Belle II and the SuperKEKB Project
Mission for New Physics

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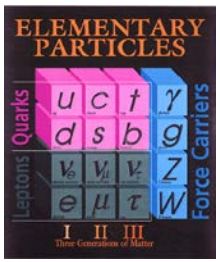
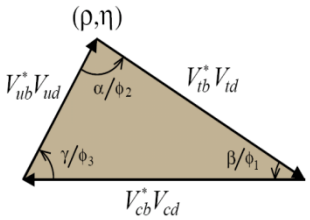
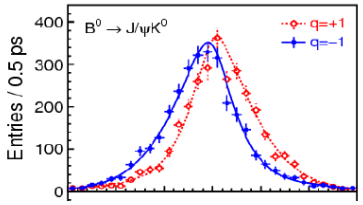
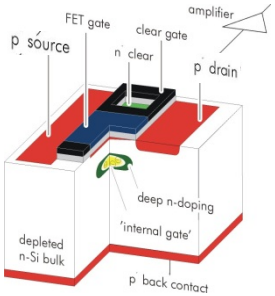
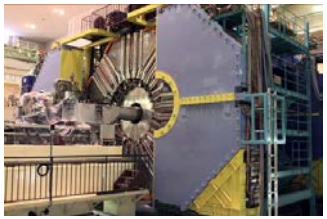




- A bit of Physics Motivation …
- Milestones from the B-Factories
- Why go beyond ?
- SuperKEKB and Belle II





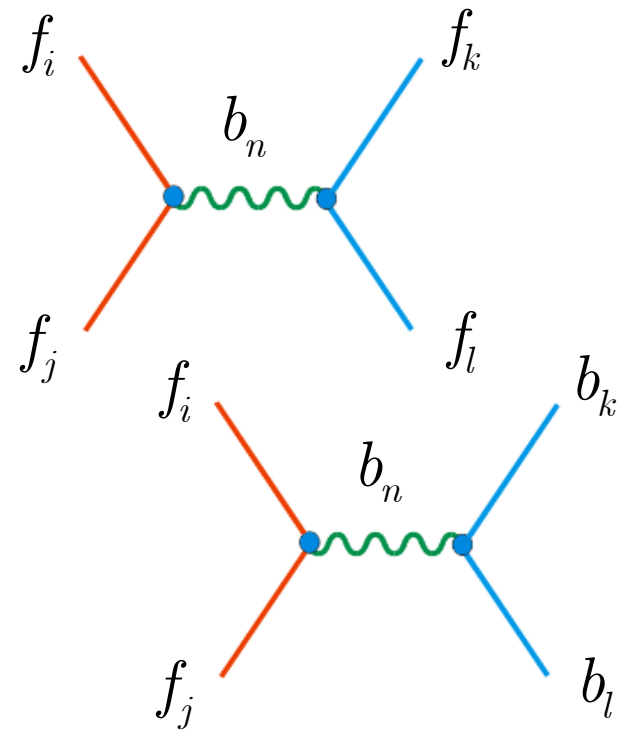


Today's Standard Model

mass →	≈2.3 MeV/c²	≈1.275 GeV/c²	≈173.07 GeV/c²	0	≈126 GeV/c²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
QUARKS	≈4.8 MeV/c²	≈95 MeV/c²	≈4.18 GeV/c²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d	s	b	γ	
	down	strange	bottom	photon	
LEPTONS	0.511 MeV/c²	105.7 MeV/c²	1.777 GeV/c²	91.2 GeV/c²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
	<2.2 eV/c²	<0.17 MeV/c²	<15.5 MeV/c²	80.4 GeV/c²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e	ν_μ	ν_τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

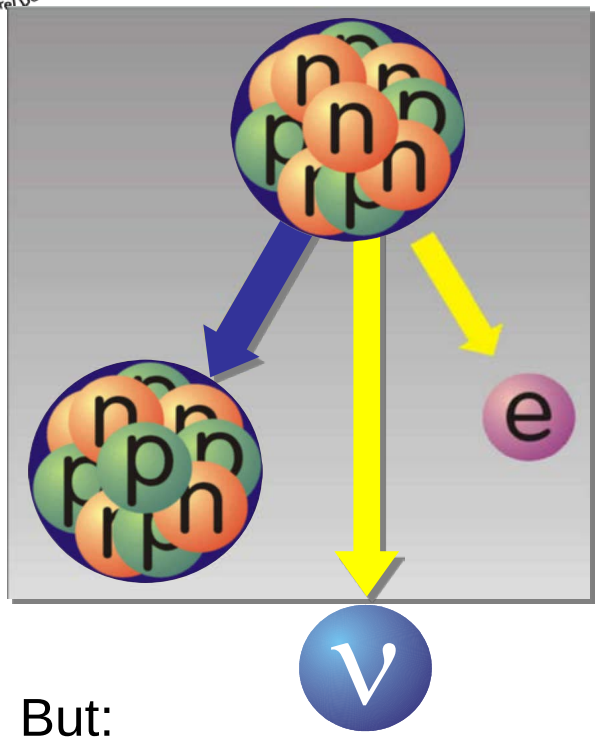
GAUGE BOSONS

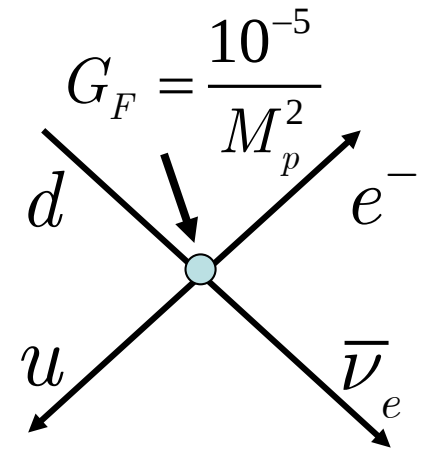
Fermions (spin ½) | Bosons (spin 1, 0)



all measured processes well described by SM

The Way to the Standard Model

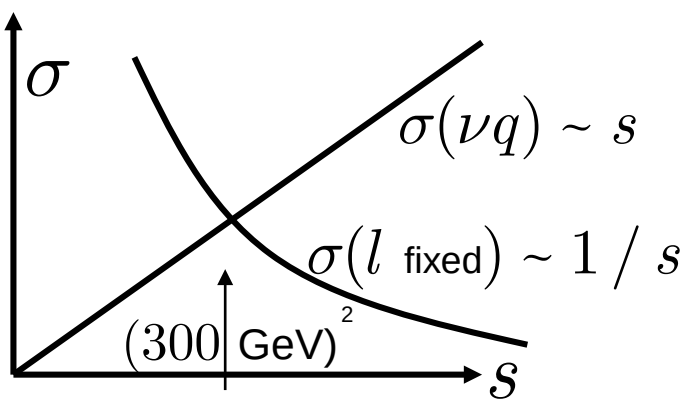


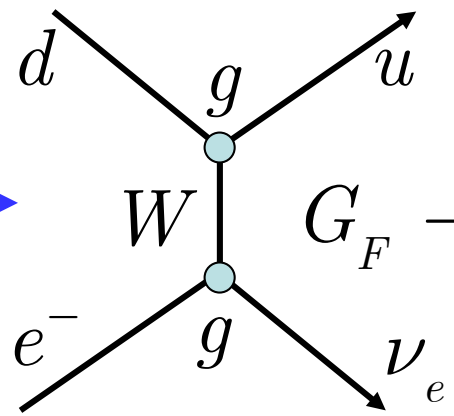


1930's: 4-fermion theory

describes low-energy weak interactions satisfactorily, including parity violation (V-A structure of currents, introduced in 1958 by Feynman and Gell-Mann)

But:
unitarity is violated at V. H.E.





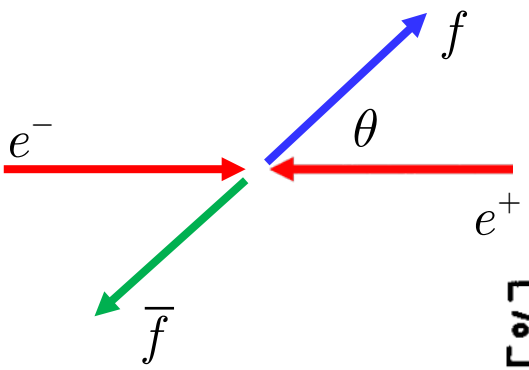
$$G_F \rightarrow \left(\frac{g^2}{q^2 - M_W^2} \right)$$

Standard Model: Tree Contibutions

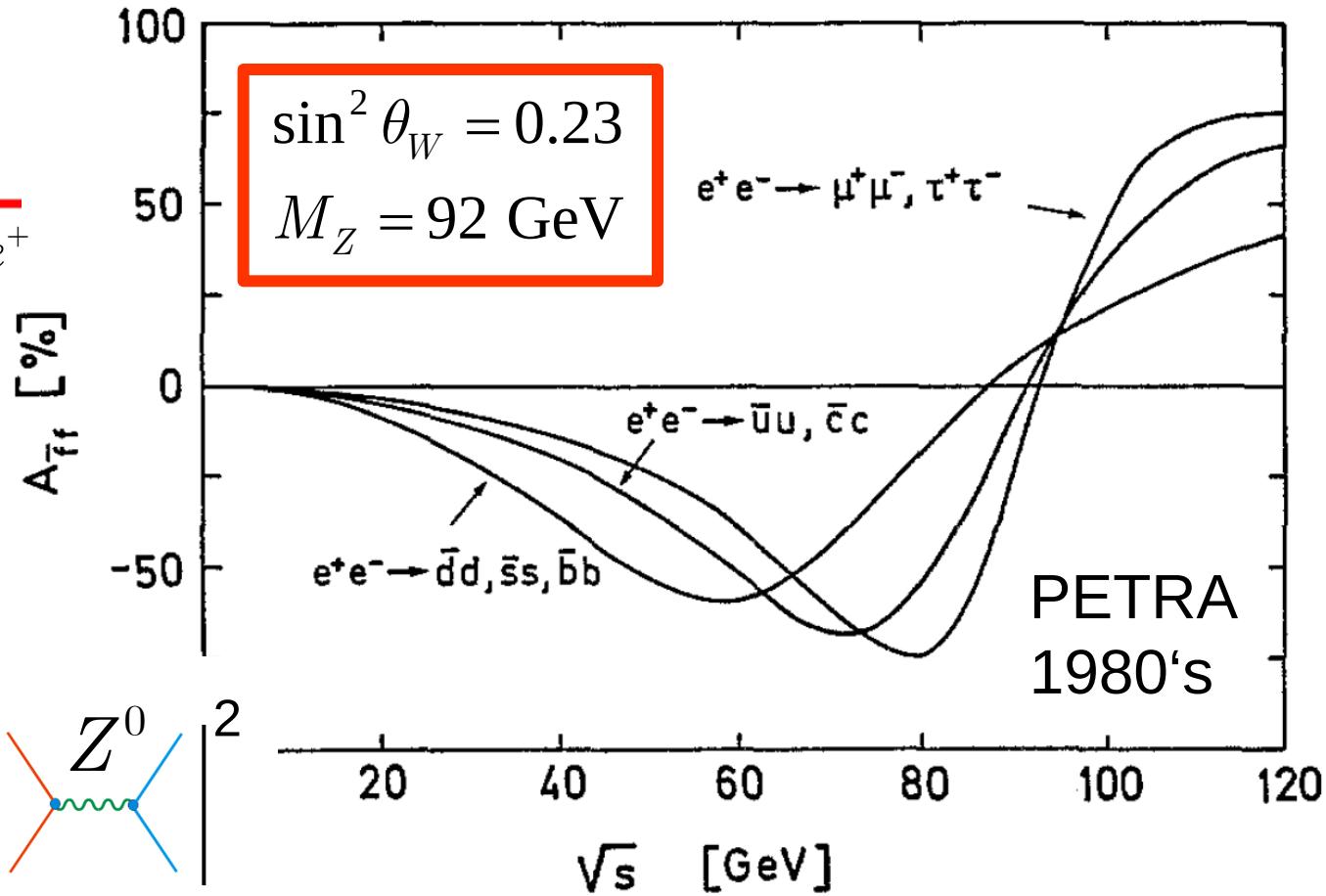
$$G_F \rightarrow \left(\frac{g^2}{q^2 - M_W^2} \right) \Rightarrow e = g \sin\theta_W \Rightarrow \frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2\sin^2\theta_W M_W^2}$$

„SM“

$$M_W / M_Z = \cos\theta_W$$



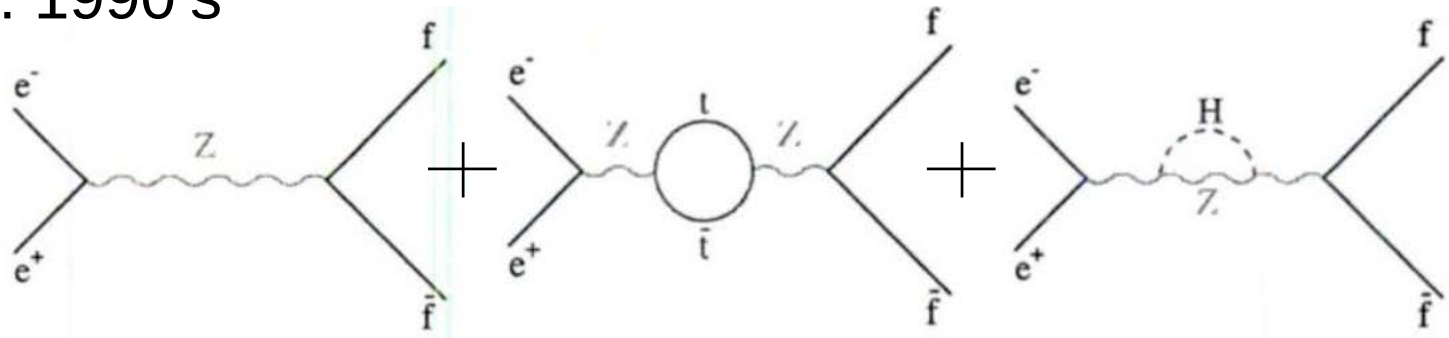
„Forward-backward“ angular asymmetry



$$\frac{d\sigma}{d\Omega} = \left| \gamma + Z^0 \right|^2$$

„Finding“ the Top and the Higgs: Quantum Loops

LEP: 1990‘s



$$M_W^2 = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W(1-\Delta r)}$$

$$\Delta r = \underbrace{\Delta r(\mathrm{had}) + \Delta r(\mathrm{top}) + \Delta r(\mathrm{Higgs})}_{\text{loop corrections}}$$

„known“ from L.E.measurements

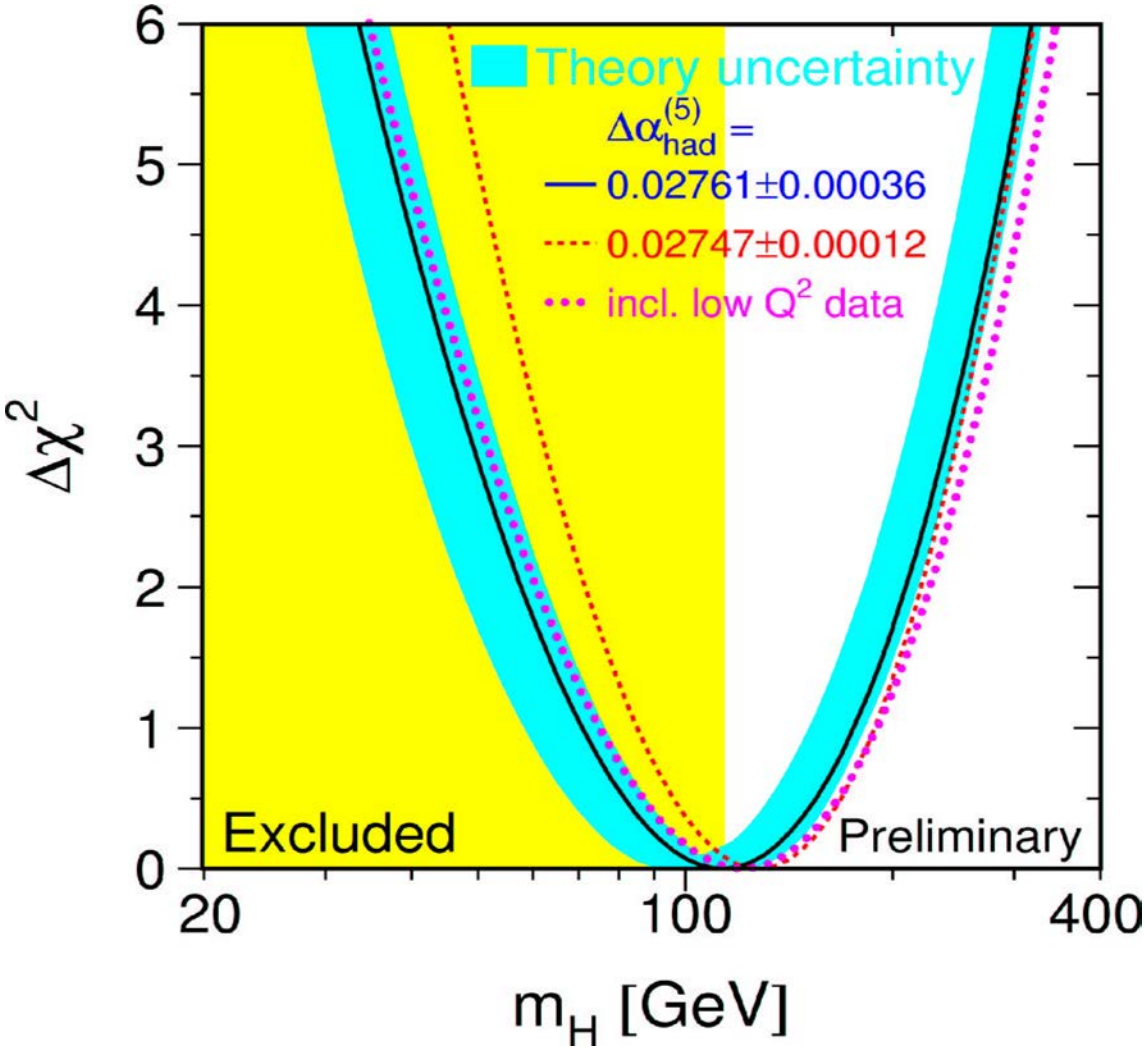
$$\Delta r(\mathrm{top}) = \frac{3G_F}{8\sqrt{2}\tan^2\theta_W} m_t^2$$

Small, but very sensitive to the top mass

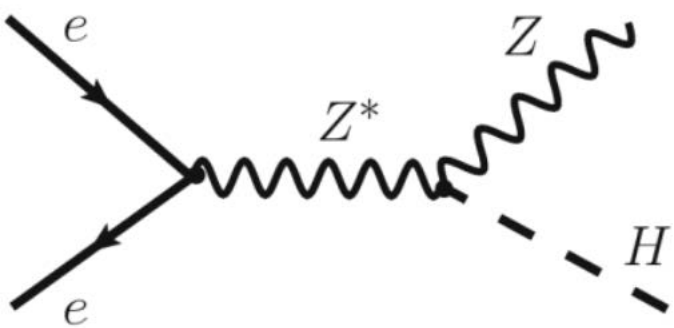
$$\Delta r(\mathrm{Higgs}) = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{m_Z^2} - \frac{5}{6}\right)$$

Small, logarithmic sensitivity, but “measurable“ when the top mass is known precisely

„Finding“ the Top and the Higgs: Quantum Loops



LEP fits suggested a very light Higgs

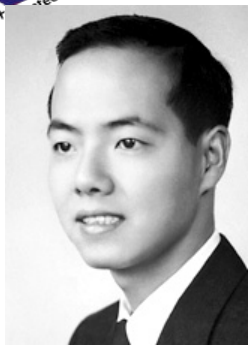


LEP 2 used to look for „Higgs-Strahlung“,

But no signal found …

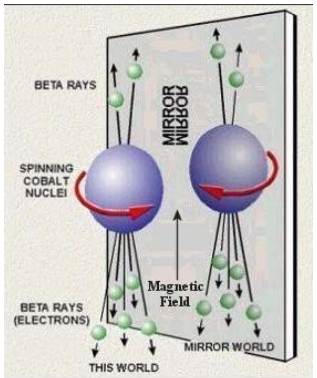
$$m_H > 113 \text{ GeV}$$

Major Discoveries in Weak Interactions of Quarks



T.D. Lee

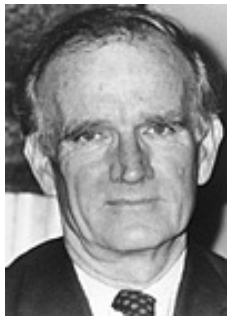
C.N. Yang



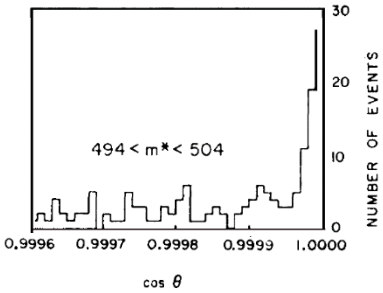
P violated maximally in weak interactions

1957

J. Cronin



V. Fitch

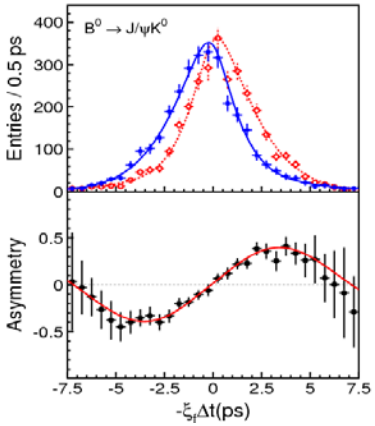


Small CP violation in neutral K system

1980

M. Kobayashi

T. Maskawa



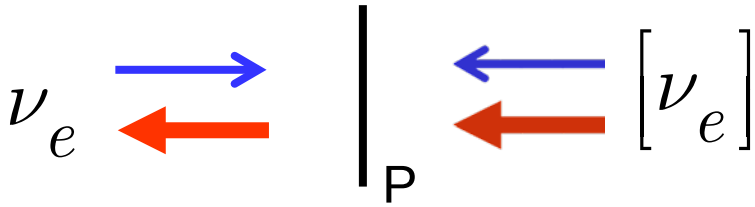
O(1) CP violation and 3 generations of quarks

2008

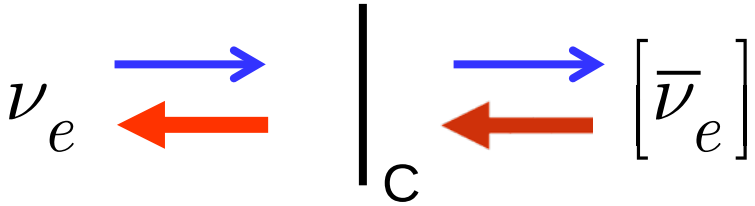
Fundamental Discrete Symmetries

$\vec{p}$ → momentum $\vec{s}$ → spin

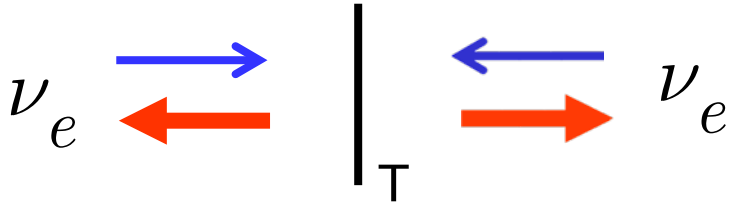
Spatial Inversion P:



Charge Conjugation C:



Time reversal T:



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$\vec{p}$ → momentum $\vec{s}$ → spin

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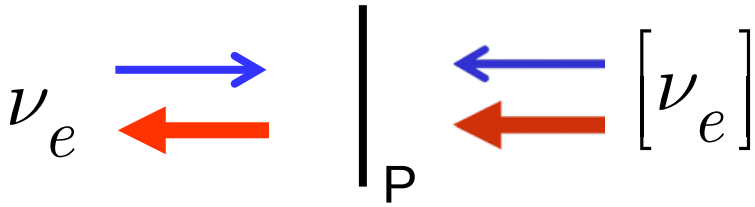
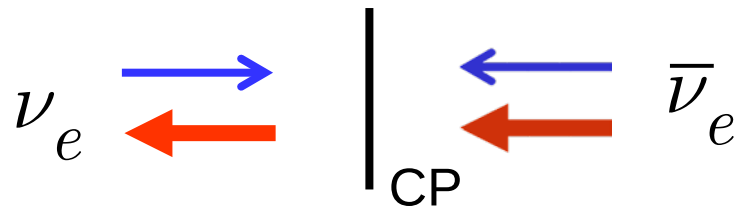
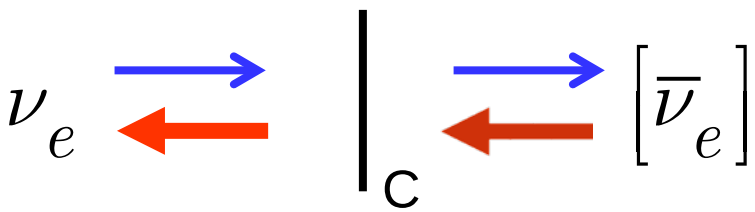


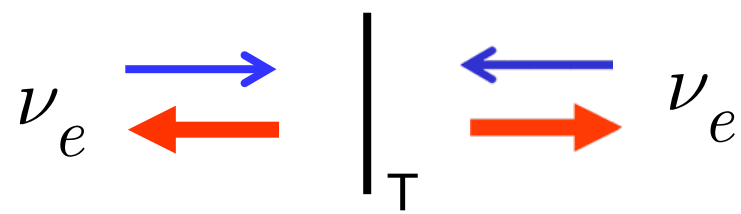
Spatial + Charge CP:



Charge Conjugation C:



Time reversal T:



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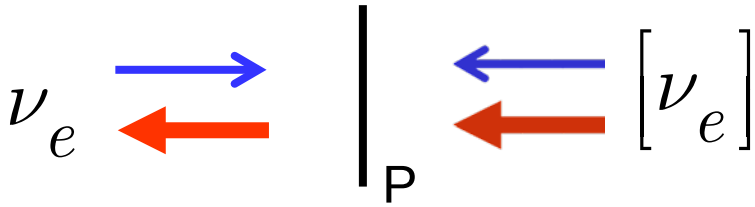
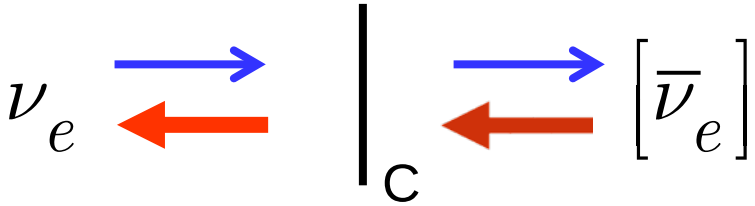
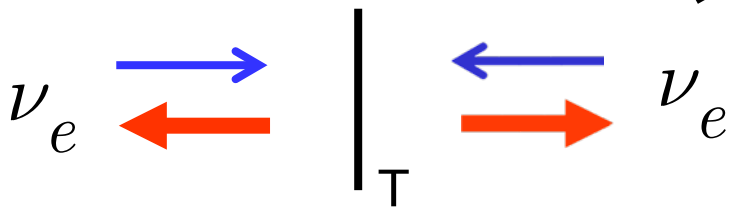


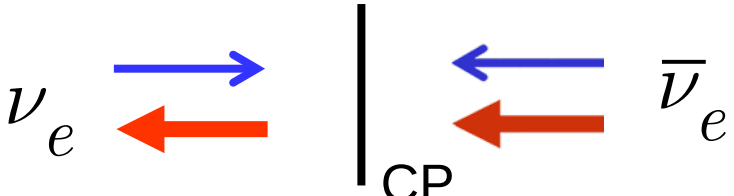
Charge Conjugation C:



Time reversal T:



Spatial + Charge CP:

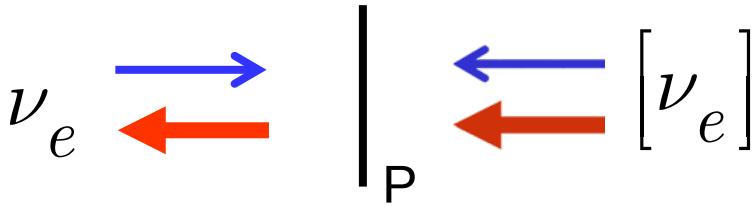


seems conserved

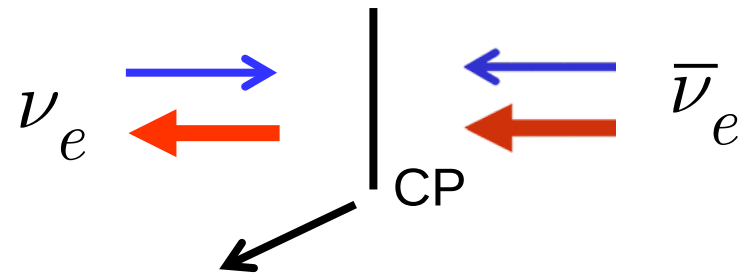
Fundamental Discrete Symmetries

$\vec{p}$ → momentum $\vec{s}$ → spin

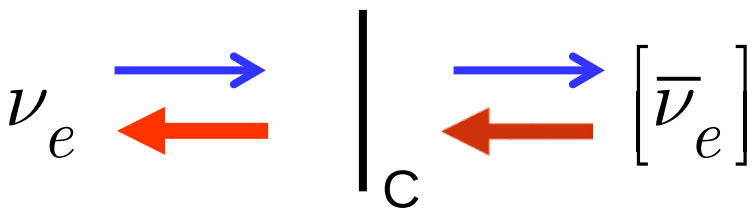
Spatial Inversion P:



Spatial + Charge CP:

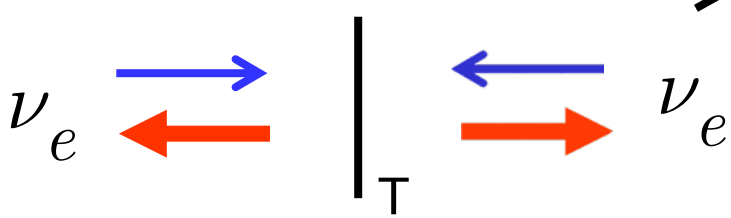


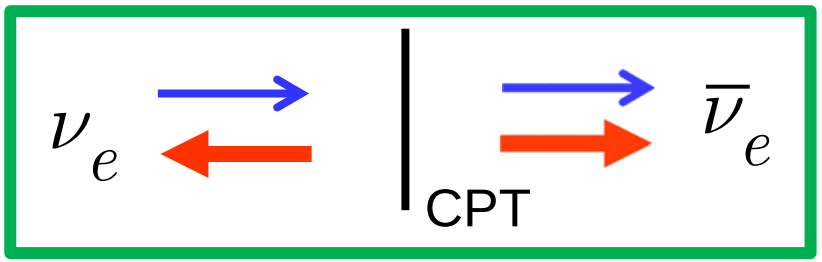
Charge Conjugation C:



conserved for ν ??

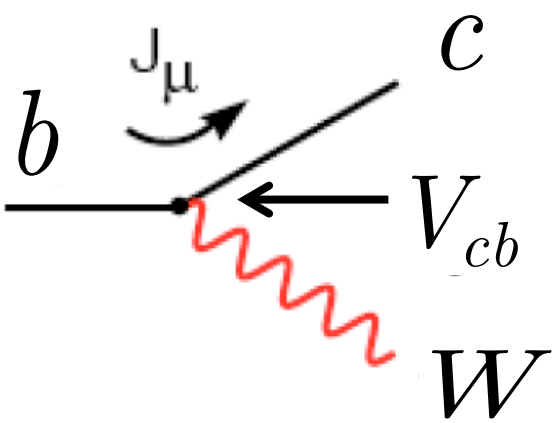
Time reversal T:





CPT: conserved in all quantum theories exhibiting Lorentz-invariance

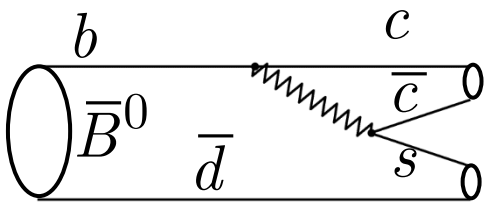
Changing Flavor: Trees, Penguins, and …



Flavor changing („charged current“) transitions proceed via a TREE DIAGRAM

first order

$$B^0(\overline{B}^0) \to J/\psi\, K_{S,L}$$



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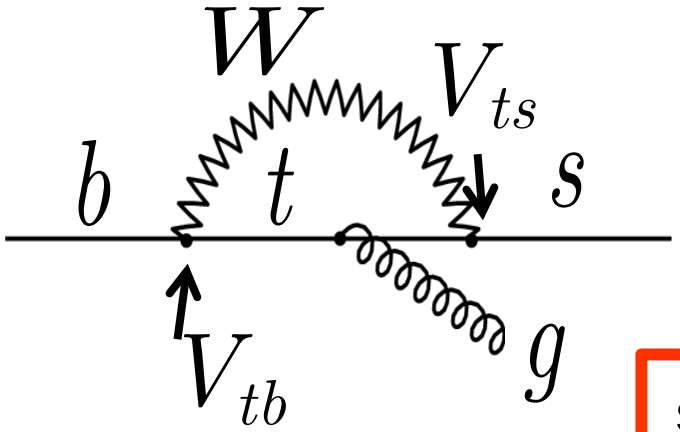
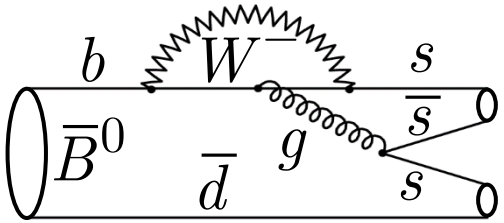


Flavor changing („neutral current“) transitions proceed via a PENGUIN DIAGRAM

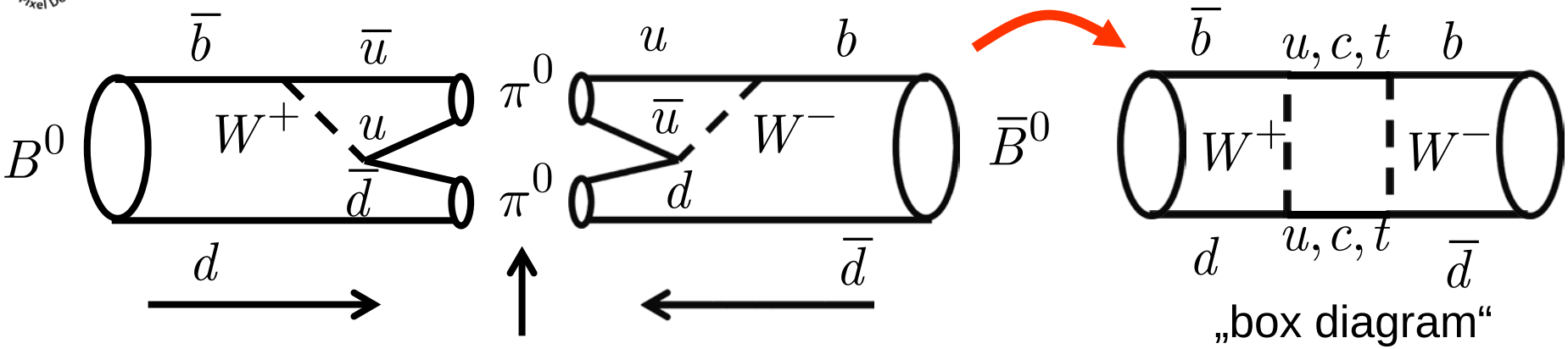
second order

$$B^0(\overline{B}^0) \to \phi\, K_{S,L}$$



P

… Boxes: Matter-Antimatter Oscillations



same final state

„box diagram“

$$\boxed{\left\langle \bar{B}^0 \middle| B^0 \right\rangle \neq 0}$$

time-dependent Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0(t) \\ \bar{B}^0(t) \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\begin{pmatrix} B^0(t) \\ \bar{B}^0(t) \end{pmatrix}$$

Mass eigenstates:

$$\left| B_L \right\rangle = p\left| B^0 \right\rangle + q\left| \bar{B}^0 \right\rangle \;: CP = +1$$

$$\left| B_H \right\rangle = p\left| B^0 \right\rangle - q\left| \bar{B}^0 \right\rangle \;: CP = -1$$

$$\left\langle B^0 \middle| \psi \right\rangle = a\left(e^{-iM_L t} + e^{-iM_H t}\right)$$

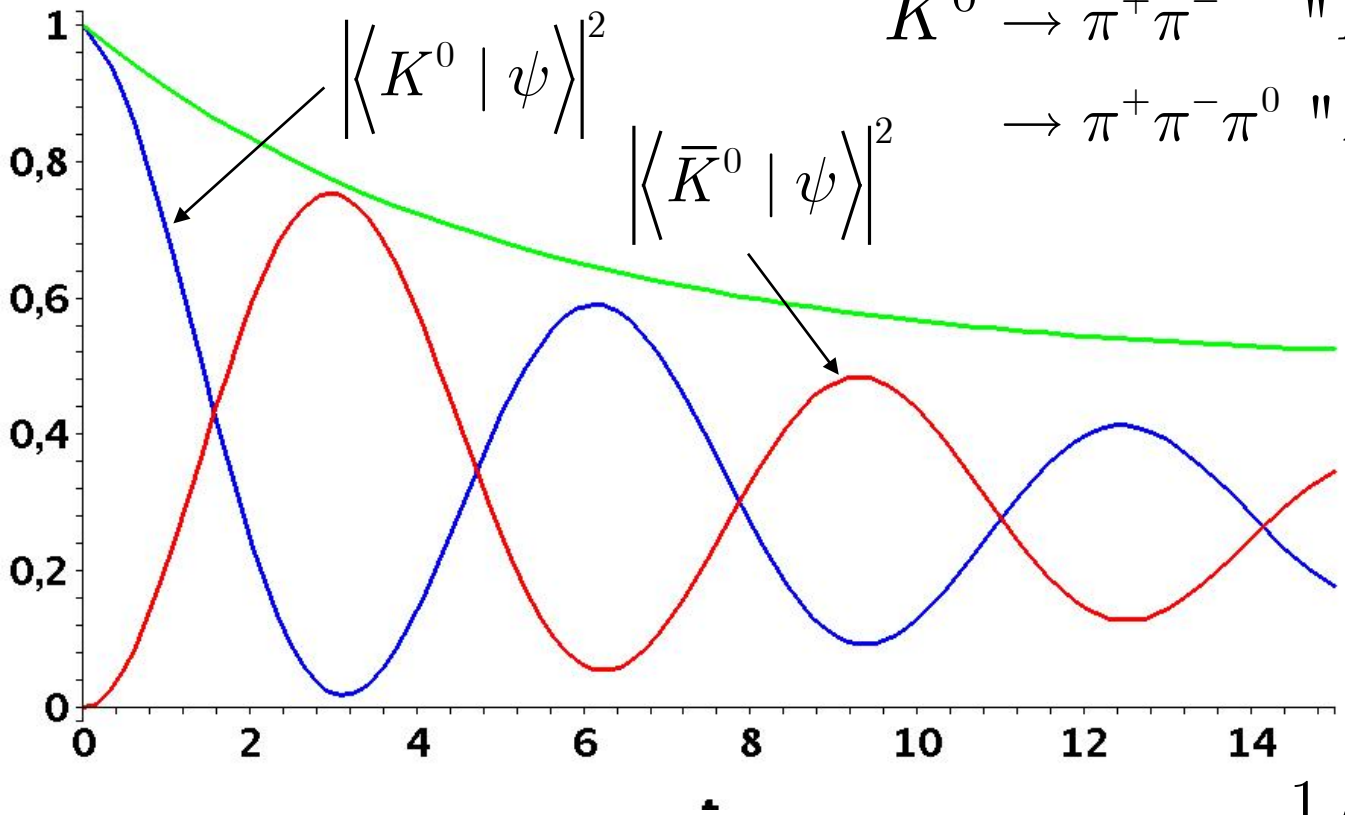
$$\left\langle \bar{B}^0 \middle| \psi \right\rangle = a\left(e^{-iM_L t} - e^{-iM_H t}\right)$$

„Flavor Oscillations“

Example for Flavor Oscillations in the K-System

Production: $\pi^- p \rightarrow \Lambda K^0$

$$K^0 \rightarrow \pi^+\pi^- \quad "K_S": CP = +1$$
$$\rightarrow \pi^+\pi^-\pi^0 \quad "K_L": CP = -1$$



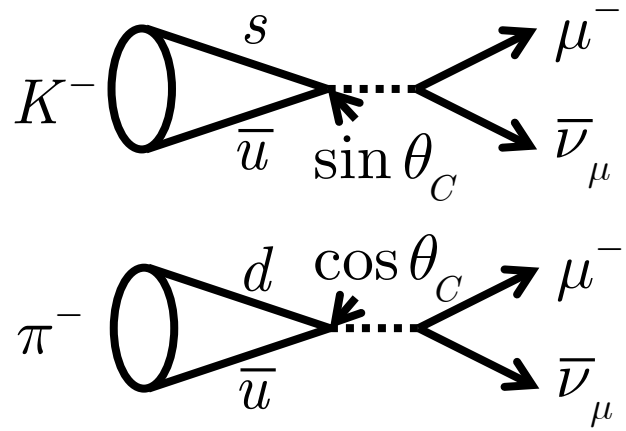
$$\Delta M = 5\Gamma_1$$
$$\Gamma_2 = 0$$
$$K - \text{System}:$$
$$\Gamma_1 / \Gamma_2 : 600$$
$$1 / \Delta M$$

Probabilities of observing kaon decays

Cronin and Fitch observe manifest CP violation: $K_L \rightarrow \pi^+\pi^-$

The Origin of CP Violation in the SM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



„flavor“ M atrix V: unitary „mass“

$$d' \approx d\cos\theta_C + s\sin\theta_C$$
$$s' \approx -d\sin\theta_C + s\cos\theta_C$$

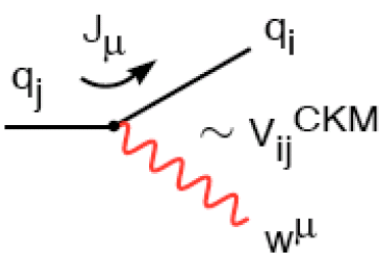
CP violation from Quark Mixing:
Extension of the Cabibbo-Matrix**!**

Mathematical reason: Matrix must have complex elements to violate CP:
only possible via n x n matrix with n > 2

Theory formulated in 1973 by Kobayashi & Maskawa
(Charm-, Bottom- and Top-Quark were not discovered yet!)

b-quark experiments have established the theory of K&M !

CKM Matrix and the Unitarity Triangle(s)



weak decays of hadrons (quarks change flavor) are described in the SM by the (unitary) CKM matrix

Cabibbo, Kobayashi, Maskawa

$$\lambda = \sin\theta_C$$

$$V^{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

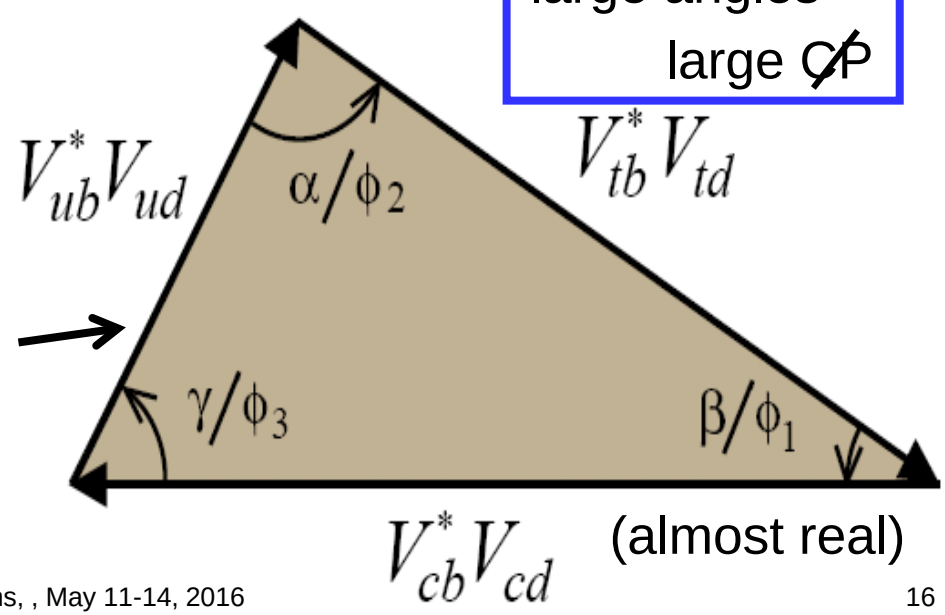
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

Triangle for K mesons

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

Triangle for B mesons

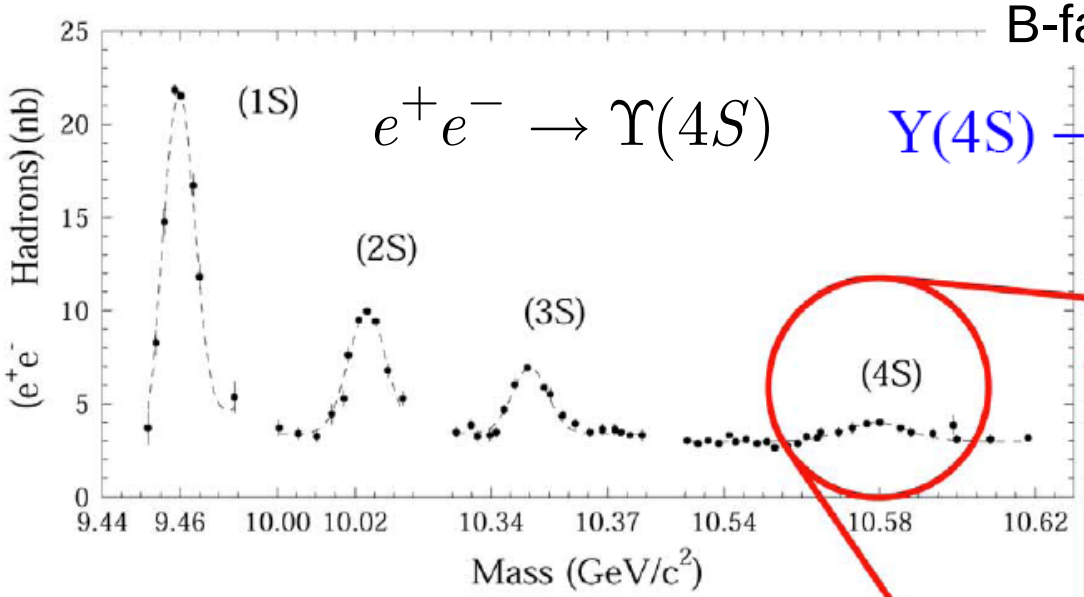
large angles = large $\not{C}\not{P}$



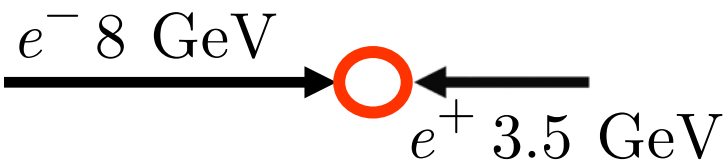
(almost real)

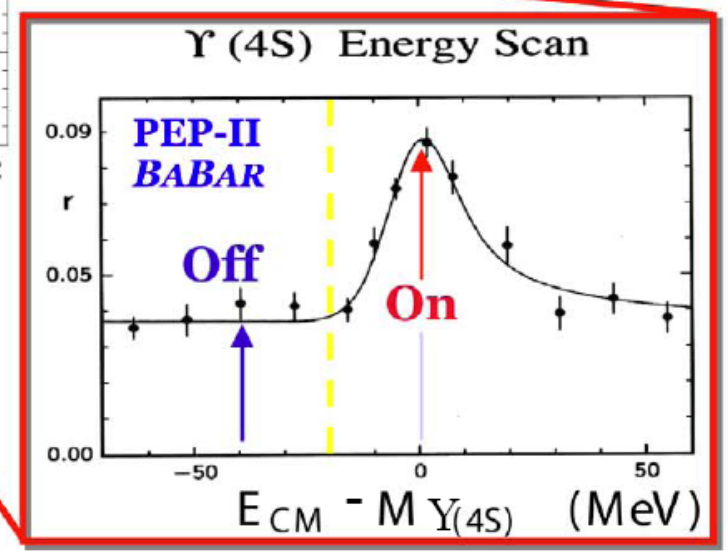
B-Factories: Where do we Measure?

B-factories at KEK and SLAC



$\Upsilon(4S) \to B^0\bar{B}^0\,(50\%),\ B^+B^-\,(50\%)$





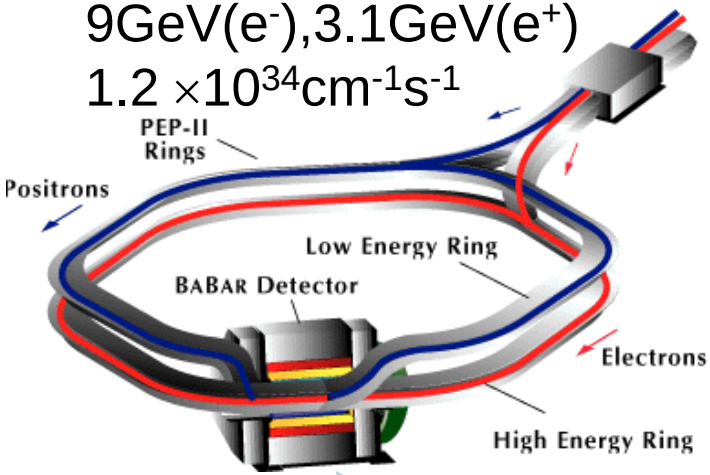
B-mesons are produced exclusively !

Beam energies are asymmetric:
both B‘s have the same Lorentz boost,
fly parallel in the lab system

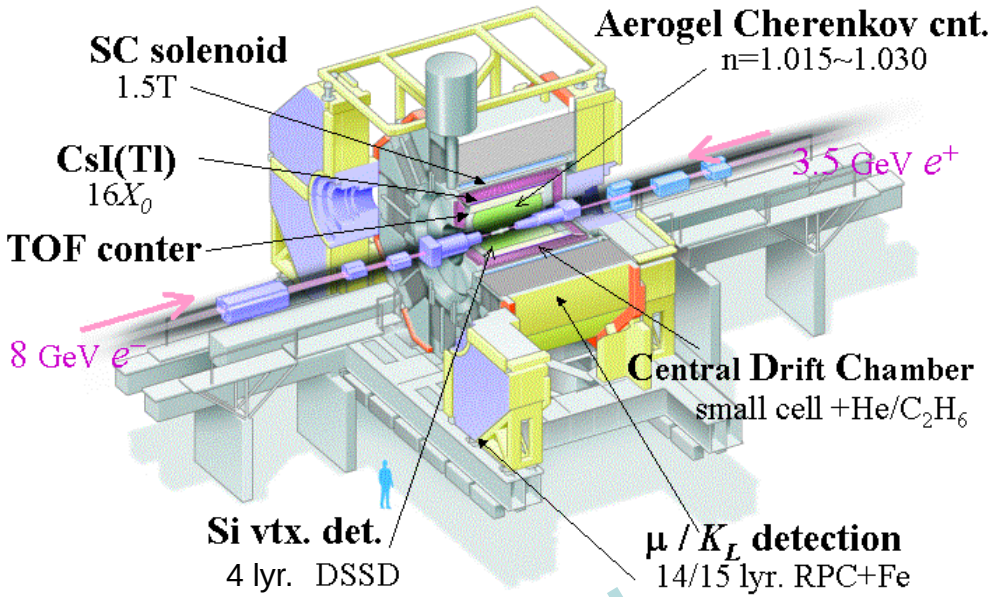
large background („continuum“)
below the resonance peak

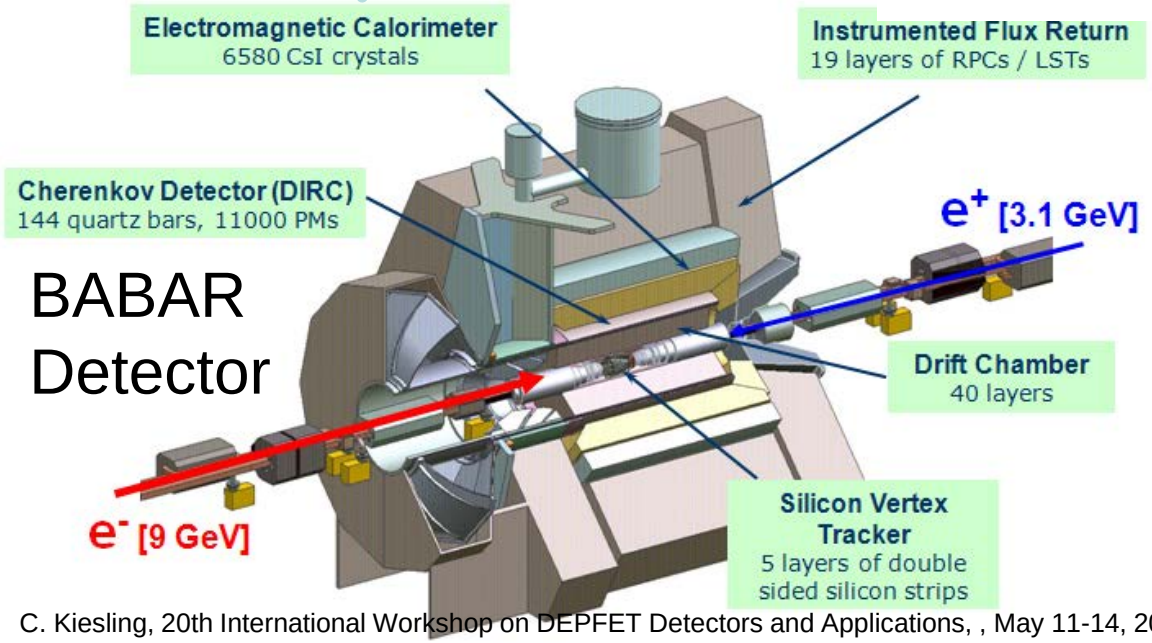
B-Factories

PEP-II
9GeV(e^-),3.1GeV(e^+)
1.2 $\times 10^{34} cm^{-1} s^{-1}$

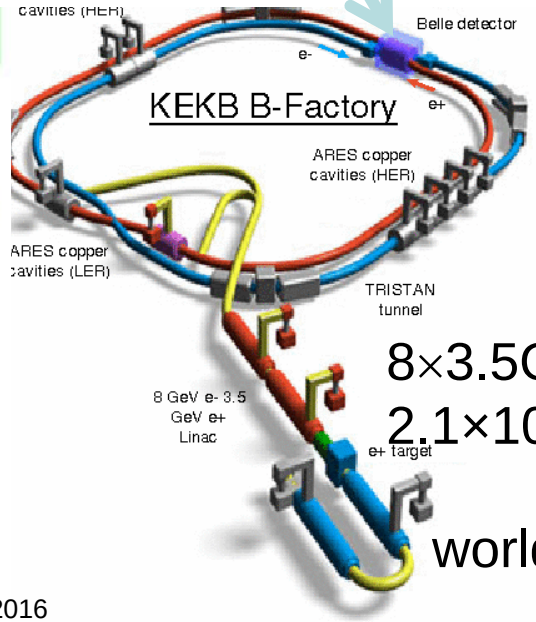


Belle Detector





BABAR Detector



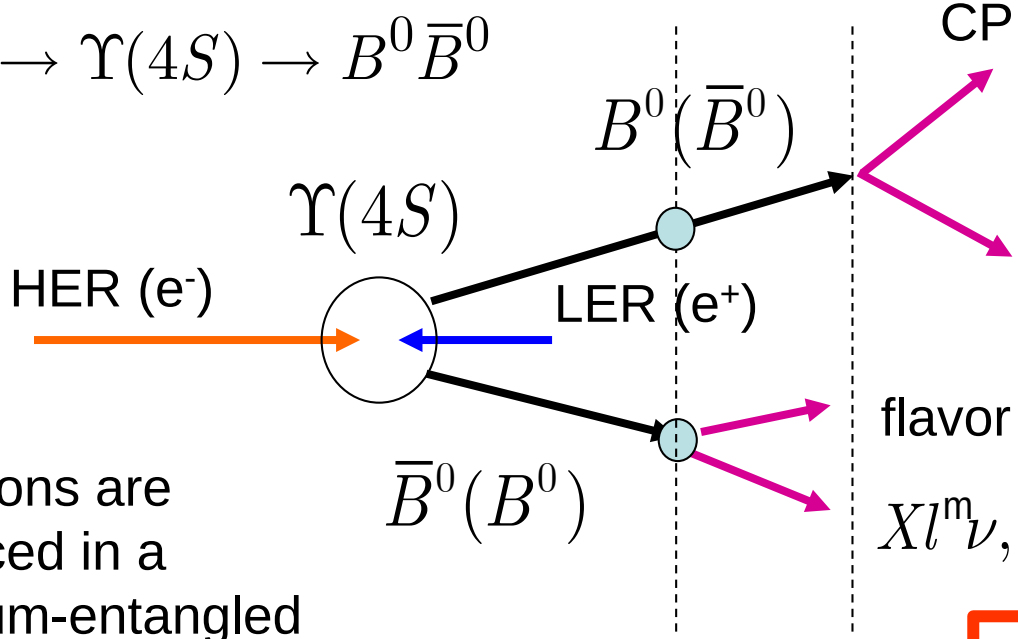
8×3.5GeV
2.1×$10^{34} cm^{-2} s^{-1}$

world record !

The $\not{C}\not{P}$ Observables: What do we measure?

B-Mesons: $\left|B^0\right\rangle = \left|\bar{b}d\right\rangle \quad \left|B^+\right\rangle = \left|\bar{b}u\right\rangle$

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$



some state $f(\bar{f})$ or CP eigenstate, e.g.

$J/\psi K_S$ the „Golden" channel

$CP = -1$

flavor eigenstate

$Xl^m\nu, D^{*\pm}X$ „flavor tagging"

B mesons are produced in a quantum-entangled state !

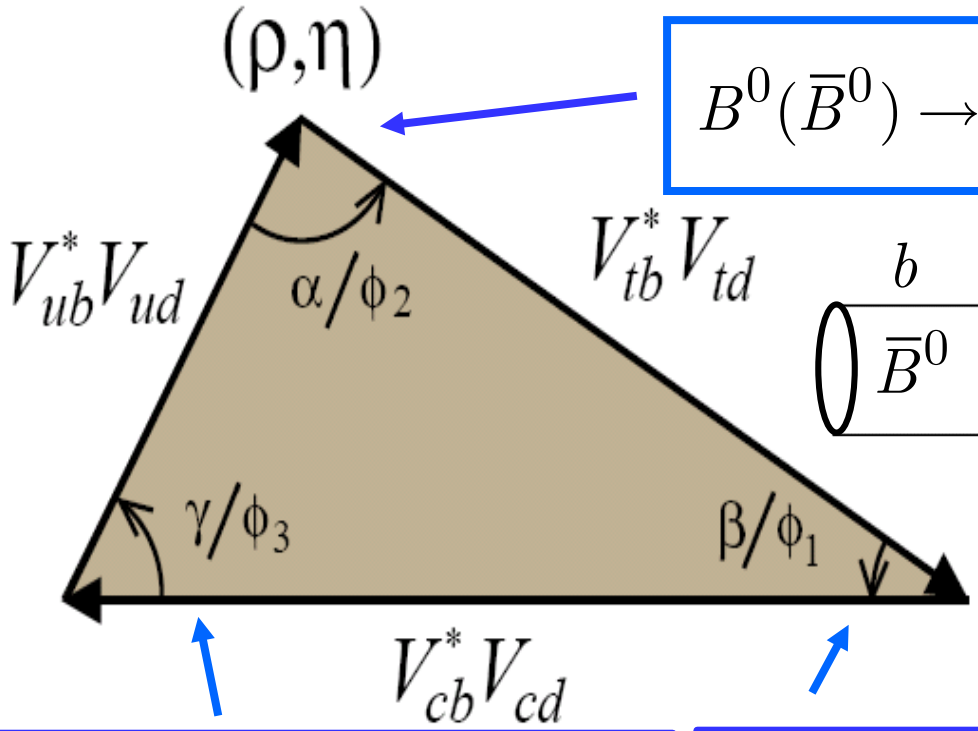
$\Delta z = \beta\gamma c \Delta t$

$$\Delta t = t_{\mathrm{CP}} - t_{\mathrm{tag}}$$

Asymmetric beam energies: translate decay time to decay length

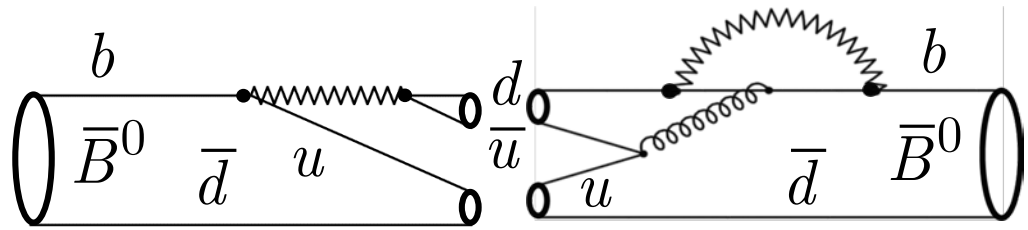
→ need excellent vertex detection

Measuring the Angles Φ_1,Φ_2,Φ_3 (β,α,γ)



$$B^0(\bar{B}^0) \to \pi\pi, \rho\rho, \rho\pi, a_1\pi$$

Br : 10^{-6}

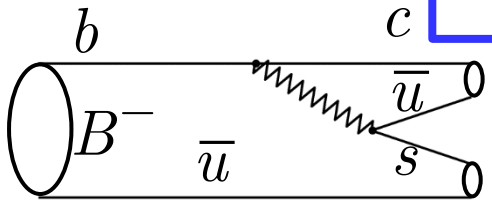


T ~ P

Tree (T) or Penguin (P) dominates

$$B^+(B^-) \to D\,K, D^*\pi$$
$$B^0(\bar{B}^0) \to K\pi$$

Br : 10^{-5}

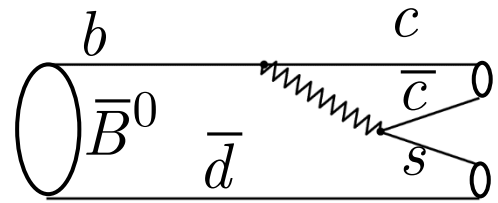


T (only)

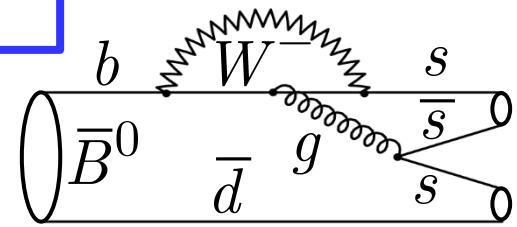
$$B^0(\bar{B}^0) \to J/\psi\, K_{S,L}$$
$$\to \phi\, K_{S,L}$$

Br : 10^{-4}

....



T

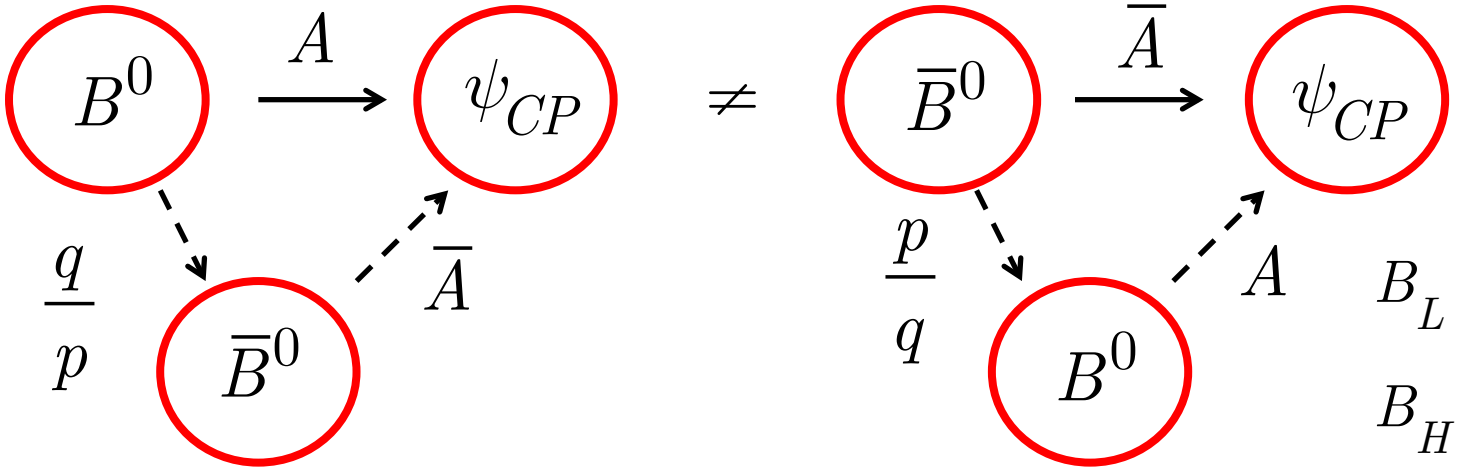


P

What are the Observables ?

$$A = \left\langle \psi_{CP} \mid B^0 \right\rangle; \quad \bar{A} = \left\langle \psi_{CP} \mid \bar{B}^0 \right\rangle$$

ψ_{CP} : CP eigenstate



$$\lambda_\psi = \frac{q}{p}\frac{\bar{A}}{A}$$

$$B_L = pB^0 + q\bar{B}^0$$

$$B_H = pB^0 - q\bar{B}^0$$

$$\mathcal{A}_{CP}(\psi, \Delta t) = \frac{\Gamma(\bar{B}^0 \to \psi; \Delta t) - \Gamma(B^0 \to \psi; \Delta t)}{\Gamma(\bar{B}^0 \to \psi; \Delta t) + \Gamma(B^0 \to \psi; \Delta t)}$$

„time-dependent CP asymmetry“

$$= \frac{1 - \left|\lambda_\psi\right|^2}{1 + \left|\lambda_\psi\right|^2} \cos \Delta m \Delta t + \frac{2\,\mathrm{Im}(\lambda_\psi)}{1 + \left|\lambda_\psi\right|^2} \sin \Delta m \Delta t$$

„direct“

„mixing-induced“

Time-Dependent CP-Asymmetries

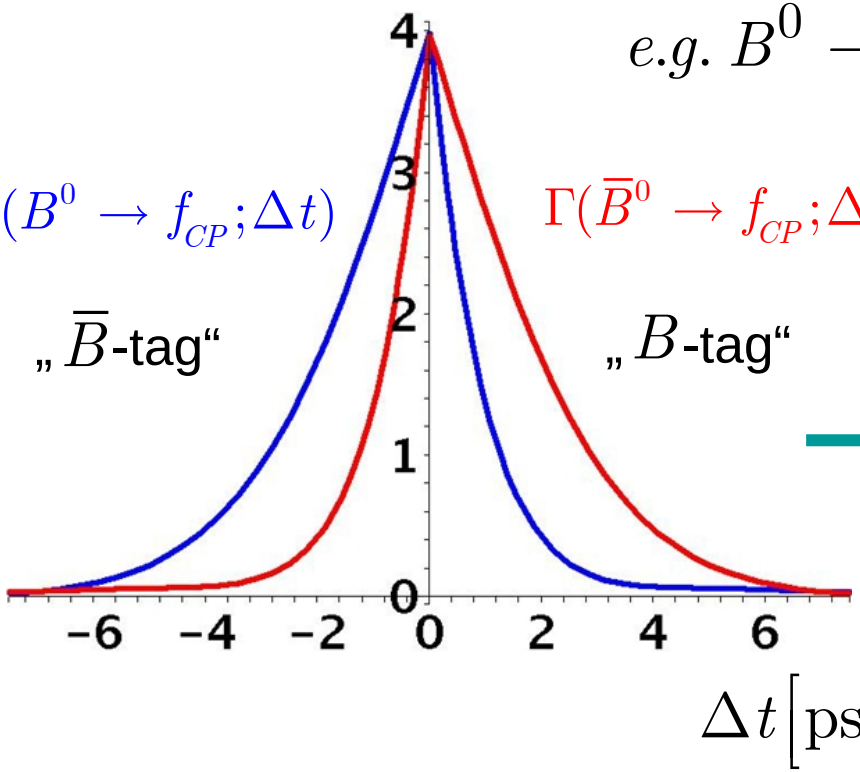
$e.g.\ B^0 \to J/\psi K_S$

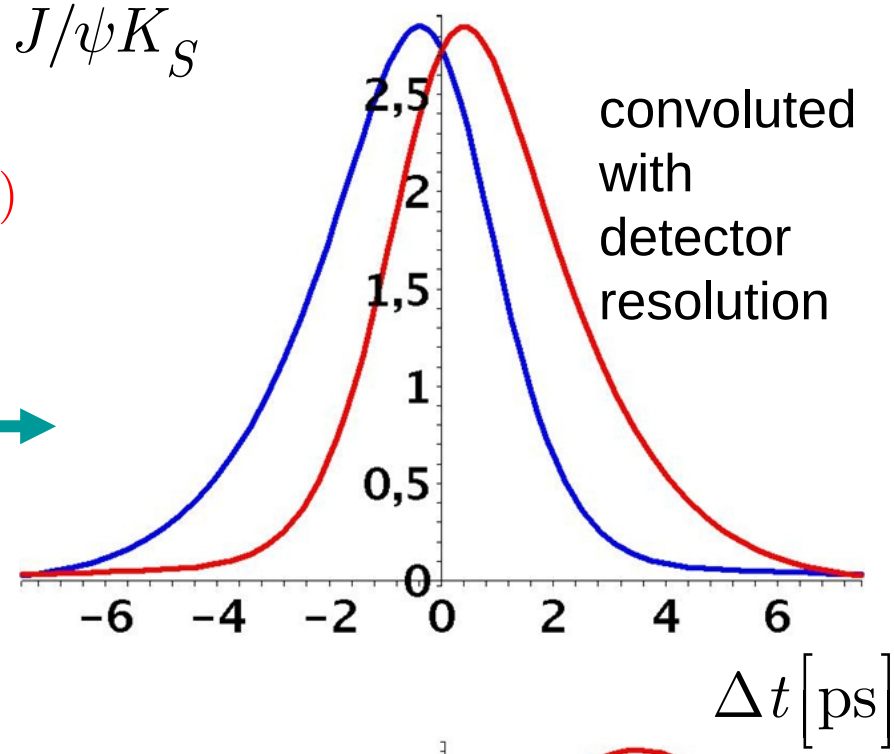
$\Gamma(B^0 \to f_{CP};\Delta t)$

„$\overline{B}$-tag“

$\Gamma(\overline{B}^0 \to f_{CP};\Delta t)$

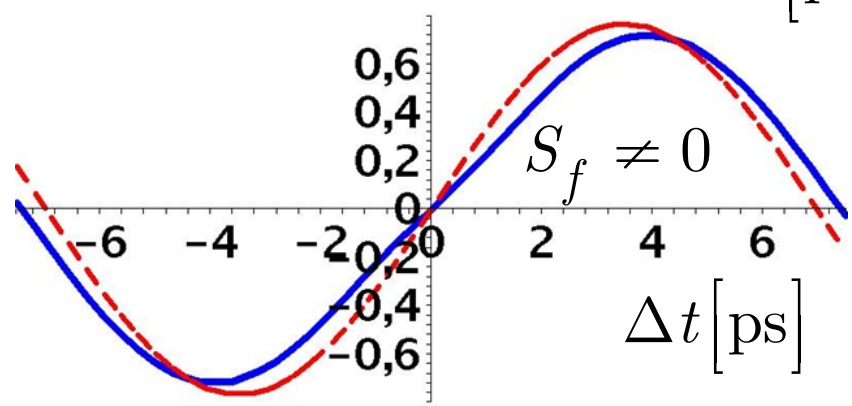
„B-tag“





convoluted with detector resolution

$$\mathcal{A}_{CP}(\Delta t) = \frac{N(\overline{B}^0,t) - N(B^0,t')}{N(\overline{B}^0,t) + N(B^0,t')}$$
$$= A_f \cos\Delta m\Delta t + S_f \sin\Delta m\Delta t$$



No direct CP violation: $A_f = 0$

Time-Dependent CP-Asymmetries

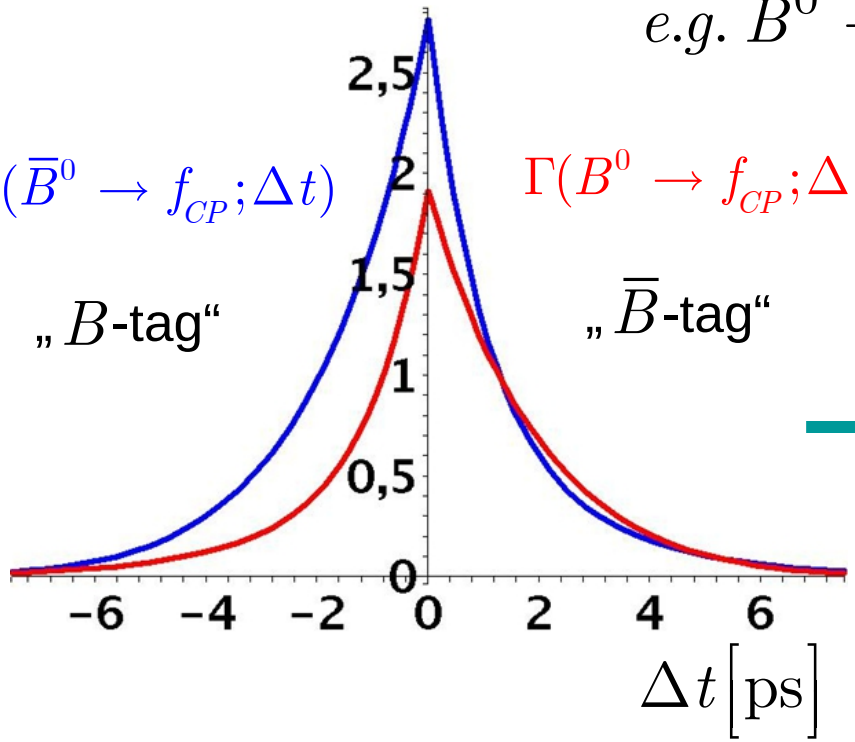
$e.g.\ B^0 \to \pi^+\pi^-$

$\Gamma(\overline{B}^0 \to f_{CP};\Delta t)$

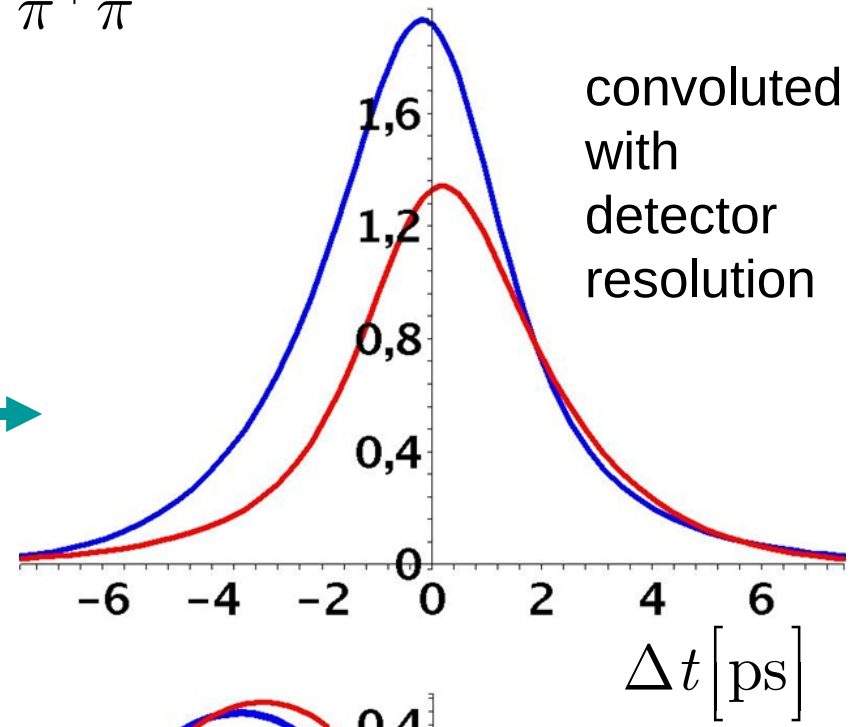
„B-tag“

$\Gamma(B^0 \to f_{CP};\Delta t)$

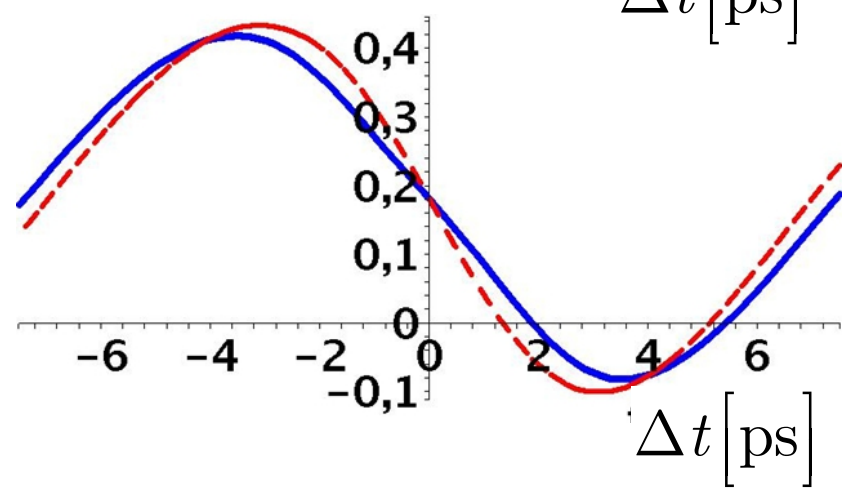
„$\overline{B}$-tag“



convoluted with detector resolution

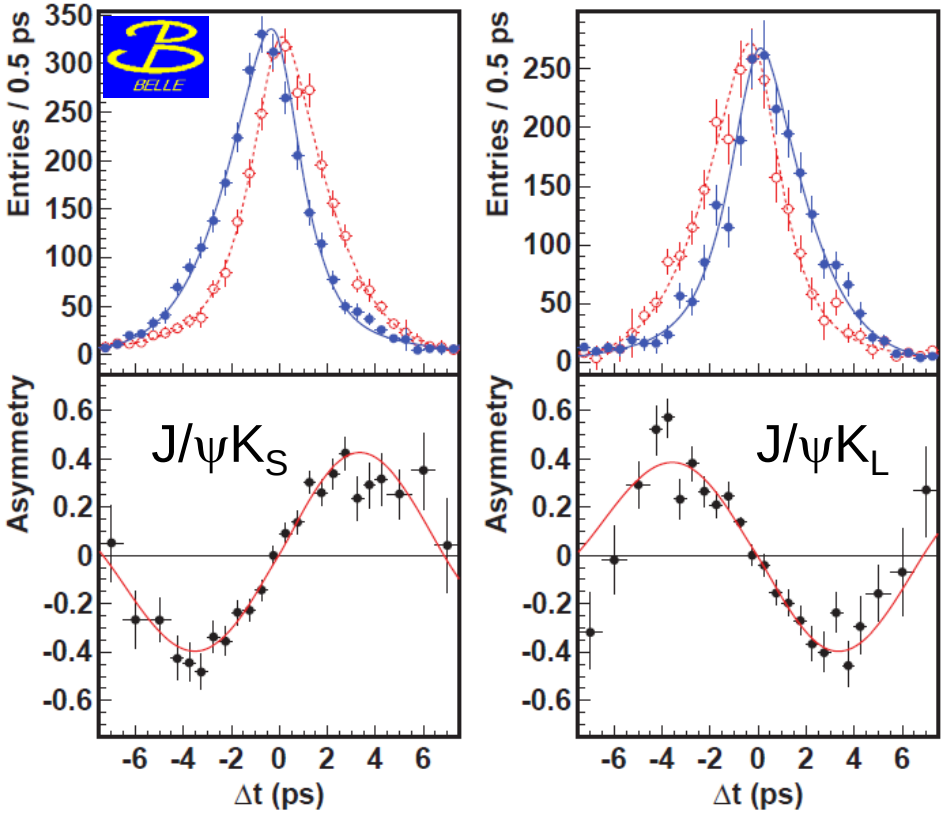


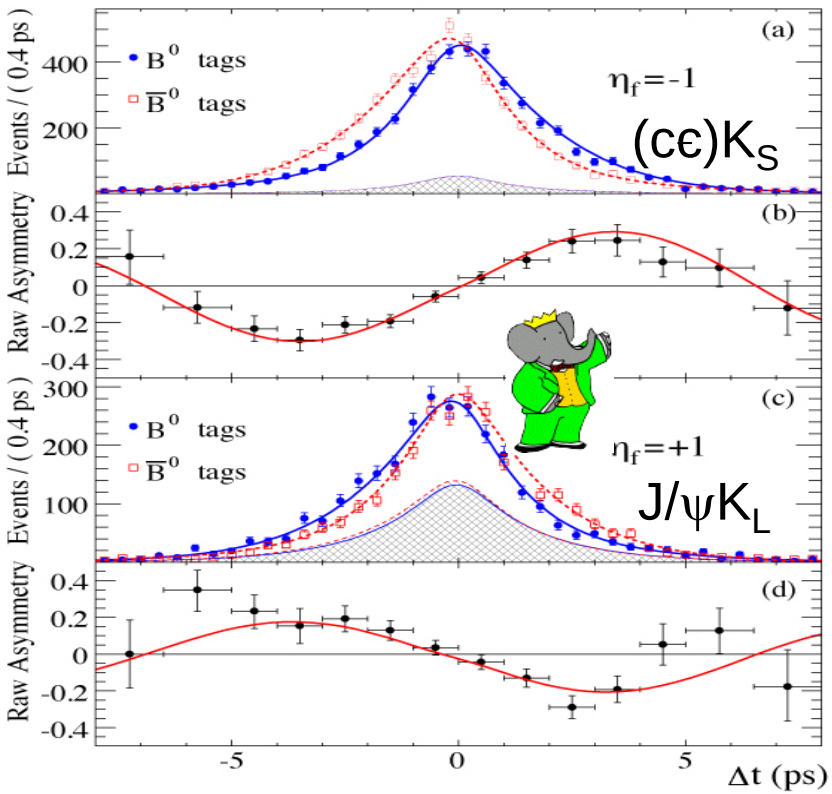
$$\mathcal{A}_{CP}(\Delta t) = \frac{N(\overline{B}^0,t) - N(B^0,t')}{N(\overline{B}^0,t) + N(B^0,t')}$$
$$= A_f \cos\Delta m\Delta t + S_f \sin\Delta m\Delta t$$



Direct CP violation: $A_f \neq 0$

Measurement of ϕ_1 (β) in Charmonium K^0 modes





$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$

$A_f = 0.006 \pm 0.016 \pm 0.012$

PRL108,171802(2012)

$\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$

$A_f = -0.024 \pm 0.020 \pm 0.016$

PRD79,072009(2009)

Puzzle: Comparison Tree and Penguins for ϕ_1 (β)

$b \longrightarrow c\bar{c}s$ tree

$b \longrightarrow sq\bar{q}$ penguins

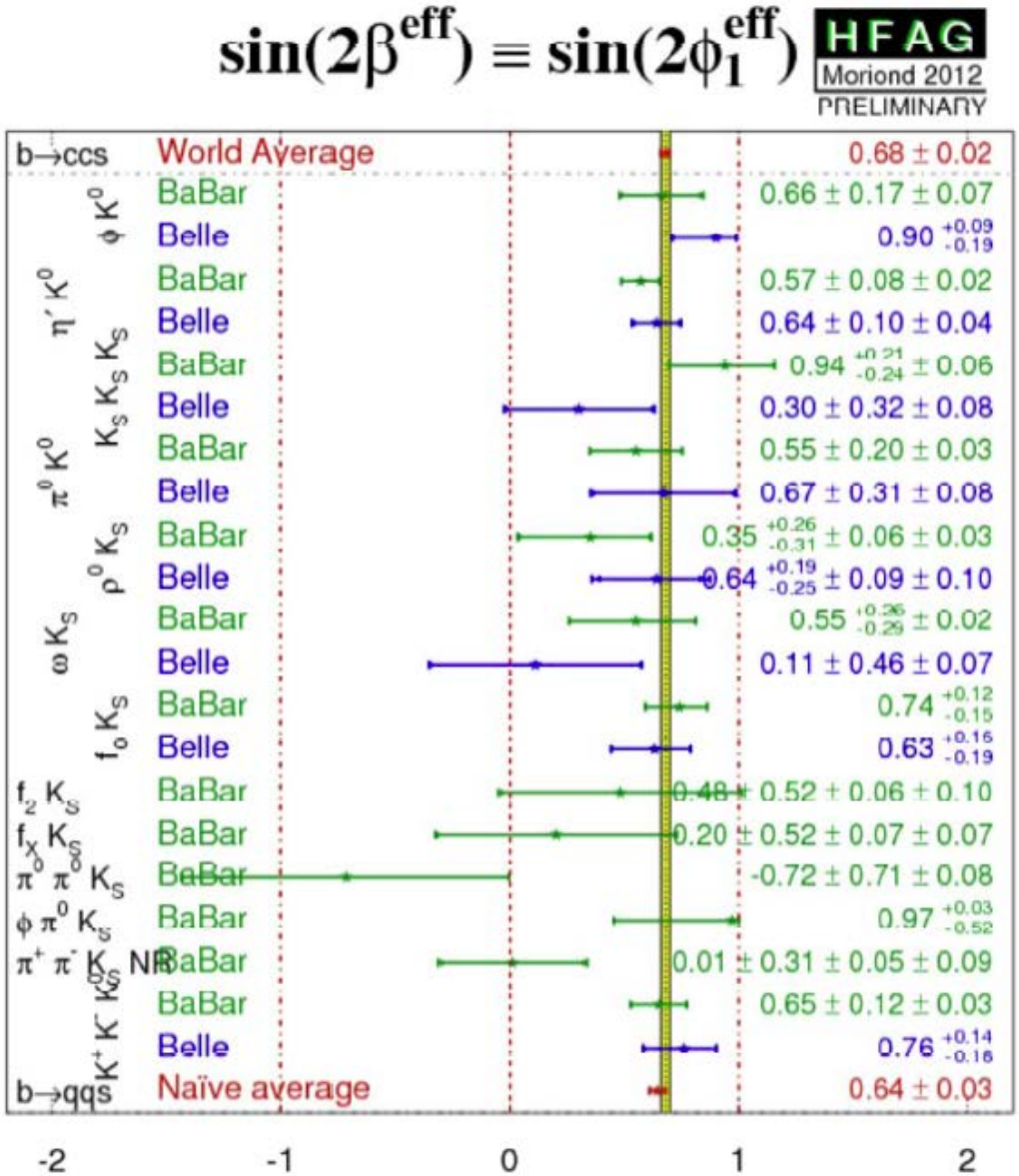
penguins from 2-body decays

penguins from Dalitz plot analysis

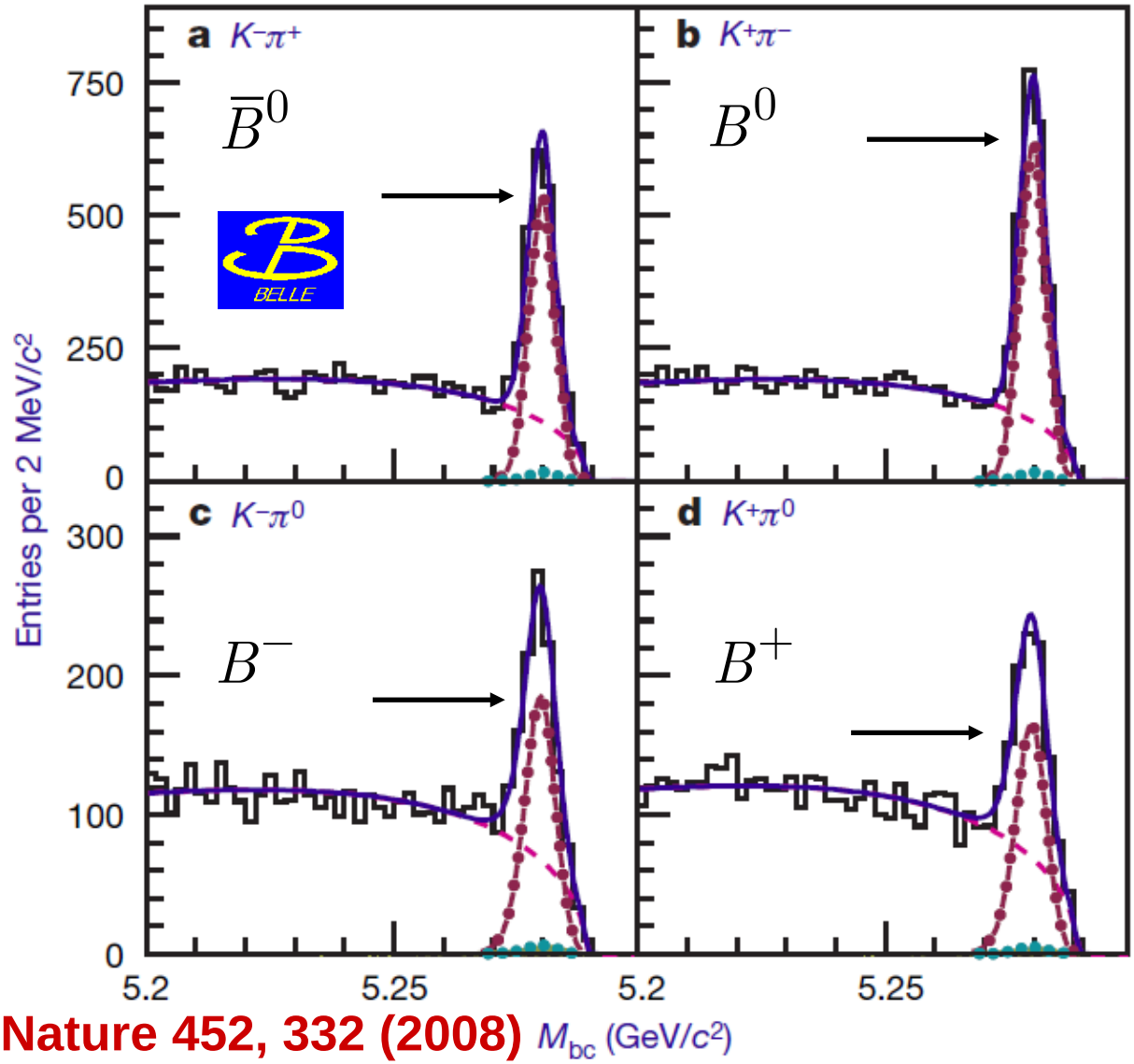
ϕ_1 from tree and penguins consistent

note: Theory would favor

$$\phi_1^{eff} > \phi_1$$



Another Puzzle: Direct CP Violation in $B \to K\pi$



Nature 452, 332 (2008)

$$A_{CP}(K^+\pi^-) < 0$$

WA: -0.098 ± 0.012

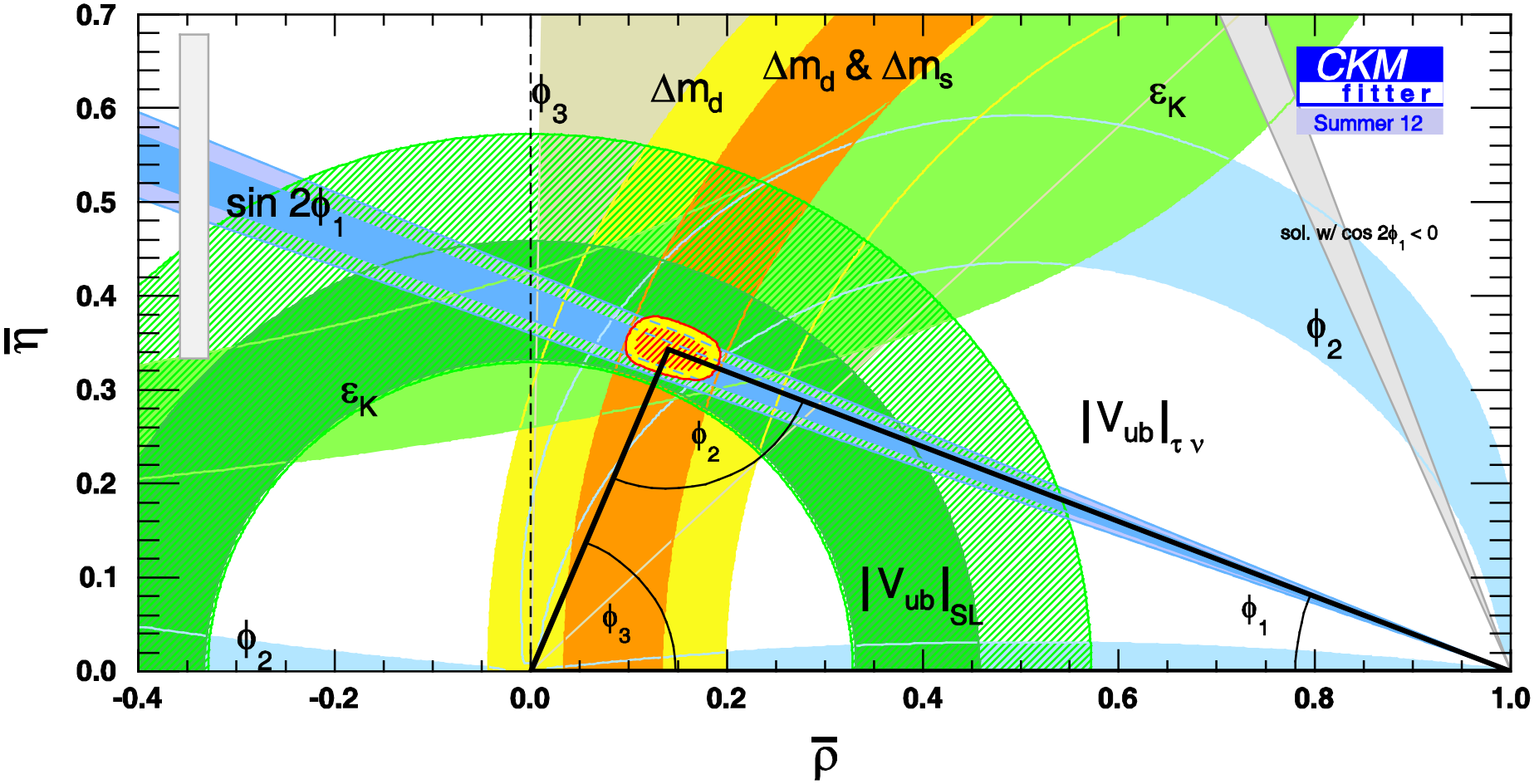
$$A_{CP}(K^+\pi^0) > 0$$

WA: $+0.050 \pm 0.025$

should be equal !

New Physics?

The Unitarity Triangle in 2012

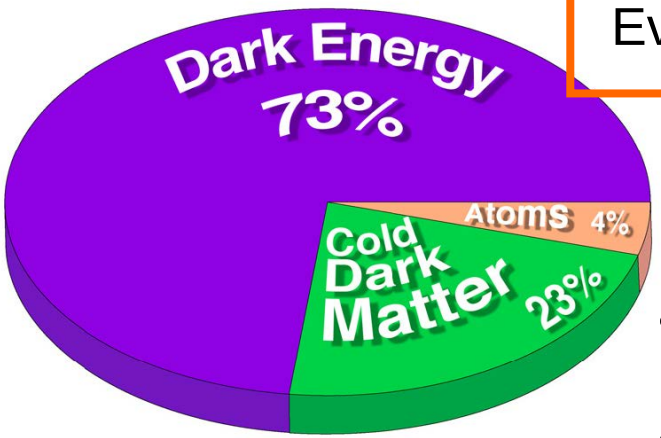


Generally consistent with SM, some „tensions“ exist …

Why do we Expect New Physics ?

The Standard Model $SU_3 \times SU_2 \times U_1$ (SM) describes all data so far

yet: cannot be the correct theory, SM only a „low energy“ approximation



Evidence for Physics beyond the Standard Model:

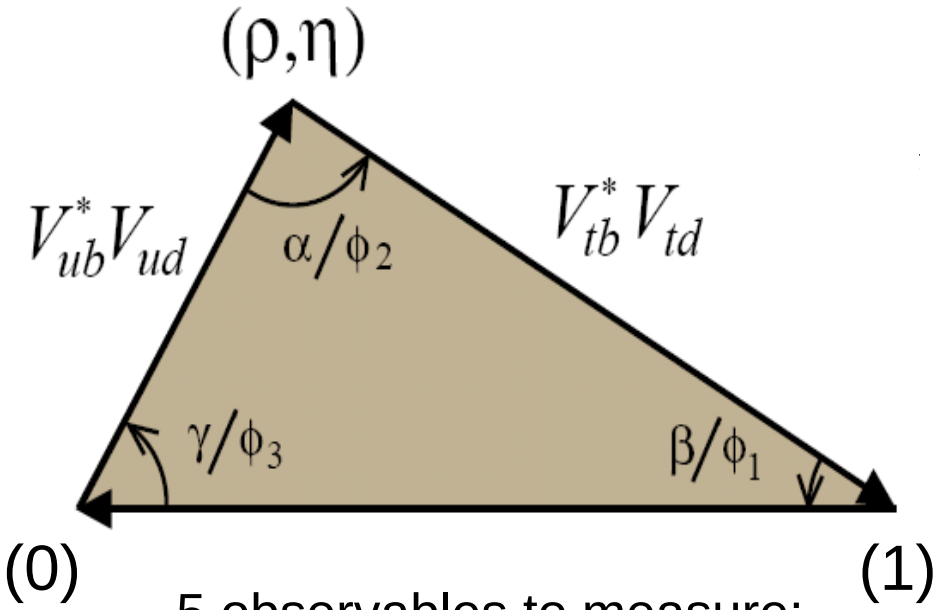
- Dark Matter exists
  (only 4% of the Universe accounted for by SM)
- Neutrinos have mass (Dirac, Majorana?)
- Baryon Asymmetry in the Universe is
  much too large (by 10 orders of magnitude)

need
very high energy
(LHC) or
very high precision
(e.g. LHCb,
SuperKEKB

At least two of them have to do with CP Violation

$\not{C}P$: One of the so-called Sakharov-conditions

New Physics Observables



5 observables to measure:
2 sides, 3 angles:
heavily over-determined

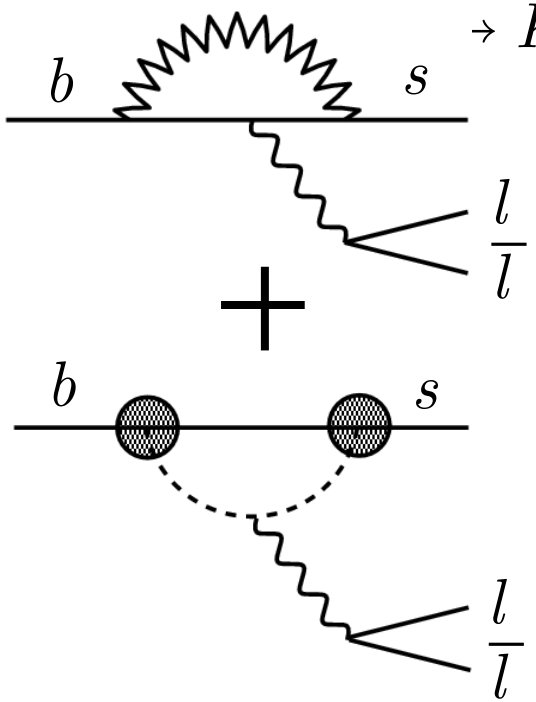
Standard Model: all 5 measurements must give consistency with the triangle

Rare decays, e.g.

$$\bar{B}^0 \to \bar{K}^0 l^+ l^-$$

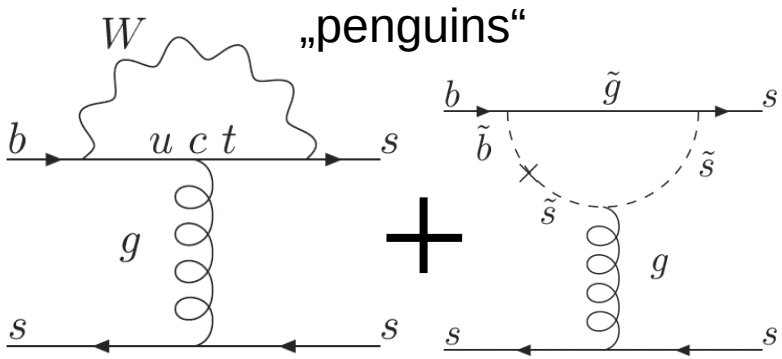
$$\to \bar{K}^0 \nu\bar{\nu}$$

„Penguin“



If triangle „does not close“ → **New Physics** ← unexpectedly „large“ branching fractions

New Physics at the Loop Level ….



SM NP

Rare Decays of *B* mesons:

$$B \to X_{s,d}\gamma \qquad \mathcal{O}\left(10^{-4}\right)$$
$$B \to X_{s,d}l^+l^- \qquad \mathcal{O}\left(10^{-6}\right)$$
$$B \to X_d\nu\overline{\nu} \qquad \mathcal{O}\left(10^{-6}\right)$$
$$B \to l^+l^- \qquad \mathcal{O}\left(10^{-10}\right)$$

SM pred.

NP in CPV asymmetries:

$$B \to J/\psi K_S \longleftrightarrow B \to \phi K_S$$

Principle:

Deviation of observable from the SM prediction signals NP

virtual particles in the loop reveal their existence $\longrightarrow \Lambda_{NP}$

leptons:

$$\left.\begin{array}{l} \tau \to \mu\gamma \\ \tau \to \mu\mu\mu \\ \tau \to \mu\eta \end{array}\right\}$$

NP could make these decays possible

need precision (statistics) to challenge the SM

SuperKEKB and Belle-II
The Precision Frontier

Belle-II Collaboration founded in Dec. 2008
now about 600 members from
99 institutions and 23 countries
strong European participation:
Austria, Germany, Czech Republic,
Poland, Spain, Slovenia,
(mainly in Pixel Vertex Detector,
Si Strip Detector)

Strategies for High Luminosity

$$\mathcal{L} = \frac{N_+ N_- f}{4\pi\sigma_x\sigma_y} R$$

basic formula for the (instantaneous) luminosity

Accelerator physicists usually like this one better:

stored current

tune shift

$$\mathcal{L} = \frac{\gamma_+}{2er_e}\left(1+\frac{\sigma_y}{\sigma_x}\right)\left(\frac{I_+\xi_{y,+}}{\beta_y}\right)\left(\frac{R}{R_{\xi_y}}\right)$$

vertical beta function at IP

$R_{,\xi}$: reduction factors (geometrical)

$\sigma_{x,y}$: beam spot size at IP

beam-beam parameter (or tune shift)

$$\xi_{y,+} = \frac{r_e}{2\pi\gamma_+}\left(\frac{\beta_y N_-}{\sigma_x\left(\sigma_x+\sigma_y\right)}\right)R_{\xi_y}$$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}}$$

beam emittance (need damping ring(s))

SuperKEKB: Nano Beam

e^+ 4GeV 3.6 A

e^- 7GeV 2.6 A

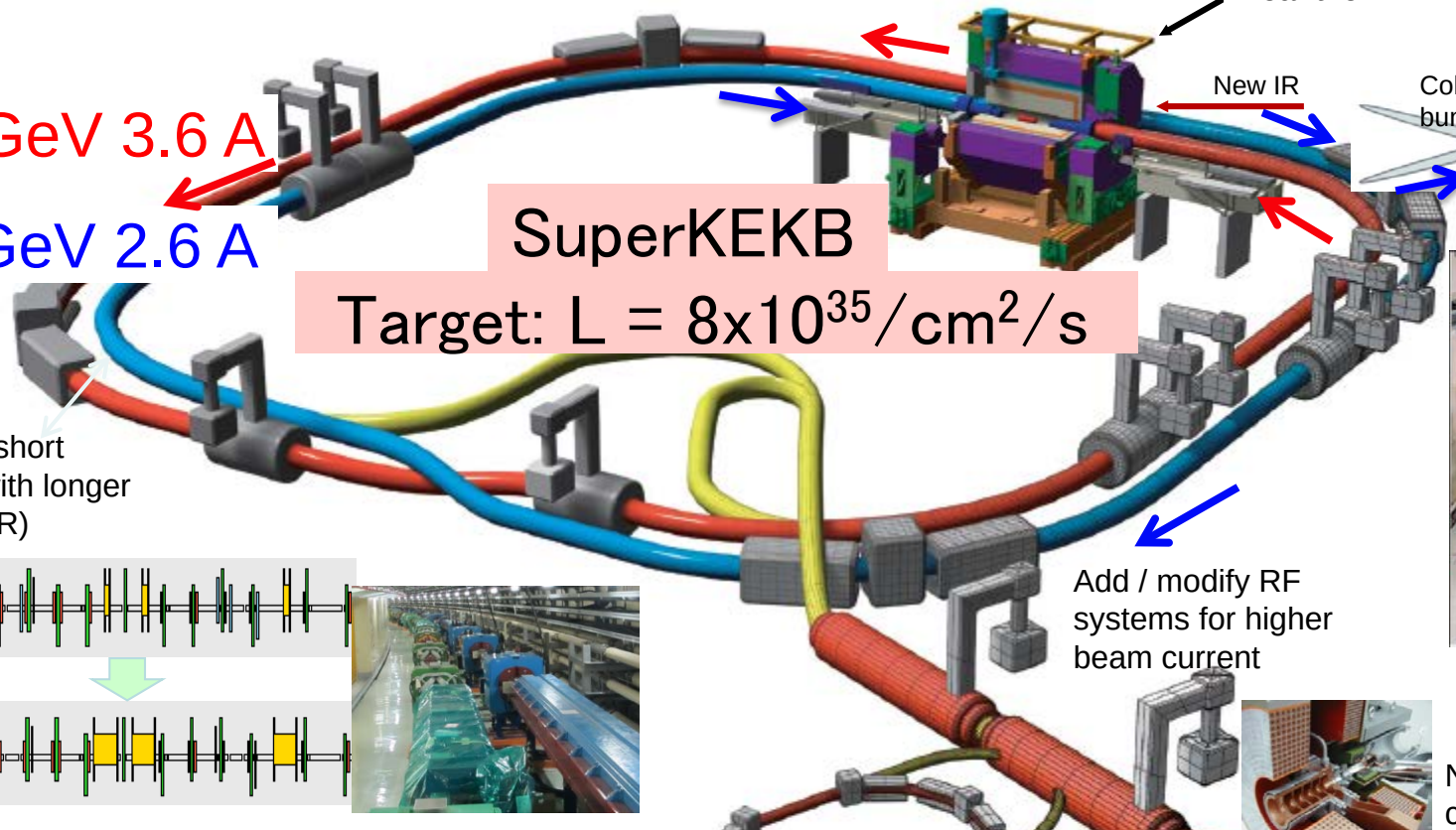
SuperKEKB

Target: L = $8 \times 10^{35}/cm^2/s$

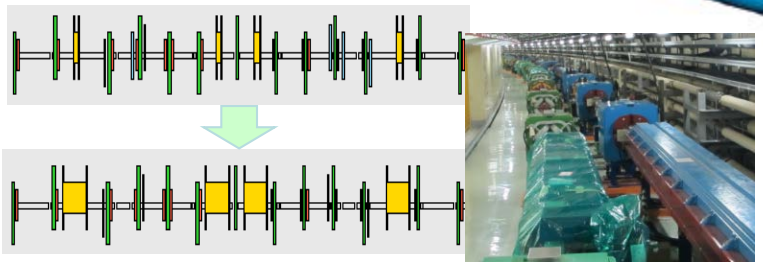
New superconducting /permanent final focusing quads near the IP

New IR

Colliding bunches



Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

Add / modify RF systems for higher beam current

Positron source

New positron target / capture section

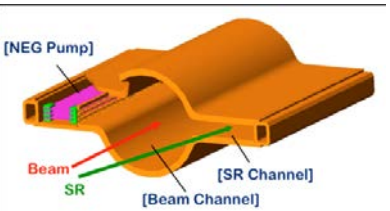
Damping ring

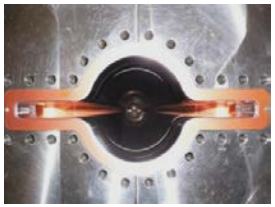
Low emittance positrons to inject

Low emittance gun

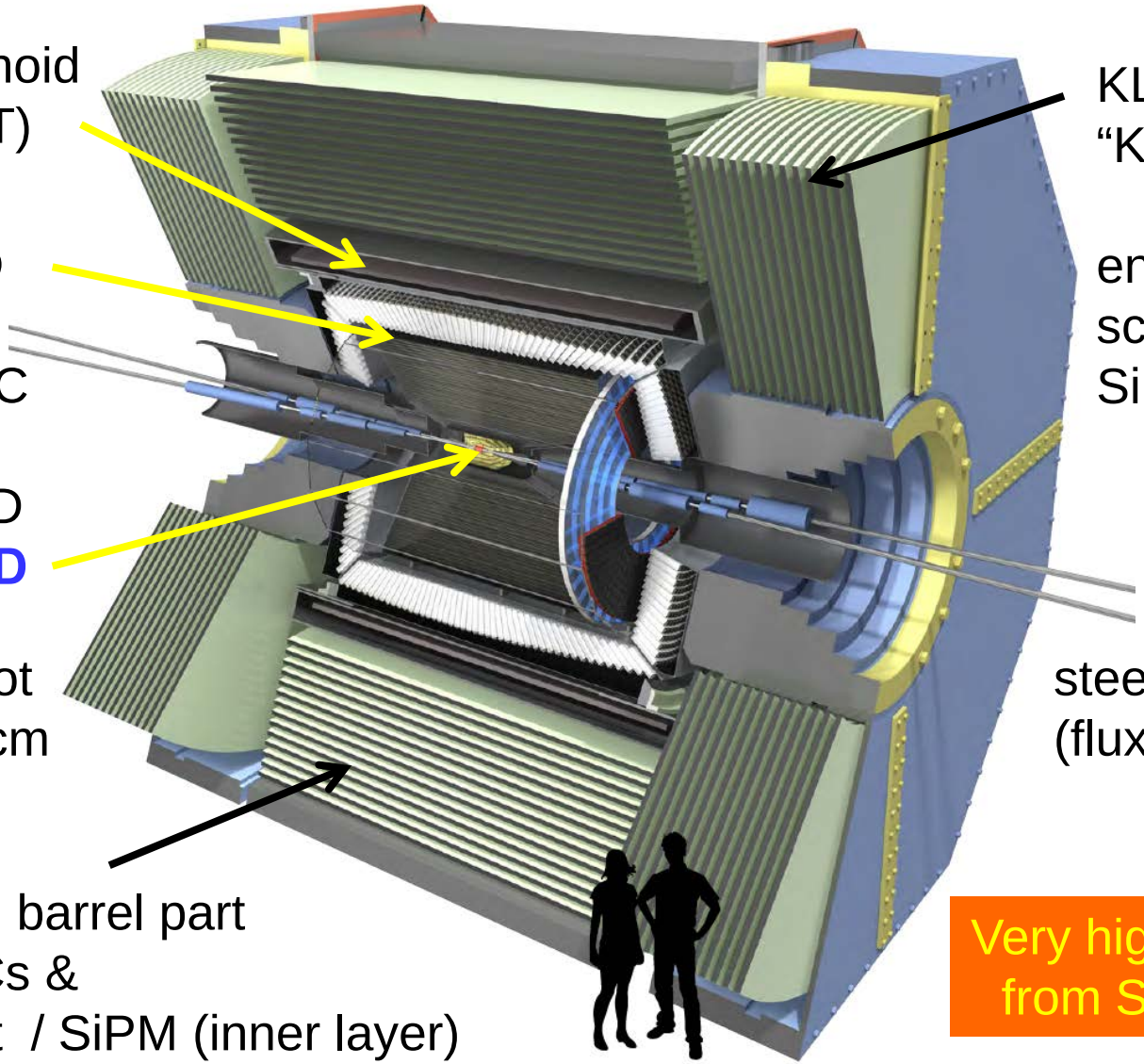
Low emittance electrons to inject

TiN-coated beam pipe with antechambers





The Belle II Detector



Solenoid
(1.5 T)

new PID

new CDC

new SVD
new PXD

(strips will not work @1.4 cm radius)

KLM barrel part
RPCs &
scint / SiPM (inner layer)

KLM
"K_L and muon"

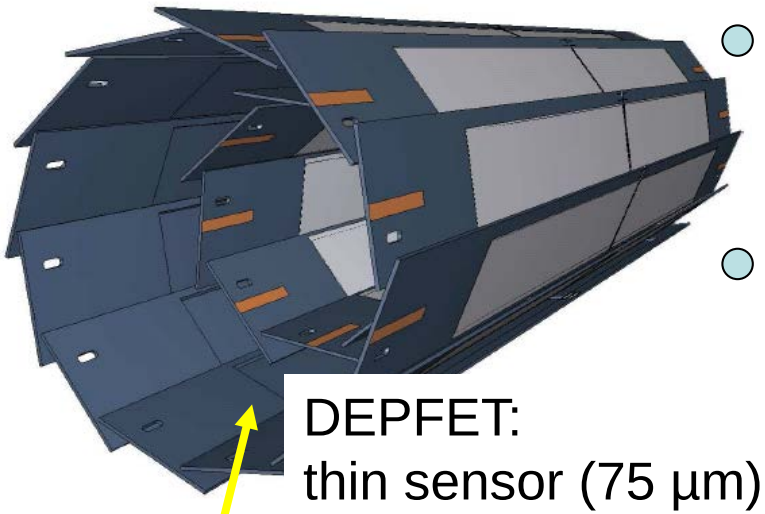
end cap:
scinillator &
SiPM

steel plates
(flux return yoke)

Very high background from SuperKEKB !!

Silicon Tracking System @ Belle II

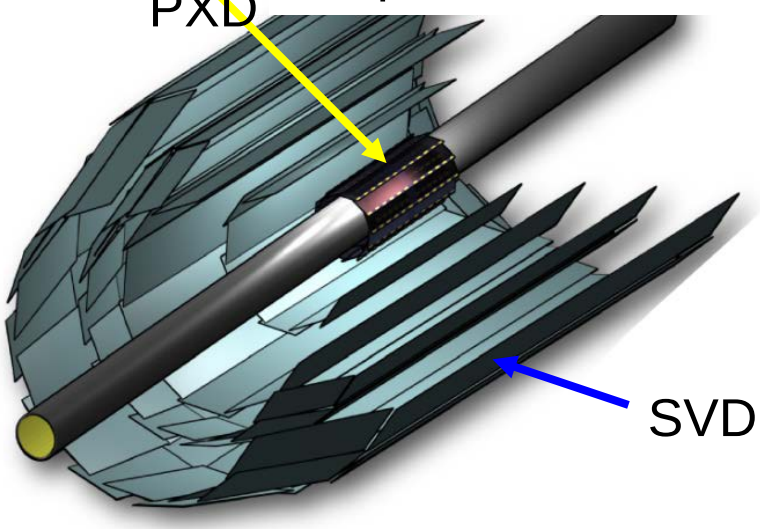
SuperKEKB: Nano beam option, 1 cm radius of beam pipe



- 2 layer Si pixel detector (DEPFET technology) „PXD“
  (R = 1.4, 2.2 cm) monolithic sensor
  thickness 75 µm (!), pixel size ~50 x 50 µm²
- 4 layer Si strip detector (DSSD) „SVD“
  (R = 3.8, 8.0, 11.5, 14.0 cm)

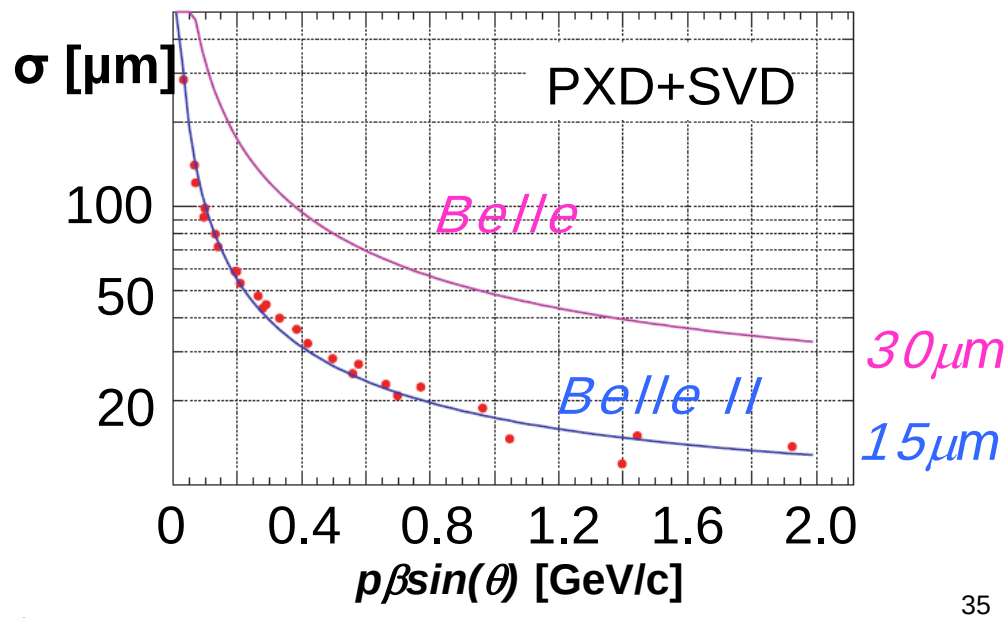
DEPFET:
thin sensor (75 µm)
unique worldwide

PXD



SVD

Significant improvement in z-vertex resolution



PXD – System Layout

Total of 0.2% of X_0

2 layers: @1.4(2.2) cm

Pixels: 50 x 60(75) µm

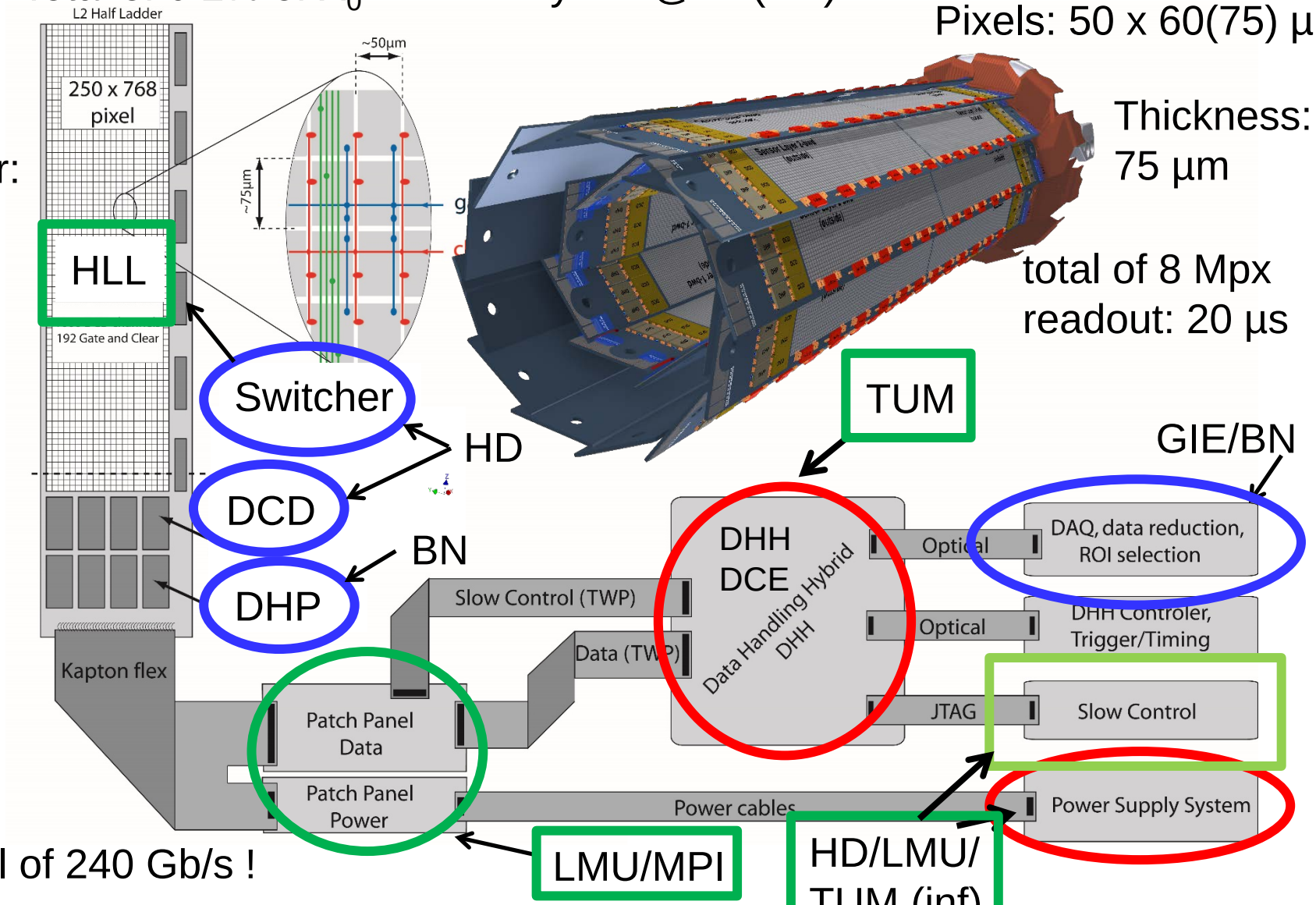
half ladder: 768 rows

250 cols

15 x 70 (85) mm

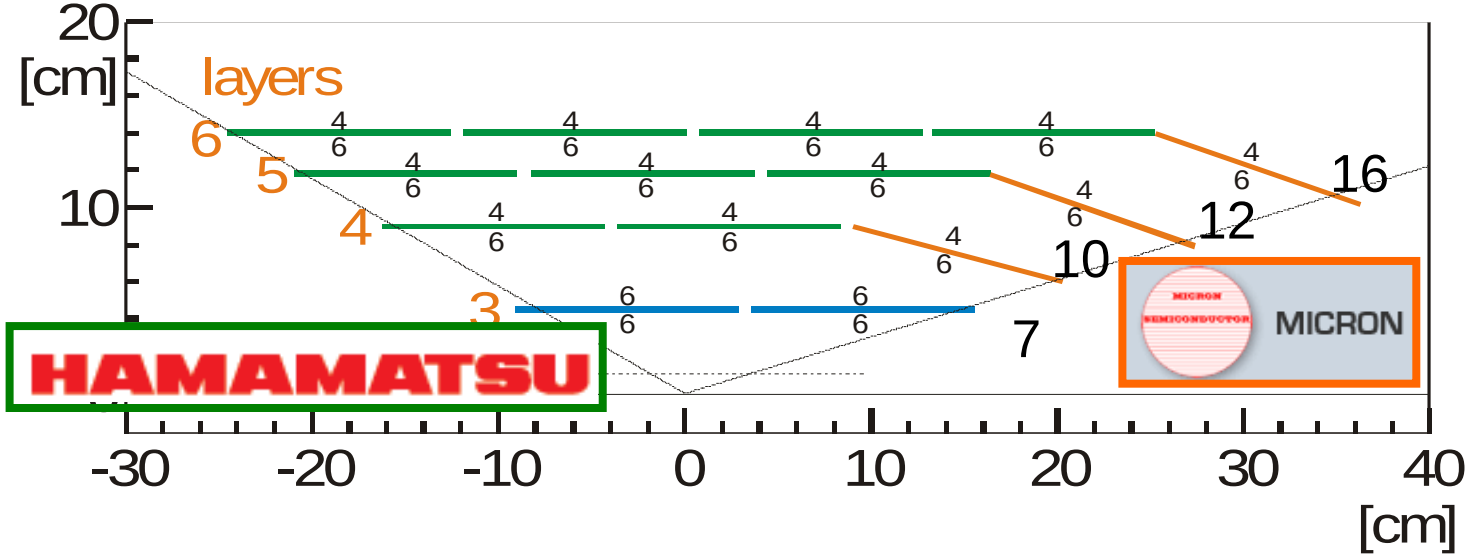
Thickness: 75 µm

total of 8 Mpx readout: 20 µs



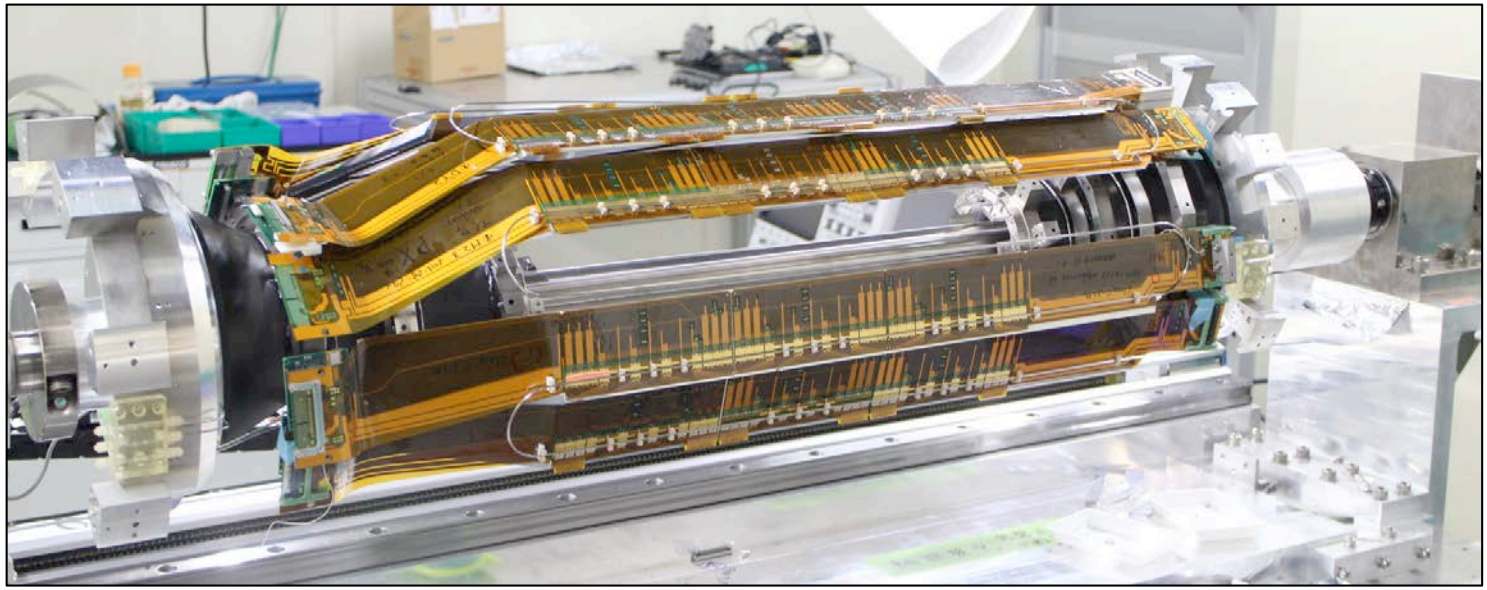
total of 240 Gb/s !

New DSSD Si-System for Belle-II: SVD



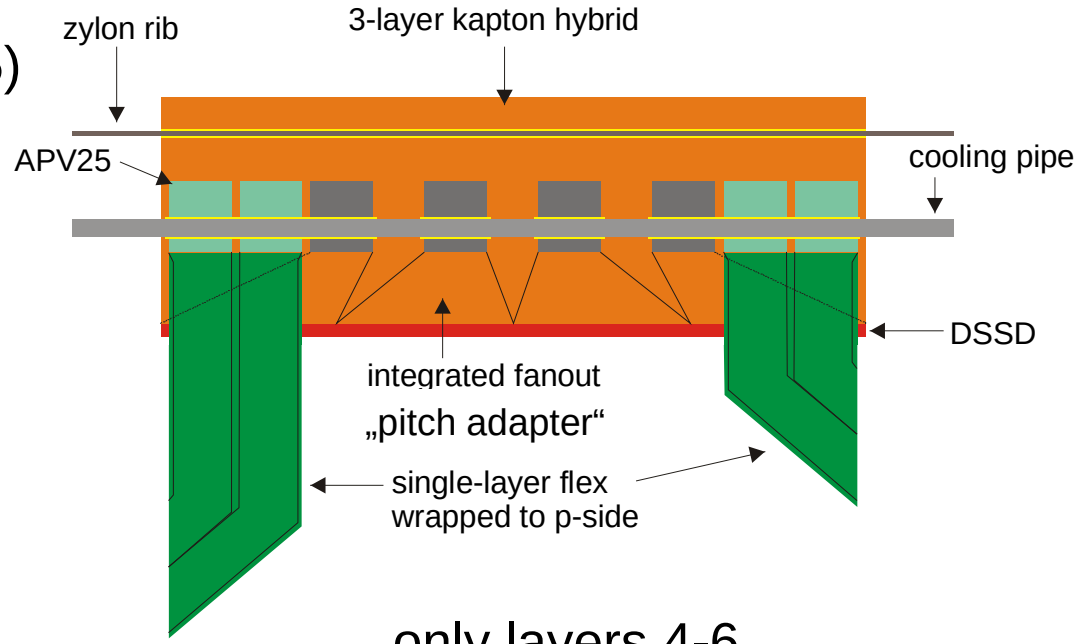
300 µm DSSD

Pitch:
50/160 µm (rect.)
50-75/160 µm (wedge)



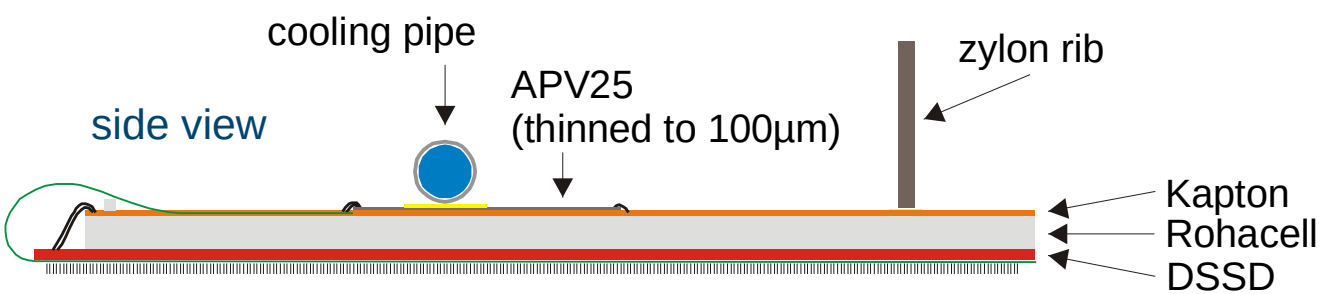
Chip on Sensor: The Origami Concept (SVD)

- Thinned readout chips (APV25) on sensor
- Strips of bottom side are connected by flex fanouts wrapped around the edge
- All readout chips are aligned → single cooling pipe
- Shortest possible connections → high signal-to-noise ratio

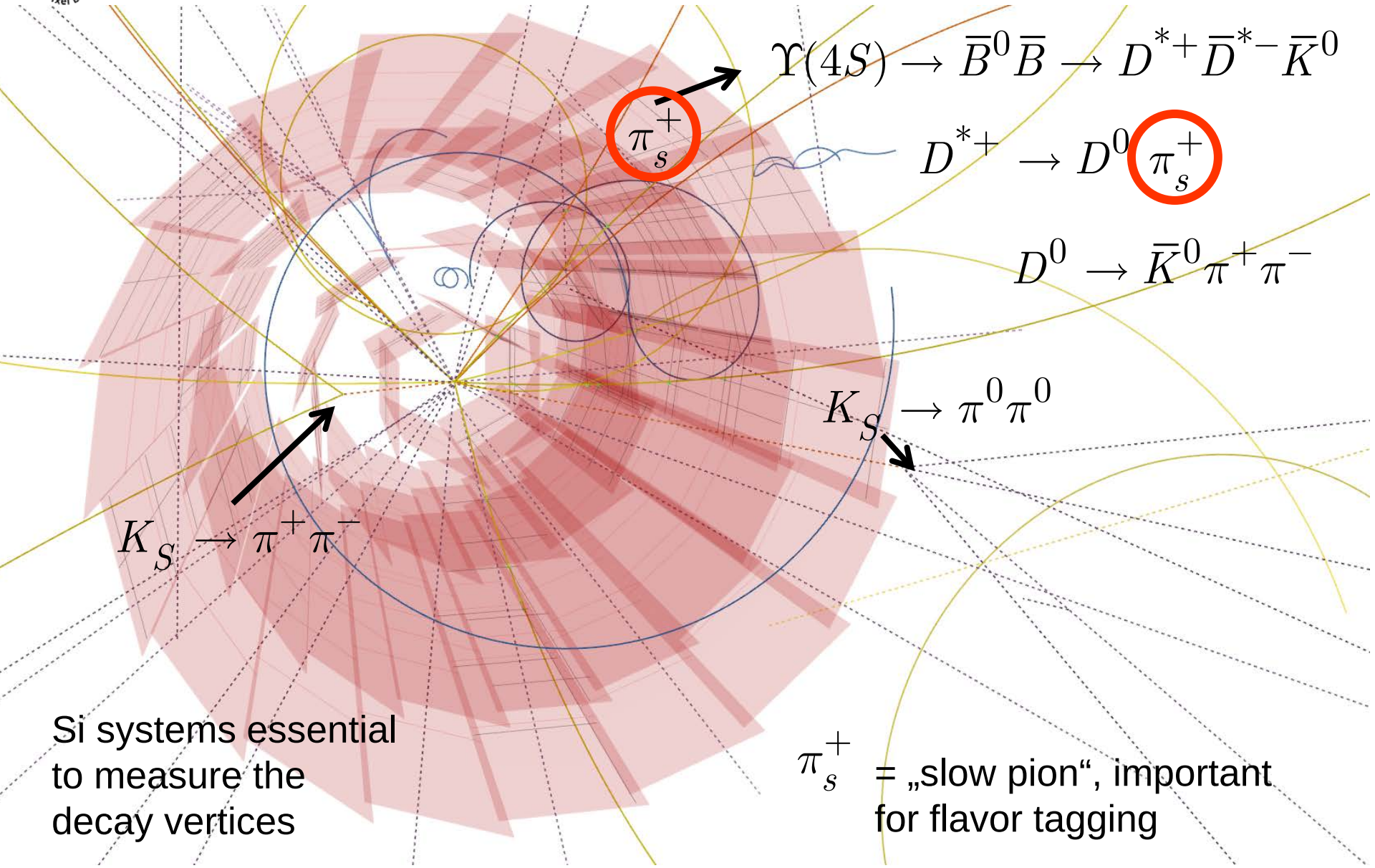


only layers 4-6
(rect. sensors)

Total material budget: 0.6% X_0
(cf. 0.48% for conventional readout)



An Event in the Silicon Tracking System (Belle)



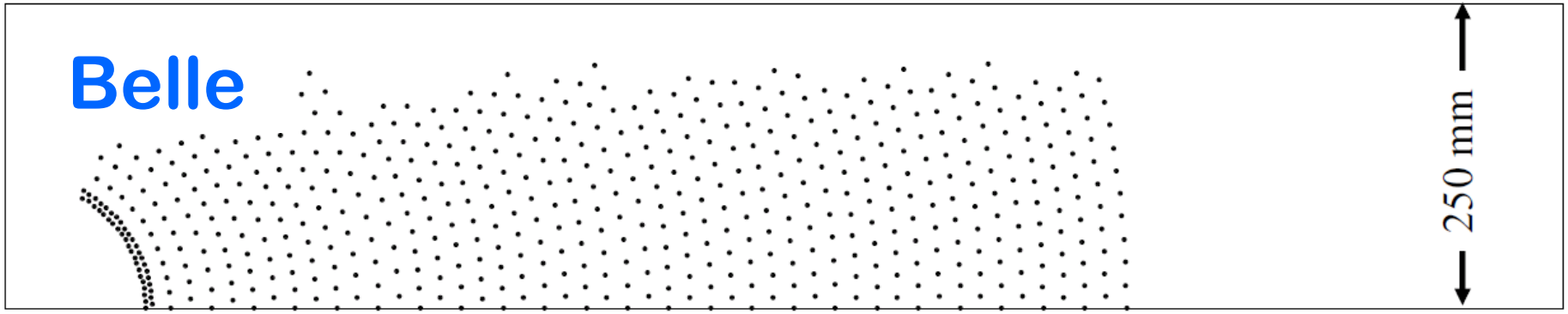
Si systems essential to measure the decay vertices

π_s^+ = „slow pion“, important for flavor tagging

New Central Drift Chamber (CDC)

	Belle	Belle-II
Radius of inner boundary (mm)	77	160
Radius of outer boundary (mm)	880	1096
Radius of inner most sense wire (mm)	88	168
Radius of outer most sense wire (mm)	863	1082
Number of layers	50	58
Number of total sense wires	8400	15104
Effective radius of dE/dx measurement (mm)	752	928
Gas	$He\text{-}C_2H_6$	$He\text{-}C_2H_6$
Diameter of sense wire (μm)	30	30

New Central Drift Chamber (CDC)

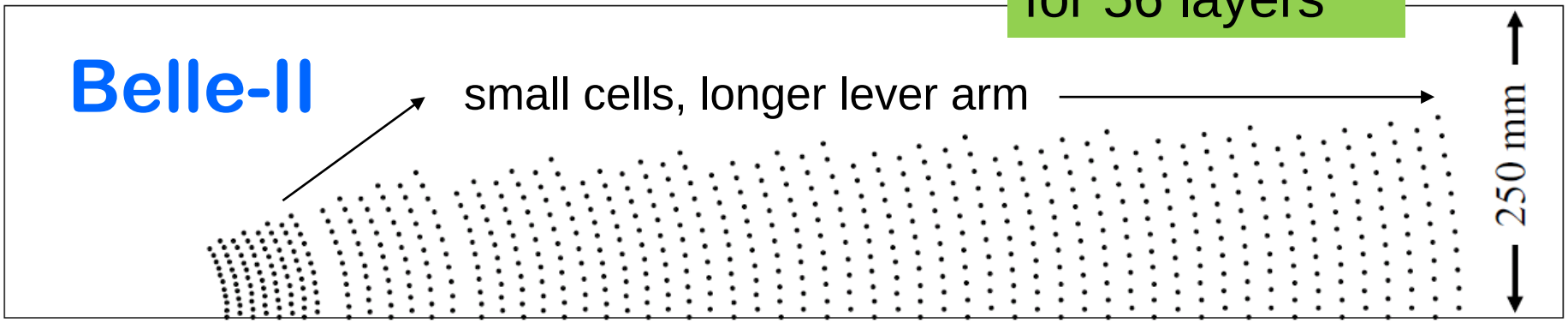


normal cell: 13.3 x 16 mm^2

small cell: 5.4 x 5.0 mm^2

1200 mm

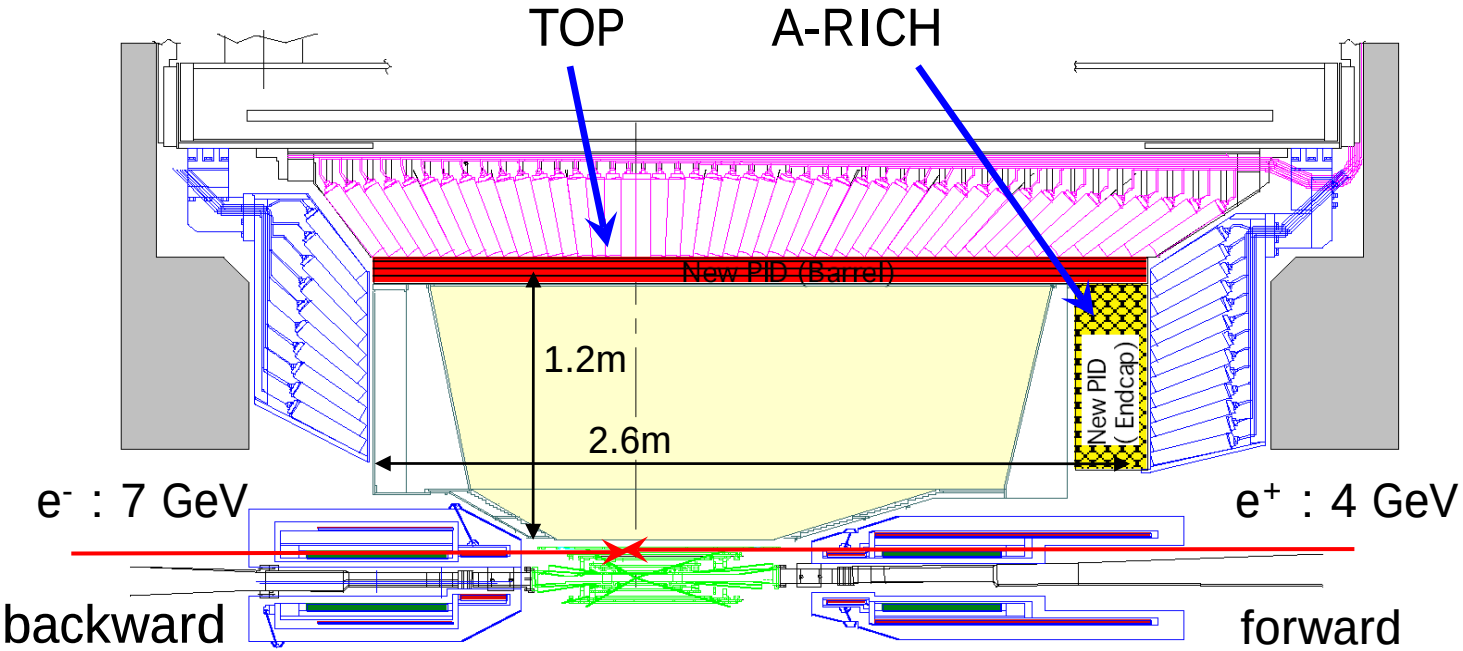
dE/dx: 4.8%
for 56 layers



z-coordinate via standard stereo wire arrangement in 9 superlayers:

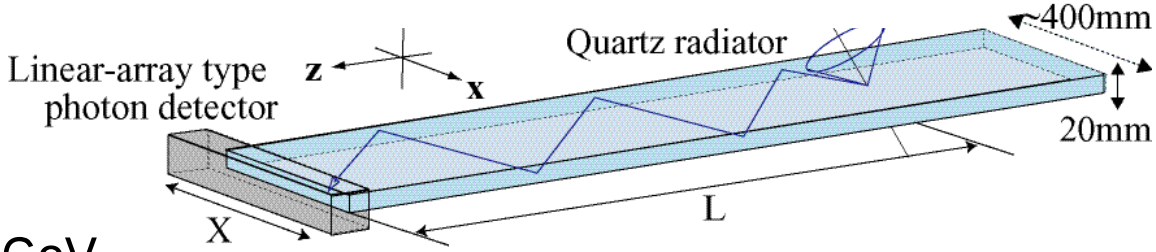
A U A V A U A V A

Upgrade: Particle Identification



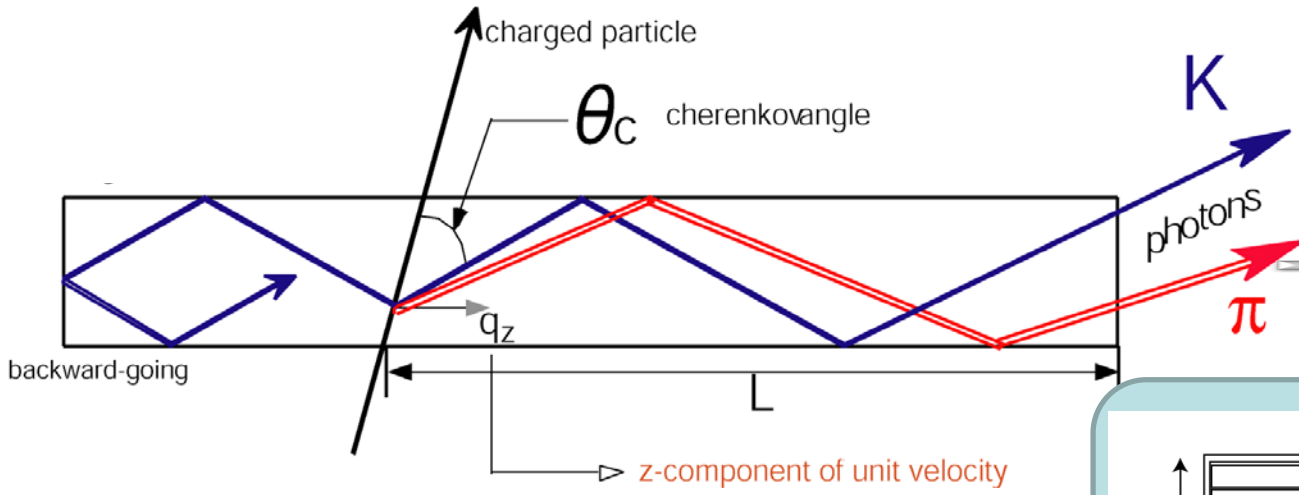
Goal:

3σ K/pi separation (barrel)
4σ K/pi separation up to 4 GeV (end caps)

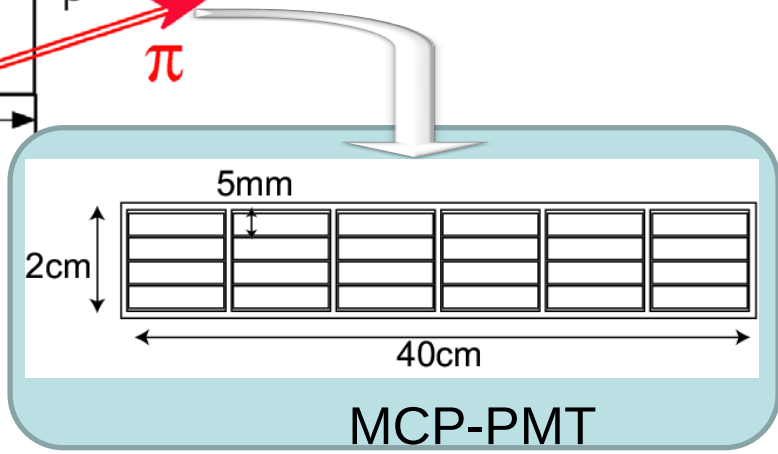


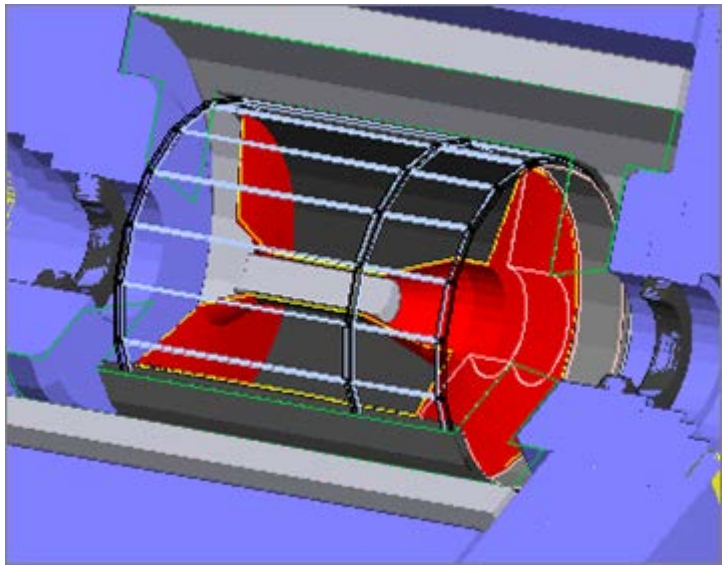
TOP: time of propagation

Design for Barrel PID (TOP)



TOP =
Time of Propagation





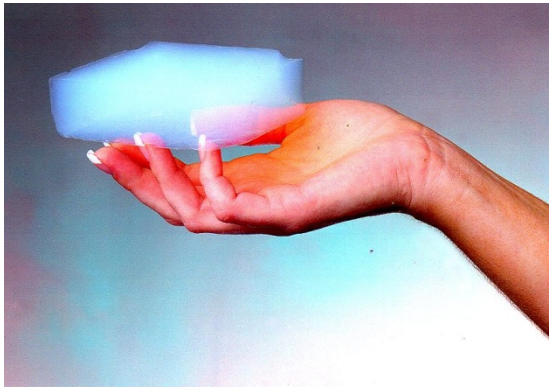
Ring imaging with :

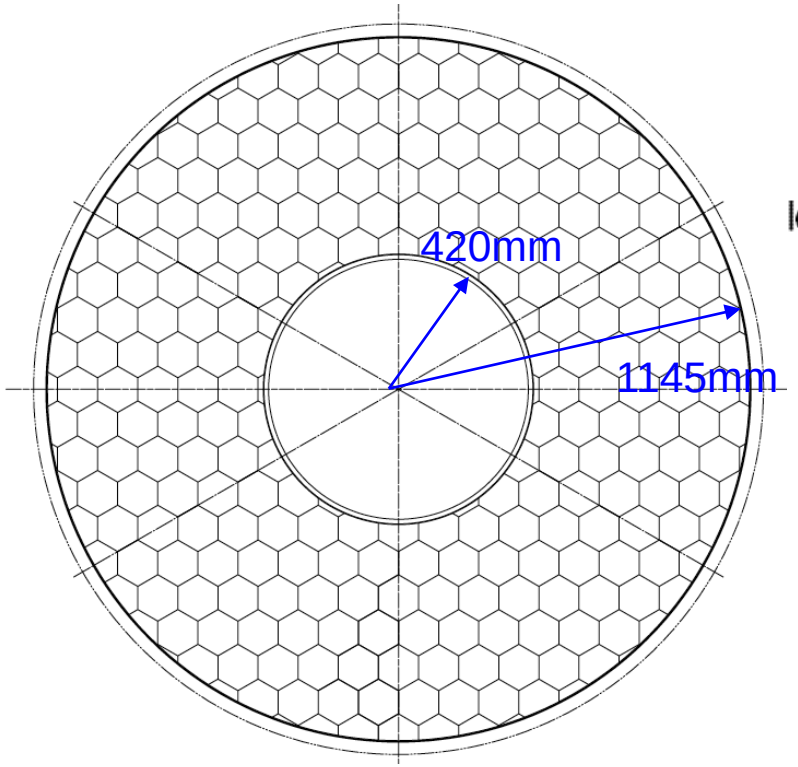
- One coordinate with a few mm precision
- Time-of-arrival

→ Excellent time resolution < ~40ps
required for single photon in 1.5T B field

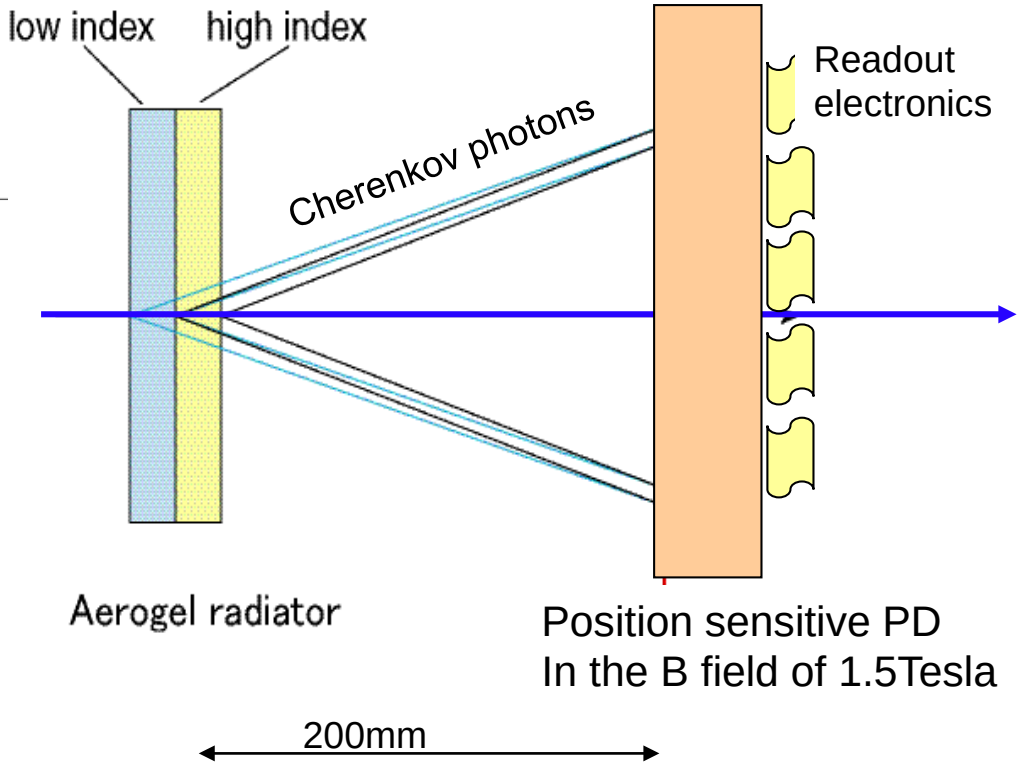
Design for Endcap PID (A-RICH)

Proximity focusing RICH with silica aerogel as Cherenkov radiator for new Belle forward PID

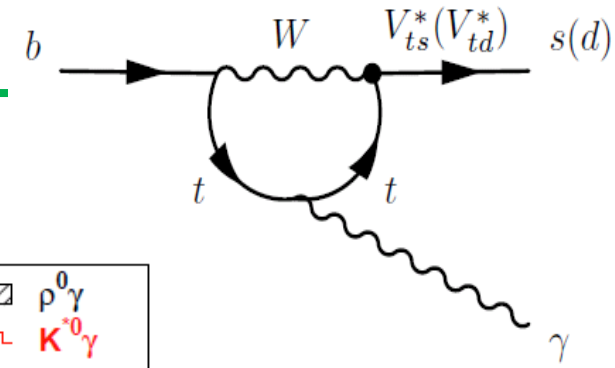




x-y view of forward end-cap

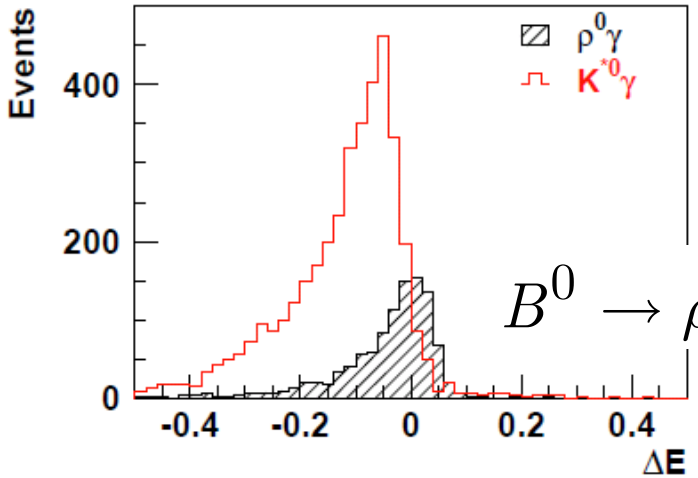


PID Improvement in Belle-II

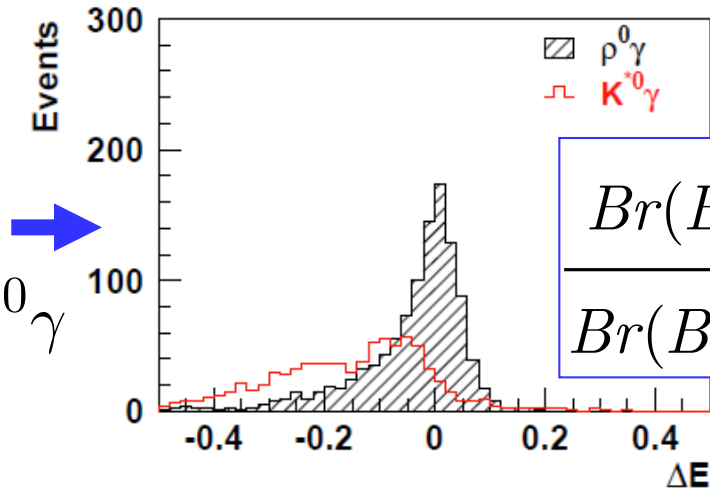


Present Belle PID

Belle II PID



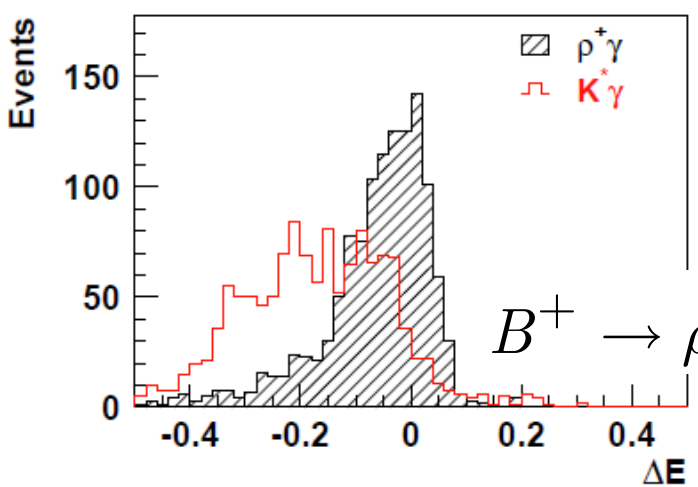
$B^0 \to \rho^0\gamma$



$$\frac{Br(B \to \rho\gamma)}{Br(B \to K^*\gamma)} \sim \left|\frac{V_{td}}{V_{ts}}\right|^2$$

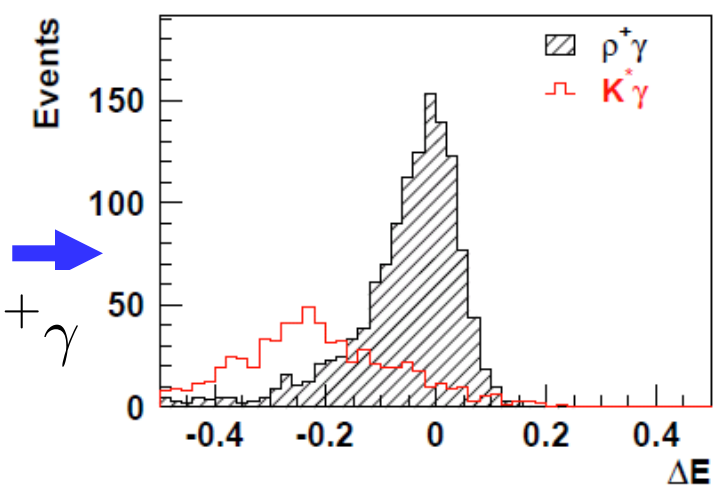
$(\sim 1/40)$

c)



$B^+ \to \rho^+\gamma$

(d)



$B \to \rho\gamma$

difficult because of dominating

$K^*\gamma$

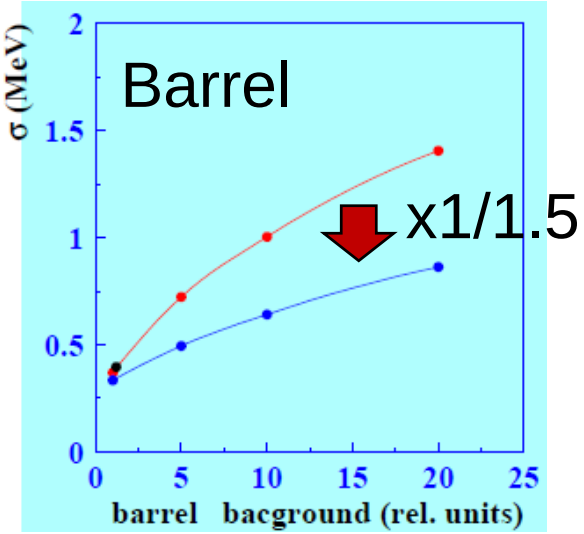
(Background from K's misident. as π's)

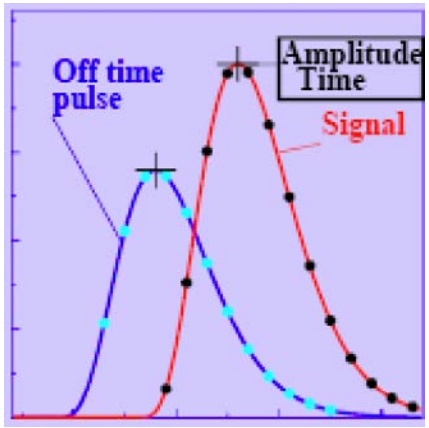
Calorimeter Upgrade (ECL)

- Increase of dark current due to neutron flux
- Fake clusters & pile-up noise

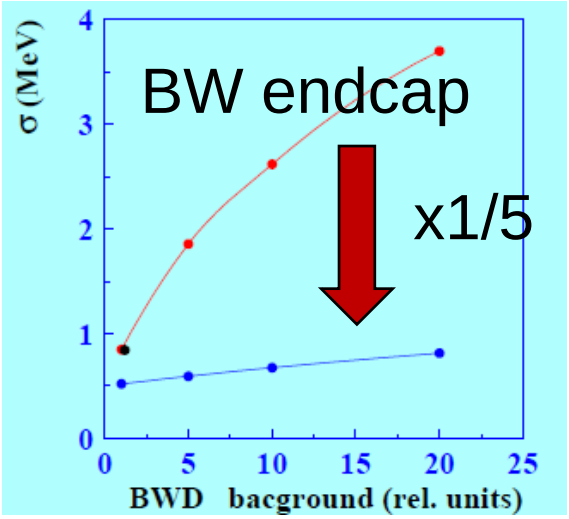
- Barrel:
  500 ns shaping + 2MHz w.f. sampling.
- Endcap:
  rad. hard crystals with short decay time (e.g. pure CsI) + photopentodes
  30ns shaping + 43MHz w.f. sampling

Pileup Reduction:



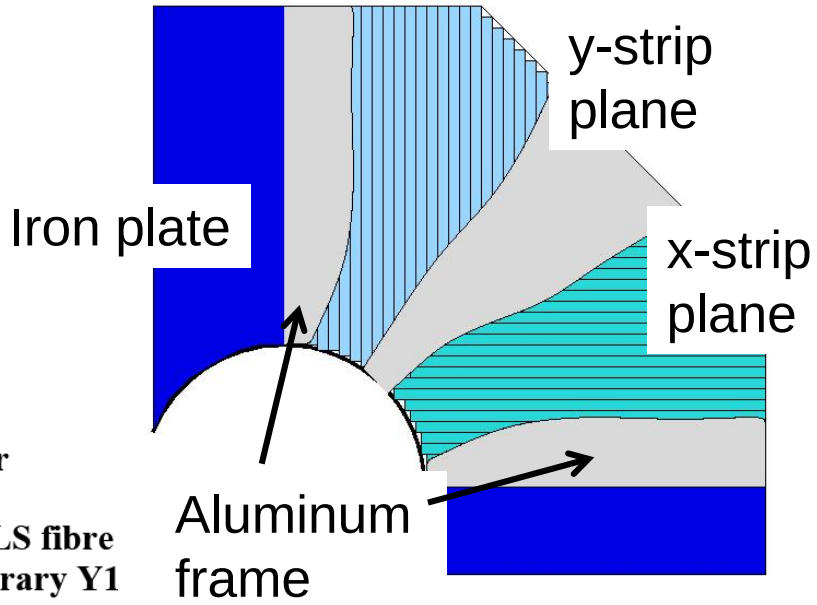


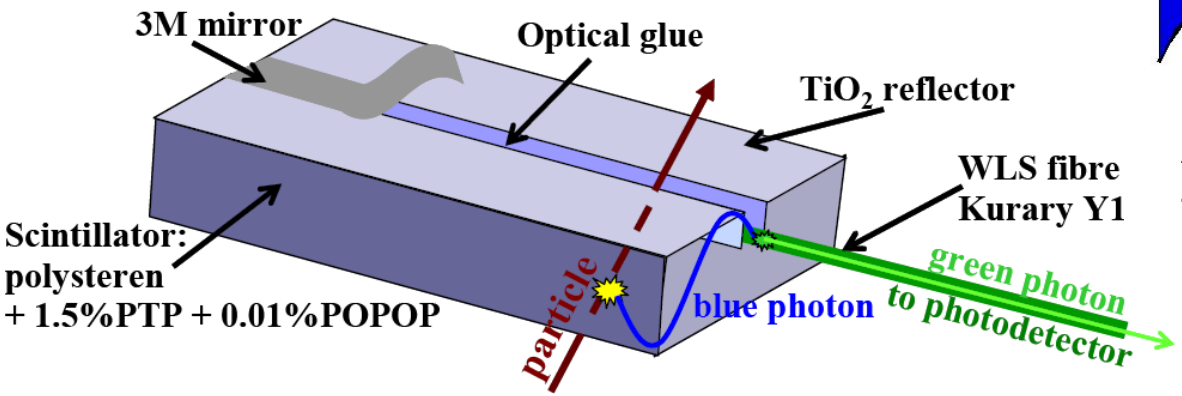
FADC: 16 samples



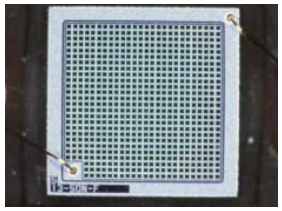
Upgrade of KLM (Endcaps)

- Standard detection technique: RPCs
- New: Two independent (x and y) layers in one superlayer made of orthogonal scintillator strips with WLS read out
- Photo-detector: avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%





676 pixels (20x20µm^2)

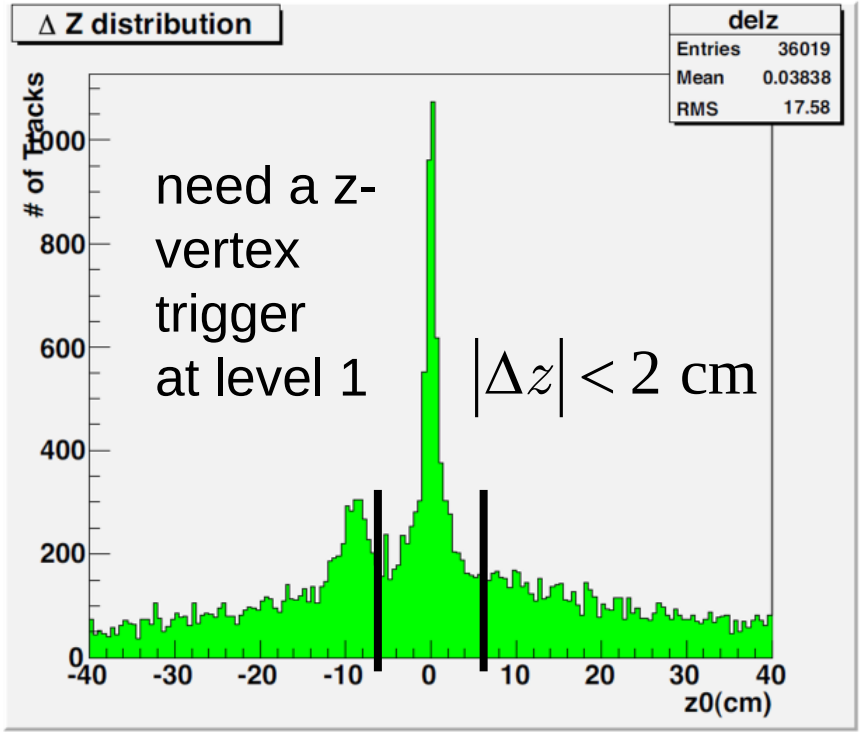


SiPM, e.g. Hamamatsu 1.3x1.3 mm^2

Improved Track Trigger Capabilities

Neural z-Vertex Trigger Project: better efficiency for low track multiplicities (developed within the Excellence Cluster: S. Neuhaus, S. Skambraks, Y. Chen)

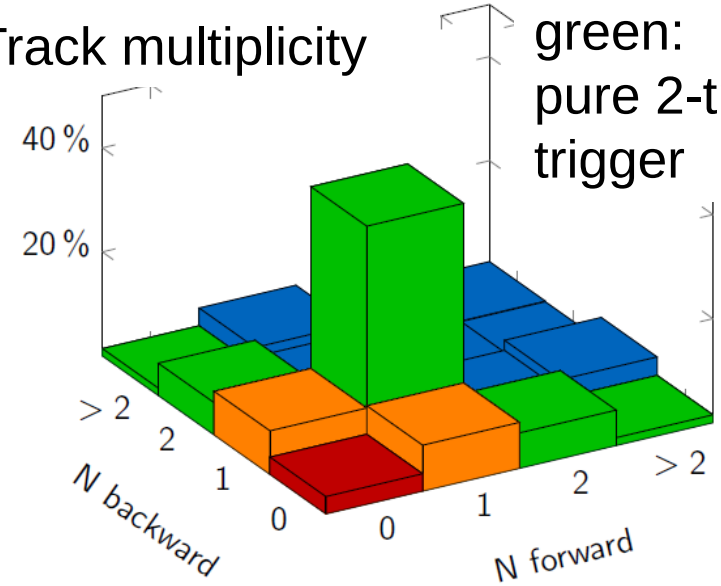
The Background Problem:



vertex distribution along beam axis (from Belle experiment)

pure 2-track trigger not possible (energy deposition ECL required)

Track multiplicity



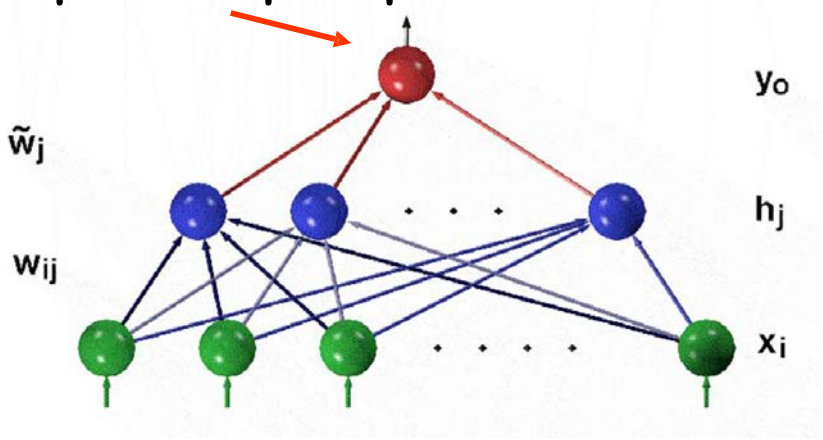
green: pure 2-track trigger

$e^-e^+ \to \tau^-\tau^+$

improve by factor >3

Neural Approach to z-Vertex Trigger

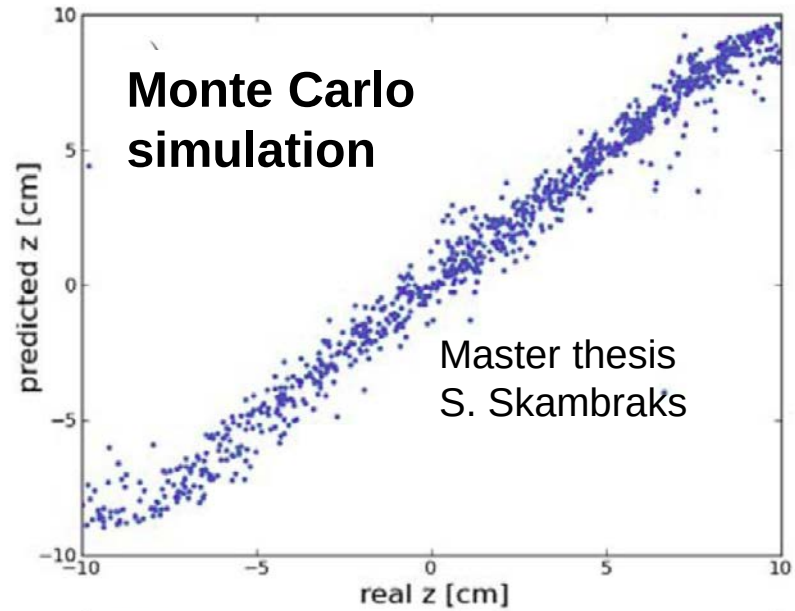
output: z-impact parameter of track

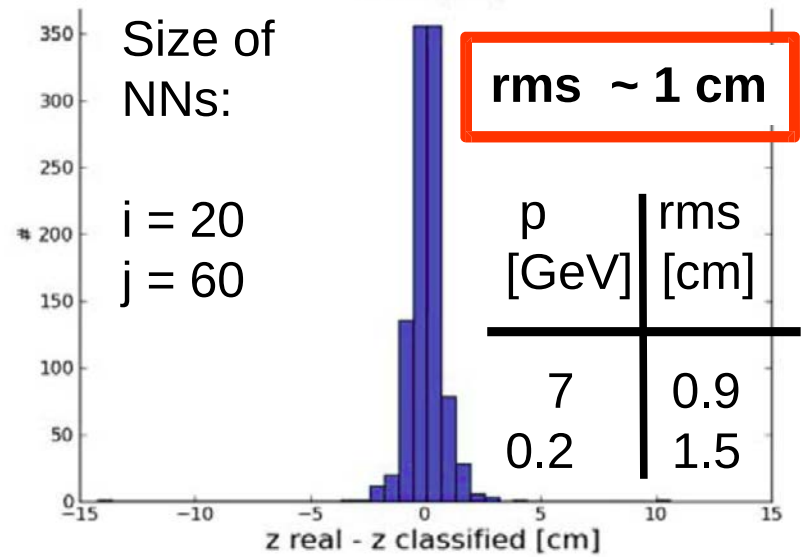


input: subset of CDC SL wires (i),

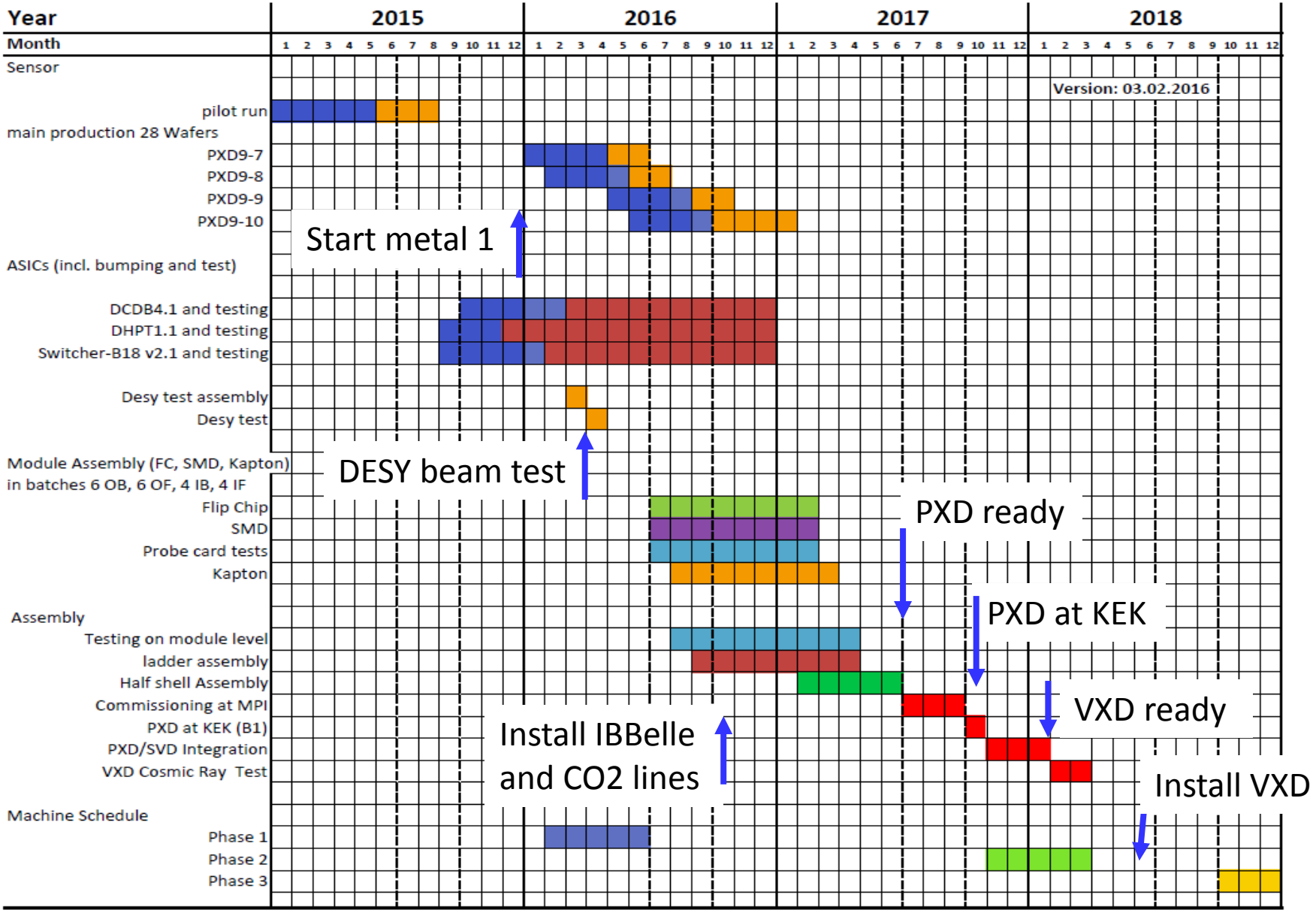
+ digital drift times x_i

Data (pre)processing:
- Track candidates via Hough transform (find sector in φ, θ, p_T)
- determine z-impact for track in given sector, using associated SL wire set

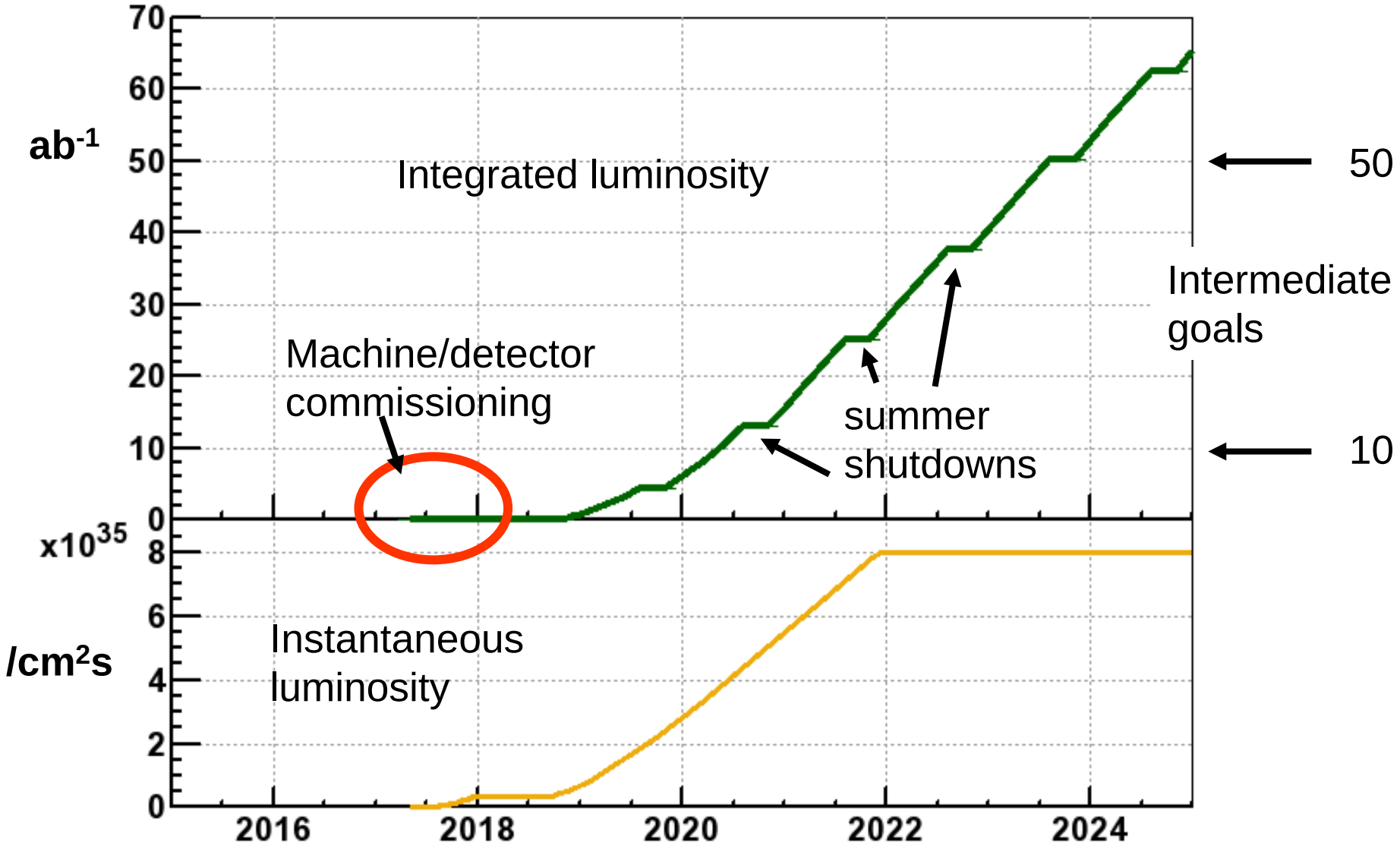




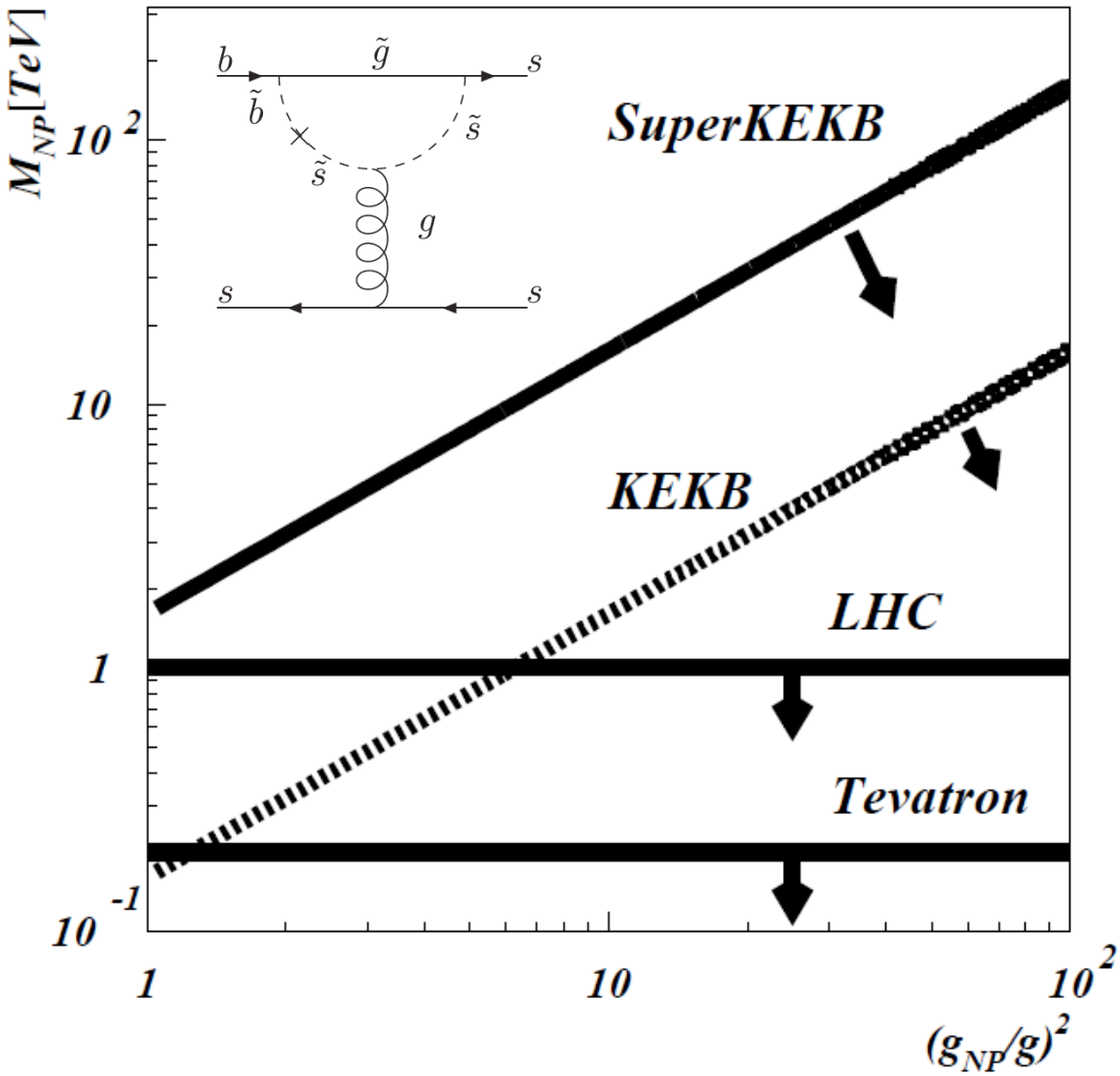
Schedule and Milestones



Updated SuperKEKB Luminosity Profile



Sensitivity to New Physics



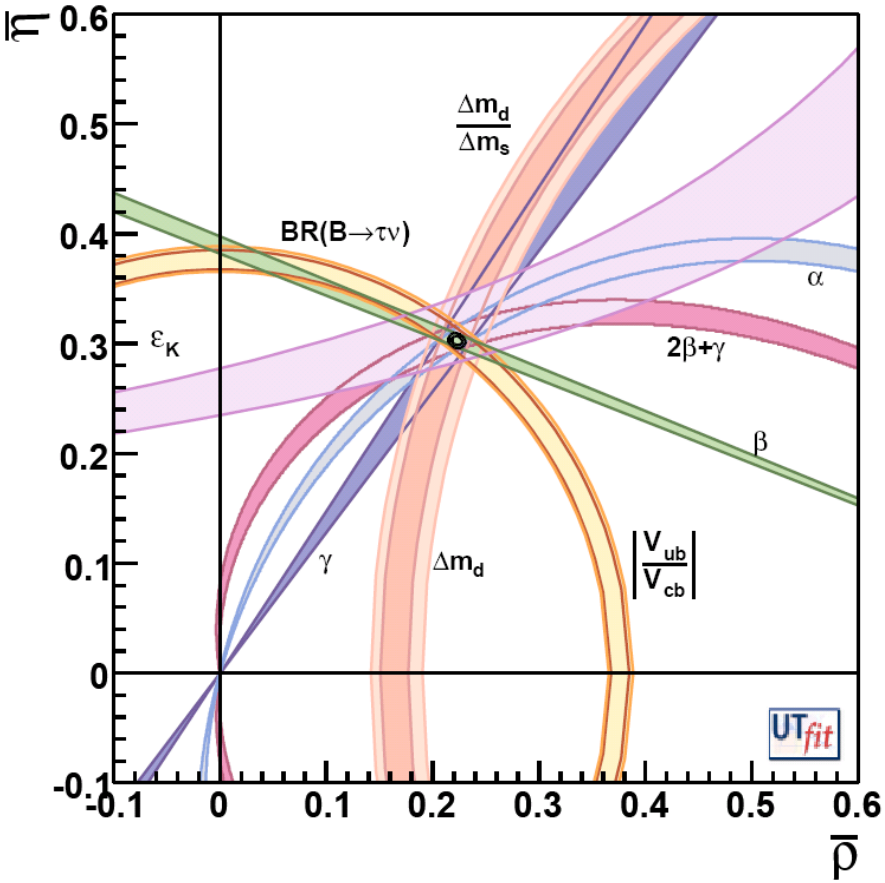
Super Flavor Factories:

Indirect discovery of New Physics In quantum loops via high precision measurements, searching for deviations from the SM

complementary to the LHC

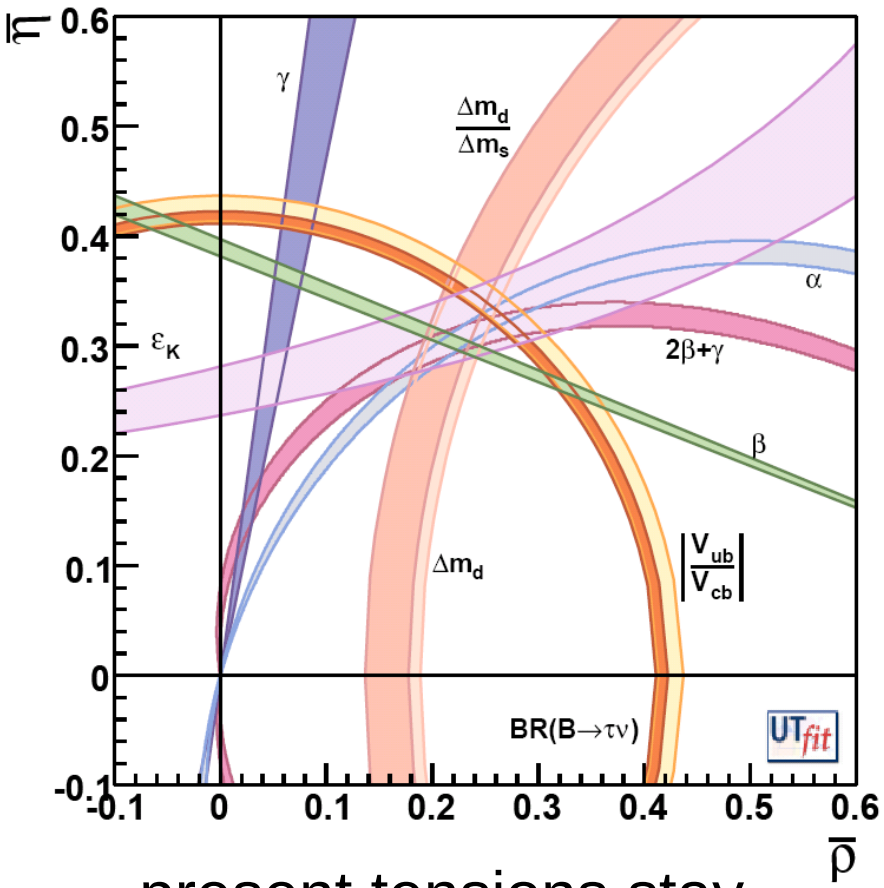
The Unitarity Triangle in the year 2024

$$\int \mathcal{L} dt = 50 \text{ ab}^{-1}$$



SM correct

a nightmare …



present tensions stay …

… the dream !

Summary and Conclusions

- „New Physics“ needed to explain the observed matter-antimatter asymmetry → new sources of CP violation
- Present measurements of the fundamental parameters of the CKM matrix show some „tensions“
- A new generation of B factories with O(50) times the present luminosity under constuction to search for NP, complementary to the LHC
- The SuperKEKB project is well underway, Phase 1 has started Belle II: Strong contribution from Europe (pixel vertex detector)
- Plan to have machine and detector ready for data taking in late 2018
- Excellent prospects for high precision flavor physics (SM & NP, exotic hadrons, τ physics ….) during this decade