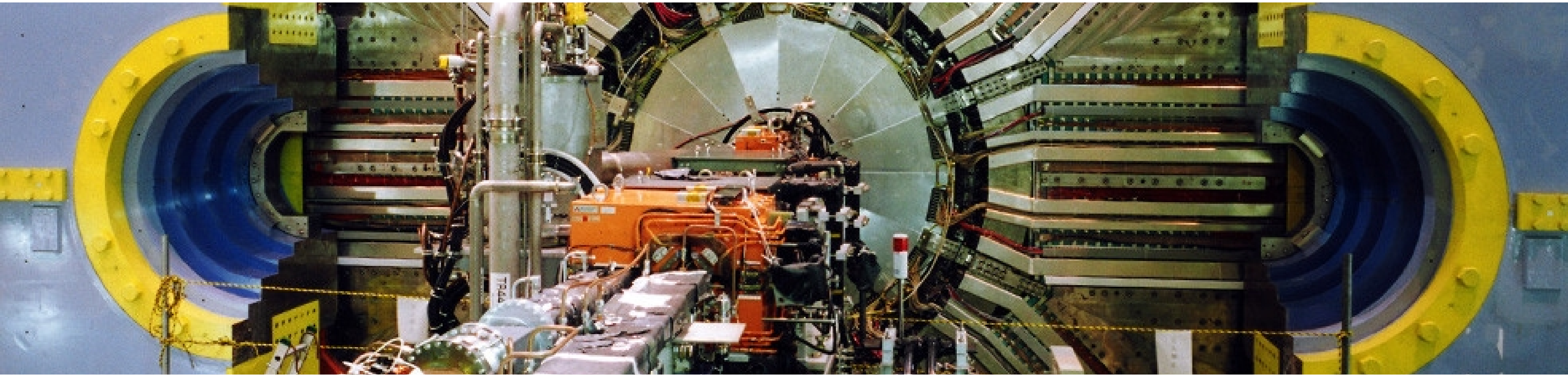
Flavour Physics (Experiment)



DESY Summer Student Lecture

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16.08.2013

Goals of this lecture

Get fascinated by and for flavour physics!

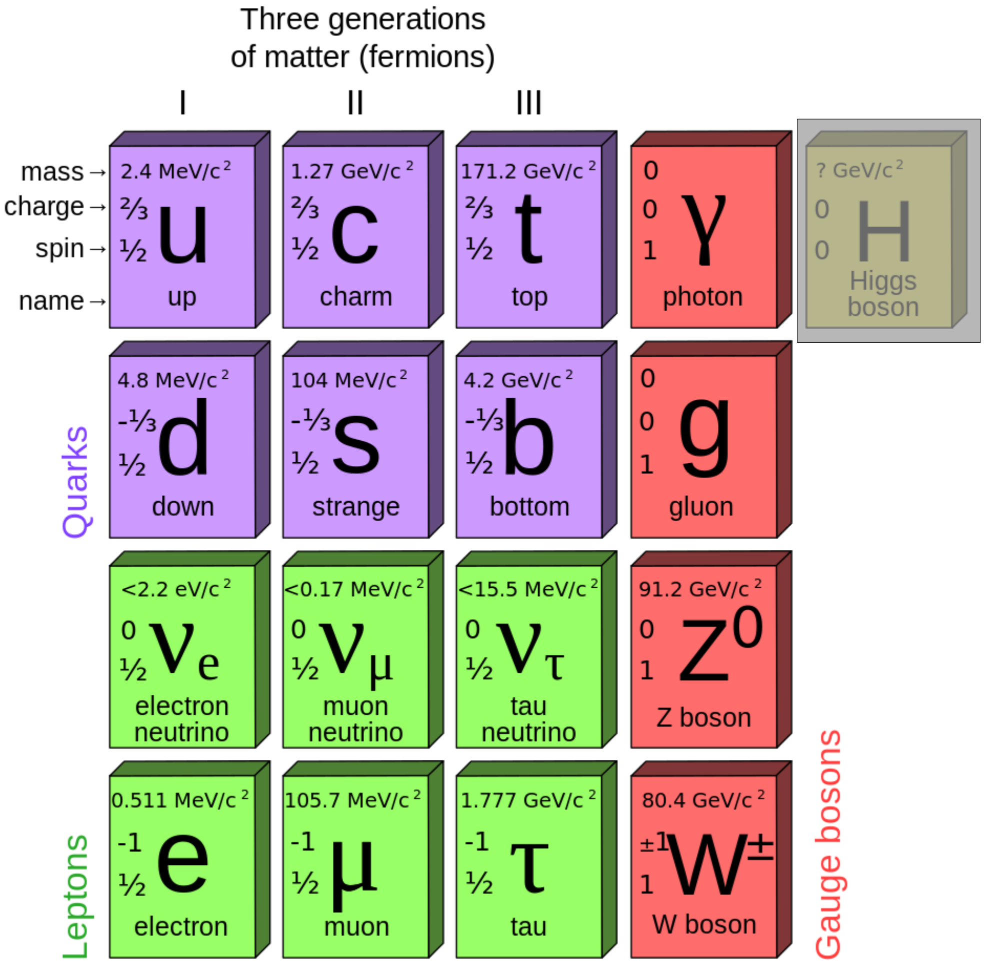
Disclaimer: This is not a review talk...

outline of this lecture

- Introduction
- Direct CP violation
- Time-dependent CP violation
- Flavour Tagging and the Belle experiment
- Other topics at flavour factories
- Future of flavour physics
- Summary

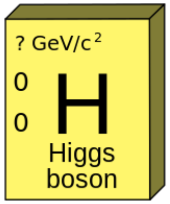
Introduction

A story of success: Standard Model (SM)



- 2 types of fermions (quarks and leptons)
- 3 generations
- 3 gauge interactions
- 4 gauge bosons
- 1 scalar

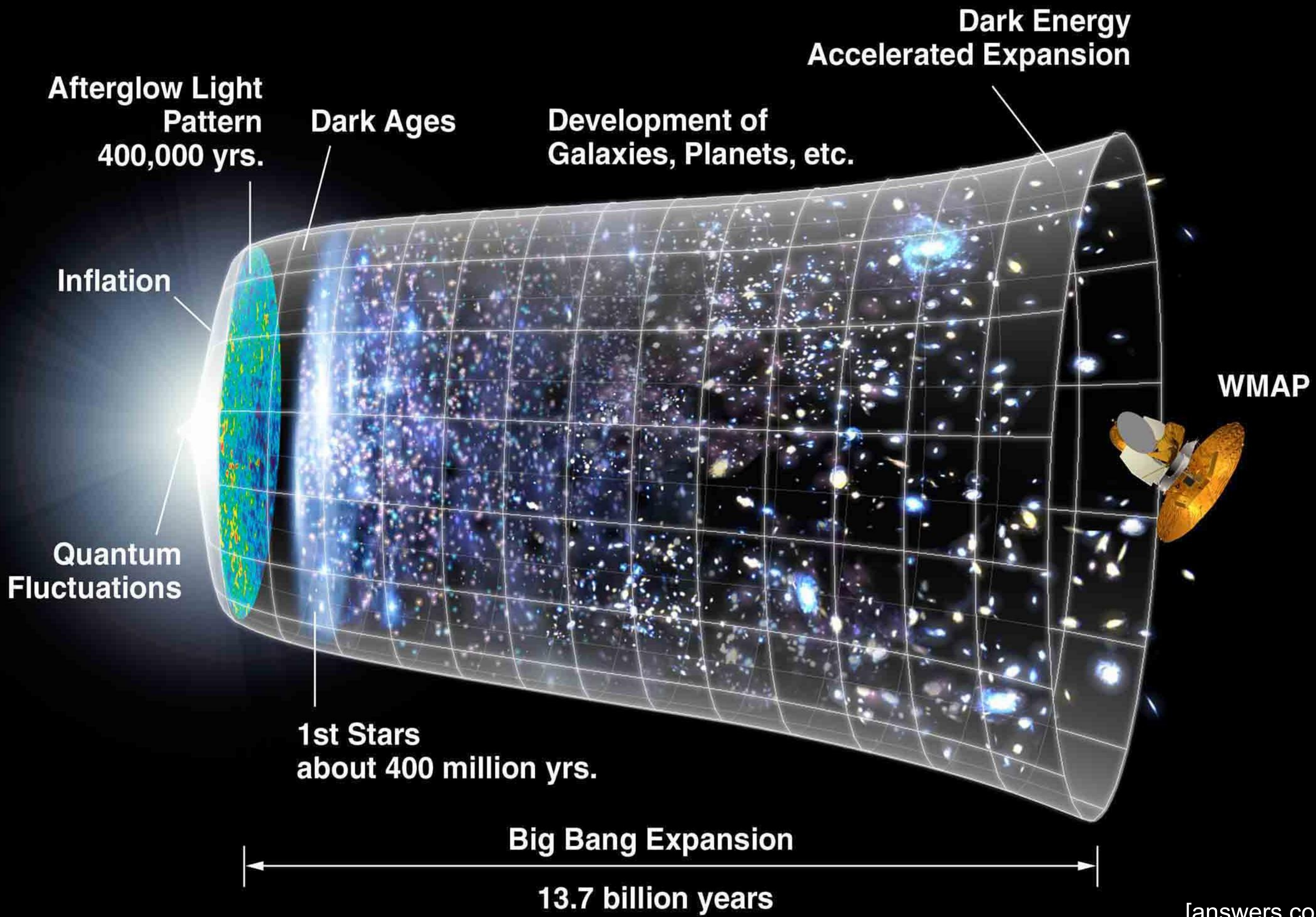
A story of success: Origin of mass in the SM



One of the fundamental question of the last decade(s):

- How do (fundamental) particles acquire mass?
  - SM: Higgs mechanism ↔ Higgs particle
  - Confirmed experimentally at LHC
- Why are the masses as they are?
  - Higgs mechanism gives no answer!
  - Understanding SM mass hierarchy requires new physics - we are sure that there is more: **new heavy particles?**

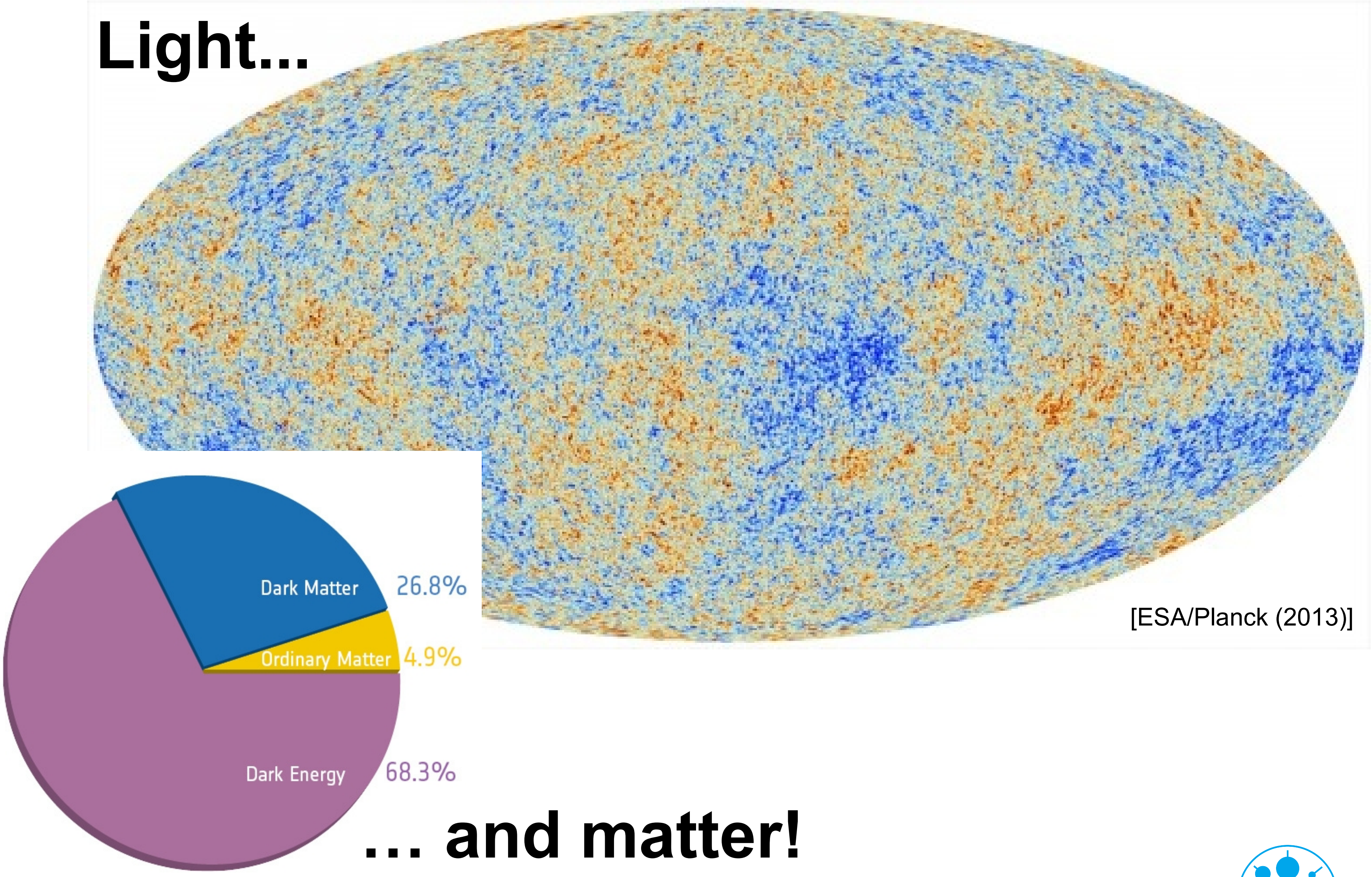
Where are we from?



[answers.com]

Where are we from: Light, matter, ...

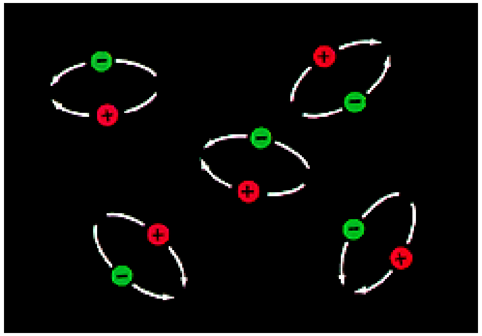
Light...



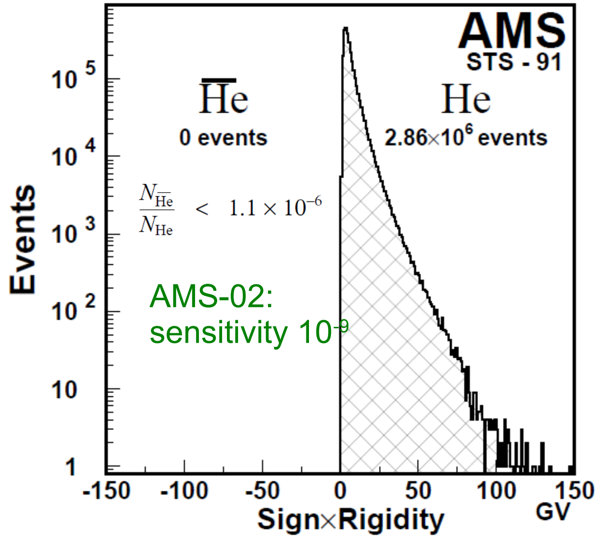
[ESA/Planck (2013)]

… and matter!

… and antimatter!



- matter + antimatter = photons
- in other words:
  the same amount of matter
  and antimatter is created. Always.
  - but wait...we are here...!
  - and we are matter... only matter...!



- Where is the antimatter?
  - no (sizeable) amount of antimatter in the universe
  - no annihilation radiation
  - no anti-nuclei in cosmic rays
- Some sort of mechanism favors matter!?!

… and antimatter!

- There is hope:
  matter + antimatter = photons + CP violation

Measured (Particle Data Group value):

$$\frac{n_{baryons} - n_{antibaryons}}{n_\gamma} \approx \frac{n_{baryons}}{n_\gamma} = (5.5 \pm 0.5) \times 10^{-10}$$

SM with maximal CP violation:

$$\frac{n_{baryons}}{n_\gamma} < 10^{-20}$$

- The Standard Model is great! But it cannot explain the key features of our universe:
  - Three generations of fermions
  - Fermion mass values
  - Gravity
  - Dark matter requires new particles
  - Dark energy is completely weird
  - CP-violation in the SM is much too small to explain matter/antimatter asymmetry in the universe
  - …
- Solving one of these issues will likely open the doors to the others...

some topics have to stay in a closed box today, sorry...

Why did you tell me that?

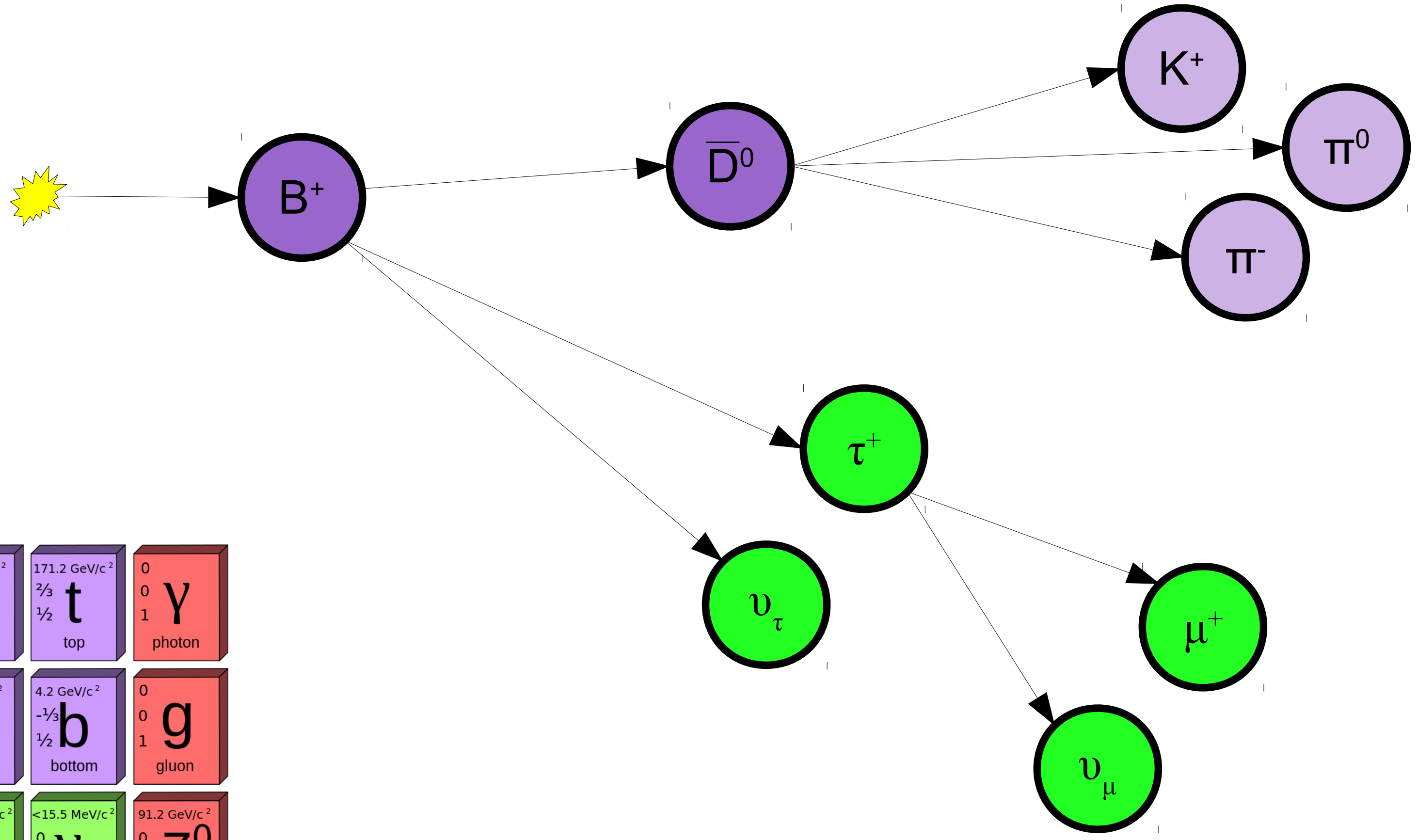
I thought this is a flavour physics lecture!

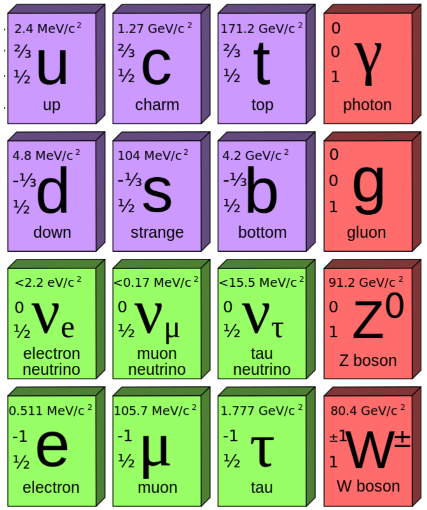
Why did you tell me that?

I thought this is a flavour physics lecture!

Because flavour physics is a lab-prototype of the entire universe - and a way to measure CP violation

Flavour physics is a prototype of the entire universe





2.4 MeV/c² ⅔ ½ u up	1.27 GeV/c² ⅔ ½ c charm	171.2 GeV/c² ⅔ ½ t top	0 0 1 γ photon
4.8 MeV/c² -⅓ ½ d down	104 MeV/c² -⅓ ½ s strange	4.2 GeV/c² -⅓ ½ b bottom	0 0 1 g gluon
<2.2 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<15.5 MeV/c² 0 ½ ν_τ tau neutrino	91.2 GeV/c² 0 1 Z^0 Z boson
0.511 MeV/c² -1 ½ e electron	105.7 MeV/c² -1 ½ μ muon	1.777 GeV/c² -1 ½ τ tau	80.4 GeV/c² ±1 1 $W^\pm$ W boson

What has that to do with flavour physics?

- How to search for CP violation (CPV)?

$$i \rightarrow f \neq \widetilde{i} \rightarrow \widetilde{f}$$

If CP is not violated, the two processes (for example), should have the same decay rate:

$$B^0 \rightarrow K^+\pi^- \qquad \overline{B}^0 \rightarrow K^-\pi^+$$

(*Spoiler alert!* In reality, the left process occurs about 13%(!!!!!!) more common than the right one...)

How to measure CP violation

- The amplitude for the process $i \to f$ is given by

$$\mathcal{M} = |\mathcal{M}| e^{i\phi} e^{i\theta} \qquad B^0 \to K^+ \pi^-$$

- The amplitude for the process $\widetilde{i} \to \widetilde{f}$ is given by:

$$\widetilde{\mathcal{M}} = |\mathcal{M}| e^{i\phi} e^{-i\theta} \qquad \overline{B}^0 \to K^- \pi^+$$

- The difference between the two matrix elements is subtile:
  - θ is a complex CKM phase ("weak phase")
  - Φ is an ordinary phase ("strong phase" → no CP violation in strong interactions observed yet)

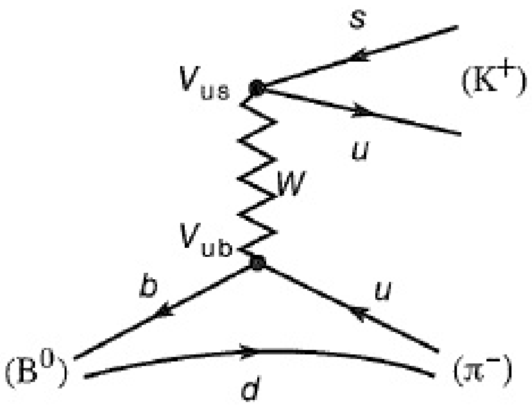
    → $\mathcal{M}$ and $\widetilde{\mathcal{M}}$ are equal, except the CKM matrix elements get conjugated...

How to measure CP violation

- But: Even if θ is complex, there is no CP violation, since the probability is proportional to the respective matrix element squared $|\mathcal{M}|^2 = |\widetilde{\mathcal{M}}|^2$
- Huh? Why are the decay rates for B^0 and $\overline{B^0}$ different by 13%?

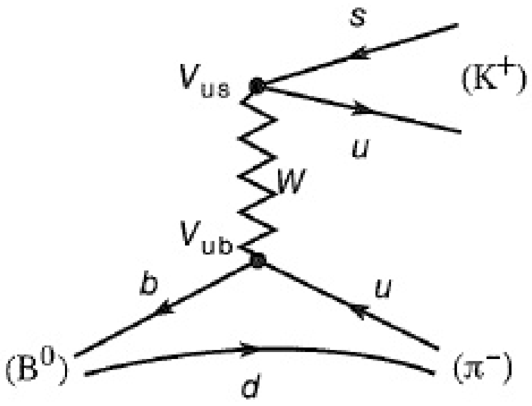
Please draw the Feynman diagram for the decay $B^0 \rightarrow K^+\pi^-$

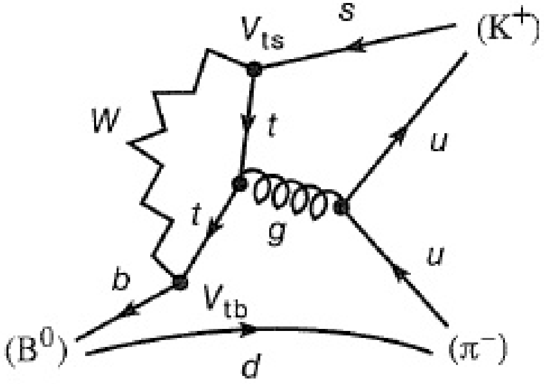
Draw the Feynman diagram(s)



Draw the Feynman diagram(s)

diagrams from [Griffiths]

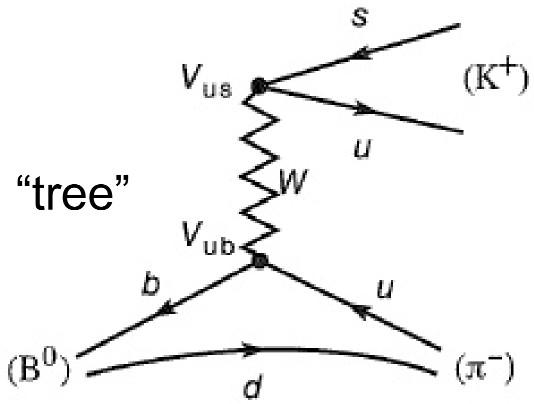




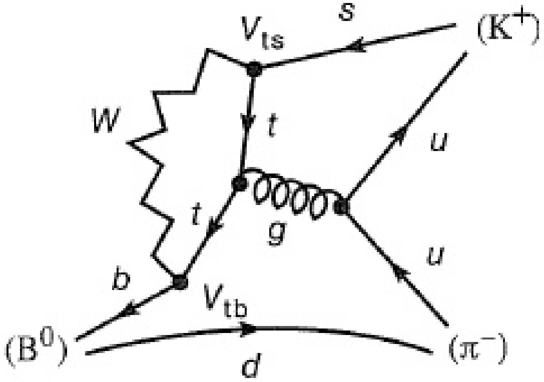
Draw the Feynman diagram(s)

diagrams from [Griffiths]

“tree”



“pinguin”



There are two routes to the same final state!

$$\mathcal{M}_1 = |\mathcal{M}_1| e^{i\phi_1} e^{i\theta_1} \qquad \mathcal{M}_2 = |\mathcal{M}_2| e^{i\phi_2} e^{i\theta_2}$$

$$\widetilde{\mathcal{M}}_1 = |\widetilde{\mathcal{M}}_1| e^{i\phi_1} e^{-i\theta_1} \qquad \widetilde{\mathcal{M}}_2 = |\widetilde{\mathcal{M}}_2| e^{i\phi_2} e^{-i\theta_2}$$

$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2$$

$$|\mathcal{M}|^2 = |\mathcal{M}_1 + \mathcal{M}_2|^2 \neq |\mathcal{M}_1|^2 + |\mathcal{M}_2|^2$$

(analogue for CP conjugated)

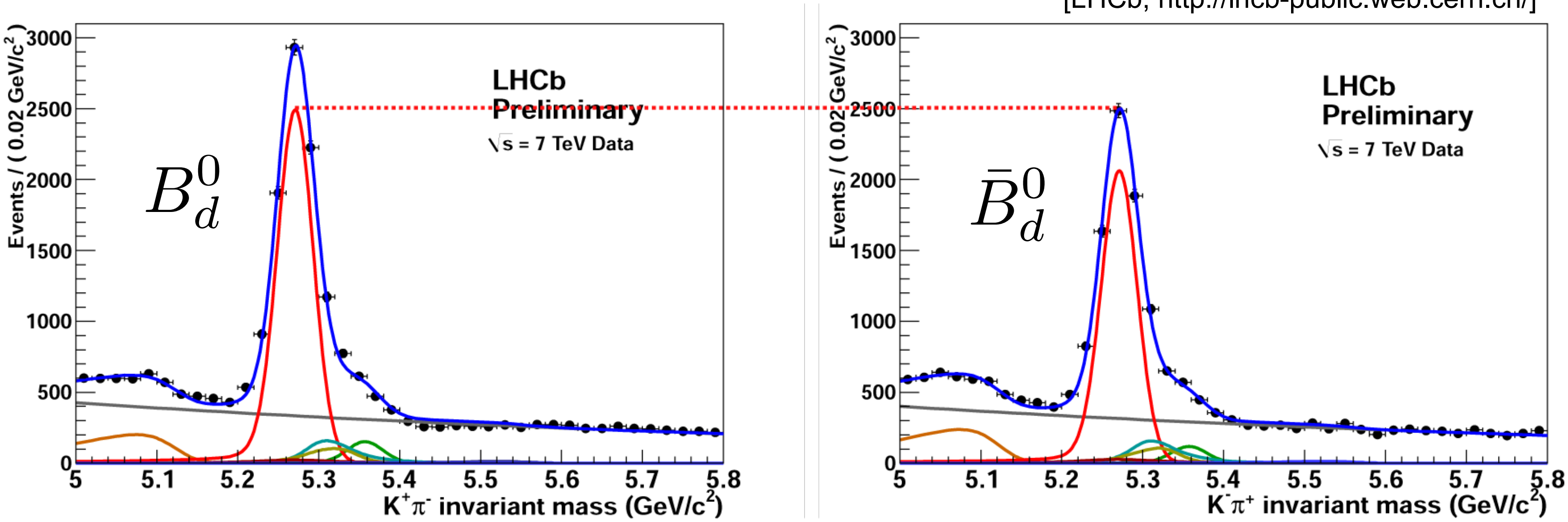
after some math (Yes, you can all do it!) and using $e^{ix}=\cos(x)+i*\sin(x)$:

$$|\mathcal{M}|^2 - |\widetilde{\mathcal{M}}|^2 = -4|\mathcal{M}_1||\mathcal{M}_2|\sin(\phi_1 - \phi_2)\sin(\theta_1 - \theta_2)$$

- Now, the rates are different, CP is violated!?
- Necessary conditions:
  - two (or more) ways to the same final state
  - a conjugated phase (different for the two ways!)
  - an ordinary phase (also different for the two ways!)

CPV by eye (CPV in decays, “direct CPV”)

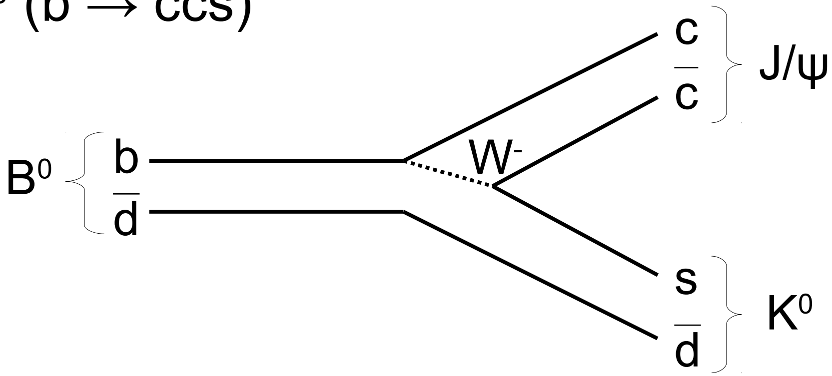
[LHCb, http://lhcb-public.web.cern.ch/]



(look at the red curves only)

CP violation at flavour factories

- Experimentally, there is a cleaner way to measure CP violation in the B system:
  - select a final state, which is a CP eigenstate, a very famous one is J/ψ+K⁰ ($b \to c\bar{c}s$)



CP violation at flavour factories

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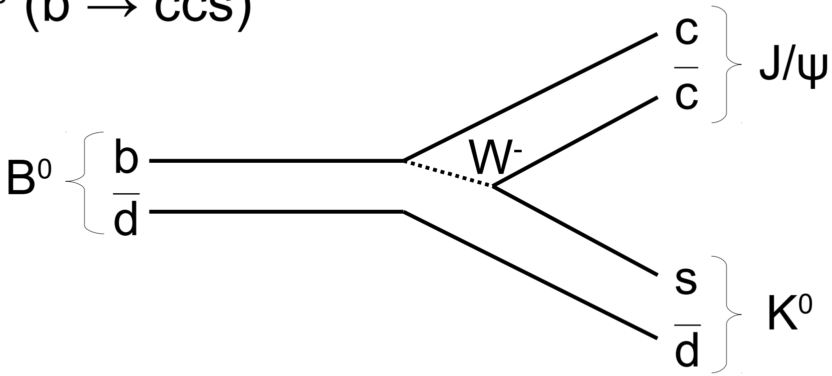
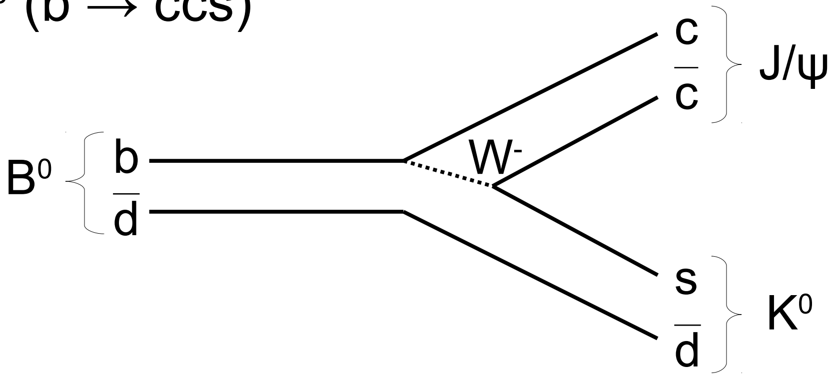


Remember:
We need a different way to the same final state...
(i.e. we need “interference”)

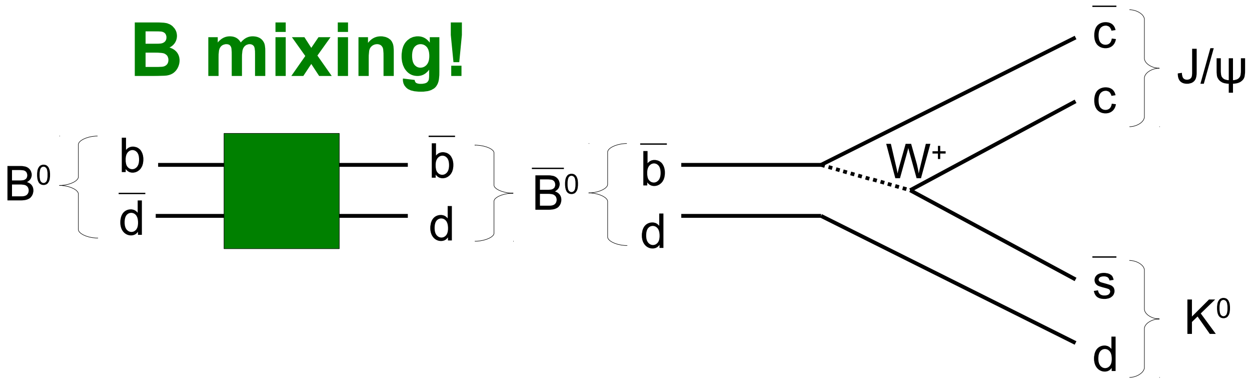
CP violation at flavour factories

- Experimentally, there is a cleaner way to measure CP violation in the B system:
  - select a final state, which is a **CP eigenstate**, a very famous one is $J/\psi+K^0$ ($b \rightarrow c\bar{c}s$)



A1

B mixing!



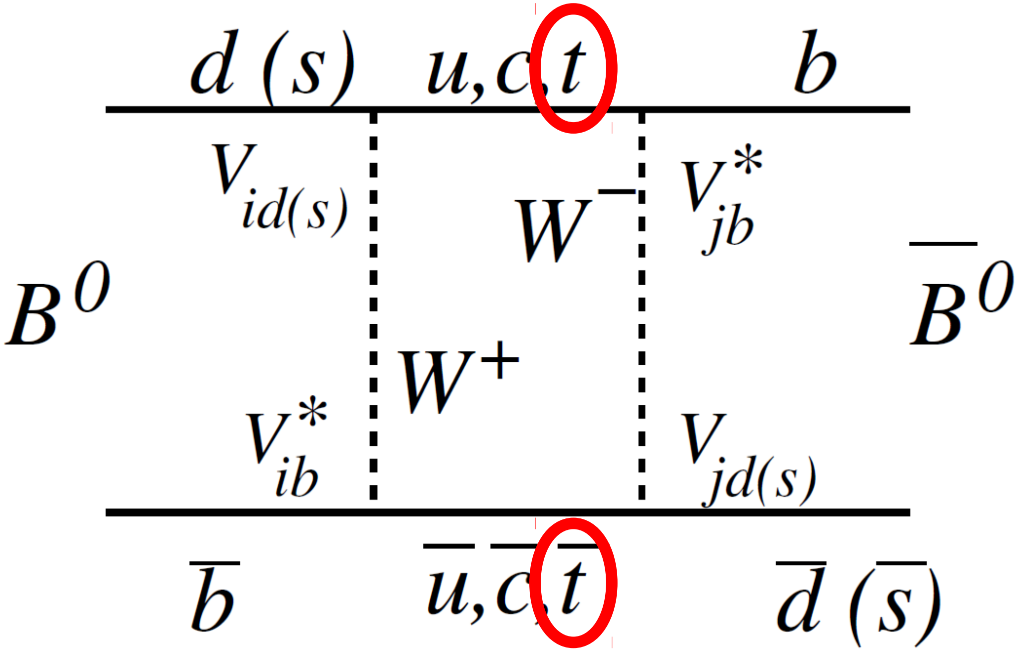
A2

B mixing

Indirect influence of the top quark - and/or all other heavy, not yet discovered, particles!

B mixing!

🟩 =



(and u,c,t ($\overline{u}$,$\overline{c}$,$\overline{t}$) interchanged by W)

B mixing

- time evolution of a QM state:

$$\left|X(t)\right\rangle = e^{-iHt}\left|X(0)\right\rangle = e^{\left(-i\Re\{H\}+\Im\{H\}\right)t}\left|X(0)\right\rangle$$

- most general Hamiltonian (X is a state):

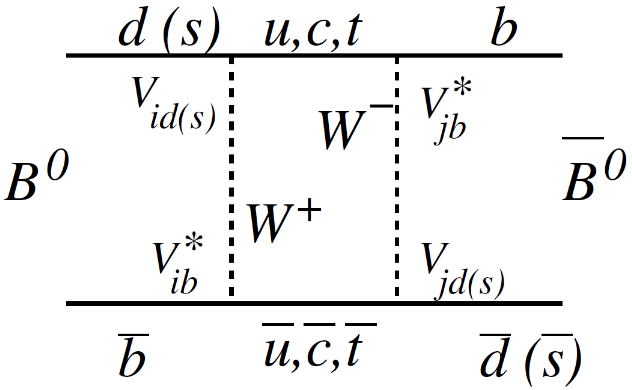
$$H\left|X\right\rangle = i\frac{d}{dt}\left|X\right\rangle = \left(M_X - \frac{i}{2}\Gamma_X\right)\left|X\right\rangle$$

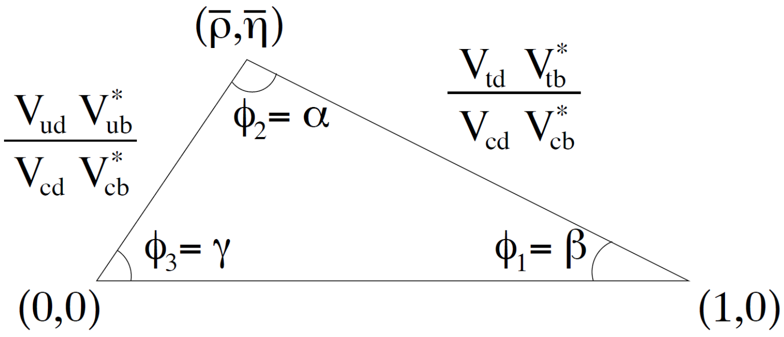
$$i\frac{d}{dt}\begin{pmatrix}\left|B_q^0(t)\right\rangle \\ \left|\overline{B}_q^0(t)\right\rangle\end{pmatrix} = \left(\underline{\underline{M_q}} - \frac{i}{2}\underline{\underline{\Gamma_q}}\right)\begin{pmatrix}\left|B_q^0(t)\right\rangle \\ \left|\overline{B}_q^0(t)\right\rangle\end{pmatrix}$$

B mixing

- $B \to J/\psi\, K^0$ and $\overline{B} \to J/\psi\, K^0$ have a different time dependence (instead of a strong phase)

- The phase of the mixed process A2 depends mostly on V_{td} → **measure CP violation and Φ_1**



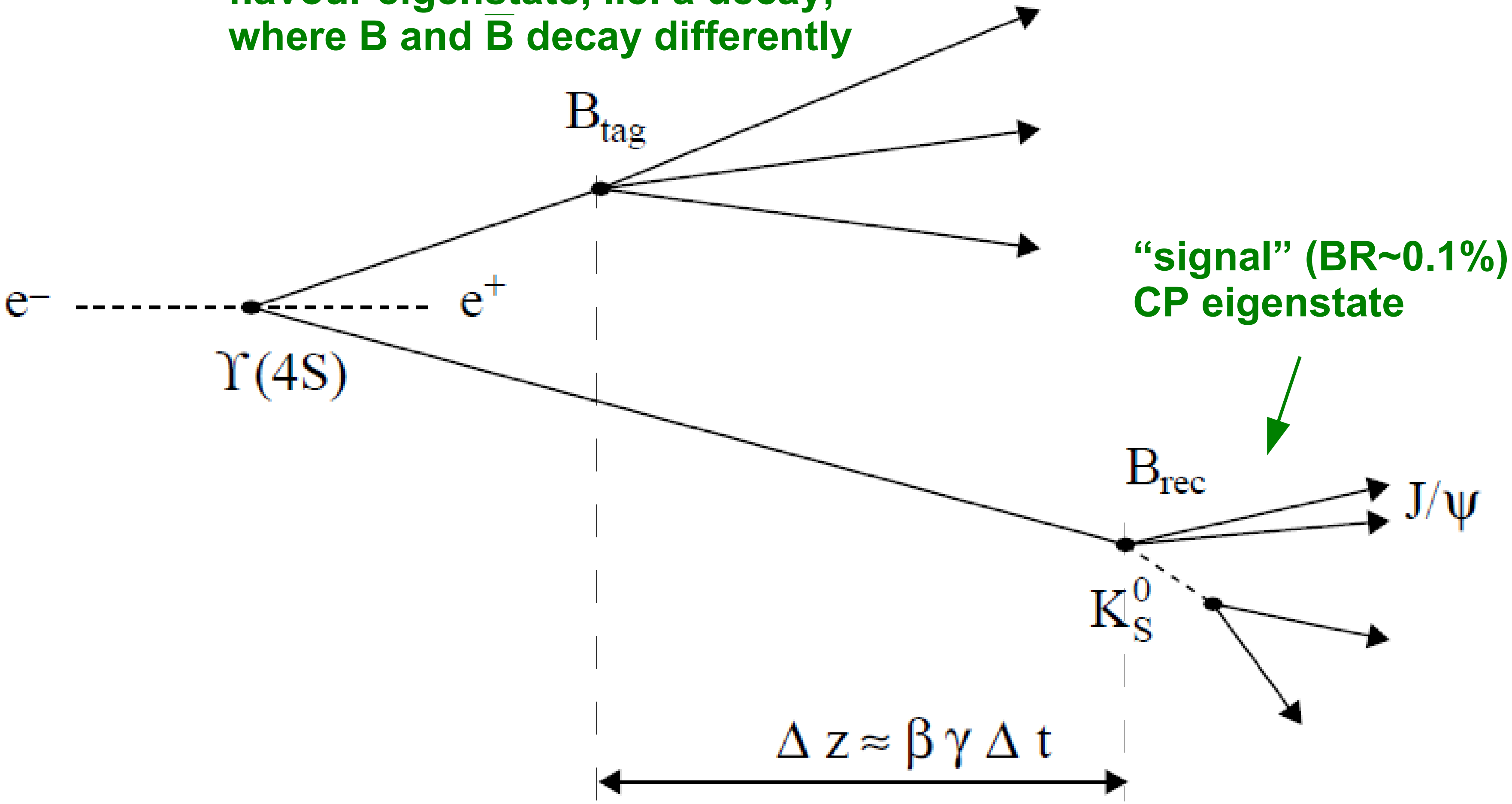


The flavour factory way

- How to measure this quantity the **flavour factory** way:
  - collide electrons and positrons to produce a Υ(4S) resonance ($b\bar{b}$)
  - Υ(4S) always decays into $B^0\bar{B}^0$ or B^+B^- (BR ~50% each)
  - The two B's are in coherent state: As long as the flavour is not measured (i.e. as long as it is not determined which B contains the $\bar{b}$ and which the b), either both or none of the B's mix - this is indistinguishable!
  - As soon as the flavour of one B is determined, the other's flavour is known - and it mixes...

- Huh? Sounds strange... lets look at a picture!

tag and signal



“tag” (BR ~80%)
flavour eigenstate, i.e. a decay, where B and $\overline{\text{B}}$ decay differently

“signal” (BR~0.1%)
CP eigenstate

- time measurement starts, if the first B decay is measured
- Δt is expressed relative to the flavour tagged B, i.e. Δt is negative if the CP eigenstate decay is the first

SM ($b \to c\bar{c}s$)

$$\boxed{\mathcal{S}_f = -\xi_f \sin 2\phi_1}$$

q=+1 (B^0)
q=-1 ($\bar{B}^0$)

ξ_f=+1 (CP odd)
ξ_f=-1 (CP even)

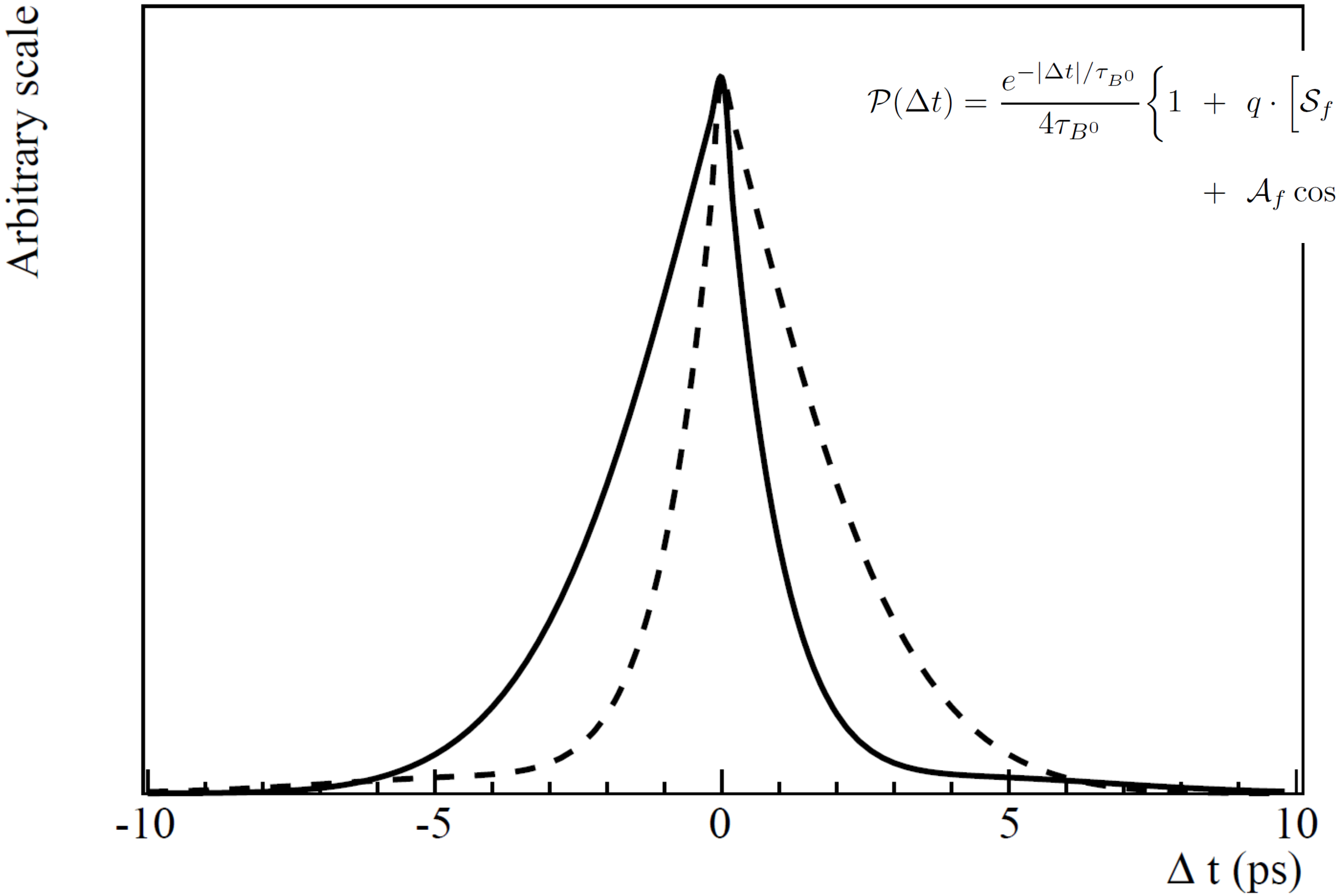
decay rate:

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 \; + \; q \cdot \Big[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t) \Big] \Big\}.$$

SM ($b \to c\bar{c}s$)

$$\boxed{\mathcal{A}_f = 0}$$

Perfect time resolution, perfect tagging

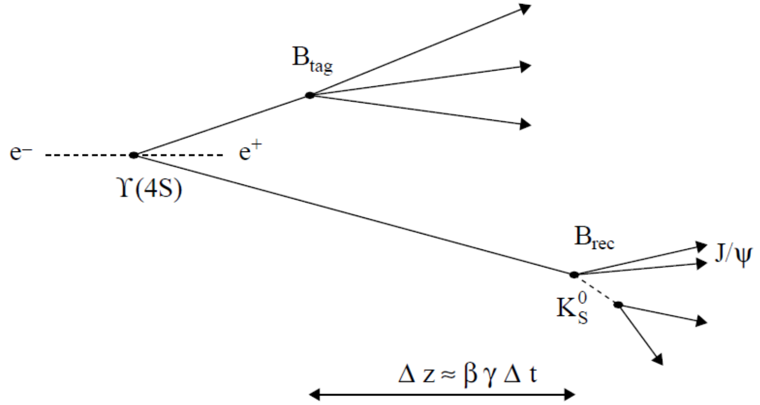


$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 \;+\; q\cdot\Big[\mathcal{S}_f \sin(\Delta m_d \Delta t) \;+\; \mathcal{A}_f \cos(\Delta m_d \Delta t)\Big]\Big\}.$$

Phys. Rev. Lett. 108, 171802 (2012)

I did not mention an important detail:

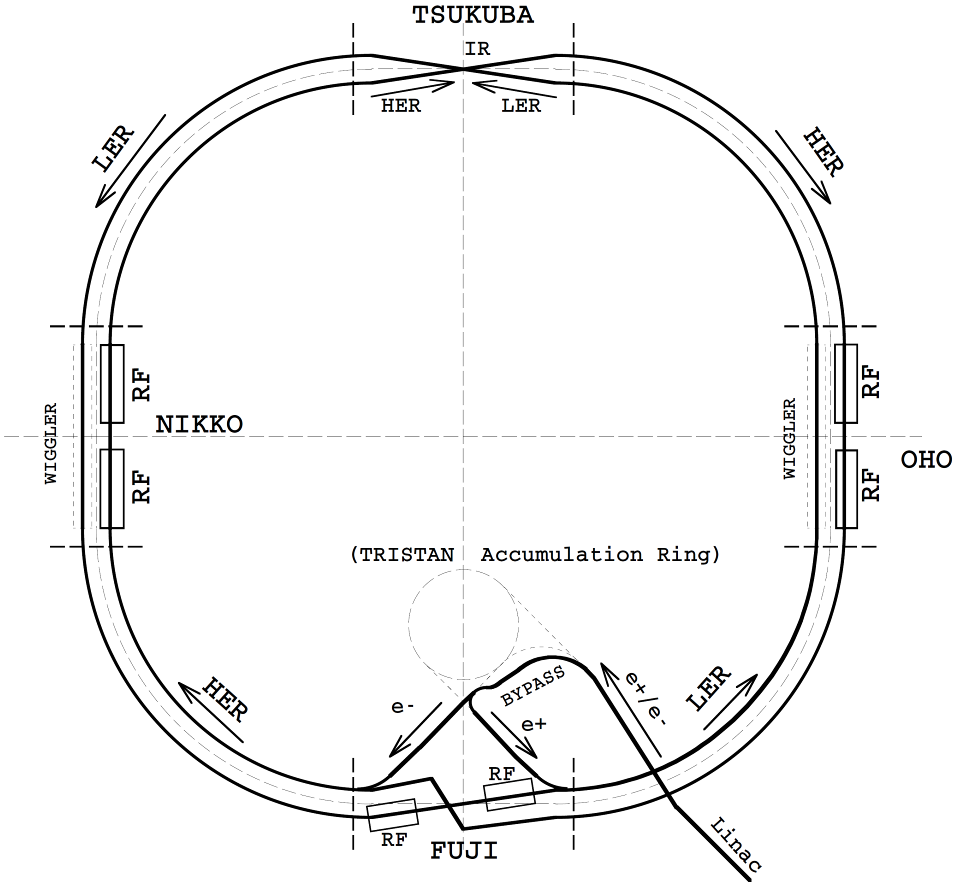
How to produce an Y(4S):
What collider, what energies...?



The Belle experiment at KEKB

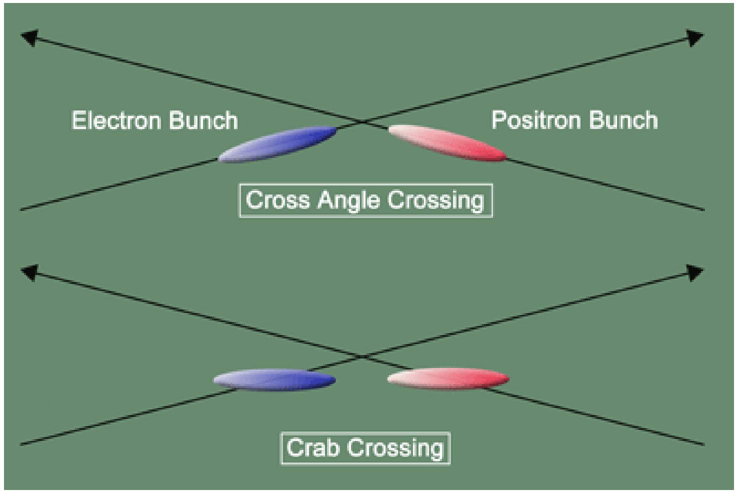
- Belle is a so-called flavour factory at the KEK accelerator in Japan (similar: BaBar at SLAC)
- 1999-2010
- KEKB:
  - 3.1km circumfence
  - crossing angle 11mrad
  - electrons (8 GeV) positrons (3.5 GeV) → βγ=0.425
  - Luminosity (final): ~2x10^{34}/cm^2/s

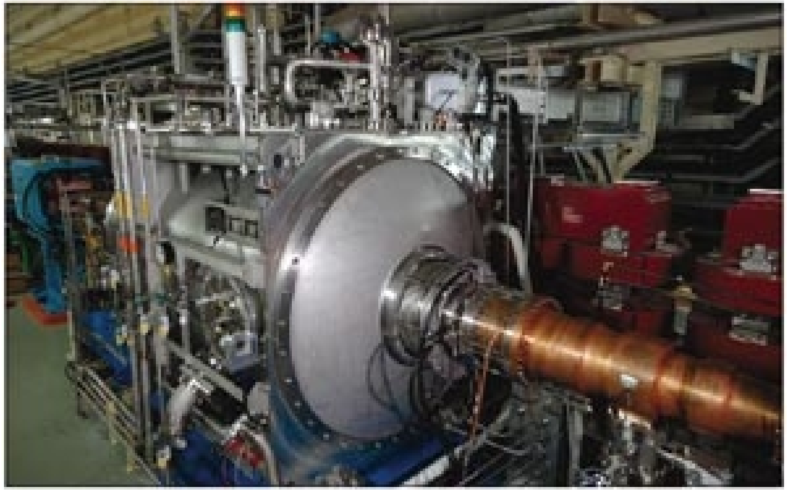
world record for colliders!
(twice the design value)



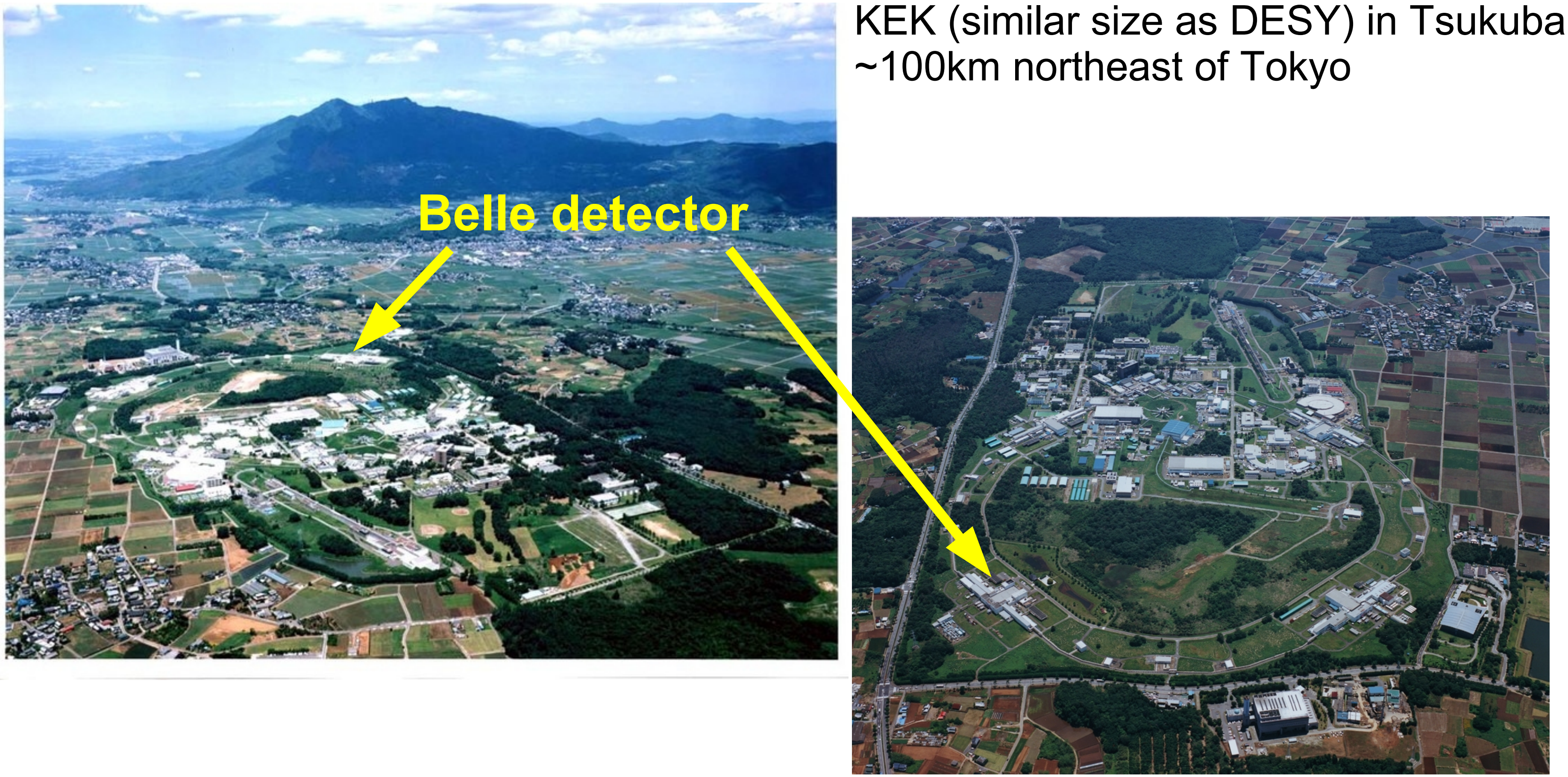
KEKB

- finite beam crossing angle needed for efficient beam separation and background reduction
- crab cavities to force head-on collisions (from 2007)
- beam sizes are tiny: ~2x100µm



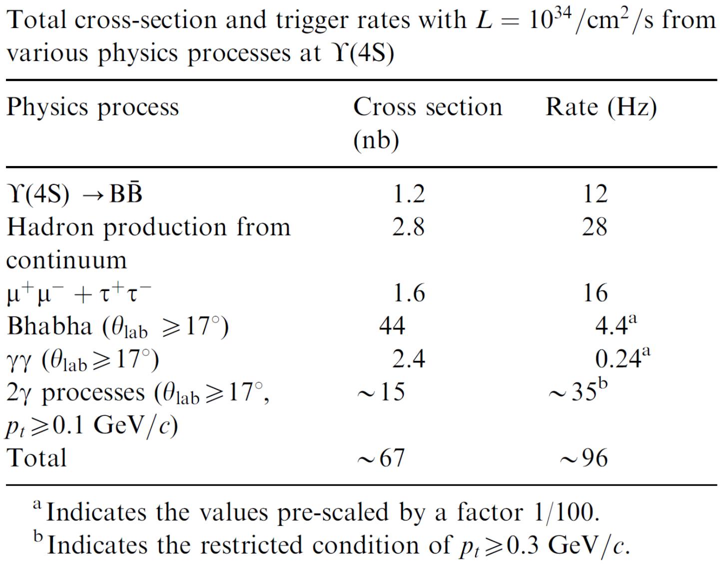


The Belle experiment at KEKB



KEK (similar size as DESY) in Tsukuba, ~100km northeast of Tokyo

Event yields at flavour factories Belle and BaBar



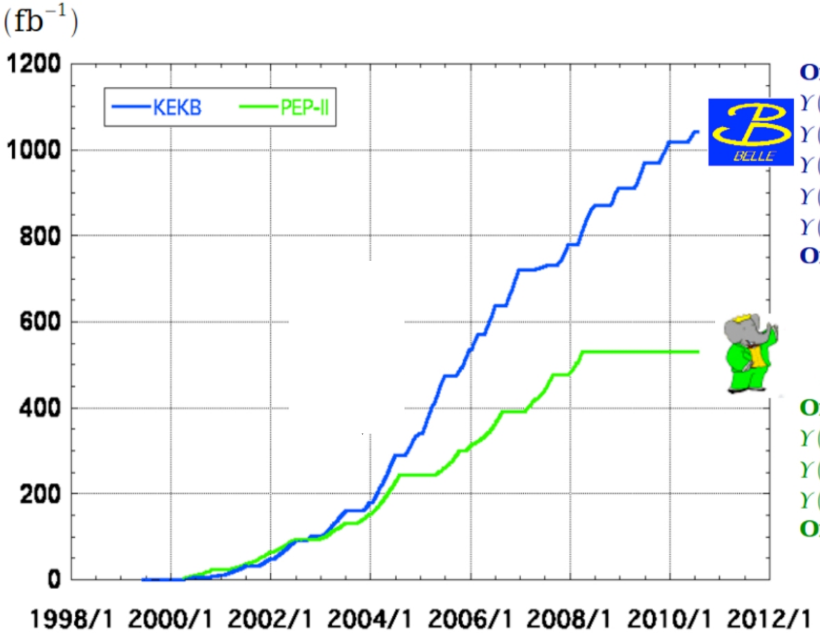
Total cross-section and trigger rates with $L = 10^{34}/\mathrm{cm}^2/\mathrm{s}$ from various physics processes at $\Upsilon(4S)$

Physics process	Cross section (nb)	Rate (Hz)
$\Upsilon(4S) \to B\bar{B}$	1.2	12
Hadron production from continuum	2.8	28
$\mu^+\mu^- + \tau^+\tau^-$	1.6	16
Bhabha ($\theta_{\mathrm{lab}} \geqslant 17°$)	44	4.4^{a}
$\gamma\gamma$ ($\theta_{\mathrm{lab}} \geqslant 17°$)	2.4	0.24^{a}
2γ processes ($\theta_{\mathrm{lab}} \geqslant 17°$, $p_t \geqslant 0.1$ GeV/c)	~15	$\sim 35^{b}$
Total	~67	~96

[a] Indicates the values pre-scaled by a factor 1/100.

[b] Indicates the restricted condition of $p_t \geqslant 0.3$ GeV/c.

[NIM A479, 117]



> 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}

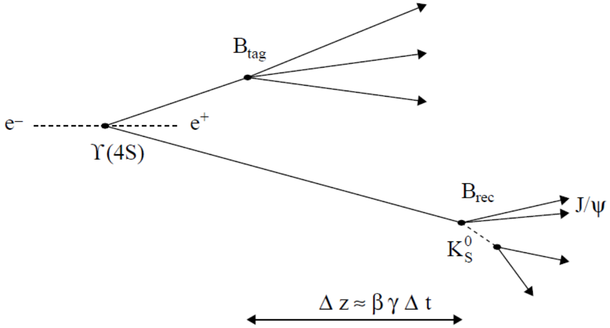
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Features of flavour factories

- about 800,000,000 $B\bar{B}$ pairs produced at Belle
- initial state very well known (unique feature of e^+e^-)
  - constraint event kinematics: each $B/\bar{B}$ has half beam energy
  - no pile up: maximally one $B\bar{B}$ event per collision
- asymmetric beam energies
  - $\Upsilon(4S)$ is boosted in forward direction, decay products not at rest
  - measure displaced decay vertices of tag and signal B



Detector requirements

- Low particle energies (100MeV - 5GeV) require low "**material budget**" (thin or gaseous detectors, no passive material)
- Tiny lifetime differences require excellent **vertex resolution** (~ some 10 µm)
- "Flavour tagging" needs excellent **charge reconstruction** (tracking in B field and **particle identification**
- Very good **energy resolution** for photons (e.g. from $\pi^0 \rightarrow \gamma\gamma$) and electrons
- Very high beam backgrounds (mostly photons) require **radiation hardness**

Detector requirements - flavour tagging

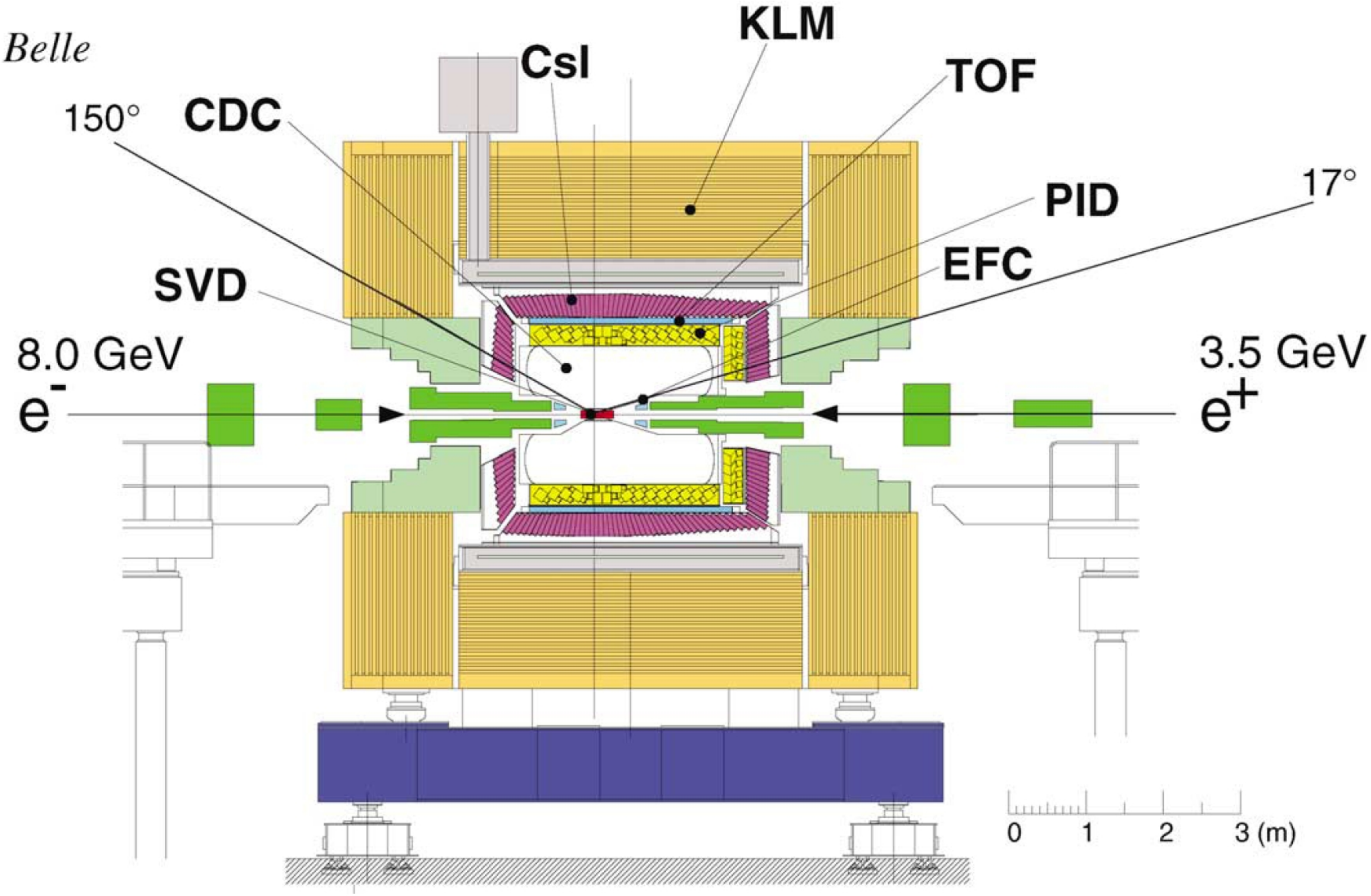
hint:
$B^0 = \bar{b}d$

- Remember: “tag side” reconstruction requires to identify the B flavour
  - in a nutshell: look in the PDG booklet, find decays that are different for B and $\bar{B}$, try to use as many of them as possible
- Fast leptons (e or μ): $\mathbf{b \rightarrow c\, l\, \nu}$ (l^+ for B)
- Slow leptons (e or μ): $\mathbf{b \rightarrow c\, [c \rightarrow s\, l\, \nu]\, X}$ (l^+ for $\bar{B}$)
- Kaons: $\mathbf{b \rightarrow c\, [\, c \rightarrow s\, X]\, X}$ (K^+ for B)

- Slow pions: $\mathbf{D^* \rightarrow D^0(D^0 \rightarrow K^+X)\pi^-_{slow}}$ (π^+ for $\bar{B}$)
- Lambda (uds): $\mathbf{b \rightarrow c \rightarrow s}$

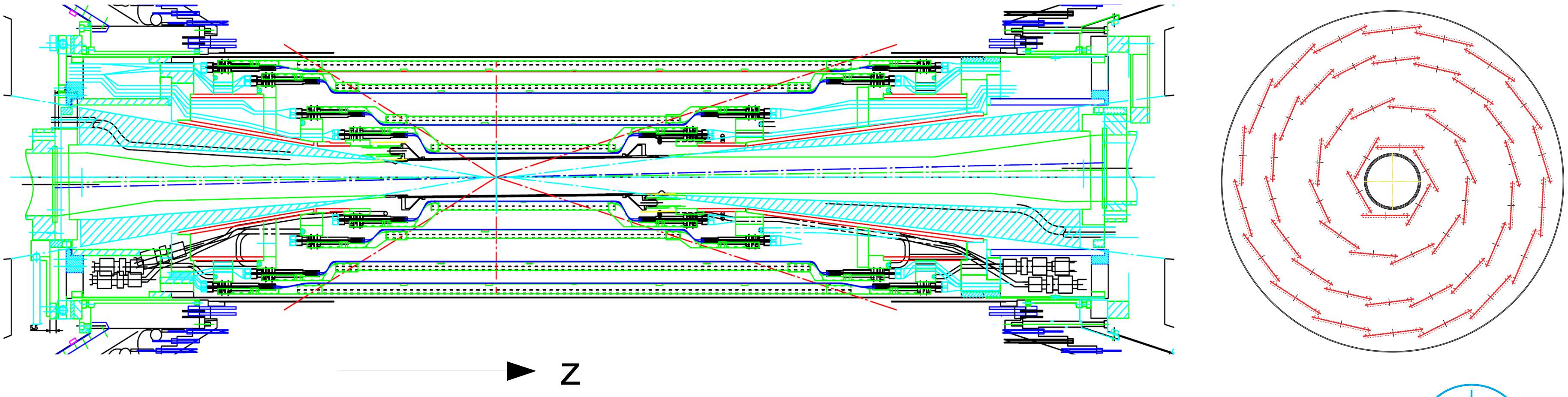
  $\mathbf{\Lambda^0 \rightarrow p^+\pi^-}$ ($\bar{\Lambda}$ for B)

The Belle detector

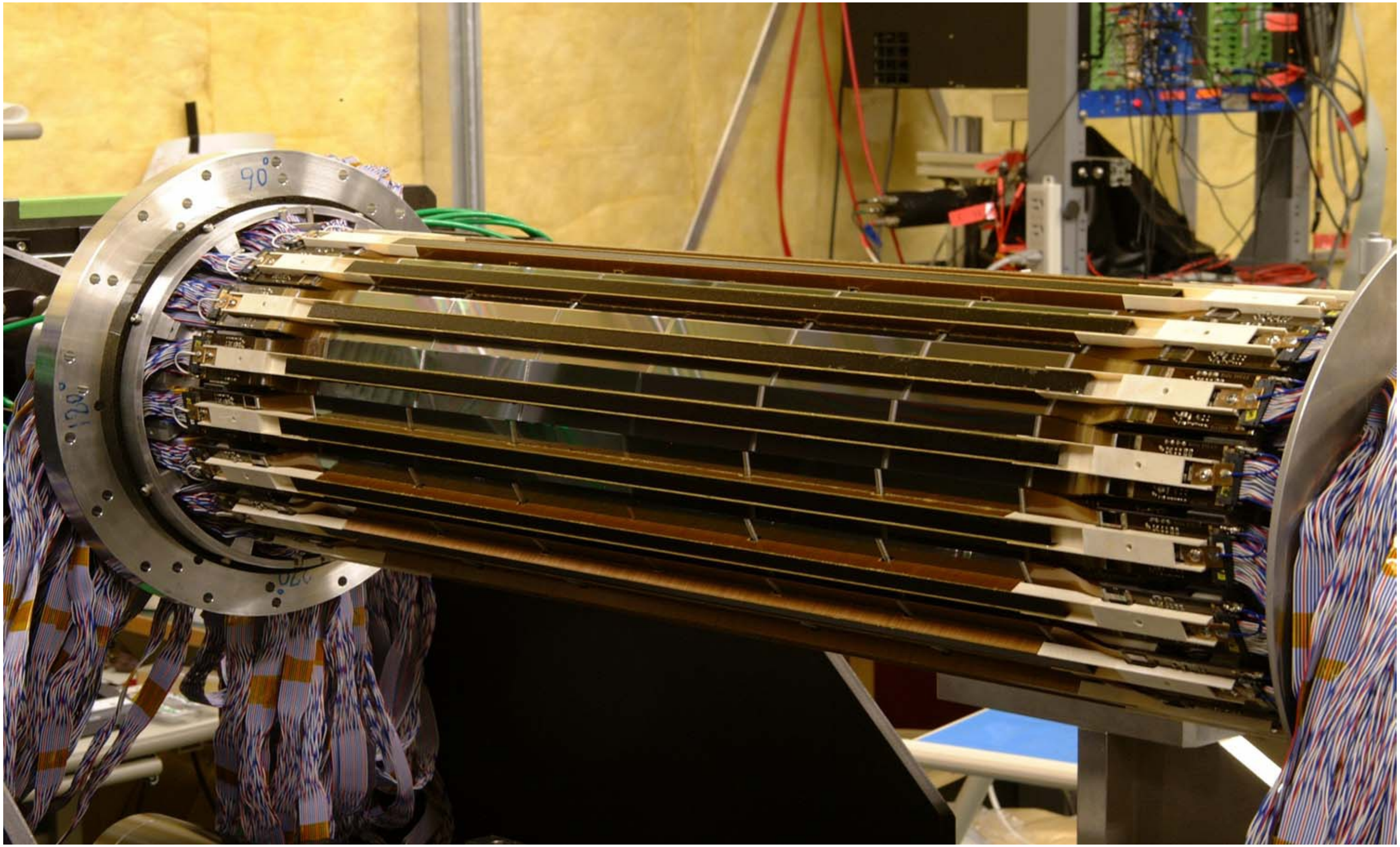


Vertex detector

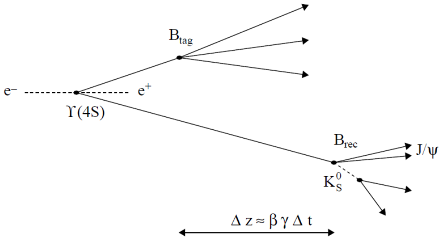
- three layers of double sided silicon strip detectors (DSSD)
  - replaced after three years and 1MRad radiation dose (S/N degraded by about 30%, IP resolution stable)
- Upgrade to four layers DSSD, smaller beam pipe (only 15mm radius)

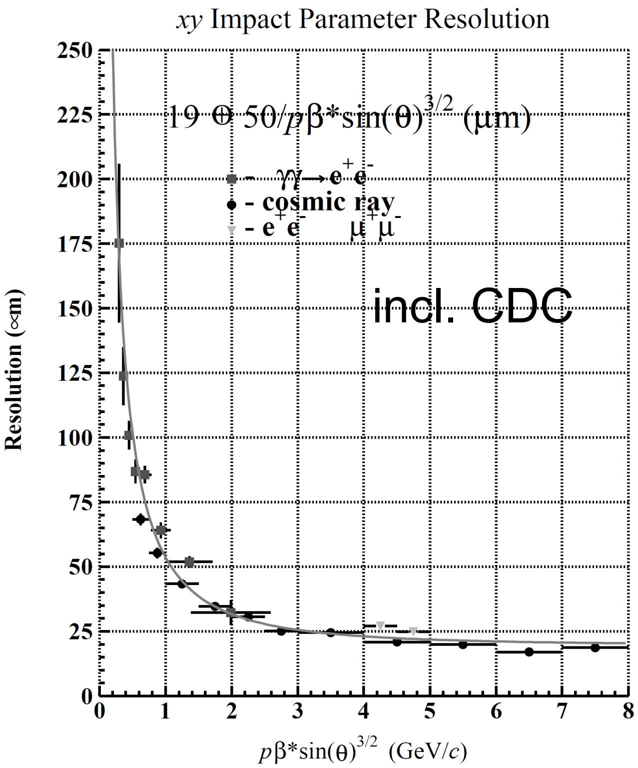


Vertex detector (new SVD)

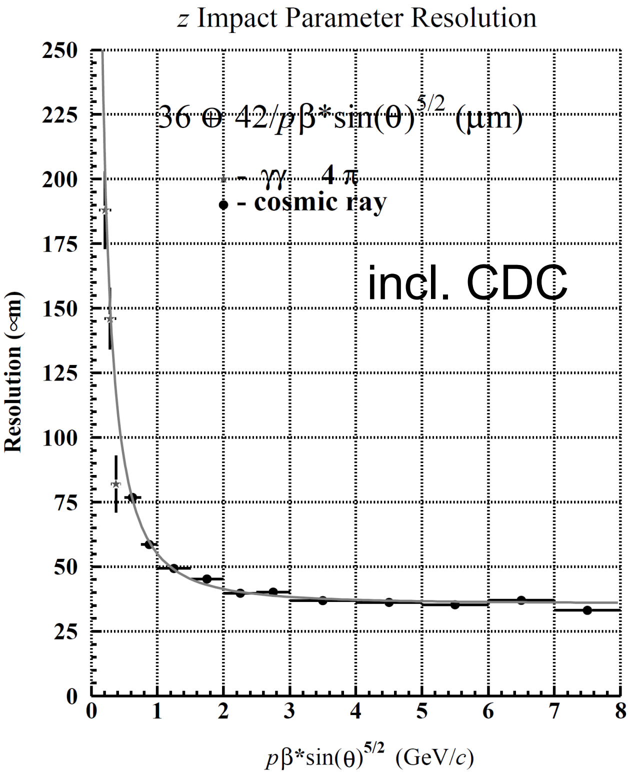


Vertex detector performance (old SVD)





incl. CDC



incl. CDC

vertex reco better if:
- energy high
- theta → 90deg

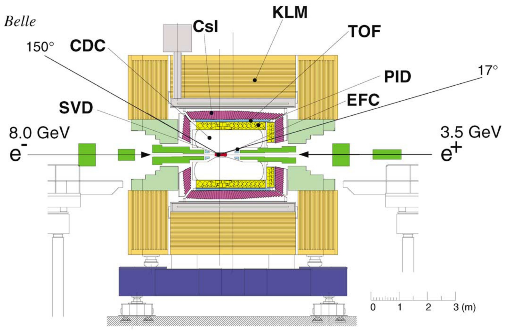
Particle identification

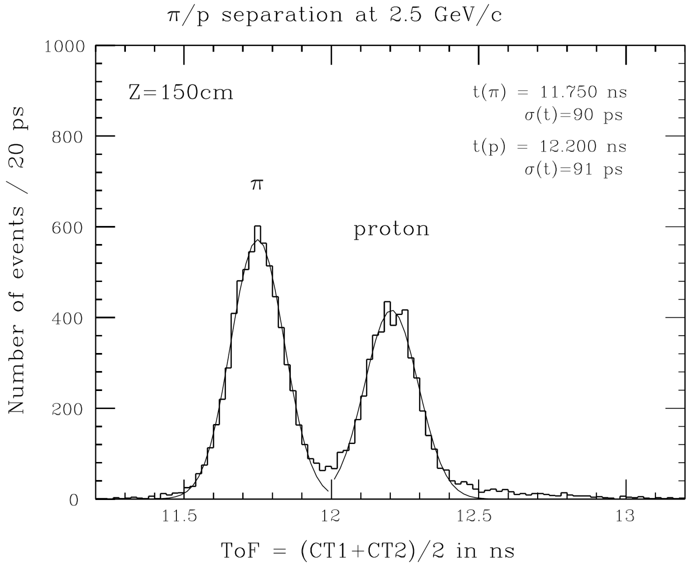
- Time-Of-Flight (TOF):
  - more mass ↔ longer flight time
- Aerogel Cerenkov Counters (ACC)
  - more velocity ↔ more photons
- measure dE/dx (CDC)
  - higher mass ↔ more deposited energy
- measure shower parameters (ECL)
  - exploit electron-like features
- penetration depth in iron (KLM)
  - (almost) only muons reach that part of the detector

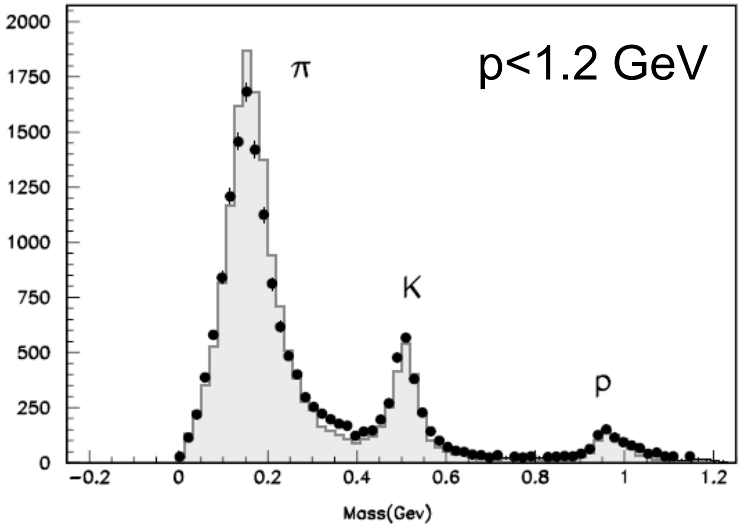
TOF

- about 1.2m away from IP
- Plastic scintillator and PMTs
- 100ps time resolution

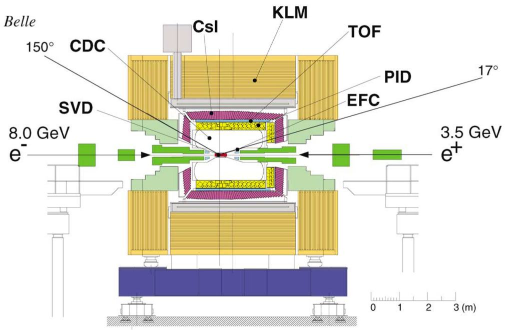
  → PID for p<1.2GeV (covers about 90% of all particles)



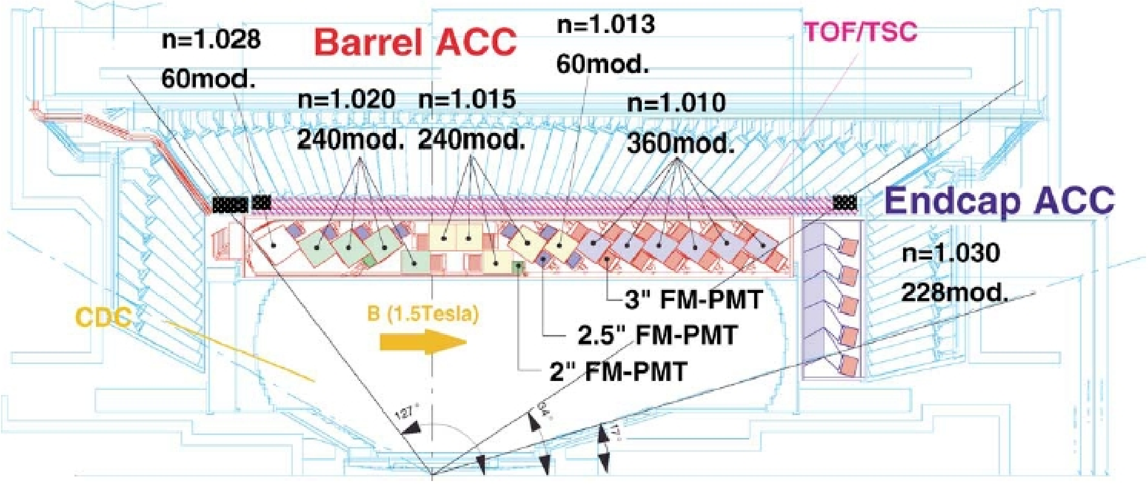




ACC (“PID” in the detector drawing)

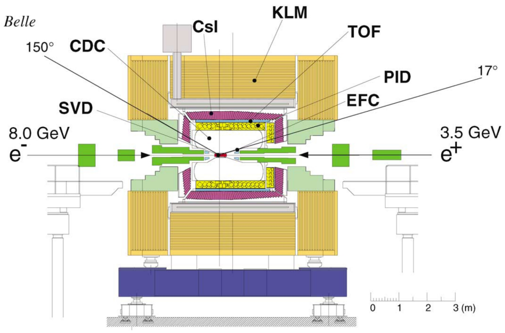


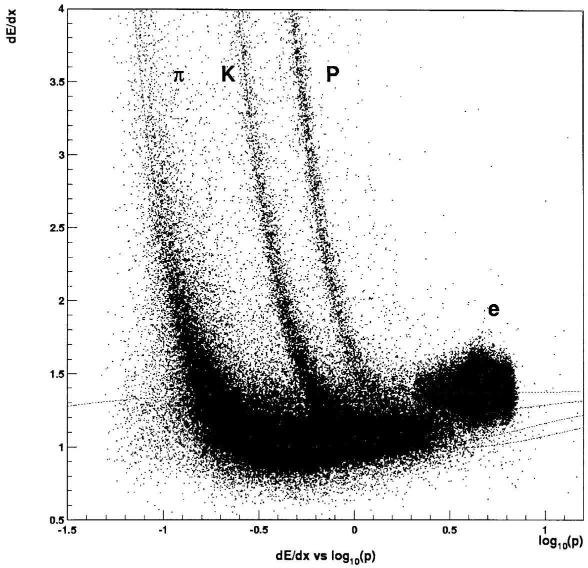
- number of emitted Cerenkov photons depends on the refraction index *n* and the particle speed
- Aerogel can be produced with different *n*
- pion/kaon separation in the range 1.2 GeV - 3.5 GeV

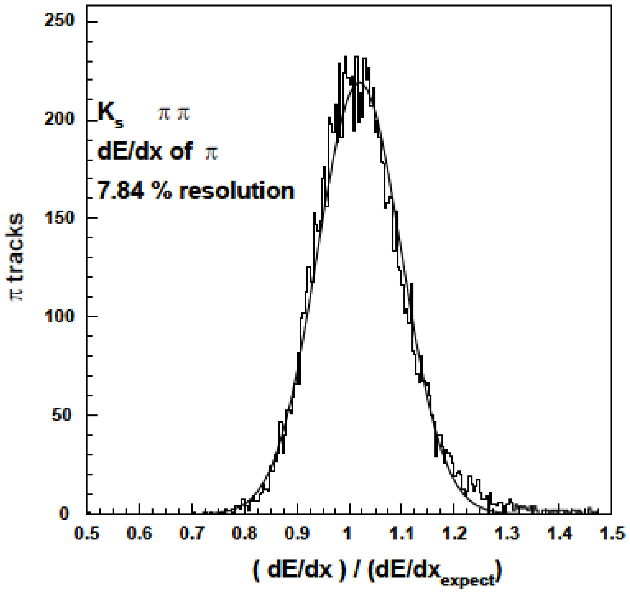


CDC

- main CDC task:
  tracking and charge determination
- measure energy loss in gas
  → very efficient at low energies
  (typical below 0.6 GeV)

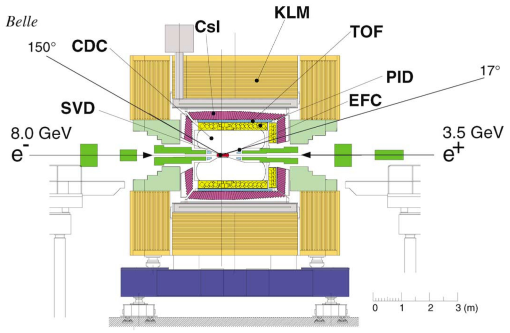






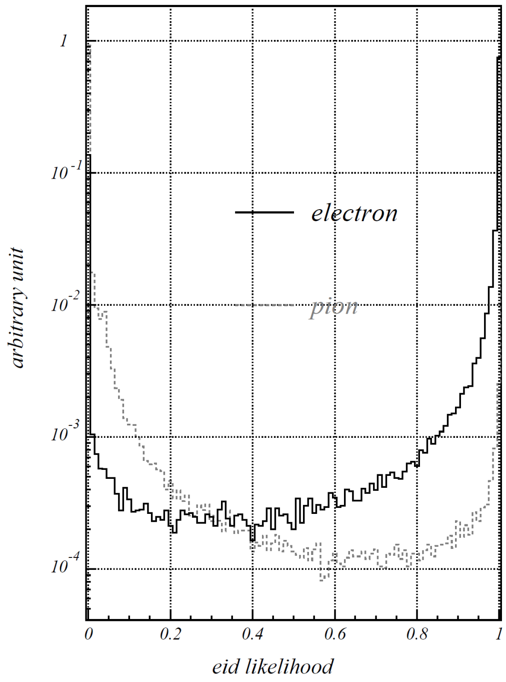
ECL

- main task:
  measure energy of electrons and photons



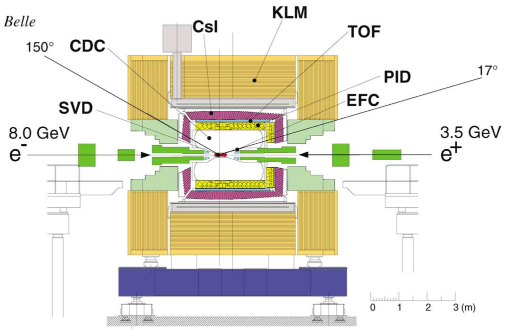
- PID for electrons:
  - ratio of energy deposited in ECL and track momentum measured by CDC (~1 for electrons)
  - transverse shower shape
  - matching between a cluster at ECL and charged track position extrapolated to ECL

  → construct likelihood from these variables

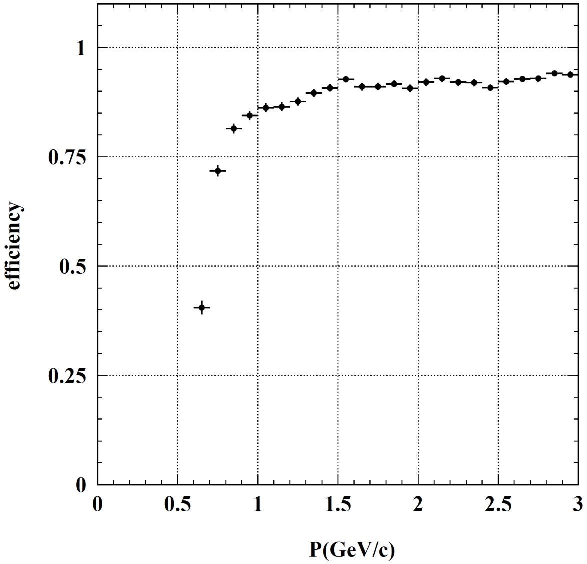


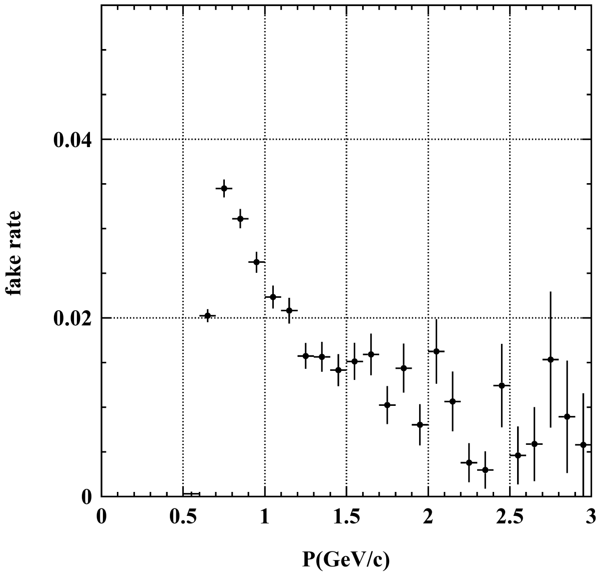
KLM (“K_L and muon detector”)

- The only particles that reach that part of the detector are muons and K_L



- Extrapolate tracks from CDC and check muon hypothesis (hits close to track, multiple scattering...)

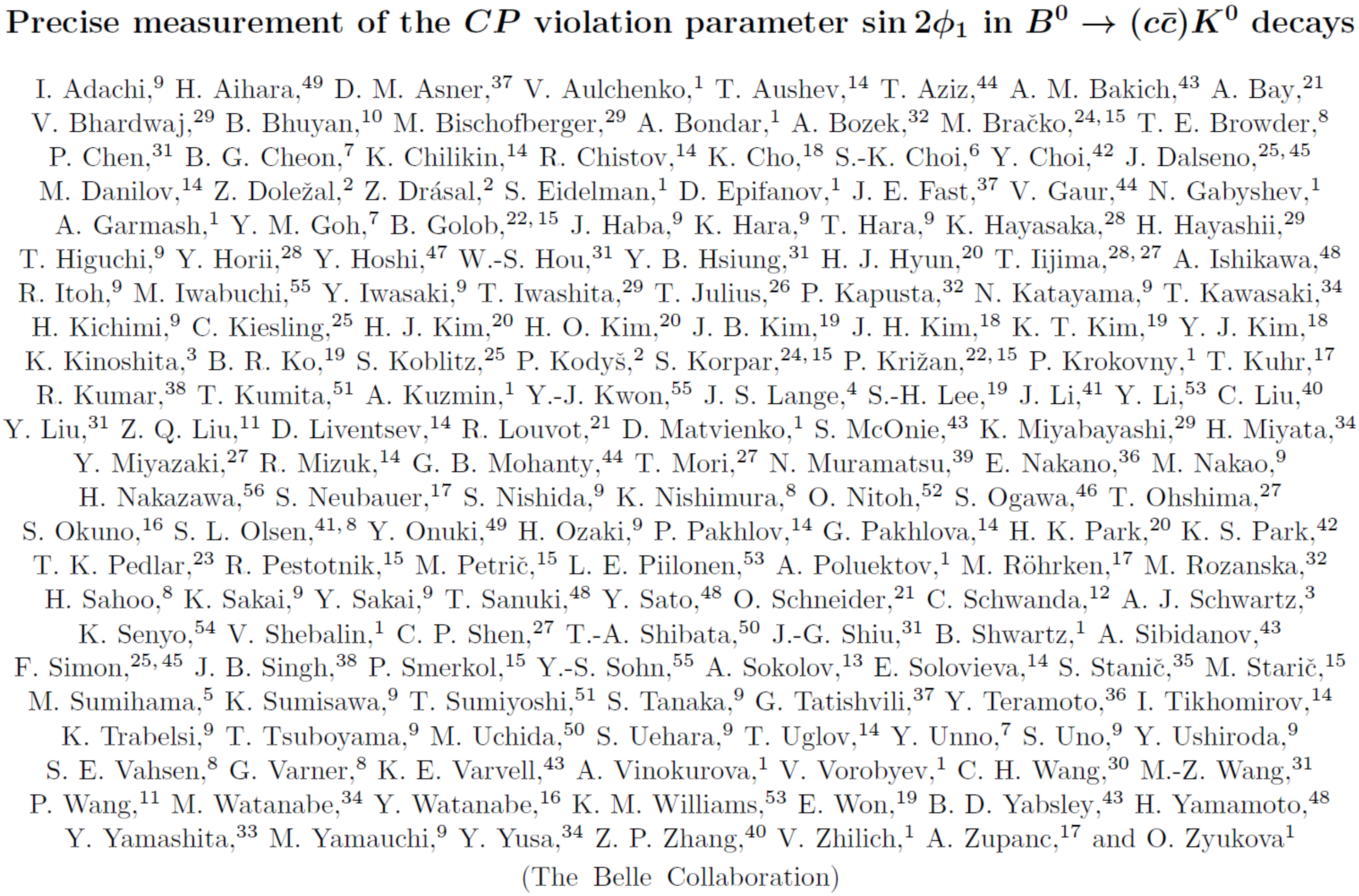




- We have the theory
- We have the experimental idea
- We have the accelerator
- We have the detector

Lets take a look at a real analysis from Belle and see if we can understand it!

(Spoiler alert: We can!)

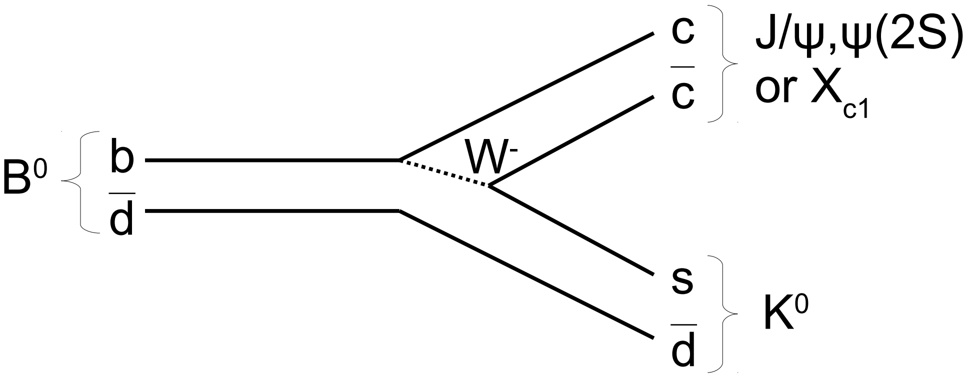


Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays

I. Adachi,[9] H. Aihara,[49] D. M. Asner,[37] V. Aulchenko,[1] T. Aushev,[14] T. Aziz,[44] A. M. Bakich,[43] A. Bay,[21]
V. Bhardwaj,[29] B. Bhuyan,[10] M. Bischofberger,[29] A. Bondar,[1] A. Bozek,[32] M. Bračko,[24,15] T. E. Browder,[8]
P. Chen,[31] B. G. Cheon,[7] K. Chilikin,[14] R. Chistov,[14] K. Cho,[18] S.-K. Choi,[6] Y. Choi,[42] J. Dalseno,[25,45]
M. Danilov,[14] Z. Doležal,[2] Z. Drásal,[2] S. Eidelman,[1] D. Epifanov,[1] J. E. Fast,[37] V. Gaur,[44] N. Gabyshev,[1]
A. Garmash,[1] Y. M. Goh,[7] B. Golob,[22,15] J. Haba,[9] K. Hara,[9] T. Hara,[9] K. Hayasaka,[28] H. Hayashii,[29]
T. Higuchi,[9] Y. Horii,[28] Y. Hoshi,[47] W.-S. Hou,[31] Y. B. Hsiung,[31] H. J. Hyun,[20] T. Iijima,[28,27] A. Ishikawa,[48]
R. Itoh,[9] M. Iwabuchi,[55] Y. Iwasaki,[9] T. Iwashita,[29] T. Julius,[26] P. Kapusta,[32] N. Katayama,[9] T. Kawasaki,[34]
H. Kichimi,[9] C. Kiesling,[25] H. J. Kim,[20] H. O. Kim,[20] J. B. Kim,[19] J. H. Kim,[18] K. T. Kim,[19] Y. J. Kim,[18]
K. Kinoshita,[3] B. R. Ko,[19] S. Koblitz,[25] P. Kodyš,[2] S. Korpar,[24,15] P. Križan,[22,15] P. Krokovny,[1] T. Kuhr,[17]
R. Kumar,[38] T. Kumita,[51] A. Kuzmin,[1] Y.-J. Kwon,[55] J. S. Lange,[4] S.-H. Lee,[19] J. Li,[41] Y. Li,[53] C. Liu,[40]
Y. Liu,[31] Z. Q. Liu,[11] D. Liventsev,[14] R. Louvot,[21] D. Matvienko,[1] S. McOnie,[43] K. Miyabayashi,[29] H. Miyata,[34]
Y. Miyazaki,[27] R. Mizuk,[14] G. B. Mohanty,[44] T. Mori,[27] N. Muramatsu,[39] E. Nakano,[36] M. Nakao,[9]
H. Nakazawa,[56] S. Neubauer,[17] S. Nishida,[9] K. Nishimura,[8] O. Nitoh,[52] S. Ogawa,[46] T. Ohshima,[27]
S. Okuno,[16] S. L. Olsen,[41,8] Y. Onuki,[49] H. Ozaki,[9] P. Pakhlov,[14] G. Pakhlova,[14] H. K. Park,[20] K. S. Park,[42]
T. K. Pedlar,[23] R. Pestotnik,[15] M. Petrič,[15] L. E. Piilonen,[53] A. Poluektov,[1] M. Röhrken,[17] M. Rozanska,[32]
H. Sahoo,[8] K. Sakai,[9] Y. Sakai,[9] T. Sanuki,[48] Y. Sato,[48] O. Schneider,[21] C. Schwanda,[12] A. J. Schwartz,[3]
K. Senyo,[54] V. Shebalin,[1] C. P. Shen,[27] T.-A. Shibata,[50] J.-G. Shiu,[31] B. Shwartz,[1] A. Sibidanov,[43]
F. Simon,[25,45] J. B. Singh,[38] P. Smerkol,[15] Y.-S. Sohn,[55] A. Sokolov,[13] E. Solovieva,[14] S. Stanič,[35] M. Starič,[15]
M. Sumihama,[5] K. Sumisawa,[9] T. Sumiyoshi,[51] S. Tanaka,[9] G. Tatishvili,[37] Y. Teramoto,[36] I. Tikhomirov,[14]
K. Trabelsi,[9] T. Tsuboyama,[9] M. Uchida,[50] S. Uehara,[9] T. Uglov,[14] Y. Unno,[7] S. Uno,[9] Y. Ushiroda,[9]
S. E. Vahsen,[8] G. Varner,[8] K. E. Varvell,[43] A. Vinokurova,[1] V. Vorobyev,[1] C. H. Wang,[30] M.-Z. Wang,[31]
P. Wang,[11] M. Watanabe,[34] Y. Watanabe,[16] K. M. Williams,[53] E. Won,[19] B. D. Yabsley,[43] H. Yamamoto,[48]
Y. Yamashita,[33] M. Yamauchi,[9] Y. Yusa,[34] Z. P. Zhang,[40] V. Zhilich,[1] A. Zupanc,[17] and O. Zyukova[1]
(The Belle Collaboration)

Phys. Rev. Lett. 108, 171802 (2012)

- dataset: 772x10^6 BB pairs (full dataset @Y(4S))
- $b \rightarrow c\,\bar{c}\,s$
  - CP even:
    - J/ψ K_S
    - ψ(2S) K_S
    - X_{c1} K_S
  - CP odd:
    - J/ψK_L



Step 1

Step 1: Search signal events: J/ψ K^0

- 1a) J/ψ → ee or J/ψ → μμ: invariant mass of the two leptons must result in J/ψ mass (within some 30-100 MeV)

- 1b) **K_S** → **$\pi^+\pi^-$** (careful, the decay length of the K_S is some cm)

  or

  K_L cluster is found in ECL or KLM and no other charged track is nearby

→ 4 charged tracks, two of them leptons (opposite charge), two of them pions (opposite charge)

or

2 charged tracks from leptons and one cluster

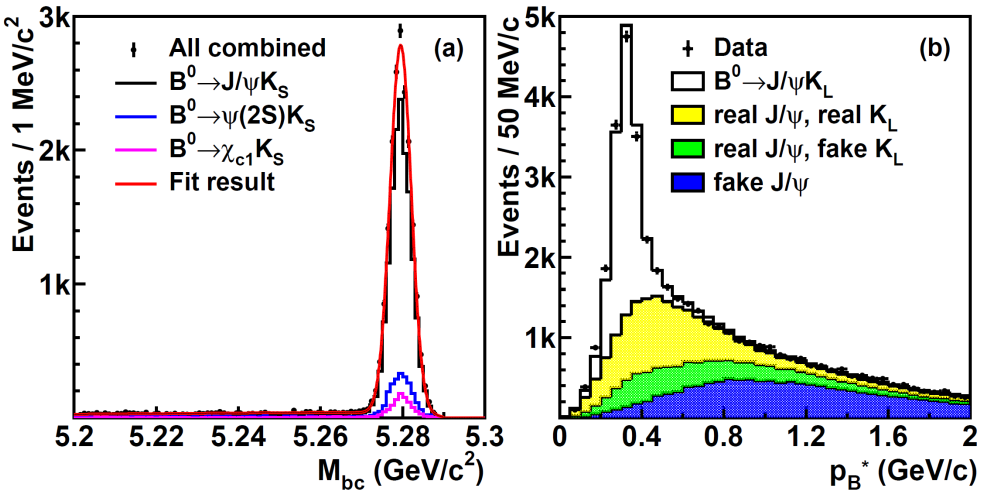
Step 2

Step 2: Make a signal B (we call it "candidate")

- Use the reconstructed J/ψ and the reconstructed K_S (or K_L) to make a B, use the fact, that you already **know** its energy (E^*_{beam}=10.58GeV/2)

$$M_{bc} = \sqrt{{E^*_{beam}}^2 - {p^*_B}^2}$$

- For the K_L, you have to calculate the four-momentum p_B^* assuming two body decay kinematics



Step 3

- 3) “tag” the other B by using the leftover tracks
  - you dont need to reconstruct everything here, just tag the flavour via one of the possible ways discussed before
  - you have to reconstruct the vertex, though...

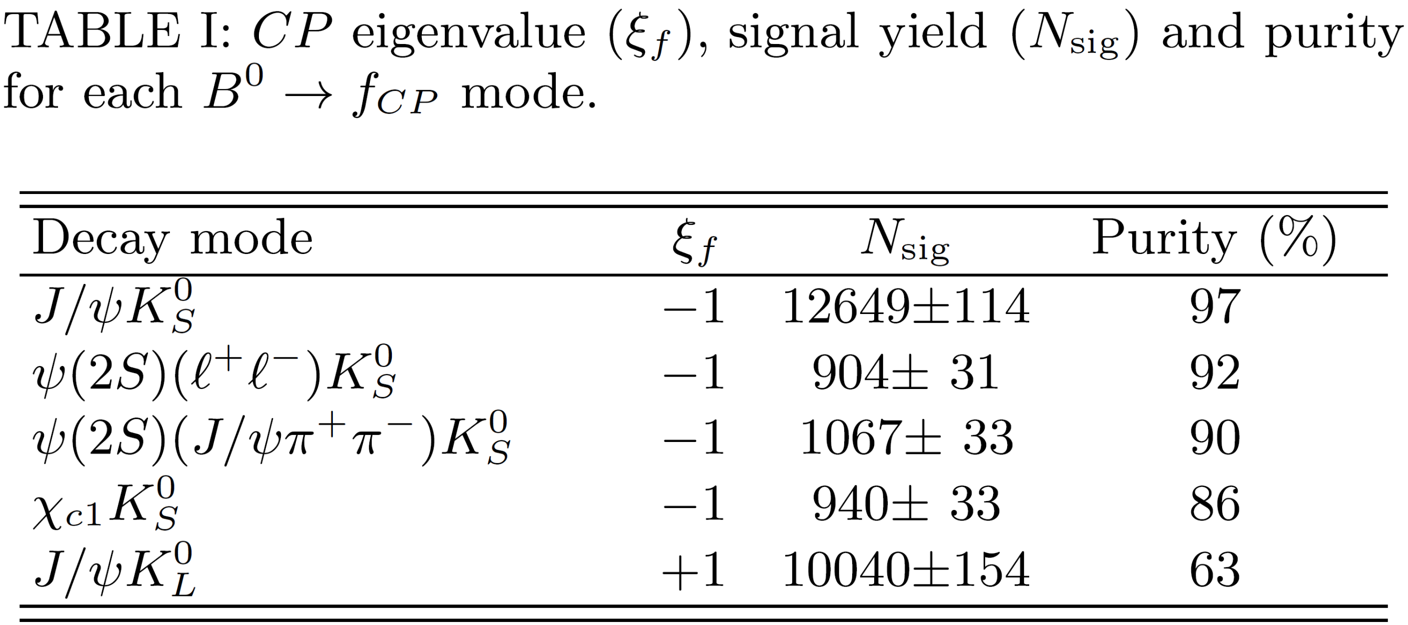
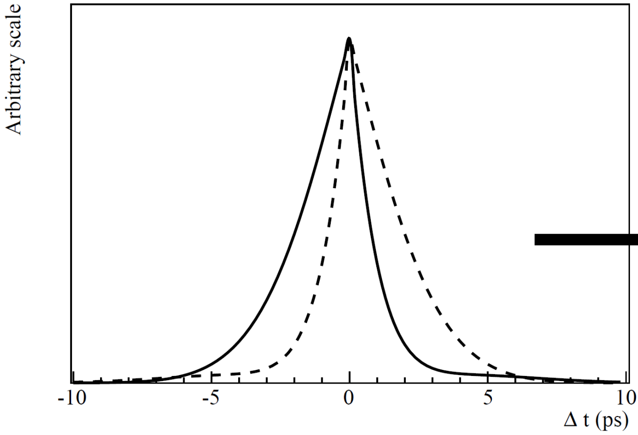


TABLE I: CP eigenvalue (ξ_f), signal yield ($N_{\rm sig}$) and purity for each $B^0 \to f_{CP}$ mode.

Decay mode	ξ_f	$N_{\rm sig}$	Purity (%)
$J/\psi K^0_S$	-1	12649±114	97
$\psi(2S)(\ell^+\ell^-)K^0_S$	-1	904± 31	92
$\psi(2S)(J/\psi\pi^+\pi^-)K^0_S$	-1	1067± 33	90
$\chi_{c1}K^0_S$	-1	940± 33	86
$J/\psi K^0_L$	$+1$	10040±154	63

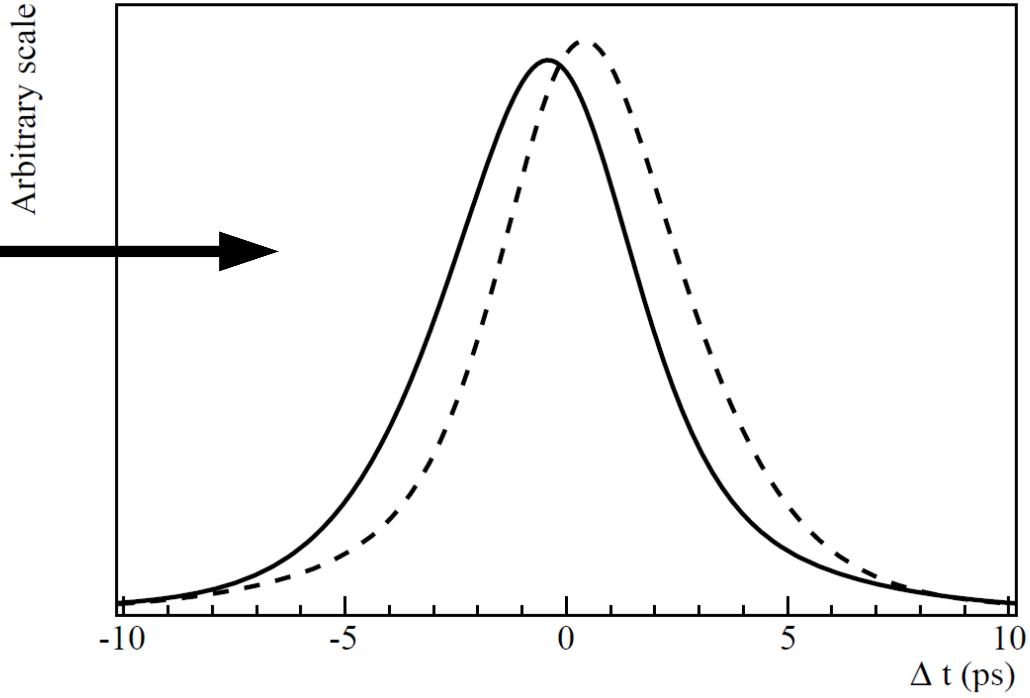
Remember: Perfect time resolution in reality

perfect

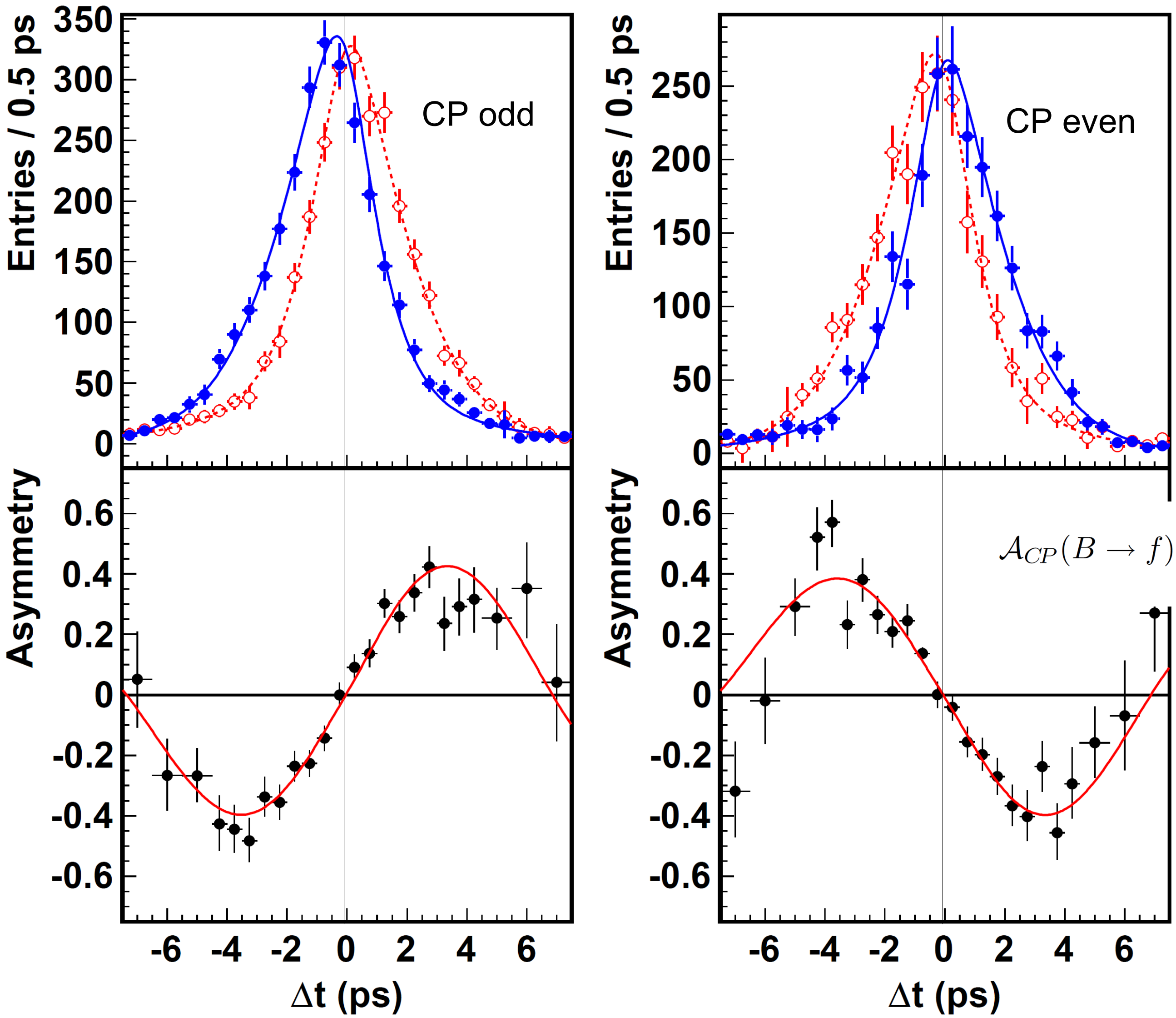


$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\cdot\left[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)\right]\right\}.$$

including resolution and “dilusion” (wrong tag)



Results



tag B^0

tag $\overline{B}^0$

$$\mathcal{A}_{CP}(B \to f) \equiv \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})}$$

$$\frac{\text{red - blue}}{\text{red + blue}}$$

Results

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 \; + \; q \cdot \Big[\mathcal{S}_f \sin(\Delta m_d \Delta t) \\ + \; \mathcal{A}_f \cos(\Delta m_d \Delta t) \Big] \Big\}.$$

Decay mode	$\sin 2\phi_1 \equiv -\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$J/\psi K_S^0$	$+0.670 \pm 0.029 \pm 0.013$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$
$\psi(2S) K_S^0$	$+0.738 \pm 0.079 \pm 0.036$	$+0.104 \pm 0.055^{+0.047}_{-0.027}$
$\chi_{c1} K_S^0$	$+0.640 \pm 0.117 \pm 0.040$	$-0.017 \pm 0.083^{+0.046}_{-0.026}$
$J/\psi K_L^0$	$+0.642 \pm 0.047 \pm 0.021$	$+0.019 \pm 0.026^{+0.017}_{-0.041}$
All modes	$+0.667 \pm 0.023 \pm 0.012$	$+0.006 \pm 0.016 \pm 0.012$

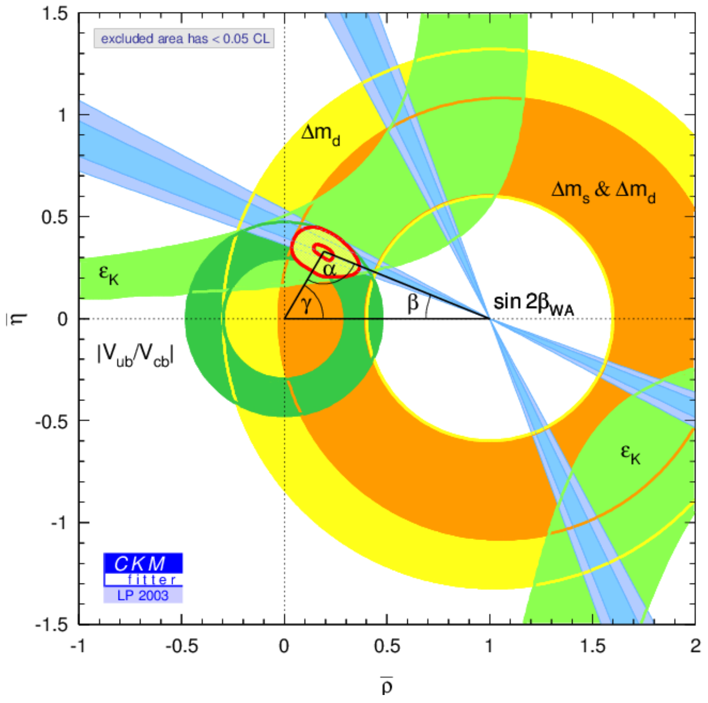
the fitted asymmetry
has a negative sign!
(previous slide)

systematic error
(in this analysis mostly vertexing)

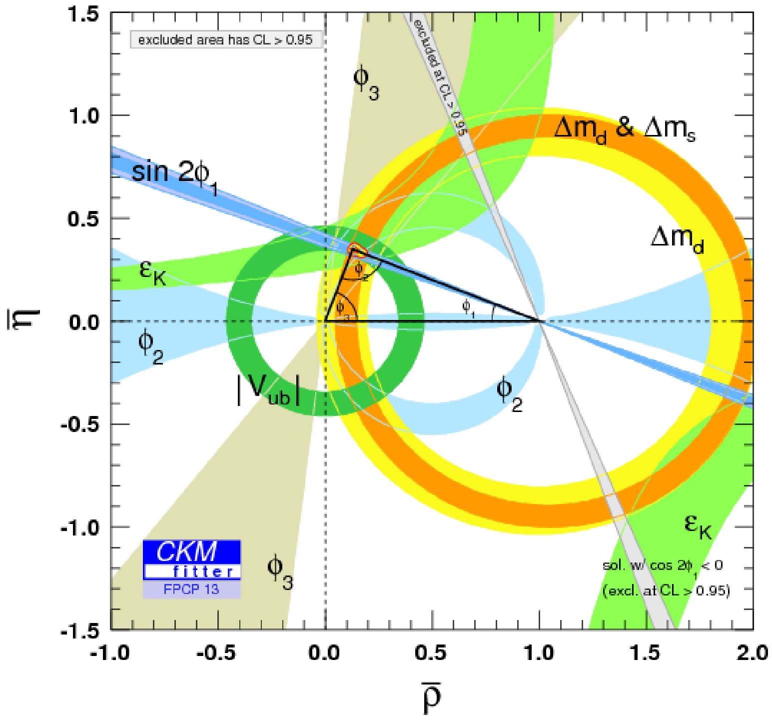
statistical error

10 years of flavour factories (+LHCb)

2003

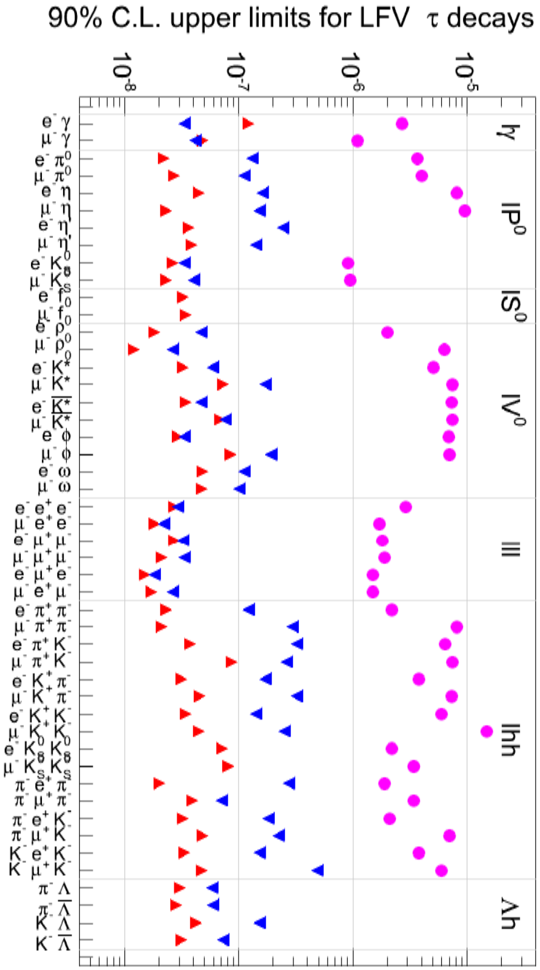


2013



Other topics at flavour factories (1)

> Lepton Flavour Violation (LFV)



PTEP 04D001 (2012), HFAG 2012

Belle update soon

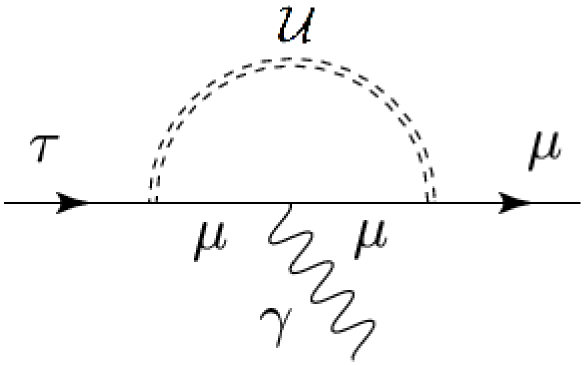
Belle
BaBar
Cleo

SM:
BR<10^{-50}

SUSY+Higgs
BR≈O(10^{-9})

large cross section for tau pair production (~1nb)

→ **tau factory**
(~2,000,000,000 τ at Belle)

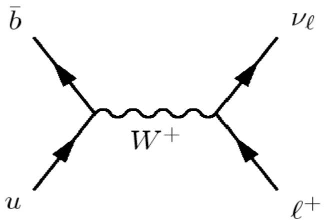


Other topics at flavour factories (2)

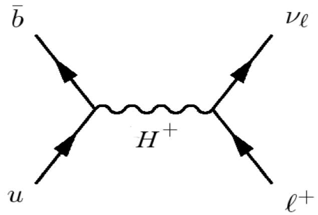
- Rare decays (example: $B^{\pm} \to \tau^{\pm}\nu$)

PRL 110, 131801 (2013) J.Phys, G29, 2311 (2003)

$$Br(B \to \ell\nu) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B \times \left(1 - \frac{tan^2\beta}{1 + \bar{\epsilon}_0 \tan\beta} \frac{m_B^2}{m_H^2}\right)^2$$



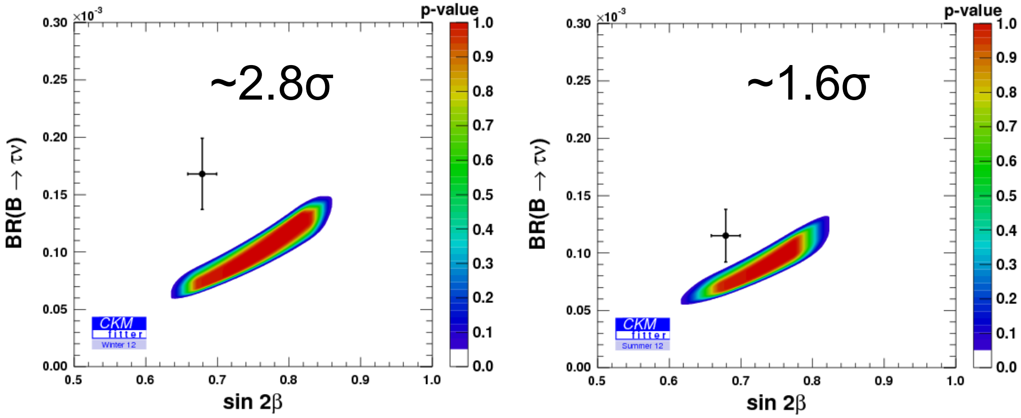
SM



charged Higgs, SUSY...

2012 world average

2013 world average incl. full Belle data

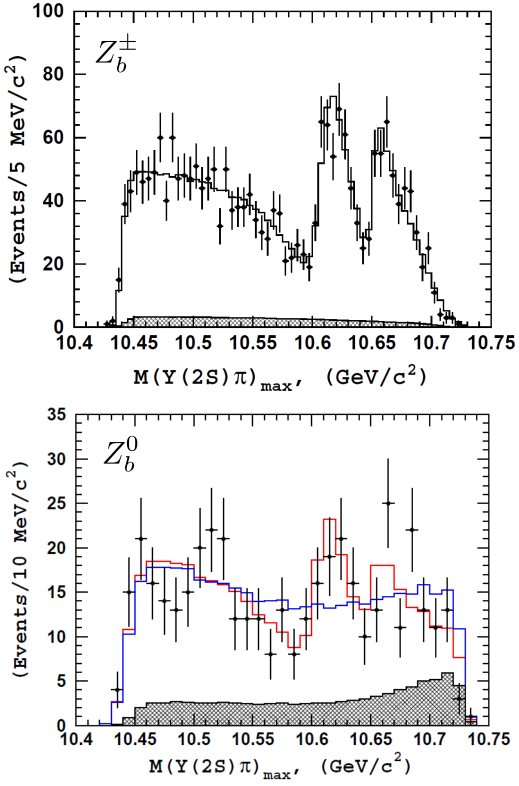


Other topics at flavour factories (3)

- Spectroscopy and exotica (tetraquarks?)

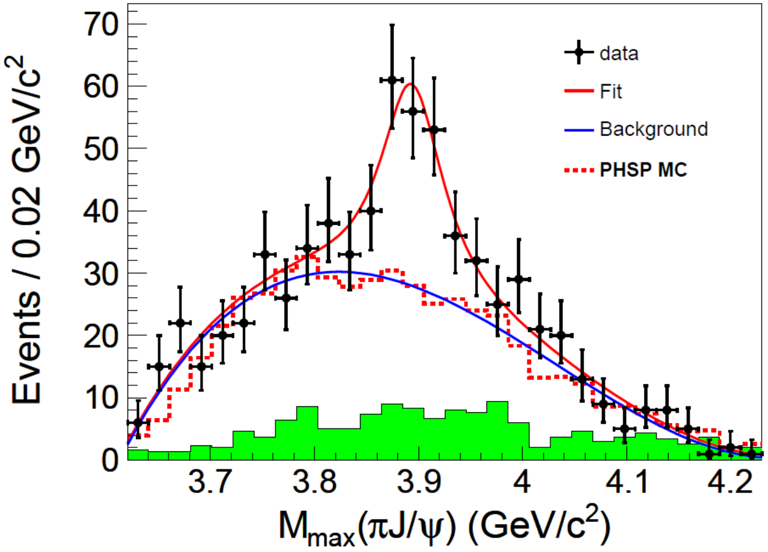
$Z_b^{\pm}, Z_b^{0}$ in $\Upsilon(5S) \to \Upsilon(2)\pi$

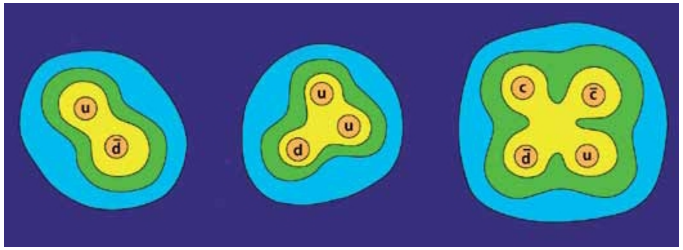
PRL 108, 122001(2012), BELLE-CONF-1271 (2012)



$X_c(3872)$ in $X(4260)J/\Psi\pi$

Phys. Rev. Lett. 110, 252002 (2013)



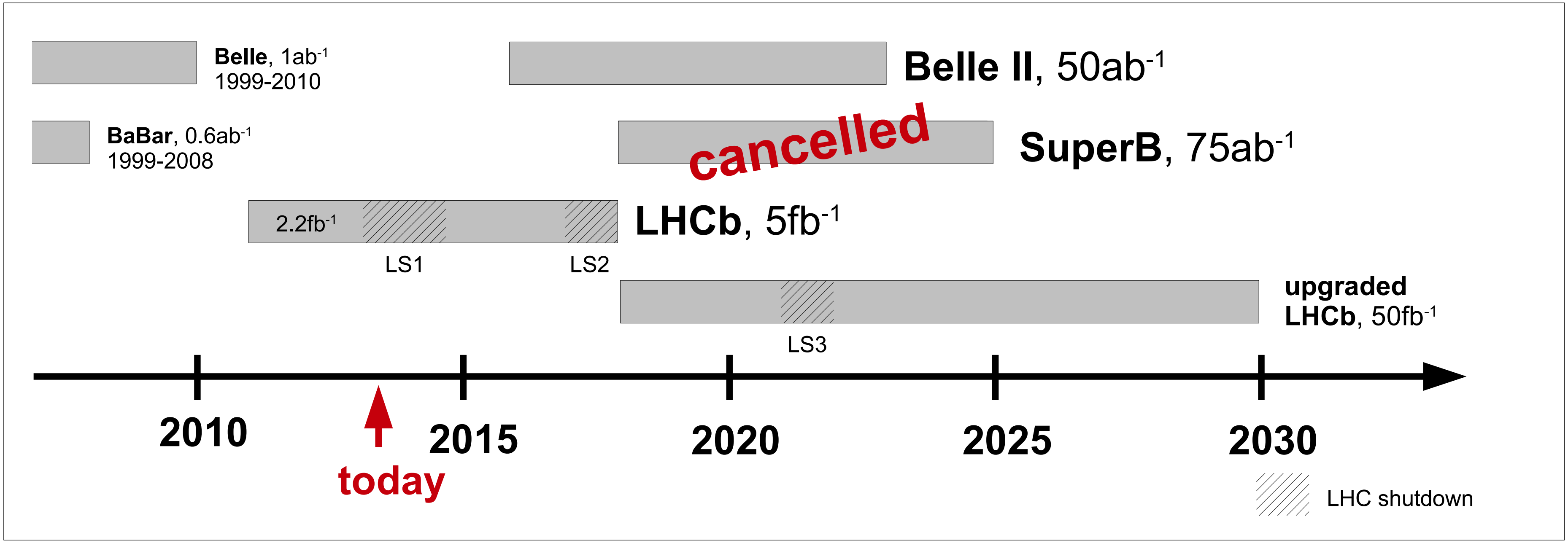


APS/Alan Stonebraker

And even more topics...

- Charm physics: Mixing and CP violation
- Inclusive decays: Full reconstruction, CKM matrix elements, …
- Precision electroweak physics (Weinberg angle)
- Hadronization
- Tau physics (LFV, precision tests)
- 2 Photon physics
- Physics at Υ(5S), involving B_s
- ...

the next 10 years

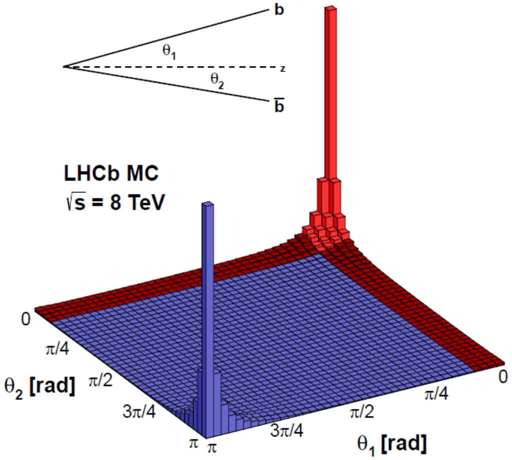


strong interplay with other intensity frontier fields, e.g.:

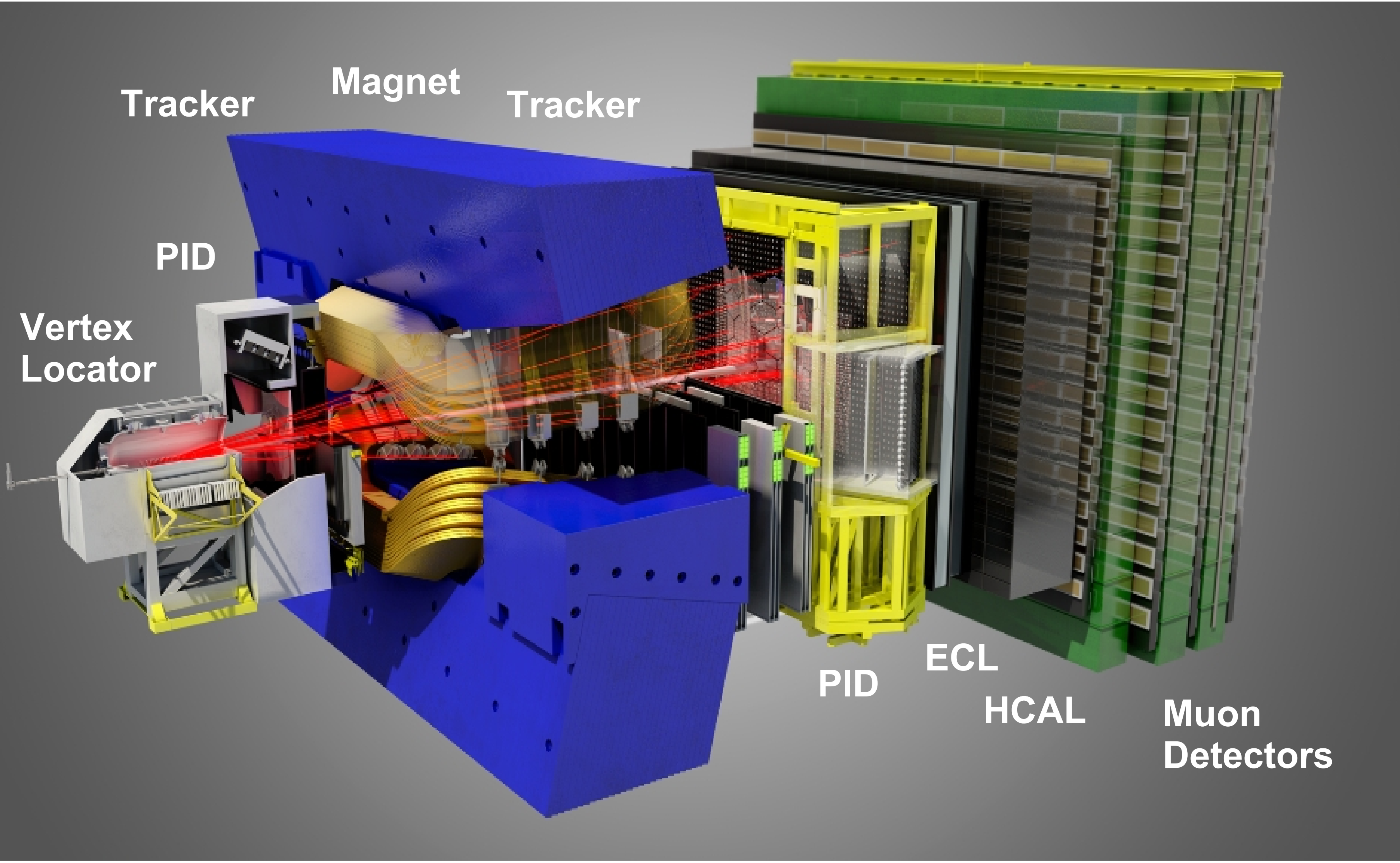
- **rare kaon decays** (NA62, KLOE2, KOTO,...)
- **lepton flavor violation** (Mu2e, COMET, MEG,...)
- **light quark factories** (BESIII, VEPP-2000,CLEO-c, ...)

LHCb

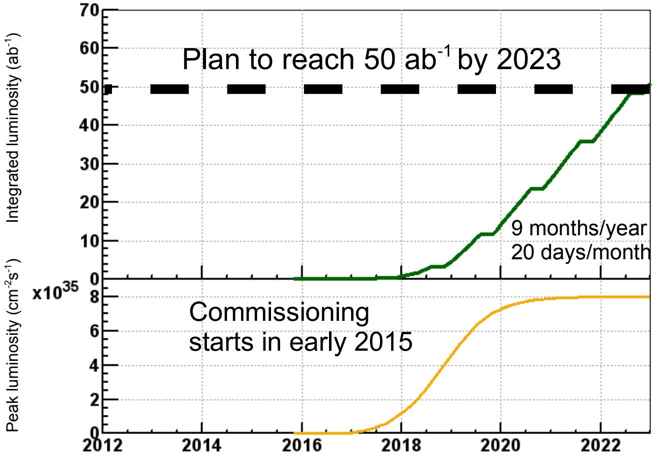
- At the LHC, $b\bar{b}$ pairs are be produced in pp collisions
- large pile up (i.e. several $b\bar{b}$ pairs per event)
- huge cross section (~300 μb @ 8 TeV)
- $b\bar{b}$ in extreme forward(or backward) direction
- rule of thumb:
  - statistically superior to Belle/BaBar for simple event kinematics (e.g. $B \rightarrow K^+\pi^-$, $B_s \rightarrow \mu\mu$, ...)
  - but: not able to reconstruct events with missing energy (neutrinos) and difficulties with photons
  - covers B_s physics (i.e. $b\bar{s}$ mesons) as well
  - complementary production and experimental methods



LHCb detector



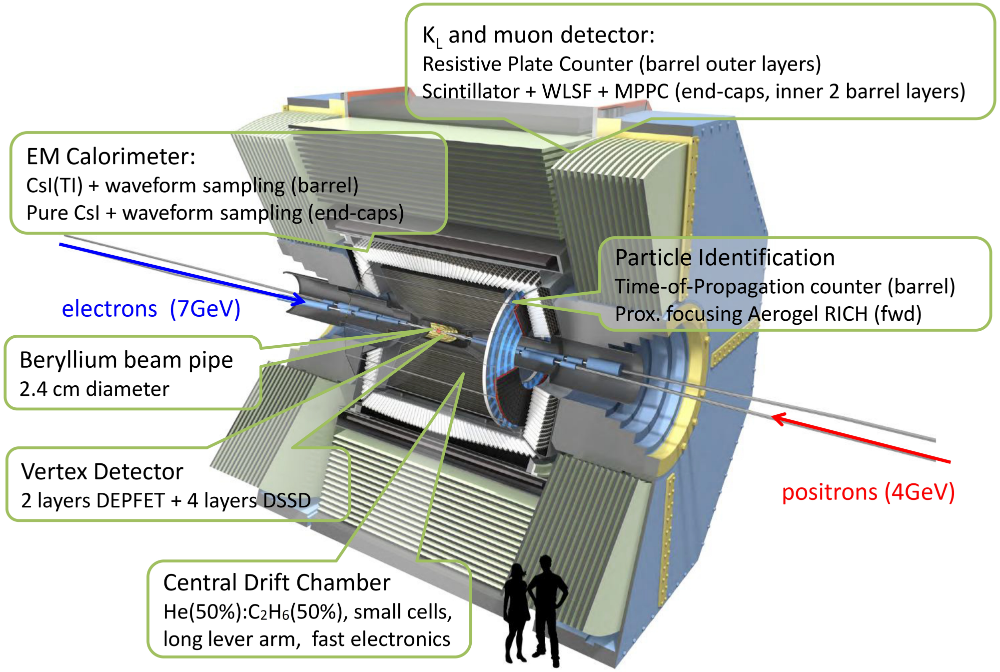
Belle 2 at SuperKEKB



start 2016

SuperKEKB

+ luminosity 50xKEKB
  (using nano beam scheme)
- less asymmetric energies
- larger crossing angle
- higher backgrounds



K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(TI) + waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2.4 cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells,
long lever arm, fast electronics

Belle II

+ DEPFET pixel vertex detector
  (vertex resolution x ~2)
+ new PID
+ new ECL+Waveform Digitizer
+ scintillator KLM

Summary

- SM is a poor description of the universe
- SM works surprisingly well in particle physics
- No physics beyond SM found in flavour physics (or the LHC) yet (take a look in the PDG booklet)
- There must be physics beyond the SM, and this physics must violate CP
- Precision experiments like Belle probe energy scales via loops and boxes direct searches can not
- Two very big players (upgraded LHCb and Belle 2) are getting ready to challenge the SM even further

Summary

more information:

belle2.desy.de (Belle and Belle 2 at DESY)

belle.kek.jp (Belle)

belle2.kek.jp (Belle 2)

slac.stanford.edu/BF/ (BaBar)

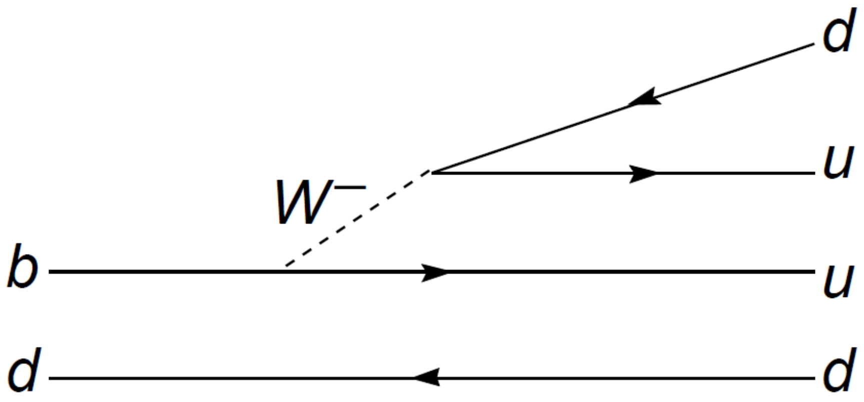
lhcb-public.web.cern.ch/lhcb-public (LHCb)

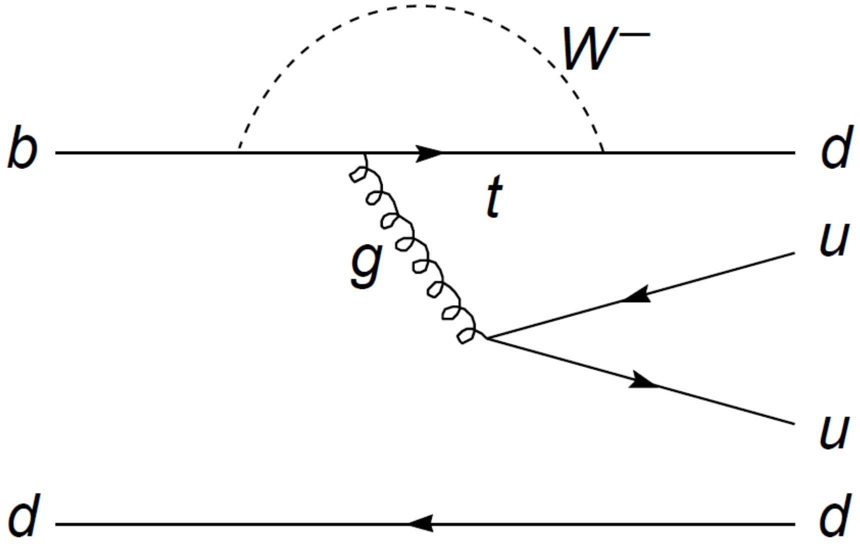
pdg.lbl.gov (Particle Data Group)

ckmfitter.in2p3.fr (global CKM fits)

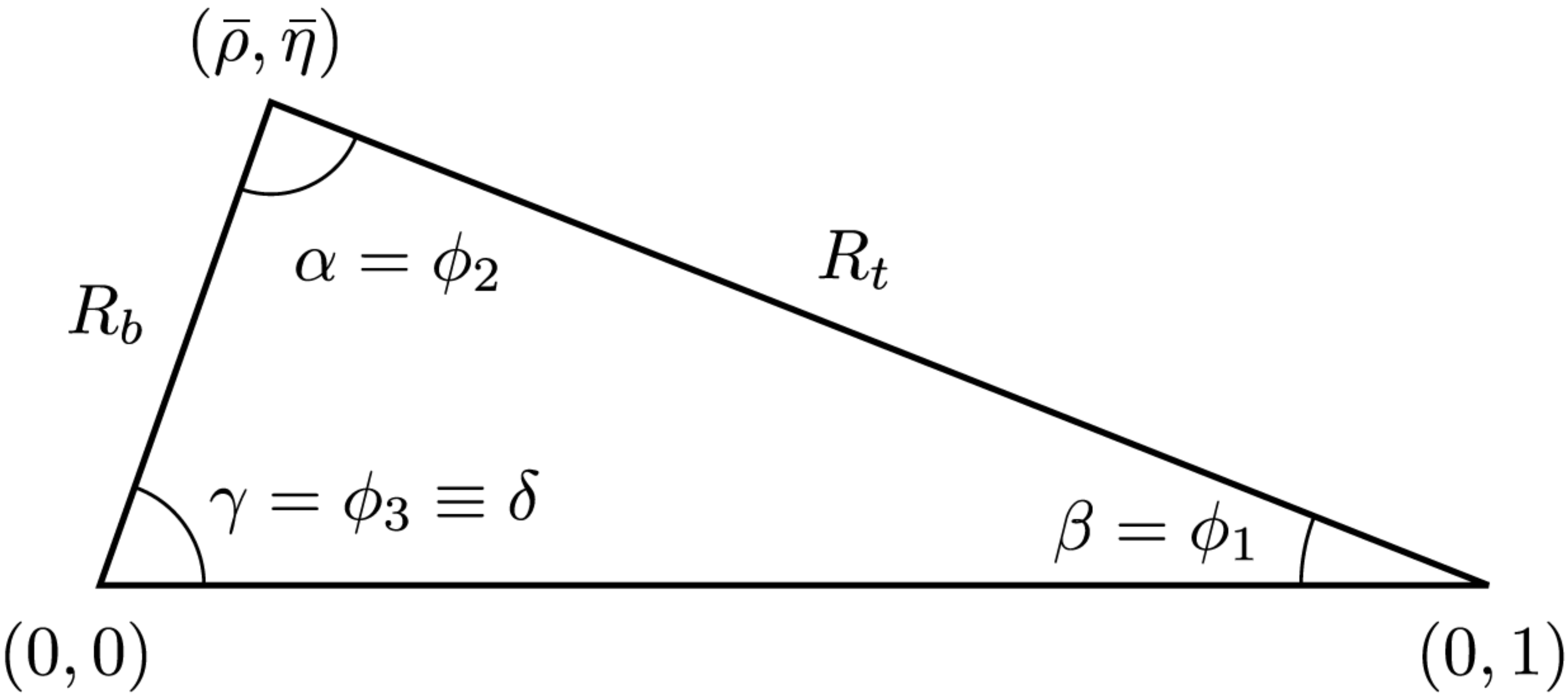
Backup

B → π π (phi1)



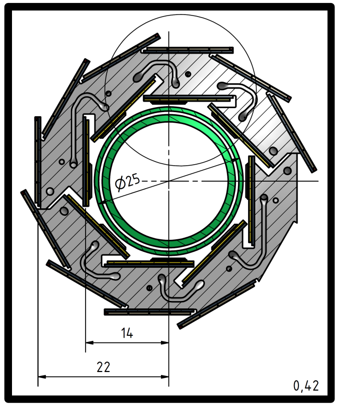


CKM, unitary triangle

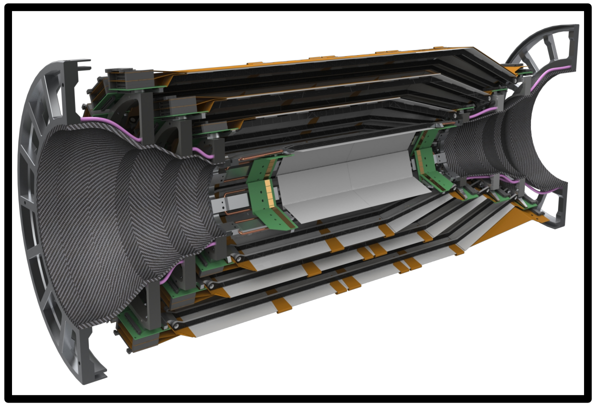


Belle II Vertex Detectors

- 2 layers of DEPFET pixel detectors (PXD)
- 4 layers of double-sided silicon strip detectors (SVD)



+



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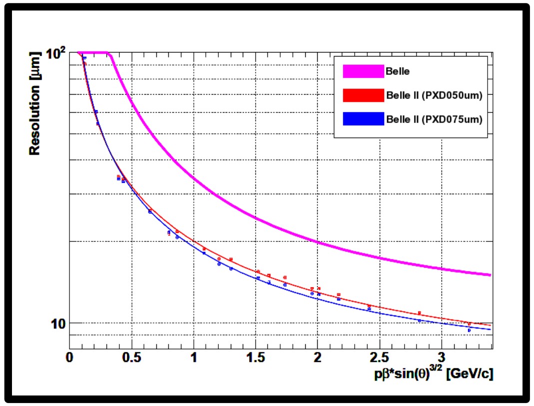


PXD
0.21% X_0/layer

pixel: 50x55/85µm
thickness: 75µm

hit time resolution: 20µs

SVD
0.55% X_0/layer

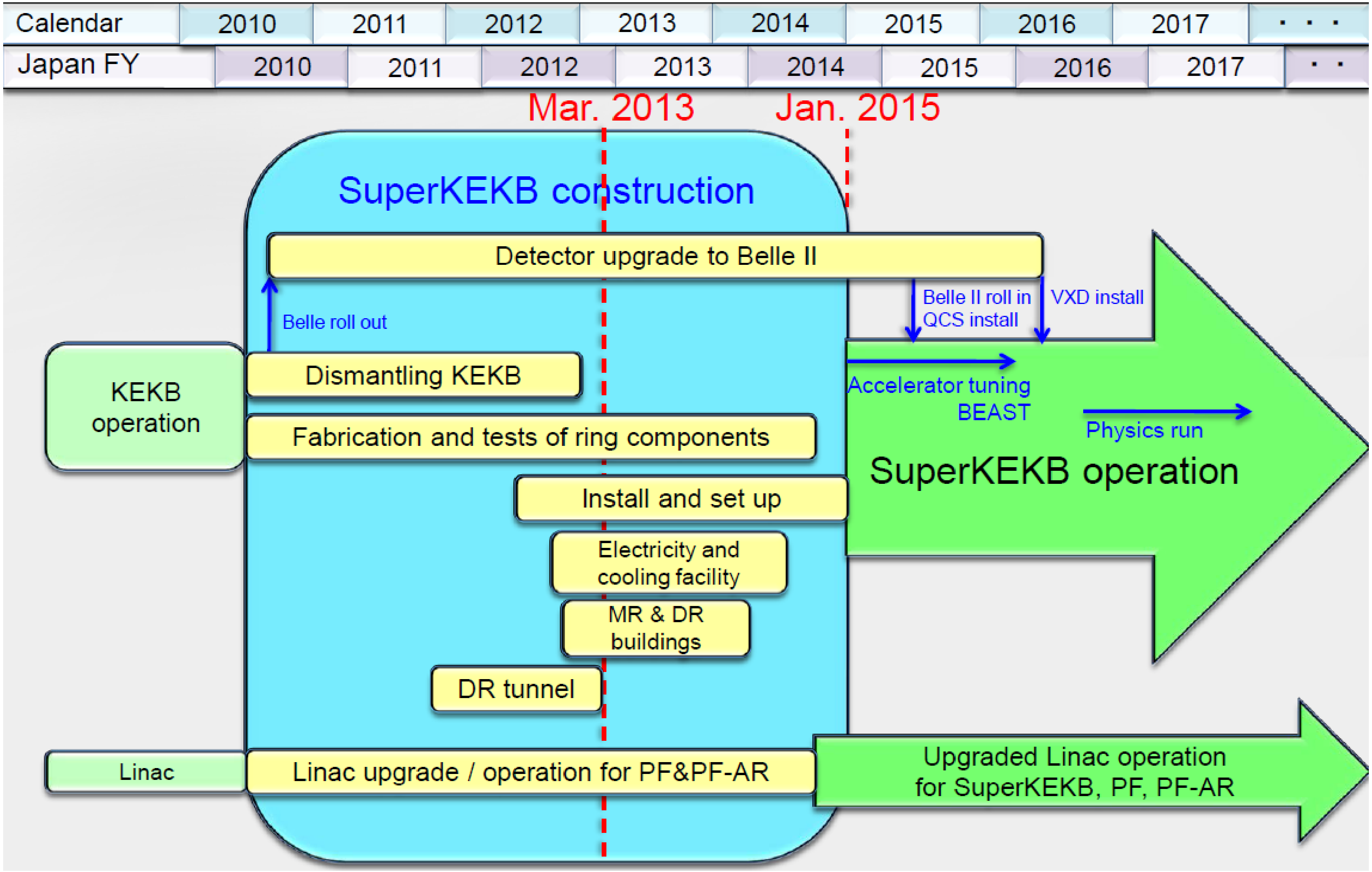
shaping time: 20ns
hit time resolution: 3ns

PXD + SVD = VXD

Z vertex resolution two times better than Belle

Improved K_s efficiency (e.g. $B \rightarrow K_s K_s K_s$, ...)

Belle II Schedule



Calendar	2010	2011	2012	2013	2014	2015	2016	2017	. . .
Japan FY	2010	2011	2012	2013	2014	2015	2016	2017	. .

Mar. 2013

Jan. 2015

SuperKEKB construction

Detector upgrade to Belle II

Belle roll out

Belle II roll in
QCS install

VXD install

KEKB
operation

Dismantling KEKB

Fabrication and tests of ring components

Install and set up

Electricity and
cooling facility

MR & DR
buildings

DR tunnel

Accelerator tuning
BEAST

Physics run

SuperKEKB operation

Linac

Linac upgrade / operation for PF&PF-AR

Upgraded Linac operation
for SuperKEKB, PF, PF-AR

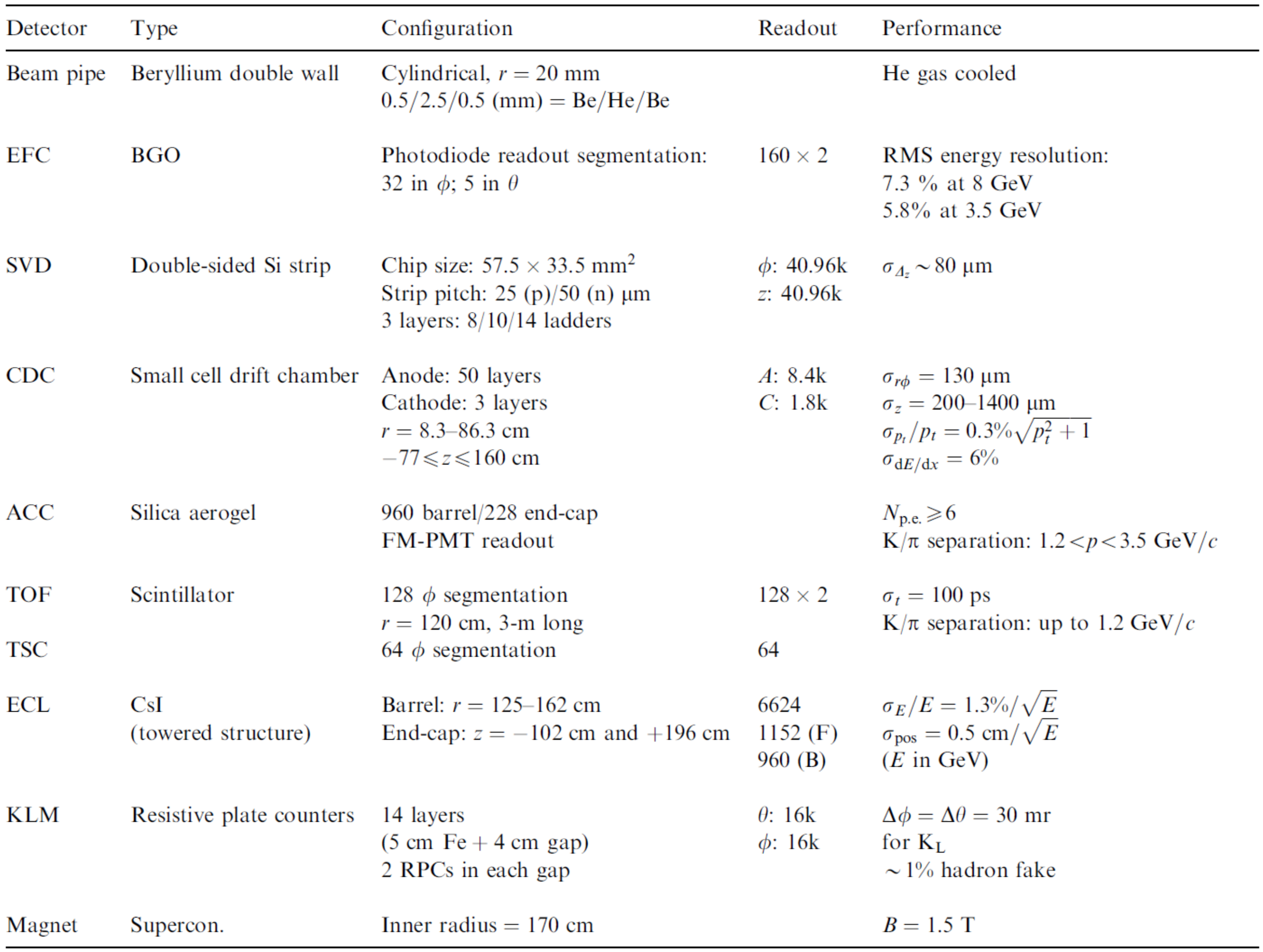
Belle II physics reach compared to LHCb

Observable/mode	Current now	LHCb (2017) 5 fb^{-1}	Super$B$ (2021) 75 ab^{-1}	Belle II (2021) 50 ab^{-1}	LHCb upgrade (10 years of running) 50 fb^{-1}	theory now
			τ Decays			
$\tau \to \mu\gamma$ ($\times 10^{-9}$)	< 44		< 2.4	< 5.0		
$\tau \to e\gamma$ ($\times 10^{-9}$)	< 33		< 3.0	< 3.7 (est.)		
$\tau \to \ell\ell\ell$ ($\times 10^{-10}$)	$< 150 - 270$	< 244 [a]	$< 2.3 - 8.2$	< 10	< 24 [b]	
			$B_{u,d}$ Decays			
BR($B \to \tau\nu$) ($\times 10^{-4}$)	1.64 ± 0.34		0.05	0.04		1.1 ± 0.2
BR($B \to \mu\nu$) ($\times 10^{-6}$)	< 1.0		0.02	0.03		0.47 ± 0.08
BR($B \to K^{*+}\nu\overline{\nu}$) ($\times 10^{-6}$)	< 80		1.1	2.0		6.8 ± 1.1
BR($B \to K^{+}\nu\overline{\nu}$) ($\times 10^{-6}$)	< 160		0.7	1.6		3.6 ± 0.5
BR($B \to X_s\gamma$) ($\times 10^{-4}$)	3.55 ± 0.26		0.11	0.13	0.23	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060		0.02	0.02		$\sim 10^{-6}$
$B \to K^*\mu^+\mu^-$ (events)	250[c]	8000	10-15k[d]	7-10k	100,000	-
BR($B \to K^*\mu^+\mu^-$) ($\times 10^{-6}$)	1.15 ± 0.16		0.06	0.07		1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	400	10-15k	7-10k	5,000	-
BR($B \to K^*e^+e^-$) ($\times 10^{-6}$)	1.09 ± 0.17		0.05	0.07		1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14[e]	[f]	0.040	0.03		-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280		8,600	7,000		-
BR($B \to X_s\ell^+\ell^-$) ($\times 10^{-6}$)[g]	3.66 ± 0.77[h]		0.08	0.10		1.59 ± 0.11
S in $B \to K_S^0\pi^0\gamma$	-0.15 ± 0.20		0.03	0.03		-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07		0.01	0.02		± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.15	0.02	0.03	0.03	± 0.02
			B_s^0 Decays			
BR($B_s^0 \to \gamma\gamma$) ($\times 10^{-6}$)	< 8.7		0.3	$0.2 - 0.3$		0.4 - 1.0
A_{SL}^s ($\times 10^{-3}$)	-7.87 ± 1.96 [i]	[j]	4.	5. (est.)		0.02 ± 0.01
			D Decays			
x	$(0.63 \pm 0.20)\%$	0.06%	0.02%	0.04%	0.02%	$\sim 10^{-2}$ [k]
y	$(0.75 \pm 0.12)\%$	0.03%	0.01%	0.03%	0.01%	$\sim 10^{-2}$ (see above).
y_{CP}	$(1.11 \pm 0.22)\%$	0.02%	0.03%	0.05%	0.01%	$\sim 10^{-2}$ (see above).
$\lvert q/p \rvert$	$(0.91 \pm 0.17)\%$	8.5%	2.7%	3.0%	3%	$\sim 10^{-3}$ (see above).
arg$\{q/p\}$ ($^\circ$)	-10.2 ± 9.2	4.4	1.4	1.4	2.0	$\sim 10^{-3}$ (see above).

canceled

arXiv:1109.5028v2

Belle detector performance



Detector	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double wall	Cylindrical, $r = 20$ mm 0.5/2.5/0.5 (mm) = Be/He/Be		He gas cooled
EFC	BGO	Photodiode readout segmentation: 32 in ϕ; 5 in θ	160×2	RMS energy resolution: 7.3 % at 8 GeV 5.8% at 3.5 GeV
SVD	Double-sided Si strip	Chip size: 57.5×33.5 mm^2 Strip pitch: 25 (p)/50 (n) μm 3 layers: 8/10/14 ladders	ϕ: 40.96k z: 40.96k	$\sigma_{\Delta_z} \sim 80$ μm
CDC	Small cell drift chamber	Anode: 50 layers Cathode: 3 layers $r = 8.3$–86.3 cm $-77 \leqslant z \leqslant 160$ cm	A: 8.4k C: 1.8k	$\sigma_{r\phi} = 130$ μm $\sigma_z = 200$–1400 μm $\sigma_{p_t}/p_t = 0.3\%\sqrt{p_t^2 + 1}$ $\sigma_{\mathrm{d}E/\mathrm{d}x} = 6\%$
ACC	Silica aerogel	960 barrel/228 end-cap FM-PMT readout		$N_{\mathrm{p.e.}} \geqslant 6$ K/π separation: $1.2 < p < 3.5$ GeV/c
TOF	Scintillator	128 ϕ segmentation $r = 120$ cm, 3-m long	128×2	$\sigma_t = 100$ ps K/π separation: up to 1.2 GeV/c
TSC		64 ϕ segmentation	64	
ECL	CsI (towered structure)	Barrel: $r = 125$–162 cm End-cap: $z = -102$ cm and $+196$ cm	6624 1152 (F) 960 (B)	$\sigma_E/E = 1.3\%/\sqrt{E}$ $\sigma_{\mathrm{pos}} = 0.5\ \mathrm{cm}/\sqrt{E}$ (E in GeV)
KLM	Resistive plate counters	14 layers (5 cm Fe + 4 cm gap) 2 RPCs in each gap	θ: 16k ϕ: 16k	$\Delta\phi = \Delta\theta = 30$ mr for K_L $\sim 1\%$ hadron fake
Magnet	Supercon.	Inner radius = 170 cm		$B = 1.5$ T

NIMA479 (2002), 117-232