New LFV results from e^+e^- colliders

16th International Conference on Heavy Quarks and Leptons (HQL2023)
TIFR, Mumbai, India
November 28 - December 02, 2023

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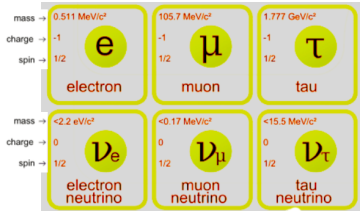
Outline

1. Motivation
2. Search for the $e^+e^- \to \ell\ell'$ decay
3. Lepton flavor violation in the τ decay
4. Recent results on LFV B and D mesons decay

- Within the standard model (SM), the coupling strength between the families of leptons and gauge bosons are equal, known as the lepton flavor universality (LFU).
- Further, the lepton number is conserved within a family for an absolutely massless left-handed neutrinos; $W \to \ell\bar{\nu}_{\ell'}$, $Z \to \ell\ell'$, or $\gamma \to \ell\ell'$ are not allowed.

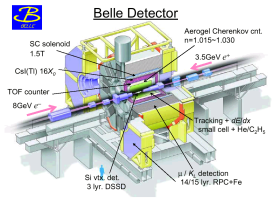


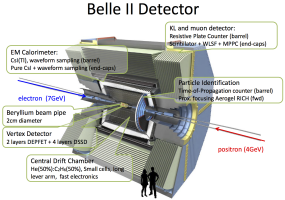
- The branching fraction of the lepton flavor violating (LFV) $\mu \to e\gamma$ decay

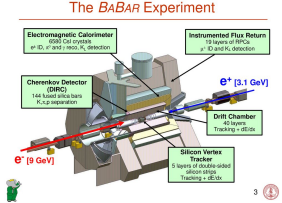
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i} - m^2_{\nu_1}}{M^2_W}\right| < 10^{-54}$$

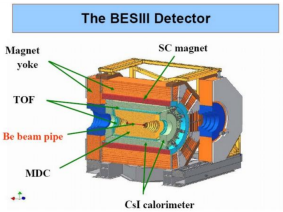
- Various physics models such as supersymmetry, two-Higgs doublet, fourth generation of quarks and leptons, etc., predict the BF of LFV decay modes, which can be observed in the high luminosity modern experiments. Any observation of such decay is a direct evidence for the new physics.

Search for the LFV at the e^+e^- collider experiments









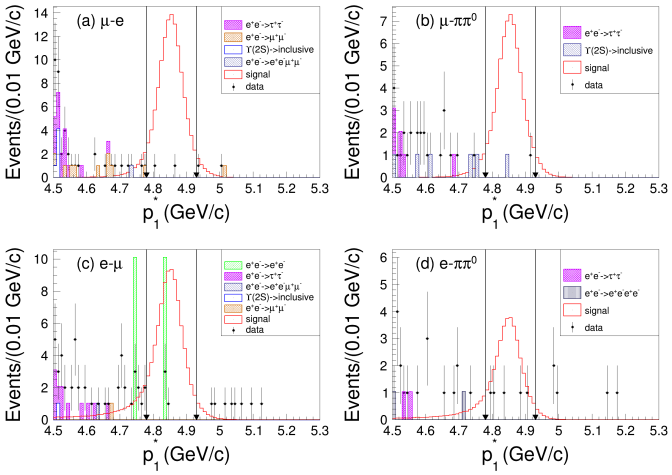
- The e^+e^- colliders at Belle, Belle II, BABAR, and BESIII experiments produce the $\Upsilon(nS)$ and $\psi(nS)$ resonances, τ and μ leptons, B and D mesons in a large abundance by tuning the center of mass (CM) energy.
- $\Upsilon(nS) \to \ell^+\ell'^-$ & $J/\psi \to \ell^+\ell'^-$ (including the radiative decays).
- $\tau^- \to \ell^-\gamma$, $e^-e^-e^+$, $e^-\mu^-e^+$, $e^-\mu^-\mu^+$, $\mu^-\mu^-\mu^+$, $\ell^- h$ (hadrons), etc.
- $D \to X\ell^\pm\ell'^\mp$ and $B \to X\ell^\pm\ell'^\mp$.

LFV $e^+e^- \to \ell\ell'$ decays

$\Upsilon(2S) \to \ell^{\pm}\tau^{\mp}$ at Belle

- τ^- is reconstructed from $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, and $\pi^-\pi^0\nu_\tau$.
- The signal region is defined based on the momentum of primary lepton in the e^+e^- system.
- Most stringent limit to date improving the previous bound on $\mathcal{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$ and $\mathcal{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$ by a factor of 13 and 3, respectively.

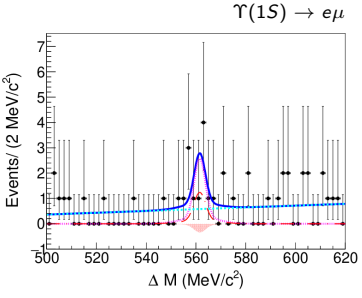
[arXiv:2309.02739]

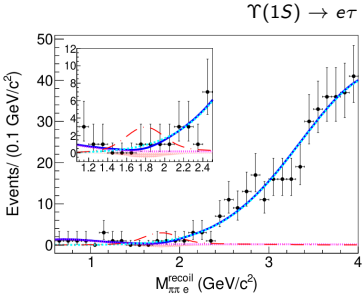


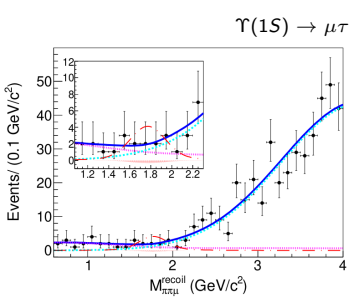
Modes	$\epsilon_{\rm sig}$ (%)	$N^{\rm bkg}_{\rm exp}$	$N_{\rm obs}$	$\mathcal{B}$ @ 90% CL
$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	11.0 ± 0.8	3.6 ± 1.2	3	$< 0.26 \times 10^{-6}$
$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$	7.3 ± 0.9	4.6 ± 2.1	9	$< 1.02 \times 10^{-6}$

- A data sample consisting of 158×10^6 $\Upsilon(2S)$ decay is analyzed to search for the LF violating $\Upsilon(1S) \to \ell\ell'$ decays [JHEP 05 (2022) 095].
- Only the events from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ are selected.

Signal Extraction : $M^{\text{recoil}}_{\pi\pi\ell} = \sqrt{(E^*_{\text{T}} - E^*_{\pi\pi\ell})^2 - |\vec{p}^{\,*}_{\pi\pi\ell}|^2}$ & $\Delta M = M_{\pi\pi\ell\ell'} - M_{\ell\ell'}$







Related results from Belle, BABAR, and BESIII Collaboration

Collaboration	Data Sample	Decay mode	UL at 90%CL	References
Belle	158×10^6 $\Upsilon(2S)$	$\mathcal{B}(\Upsilon(1S)\to e^\pm\mu^\mp)$	3.9×10^{-7}	JHEP 05 (2022) 095
		$\mathcal{B}(\Upsilon(1S)\to \mu^\pm\tau^\mp)$	2.7×10^{-6}	
		$\mathcal{B}(\Upsilon(1S)\to e^\pm\tau^\mp)$	2.7×10^{-6}	
		$\mathcal{B}(\Upsilon(1S)\to \gamma e^\pm\mu^\mp)$	4.2×10^{-7}	
		$\mathcal{B}(\Upsilon(1S)\to \gamma \mu^\pm\tau^\mp)$	6.1×10^{-6}	
		$\mathcal{B}(\Upsilon(1S)\to \gamma e^\pm\tau^\mp)$	6.5×10^{-6}	
BABAR	118×10^6 $\Upsilon(3S)$	$\mathcal{B}(\Upsilon(3S)\to e^\pm\mu^\mp)$	3.6×10^{-7}	PRL 128, 091804
BESIII	9×10^9 J/ψ	$\mathcal{B}(J/\psi\to e^\pm\mu^\mp)$	4.5×10^{-9}	arXiv:2206.13956v2[1]
	10×10^9 J/ψ	$\mathcal{B}(J/\psi\to e^\pm\tau^\mp)$	7.5×10^{-9}	PRD 103, 112007

- In the supersymmetric extension of SM (BLMSSM model), the branching fractions are expected to be of the order of $10^{-10}-10^{-9}$ [PRD 97, 056027].
- These results can provide constraints on the new physics models based on supersymmetry, GUT, two Higgs doublet model, etc., in the references of [1].

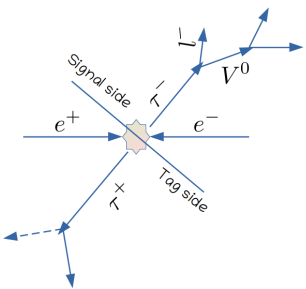
LFV in the τ decay

Search for the $\tau^{\pm} \to \ell^{\pm} V^0$ decay at Belle and Belle II

- The leptoquark model accomodating the anomalies in leptonic B decays predict the branching fraction of the order of $\mathcal{O}(10^{-11}) - \mathcal{O}(10^{-8})$ [PRD 104, 055017], [JHEP 08, 050].
- A signal $\tau^{\pm}$ is reconstructed from the $\ell^{\pm}$ and V^0 daughters, where $V^0 \in [\rho\ (\rho \to \pi^+\pi^-),\ \phi\ (\phi \to K^+K^-),\ \omega\ (\omega \to \pi^+\pi^-\pi^0),\ K^{*0}\ (K^{*0} \to K^+\pi^-)]$.

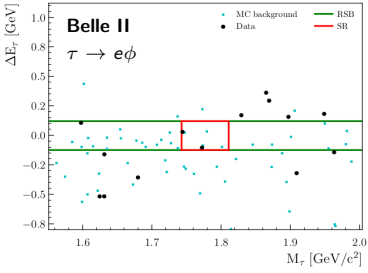
- No tagging of the other τ in the Belle II analysis [2305.04759].
- Backgrounds from $\tau^+\tau^-$ generic decay, low multiplicity (four leptons in the final state) events, and $e^+e^- \to q\bar{q}$ (continuum) are studied using the MC simulated and side band data.

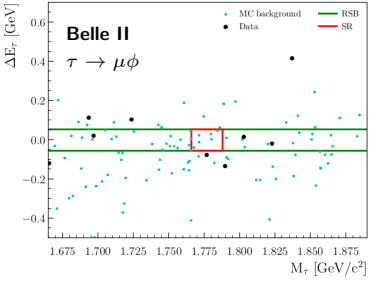
Signal Extraction: M_τ and $\Delta E = E^*_\tau - \sqrt{s}/2$

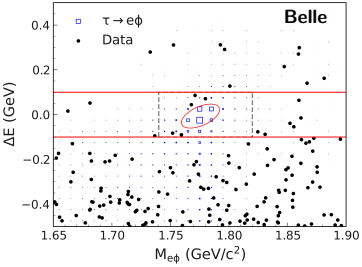


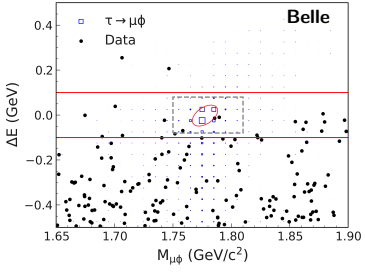
c.m. frame

Results on LFV $\tau^{\pm} \to \ell^{\pm} V^0$ decay









Coll.	Data	BF	UL (90%CL)	References
Belle	980 fb^{-1}	$\mathcal{B}(\tau \to \mu\phi)$	2.3×10^{-8}	JHEP 06 (2023) 118[2]
		$\mathcal{B}(\tau \to e\phi)$	2.0×10^{-8}	
Belle II	190 fb^{-1}	$\mathcal{B}(\tau \to \mu\phi)$	9.7×10^{-8}	2305.04759
		$\mathcal{B}(\tau \to e\phi)$	23×10^{-8}	

- The Belle collaboration set an upper limit on the $\tau \to \ell V^0(\rho, \phi, \omega, K^{*0}, \bar{K}^{*0})$ decays in the range of $(1.7 - 4.3) \times 10^{-8}$ at 90% CL [2].

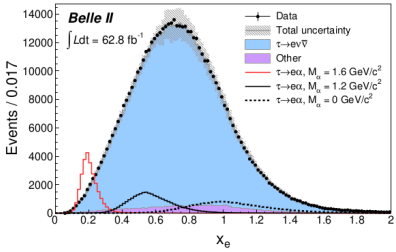
Search for the LFV invisible decay of τ at Belle II: $\tau^{\pm} \to \ell^{\pm}\alpha$

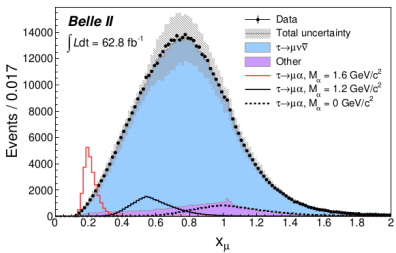
- Studying the LFV $\tau^{\pm} \to \ell^{\pm}\alpha$ decay is a good hunt for the axion like particles, where α is a spin-0 boson.
- $\tau_{\text{tag}} : \tau^- \to h^+h^-h^-\nu_\tau$ decays.

Signal Extraction: $x_\ell = \frac{2E_\ell^*}{m_\tau c^2}$

- $\frac{\mathcal{B}(\tau^- \to \ell^-\alpha)}{\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\mu\nu_\tau)}$ for a range of $m_\alpha \in (0.0 - 1.6)$ GeV/c^2 are:

Coll.	Data	ℓ	UL (10^{-3}) at 95%CL	References
Belle II	62.8 fb^{-1}	μ	$0.7 - 12.2$	PRL 130, 18, 181803
		e	$1.1 - 9.7$	
ARGUS	—	μ	$3 - 34$	Z.P.C 68 (1995) 25-28
		e	$6 - 36$	



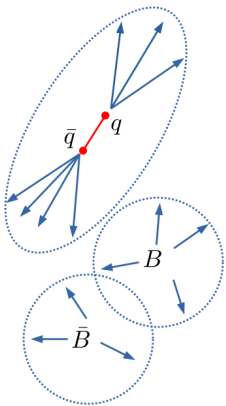


LFV in B and D decay

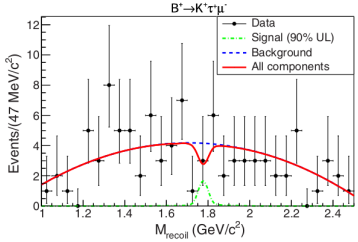
Search for the LFV $B^+ \to K^+\tau^\pm\ell^\mp$ decay at Belle

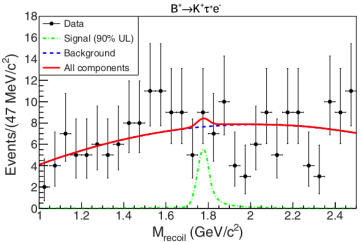
- The leptoquark models predict the $\mathcal{B}(B^+ \to K^+\tau^\pm\mu^\mp)$ via a vector mediator (U_1) with the SM quantum numbers of $(3,1)_{\frac{2}{3}}$ to be $> 0.7 \times 10^{-7}$ [PRD 104, 055017].
- Signal mode: $B^\pm \to K^\pm\tau(\tau \to \ell\nu\nu \text{ or } \pi\nu)\ell(e,\mu)$.
- Accompanying B (B_{tag}) is reconstructed using Full Event Interpretation (FEI) [arXiv:1807.08680].
- The BDT classifier based on the event topology of the B_{sig} and the number of unused ECL clusters rejects the combinatorial B background.
- Another BDT classifier based on the difference in event topology suppresses the continuum background.

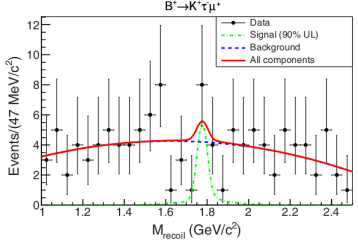
Signal Extraction : $M_{\text{recoil}} = m_B^2 + m_{K\ell}^2 - 2\left(\frac{E^*_{\text{beam}}E^*_{K\ell}}{c^4} + \frac{p^*_{B_{\text{tag}}}p^*_{K\ell}\cos\theta}{c^2}\right)$

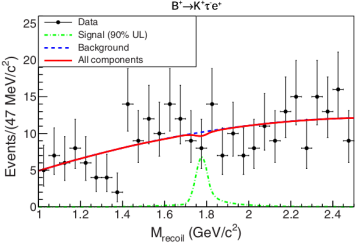


Results on LFV $B^+ \to K^+\tau^\pm\ell^\mp$ decay









Decay mode	BF UL (10^{-5}) at 90% CL	
	Belle	BABAR
$B^+ \to K^+\tau^+\mu^-$	0.59	4.8
$B^+ \to K^+\tau^-\mu^+$	2.45	
$B^+ \to K^+\tau^+e^-$	1.51	3.0
$B^+ \to K^+\tau^-e^+$	1.53	
$\#B\bar{B}$ pairs (10^6)	772	472
References	PRL 130, 261802	PRD 86, 012004

Search for the LFV D^0 decays at BABAR

- Within the SM, the BF for the decay $D^0 \to X^0 e^{\pm}\mu^{\mp}$ is suppressed $\sim \mathcal{O}(10^{-50})$.
- For certain leptoquark coupling, the new physics models predicts the BF of the order of $\mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$.
- The BABAR collaboration has reported the UL on three and four body LFV decays of D^0 mesons [PRD 101, 112003], [PRL 124, 071802].
- The signal reconstruction:
  - $D^0 \to X^0 e^{\pm}\mu^{\mp}$ for three body
  - $D^0 \to h^{\pm}h'^{\mp}e^{\pm}\mu^{\mp}$ for four body
- Considered neutral mesons: $X^0 \in (\pi^0, K^0_s, \bar{K}^{*0}, \rho^0, \omega, \eta)$.
- The background from $e^+e^- \to c\bar{c}$ events is suppressed using BDT classifier with the input variables based on the topology of D^0_{sig} mesons.

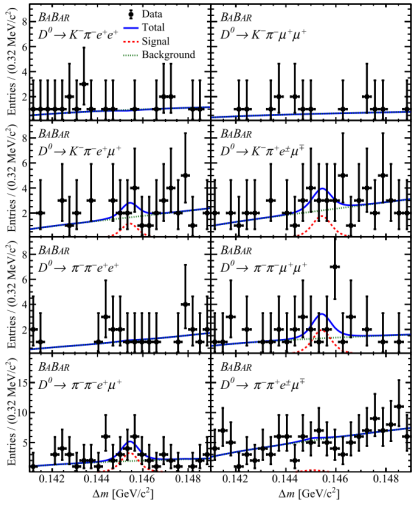
Signal Extraction : $\Delta m = m_{D^{*+}} - m_{D^0}$

Results on LFV D^0 decays

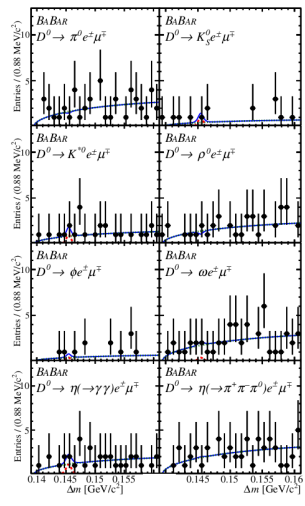
- The signal events are found to be compatible with zero.
- Using 468 fb^{-1} of e^+e^- collision data at or close to $\Upsilon(4S)$ data

Decay mode	BF UL (10^{-7}) at 90% CL
Three body	5.0–22.5
Four body	1.0–30.6

- The reported ULs on the BF of three and four body decay can provide the bounds on the leptoquark couplings!!!



Four-body



Three-body

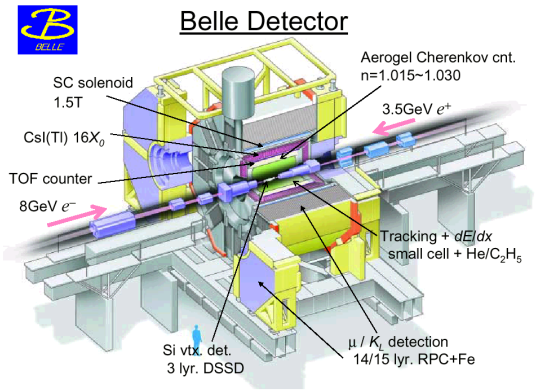
Summary

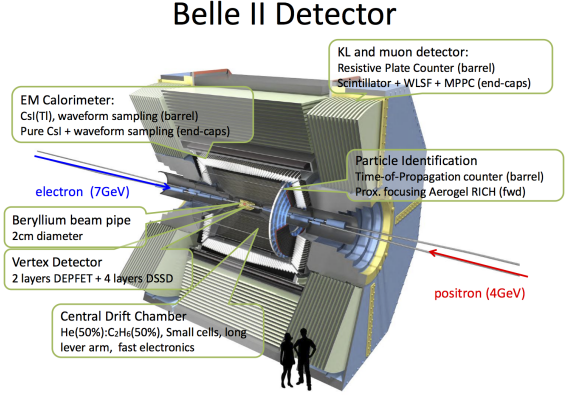
- We presented the recent results on the LFV decay modes at e^+e^- collider experiments: (a) Belle, (b) Belle II, (c) BABAR, and (d) BESIII.
- New physics models such as the supersymmetry, two-Higgs doublet, leptoquark, etc. predict the branching fractions for LFV decay modes, which are accessible to the high luminosity modern experiments.
- So far, no signal for the LFV decay could be observed.
- Hope to find out in the near future at Belle II and BESIII experiments... if nature allows!!!

Thank you for your attention.

Back up Slides

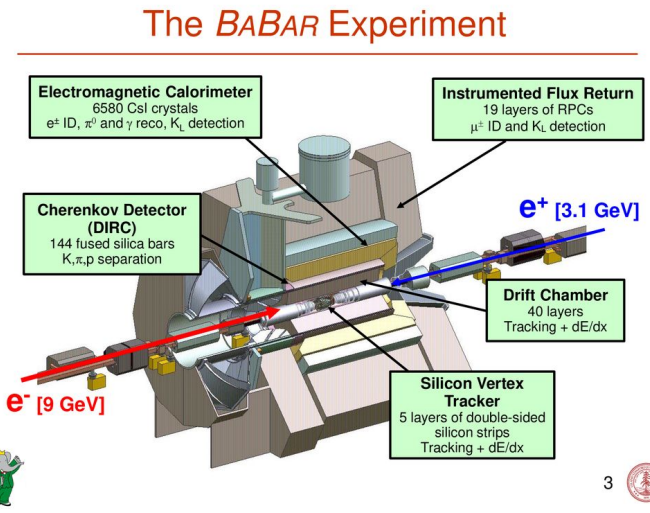
The Belle and Belle II detector





- The Belle II detector is a multipurpose magnetic spectrometer located at the SuperKEKB.
- Addition of the PXD to the vertex detector improving the vertex resolution.

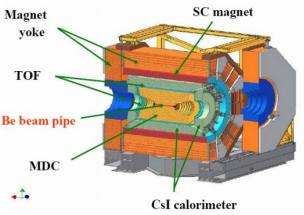
- The BABAR detector collected the data at e^+e^- PEP-II collider in the SLAC National Accelerator Laboratory.
- From 1999-2008, the detector collected the collision data corresponding to an integrated luminosity of 514 fb^{-1}.



- The BESIII detector is magnetic spectrometer located at the Beijing Electron Positron Collider (BEPCII).
- Helium based Multilayer Drift Chamber
- Plastic scintillator time of flight system
- CsI(Tl) electromagnetic calorimeter
- Resistive plate counters interspersed with steel for μ detection.

BESIII

The BESIII Detector



Sub-detectors			Performance
MDC	Momentum resolution		0.5%@1GeV
	dE/dx resolution		6%
EMC	Energy resolution		2.5%@1GeV
	Spatial resolution		6 mm
TOF	Time resolution	Barrel	80 ps
		Endcap	110 (70) ps
MUC	9 layers RPC, 8 layers for endcap		

Trigger rate: ~ 4 KHz
Data rate : ~ 40 MB/s