Results on Tau Spectral Functions from Belle

$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$

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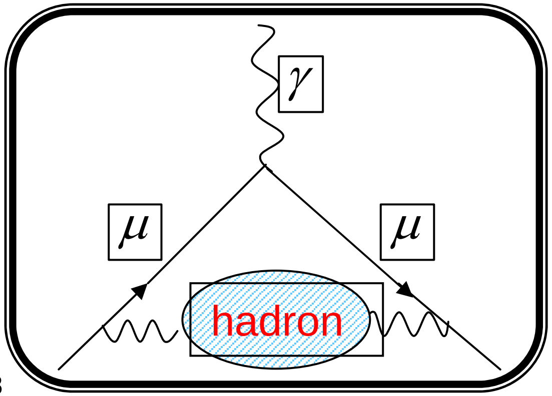
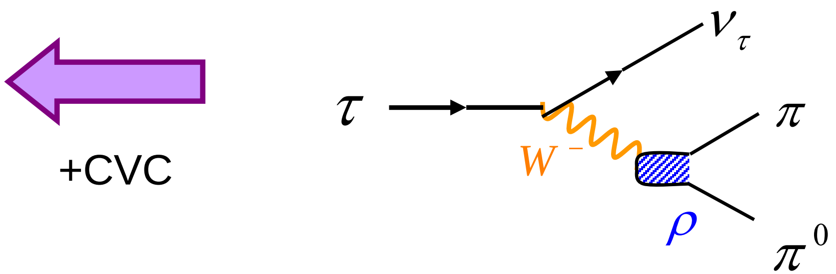
Hisaki Hayashii

Nara Women's University

Introduction

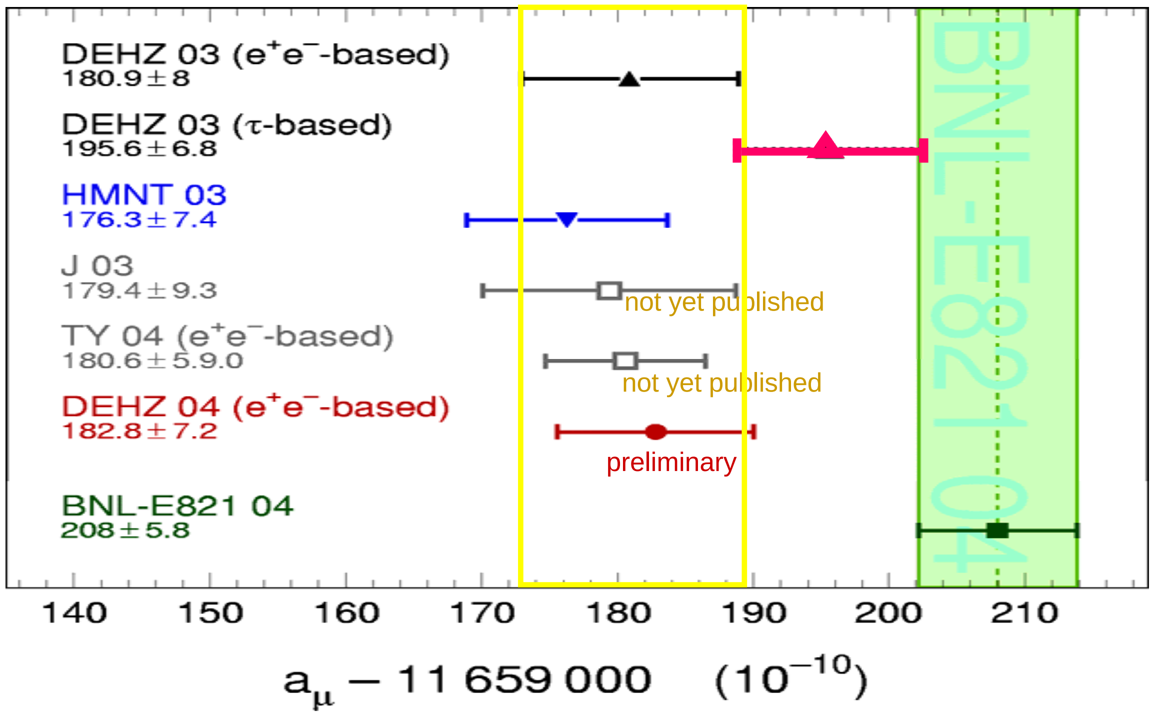
- Hadronic decays of tau lepton provide clean environment for studying the dynamics of hadronic states. $\alpha_s(s)$, a_μ, V_{us}, m_s
- $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$
  - has the largest Br
  - CVC relation with $e^+e^- \rightarrow \pi^+ \pi^-$
  - Plays an important role for the h. v. p. term in the muon anomalous magnetic moment. $a_\mu=(g_\mu-2)/2$





Introduction (cont.)

- Recent data indicate that there is a systematic difference between the 2π system in e^+e^- reaction and τ-decays, even after applying known iso-spin violation correction. Main difference btw a_μ^τ and a_μ^{ee} is from 2π mode.



ICHEP-2006(M.Davier et al.):

$a_\mu(\text{exp})-a_\mu(\text{th})$ is

3.3σ

A hint to New Physics beyond the SM!

What should be measured

- In this talk, We present update results from Belle experiment based on 5.6x 10^6 $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ decays (72.2/fb).
  - Final for 72.2/fb data.

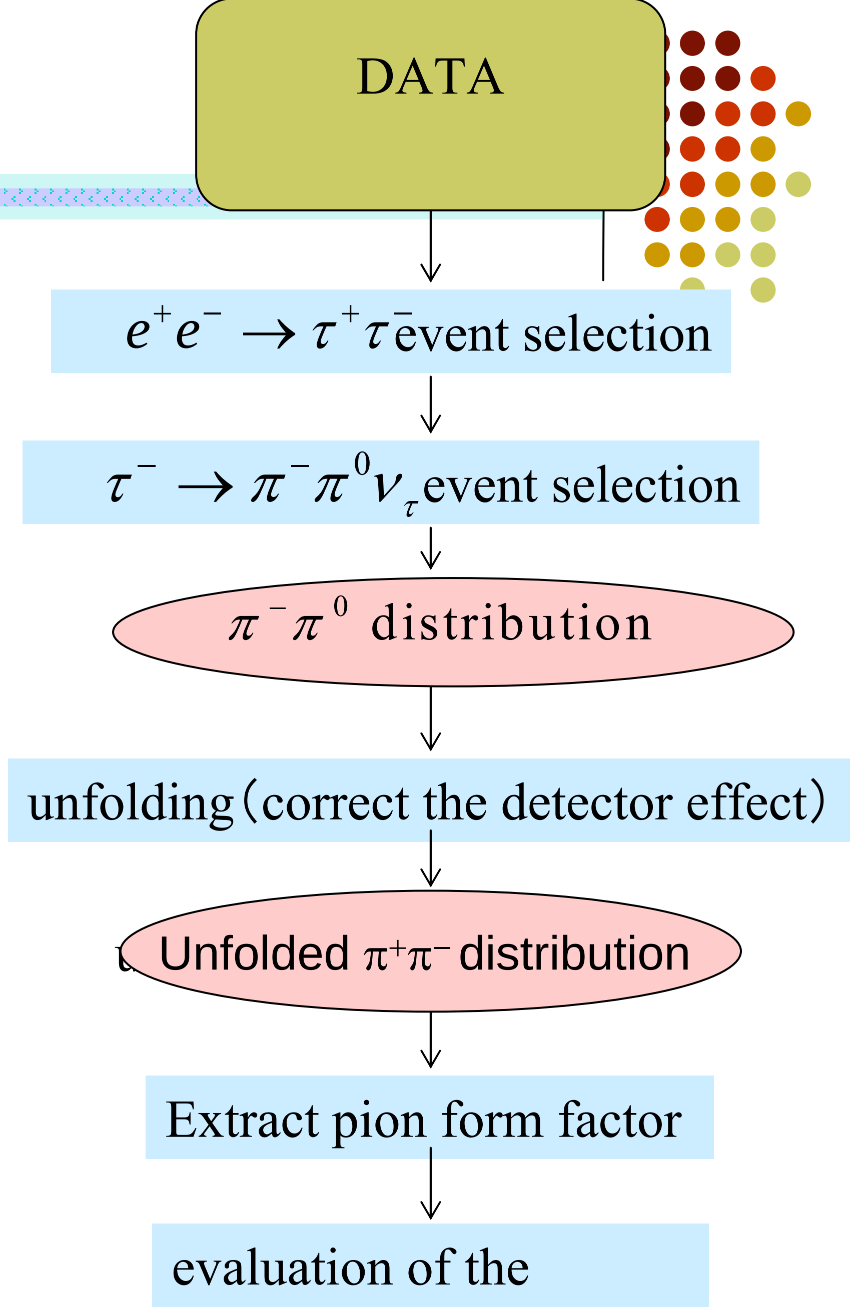
$$a_\mu^{\pi\pi} = \frac{\alpha(0)^2}{\pi} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} \, v^{\pi\pi}(s) \quad \longleftarrow \text{spectral function}$$

$$v^{\pi\pi}(s) = \frac{m_{\tau^2}}{6\pi |V_{ud}|^2 S_{EW}} \cdot \frac{B_{\pi\pi^0}}{B_e} \cdot \left[\left(1 - \frac{s}{m_{\tau^2}}\right)^2 \left(1 + \frac{2s}{m_{\tau^2}}\right) \right]^{-1} \cdot \frac{1}{N_{\pi\pi^0}} \frac{dN_{\pi\pi^0}}{ds}$$

- Branching Fraction
- Mass Spectrum

Analysis Procedure

- $e^+e^- \to \tau^+\tau^-$ selection
- $\tau^- \to \pi^-\pi^0\nu_\tau$ selection
- Background subtraction
- Unfolding
- Br measurement
- Extract pion form factor $|F_\pi(s)|^2$
- Fit with Breit-Wigner Form
- Evaluation of a_μ

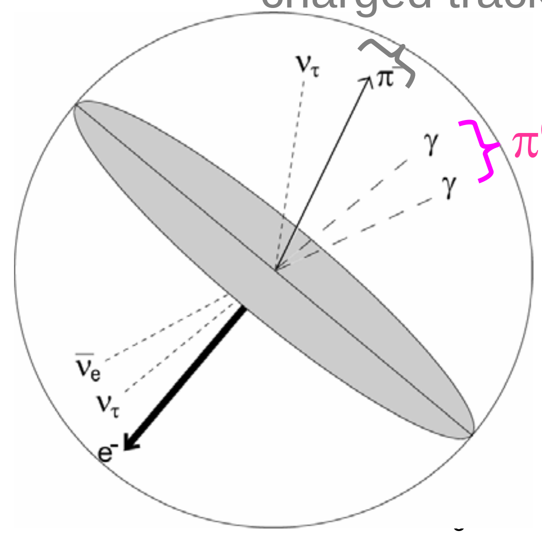


Event Selection

$e^+e^- \rightarrow \tau^+\tau^-$ Selection

- Low multiplicity:
  Number of charged tracks：2 or 4, net charge=0
- Beam background rejection: Event Vertex Position
- Physics background rejection:
  - Use Missing Mass and Missing Angle information.(Bhabha,2photon)
  - Low track and gamma multiplicity. (qq continuum)

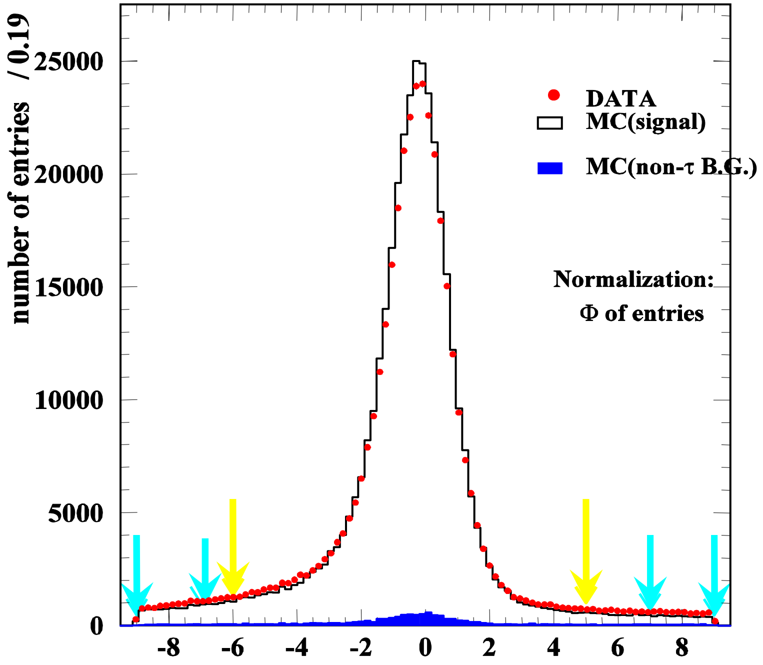
charged track



$\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ Selection

- one charged track in the event hemisphere.
- one π^0 in the event hemisphere.
- No additional g with Eg≥200MeV
- Tag-side condition:
  2,4 prong+ any γ/1 prong + no γ

π^0 Signal



Signal region

$-6 < S_{\gamma\gamma} < 5$

Sideband region

right: $-9 < S_{\gamma\gamma} < -7$

left: $7 < S_{\gamma\gamma} < 9$

•Sideband region is used to estimate the non-π^0 background

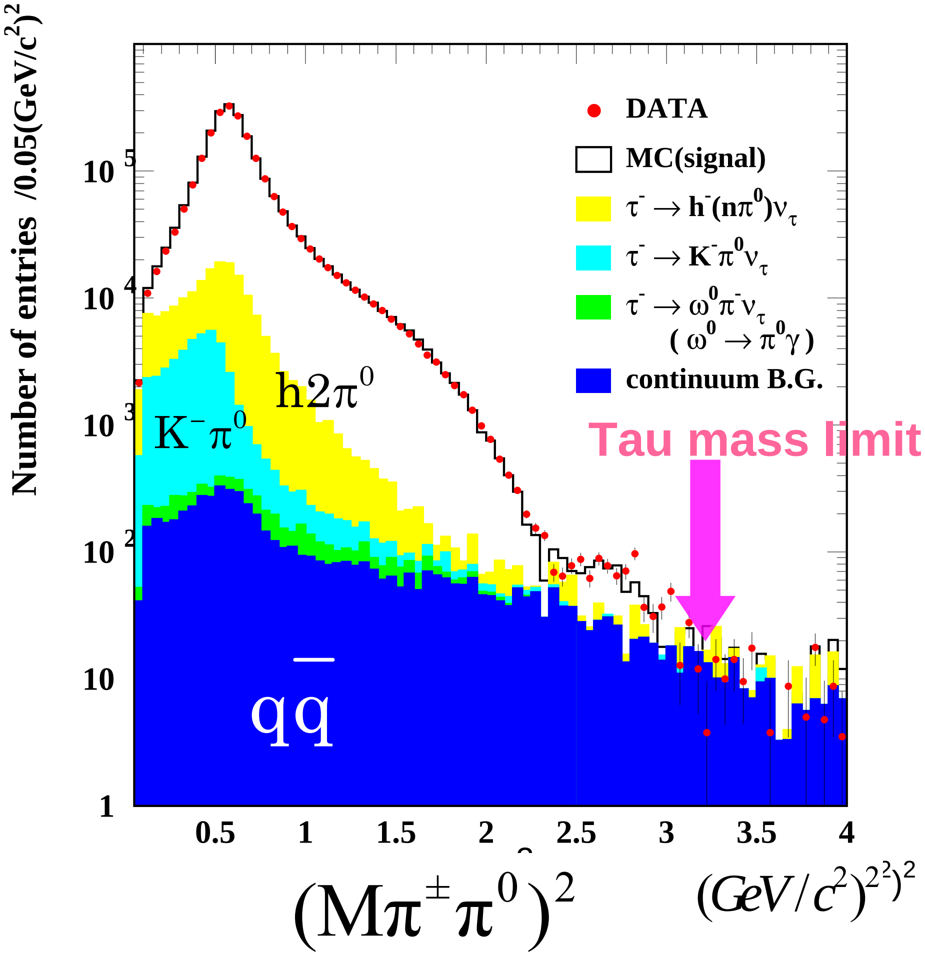
Generally background free, but non-negligible BK In the low $M\pi\pi^0$ region.

$$S_{\gamma\gamma} \equiv \frac{(m_{\gamma\gamma} - m_{\pi^0})}{\sigma_{\gamma\gamma}}$$

$\sigma_{\gamma\gamma}$: 5 – 8 MeV

5.6M $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ events

$m^2_{\pi\pi}$ distribution



- The signal level is different more than 4th order of magnitude between $\rho(770)$ and $\rho''(1700)$.

- Background
  - non-τ B.G.

    $q\bar{q}$ 2.22±0.05%
  - feed down B.G.

    $h \geq 2\pi^0\nu_\tau$ 6.0%

    $K^-\pi^0\nu_\tau$ 1.6%

    $\tau^- \to \pi^-\omega\nu_\tau(\omega \to \pi^0\gamma)$

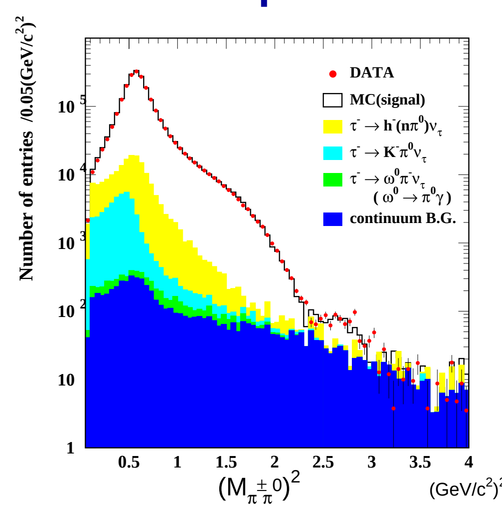
    0.5%

BG is important at threshold and ρ'' region.

Some important features

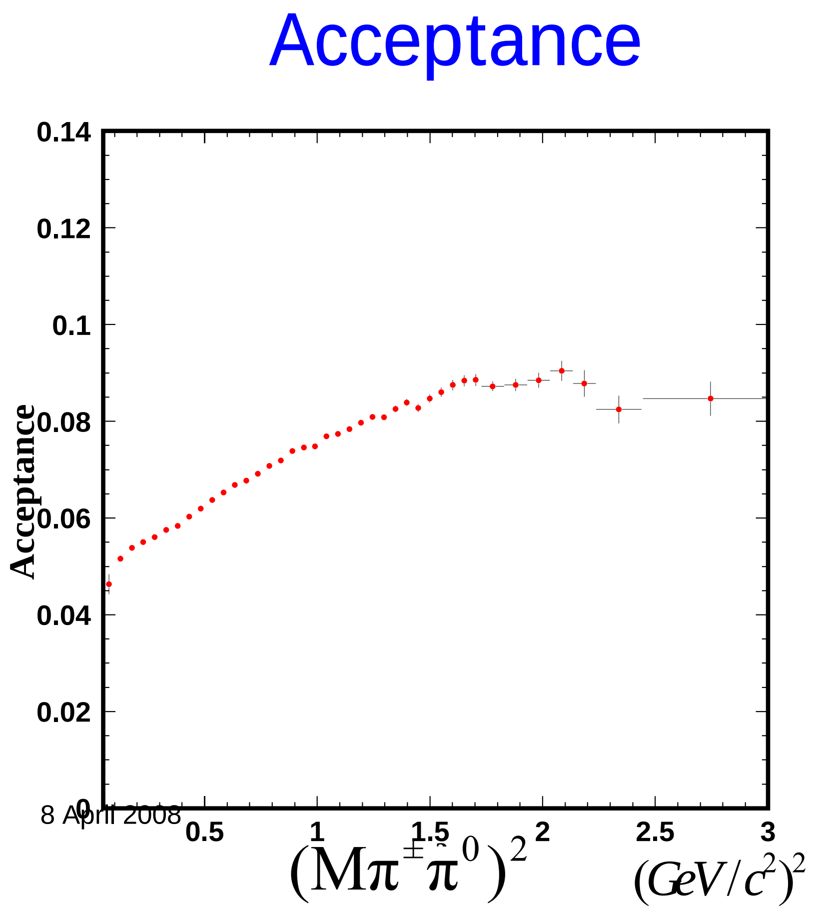
- New MC set
  - New τ MC (include ρ" to TAUOLA MC)
- More reliable estimate of continuum BG
  - Estimate continuum using BG enriched sample.
  - Require stronger cut for tag side
    - 1 charged track + no γ
- More reliable estimate of feed-down BG.

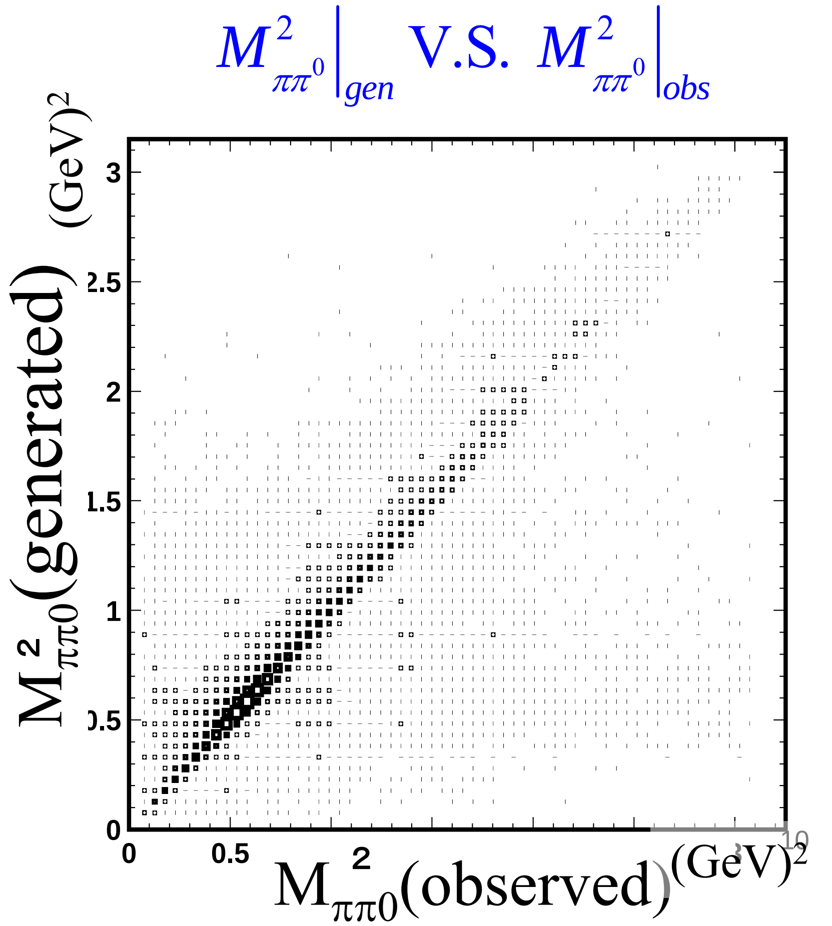
  some modes have small Br but dominate in the special region. i.e. threshold region
  - $\tau^- \rightarrow \pi^- \omega \nu_\tau (\omega \rightarrow \pi^0 \gamma)$
  - $\tau^- \rightarrow \pi^- \pi^0 K_L \nu_\tau$ etc.
- Extensive systematic study
  - Non-π^0 background, efficiency



Acceptance

Data are Unfolded with
the Singular Value Decomposition (SVD) method.





Results

- Br
- Mass Spectrum
- Pion form factor
- Extract resonance Parameters
- Comparison with previous exp.
- Evaluation of a_{μ} and iso-spin violation correction.

Result (1) Branching Fraction

- Normalized to the number of τ-pairs

$$Br_{2\pi} = \frac{N^{obs}_{2\pi}}{2N^{obs}_{\tau\tau}} \cdot \frac{(1-b^{\text{feed-down}}-b^{\text{non-}\tau})}{(1-b^{\tau\tau}_{bg})} \cdot \frac{\varepsilon^{\tau\tau}}{\varepsilon^{\tau\tau}_{2\pi}} \cdot \frac{1}{\varepsilon^{ID}_{2\pi}}$$

- Tau-pair selection
  - acceptance : 32.6 ± 0.05%
  - $f_b = \frac{\varepsilon^{\tau\tau}_{2\pi}}{\varepsilon^{\tau}}$: 1.112 ± 0.003
  - background : 7.4 ± 0.03%
- $\pi\pi^0$ selection
  - Acceptance: 41.0 ± 0.1 %
  - Background
    - feed down: 7.02 ± 0.08 %
    - qq-conti. : 2.22 ± 0.05 %

Belle
25.17 ± 0.04 ± 0.40

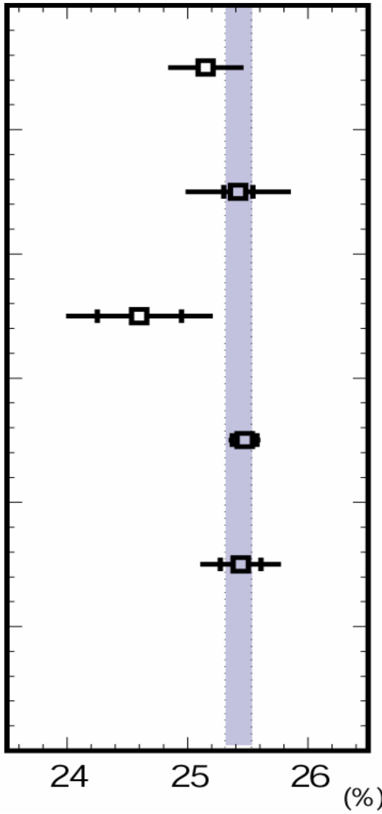
CLEO
25. 42 ± 0. 12 ± 0. 42

L3
24. 60 ± 0. 35 ± 0. 50

ALEPH
25. 474 ± 0. 101 ± 0. 085

OPAL
25. 44 ± 0. 17 ± 0. 29

Average
25. 42 ± 0. 11



- **Br = (25.17 ± 0.04 (stat) ± 0.40(sys))%**

Preliminary

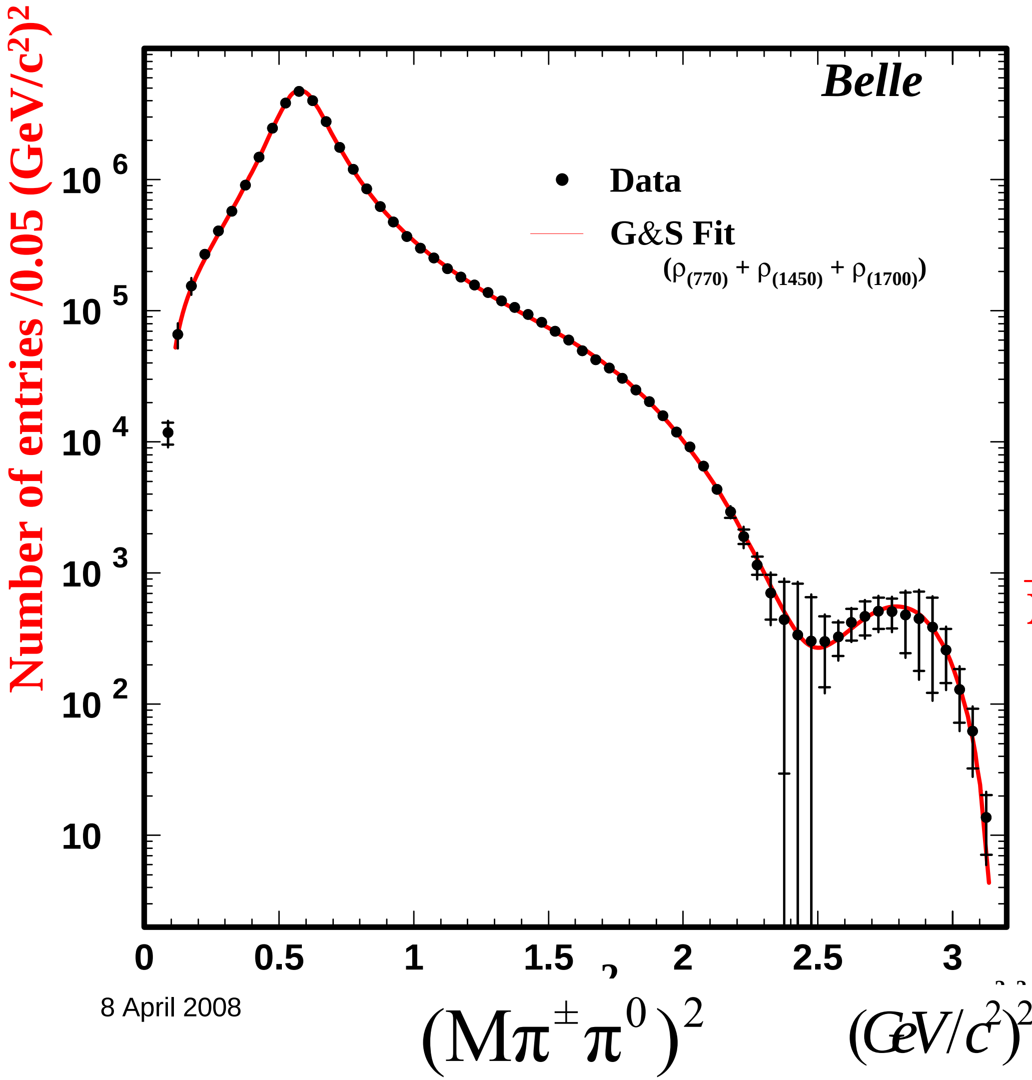
Systematic on Br Measurement

Source	$\Delta B / B$ (%)
Tracking efficiency	0.47
π^0 efficiency	1.4
Background in τ-pair	0.36
Feed down background	0.16
Continuum background	0.20
γ veto	0.20
Trigger	0.32
MC statistics	0.08
Total	1.6

- Systematic is dominated by the uncertainty of the π^0 efficiency
  - Calibrated by η signals ($\eta \to \pi^0\pi^0\pi^0 / \eta \to \gamma\gamma$).
  - Checked by using electron tracks.
  - ($\gamma\gamma \to \pi^0\pi^0$ can use to improve π^0 efficiency in near future.)

Result (2): Mass spectrum

Unfolded Results



Mass spectra

= Phase space

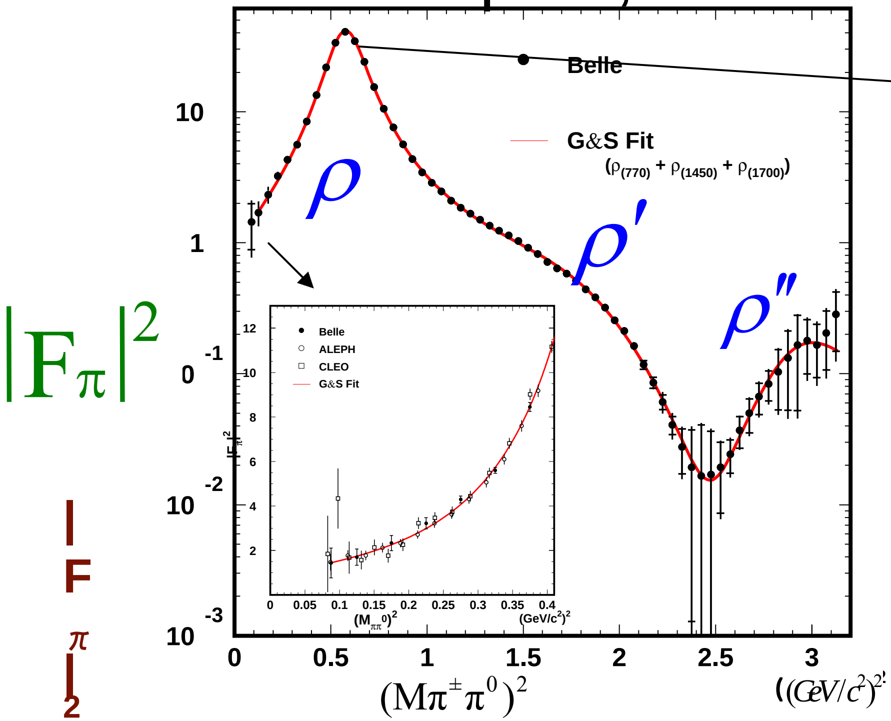
× Form Factor

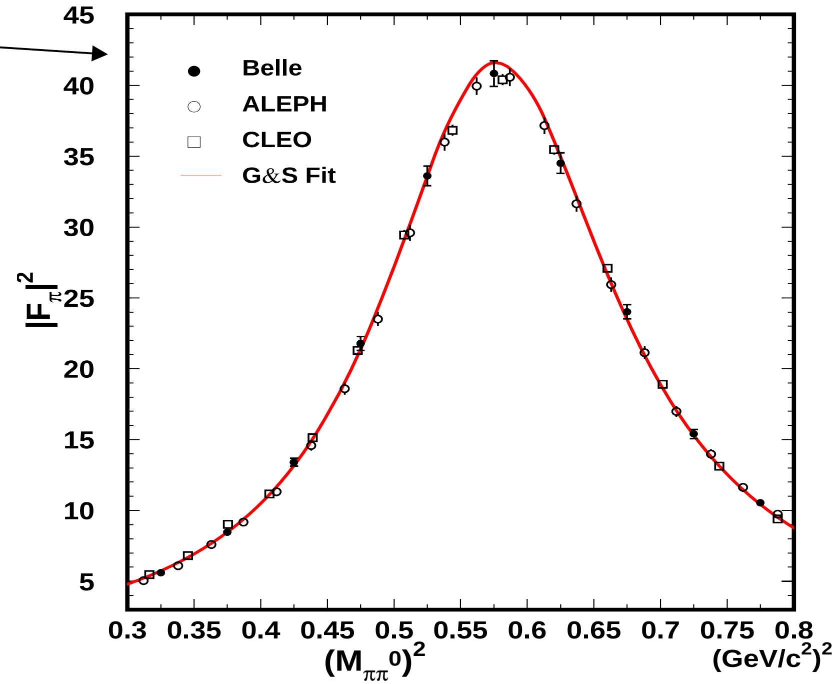
$$\frac{1}{N_{\pi\pi^0}}\frac{dN_{\pi\pi^0}}{ds} = \frac{6\pi|V_{ud}|^2 S_{EW}}{m_\tau^2} \times \frac{B_e}{B_{\pi\pi}}\left[\left(1-\frac{s}{m_\tau^2}\right)^2\left(1+\frac{2s}{m_\tau^2}\right)\right] v^{\pi\pi^0}(s)$$

$$v^{\pi\pi^0}(s) = \frac{\beta^3(s)}{12\pi}\left|F_\pi(s)\right|^2$$

Result (3) Pion Form Factor $|F_\pi|^2$

From 64M $\tau^+\tau^-$ pairs, Belle selects 5.5M $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ events!





- Error bars include both statistical and systematic
- Interference between ρ' and ρ"
- ——— Fit with BW

$B_{Belle} = (25.17 \pm 0.04 \pm 0.40)\%$

$B_{ALEPH} = (25.471 \pm 0.097 \pm 0.085)\%$

Systematic on the Mass Spectrum / Form Factor

$M^2_{\pi\pi}$	threshold	ρ region	ρ' region	ρ" region
Unfolding (MC)	**0.79**	**0.31**	**1.5**	**1.50**
Unfolding (cond)	**0.53**	**0.09**	**0.58**	**9.19**
BKG (continuum)	**0.09**	**0.01**	**0.52**	**5.76**
BKG (feed-down)	**0.65**	**0.10**	**---**	**0.50**
BKG(non-π^0)	**4.80**	**---**	**---**	**---**
Acceptance	**1.44**	**0.03**	**0.15**	**0.40**
Energy scale	**1.08**	**0.59**	**0.05**	**0.50**
Total	**5.3**	**0.7**	**1.8**	**11.4**

(%)

Check by known MC distribution

Systematic	Region	Dominant Factor
0.7-1.8%	ρ, ρ'	Energy scale/Unfolding
5%	threshold	Background (π^0, feed down)
10%	ρ''	Continuum BG

Result(4) Resonance parameters

- Fit with BW form ρ(770), ρ'(1400), ρ''(1700)

$$F_\pi(s) = \frac{1}{1+\beta+\gamma}\left(BW_\rho + \beta BW_{\rho'} + \gamma BW_{\rho''}\right)$$

- Gounaris-Sakurai (GS) parameterization

$$BW_\rho^{G\&S} = \frac{M_\rho^2 + d(s) M_\rho \Gamma_\rho(s)}{(M_\rho^2 - s) + f(s) - i\sqrt{s}\,\Gamma_\rho(s)}$$

- 10 fit parameters

M_ρ, Γ_ρ	: ρ mass and width
$M_{\rho'}$, $\Gamma_{\rho'}$	: ρ′ mass and width
$M_{\rho''}$, $\Gamma_{\rho''}$	: ρ″ mass and width
β , ϕ_β	: ρ′amplitude
γ , ϕ_γ	: ρ″amplitude

- The normalization of the GS form is given by $|F_\pi(0)|^2 = 1$

Fit Results

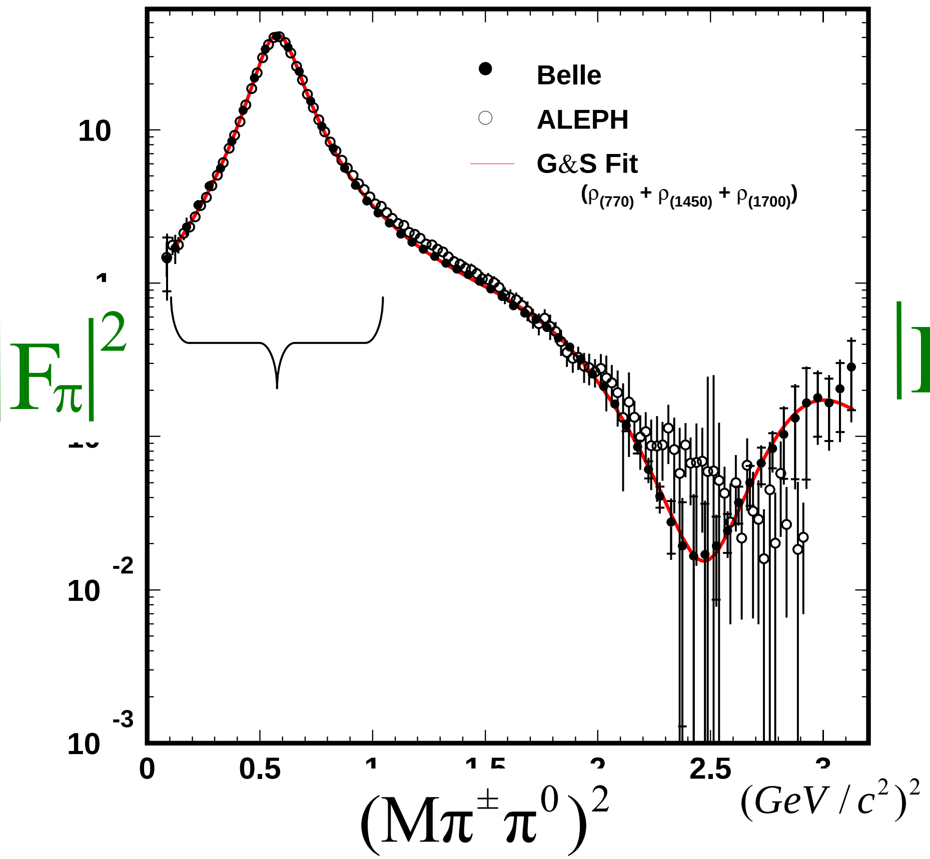
Fit parameter	Norm fixed	PDG2006 τ, e+e-	PDG2006 hadronic
Norm $\lvert F_\pi(0)\rvert^2$	**[1.0]**		
M_ρ (MeV)	**774.5±0.2±0.5**	775.4±0.4	766.5±1.1
Γ_ρ (MeV)	**148.1±0.4±1.7**	146.4±1.1	150.2± 2.4
$M_{\rho'}$ (MeV)	**1446±7±28**		1459± 11
$\Gamma_{\rho'}$ (MeV)	**434±16±60**	⟷	147±40
$\lvert\beta\rvert$	$0.15 \pm 0.05 \pm^{0.15}_{0.04}$		
ϕ_β (degree)	$202 \pm 4 \pm^{41}_{8}$		
$M_{\rho''}$ (MeV)	**1728±17±89**		1720± 20
$\Gamma_{\rho''}$ (MeV)	$164 \pm 21 \pm^{89}_{26}$		250 ± 100
$\lvert\gamma\rvert$	$0.028 \pm 0.020 \pm^{0.059}_{0.009}$		
ϕ_γ (degree)	$24 \pm 9 \pm^{118}_{28}$		
χ^2/d.o.f	**80/52**		

- All ρ, ρ', ρ'' resonance parameters are determined at the same time!

→ Most precise !

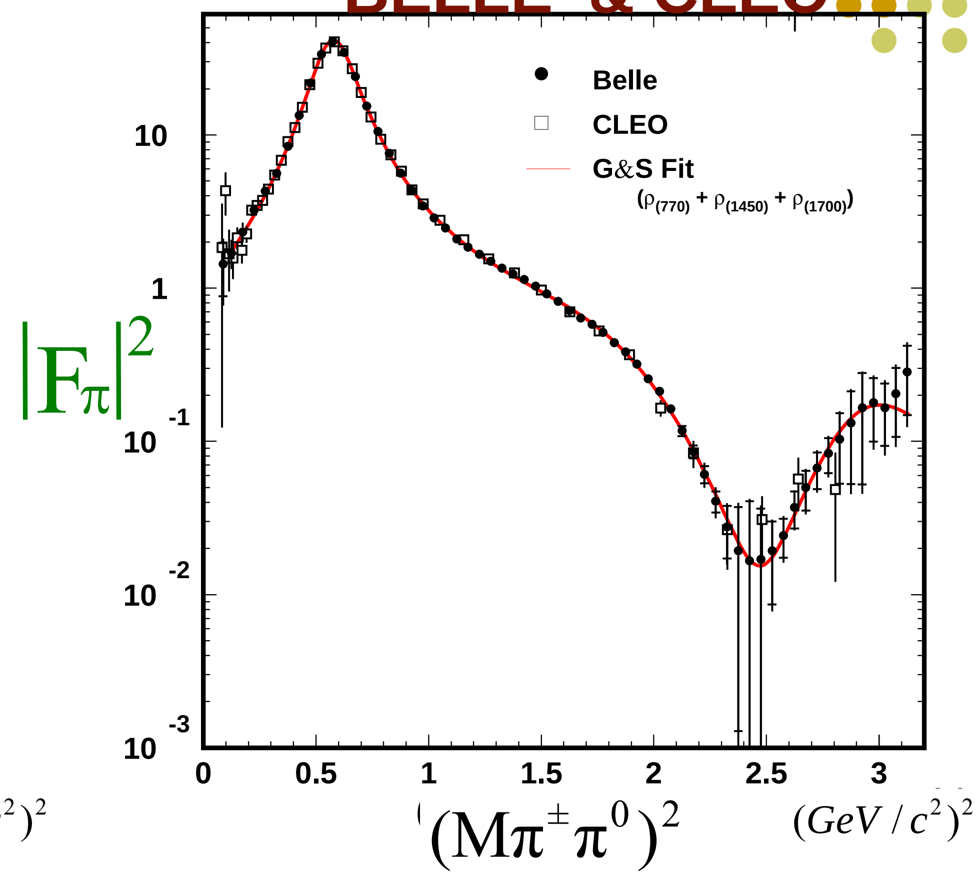
Comparison with previous exp.

BELLE & ALEPH



Ref: Phys. Rep.421 (2005) 191

BELLE & CLEO

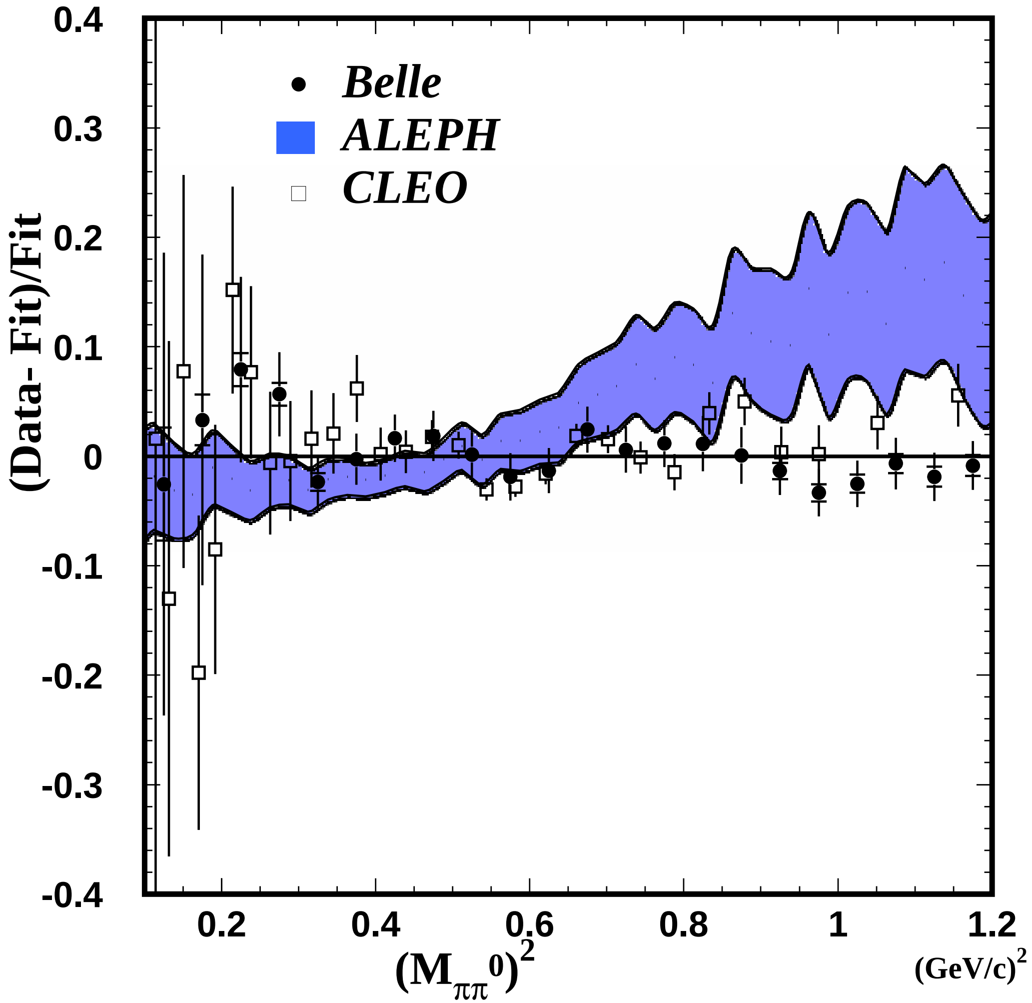


Ref: Phys. Rev. D61, 112002(2000) 1

- Agree with previous exp. of data.
- Our result is more precise especially in high mass region.

Detailed Comparison: ρ, ρ' region

Fit: Fit to Belle Data



- Belle-CLEO consistent,
- ALEPH is higher

  at $(M_{\pi\pi})^2 > 0.8$ GeV^2;

Effect on $a_\mu^{2\pi}$?

i

Results (5) a_μ (2π)

$$a_\mu^{had,LO} = \frac{\alpha^2}{\pi}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} v^{\pi\pi}(s) \qquad v^{\pi\pi}(s) = \frac{m_{\tau^2}}{6\pi |V_{ud}|^2 S_{EW}} \cdot \frac{B_{\pi\pi^0}}{B_e} \cdot \left[\left(1-\frac{s}{m_{\tau^2}}\right)^2 \left(1+\frac{2s}{m_{\tau^2}}\right)\right]^{-1} \cdot \frac{1}{N_{\pi\pi^0}} \frac{dN_{\pi\pi^0}}{ds}$$

range (GeV^2)	Belle	ALEPH
0.08-0.20	39.57	38.23
0.20-0.35	70.65	66.89
0.35-0.50	123.30	119.20
0.50-0.65	196.90	194.20
0.65-0.80	62.37	62.39
0.80-0.95	15.64	16.41
0.95-1.10	5.74	6.50
1.10-1.25	2.86	3.27
1.25-1.40	1.65	1.89
1.40-3.20	2.43	2.77
0.08-3.20	521.1	511.5

X 10^{-10}

Belle> ALEPH

Belle<ALEPH

No iso-spin violation correction is applied

⇦ Total

Iso-spin Violation Correction

- Ref. V. Cirgliano et al., J. High Energy Phys. 08, 002(2002)
  A.Flores-Tlalpa et al., Phys. Rev. D 74, 071301 (2006)

$\times 10^{-10}$

Source	Correction	Uncertainty
Short distance rad. Cor (S_{EW})	-12.0	+/- 0.2
Long distance rad. Cor.(G_{EM})	-1.0	
$m_{\pi^-} \neq m_{\pi^0}$ (in phase space)	-7.0	
ρ-ω interference	+3.5	+/- 0.6
$m_{\pi^-} \neq m_{\pi^0}$ (in decay width)	+4.2	
Electromagnetic decays	-1.4	
$m_{\rho^0} \neq m_{\rho^-}$	-	+/- 1.4
Total	-13.7	+/- 2.0

ρ–ω interference

- ρ-ω interference effects are estimated using following form for the amplitude.

$$F_\pi^0(s)_{\rho-\omega} = -\frac{\theta_{\rho\omega}}{3m_\rho^2}\frac{s}{m_\omega^2 - s - im_\omega\Gamma_\omega}$$

$$\theta_{\rho\omega} = (-3.3 \pm 0.7)\times 10^{-3}\ \mathrm{GeV}^2$$

$$m_\omega = 0.783\ \mathrm{GeV}$$

$$\Gamma_\omega = 0.00844\ \mathrm{GeV}$$

Results (5) $a_\mu(2\pi)$

- Integrated region: $\sqrt{s} = m_\pi - 1.8\ \mathrm{GeV/c^2}$
- After applying the known iso-spin violation correction.

Belle(τ)

$$a_\mu^{\pi\pi} = (519.4 \pm 1.5(\mathrm{exp.}) \pm 2.7(\mathrm{Br}) \pm 2.5(\mathrm{isospin}))\mathrm{x}10^{-10}$$

- ALEPH, CLEO, OPAL (τ) Ref. Eur. Phys. J. C27, 497 (2003)

$$a_\mu^{\pi\pi} = (520.1 \pm 2.4(\mathrm{exp.}) \pm 2.7(\mathrm{Br}) \pm 2.5(\mathrm{isospin}))\mathrm{x}10^{-10}$$

- CMD2,SND (e^+e^-) Ref. Nucl. Phys. Proc. Suppl. 169, 288 (2007)

$$a_\mu^{\pi\pi} = (504.6 \pm 3.1(\mathrm{exp.}) \pm 0.9(\mathrm{rad.}))\mathrm{x}10^{-10}$$

→ τ results are higher than those from $e^+ e^-$.

Summary

- We have studied $\tau^- \to \pi^- \pi^0 \nu_\tau$ using high statistics Belle data

Preliminary

- Br measurement: $Br(\tau^- \to \pi^- \pi^0 \nu_\tau) = (25.17 \pm 0.04 \pm 0.40)\%$

(1.6% accuracy)

- Precise 2π mass spectrum and the pion form factor are determined. We can provide them by a table.
- In addition to $\rho(700)$, $\rho'(1400)$, the production of $\rho''(1700)$ is unambiguously identified and its parameters are determined.
- Our results for $a_\mu^{\pi\pi}$ agree with the previous τ based results but are higher than those from $e^+ e^-$.

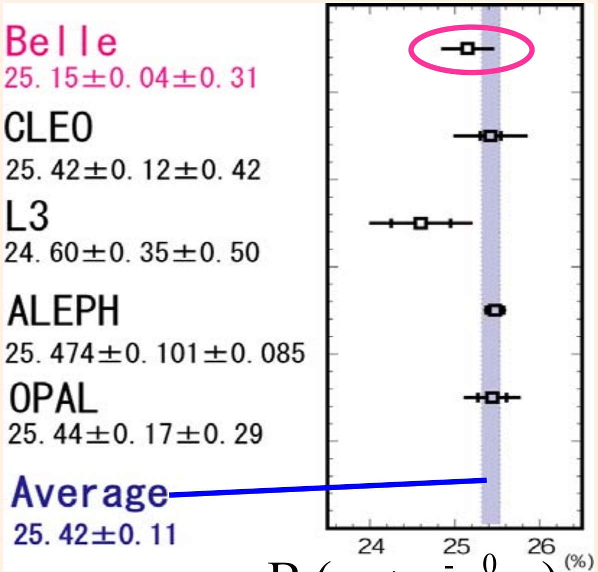
Backup Slide

External parameters

Item	Value	$\Delta a_\mu^{\pi\pi}$ $(unit: \times 10^{-10})$
S_{EW} :electroweak radiative correction	1.0233±0.0006	±0.32
$\|V_{ud}\|$: CKM matrix element	0.9734±0.0008	±0.42
$B_e : \tau^- \to e^- \overline{\nu}_e \nu_\tau$ Branching Fraction	(17.84±0.06)%	±1.82
$B_{\pi\pi^0} : \tau^- \to \pi^- \pi^0 \nu_\tau$ Branching Fraction	(25.42±0.11)%	±2.30
Total		±3. 0

$B_{\pi\pi^0} : \tau^- \to \pi^- \pi^0 \nu_\tau$ Branching Fraction

World average is calculated combining our new result and the preceding measurements of other experiments.



$Br(\tau \to \pi^- \pi^0 \nu_\tau)$

Iso-spin Violation Correction

- Ref. V. Cirgliano et al., J. High Energy Phys. 08, 002(2002)
  A.Flores-Tlalpa et al., Phys. Rev. D 74, 071301 (2006)

$\times 10^{-10}$

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Electromagnetic decays	-1.4	
$m_{\rho^0} \neq m_{\rho^-}$	-	+/- 1.4
Total	-13.7	+/- 2.0

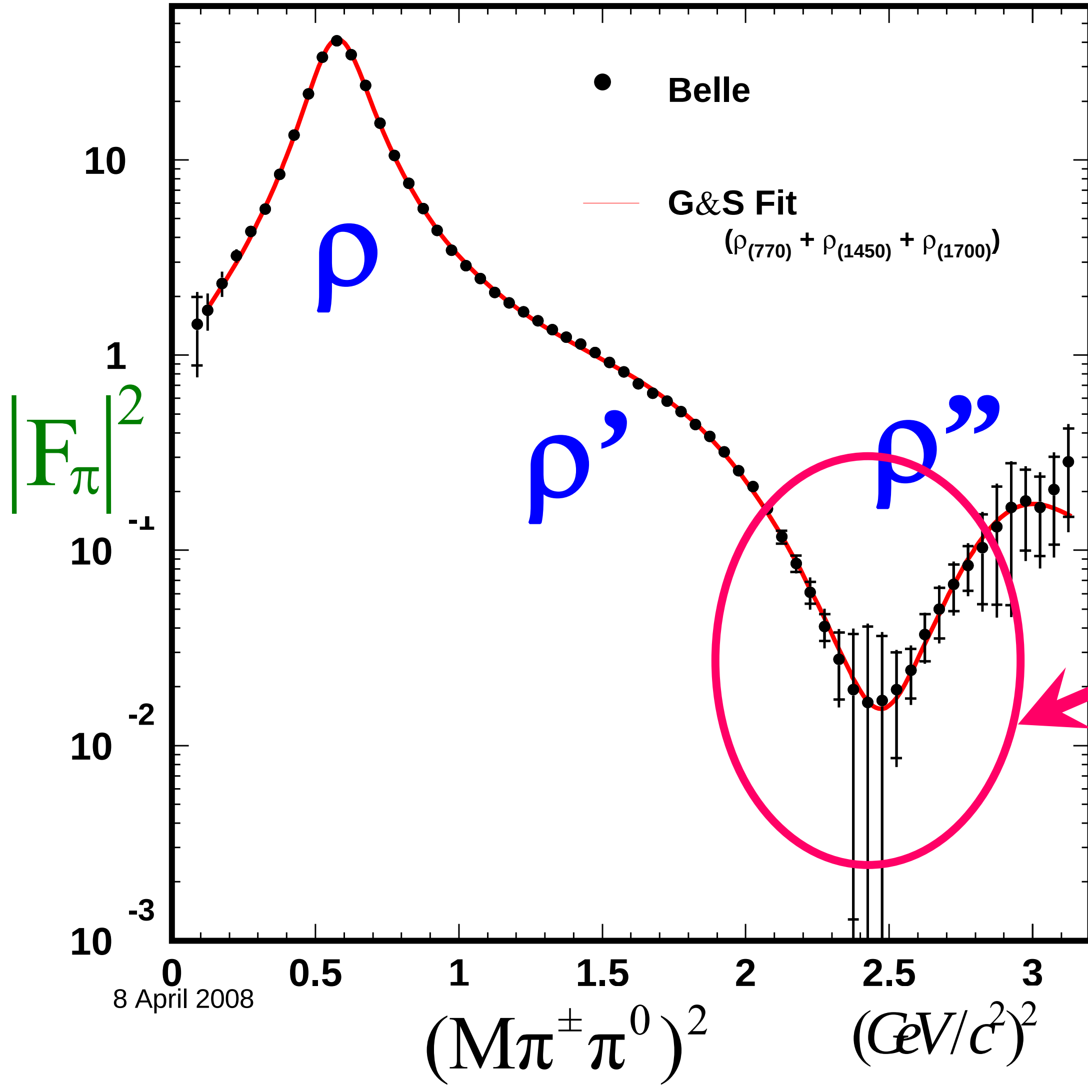
Internal Systematic Error

$m_{\pi\pi}^2 \geq 0.25 GeV^2$

source	$\Delta a_\mu^{\pi\pi}$ $(unit : \times 10^{-10})$
Background estimation ・non- τ(ee->hadron) ・feed-down $h \geq 2\pi^0\nu$ ・feed-down $K^-\pi^0\nu$	 ±0.11 ±0.09 ±0.15
π^0/γ selection efficiency/shape cuts	 ±0.35
Energy scale	±0.10
Gamma veto	±0.93
γ/track overlap	0.24
Tagging Dependence	<0.1
Smearing/Migration effect	
Total	±1.04

Result(3) Pion Form Factor $|F_\pi|^2$

From 64M $\tau^+\tau^-$ pairs, Belle selects 5.6M $\tau^- \to \pi^-\pi^0\nu_\tau$ events!



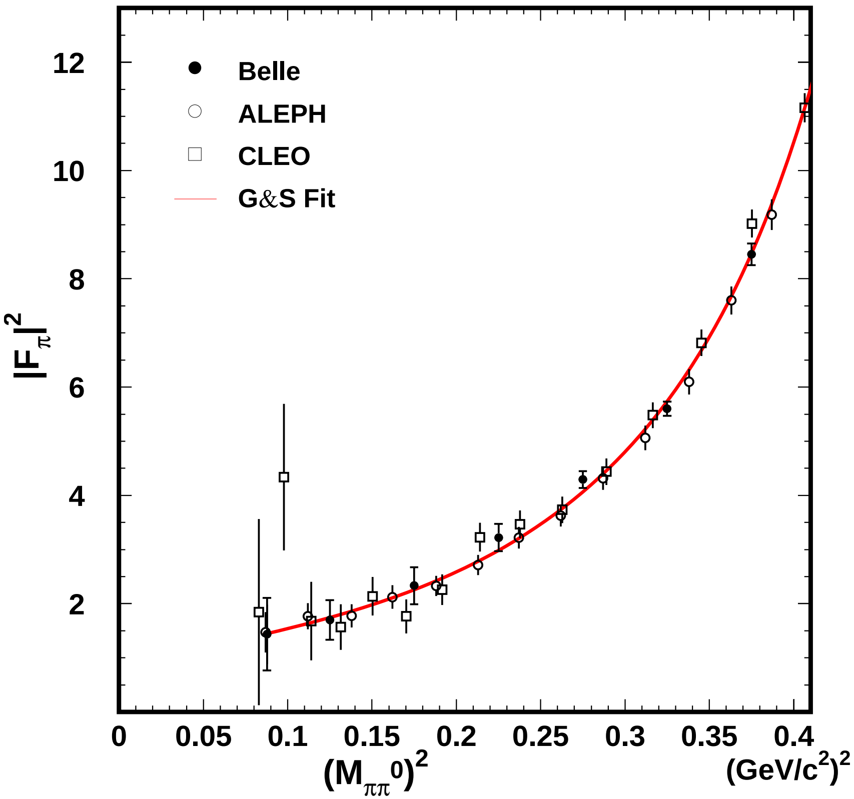
- Fit with BW Forms. →Next slide

Dip at s=2.5 GeV2

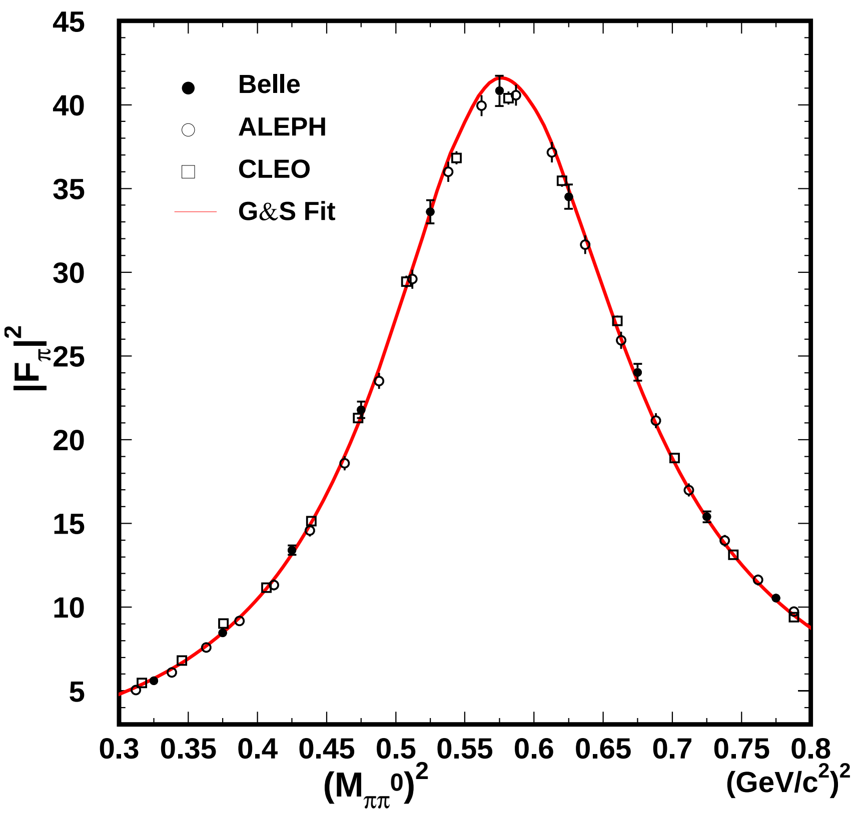
- Interference between ρ' and ρ''

Pion Form Factor $|F_\pi|^2$ (linear scale)

Low mass region



ρ mass region



Error bars include both statistical and systematic

Systematic on the mass distribution (1)

- Unfolding procedure
  - Checked by Signal MC（UNF①）
  - Unfolding condition：value±5 （UNF②）
- Acceptance (Accept.)

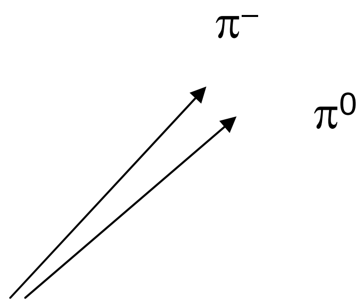
–π^0 efficiency uncertainty

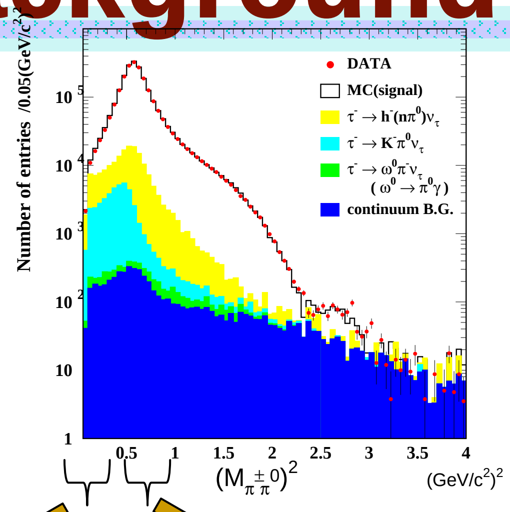
  - Effect of γ-track isolation
    - Change a cut on the cluster-track distance（default and tighter one(30cm)）)
- Momentum or energy scale (ENS)
  - Change Eγ by it’s uncertainty estimated from the π^0 mass peak position.(±0.2%)

Systematic on the mass distribution (2)

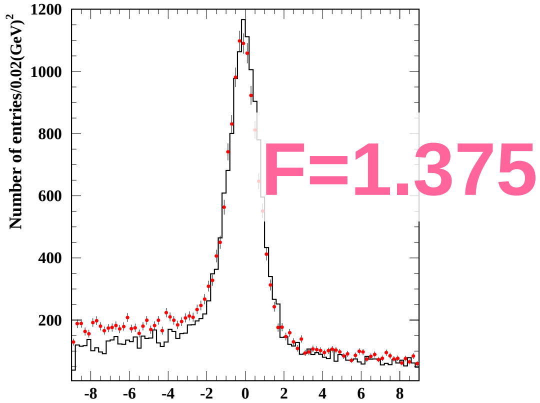
- Background
  - **continuum BG (BKG①)**
    - estimate at the mass region higher than m_τ
    - uncertainty is estimated to be 10%
  - **Feed down BG (BKG②)**
    - dominated by $\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$
    - systematic is estimated by changing the Br in PDG by 1σ
  - **non-π^0 BG (BKG③)**
    - dominated in the low $(M_{\pi\pi^0})^2$region.
    - In this region, the size of the non-π^0 background in the lower $M_{\gamma\gamma}$ side is different between data and MC. This differences is estimated as a systematic.

Non-π^0 background(details).



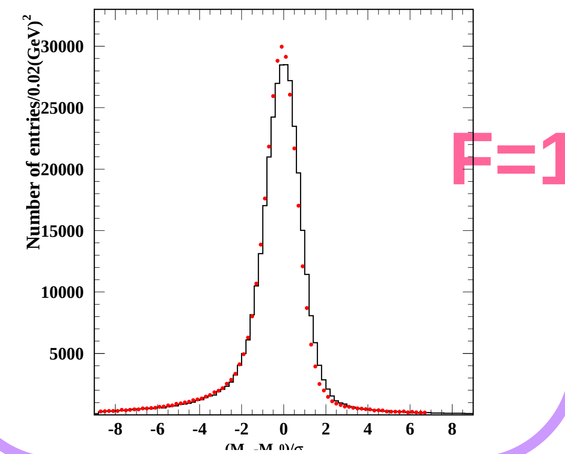


$0.10<(M_{\pi\pi^0})^2<0.15$



Mγγ

$0.55<(M_{\pi\pi^0})^2<0.60$

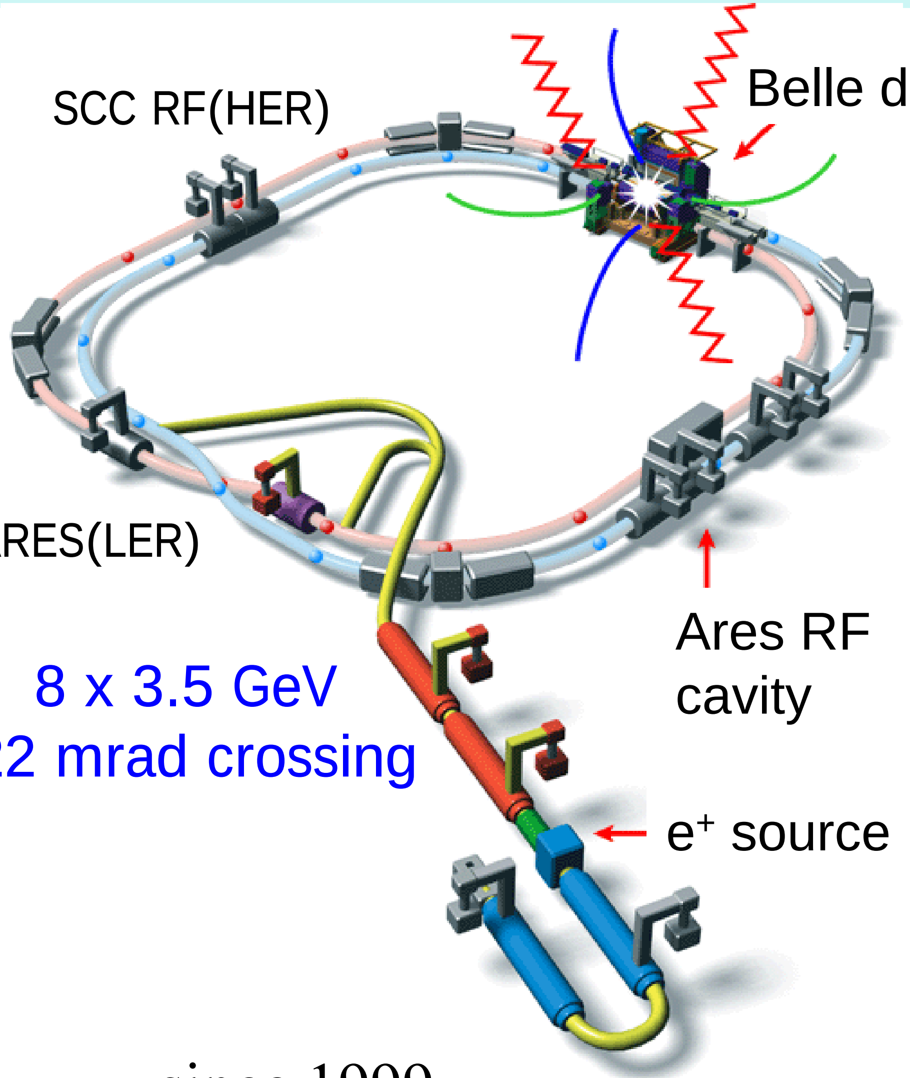


Mγγ

Systematic of resonance parameters

Source of systematics	$M\rho$ (MeV)	$\Gamma\rho$ (MeV)	$M\rho'$ (MeV)	$\Gamma\rho'$ (MeV)	β	ϕ_β (deg.)	$M\rho''$ (MeV)	$\Gamma\rho''$ (MeV)	γ	ϕ_γ (deg.)
Fit bias	**0.3**	**1.6**	**25**	**49**	**0.028**	**4**	**75**	**10**	**0.038**	**13**
Unfold	**0.3**	**0.3**	**4**	**24**	**0.001**	**4**	**11**	**14**	**0.002**	**12**
B.G.	**0.3**	**--**	**11**	**25**	**+0.14 -0.03**	**+41 - 5**	**13**	**+86 -10**	**+0.053 -0.020**	**+117 - 22**
Acceptance	**--**	**0.1**	**1**	**4**	**---**	**0.6**	**0.1**	**7**	**---**	**1**
Momentum scale	**0.3**	**0.6**	**2**	**1**	**---**	**2**	**45**	**15**	**---**	**1**
total	**0.5**	**1.7**	**28**	**60**	**+0.15 -0.04**	**+41 -8**	**89**	**+89 -26**	**+0.065 -0.009**	**+118 - 28**

The KEKB Collider



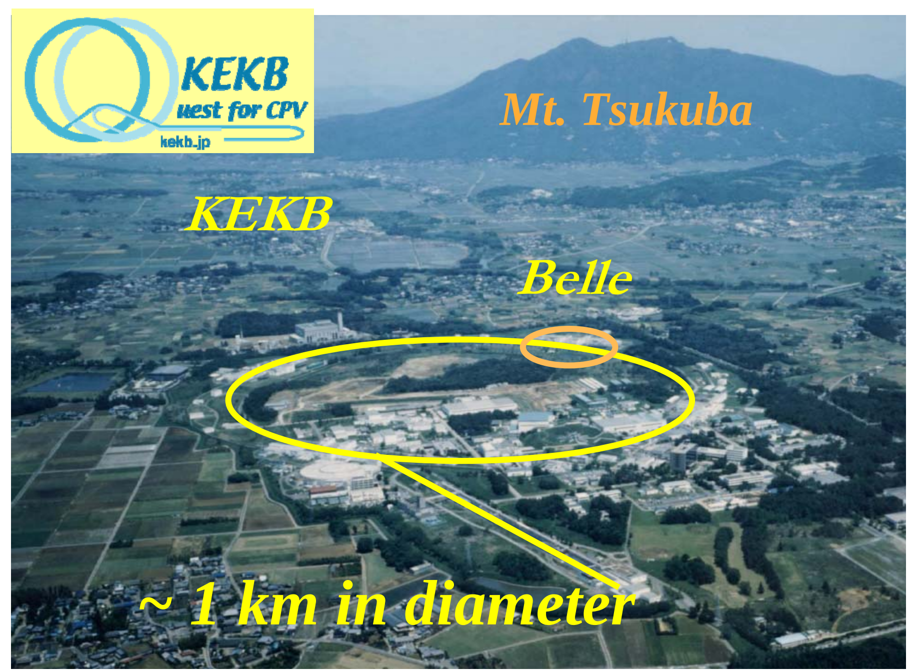
8 x 3.5 GeV
22 mrad crossing

since 1999

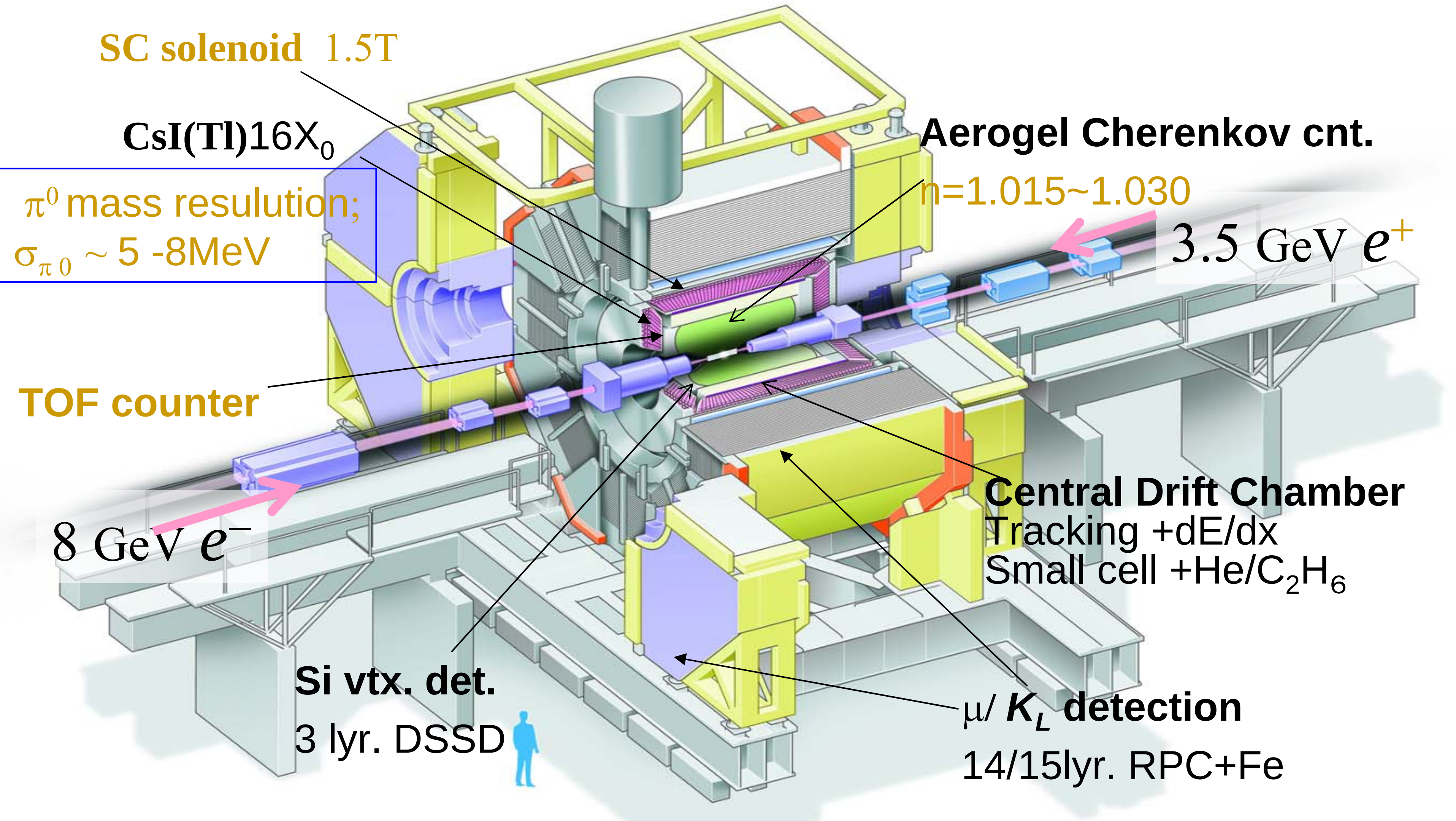
World record:

$L = 1.7118 \times 10^{34}/cm^2/sec$

First successful op. of Crab cavities



Belle detector



Good tracking and particle identification