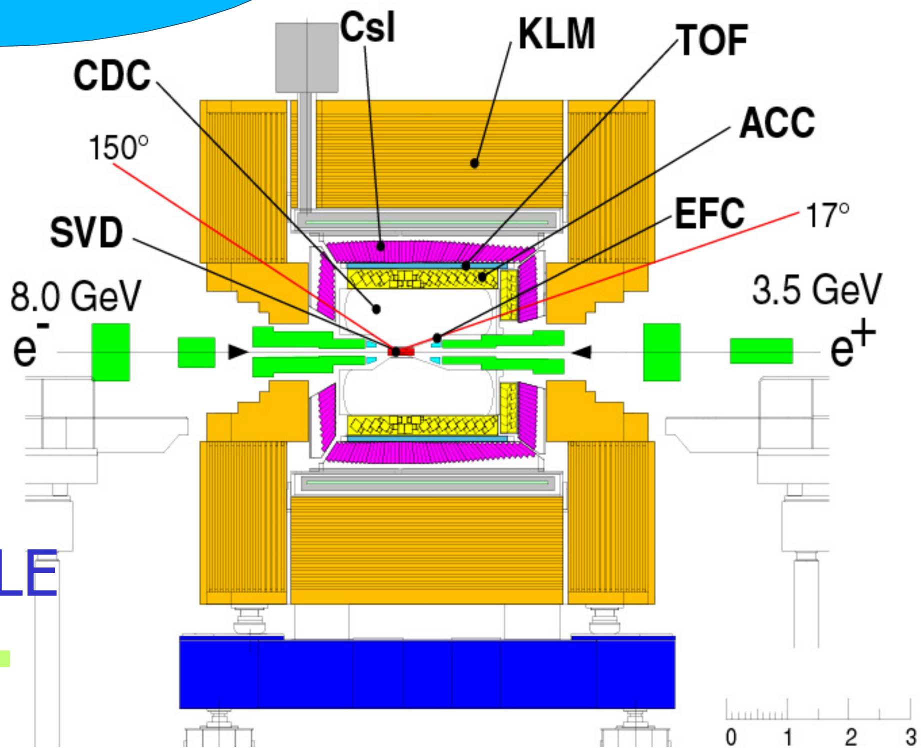
Detector form: symmetric for symmetric energy beams; slightly extended in the boost direction for an asymmetric collider.



Exaggerated plot: in reality $\beta\gamma=0.5$

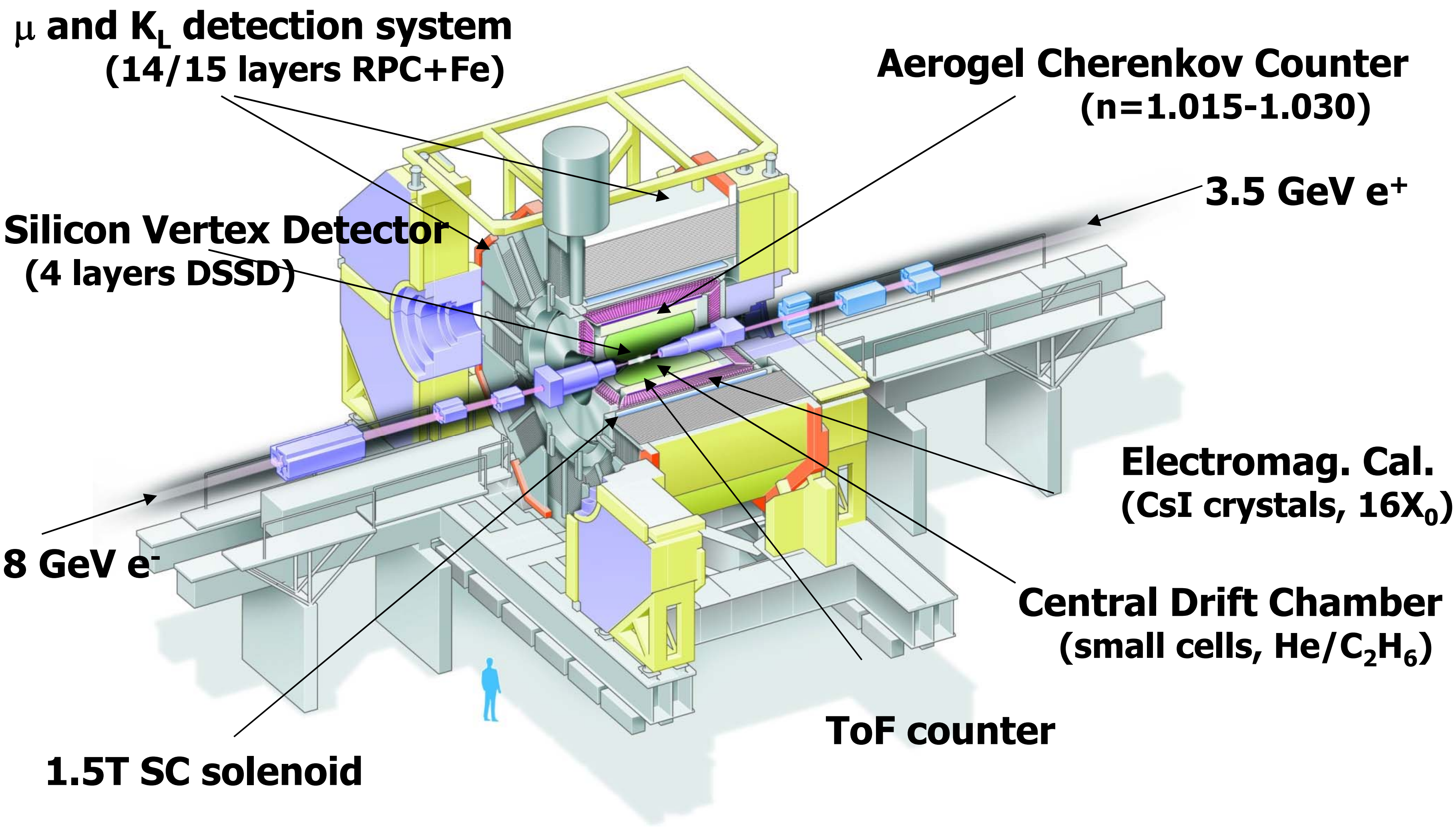


CLEO

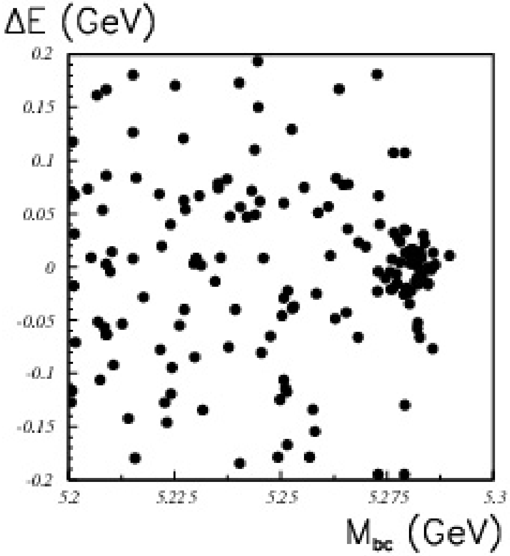


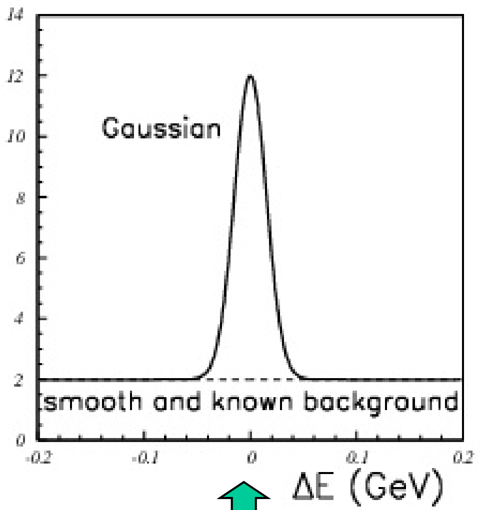
BELLE

Belle spectrometer at KEK-B



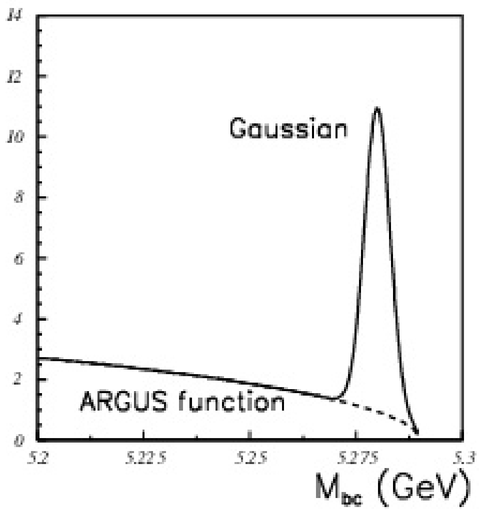
Reconstruction of rare B meson decays





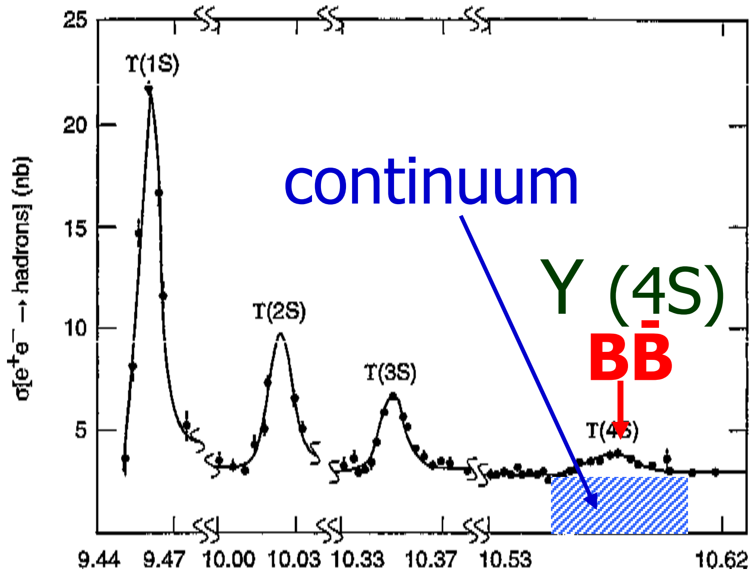
Reconstructing rare B meson decays at Y(4s): use two variables,
beam constrained mass M_{bc}
and
energy diference DE

$$\Delta E \equiv \sum E_i - E_{CM}/2$$



$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

Continuum suppression



$e^+e^- \rightarrow$ *qq* "continuum" (~3x BB)

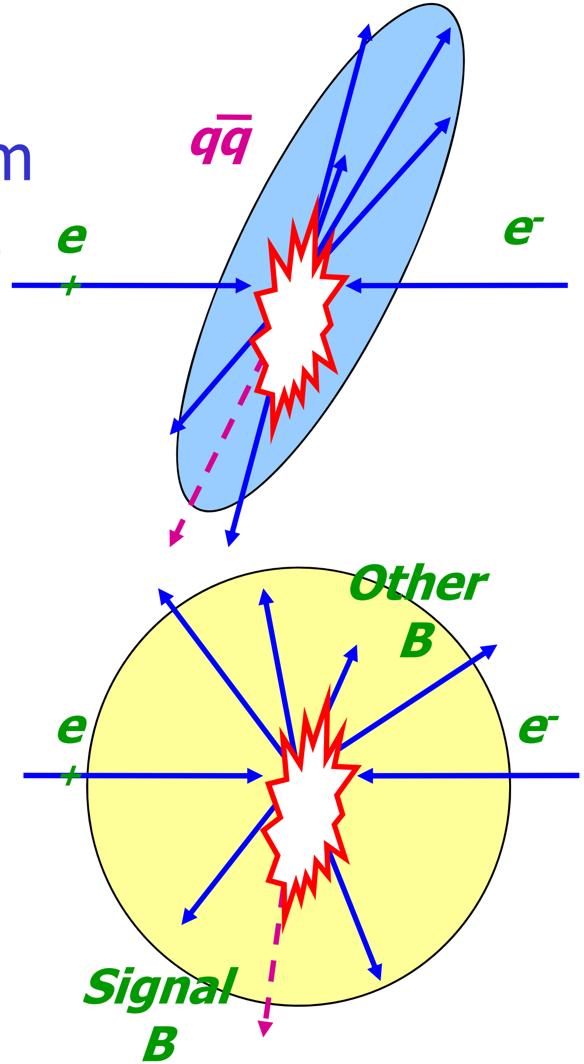
To suppress: use event shape variables

Continuum

Jet-like

BB

spherical



CP violation measurement

Want to measure the asymmetry between B and anti-B mesons,

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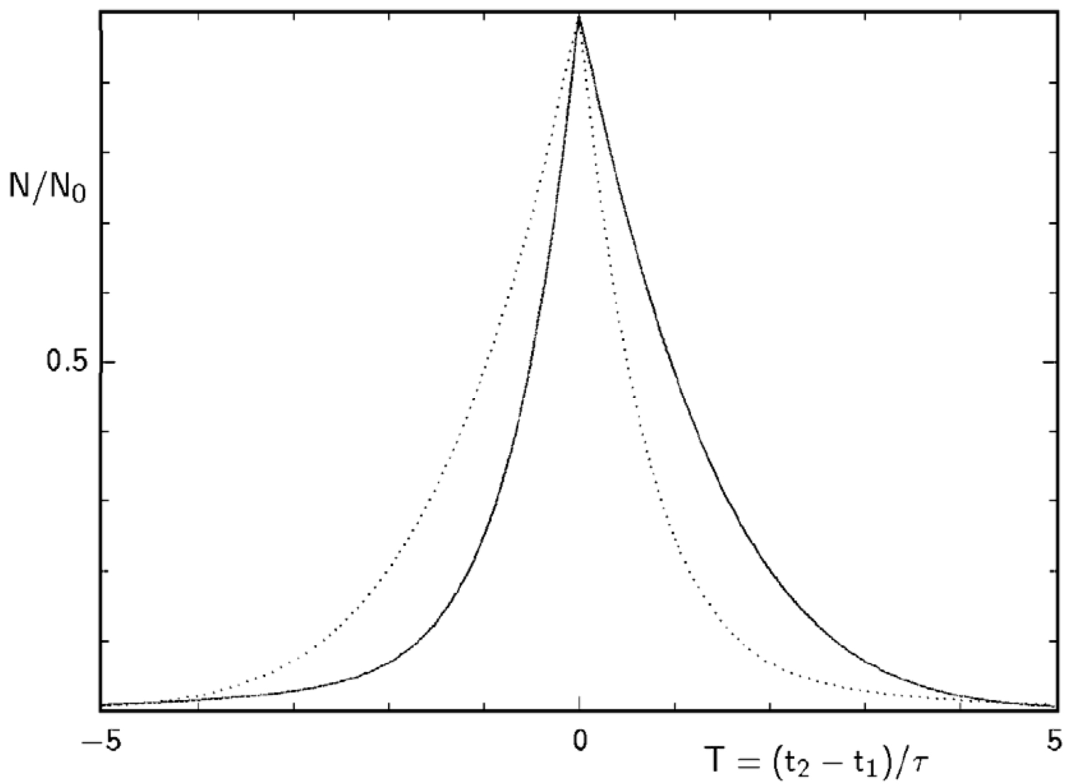
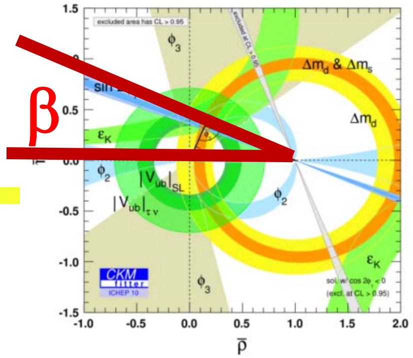


→Want to distinguish the decay rate of B (dotted) from the decay rate of anti-B (full).

Integrals are equal, time information mandatory! (true at Y(4s), but not for incoherent production)

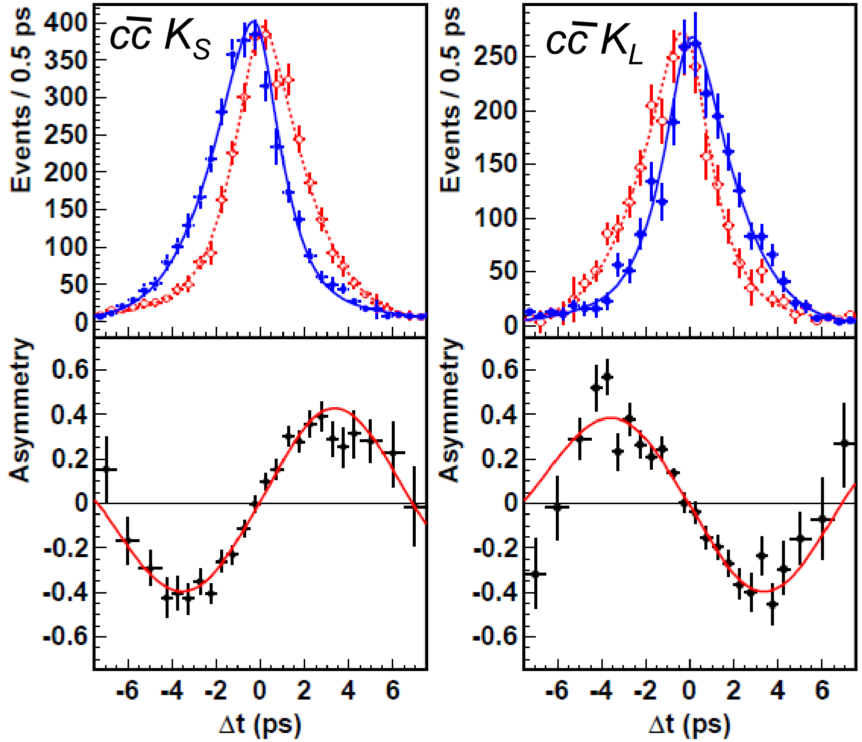
Resolution ~B lifetime

Final measurement of $\sin 2\phi_1$ (=$\sin 2\beta$)

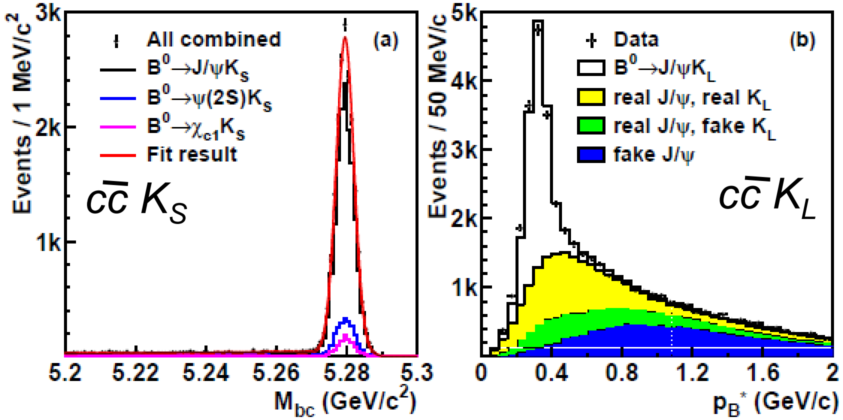


ϕ_1 from CP violation measurements in $B^0 \to c\bar{c}\, K^0$

Final measurement: with improved tracking, more data, improved systematics (50% more statistics than last result with 492 fb^{-1});
$cc = J/\psi,\ \psi(2S),\ \chi_{c1}$ → 25k events



Detector effects: wrong tagging, finite Δt resolution → determined using control data samples



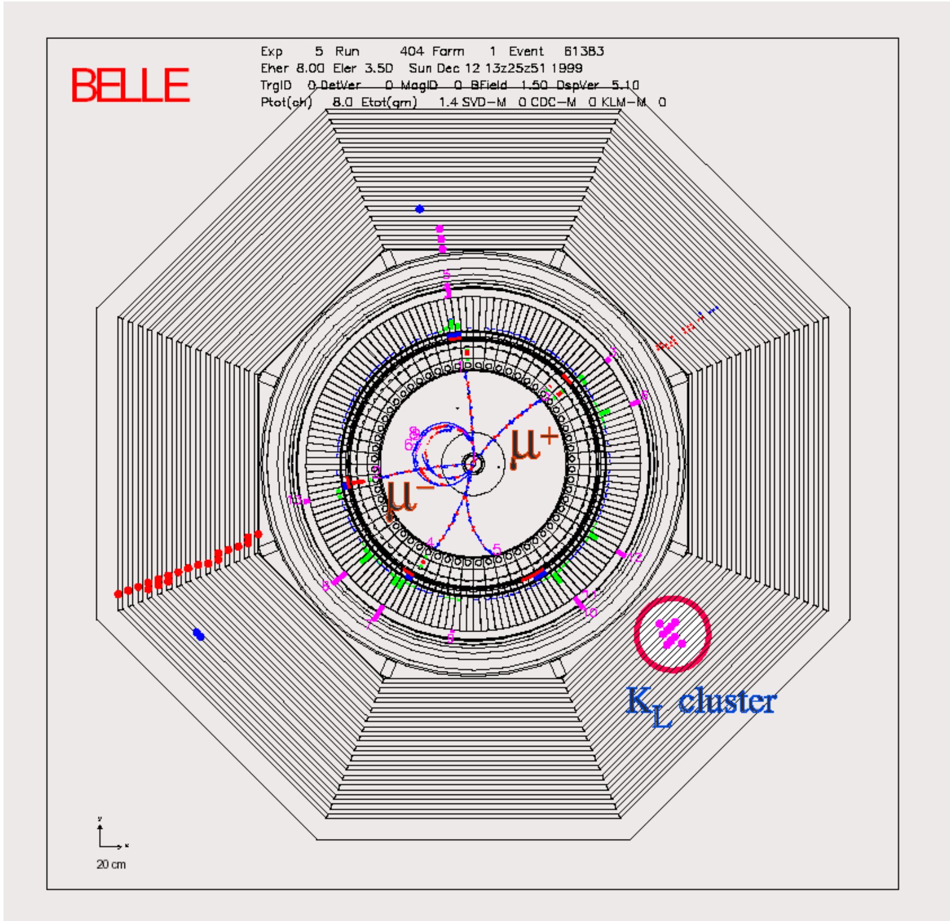
Belle, final, 710 fb^{-1}, PRL 108, 171802 (2012)

K_L detection

Important cross check:

Measure CP violation for B → CP=+1 eigenstate

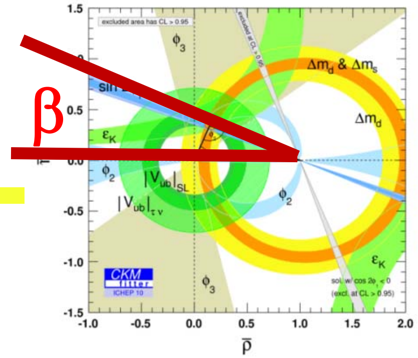
→ B → J/ψ K_L



Need a detector for K_Ls – muon detections system acts as a hadron calorimeter

Measure only the K_L interaction point coordinate, not the K_L energy.

Final measurements of $\sin 2\phi_1$ (=$\sin 2\beta$)



ϕ_1 from $B^0 \rightarrow c\bar{c}\, K^0$

Final results for $\sin 2\phi_1$

Belle:	0.668 ± 0.023 ± 0.012
BaBar:	0.687 ± 0.028 ± 0.012

Belle, PRL 108, 171802 (2012)

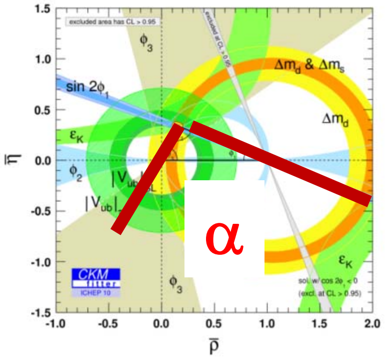
BaBar, PRD 79, 072009 (2009)

with a single experiment precision of ~4%!

Comparison with LHCb:

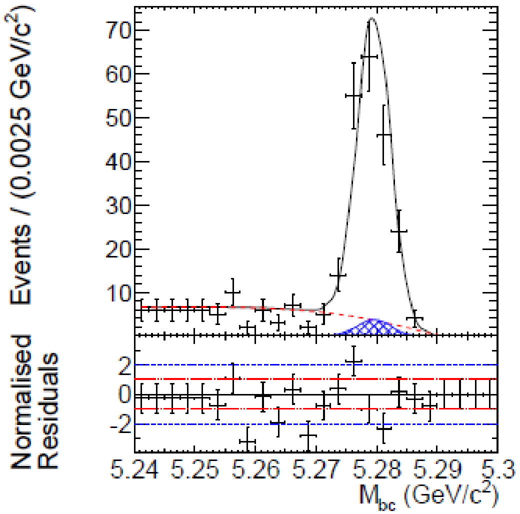
- The power of tagging at B factories: 33% vs ~2-3% at LHCb
- LHCb: with 8k tagged $B_d \rightarrow J/\psi K_S$ events from 1/fb measured
  $\sin 2\beta = 0.73 \pm 0.07(\text{stat.}) \pm 0.04(\text{syst.})$
- Uncertainties at B factories - e.g., Belle final result
  $\sin 2\beta = 0.668 \pm 0.023(\text{stat.}) \pm 0.012(\text{syst.})$ - are 3x smaller than at LHCb

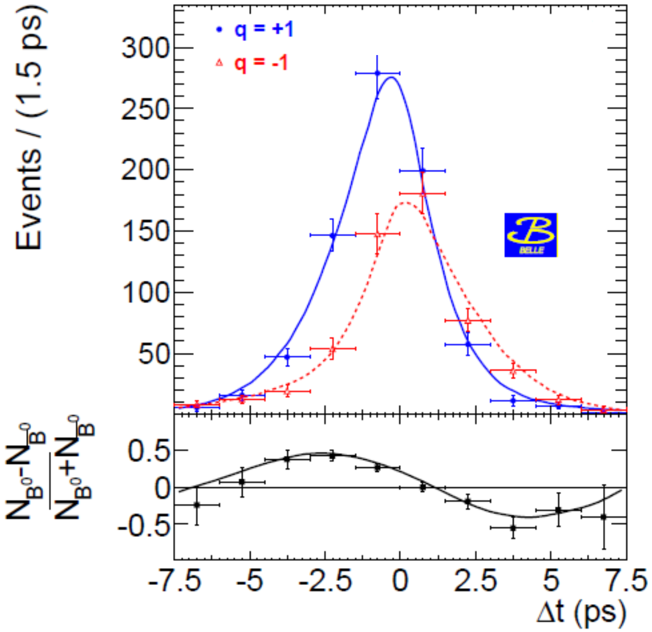
Final measurement of ϕ_2 (α) in B $\rightarrow \pi^+\pi^-$ decays



ϕ_2 from CP violation measurements in $B^0 \rightarrow \pi^+\pi^-$

Belle, 710 fb^{-1}
PRD **88**, 092003 (2013)



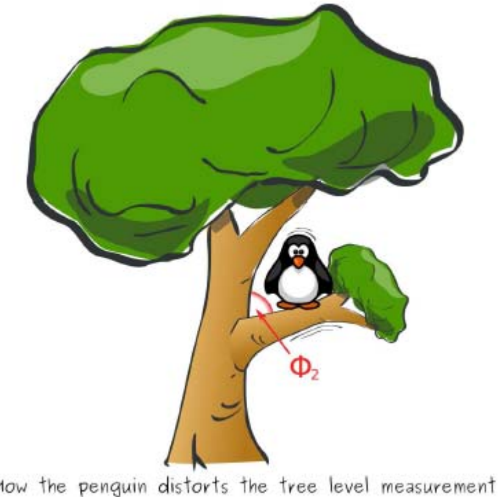


$$a_{f_{CP}} = C\cos(\Delta m t) + S\sin(\Delta m t)$$

Belle, this measurement:
S = −0.64 ± 0.08 ± 0.03
C = −0.33 ± 0.06 ± 0.03

BaBar:
S = −0.68 ± 0.10 ± 0.03
C = −0.25 ± 0.08 ± 0.02

Measurement of B → $\pi^0\pi^0$ decays



Pit Vanhoefer, CKM2014

ϕ_2 from CP violation measurements in $B^0 \to \pi^+\pi^-$
Extraction not easy because of the penguin contribution

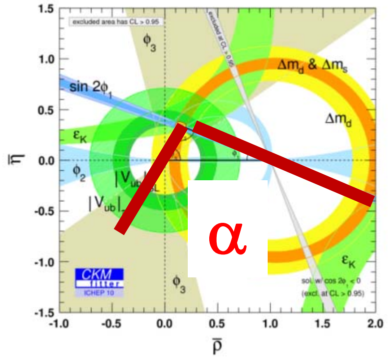
BR for the $B \to \pi^0\pi^0$ decay important to resolve this issue.

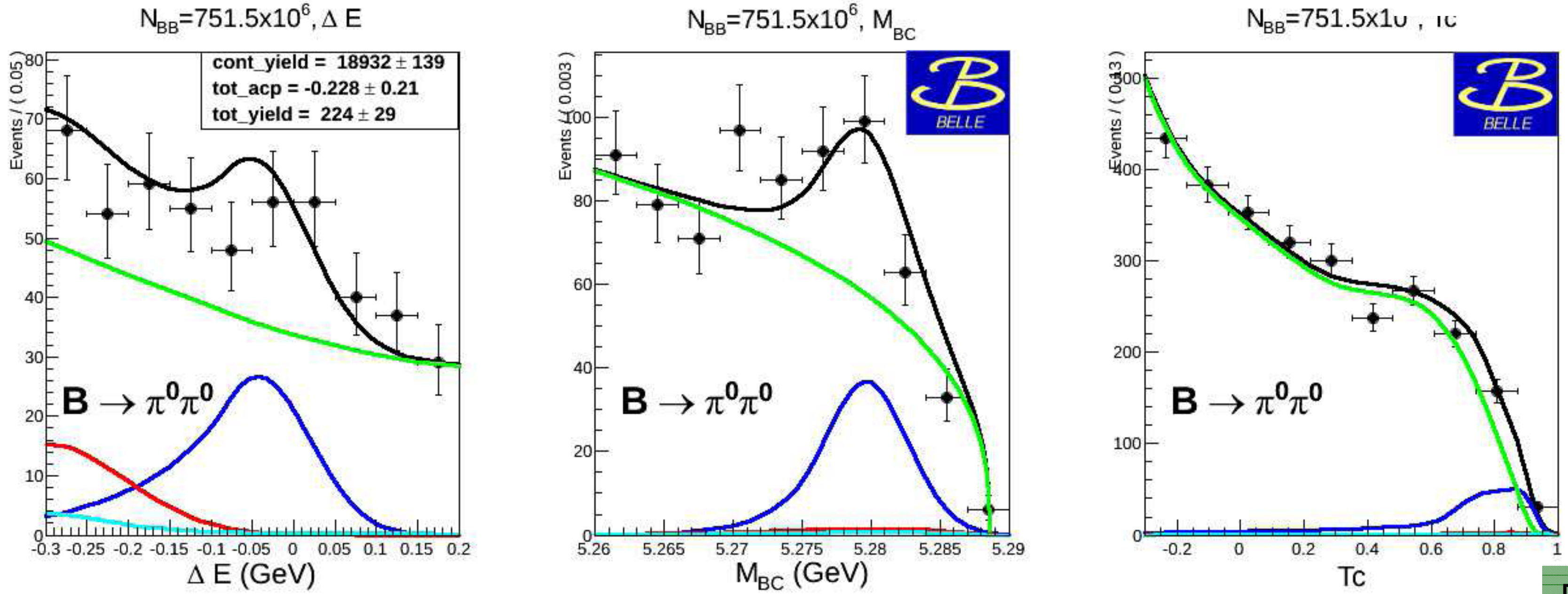
Hard channel to measure: four gammas, continuum (ee→qq) background

- Theory: BR<1x10-6 (Phys.Rev.D83:034023,2011)
- Belle, 1/3 of data PRL 94, 181803(2005) = (2.32 +0.4-0.5 +0.2-0.3) 10^{-6}
- BaBar PR D87 052009 (1.83 ± 0.21 ± 0.13) 10^{-6}

Belle new result with full data set: Improved rejection of out-of-time electromagnetic calorimeter hits (some of which contribute to a peaking background).

Measurement of $B \to \pi^0\pi^0$ decays





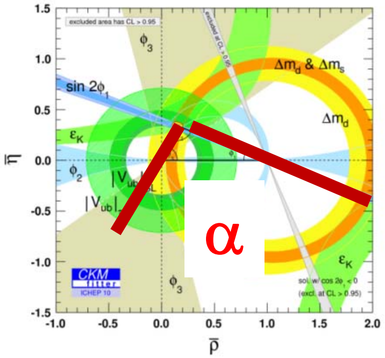
Preliminary

$Br(B \to \pi^0\pi^0) = (0.90 \pm 0.20\,(\text{stat}) \pm 0.15(\text{syst}))\cdot 10^{-6}$

(6.7σ significance)

A_{CP} under preparation → stay tuned

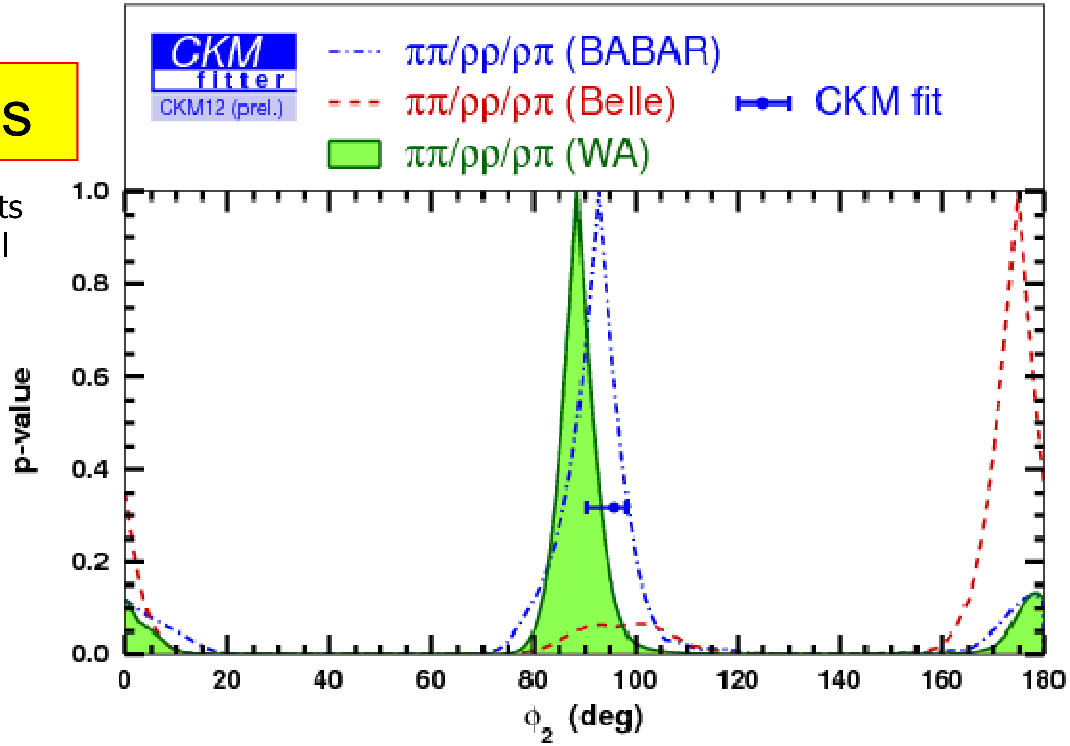
Improved measurement of ϕ_2 (α) in B → ππ, ρρ, ρπ decays



ϕ_2 (α) from CP violation and branching fraction measurements in B → ππ, ρρ, ρπ

$\phi_2 = \alpha = (85.4^{+4.0}_{-3.8})$ degrees

http://ckmfitter.in2p3.fr/www/results/plots_fpcp13/ckm_res_fpcp13.html



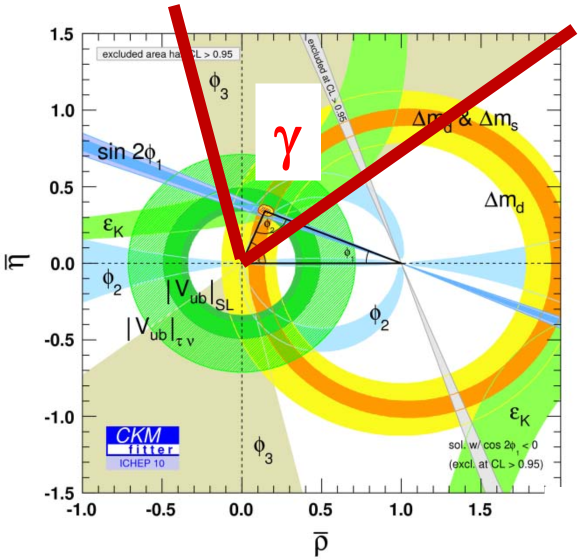
Still to be updated for the final version: new results expected from Belle on $\rho^+\rho^-$, ρπ; a new ρπ, analysis published by BaBar
→PRD88, 012003 (2013).

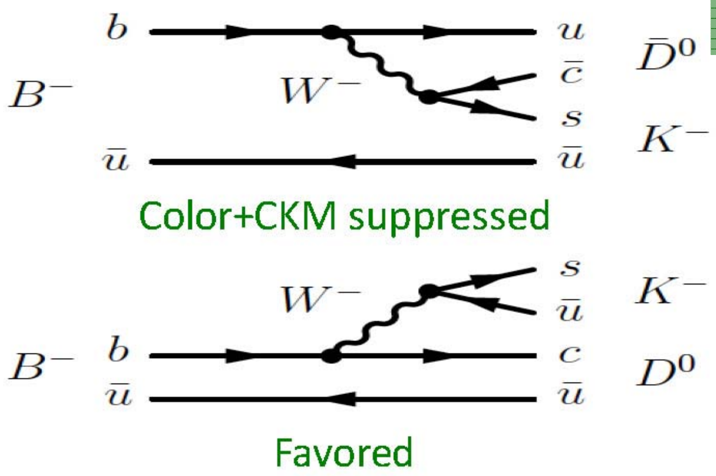
ϕ_3 (=γ) with Dalitz analysis

A. Giri et al., PRD68, 054018 (2003)
A. Bondar et al (Belle), Proc. BINP Meeting on Dalitz Analyses, 2002

GGSZ method:

The best way to measure ϕ_3

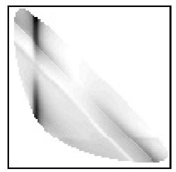
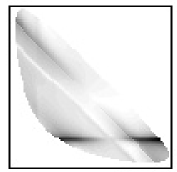




$\overset{(-)}{D^0} \to K_S\pi^+\pi^-$

3-body $D^0 \to K_S\pi^+\pi^-$ Dalitz amplitude

$$|M_\pm(m_+^2, m_-^2)|^2 = |f_D(m_+^2, m_-^2) + re^{i\delta_B \pm i\phi_3} f_D(m_-^2, m_+^2)|^2$$

$= \Big|$  $+ re^{i\delta_B \pm i\phi_3}$  $\Big|^2$

Model dependent description of f_D using continuum D* data ⇒ systematic uncertainty

ϕ_3=(78 ± 12 ± 4 ± 9)°

Belle, PRD81, 112002, (2010), 605 fb^{-1}

ϕ_3=(68 ± 14 ± 4 ± 3)°

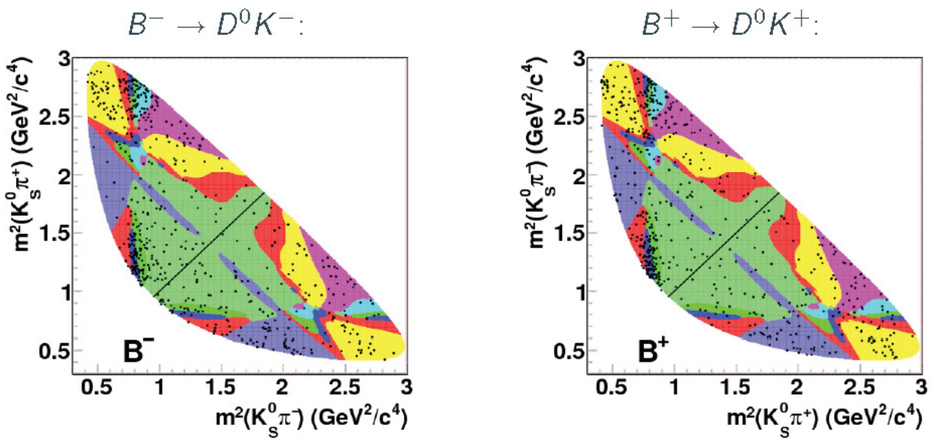
BaBar, PRL 105, 121801, (2010)

ϕ_3 (=γ) from model-independent/binned Dalitz method

GGSZ method: How to avoid the model dependence?
→ Suitably subdivide the Dalitz space into bins

$$M_i^{\pm} = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i + y_{\pm} s_i)\}$$

$$x_{\pm} = r_B \cos(\delta_B \pm \phi_3) \quad y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$$



M_i: # B decays in bins of D Dalitz plane, K_i: # D^0 ($\overline{D^0}$) decays in bins of D Dalitz plane ($D^* \to D\pi$), c_i, s_i: strong ph. difference between symm. Dalitz points ← Cleo, PRD82, 112006 (2010)

Use only DK
N_{sig} = 1176 ± 43

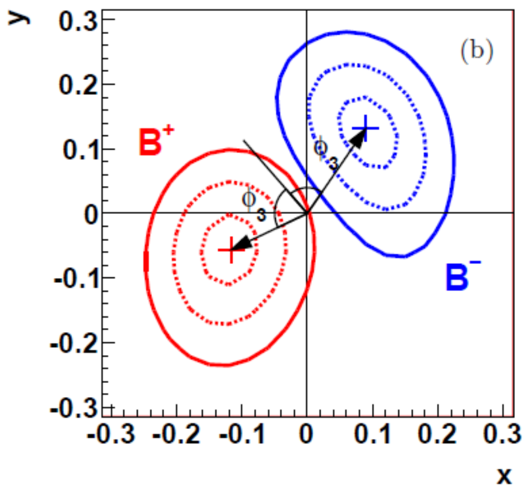
Belle, 710 fb^{-1}, Phys. Rev. D85 (2012) 112014

4-dim fit for signal yield (ΔE, M_{bc}, $\cos\theta_{thrust}$, $\mathcal{F}$);

ϕ_3=(77.3 ± 15 ± 4.1 ± 4.3)^o

from c_i, s_i (statist.!)

to be reduced with BESIII data

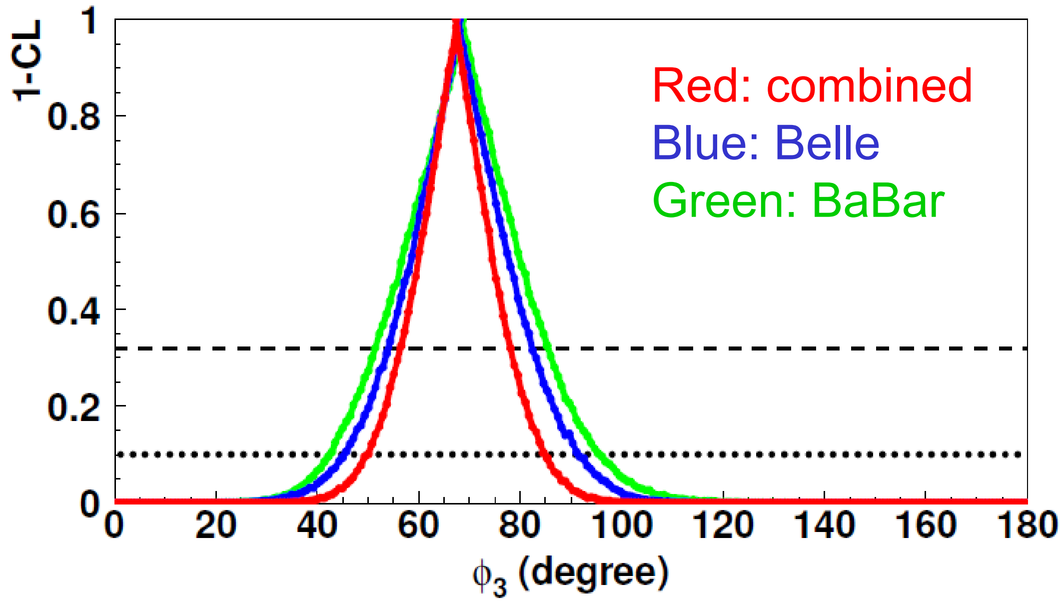


New method pioneered by Belle, very important for large event samples at LHCb and super B factory

ϕ_3 measurement

Combined ϕ_3 value:

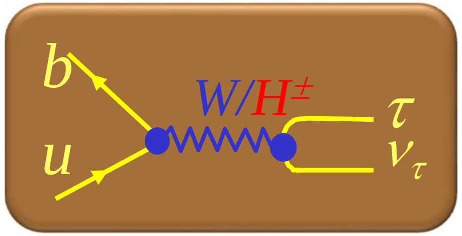
ϕ_3 =(67 ± 11) degrees

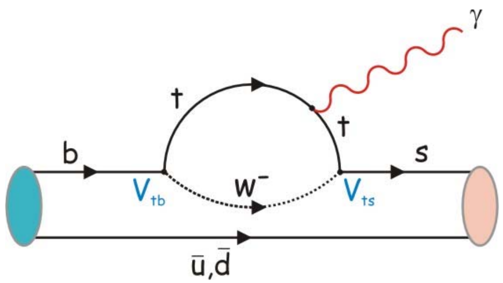


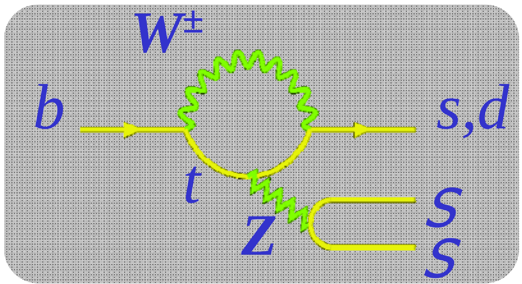
Note that at B factories the measurement of ϕ_3 finally turned out to be much better than expected!

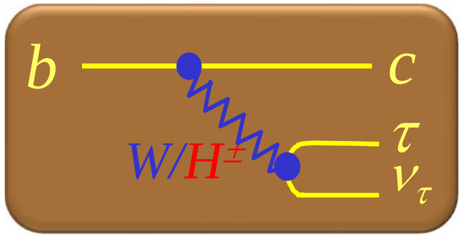
This is not the last word from B factories, analyses still to be finalized...

Rare B decays





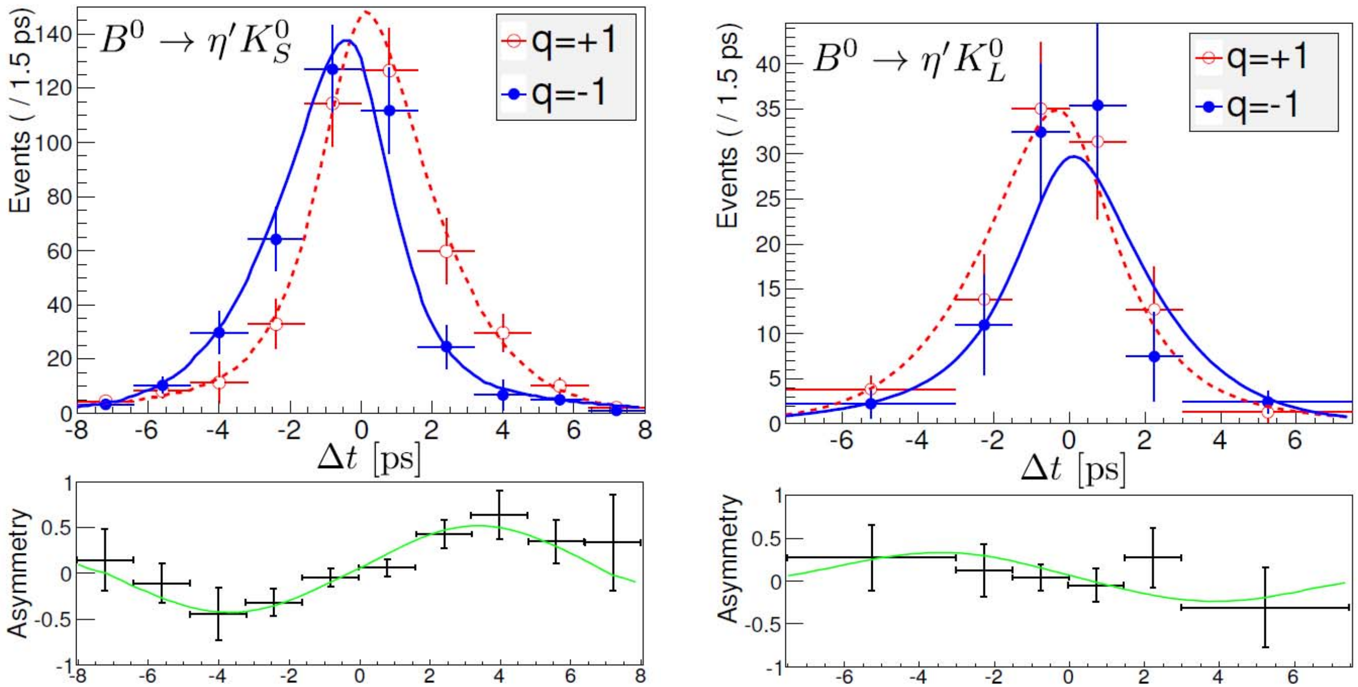




CP violation in penguin dominated b → qqs transitions

CP violation given by the same parameter sin2ϕ1 as in J/ψ K decays

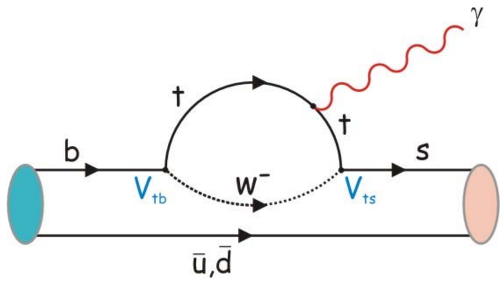
→ to be publisehd in JHEP



Decay mode	$-\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
η' K^0_S	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
η' K^0_L	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
η' K^0	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

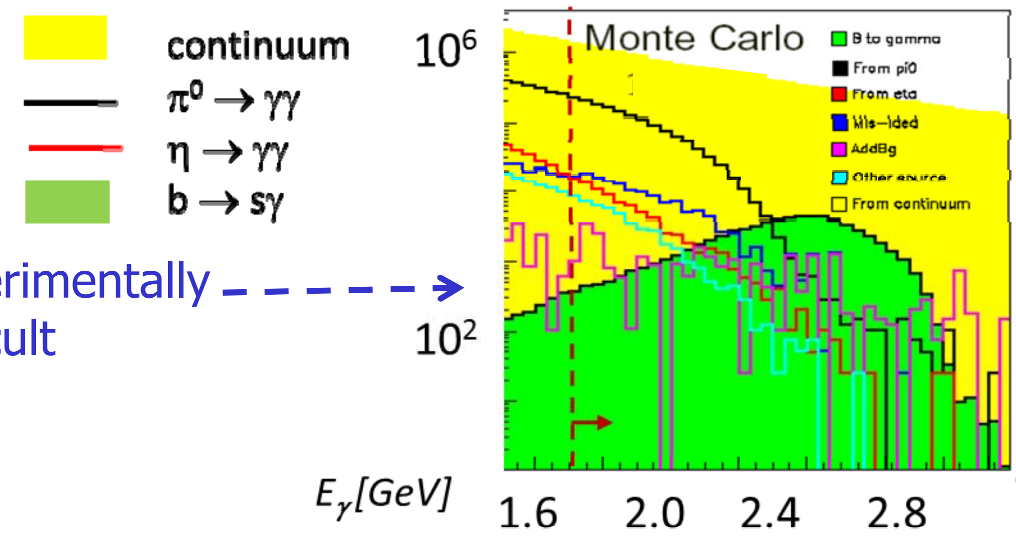
$B \to X_s\gamma$ inclusive

Advantage of B factories!



Radiative decay sensitive to charged Higgs

Experimentally difficult



Experiment: measure low E_γ

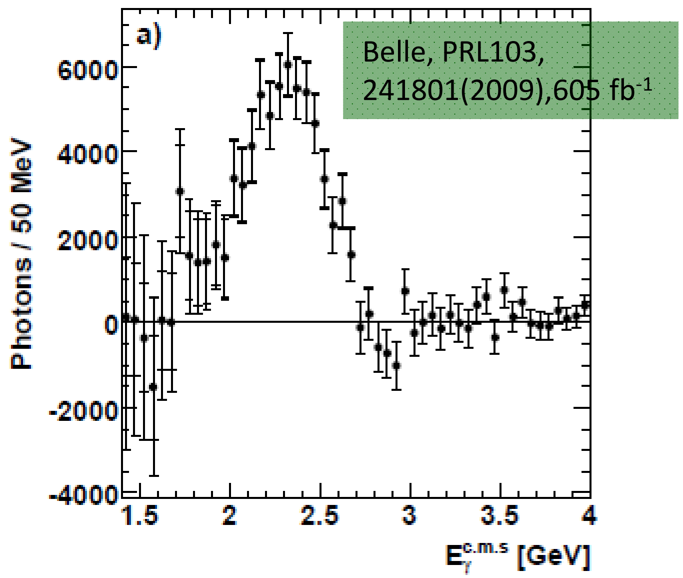
$\Rightarrow$ huge bkg. $\Rightarrow E_\gamma > E_{cut}$

Theory:

parameter extraction from partial Br($E_\gamma > E_{cut}$) $\Rightarrow$ extrapolation needed;

Only γ on signal side reconstructed

Improve S/B by tagging the other B



$$\mathcal{B}(B \to X_s\gamma; 1.7\,GeV < E_\gamma < 2.8\,GeV) = (3.47 \pm 0.15 \pm 0.40) \cdot 10^{-4}$$

$B \to X_s\gamma$ inclusive

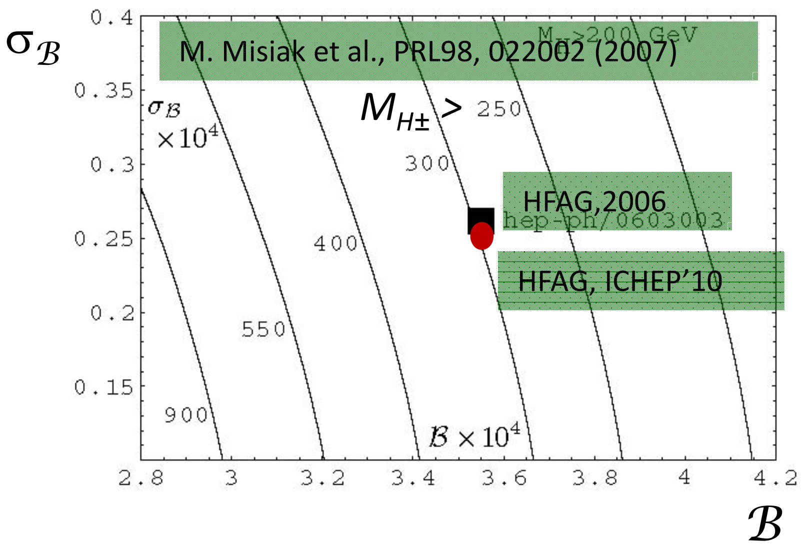
Branching fraction, world average

HFAG, ICHEP'10

$$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,GeV) =$$
$$= (3.55 \pm 0.24(stat. + syst.) \pm 0.09(shape\ f.) \cdot 10^{-4}$$

Decay rate sensitive to
charged Higgs

→ tight constraints on models of new physics, two-Higgs-doublet model II mass limit at ~300 GeV/c^2



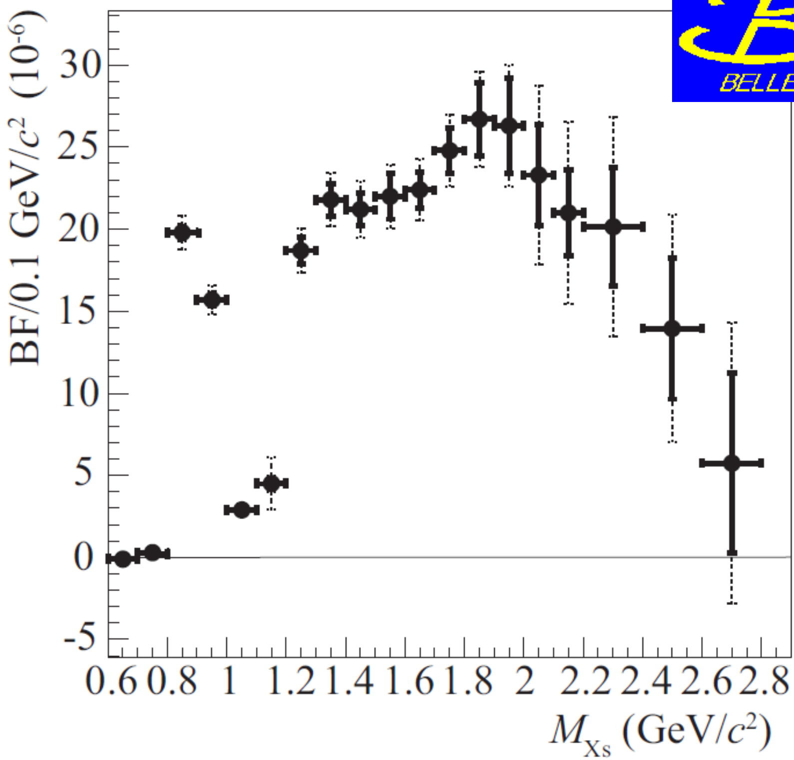
Measurements systematics dominated

Systematics can be reduced by stronger tagging (e.g. full reconstruction of the other B) on the account of stat. uncertainty
$\Rightarrow$ need a larger sample → Super B factory

B → $X_s\gamma$, semi-inclusive

Sum of 38 exclusive channels

Mode ID	Final State	Mode ID	Final State
1	$K^+\pi^-$	20	$K^0_S\pi^+\pi^0\pi^0$
2	$K^0_S\pi^+$	21	$K^+\pi^+\pi^-\pi^0\pi^0$
3	$K^+\pi^0$	22	$K^0_S\pi^+\pi^-\pi^0\pi^0$
4	$K^0_S\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24	$K^0_S\eta$
6	$K^0_S\pi^+\pi^-$	25	$K^+\eta\pi^-$
7	$K^+\pi^+\pi^0$	26	$K^0_S\eta\pi^+$
8	$K^0_S\pi^+\pi^0$	27	$K^+\eta\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	28	$K^0_S\eta\pi^0$
10	$K^0_S\pi^+\pi^+\pi^-$	29	$K^+\eta\pi^+\pi^-$
11	$K^+\pi^+\pi^-\pi^0$	30	$K^0_S\eta\pi^+\pi^-$
12	$K^0_S\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
13	$K^+\pi^+\pi^+\pi^-\pi^-$	32	$K^0_S\eta\pi^+\pi^0$
14	$K^0_S\pi^+\pi^+\pi^-\pi^-$	33	$K^+K^+K^-$
15	$K^+\pi^+\pi^-\pi^-\pi^0$	34	$K^+K^-K^0_S$
16	$K^0_S\pi^+\pi^+\pi^-\pi^0$	35	$K^+K^+K^-\pi^-$
17	$K^+\pi^0\pi^0$	36	$K^+K^-K^0_S\pi^+$
18	$K^0_S\pi^0\pi^0$	37	$K^+K^+K^-\pi^0$
19	$K^+\pi^-\pi^0\pi^0$	38	$K^+K^+K^0_S\pi^0$



Branching fraction,
(corresponding to a minimum photon energy of 1.9 GeV)

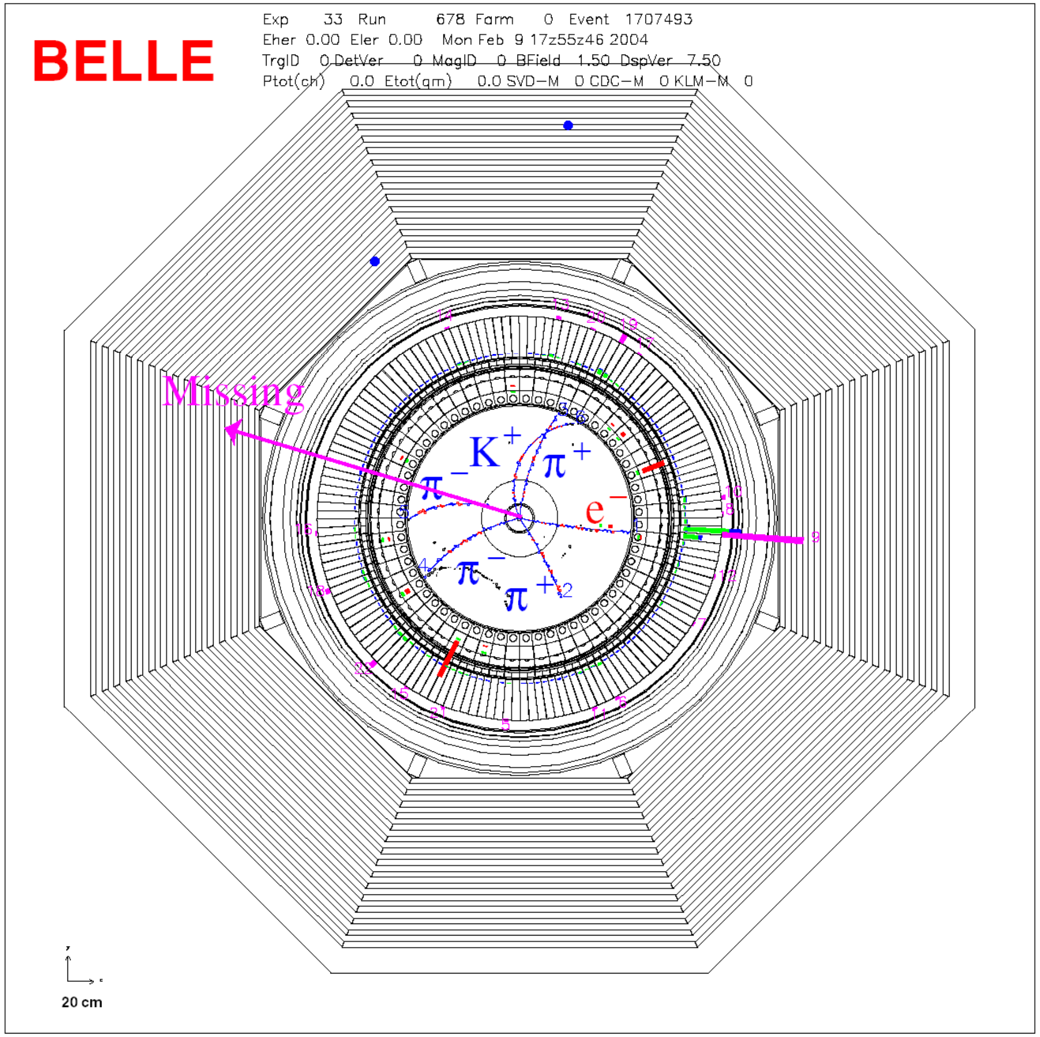
$$\mathcal{B}(B \to X_s\gamma; M_{Xs} < 2.8 GeV/c^2) =$$
$$= (3.51 \pm 0.17(stat.) \pm 0.33(syst)) \cdot 10^{-4}$$

To be submitted to PRD

$B^- \rightarrow \tau^- \nu_\tau$

Example of a missing energy decay

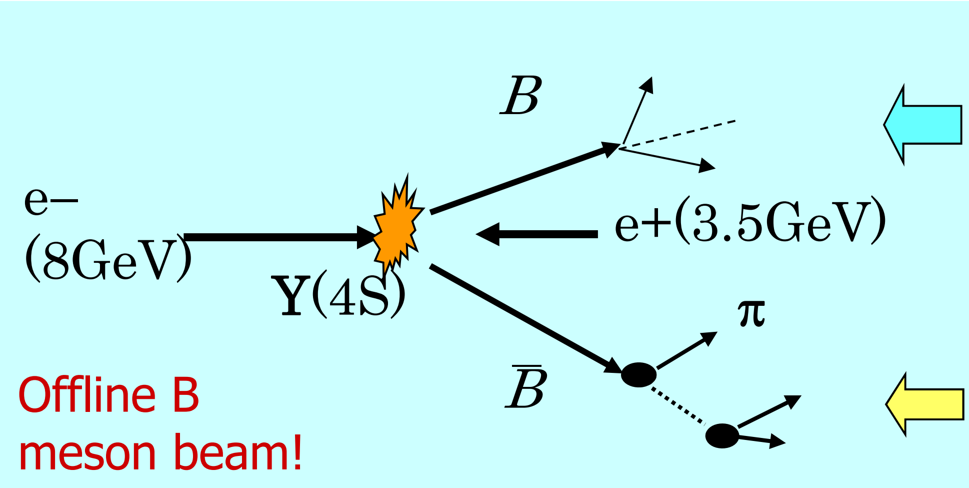
$$B^+ \rightarrow D^0\pi^+$$
$$(\rightarrow K\pi^-\pi^+\pi^-)$$
$$B^- \rightarrow \tau(\rightarrow e\nu\bar{\nu})\nu$$



Full reconstruction tagging

Idea: fully reconstruct one of the B's to tag B flavor/charge, determine its momentum, and exclude decay products of this B from further analysis

(exactly two B's produced in Υ(4S) decays)



Decays of interest
- $B \to X_u l \nu$,
- $B \to K \nu \nu$
- $B \to D\tau\nu$, $\tau\nu$

full reconstruction
$B \to D\pi$ etc. (0.1-0.3%)

Powerful tool for B decays with neutrinos, used in several analyses in this talk

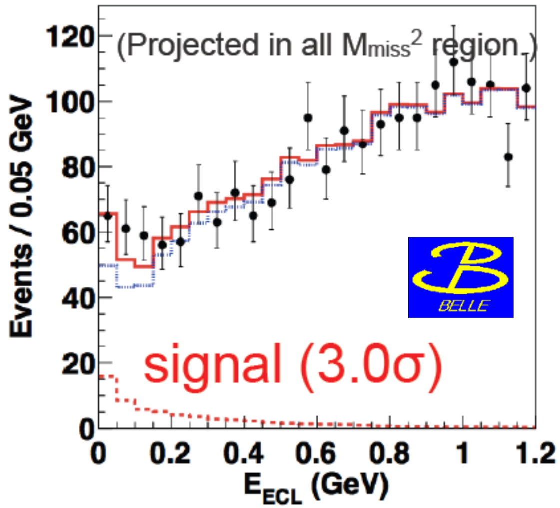
→unique feature at B factories

$B^- \to \tau^- \nu_\tau$

Method: tag one B with full reconstruction, look for the $B^- \to \tau^- \nu_\tau$ in the rest of the event.

Main discriminating variable on the signal side: remaining energy in the calorimeter, not associated with any charged track or photon

→ Signal at $E_{ECL} = 0$

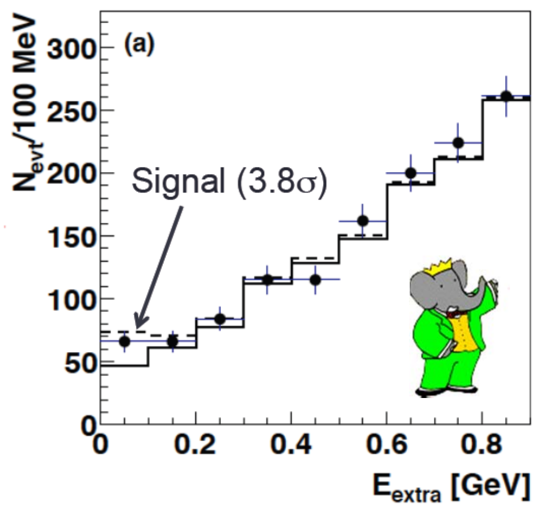


Belle $$Br(B \to \tau\nu) = [0.72\,^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$$

PRL 110, 131801 (2013)

BaBar $$Br(B \to \tau\nu) = [1.83\,^{+0.53}_{-0.49} \pm 0.24] \times 10^{-4}$$

Phys. Rev. D 88, 031102(R) (2013)

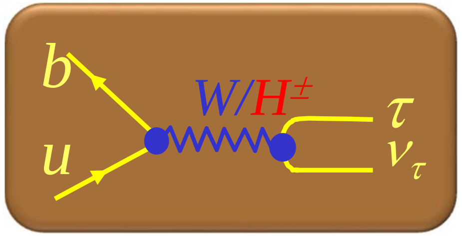


All measurements combined

$$BF(B \to \tau\nu) = (1.15 \pm 0.23) \cdot 10^{-4}$$

$$r_H = \frac{BF(B \to \tau\nu)_{meas}}{BF(B \to \tau\nu)_{SM}} = 1.14 \pm 0.40$$

Charged Higgs limits from $B \to \tau^- \nu_\tau$



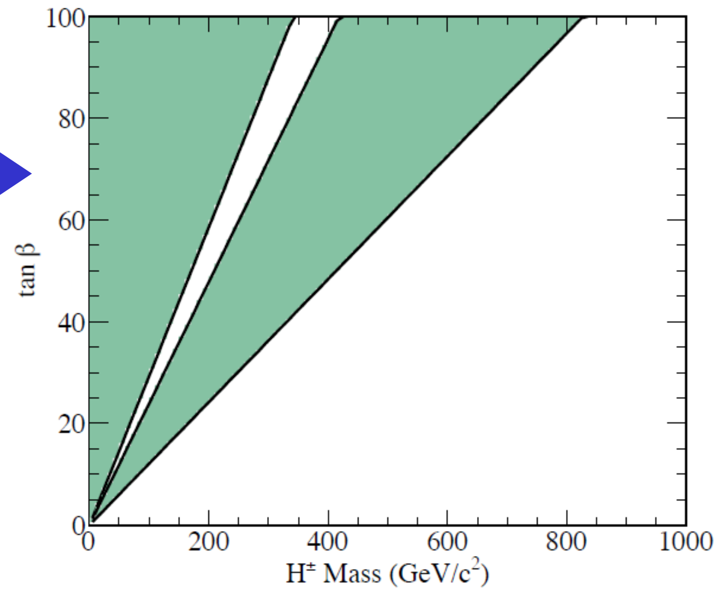
Measured value

$$r_H = \frac{BF(B \to \tau\nu)}{BF(B \to \tau\nu)_{SM}} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

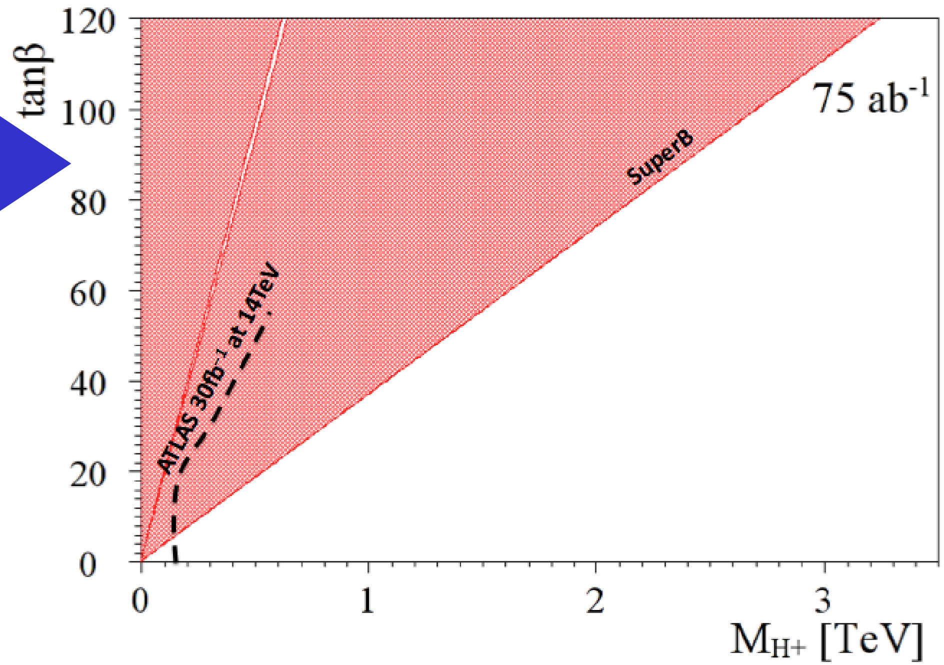
→ limit on charged Higgs mass vs. tanβ

(for type II 2HDM)

B factories: Exclusion plot

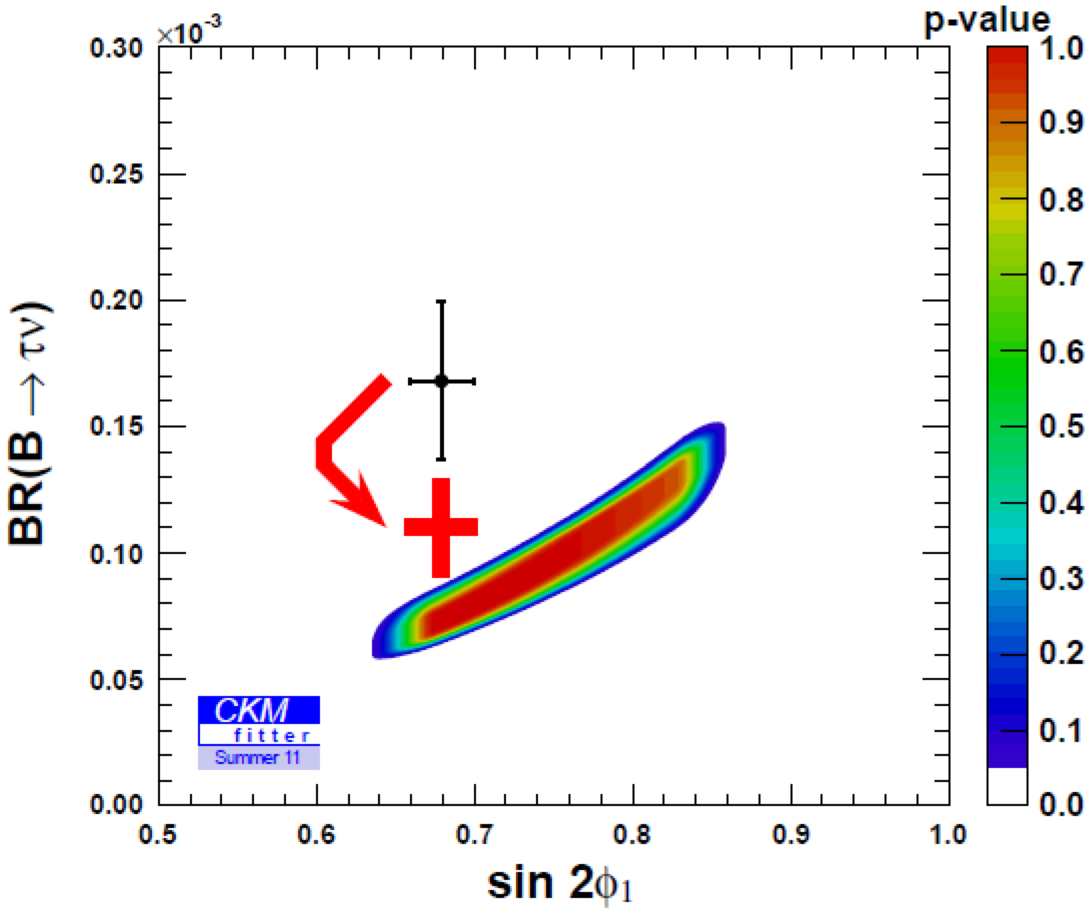


Super B factory: Discovery plot: very much competitive with LHC!



sin$2\phi_1$ (=sin2β) vs. $\mathcal{B}(B\to \tau\nu)$

Tension between $\mathcal{B}(B\to \tau\nu)$ and sin$2\phi_1$
very much reduced (from ~2.5 σ)

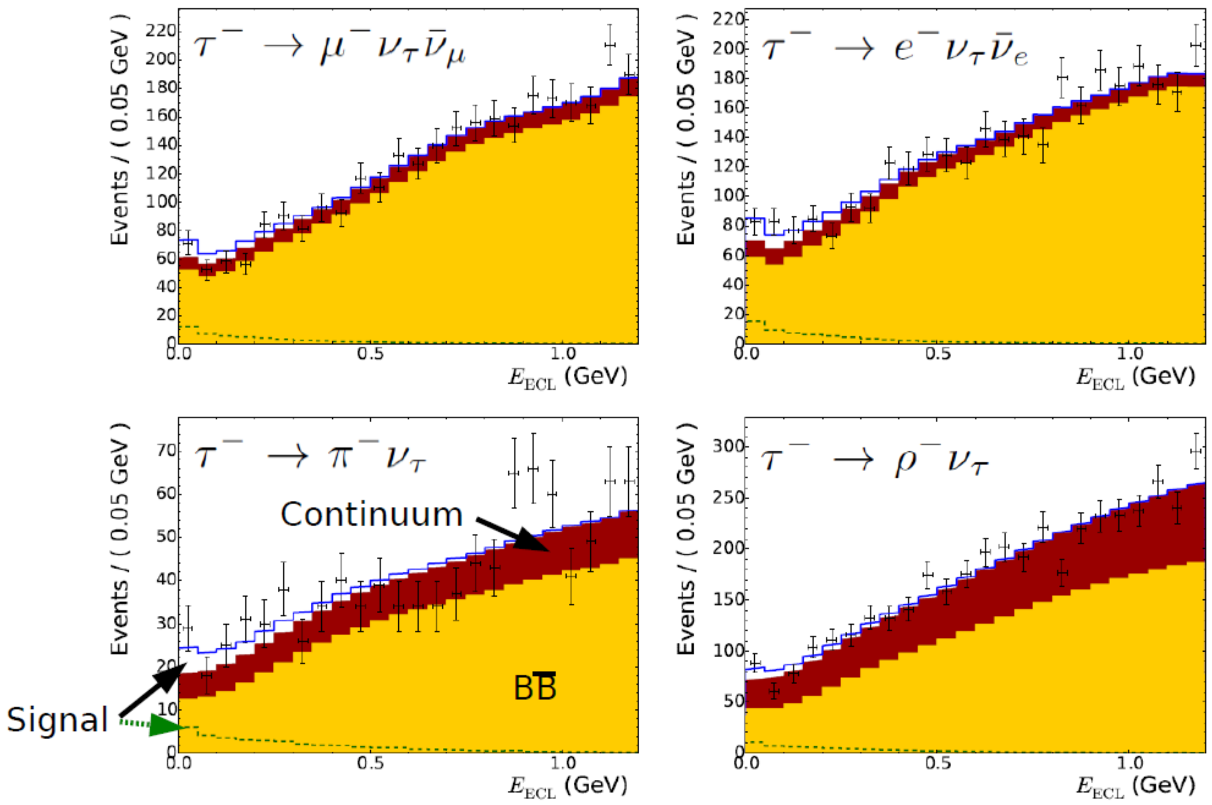


Belle update $B^- \to \tau^- \nu_\tau$

Method: tag with a semileptonic B decay, look for the $B^- \to \tau^- \nu_\tau$ in the rest of the event.

Again: Main discriminating variable on the signal side: remaining energy in the calorimeter, not associated with any charged track or photon

$\to$ Signal at $E_{ECL} = 0$



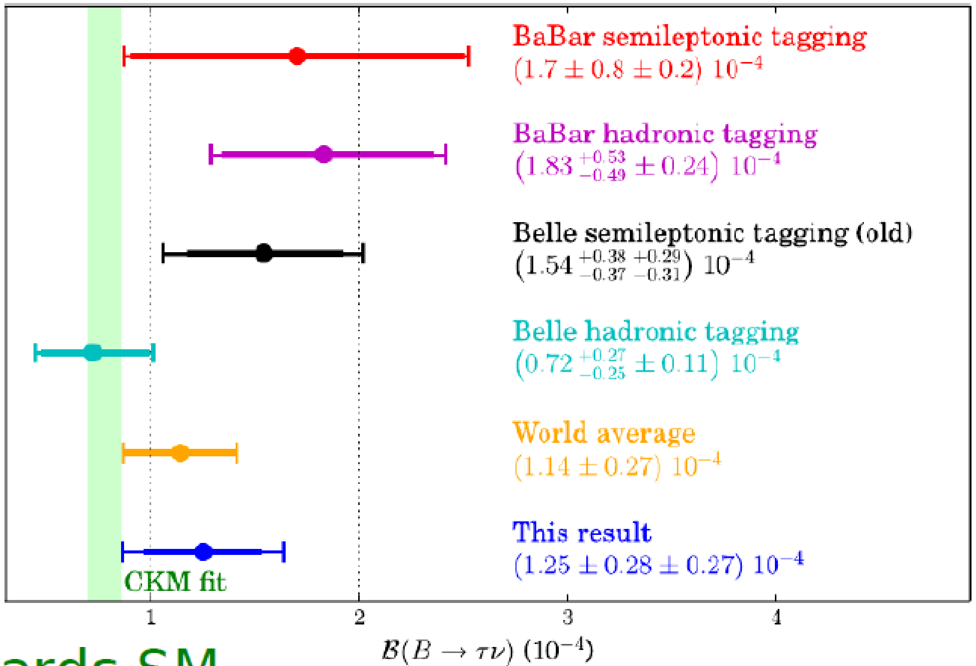
Belle update $B^- \to \tau^- \nu_\tau$, tag with a semileptonic B

Belle-CONF-1401

- $\mathcal{B}(B \to \tau\nu) = [1.25 \pm 0.28\ (\text{stat}) \pm 0.27\ (\text{syst})] \times 10^{-4}$
- Signal significance of 3.4σ including systematics

Decay Mode	N_{sig}	$\mathcal{B}(10^{-4})$
$\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$	13±21	0.34±0.55
$\tau^- \to e^- \nu_\tau \bar{\nu}_e$	47±25	0.90±0.47
$\tau^- \to \pi^- \nu_\tau$	57±21	1.82±0.68
$\tau^- \to \rho^- \nu_\tau$	119±33	2.16±0.60
Combined	222±50	1.25±0.28

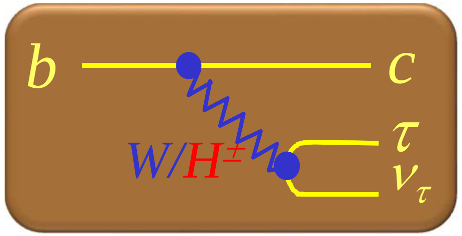
statistical errors only



- Consistent results among tau channels
- → Central value shifted towards SM
- Combination with Belle hadronic tag result in progress

$B \to D^{(*)}\tau\nu$ decays

Semileptonic decay sensitive to charged Higgs



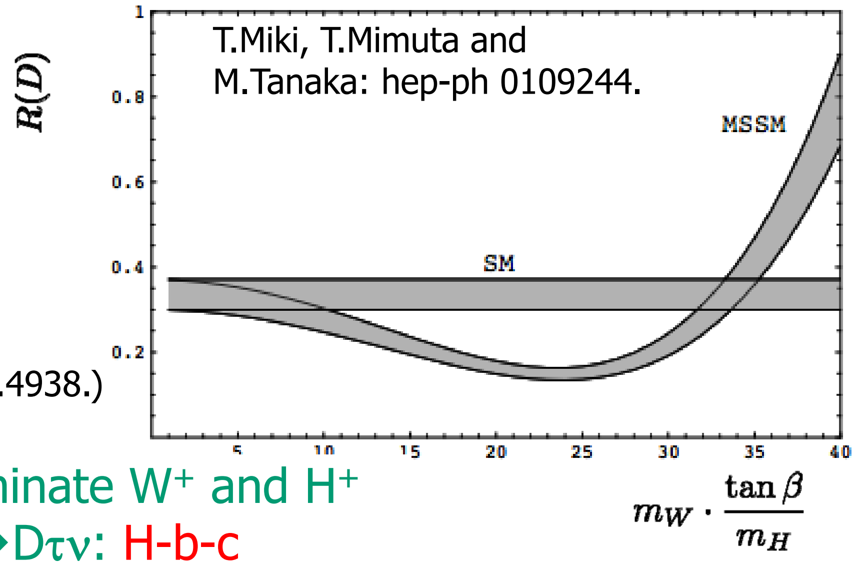
Ratio of τ to μ,e could be reduced/enhanced significantly

Kamenik, Mescia arXiv:0802.3790

$$R(D) \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

Complementary and competitive with $B \to \tau\nu$

1. Smaller theoretical uncertainty of R(D)
   (For $B \to \tau\nu$, There is O(10%) f_B uncertainty from lattice QCD)
2. Large Brs (~1%) in SM (Ulrich Nierste arXiv:0801.4938.)



3. Differential distributions can be used to discriminate W^+ and H^+
4. Sensitive to different vertex $B \to \tau\nu$: H-b-u, $B \to D\tau\nu$: H-b-c
   (LHC experiments sensitive to H-b-t)

First observation of $B \to D^{*-}\tau\nu$ by Belle (2007) → PRL 99, 191807 (2007)

$B \to D^{(*)} \tau \nu$ decays

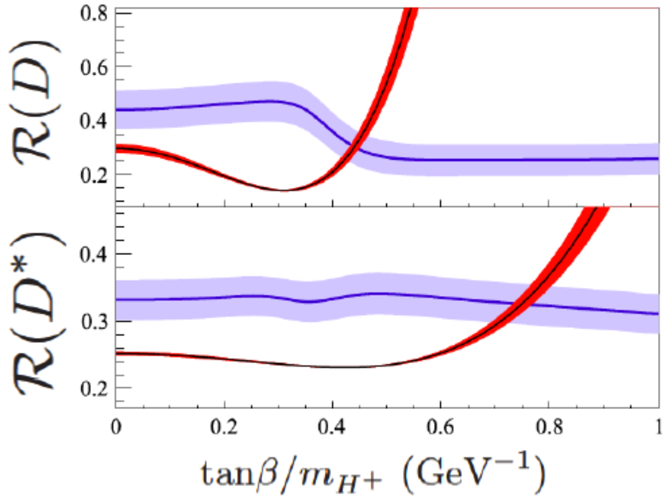
Exclusive hadron tag data

$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072$ — 2.0σ — $\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017$

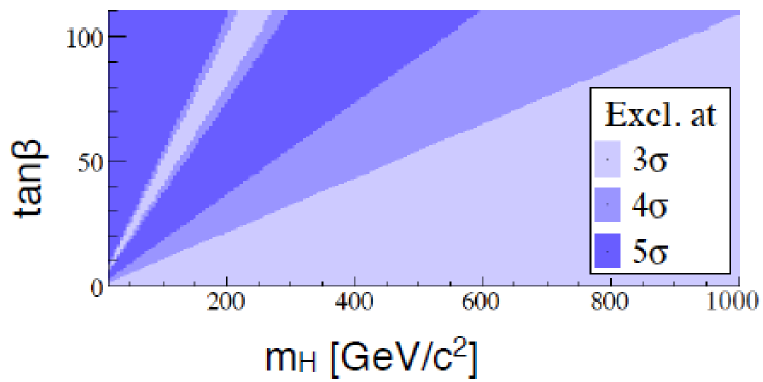
$\mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$ — 2.7σ — $\mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$

SM expectations in S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012).

→ Combined result: 3σ away from SM.



Blue: this result, red: Type-II 2HDM.

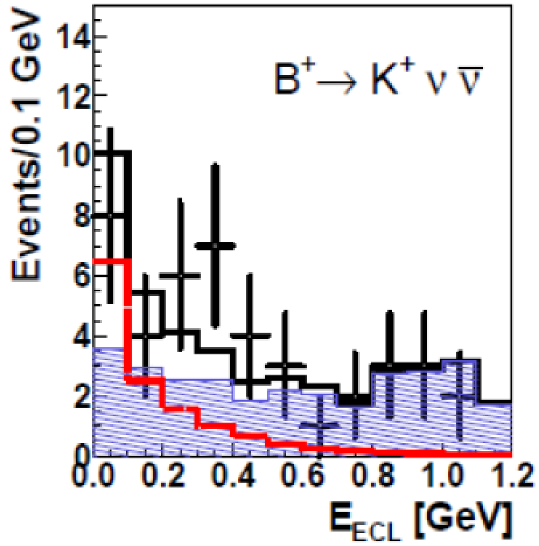


→ Combined result: Type II 2HDM excluded at 99.8% C.L. for any values of tanβ and charged Higgs mass

More discussion of the implications: BaBar, Phys. Rev. Lett. 109, 101802 (2012)

$B \to h\nu\bar{\nu}$ decays

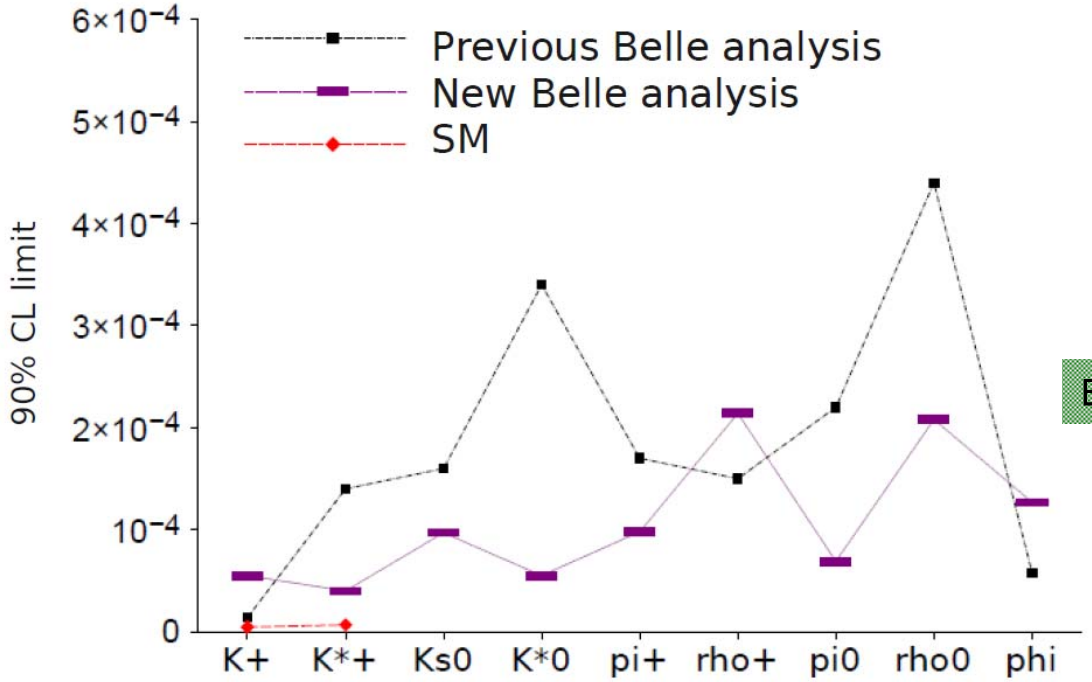
Method: again tag one B with full reconstruction, search for signal in the remaining energy in the calorimeter, at $E_{ECL} = 0$



$$N_{Sig} = 13.3^{+7.4}_{-6.6}(stat) \pm 2.3(syst)$$

$$S_{stat+syst} = 2.0\sigma$$

Present status: recent update from Belle



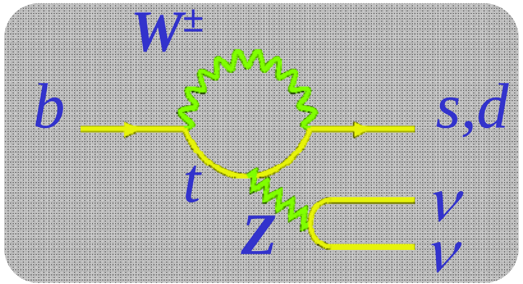
Belle, Phys. Rev. D 87, 111103(R) (2013)

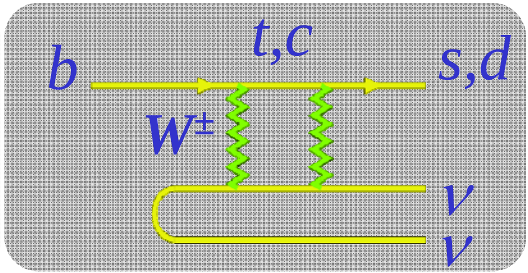
$B \to K^{(*)}\nu\bar{\nu}$

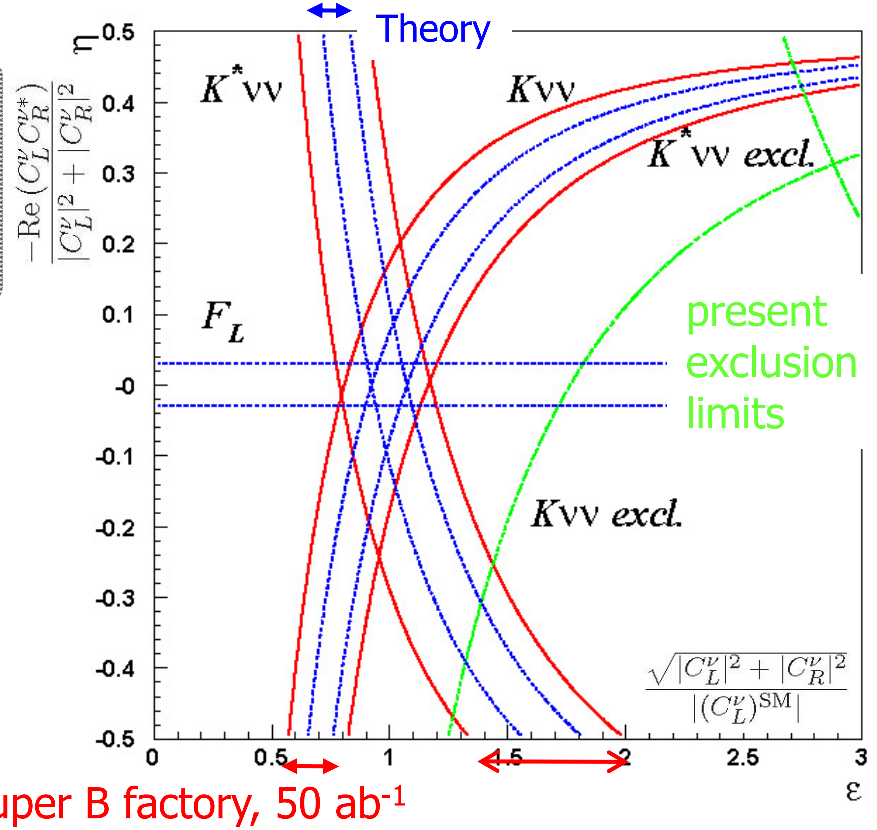
arXiv:1002.5012

adopted from W. Altmannshofer et al., JHEP 0904, 022 (2009)

SM: penguin + box diagrams



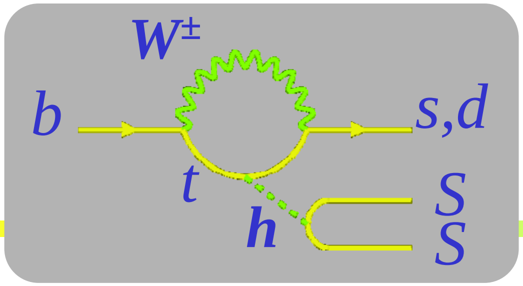


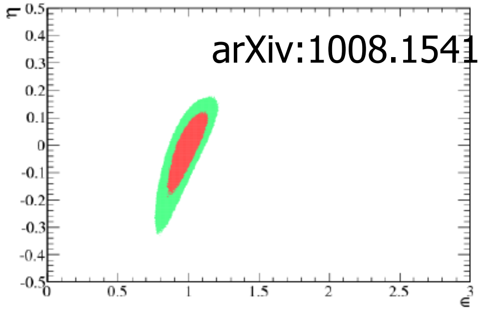


$B \to K\nu\nu$, $\mathcal{B} \sim 4{\cdot}10^{-6}$
$B \to K^*\nu\nu$, $\mathcal{B} \sim 6.8{\cdot}10^{-6}$

Look for deviations from the expected values → information on anomalous couplings C^{ν}_{R} and C^{ν}_{L} compared to $(C^{\nu}_{L})^{SM}$

from, e.g.,





Charm and τ physics

B factories = charm and τ factories

Charm and τ can be found in any "Y(nS) samples"

→ the integrated luminosity of the samples used for charm and τ studies is larger than for the B physics studies (Belle ~ 1 ab^{-1}, BaBar ~0.550 ab^{-1})

→ This will of course remain true for the super B factory

A few examples of the strengths of B factories:

- CP violation in charm at B factories (and super B factories) →can measure CPV separately in individual decay channels, $\pi^+\pi^-$, K^+K^-, $K_S\,\pi$,...
- $D\bar{D}$ pairs produced with very few light hadrons
- Full reconstruction of events →

Rare charm decays: tag with the other D

Again make use of the hermeticity of the apparatus!

Example: leptonic decays of D_s

$$e^+e^- \rightarrow c\bar{c} \rightarrow \overline{D}_{\mathrm{tag}} K X_{\mathrm{frag}} D_s^{*+}$$

Recoil method in charm events:

- Reconstruct D_{tag} to tag charm, kaon to tag strangeness
- Additional light mesons (X_{frag}) can be produced in the fragmentation process (π, $\pi\pi$, …)

2 step reconstruction:

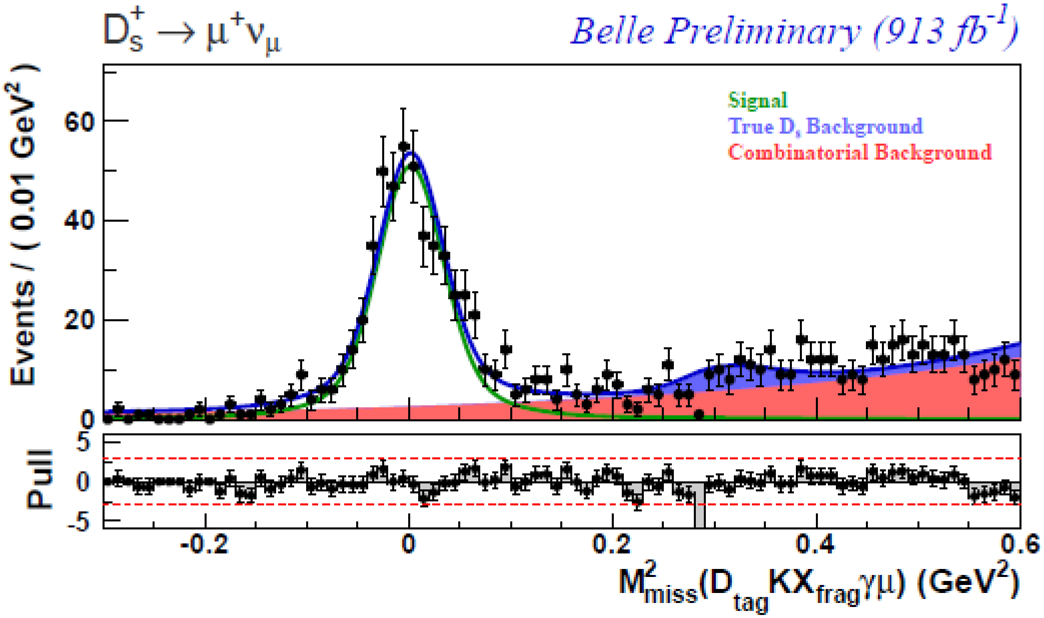
- Inclusive reconstruction of D_s mesons for normalization (without any requirements upon D_s decay products)
- Within the inclusive D_s sample search for D_s decays
  - $D_s \rightarrow \mu\nu$: peak at $m_\nu^2 = 0$ in $M^2_{\mathrm{miss}}(D_{\mathrm{tag}} K X_{\mathrm{frag}} \gamma\mu)$
  - $D_s \rightarrow \tau\nu$: peak towards 0 in extra energy in calorimeter

$D_s^+ \to \mu^+ \nu_\mu$

Fit to the missing mass squared – $M^2_{\rm miss}(D_{\rm tag} K X_{\rm frag} \gamma \mu^\pm)$

Selection:

- $M_{\rm miss}(D_{\rm tag} K X_{\rm frag} \gamma)$ signal region
- 1 charged track pointing to the IP
- passing muon PID requirements



Belle, arxiv:1301.7218

$$N^{\rm excl}_{D_s \to \mu\nu} = 489 \pm 26$$

Belle preliminary @ 913 fb^{-1}

$$\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (0.528 \pm 0.028(\text{stat.}) \pm 0.019(\text{syst.}))\%$$

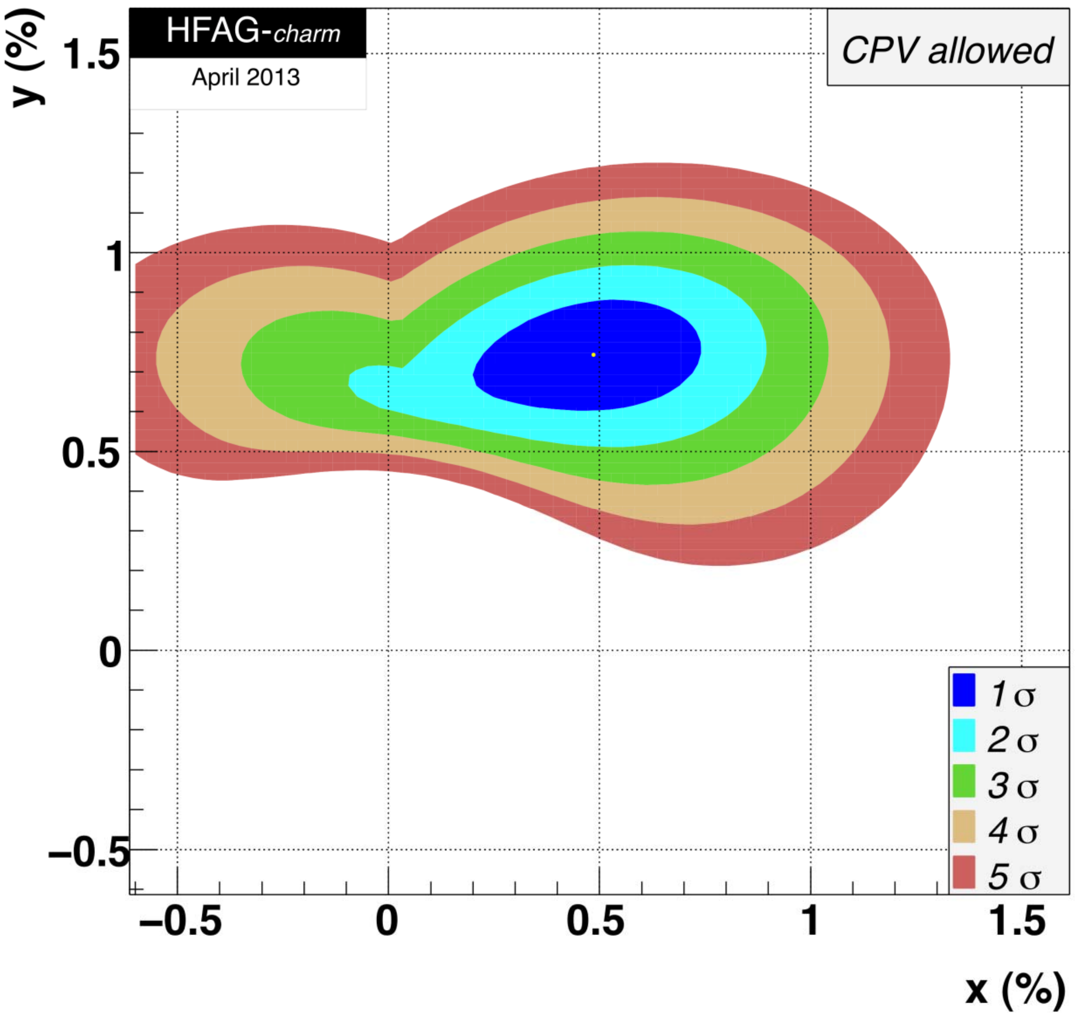
Most precise measurement up to date.

Extract f_{Ds} :

$$f_{D_s} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi \mathcal{B}(D_s \to \ell \nu_\ell)}{M_{D_s} \tau_{D_s}}}$$

Charm: last but not least…

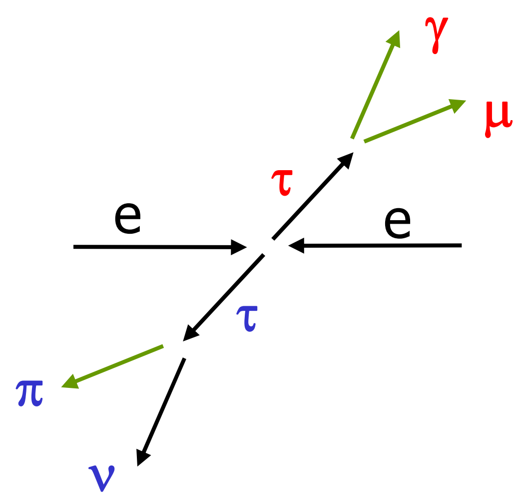
D mixing was discovered at Belle and BaBar…



… and there remains a lot for us to do in the era of super B factories.

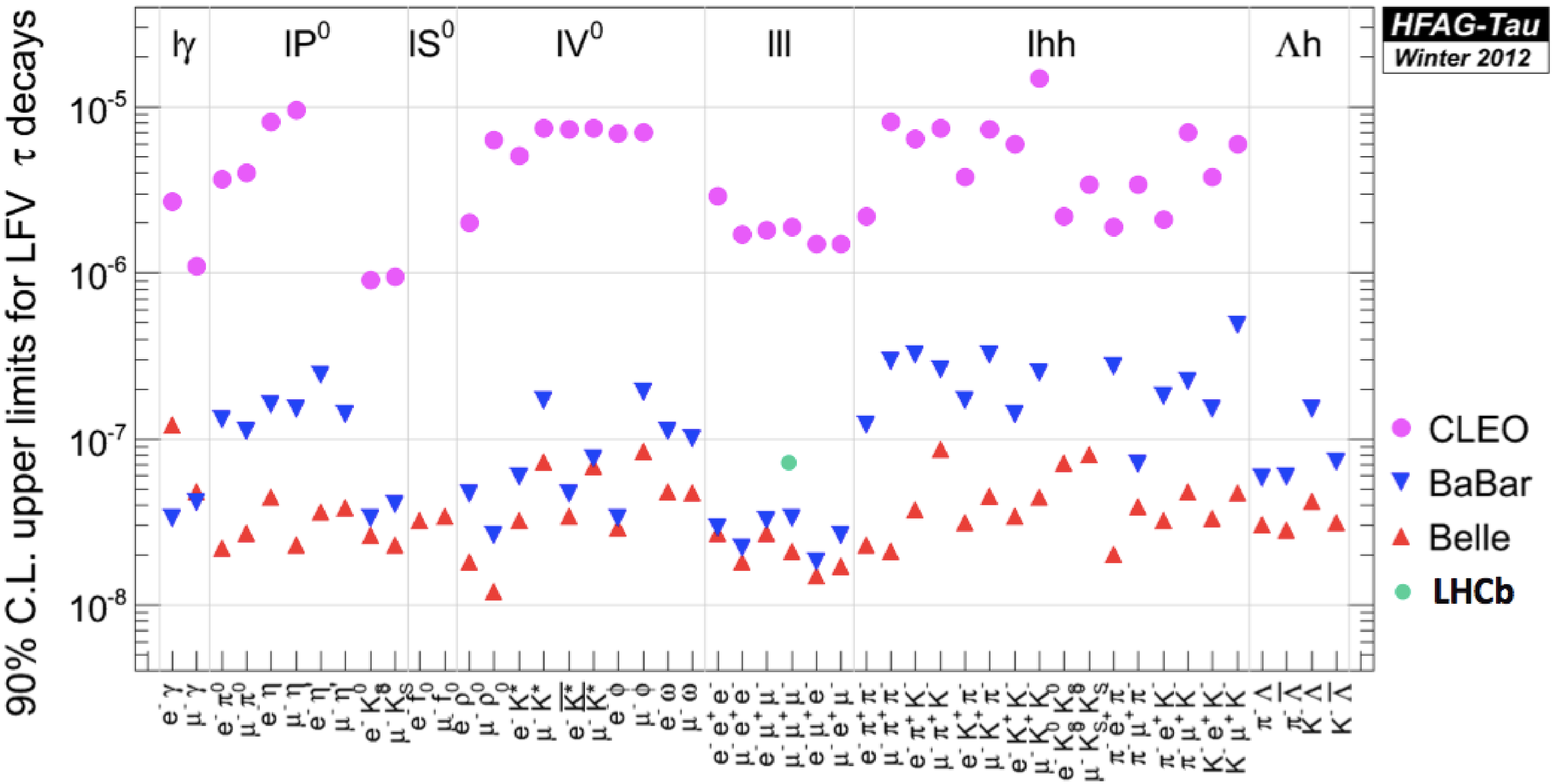
Rare τ decays

Example: lepton flavour violating decay $\tau \rightarrow \mu\,\gamma$



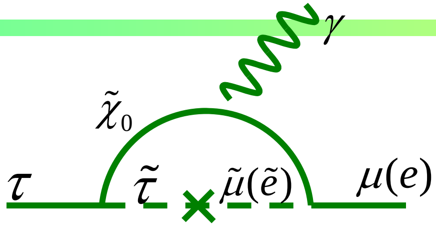
LFV in tau decays: present status

Lepton flavour violation (LFV) in tau decays: would be a clear sign of new physics



LFV and New Physics

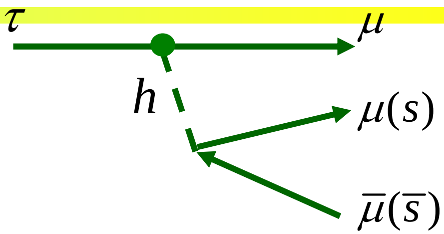
$\tau \to l\gamma$



- SUSY + Seasaw $(m^2_{\tilde{l}})_{23(13)}$
- Large LFV $Br(\tau\to\mu\gamma)=O(10^{-7\sim9})$

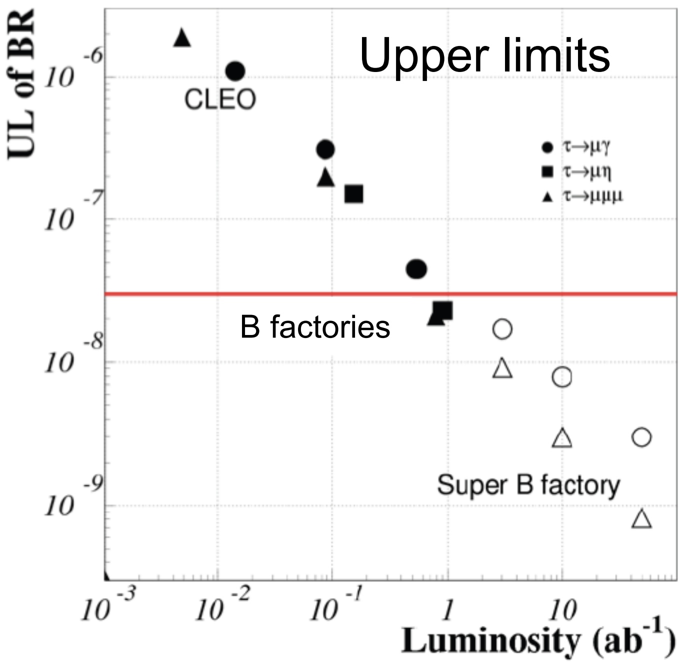
$$Br(\tau\to\mu\gamma)\simeq 10^{-6}\times\left(\frac{(m^2_{\tilde L})_{32}}{\bar m^2_{\tilde L}}\right)\left(\frac{1TeV}{m_{SUSY}}\right)^4\tan^2\beta$$

$\tau \to 3l, l\eta$



- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

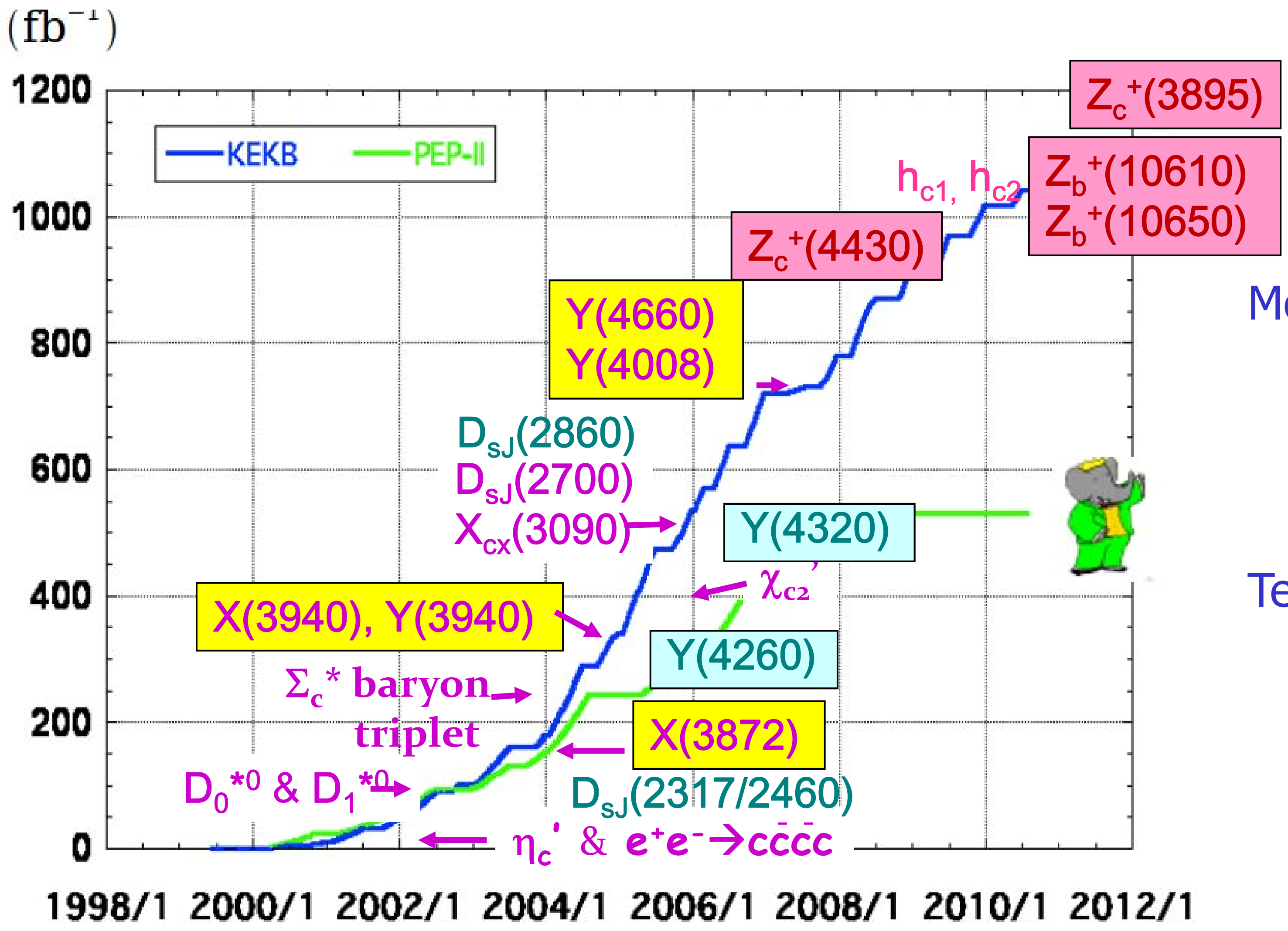
$$Br(\tau\to 3\mu)=$$
$$4\times10^{-7}\times\left(\frac{(m^2_{\tilde L})_{32}}{\bar m^2_{\tilde L}}\right)\left(\frac{\tan\beta}{60}\right)^6\left(\frac{100GeV}{m_A}\right)^4$$



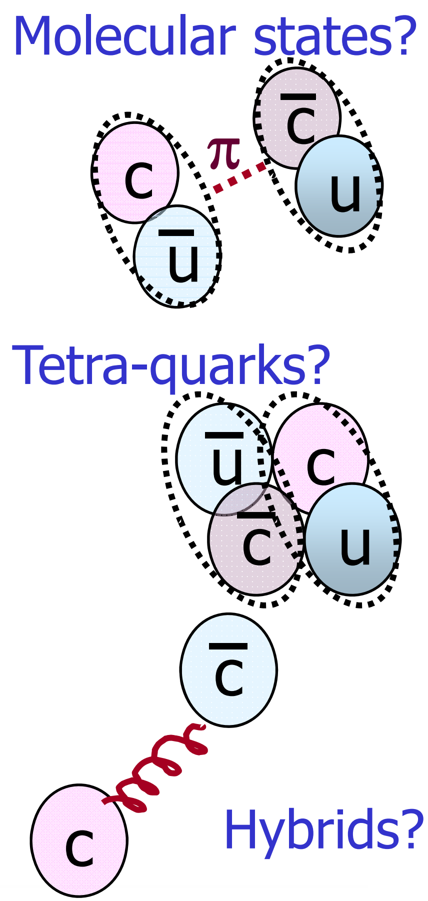
Integ. Lum.(ab-1)

model	$Br(\tau\to\mu\gamma)$	$Br(\tau\to lll)$
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

New hadrons at B-factories



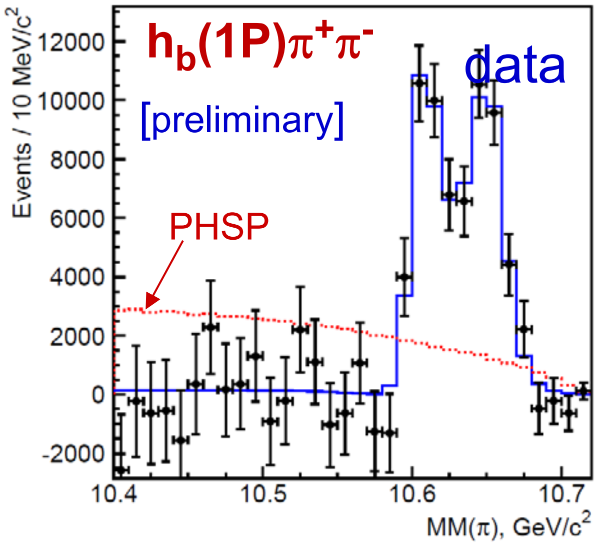
Coloured boxes: exotic candidates



Resonant substructure in $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$

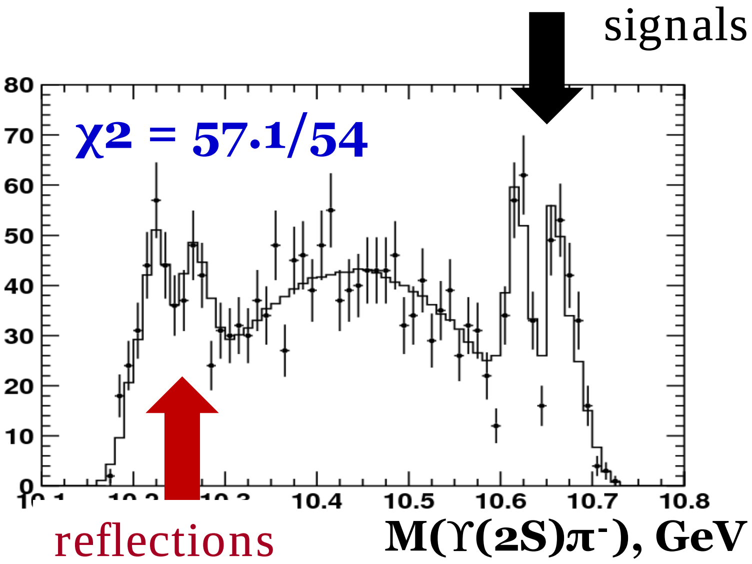
Look at $M(h_b\pi^+) = MM(\pi^-)$

measure $\Upsilon(5S) \to h_b\pi\pi$ yield in bins of $MM(\pi)$



Exclusive searches:

Observed in $\Upsilon(5S) \to$ **$\Upsilon(1S)$** $\pi^+\pi^-$, **$\Upsilon(2S)$** $\pi^+\pi^-$ and **$\Upsilon(3S)$** $\pi^+\pi^-$



$Z_b(10610)$ — $M = 10608.1 \pm 1.7$ MeV, $\Gamma = 15.5 \pm 2.4$ MeV

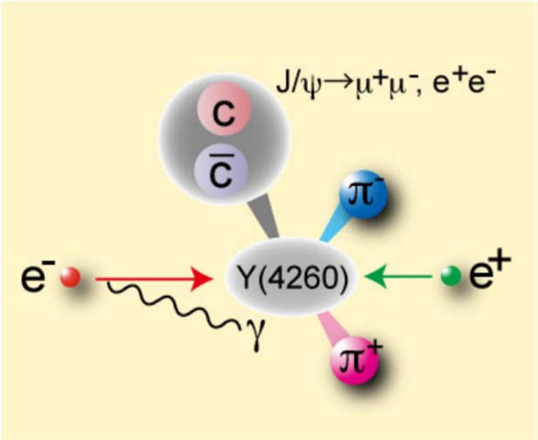
$Z_b(10650)$ — $M = 10653.3 \pm 1.5$ MeV, $\Gamma = 14.0 \pm 2.8$ MeV

Seen in 5 different final states, parameters are consistent

$J^P=1^+$ in agreement with data; other J^P are disfavored

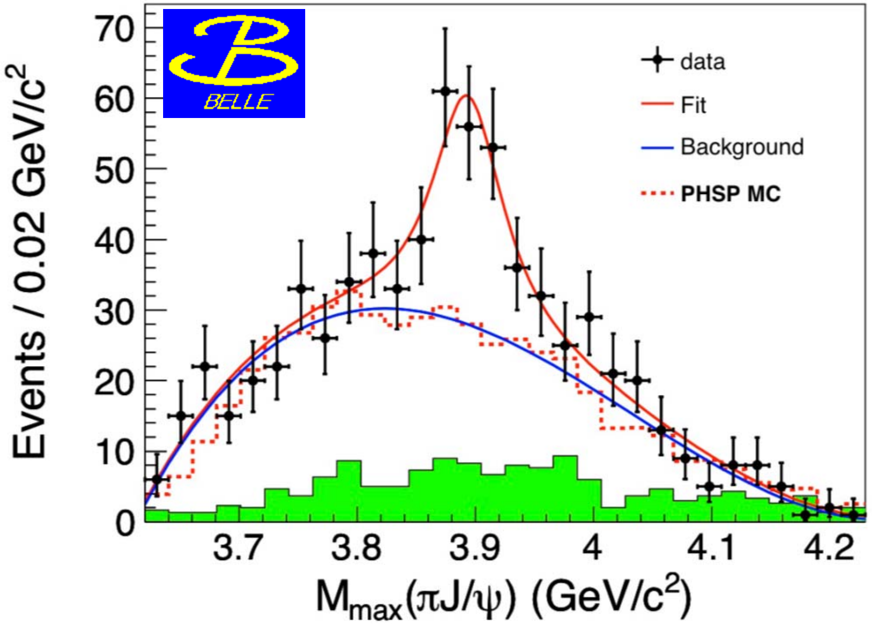
→ What is the nature of Z_b^+? Molecules, tetraquarks, cusps, ... ?

Charged charmonium in Y(4260) → J/ψ $\pi^+ \pi^-$



Y(4260) produced via ISR
(Initial State Radiation)

Look for a resonance in J/ψ π^+



Found! → $Z_c^+(3895)$

Observed also by BES III.
They also recently found a peak in $(DD^*)^+$ at 3885 MeV
PRL110, 252001 (2013)
PRL112, 022001 (2014)

PRL110, 252002 (2013)

very similar to
$\Upsilon(5S) \rightarrow Z_b^+ \pi^- \rightarrow \Upsilon(1s) \pi^+ \pi^-$

B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \rightarrow \tau\nu$, $D\tau\nu$)
- $b \rightarrow s$ transitions: probe for new sources of CPV and constraints from the $b \rightarrow s\gamma$ branching fraction
- Forward-backward asymmetry (A_{FB}) in $b \rightarrow sl^+l^-$
- Observation of D mixing
- Searches for rare τ decays
- Discovery of exotic hadrons including charged charmonium- and bottomonium-like states

B factories remain competitive in many measurements because of their unique capabilities.

What next?

Next generation: Super B factories → Looking for NP

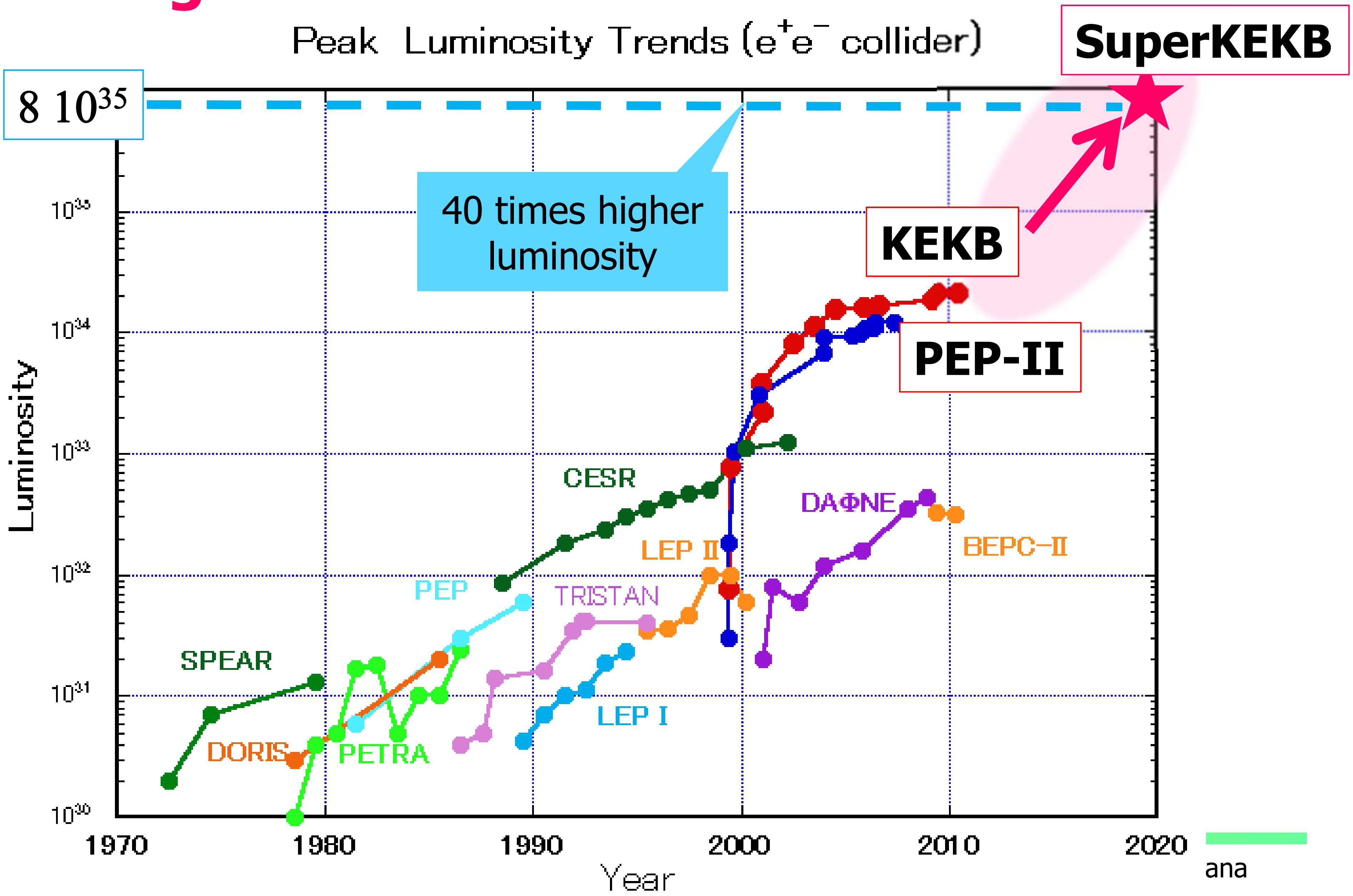
→ Need much more data (almost two orders!)

However: it will be a different world in three years, there is a hard competition from LHCb and BESIII

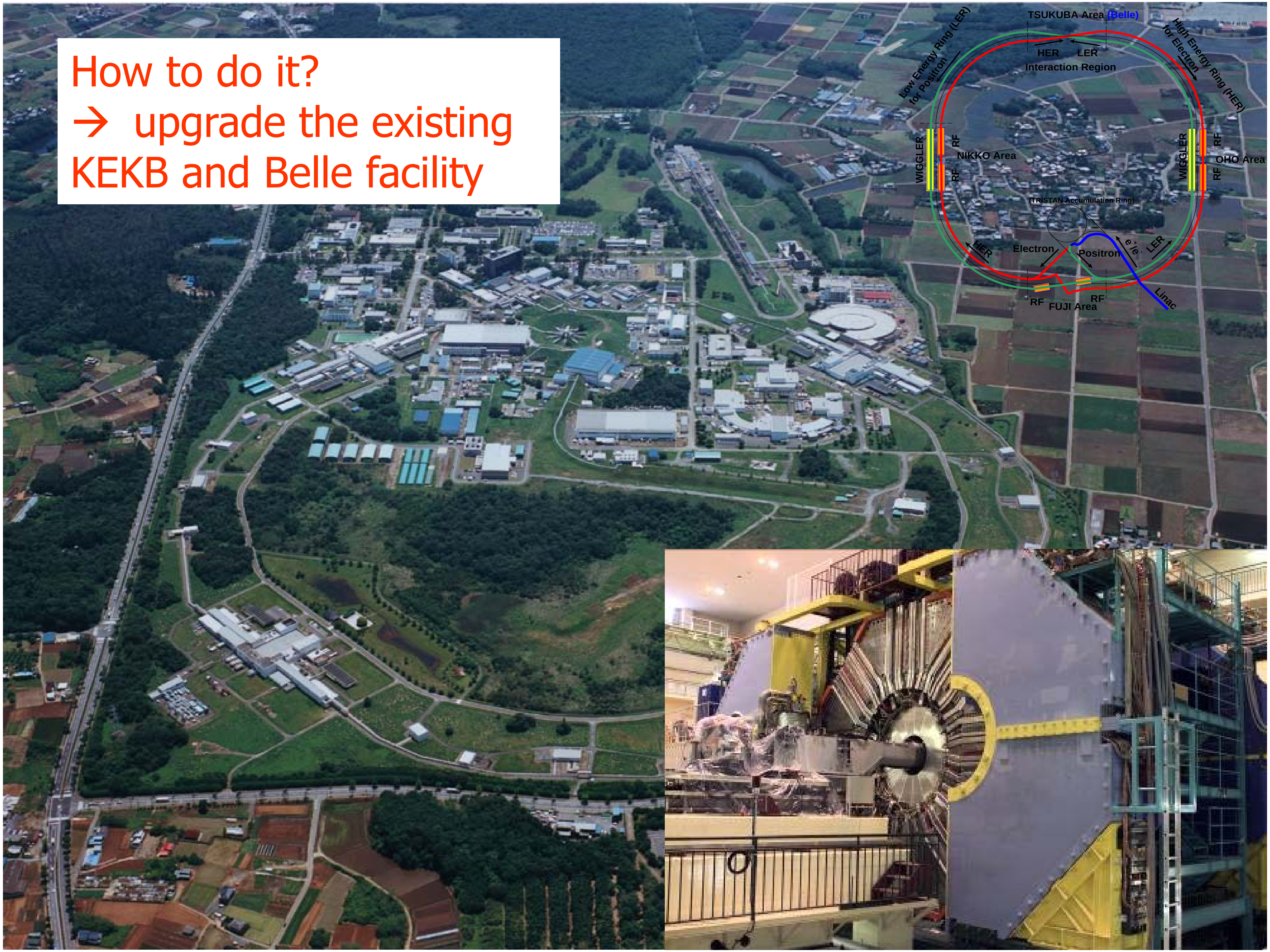
Still, e^+e^- machines running at (or near) Υ(4s) will have considerable advantages in several classes of measurements, and will be complementary in many more

→ Physics at Super B Factory, arXiv:1002.5012 (Belle II)
→ SuperB Progress Reports: Physics, arXiv:1008.1541 (SuperB)

Need O(100x) more data →Next generation B-factories



How to do it?
→ upgrade the existing KEKB and Belle facility



How to increase the luminosity?

Beam-beam parameter

Lorentz factor

Beam current

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

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 - 1
(short bunch)

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

"Nano-Beam" scheme

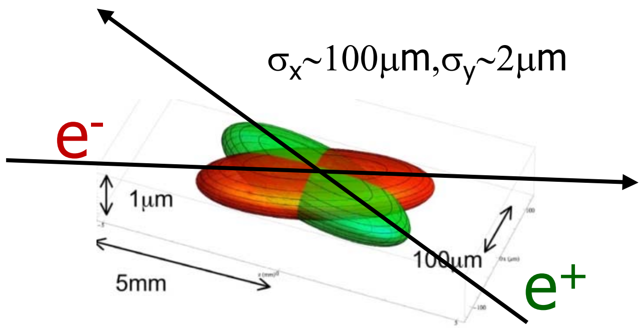
Collision with very small spot-size beams

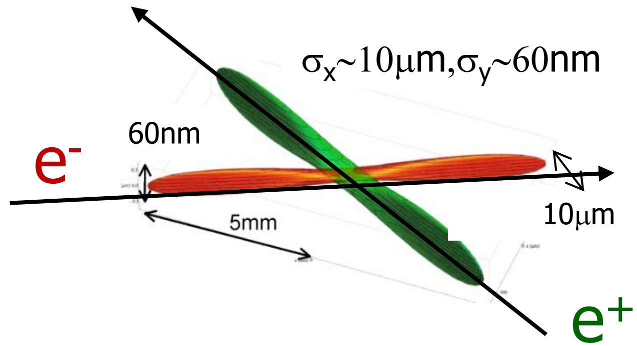
Invented by Pantaleo Raimondi for SuperB

How big is a nano-beam ?

How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

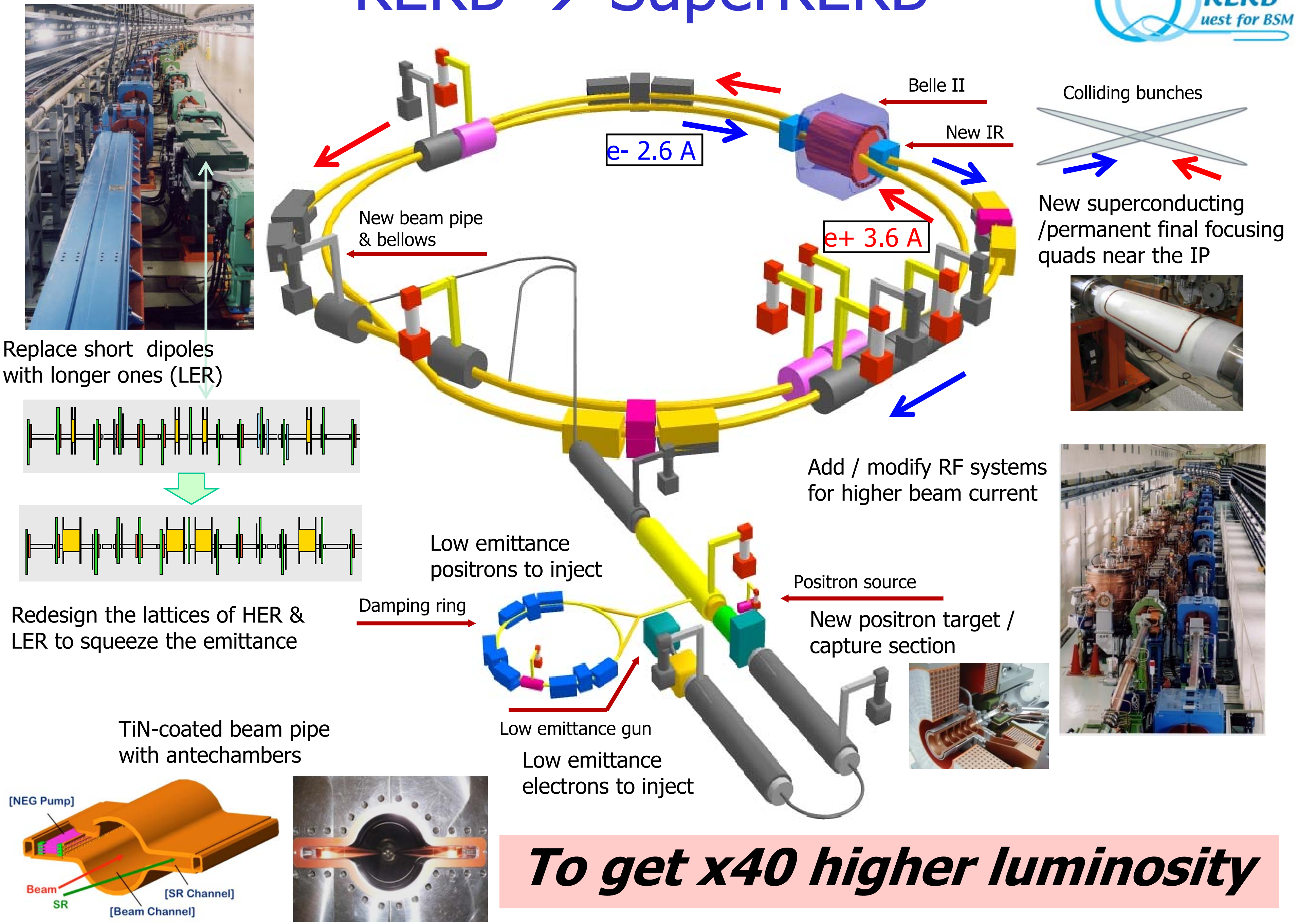
In KEKB, colliding electron and positron beams were already much thinner than a human hair...



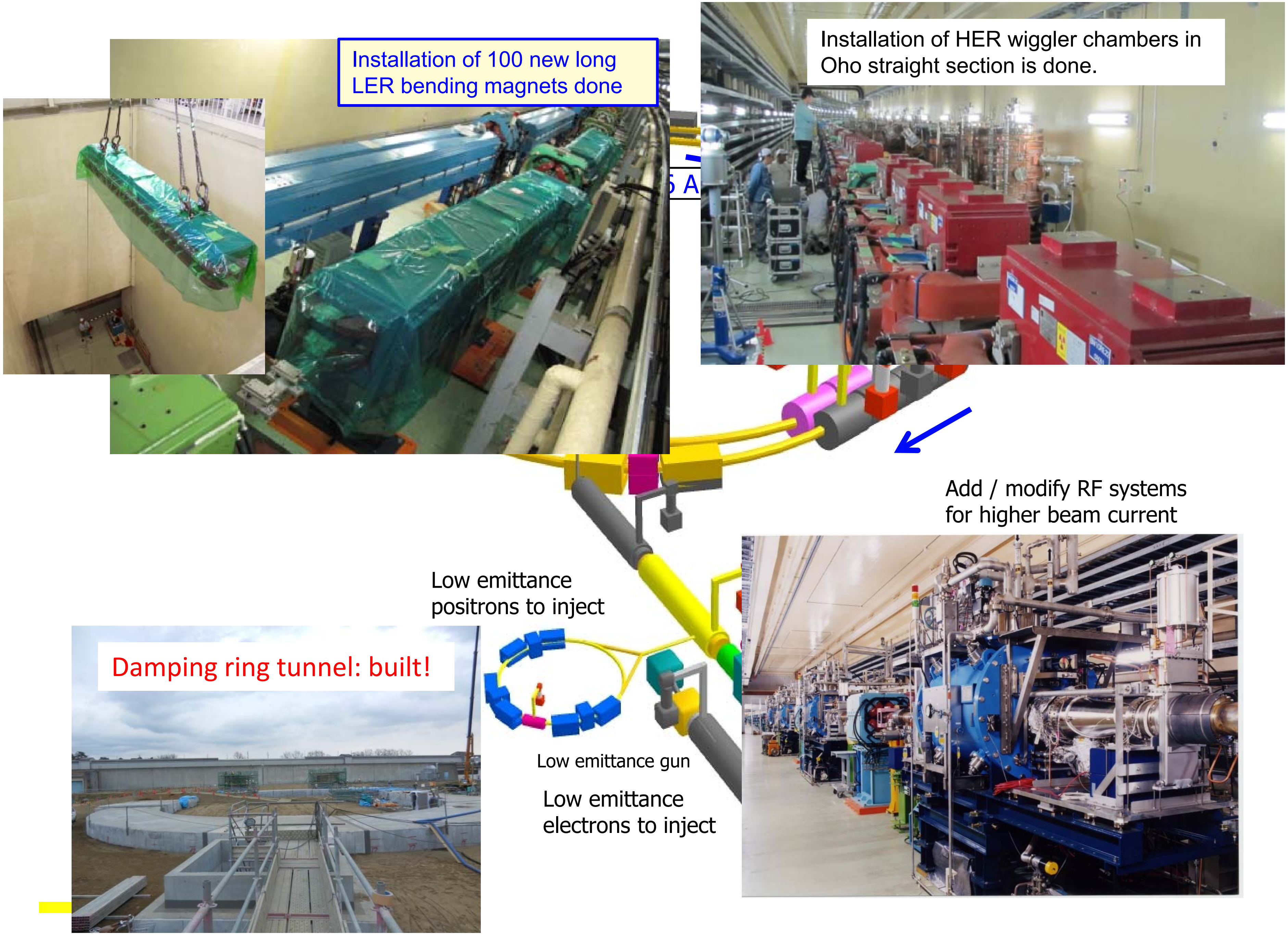


... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

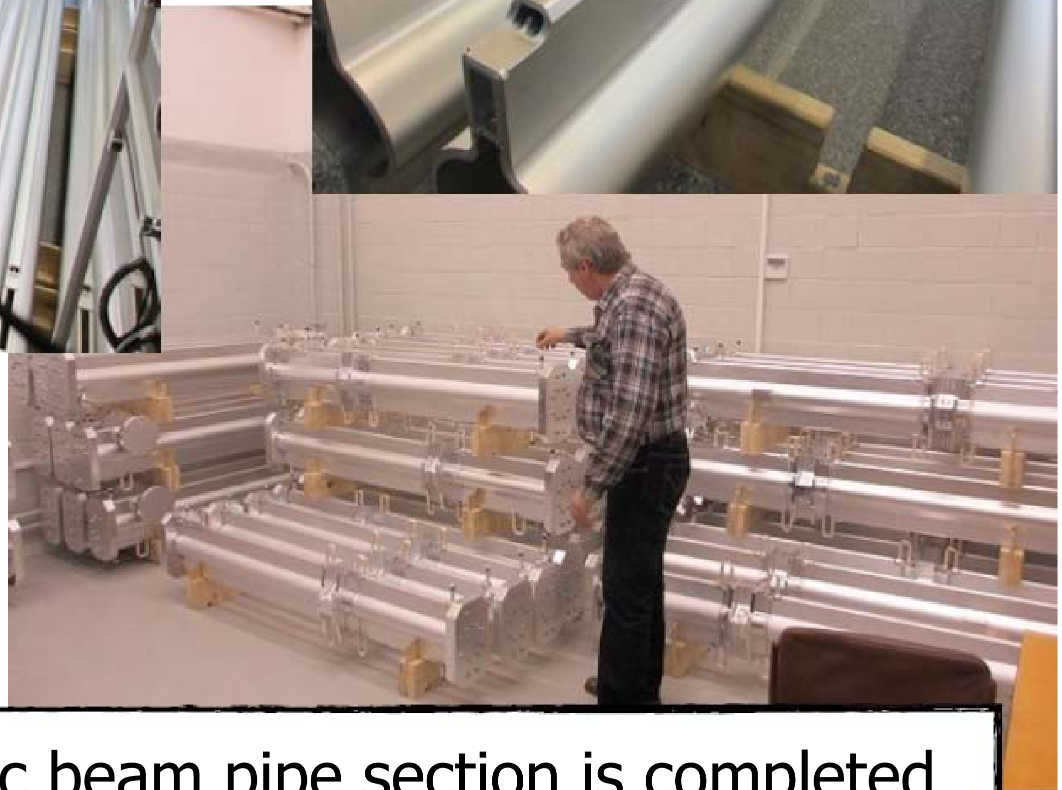
KEKB → SuperKEKB



To get x40 higher luminosity


Installation of 100 new long LER bending magnets done
Installation of HER wiggler chambers in Oho straight section is done.
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Damping ring tunnel: built!
Low emittance gun
Low emittance electrons to inject

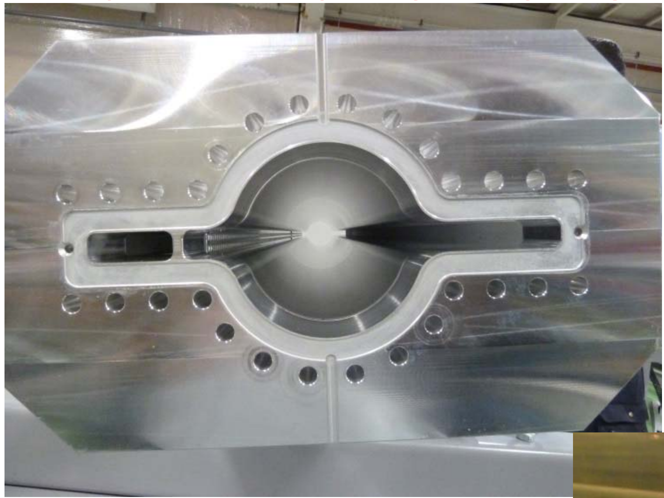
Entirely new LER beam pipe with ante-chamber and Ti-N coating

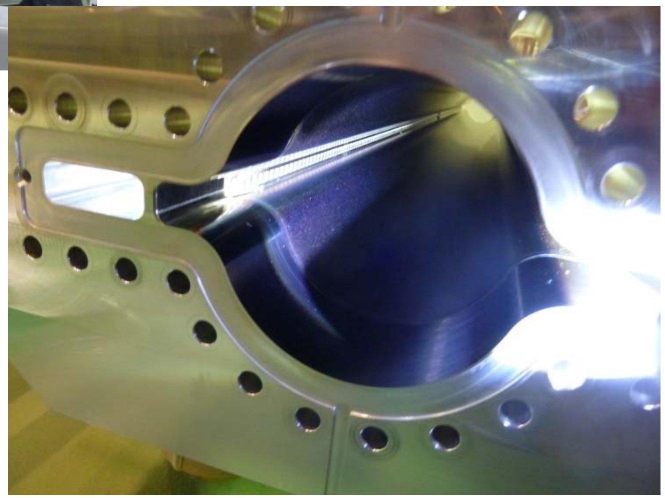


Beam pipe is made of aluminum.

Fabrication of the LER arc beam pipe section is completed

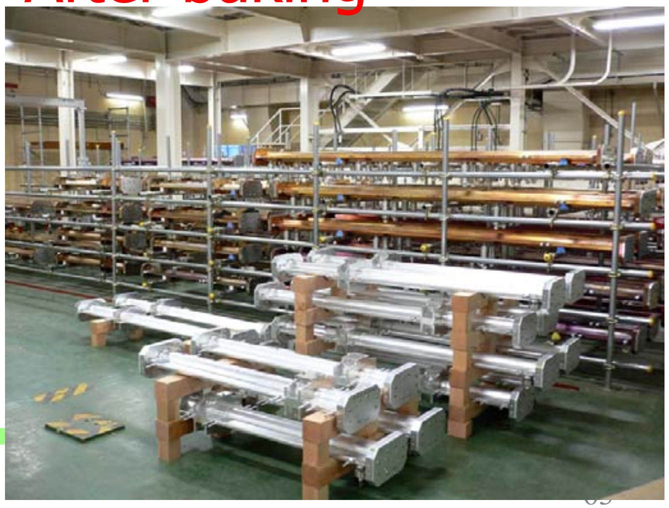
Al ante-chamber before coating





After TiN coating
before baking

After baking



All 100 4 m long dipole magnets have been successfully installed in the low energy ring (LER)!

Three magnets per day !

Installing the 4 m long LER dipole **over** the 6 m long HER dipole (remains in place).

Magnet installation

field measurement

move into tunnel

Installation of 100 new LER bending magnets done

carry on an air-pallet

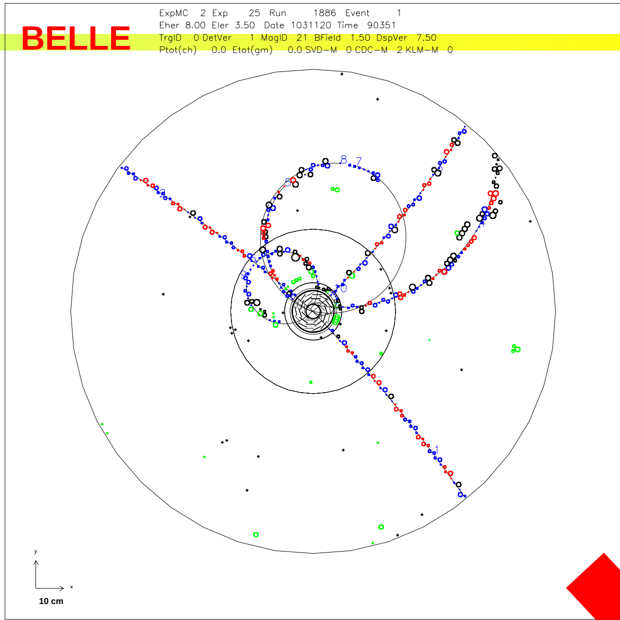
carry over existing HER dipole

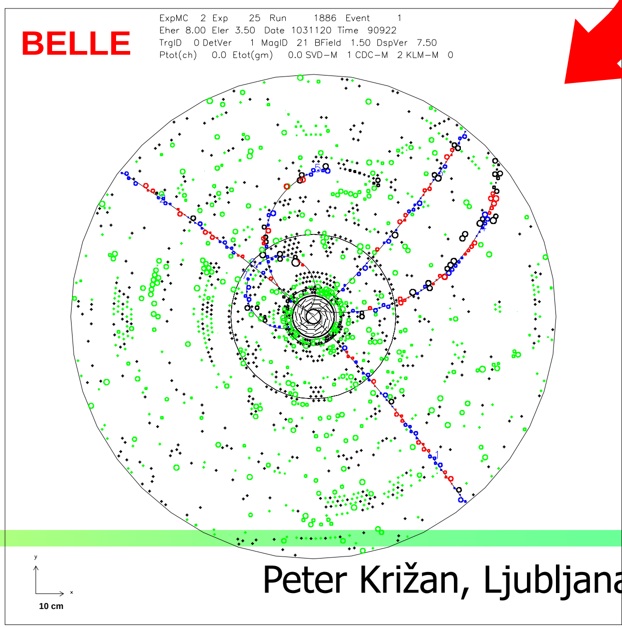
installation done

Requirements for the Belle II detector

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low *p* μ identification ← sμμ recon. eff.
  - hermeticity ← ν "reconstruction"

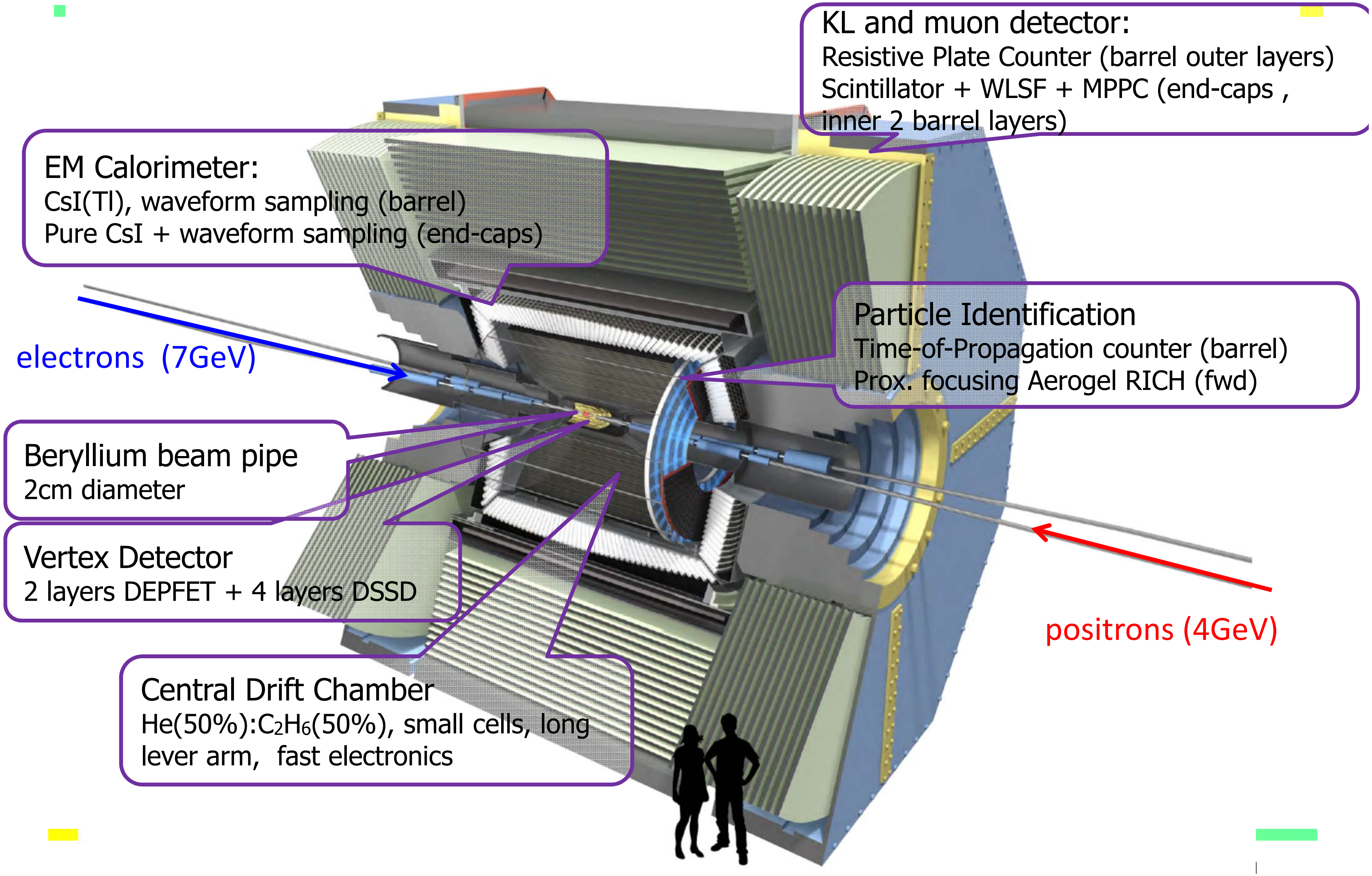




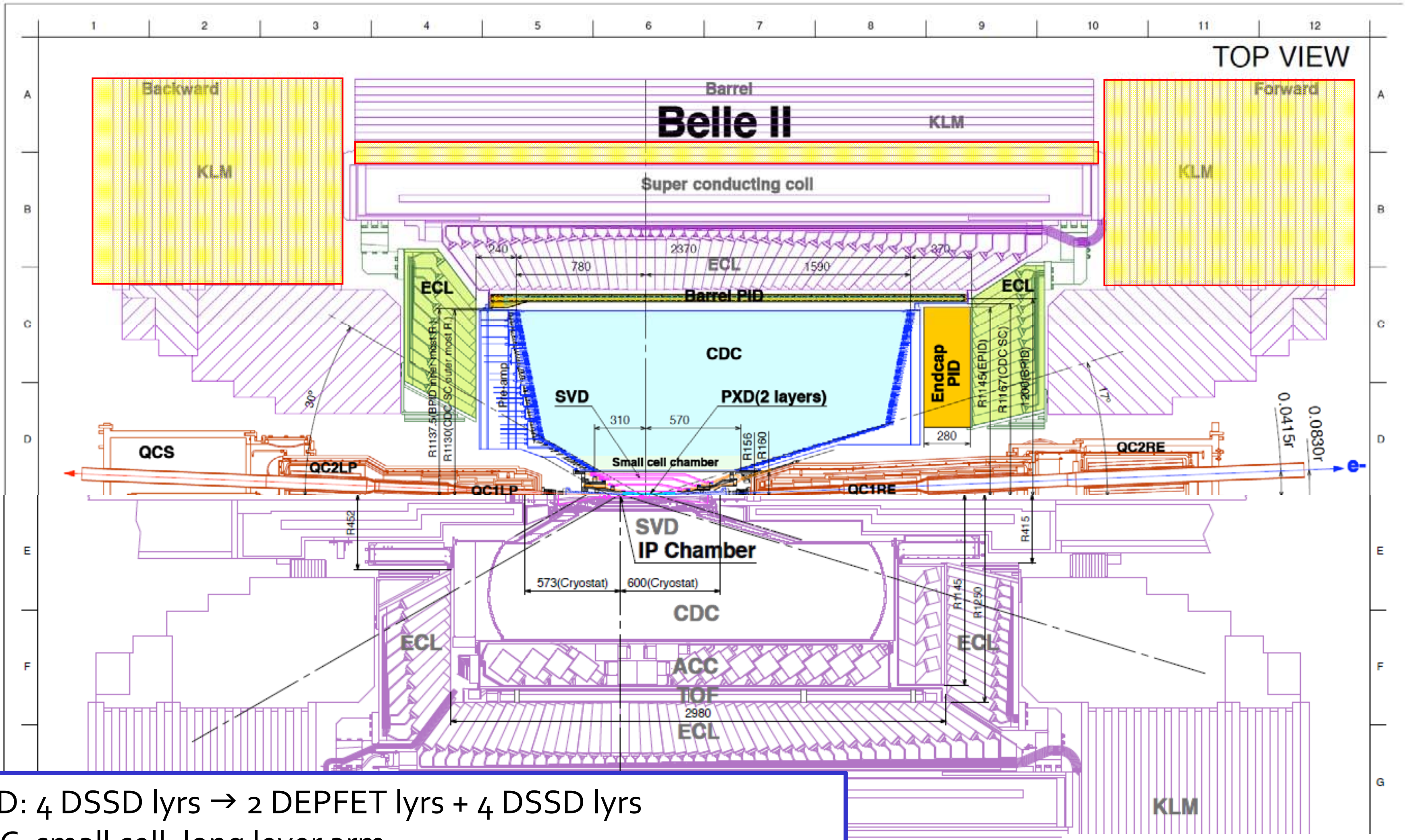
Solutions:
- Replace inner layers of the vertex detector with a pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace endcap calorimeter crystals
- Faster readout electronics and computing system.

Belle II TDR, arxiv:1011.0352v1[physics.ins-det]

Belle II Detector



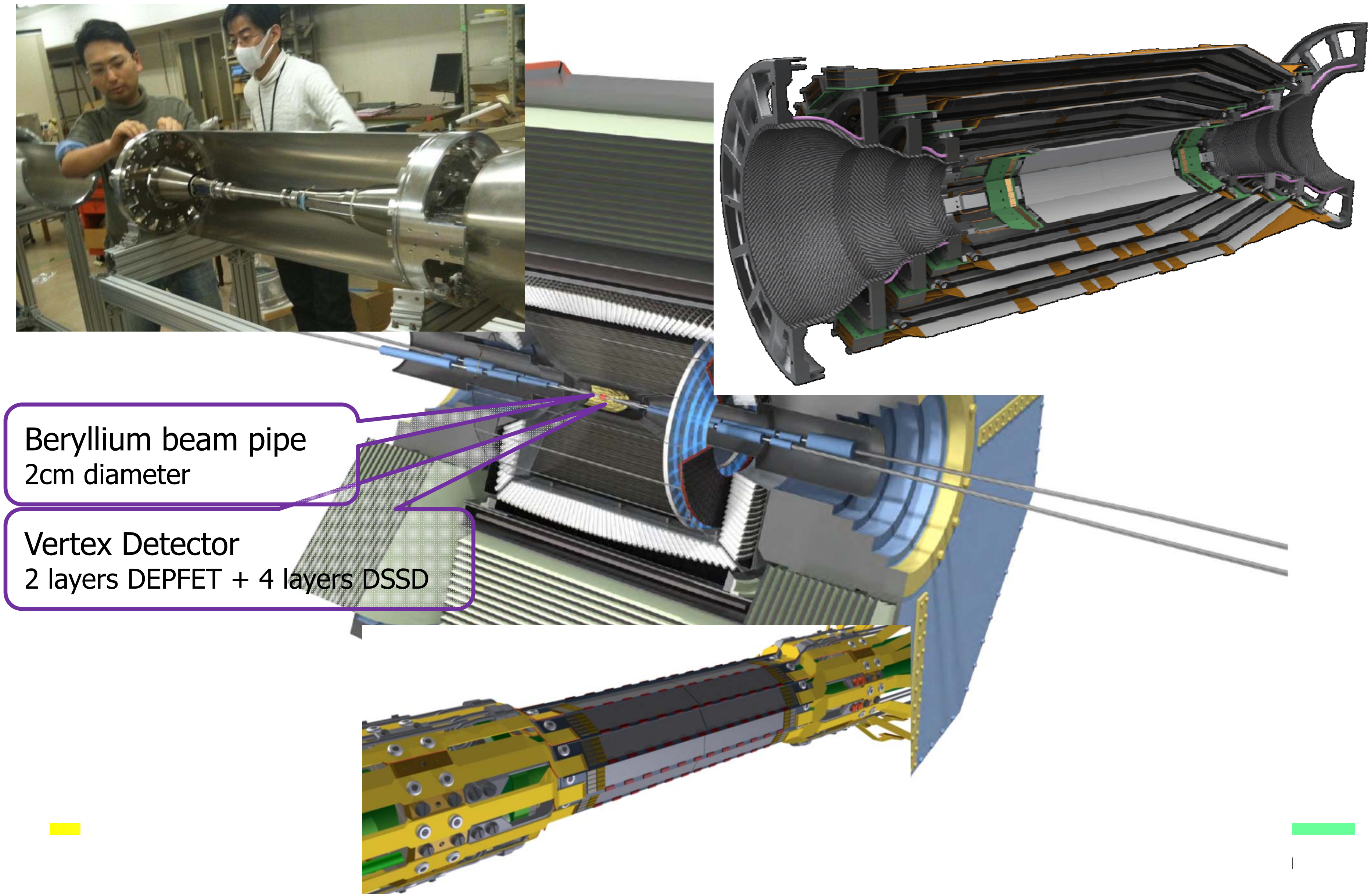
Belle II Detector (in comparison with Belle)



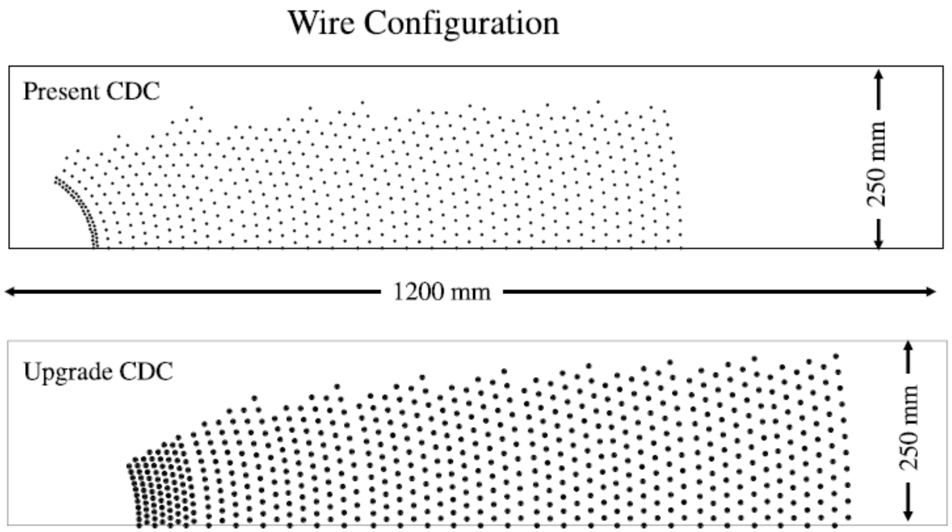
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

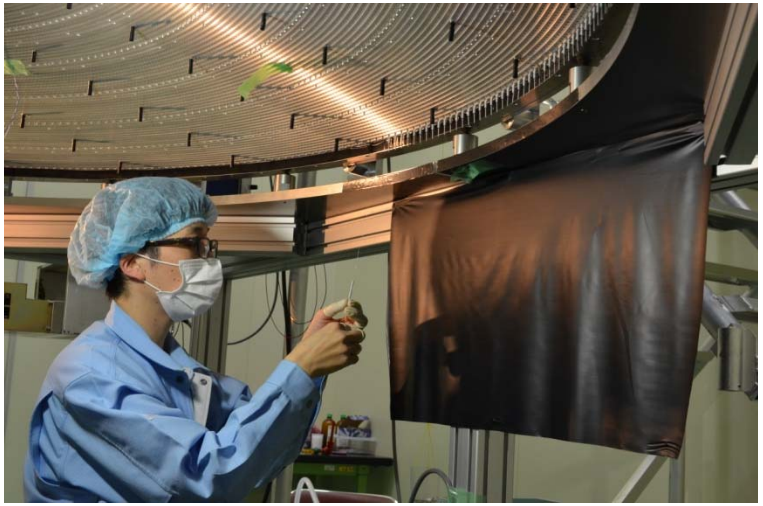
Belle II Detector – vertex region



Belle II CDC



Much bigger than in Belle!

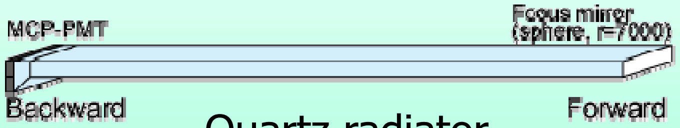


Wire stringing in a clean room

- thousands of wires,
- 1 year of work...

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



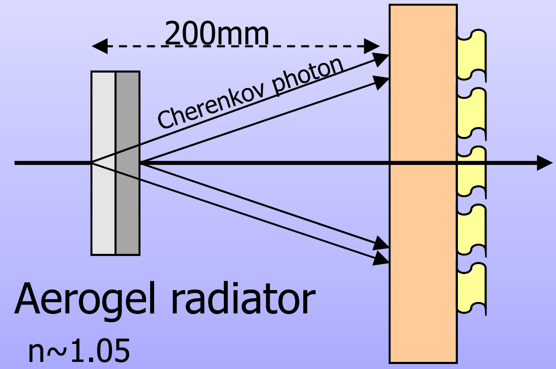
Quartz radiator

Focusing mirror

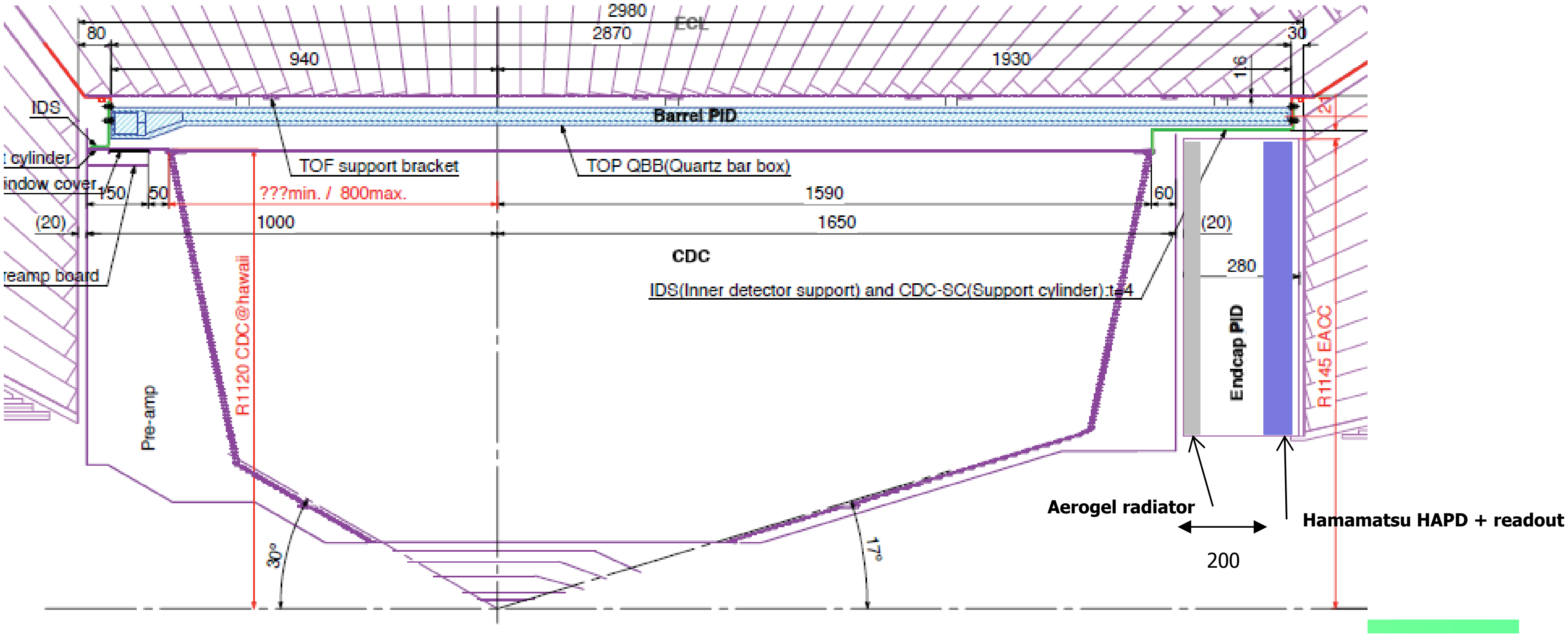
Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

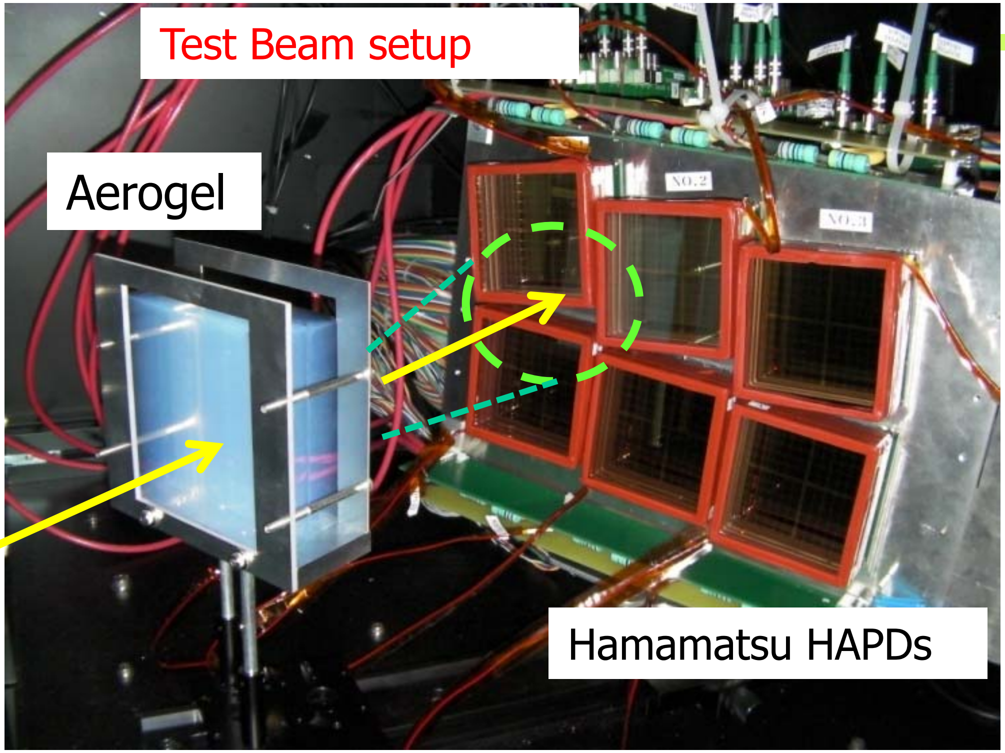
Endcap PID: Aerogel RICH (ARICH)

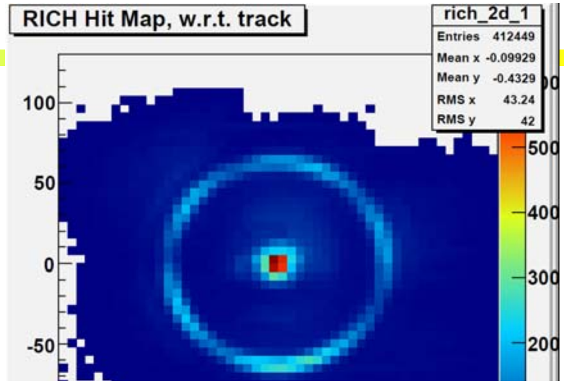


Hamamatsu HAPD



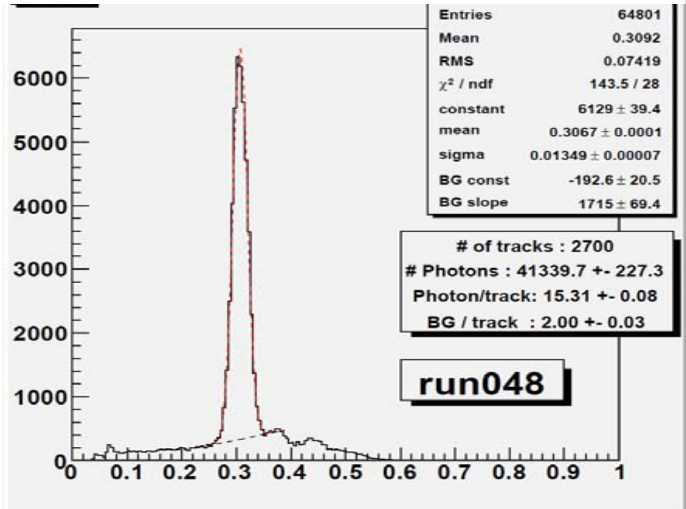
Aerogel RICH (endcap PID)





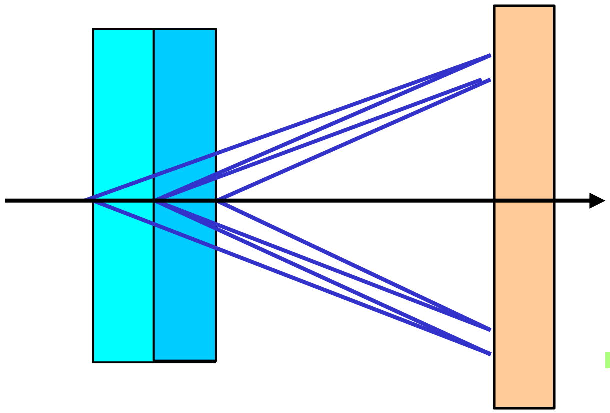
Clear Cherenkov image observed

Cherenkov angle distribution



RICH with a novel "focusing" radiator – a two layer radiator

Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.



6.6 σ π/K at 4GeV/c !

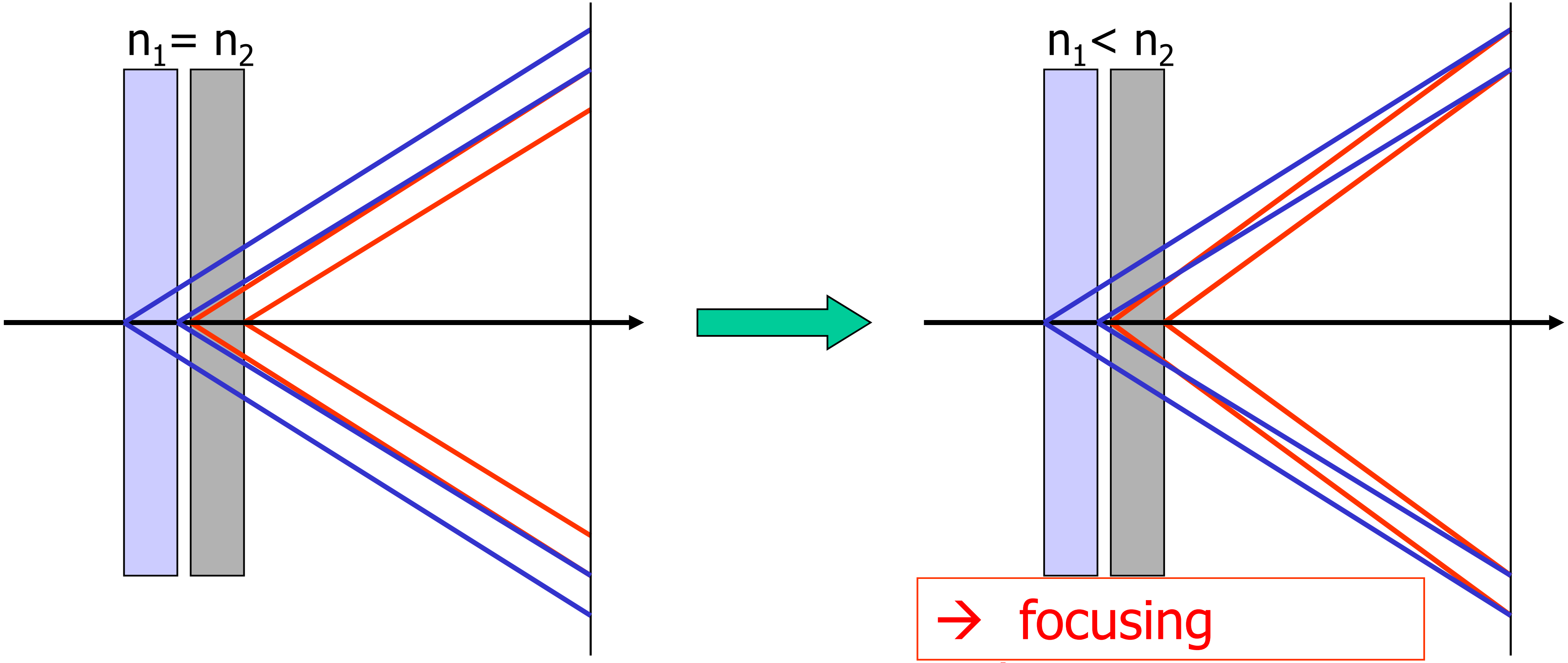
Peter Križan, Ljubljana

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

normal

→ stack two tiles with different refractive indices: "focusing" configuration



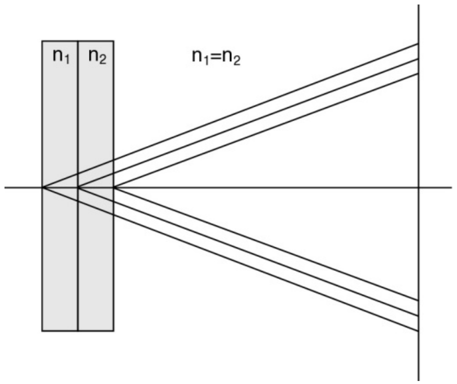
→ focusing

Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

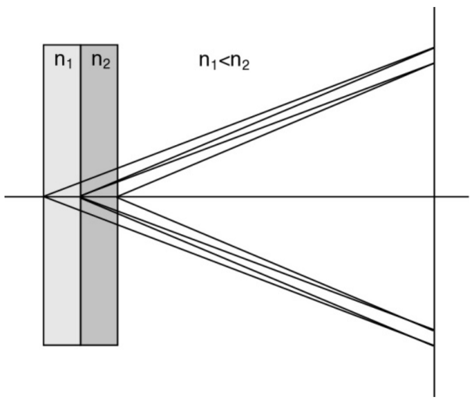
Focusing configuration – data

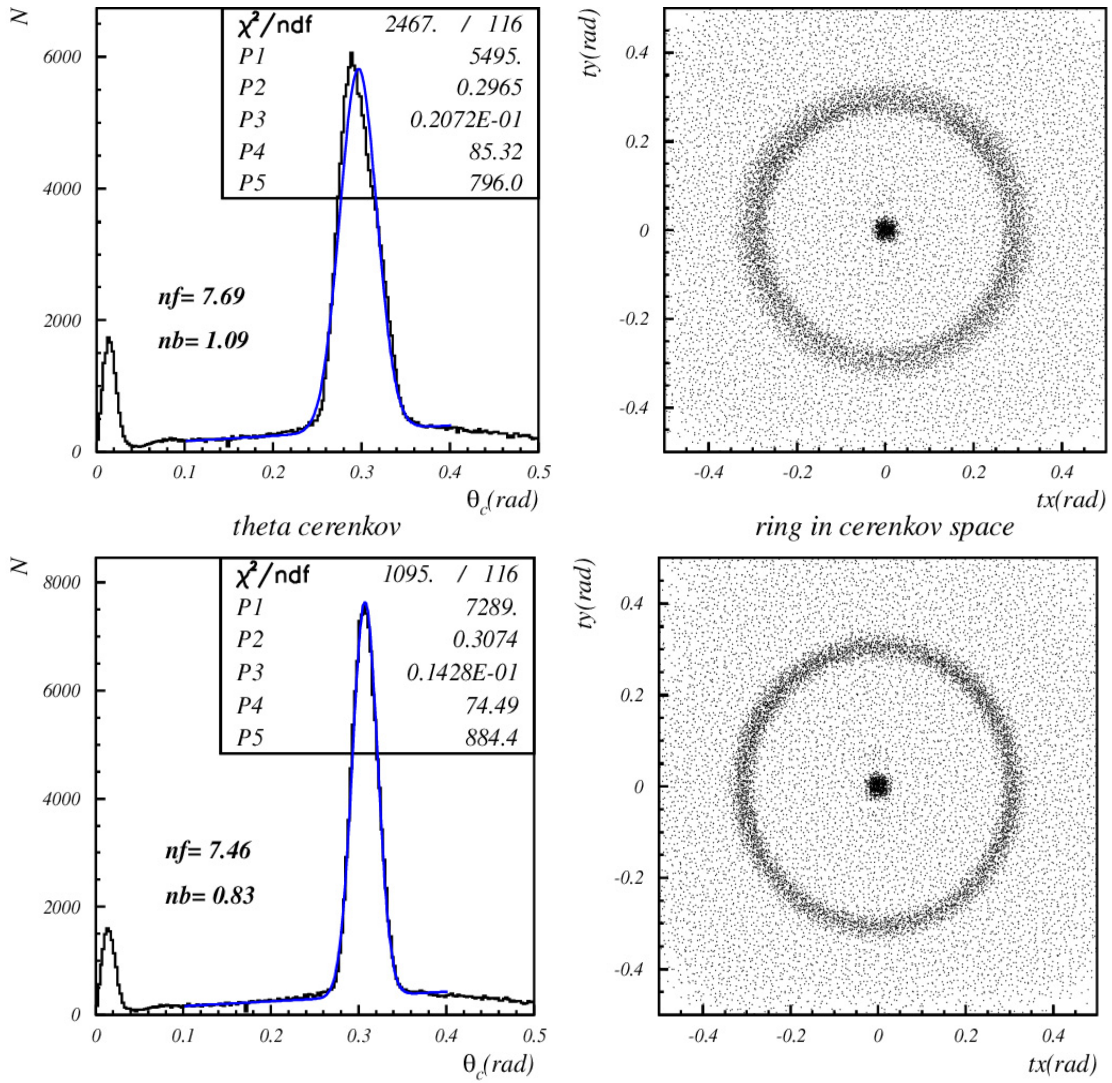
Increases the number of photons without degrading the resolution

4cm aerogel single index



2+2cm aerogel

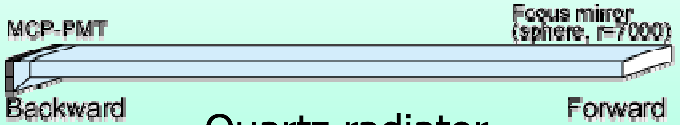




→NIM A548 (2005) 383

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



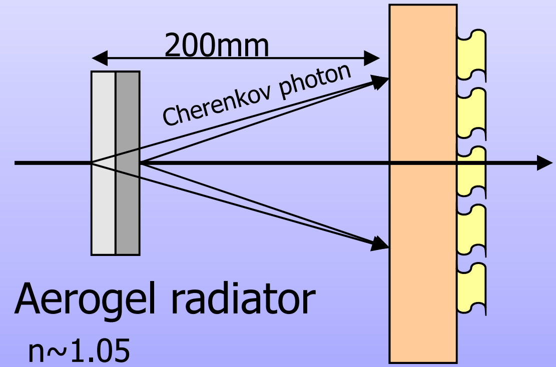
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

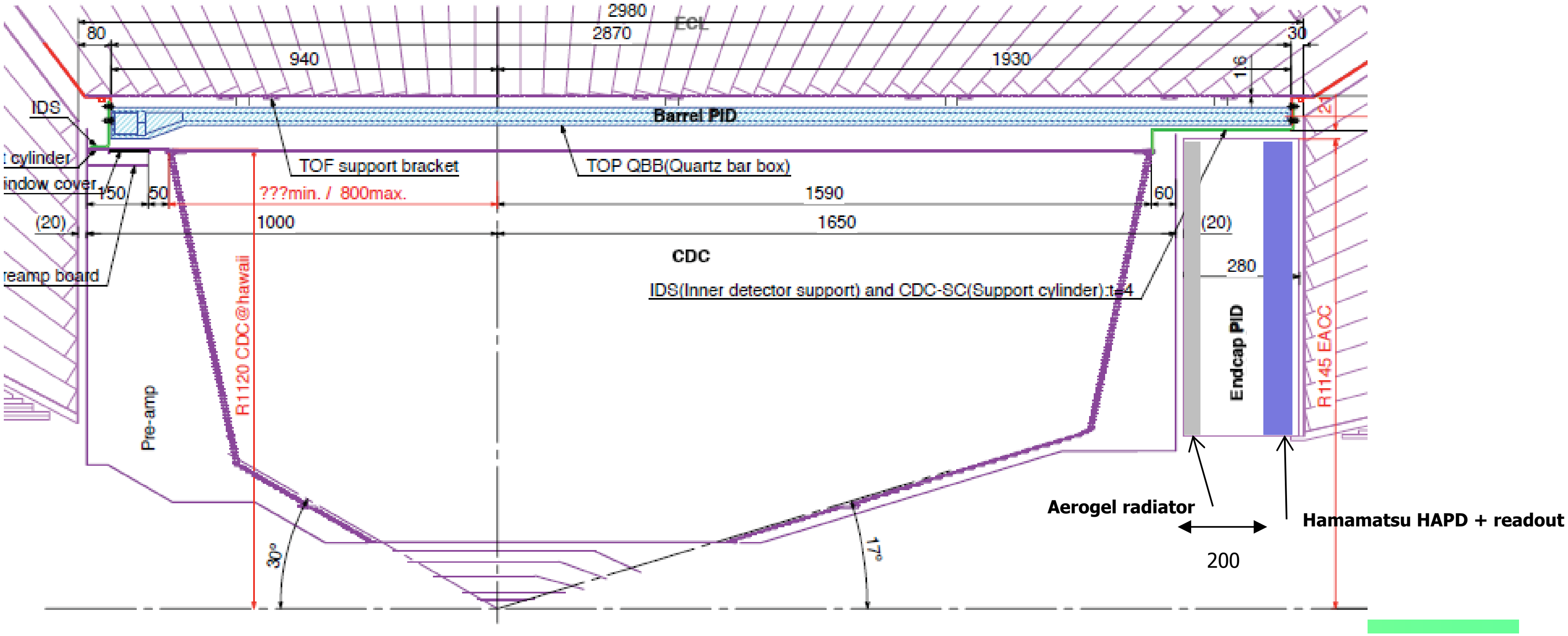


Aerogel radiator

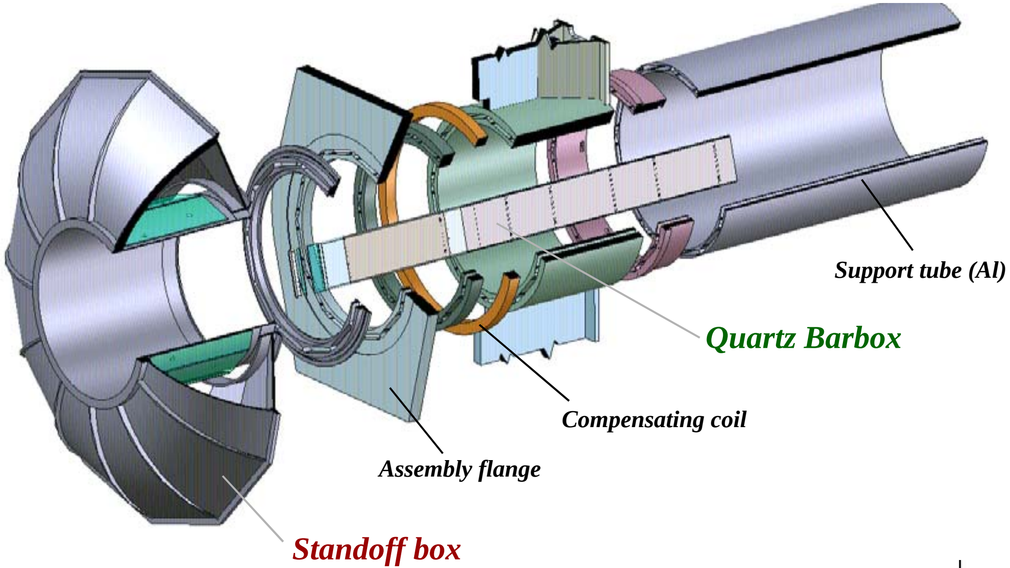
n~1.05

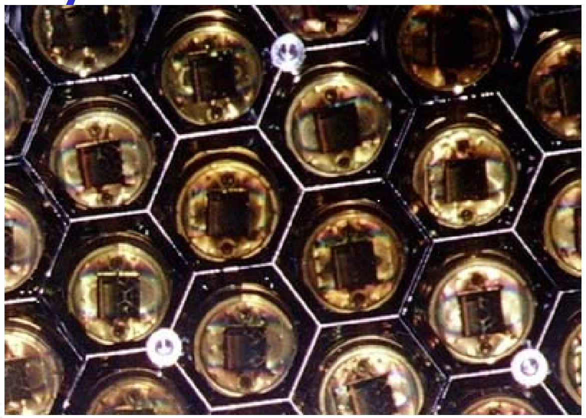
Hamamatsu HAPD

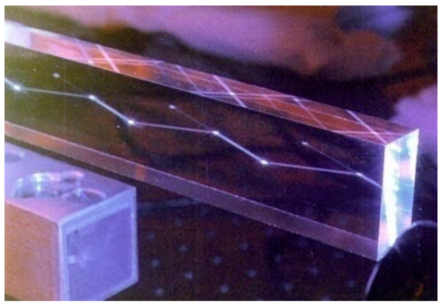
+ new ASIC

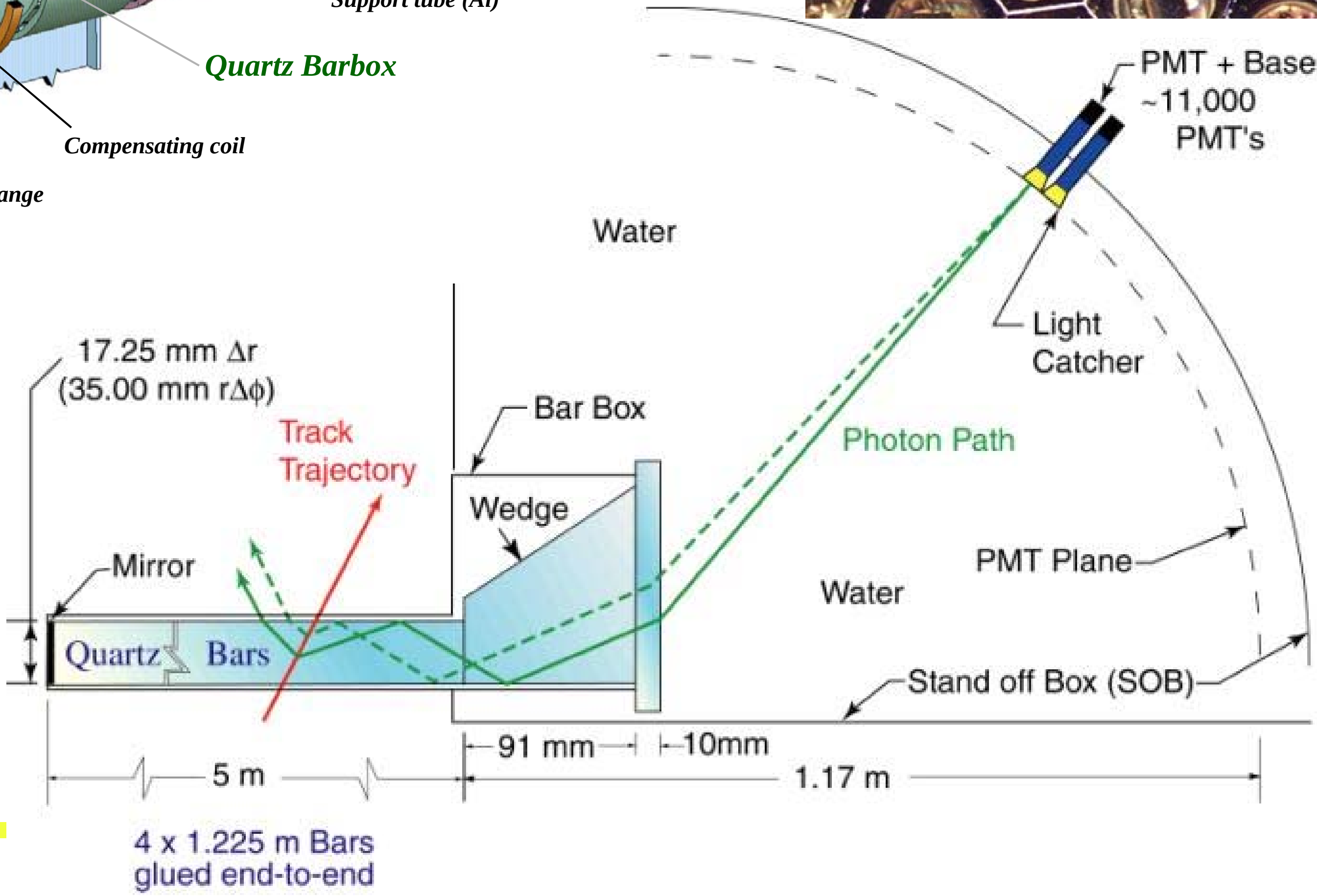


DIRC (@BaBar) - detector of internally reflected Cherenkov light

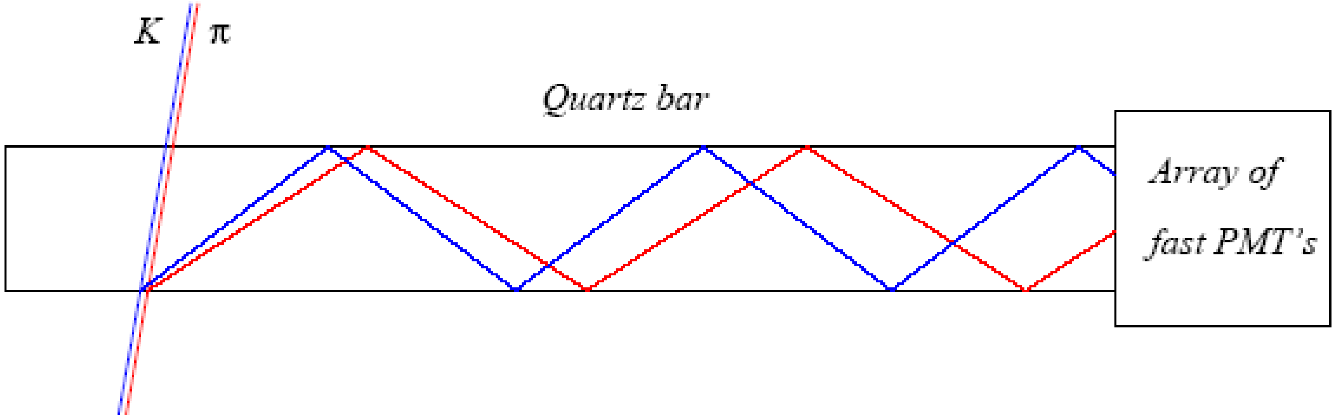


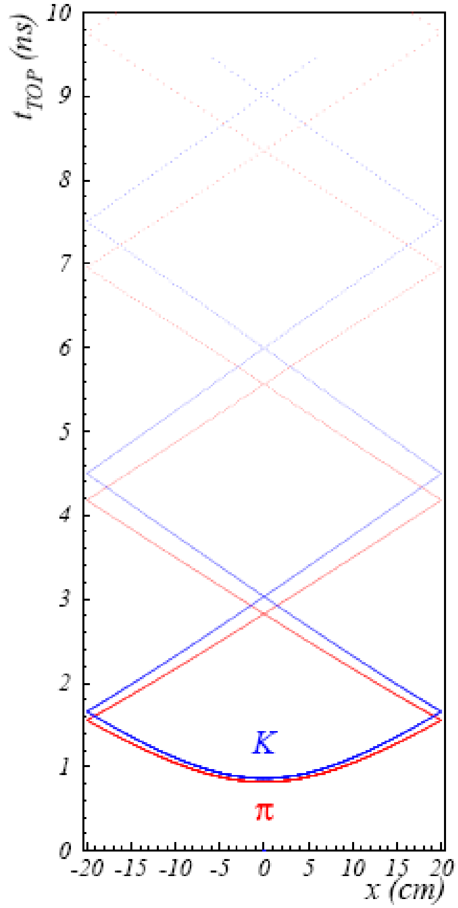






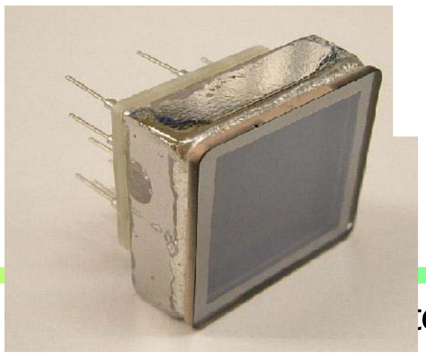
Belle II Barrel PID: Time of propagation (TOP) counter



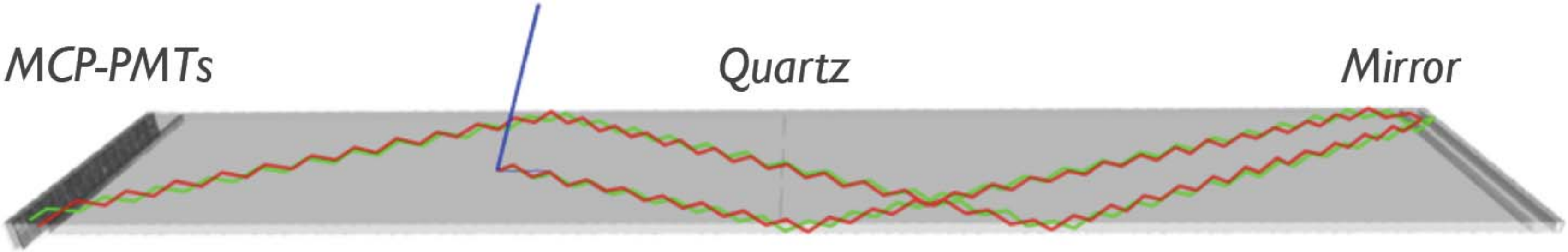


- Cherenkov ring imaging with precise time measurement.
- Uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and

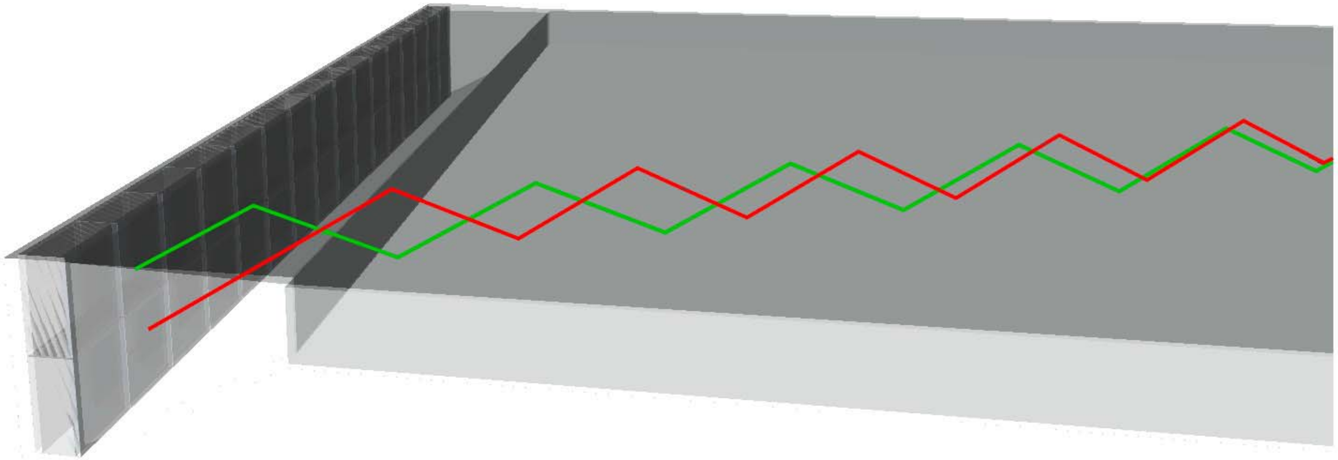
the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5



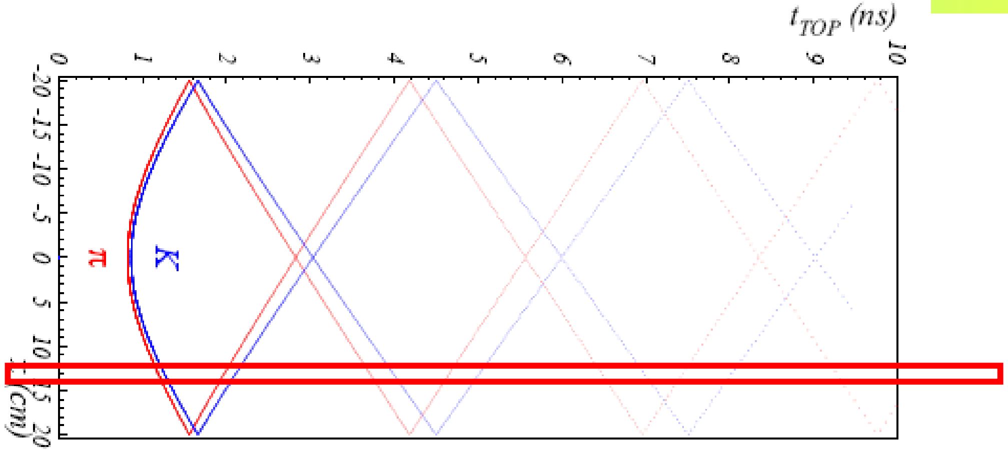
Barrel PID: Time of propagation (TOP) counter



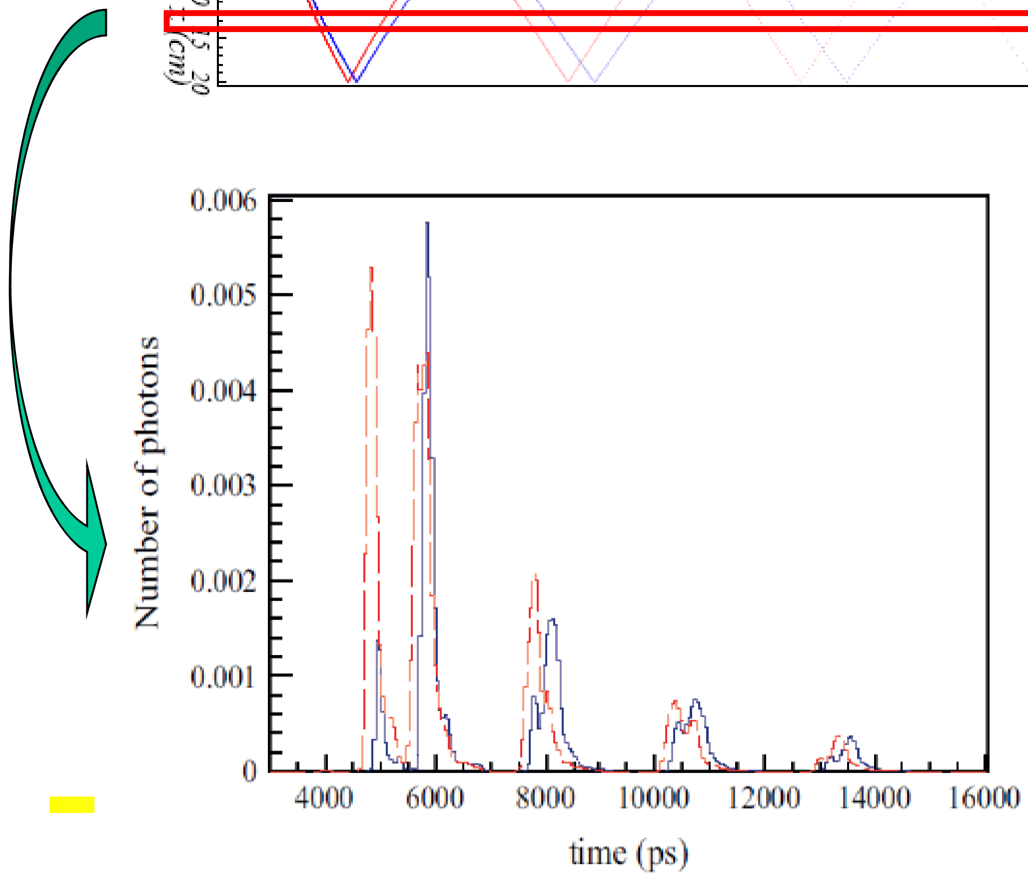
Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.



TOP image



Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels



Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

The Belle II Collaboration

A very strong group of ~600 highly motivated scientists!

SuperKEKB/Belle II Status

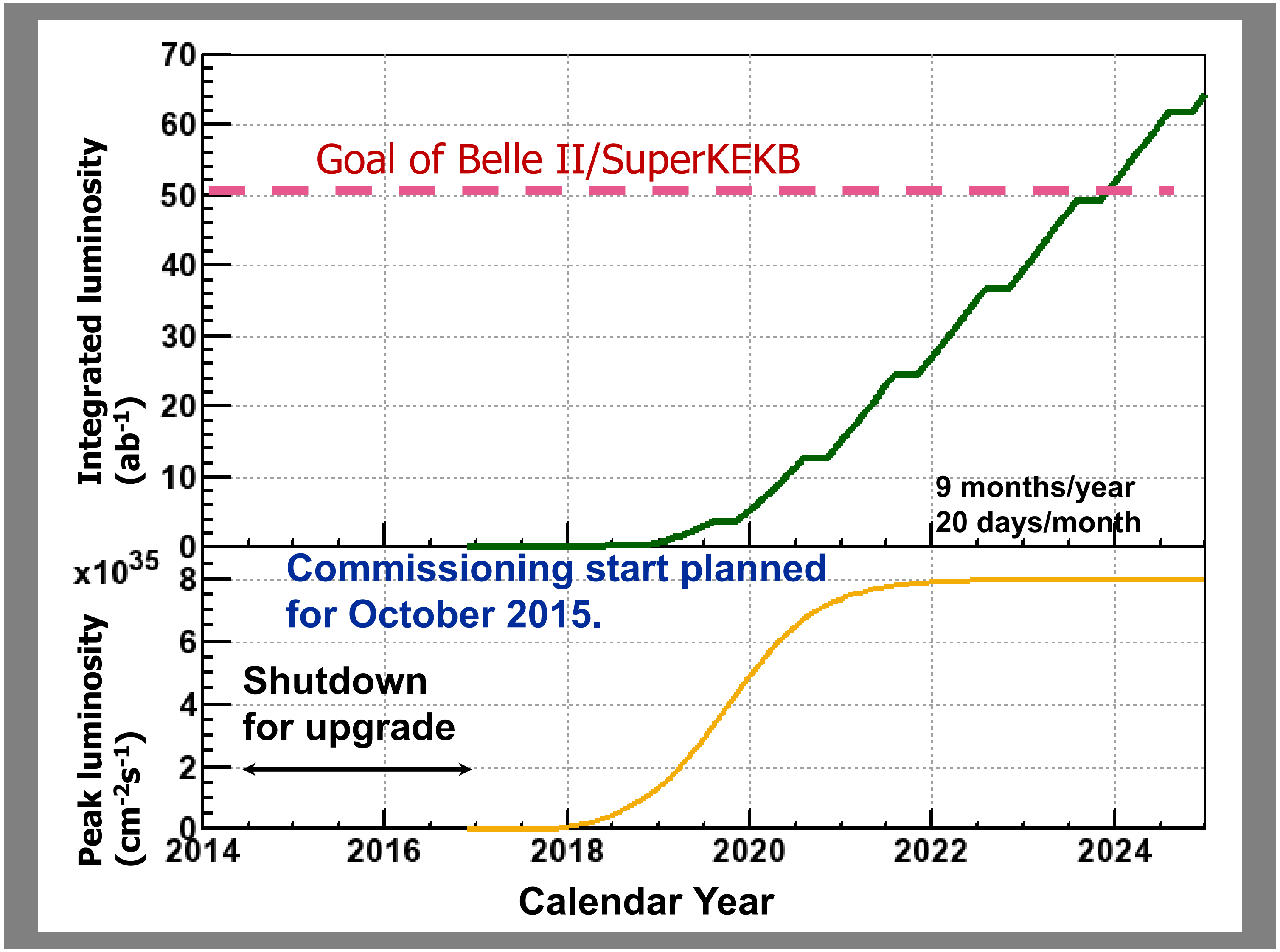
Funding

- ~100 MUS for machine approved in 2009 -- Very Advanced Research Support Program (FY2010-2012)
- Full approval by the Japanese government in December 2010; the project was finally in the JFY2011 budget as approved by the Japanese Diet in 2011
- Non-Japanese funding agencies have also allocated sizable funds for the upgrade of the detector.

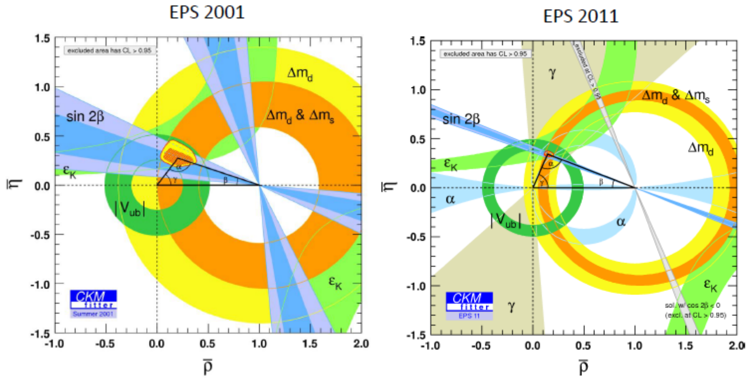
SuperKEKB and Belle II construction proceeding, nearly on schedule.

Commissioning start delayed 9 months from original plan, now scheduled for October 2015.

SuperKEKB luminosity projection



Summary



- B factories have proven to be an excellent tool for flavour physics, with reliable long term operation, constant improvement of the performance, achieving and surpassing design perfomance
- Super B factory at KEK under construction 2010-15 → SuperKEKB+Belle II, L x40, construction at full speed – the biggest particle physics project under preparation
- Expect a new, exciting era of discoveries, complementary to the LHC