Tau lepton physics at Belle and Belle II/SuperKEKB

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Contents

- Belle II/SuperKEKB Projects
  - Naming: KEKB → superKEKB (machine)

    Belle → Belle II (detector)

    → (logo)
- Prospect of τ Physics at Belle and Belle II
  - Lepton Flavor Violation
  - CP Violation
  - Lepton Universality
  - Hadronic Decays, Spectral Functions, Form Factors
  - Others

- BelleII/SuperKEKB documents
  - T. Aushev et al., (2010) arxiv: 1002.5012
  - A.G. Akeroyd et al., (SuperKEKB Physics Working Group) (2004) arxiv: hep-ex/0406071

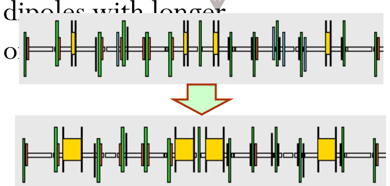
Super KEKB collider

- Target Luminosity 8×10^{35} $cm^{-2}s^{-1}$
- Accumulate $50 ab^{-1}$, x 50 as large as the luminosity achieved by KEKB, within 5 years after end of construction.

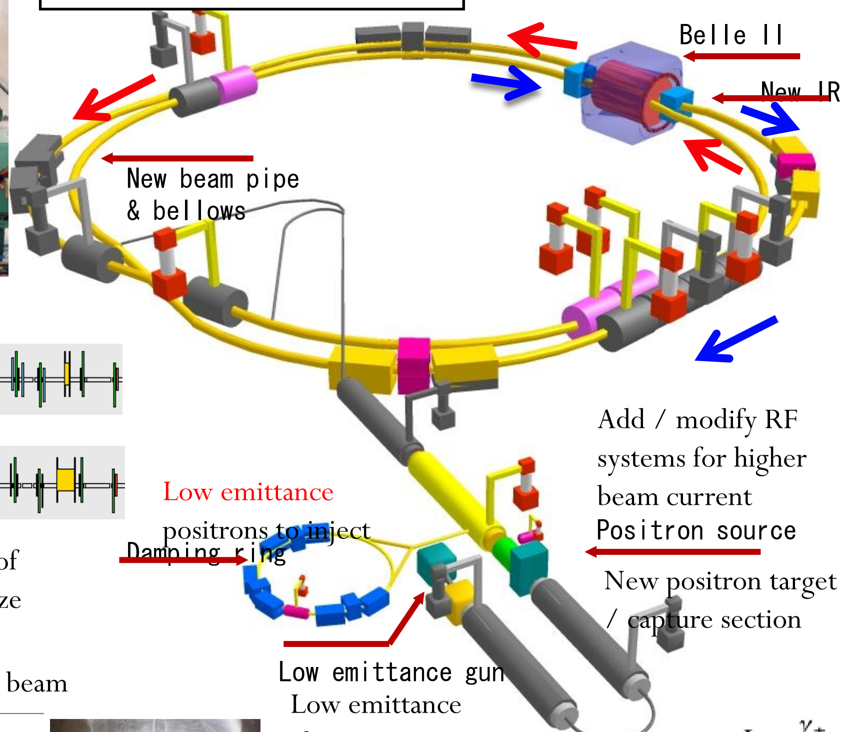
e⁻ 7GeV 2.6 A

e⁺ 4GeV 3.6 A

Replace short dipoles with longer o



Redesign the lattices of HER & LER to squeeze the emittance

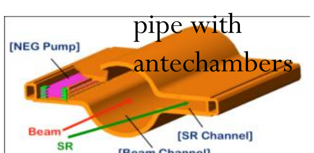


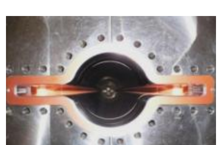
New superconducting /permanent final focusing quads near the IP

Add / modify RF systems for higher beam current

New positron target / capture section

TiN-coated beam pipe with antechambers





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

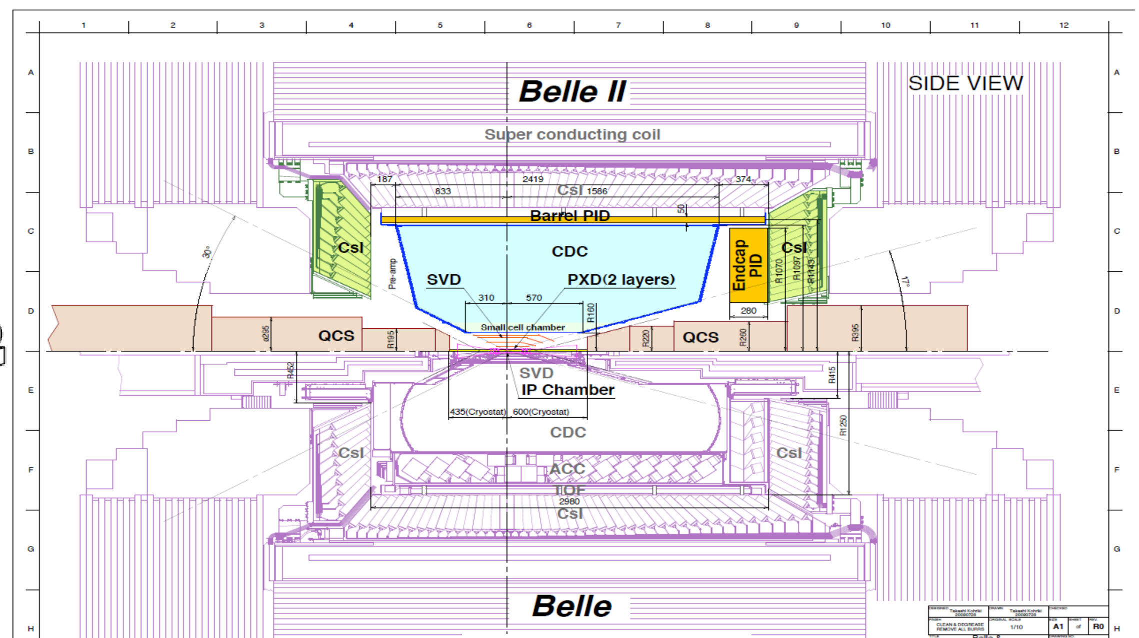
Belle II Detector

- Very Precise vertex determination with Pixel detectors and Si strip detectors.
- Tracking : Larger volume + larger sampling + improve dEdx
- Calorimeter: CsI(Tl) with wave form sampling. less materials in front.
- Particle ID : TOP counter + A-RICH; (Reconstruct č Ring-image) improved performance of Kaon ID
- muon/KL: Scintillation counters instead of RPC
- New DAQ system,
- New trigger

Time Of Propagation counter
=Compact DIRC

Quartz radiator

MCP-PM＝Micro-Channel Plate Photomultiplier



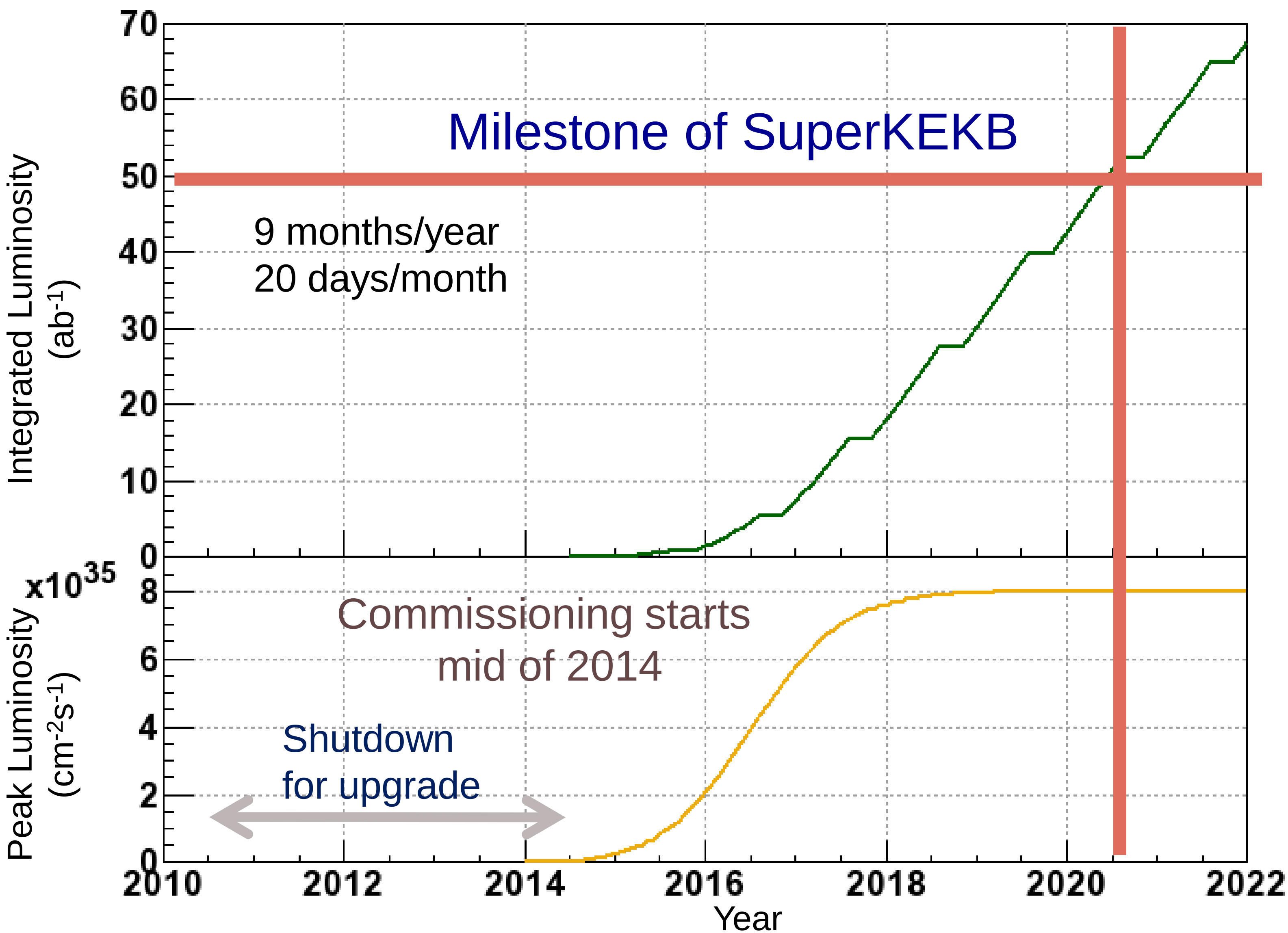
Parameters are preliminary : are not fixed yet

Tau Lepton Factories

Group	Int. Luminosity fb^{-1}	$N_{\tau\tau}$, 10^6
LEP(Z-peak)	0.34	0.33
CLEO(10.6 GeV)	13.8	12.6
Babar(10.6 GeV)	516	482
Belle(10.6GeV)	1014	933
tau-c (4.2 GeV)	10	32,000
BelleII/SuperKEKB	50,000	46,000
SuperB	75,000	69,000

✓Babar and Belle collected together about 1.5 ab^{-1}
✓Belle II/SuperB are planning to collect additional x50-75 times more data.
✓At $\Upsilon(4S)$ $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$=0.919nb, so B-factory is also a tau factory.
Belle II/SuperB with 50 ab^{-1} will yield 4.5x 10^{10} $\tau^+\tau^-$ pairs.

Luminosity upgrade plan



We are planning to reach 50 ab^{-1} in 2020~2021.

Y. Ohnishi

τ Lepton Physics Overview

Goal/Dream | **Category** | **Physics** | **Important factors**

New Physics

Absent in SM

- Lepton Flavor Violation → Luminosity
- Charged Lepton CPV
- τ EDM
- CPT violation

Belle II

Precision Measurement, search for deviation from SM

- Lepton Universality

  $m_{t,}$ τ –lifetime, Be, B_{μ}, $B_{\pi,} B_K$
- $(g\text{-}2)_{\tau}$

Hadrons

Understand various pQCD and non-pQCD aspect s of Hadrons from 1[st] principle.

Inclusive Measurements

s u m

- (strange) Br, spectral functions

  α_s, Vus, m_s , $<q\bar{q}>$

  $(g\text{-}2)_{\mu}$?/CVC

Exclusive Measurements

- Br, mass spectrums
- Form Factors(A,V, S)
- 2[nd] Class Current
- Resonances. Rare decays

τ is an ideal to study hadrons

String Theory helps us? AdS/CF

Important factors:

- Luminosity
- Background
- Particle ID (π/K)
- π^0
- Knowledge of decay angles
- Spin-Spin corr.
- Knowledge of τ direction
- Beam polarization

2010/9/17

Note:

I will discuss both subjects in a mixed form.

1. Subjects to be done mainly using Belle data.
   - Test of Lepton Universality
   - Br's, Hadron Spectral Functions.
   - ....
2. Subjects to be done using Belle data but also important in Belle II experiments.
   - Lepton Flavor Violation
   - CP Violation
   - CPT test, $(g\text{-}2)_\tau$

Lepton Flavor Violation (LFV)

- Charged lepton flavor violation is strongly suppressed in SM,

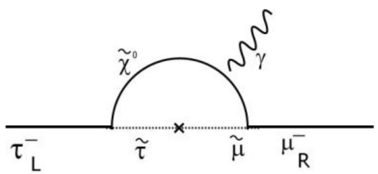
$$Br(\tau \to \ell\gamma) \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \approx 10^{-49\sim-54}$$

W.J. Marciano, A.I. Sanda (1977)

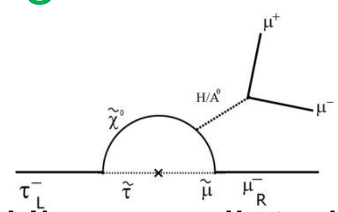
but a feature common to many possible extensions of the SM.

MSSM + seesaw, -- dipole as well as Higgs mediated.

Little Higgs, TeV scale ν_R, 4th generation … (arxiv: 0801.1826)



dipole



Higgs mediated

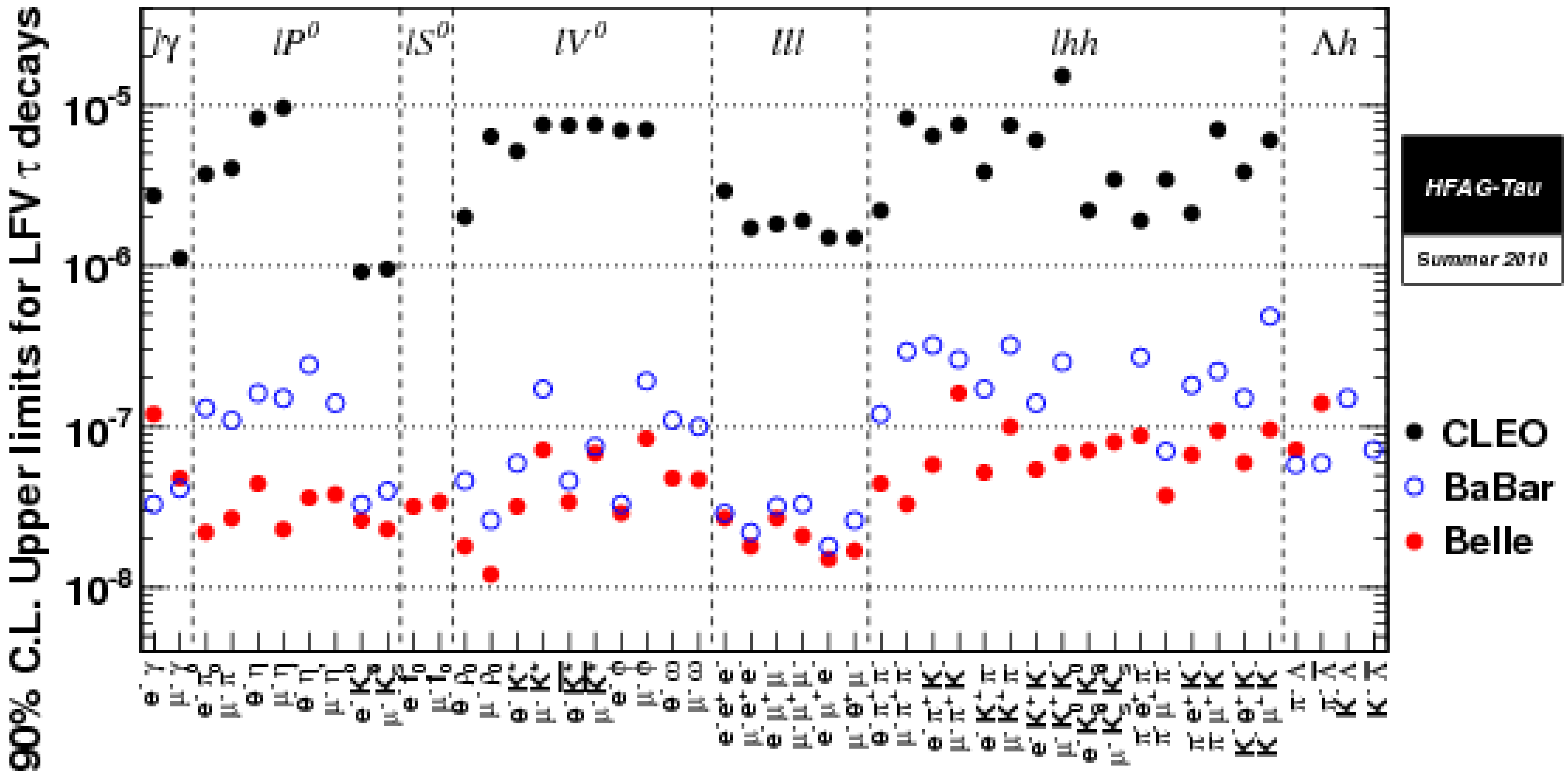
- Some of models predict rather high branching fraction comparable with current experimental sensitivity.
- Interesting interplay between τ LFV and μ → e γ (MEG exp.) : complementary

$\mu \to e\,\gamma$: good sensitivity for MSSM + seesaw(dipole)

τ LFV : good sensitivity for Higgs mediated scenario
Many decay modes:

LFV: Current Status

2010 Summer Status

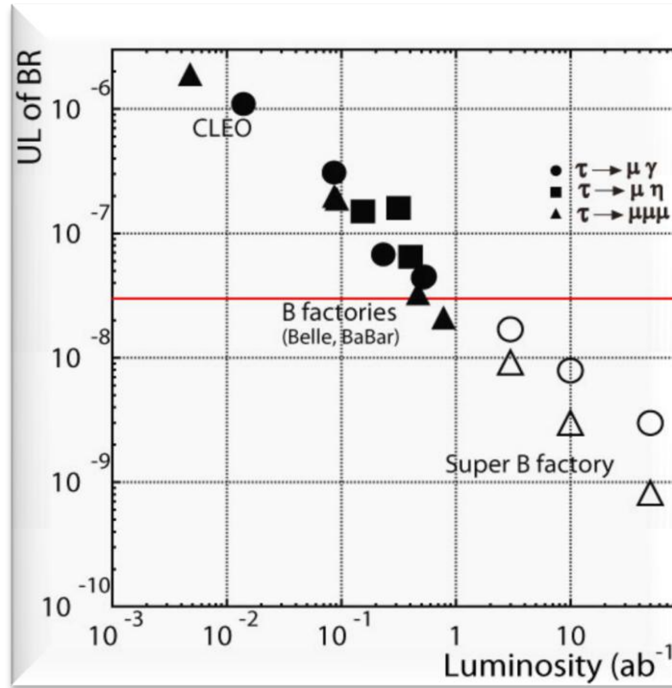


✓ 4 9 LFV modes are studied.

✓ Our sensitivity reaches O(10^{-8})

LFV: Prospect at Belle II

- Accessible Br. at 50 ab^{-1}
  - ✓ $\tau \to \mu\gamma$, $e\gamma$ — 3×10^{-9} (limited BG)
  - ✓ $\tau \to \mu\eta$ — 2×10^{-9}
  - ✓ $\tau \to 3l$ ($\mu\mu\mu$ ..) 8×10^{-10} (*BG free*)



✓Expectation is obtained assuming the current level of background and efficiency conservatively without assuming any improvement.

✓Further improvements are expected by better detector performance and …

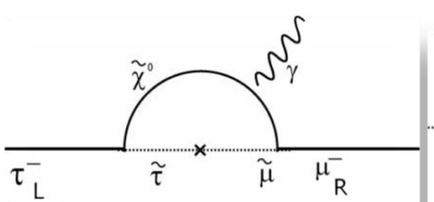
✓ $\tau \to \mu\gamma$, $e\gamma$;

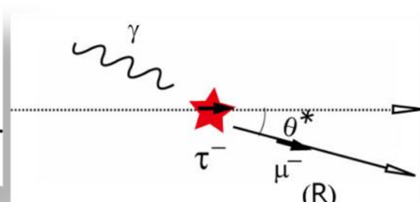
Main BG is from the ISR photon + $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\ell(\gamma)$

Ref. arxiv:1002.5012

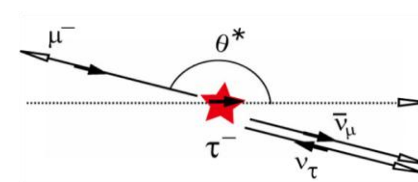
✓ Beam polarization or spin-correlation are expected to be useful to reduce these backgrounds. Chirality is changed (L↔R) in $\tau \to \mu\gamma$

$\tau \to \mu\nu_\mu\nu_\tau$





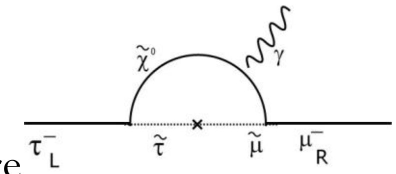
VS

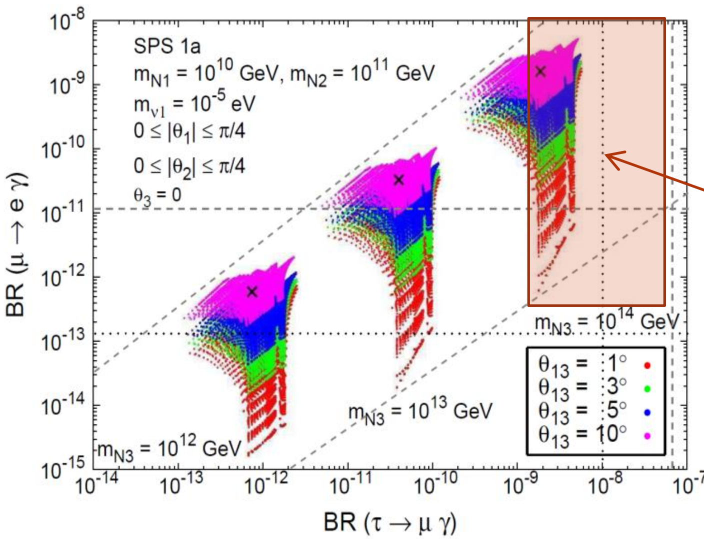


Belle II Sensitivity for some models

$\tau \to \mu\gamma$ vs. $\mu \to e\gamma$

MSSM+seesaw, dipole diagrams are dominated.

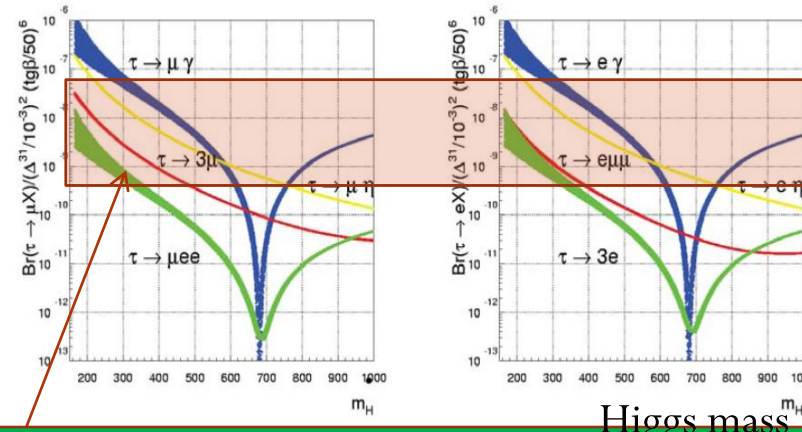




S. Antusch et al., JHEP 11, 090 (2006).

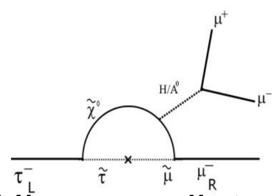
$\tau \to 3\mu$ $\tau \to \mu\eta$ Higgs madiated

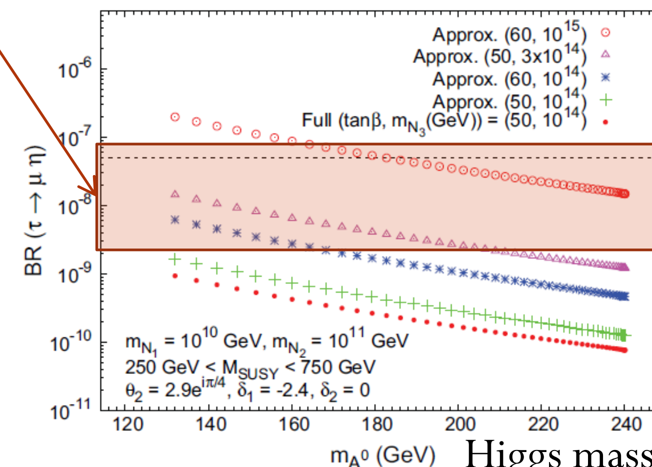
Paradisi., 0602 (2006) 050



Region covered by Belle II experiments

$\tau \to \mu\eta$ UHM





MSSM + seesaw + light Higgs

M. Herrero et al. arxiv:0903.5151

✓If Higgs mass is light (130- 400 GeV), where Higgs mediated diagrams play an important role. Belle II has a good sensitivity for that scenario.

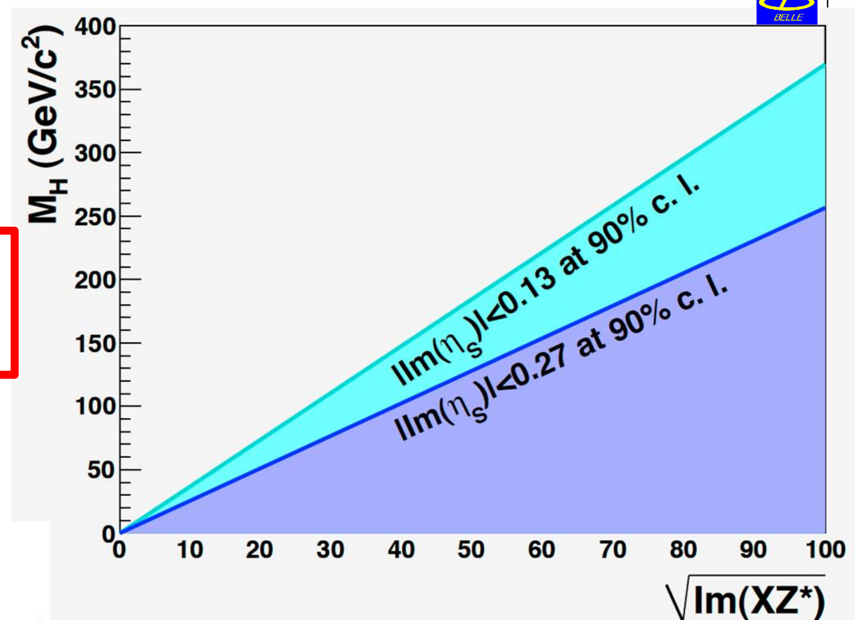
CP violation in τ decay s

- CP violation in charged leptons is absent in SM but it is possible some models beyond the SM such as multi-Higgs-doublet -model (3HDM).
- Belle reports the results for search for CPV in $\tau^- \to K_s \pi^- \nu_\tau$ with 700 fb^{-1} data (M. Bischofberger).
- Obtained U.L. of CP asymmetry is

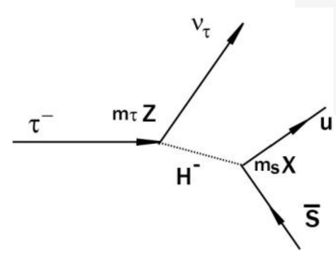
  $-0.005 < A_{cp} < 0.008$

  $|Im(\eta_s)| < 0.13\text{-}0.27$ at 90%C.L.
- Limit for New Physics scenario 3HDM

$$\mathrm{Im}(\eta_S) = -\frac{m_\tau M_N}{M_H^2} \cdot \mathrm{Im}(XZ^*) \quad \text{with} \quad M_N = 1\,\mathrm{GeV}/c^2$$



- ✓ M_H : mass of the lightest charged Higgs
- ✓ X,Z,:complex coupling constants:

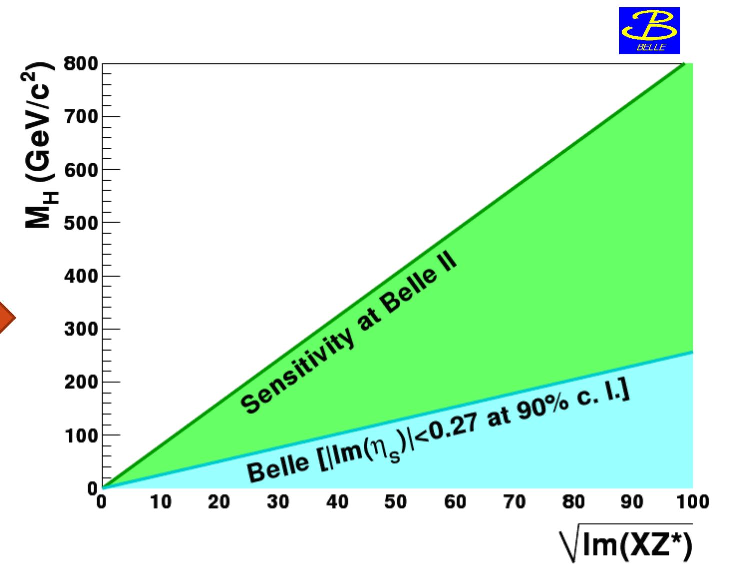


Prospect for CPV at Belle II

- ✓ Bias from detector charge asymmetry , γ-Z int. effects are small O(10^{-3}).
- ✓ Systematic is determined by the stat. error of control sample, then it can be improved if statistic is increased.

- 10 times improvement is expected at Belle II (50 ab^{-1}).

  The accessible region for NP searches increases twice .



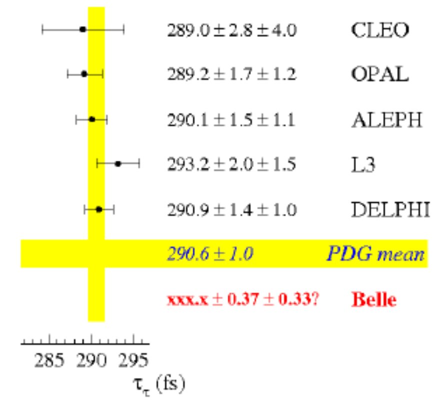
- Direct extraction of S-wave amplitude using decay angular distribution is needed.
- Interesting possibility for CPV searches in other decay modes

  $\rho\pi$. $K\pi\pi$ ....

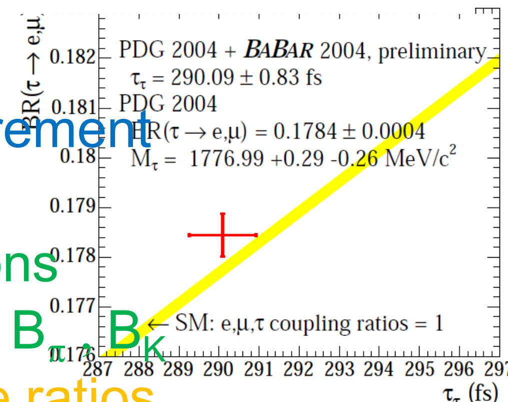
Lepton Universality

- Precise tests of the Lepton Universality is good place to look for BSM.
- There are various relations between fundamental observables $m_\tau, \tau_\tau, B_e, B_\mu, B_\pi, B_K$

$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 Br\left(\tau^- \to e^- \overline{\nu}_e \nu_\tau\right) \frac{f\left(m_e^2/m_\mu^2\right) F_W^\mu F_{rad}^\mu}{f\left(m_e^2/m_\tau^2\right) F_W^\tau F_{rad}^\tau}$$



- ✓ Need a precision of 0.1-0.2%
- ✓ Belle measures m_τ, and can provide a precise measurement of tau lifetime τ_τ, soon
- ✓ We are planning to measure leptonic branching fractions B_μ, B_e as well as a single hadron branching fractions B_π, B_K
- ✓ A high accuracy measurements will be possible for the ratios B_μ/B_e, B_π/B_e, B_K/B_e.



This test is planned using Belle data.

Hadronic Decays

- Inclusive measurements

  $\alpha_s, V_{us,}\ m_{s,}\ \langle qq \rangle$ ..

- Exclusive Measurements

  Br, mass spectrum, Spectral Function, Form Factors

To get Inclusive quantities, we need many exclusive measurements.

Cabibbo suppressed decays

- Cabibbo suppressed (strange) τ decays are important for the determination of Vus, ms plus non-p-QCD parameters at low-Q^2
- Status of Vus is nicely summarized by Sobie/Swagato
- There is a systematic difference between the one determined by Kaon decays and one using τ inclusive decays.
- Vus determination using Inclusive τ strange decays is the cleanest theoretically.

.

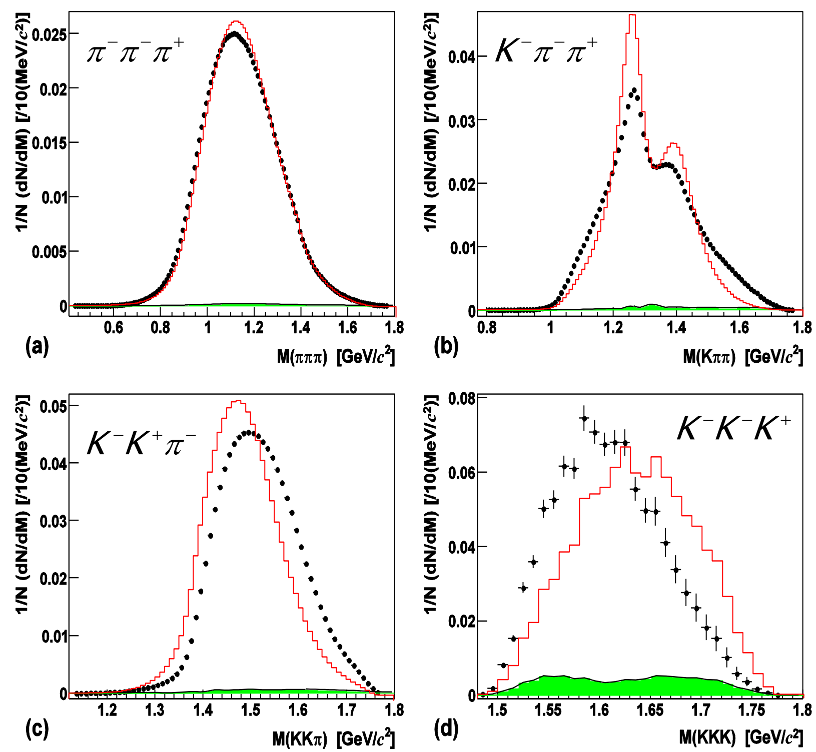
✓-We will need measurements of Br of all strange decays also need Spectral Functions for theoretical consistency check.(Maltman Tau08).

Recently, Belle provides precise unfolded mass spectrum for 2 strange decay modes; $\tau^- \to K^-\pi^+\pi^-\nu_\tau$, $K^-K^+K^-\nu_\tau$.and 2 non-strange decays $\pi^-\pi^+\pi^-\nu_\tau$, $K^-K^+\pi^-\nu_\tau$

•Green band is the systematic errors, including dependence of the resonance model for efficiency determination. Red histogram TAUOLA

•The mass spectrum with Kaon does not agree with TAUOLA.

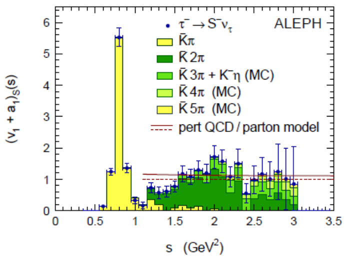
Published in PRD 81, 113007 (2010)

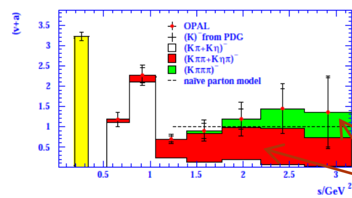


Strange spectral function

■Should be compared with the previous LEP exp.

Strange spectral function

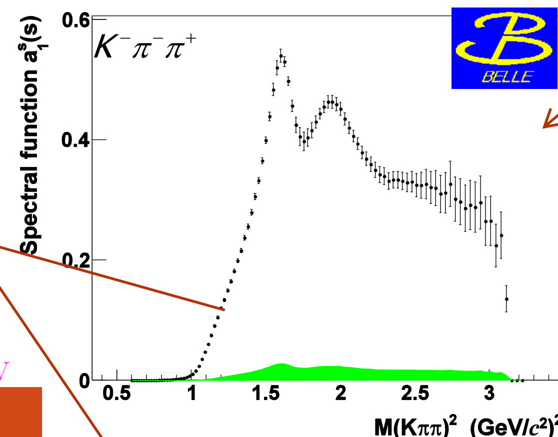


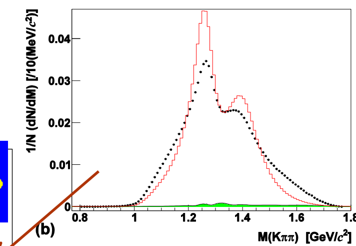


ALEPH: $|V_{us}| = 0.2204 \pm 0.0028_{\rm exp} \pm 0.0003_{\rm th} \pm 0.0001_{m_s}$

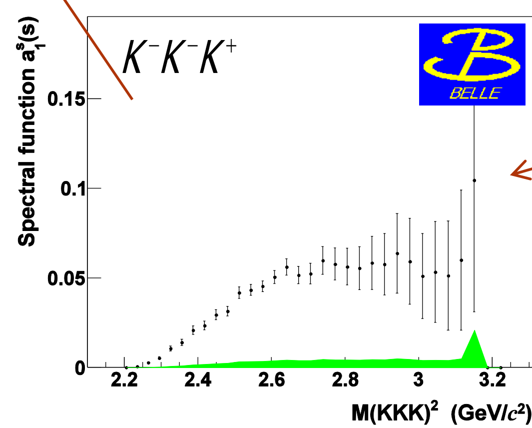
J.Prades from OPAL data: $|V_{us}| = 0.2219 \pm 0.0034, \quad m_s = (81 \pm 20)$ MeV

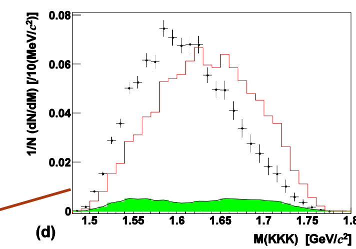
mode	Br	Spectral func.
K		-
Kπ	BELLE	BELLE (no. e-matrix)
Kππ	BELLE	BELLE
Kπππ+Kη	BELLE (Kη)	
K4π		
KKK	BELLE	BELLE





PRD 81 ,113007 (2010).

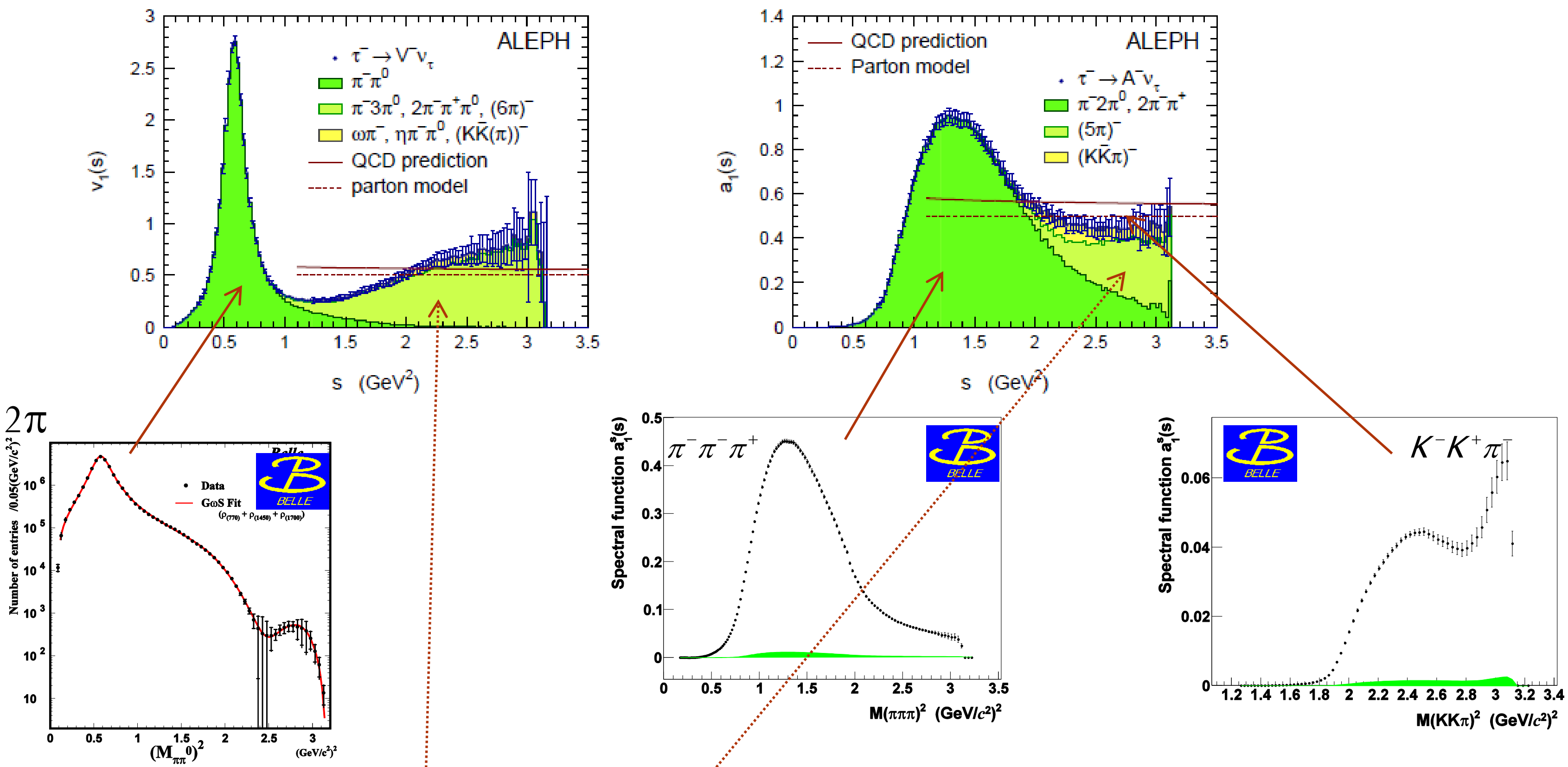




Needed to measure missing parts.

We can provide mass spectrums and their error matrix. Please contact us if it is needed.

Belle also contribution for Non-strange spectral functions



Missing are $\tau \to 4\pi\nu$, $\omega\pi\nu$, $5\pi\nu$, $\eta\pi\pi\nu$ .....

High static data are important at high mass region, where p-QCD plays an important role.

Prospect for Form Factor Measurements

✓Form Factors include all information of hadron system.

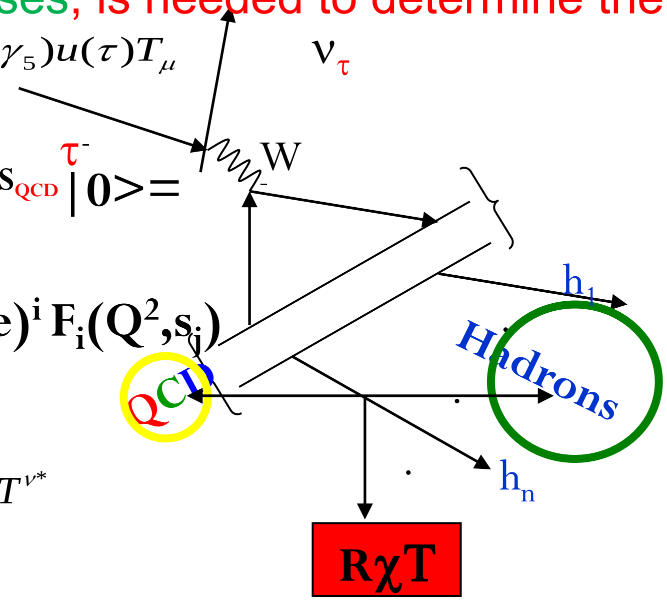
✓Multi-dimensional analysis, two angles and three masses, is needed to determine them.

$$\mathfrak{M} = \frac{G_F}{\sqrt{2}} V_{CKM} \overline{u}(\nu_\tau)\gamma^\mu(1-\gamma_5)u(\tau)T_\mu$$

✓Determination of FF is one of the ultimate goal of B factory experiments.

$$T_\mu = \langle Hadrons \,|\, (V\text{-}A)_\mu \, e^{iS_{QCD}} \,|\, 0 \rangle =$$

$$= \Sigma_i (\text{Lorentz Structure})^i \, F_i(Q^2, s_j)$$



P. Roig at Tau08

1) $L_{\mu\nu} T^\mu T^{\nu *}$

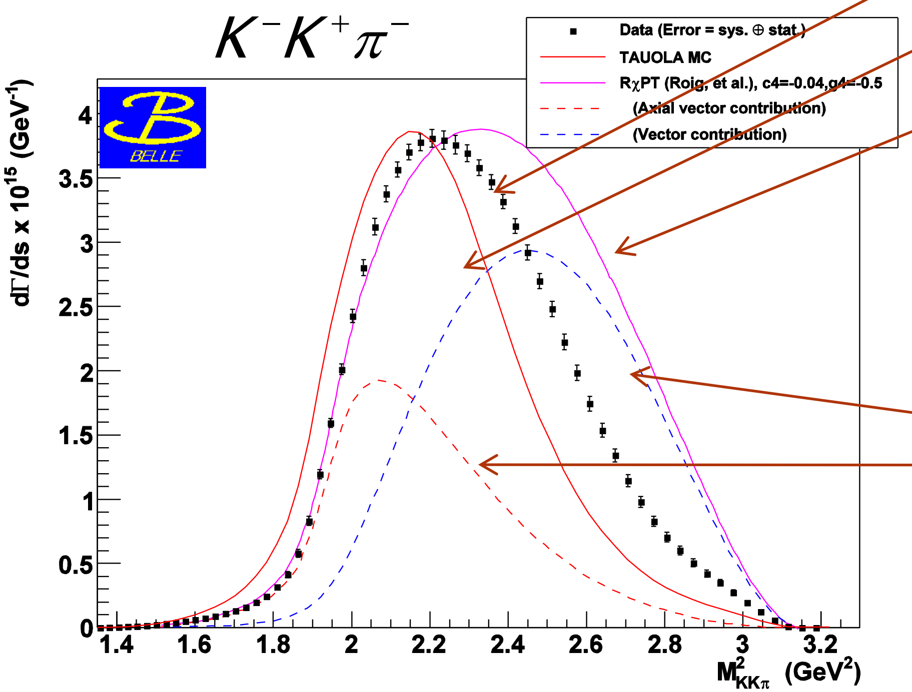
Table 2.6. Form factors of the three-meson final states in TAUOLA [297]. F_1 and F_2 axial-vector, F_4 pseudoscalar, and F_5 Wess–Zumino anomaly. The number in the left column is the internal ID of the channel

	Mode	F_1	F_2	F_4	F_5
5	$\tau \to 3\pi\,\nu_\tau$	$a_1 \to \rho\,\pi$ $\rho \to \pi\,\pi$	$a_1 \to \pi\,\rho$ $\rho \to \pi\,\pi$	$\pi'(1300)$ optional	–
14	$\tau \to K^+ K^- \pi^\pm \nu_\tau$	$a_1 \to K^* K$ $K^* \to K\,\pi$	$a_1 \to \pi\,\rho$ $\rho \to K\,K$		$\rho \to K^* K$ $K^* \to K\,\pi$
15	$\tau \to K^0 \bar{K}^0 \pi^\pm \nu_\tau$	$a_1 \to K^* K$ $K^* \to K\,\pi$	$a_1 \to \pi\,\rho$ $\rho \to K\,K$		$\rho \to K^* K$ $K^* \to K\,\pi$
16	$\tau \to K^\pm K^0 \pi^0 \nu_\tau$	–	$a_1 \to \pi\,\rho$ $\rho \to K\,K$	–	–
17	$\tau \to K^\pm \pi^0 \pi^0 \nu_\tau$	$K_1 \to K^* \pi$ $K^* \to K\,\pi$	$K_1 \to \pi\,K^*$ $K^* \to K\,\pi$		–
18	$\tau \to K^\pm \pi^+ \pi^- \nu_\tau$	$K_1 \to K\,\rho$ $\rho \to \pi\,\pi$	$K_1 \to \pi\,K^*$ $K^* \to K\,\pi$	–	$K^* \to \rho\,K$ $\rho \to \pi\,\pi$
19	$\tau \to K^0 \pi^\pm \pi^0 \nu_\tau$	–	$K_1 \to K\,\rho$ $\rho \to \pi\,\pi$	–	$K^* \to \rho\,K$ $\rho \to \pi\,\pi$
20	$\tau \to \eta\,\pi^\pm \pi^0 \nu_\tau$	–	–	–	$\rho \to \rho\,\eta$ $\rho \to \pi\,\pi$

Scalar and Vector parts are poorly known.

A comparison with RχT prediction

Exclusive hadron spectrum is useful for a test of theoretical models in resonance region.



PRD 81 ,113007 (2010).

Plots: Belle unfolded spectrum

Read line : TAUOLA MC

Purple line: A prediction based on χRT by G. Dumm, Pich, Portoles, P. Roig (Tau08)

No good agreement indicates need for further tuning /study of the Theory

Vector

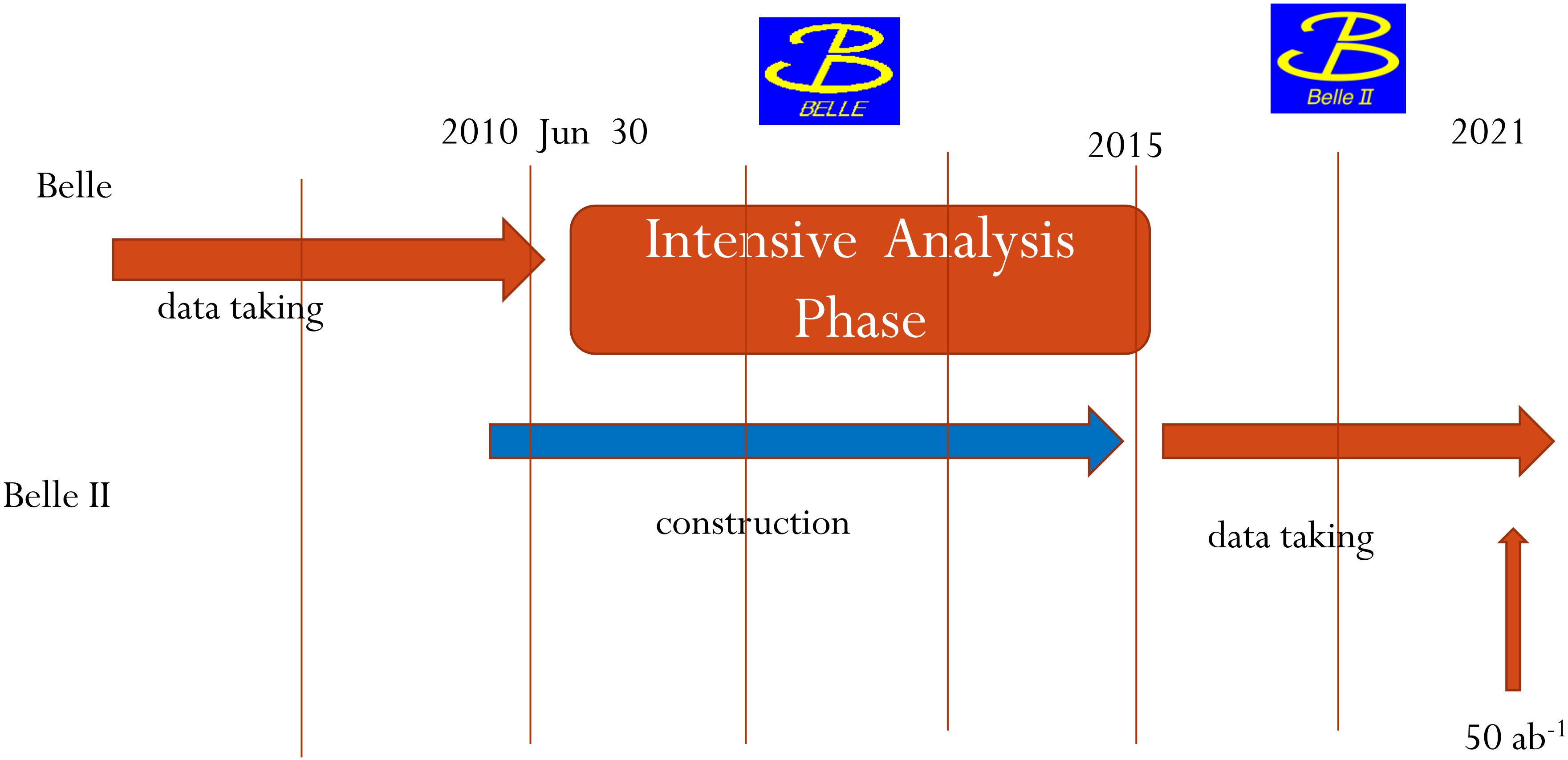
Axial Vector

In order separate Axial Vector and Vector (Wess-Zumino) terms, need to analyze decay angle distribution.

Summary

- Huge τ data ($1ab^{-1}$) from both B-factory experiments are great source of the information of SM and Beyond SM physics.
- Many physics items still not explored yet.
- Yet, additional 50-100 times data are expected in the BelleII/SuperB exp. in the next decades.
  - ✓Probe τ LFV to $O(10^{-9})$-$O(10^{-10})$
  - ✓Probe τ CPV to $O(10^{-4})$ w/o beam polarization.
  - ✓More sensitive check on Lepton universality, $(g-2)_\tau$ □
  - ✓Improved understanding of Hadrons. Bernabeu, arxiv: 0707.2496
    - Through measurements of Br, Spectral Functions and Form Factors for various τ decay modes.

Analysis Plan: Belle and Belle II



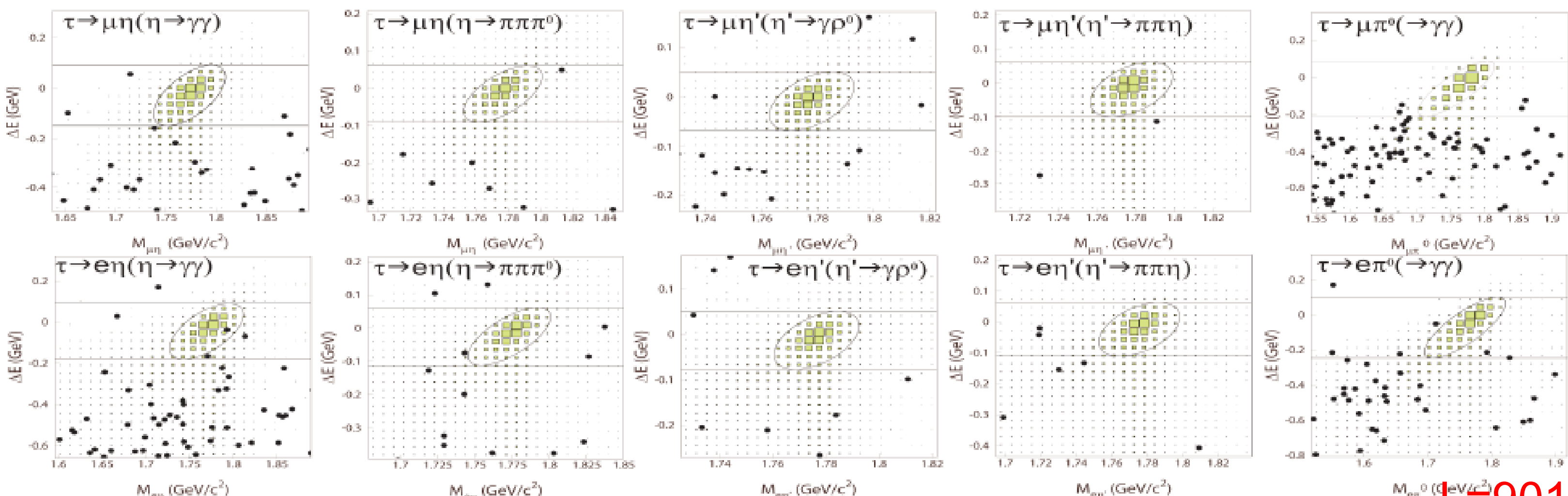
We still have many things can/should be done using Belle data, and have a great future at Belle II.

Stay tuned.

Backup Slide

Backup

Search for decays $\tau^- \to l^- P^0\ (\pi^0, \eta, \eta')$



Belle preliminary, ICHEP10

L=901 fb^{-1}

$\tau \to$	Eff.	N_{BG}^{exp}	UL($\times 10^{-8}$)	$\tau \to$	Eff.	N_{BG}^{exp}	UL($\times 10^{-8}$)
$\mu\eta(\to\gamma\gamma)$	8.2%	0.63±0.37	3.6	$\mu\eta'(\to\pi\pi\eta)$	8.1%	0.00+0.16-0.00	10.0
$\mu\eta(\to\pi\pi\pi^0)$	6.9%	0.23±0.23	8.6	$\mu\eta'(\to\rho^0\gamma)$	6.2%	0.59±0.41	6.6
$\mu\eta$(comb.)			2.3	$\mu\eta'$ (comb.)			3.8
$e\eta(\to\gamma\gamma)$	7.0%	0.66±0.38	8.2	$e\eta'(\to\pi\pi\eta)$	7.3%	0.63±0.45	9.4
$e\eta(\to\pi\pi\pi^0)$	6.3%	0.69±0.40	8.1	$e\eta'(\to\rho^0\gamma)$	7.5%	0.29±0.29	6.8
$e\eta$(comb.)			4.4	$e\eta'$ (comb.)			3.6
$\mu\pi^0(\to\gamma\gamma)$	4.2%	0.64±0.32	2.7	$e\pi^0(\to\gamma\gamma)$	4.7%	0.89±0.40	2.2

$(g\text{-}2)_\tau$

- ✓ Current muon anomalous magnetic moment shows 3 σ difference between data and theory,

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} \approx (3 \pm 1)x10^{-9}$$

- ✓ Natural scaling of the NP effects on the lepton magnetic dipole moments is

$$\frac{\Delta a_\tau}{\Delta a_\mu} \propto \frac{m_\tau^2}{m_\mu^2} = 290$$

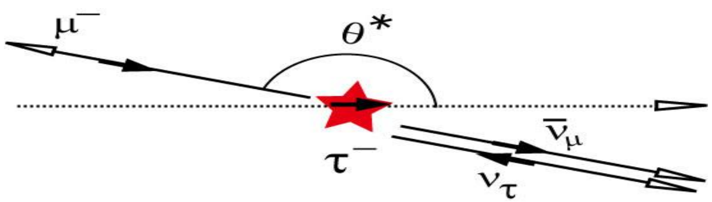
- ✓ If we interpret the present muon discrepancy as NP effects, we expect $\Delta a_\tau \approx 10^{-6}$
  In the special SUSY scenario even $\Delta a_\tau \approx 10^{-5}$ is expected.
- ✓ At Belle II/Super B, we will able to measure in the similar level of accuracy,
  Bernabeu, arxiv: 0707.2496

Need to study.

- reliability of measurement with or w/o beam pol.
- how to know the tau direction.
- How beam pol. is useful ?

Background suppression using τ spin

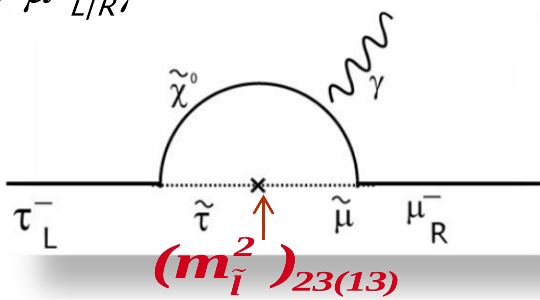
$$\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau$$

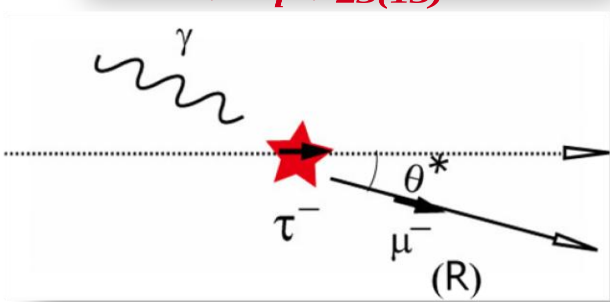


✓Since muon is mostly left handed, the direction of muon is preferentially against the t spin

$$\frac{d\Gamma}{dx^* d\cos\theta^*} \propto x^{*2}\left[\left(\frac{1}{2}-\frac{1}{3}x^*\right)+h_\tau \cos\theta^*\left(\frac{1}{6}-\frac{1}{3}x^*\right)\right], x^* = \frac{E^*_\mu}{E^{max}_\mu}$$

$$\tau^-_{R/L} \to \mu^-_{L/R}\gamma$$





✓Chi rarity is changed (L→R, R→L) in the $\tau^- \to \mu^- \gamma$ decay.

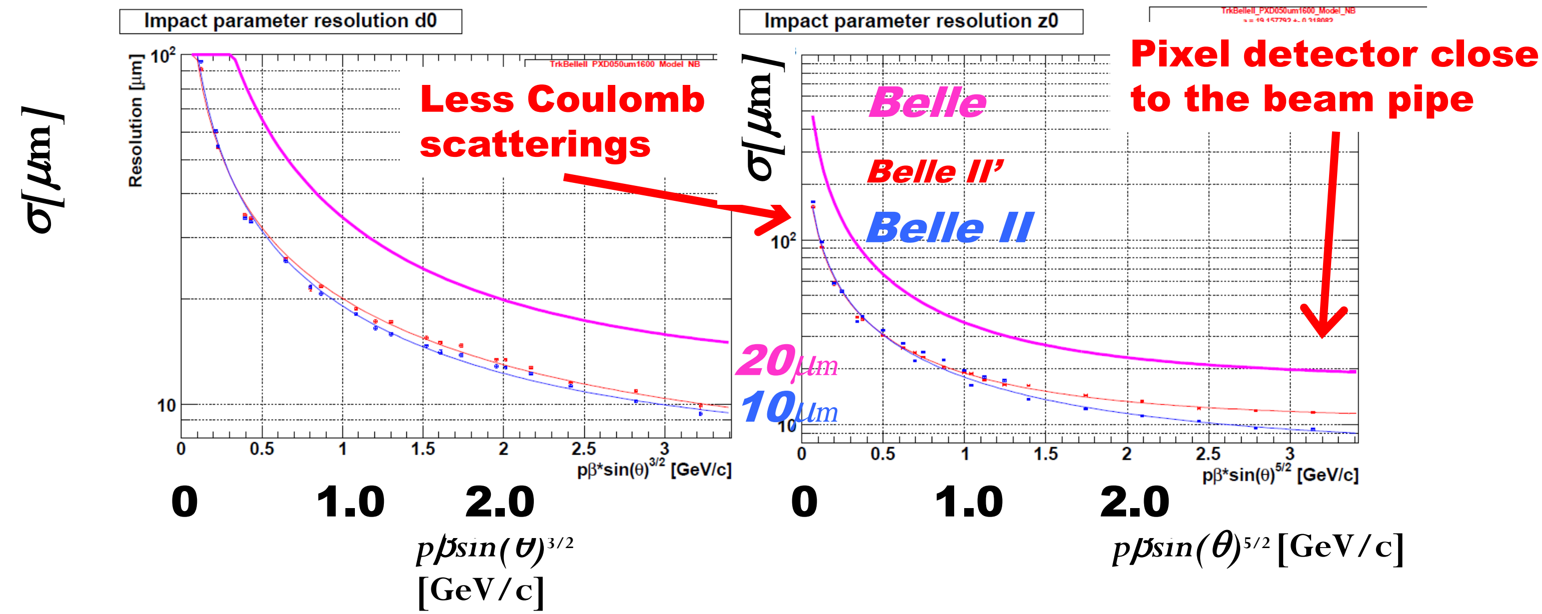
✓Photon polarization is perpendicular to the photon direction.

✓The direction of muon is preferentially parallel to the τ spin

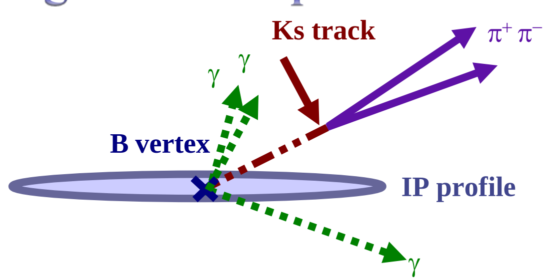
Expected performance

$$\sigma = a + \frac{b}{p\beta \sin^{\nu}\theta}$$

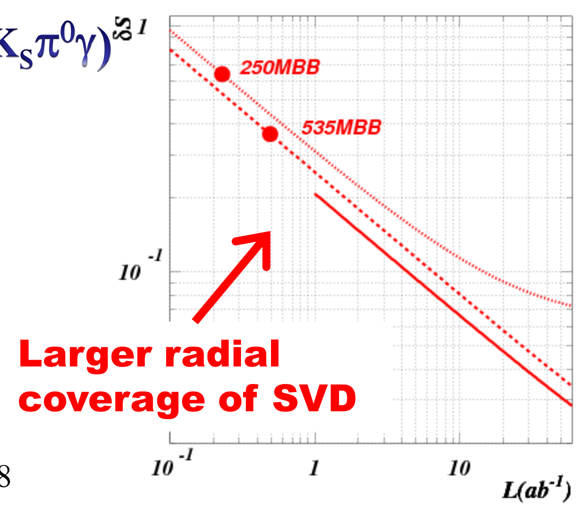
Significant improvement in IP resolution!



Significant improvement in $\delta S(K_S\pi^0\gamma)$

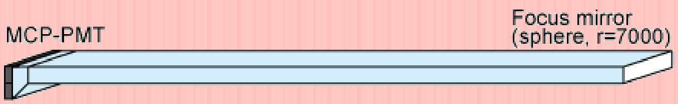


B decay point reconstruction with K_S trajectory



Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



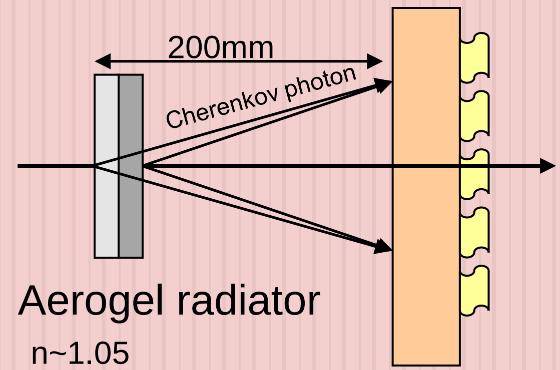
Quartz radiator

Focusing mirror

Small expansion block

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

End cap PID: Aerogel RICH (ARICH)

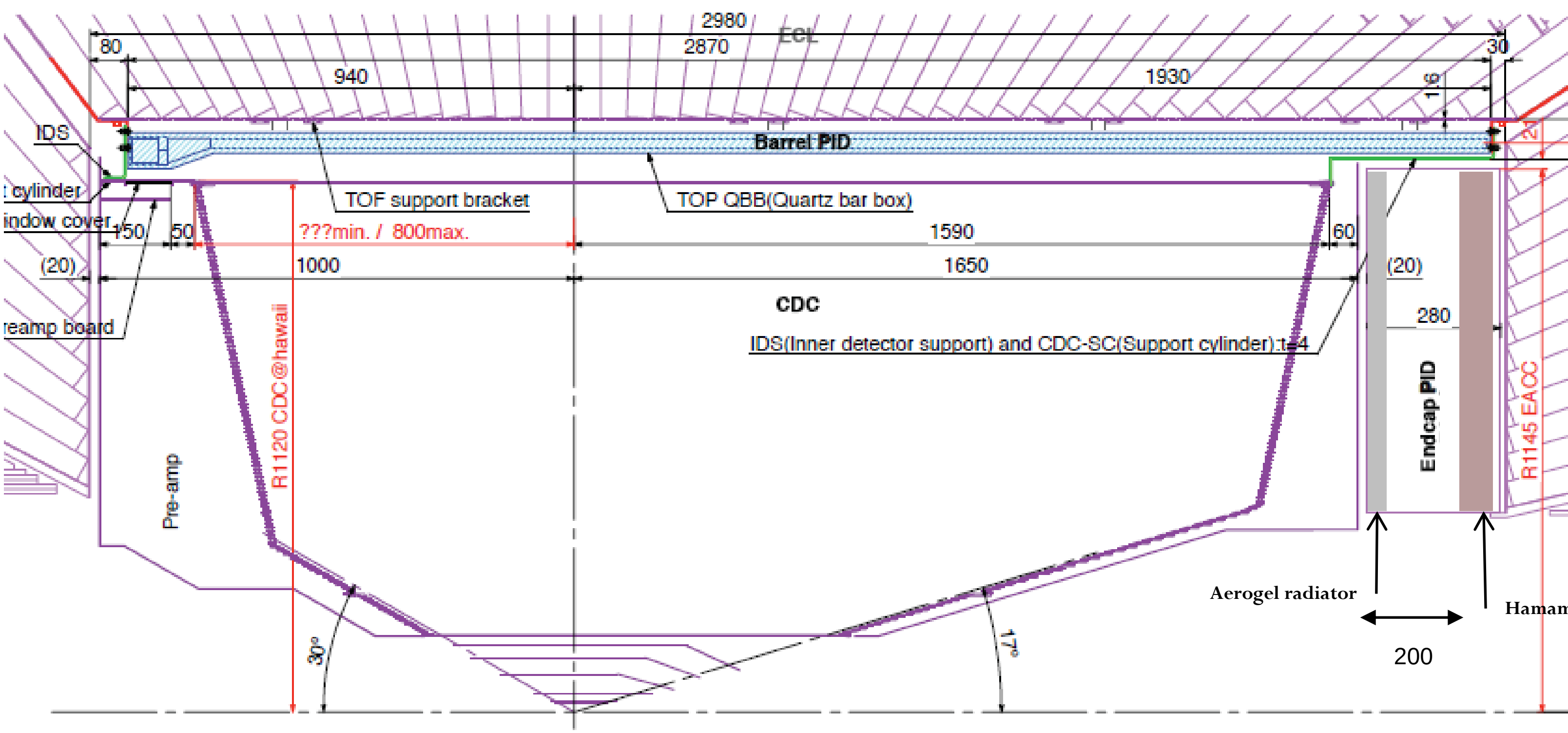


Aerogel radiator

n~1.05

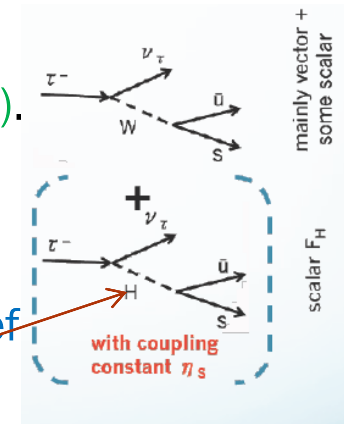
Hamamatsu HAPD

+ new ASIC



CP violation in τ decays.

- CP violation in charged leptons are absent in SM but it is possible some models beyond the SM such as multi-Higgs-doublet -model (3HDM).
- Belle reports the results for search for CPV in $\tau^- \to K_s \pi^- \nu_\tau$ with 700 fb^{-1} data (M. Bischofberger).



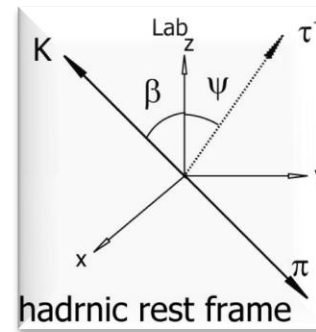
To see CPV effects, they uses “modified” CP asymmetry parameter A_{cp} def

$$A_{cp} \equiv \frac{1}{\Gamma'}\int \cos\beta\cos\psi \left[\frac{d\Gamma^{(\tau^-)}}{dQ^2 d\cos\beta\cos\psi} - \frac{d\Gamma^{(\tau^+)}}{dQ^2 d\cos\beta\cos\psi}\right] dQ^2 d\cos\beta d\cos\theta$$

η_s

$$\propto \mathrm{Im}(FF_s^*)\,\mathrm{Im}(\eta_s)$$

$$\Gamma' \equiv \int \frac{d\Gamma^{(\tau^-)}}{dQ^2 d\cos\beta\cos\psi} dQ^2 d\cos\beta d\cos\theta$$



Note:

✓ The CP asymmetry is measured with angular weights. This Acp has a similar sensitivity with an optimum observable used by CLEO but does not depend on the S-wave amplitude which is not well known.

✓ The observable Acp is proportional to Im(FFs)Im(η_s), where F is dominant P-wave, Fs is the S-wave amp. And η_s is a CP violating coupling constant in NP model.

✓Our definition of η_s is the same as the one defined in the original paper , J.H. Kuhn and E. Mirkes, Phys. Lett. B398 (1997) 407-414 but with different scale.

$$\left(\frac{\eta_s}{m_N}\right)_{ours} = \left(\frac{\eta_s}{m_d - m_s}\right)_{Kuhn}$$