Charged LFV searches at Belle II

with a brief review of Belle results

Youngjoon Kwon
Yonsei Univ., Seoul, Korea

For Belle II collaboration at WIN2017, Jun.19-24, 2017

Belle works on LFV, LNV, LUV

- charged LFV, LNV
  - ✓ $D^0 \to e^\pm \mu^\mp$ **PRD 68, 111101(R) (2003)**
  - ✓ $B^0 \to e^\pm \mu^\mp$ **PRD 81, 091102(R) (2010)**
  - ✓ $B \to K^{(*)} e^\pm \mu^\mp$ **on-going**
  - ✓ $B^+ \to D^- \ell^+ \ell'^+$ **PRD 84, 071106(R) (2011)**
  - ✓ τ LFV, LNV decays

this talk!

- charged LUV
  - ✓ $R(D)$, $R(D^*)$ **3 Belle papers since 2015**
  - ✓ $B \to K^{(*)} e^+ e^-$ vs. $K^{(*)} \mu^+ \mu^-$ **PRL 118, 111801 (2017)**

Outline

- Intro. & Motivation
  - why LFV in τ ?
  - how to study τ decays @ e^+e^- B-factory
- τ LFV (LNV) search results at Belle *(reporting just a few)*
  - $\tau^+ \to \ell^+\gamma$ and current status — PLB 666, 16 (2008)
  - $\tau^+ \to \ell_1^+\ell_2^-\ell_3^+$ — PLB 687, 139 (2010)
  - $\tau^+ \to \ell^+h^-h'^+$ and $\ell^-h^+h'^+$ — PLB 719, 346 (2013)
- Belle II prospects
  - MC study of $\tau \to \mu\gamma$
  - other LFV, LFUV @ Belle II

New physics (NP) searches with τ

- the τ lepton
  - the heaviest charged lepton
  - highly sensitive to NP

	electron	muon	tau
Gen.	I	II	III
Mass [MeV]	0.511	106	1780
Life	∞	2.20μs	0.291ps

- Unique lab to look for NP
  - **LFV**
  - EDM, *g*-2, CPV
  - *B* (*D*) decays to τ
  - BNV, too $(m_\tau > m_\Lambda, m_p, \ldots)$

Lepton-flavor-violating (LFV) τ decay

- In the Standard Model with non-zero ν mass, τ LFV can happen, but the rate is really tiny.

$$\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m^2_W} \right|^2 \leq 10^{-53} \sim 10^{-49}$$

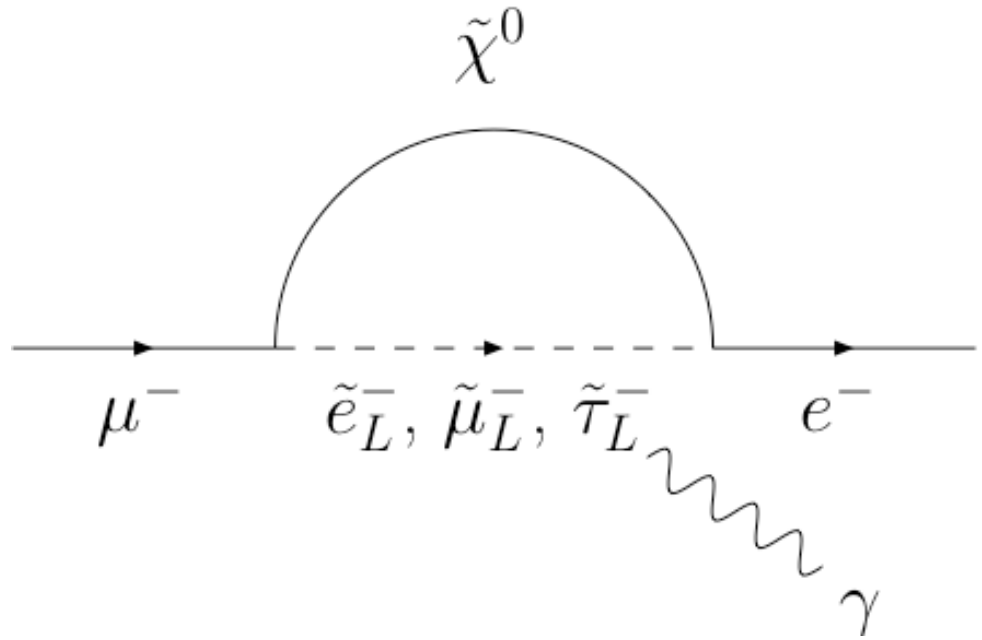
- However, in many new physics models it can become large enough to be within sensitivity of Belle (or Belle-II)
  - For example, with SUSY-GUT,

Calibbi et al.,
PRD 74, 116002 (2006)

$$\mathcal{B}(\tau \to \mu\gamma) \simeq (4.5 \times 10^{-6}) |(\delta_{LL})_{32}|^2 \left(\frac{500 \text{ GeV}}{m_{\text{SUSY}}} \right)^4 \left(\frac{\tan\beta}{10} \right)^2$$

  - For $(\delta_{LL})_{32}$, not determined in generic SUSY, need to specify models.

τ LFV in new physics beyond-SM



Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z’	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

τ LFV in new physics beyond-SM

Ratios of τ LFV decay's BF's allow one to discriminate between new physics models

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z'
$\frac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	~2 x 10^{-3}	0.06 - 0.1	0.4 - 2.3	~16
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	~1 x 10^{-2}	~1 x 10^{-2}	0.3 - 1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{\max}$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

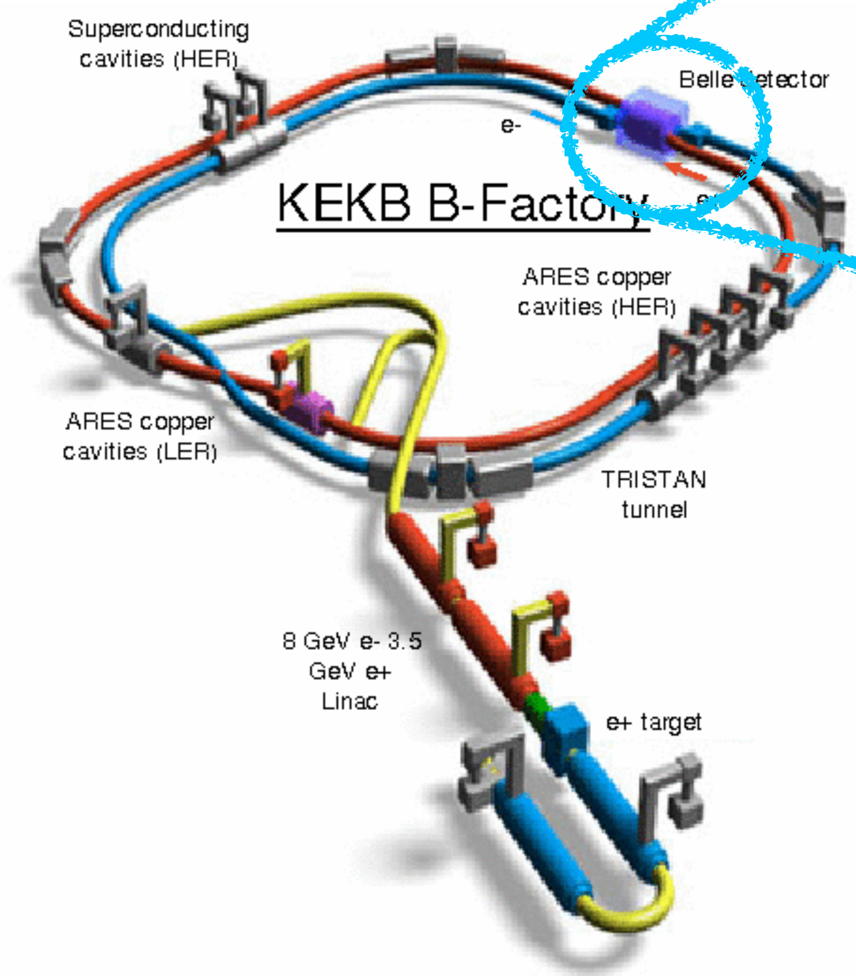
JHEP 0705, 013 (2007); PLB 547, 252 (2002)

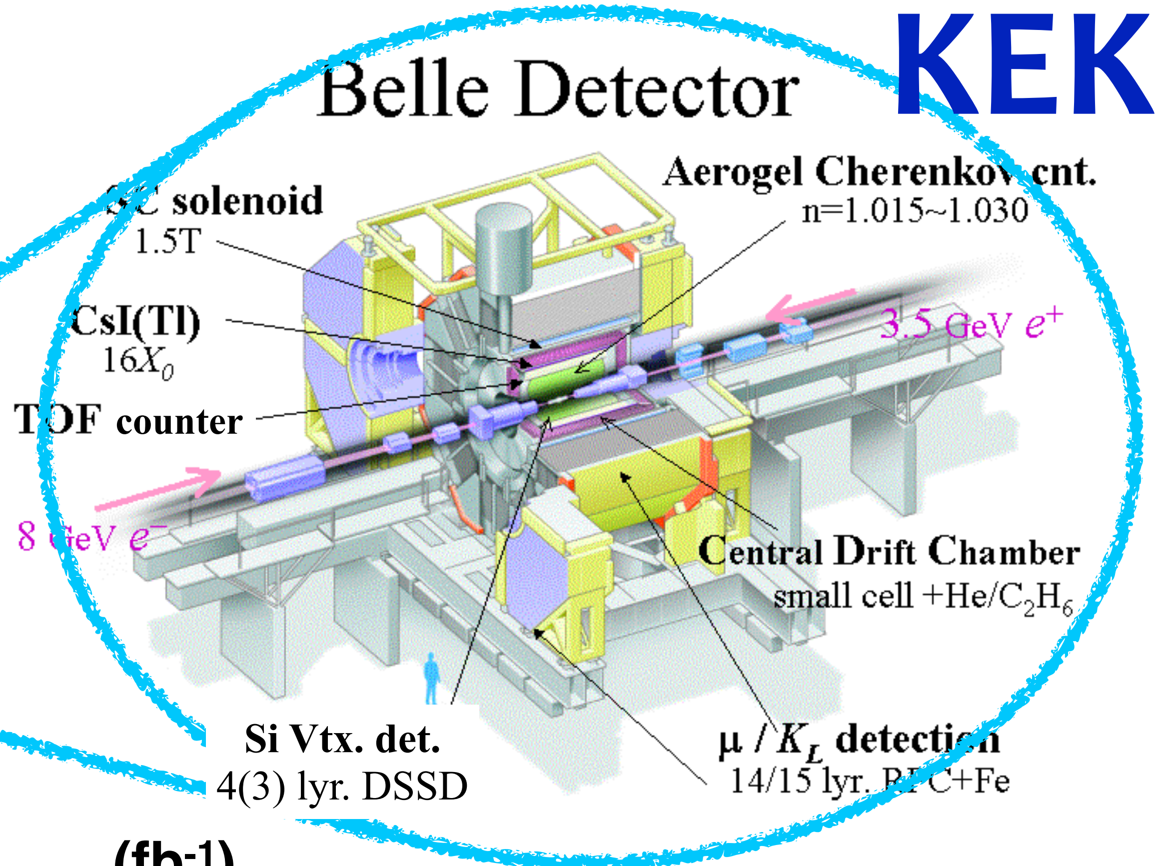
$\therefore$ Good to measure LFV in as many modes as possible!

KEKB & Belle

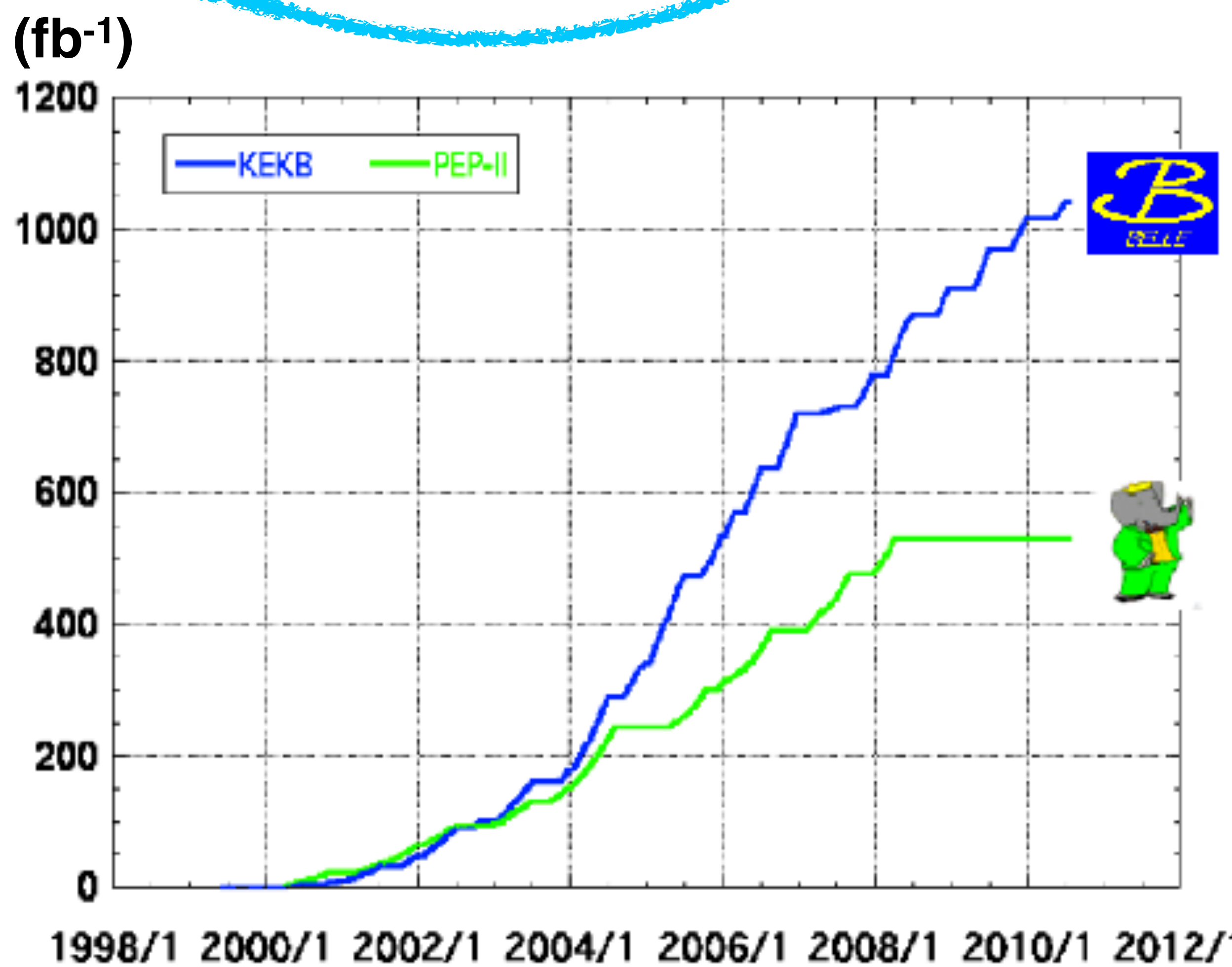
20 countries
90 institutions
~450 members

$$\mathcal{L}_{\text{peak}} = 21.1\ \text{nb}^{-1}\text{s}^{-1}$$



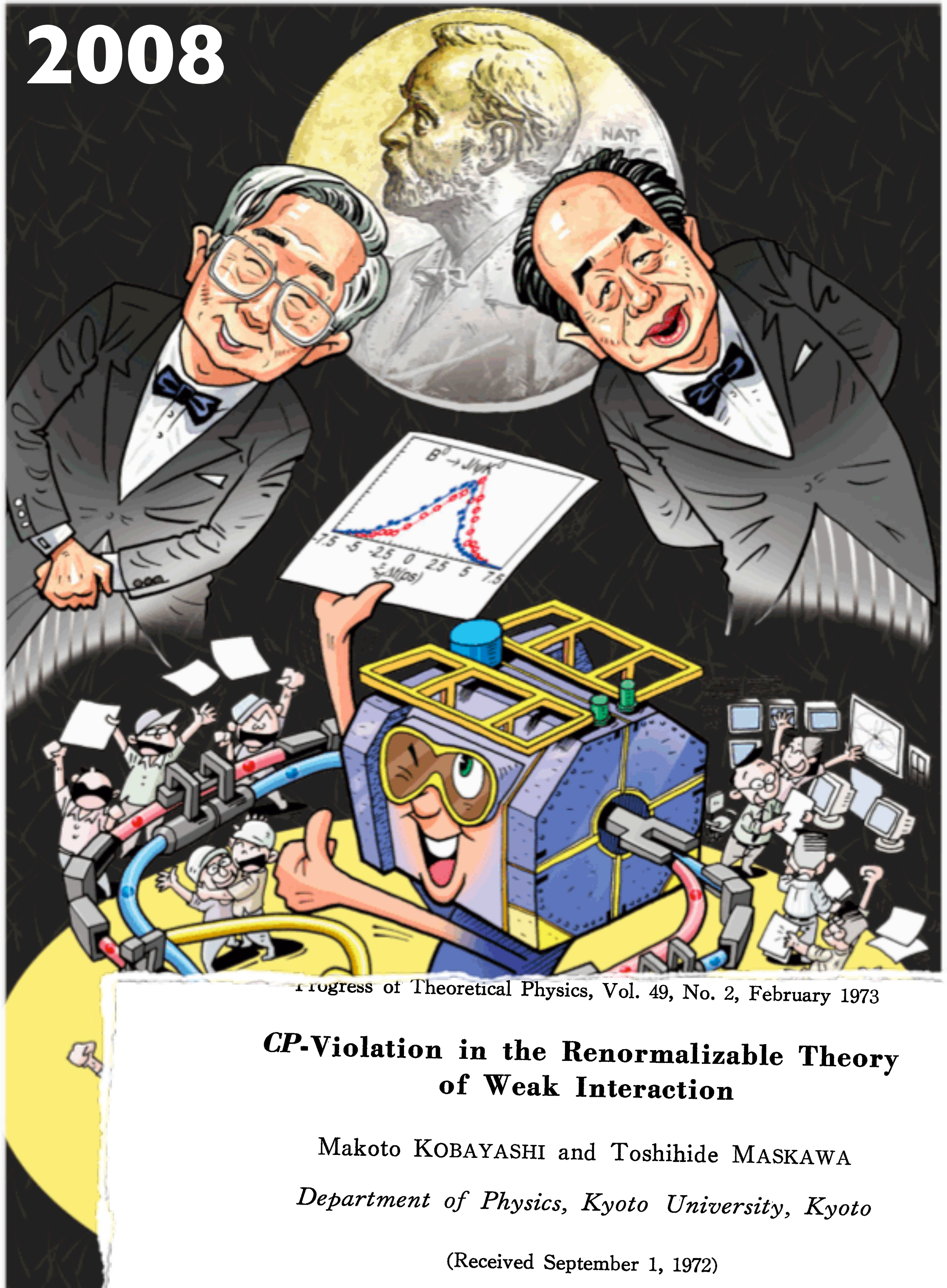


$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1] to the hadron

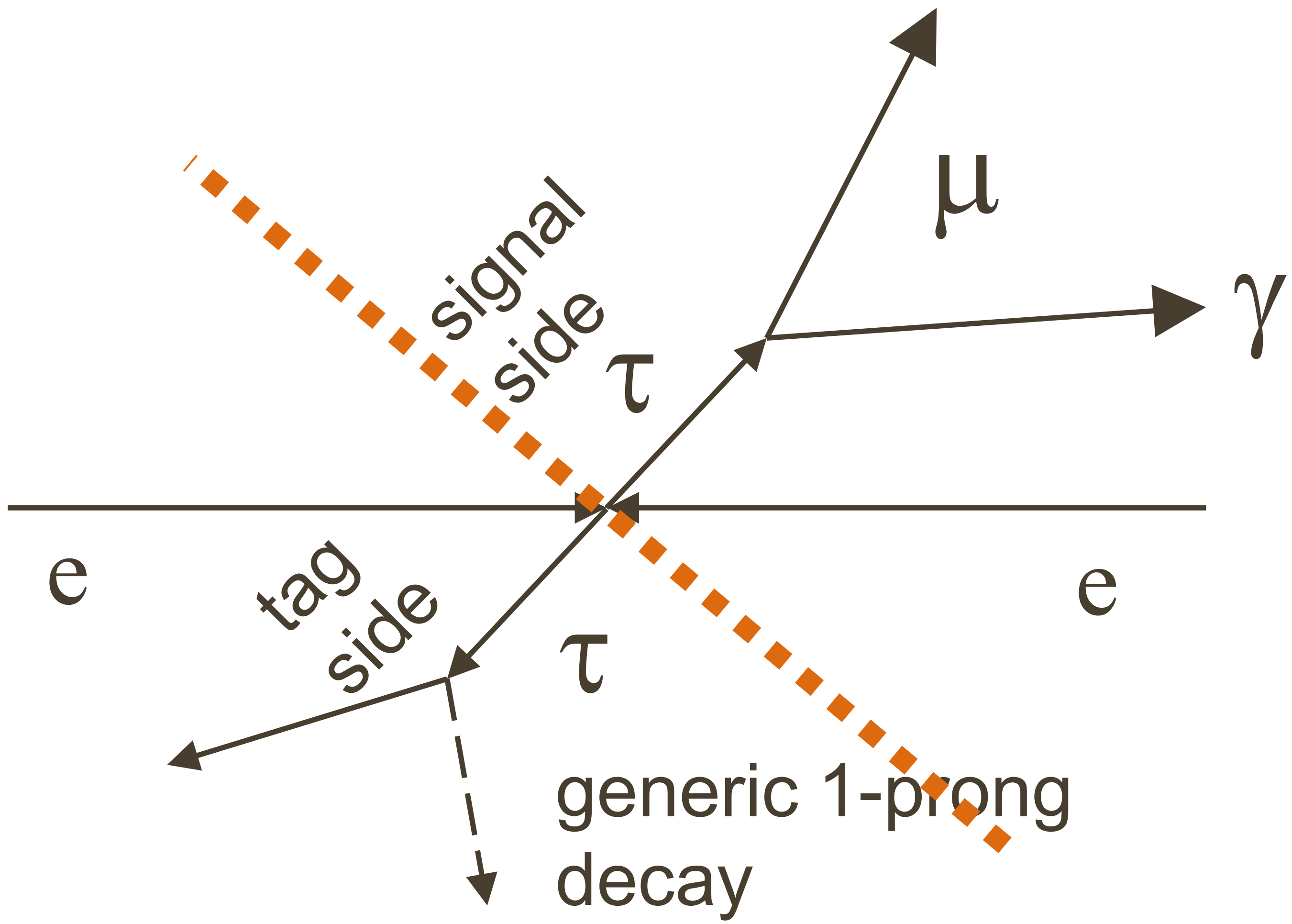
CPV is due to an irreducible phase in the unitary quark mixing matrix in 3 generations

The Belle experiment

- played critical role (along with BaBar) in verifying the KM hypothesis with CP violations in *B* mesons; recognized and cited by the Nobel Foundation
- made a series of first observations of electroweak penguin *B* decays
- discovered mixing in charm mesons
- discovered a series of exotic hadron states, e.g. X(3872), $Z(4430)^+$, $Z_b(10610)^+$, etc.
- …

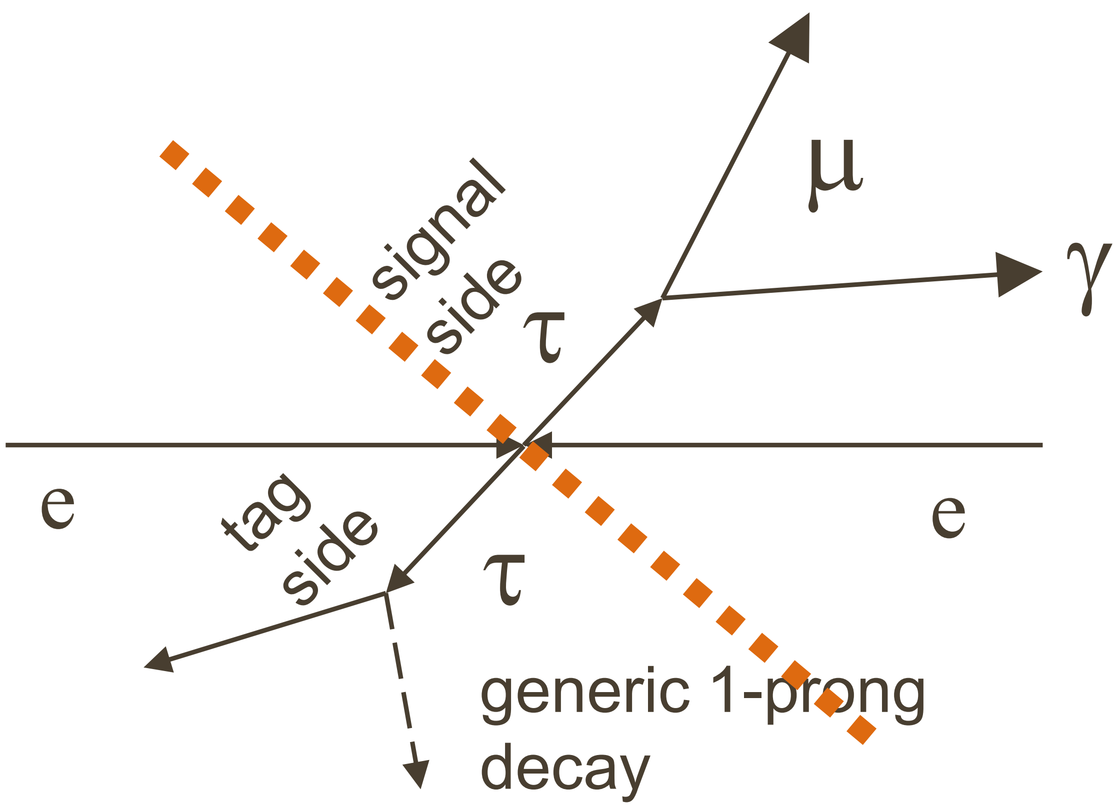
Studying τ LFV @ e+e- B-factory

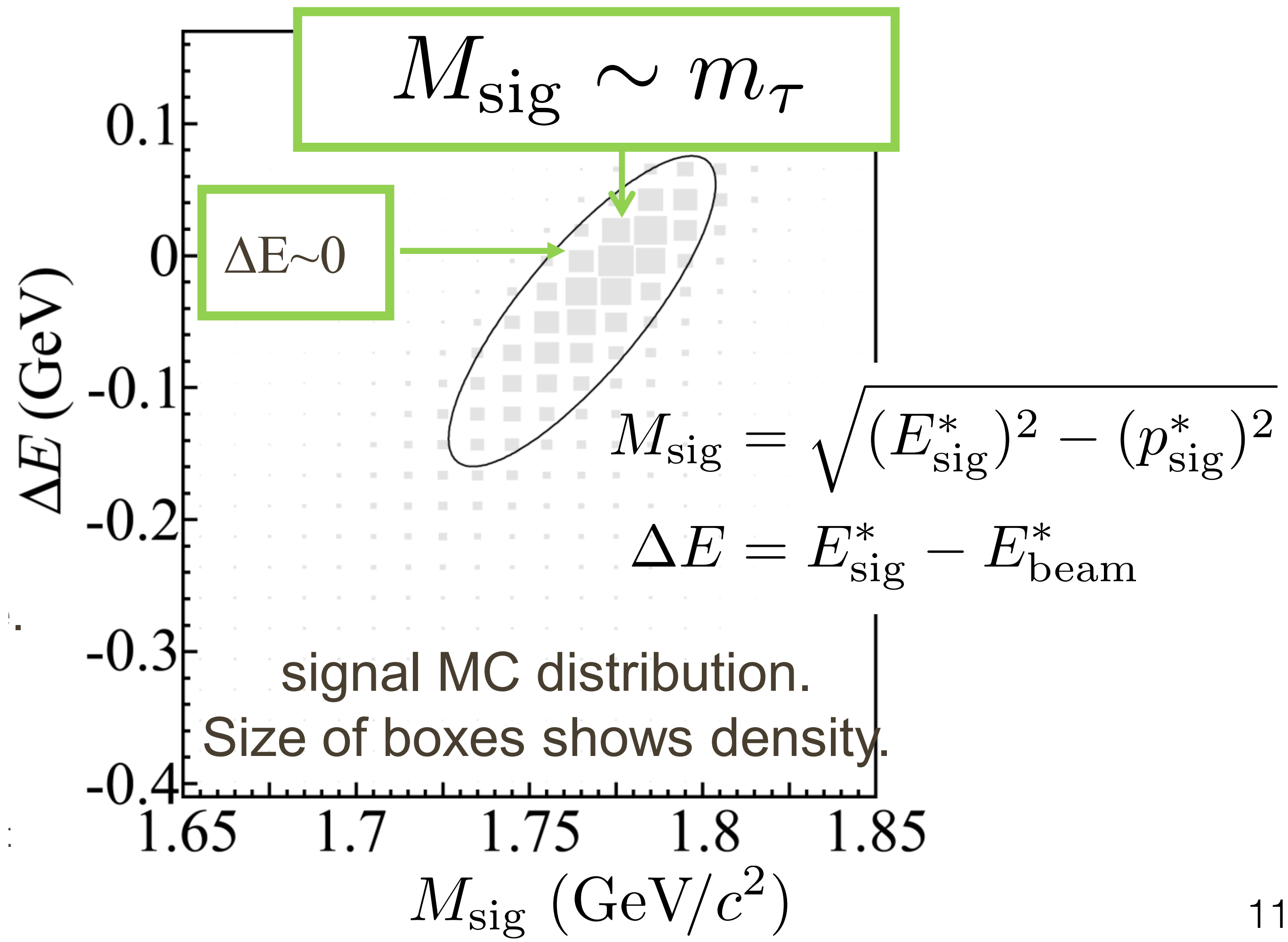
- **hermeticity** of Belle (and Belle II) helps greatly!
- efficient τ-tagging, with minimal trigger bias



Studying τ LFV @ e+e- B-factory

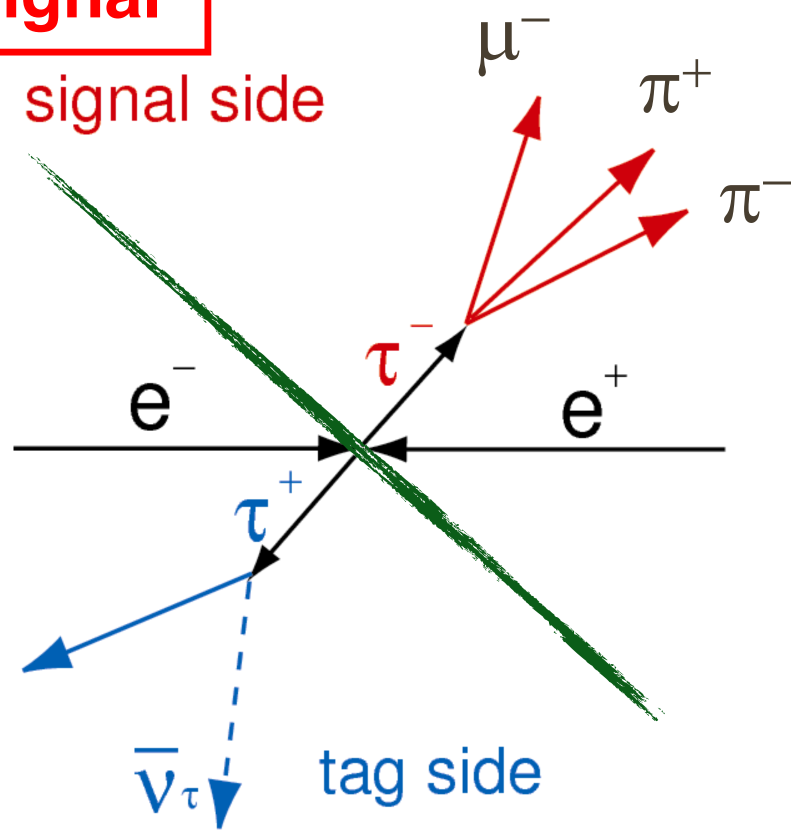
- $\sigma(e^+e^- \to \tau^+\tau^-) = (0.919 \pm 0.003)\ \mathrm{nb} \approx \sigma_{b\bar{b}}$, at $\sqrt{s} \approx 10.58\ \mathrm{GeV}$
  $\therefore e^+e^-$ B-factory is, at the same time, a τ-factory, too!
- tag-side and signal-side τ decays are cleanly separated
- signal extraction by M_{sig} and ΔE





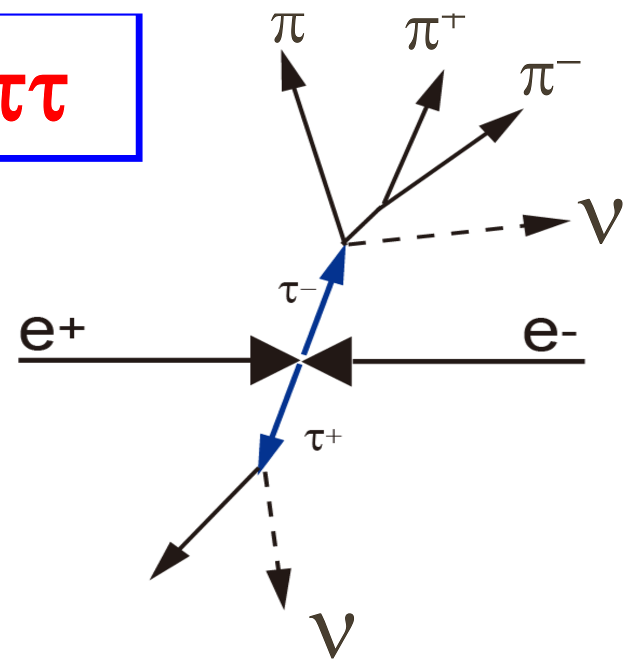
τ LFV signal & background signatures

signal



- Neutrino(s) in tag side
- Particle ID
- Mass of mesons

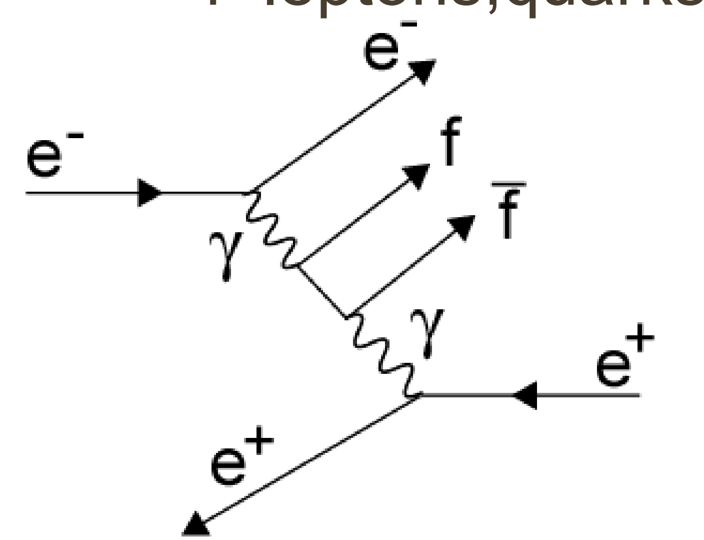
ττ



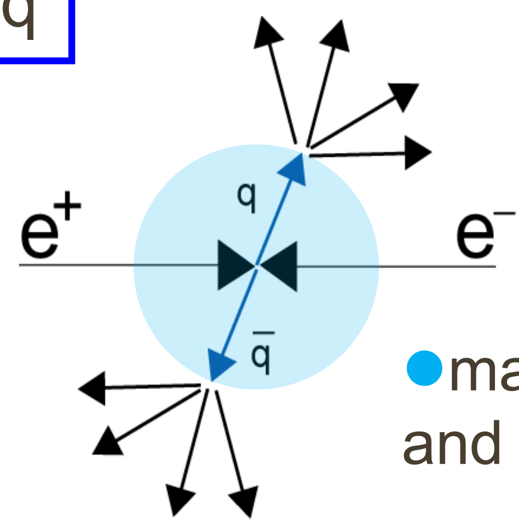
- Neutrinos in both side
- Missing energy in signal side

2photon process

f=leptons,quarks

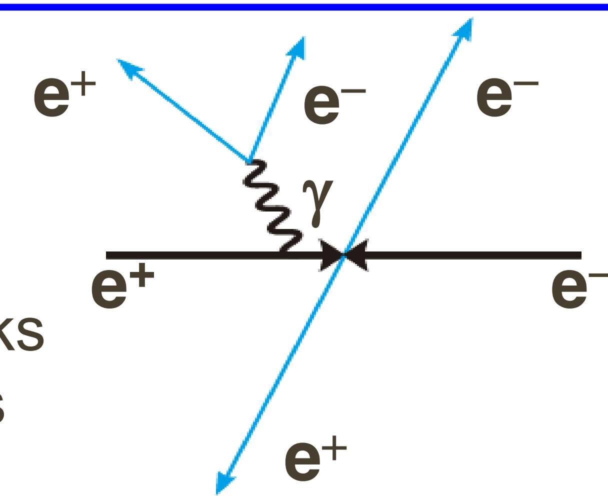


$q\bar{q}$



- many tracks and photons

radiative Bhabha process

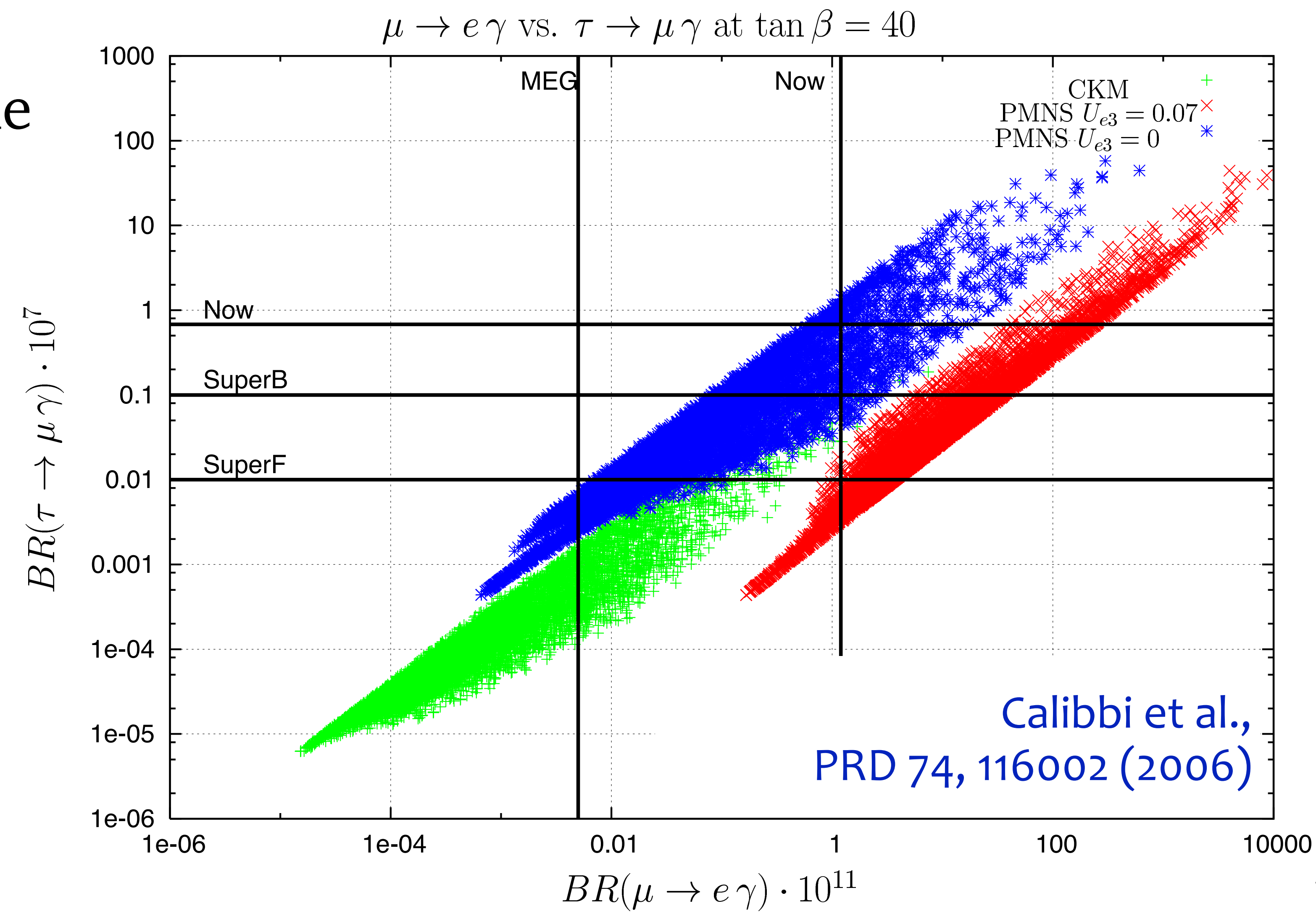


from K. Hayasaka @ Tau 2014

$\tau^+ \rightarrow \ell^+ \gamma$

Motivations

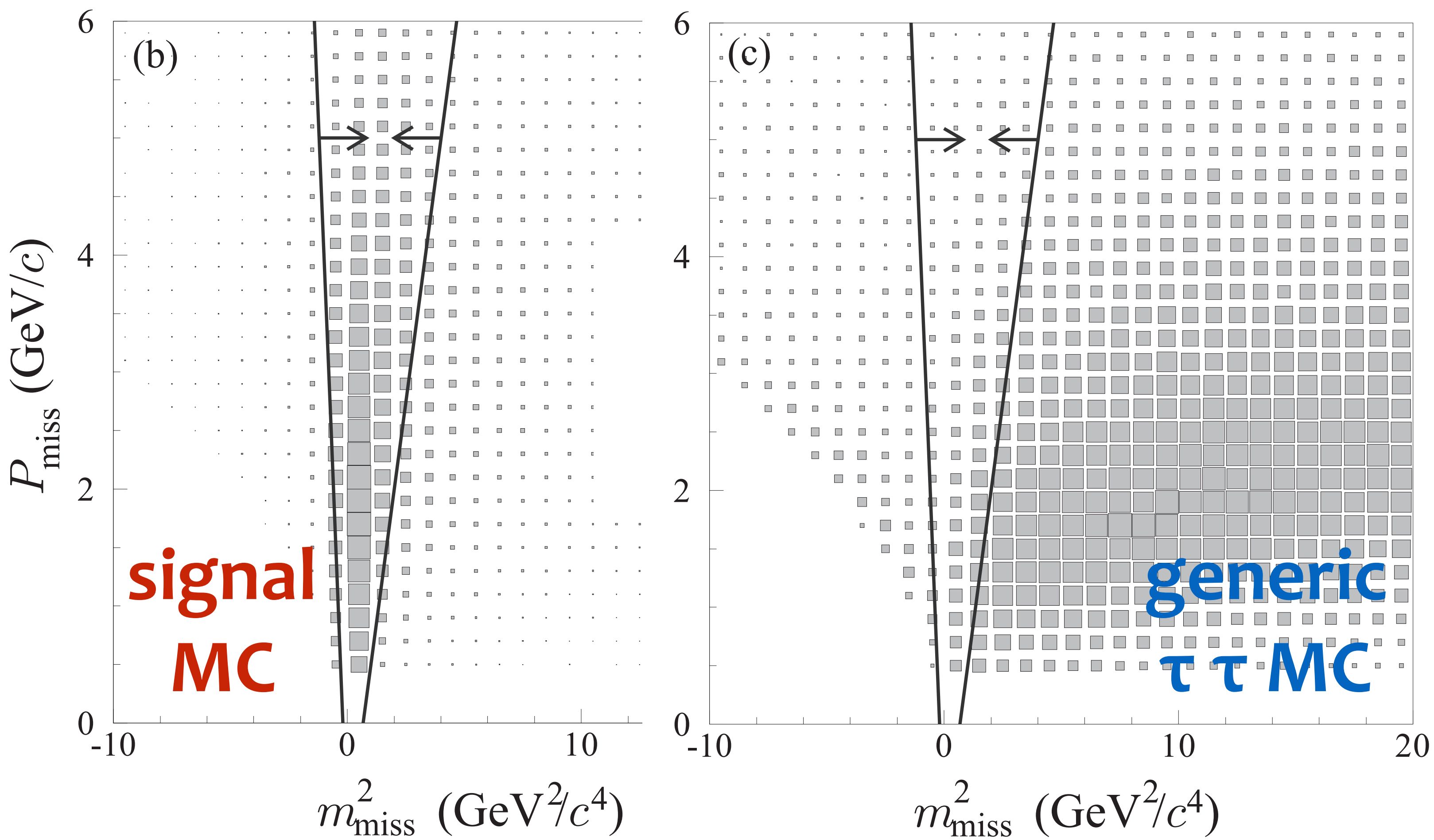
- There exists very stringent bound from $\mu \rightarrow e\,\gamma$,
- but, $\mu \rightarrow e\,\gamma$ alone will not provide enough info. to nail down the LFV mechanism
- many NP models predict sizable ($O(10^{-7}\sim10^{-8})$) $BF(\tau \rightarrow \ell\,\gamma)$
- moreover, the BF's of many LFV modes are correlated differently on different hypotheses



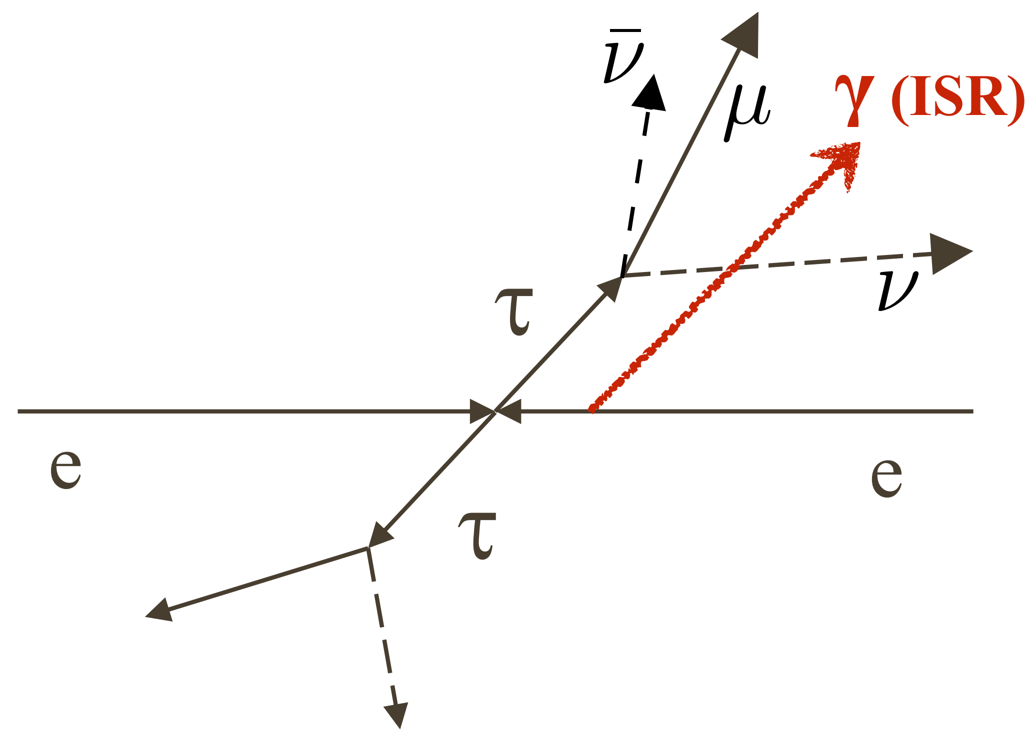
Calibbi et al., PRD 74, 116002 (2006)

$\tau^+ \rightarrow \ell^+ \gamma$

- Procedures
  - 535 fb^{-1} sample with 4.77x10^8 $\tau^+\tau^-$ events
  - generic $\tau^+\tau^-$ events are suppressed by 2D p_{miss} vs. m^2_{miss} cut



- Irreducible background
  - $\tau \rightarrow \ell\nu\nu$ with ISR



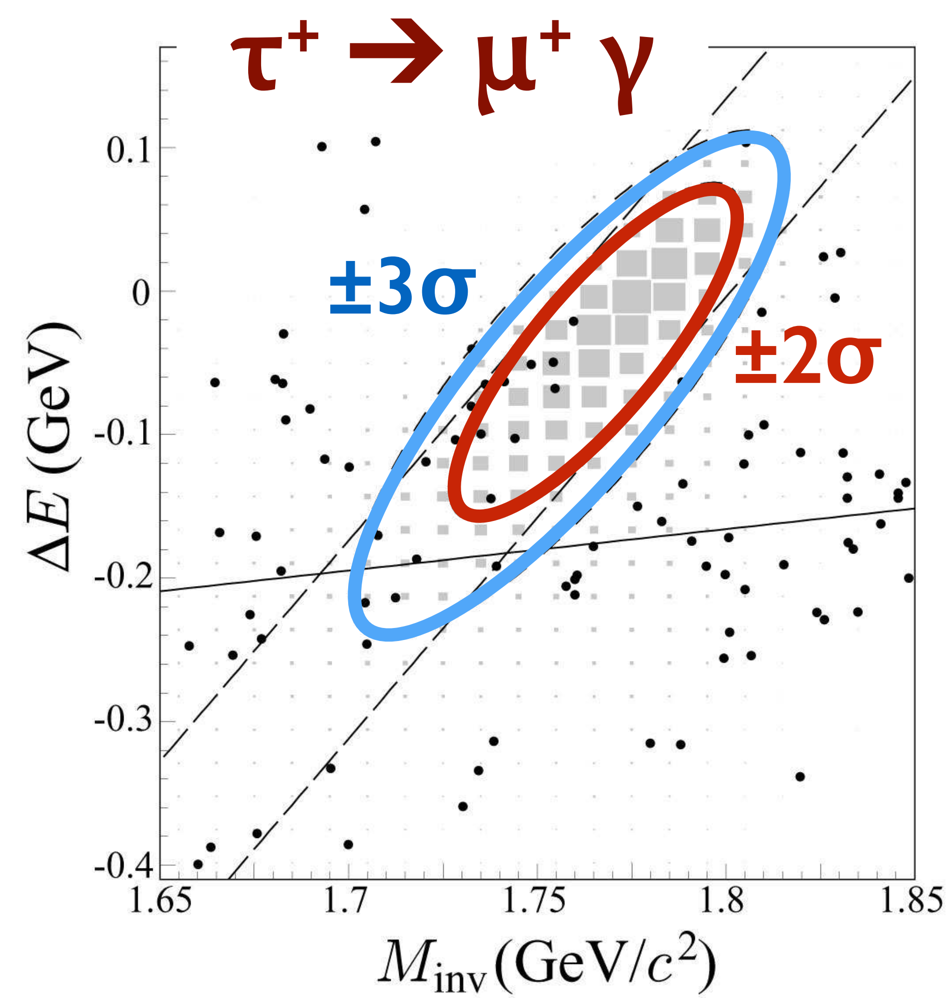
$\tau^+ \rightarrow \ell^+ \gamma$

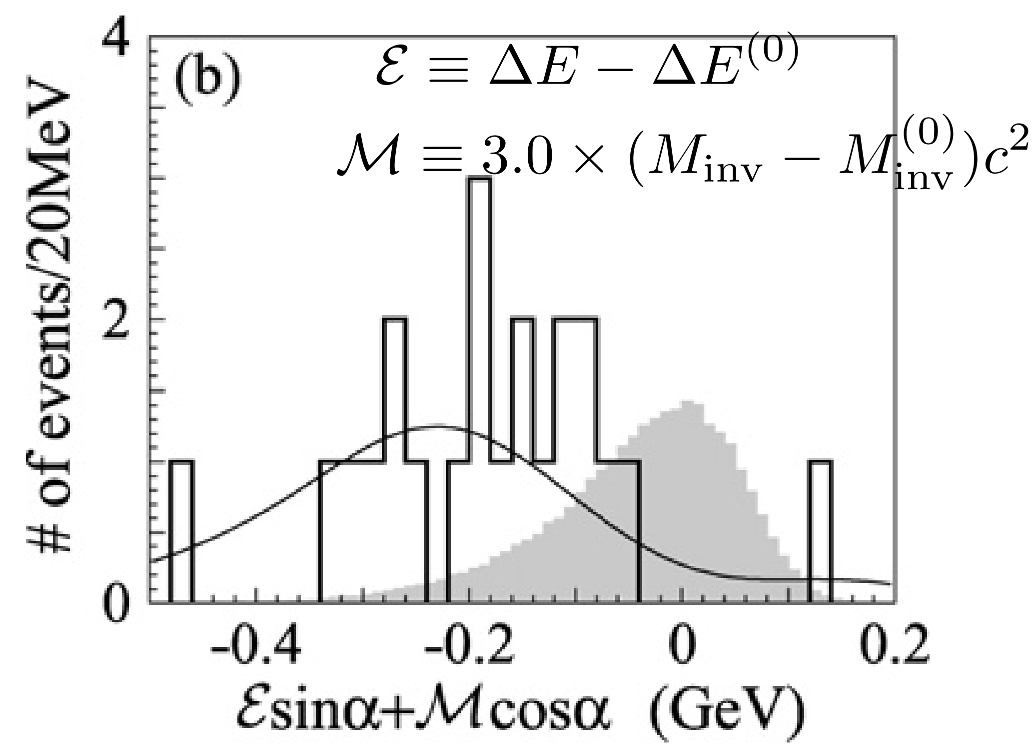
- Signal extraction
  - by unbinned extended max. lik. fit to ΔE vs. M_{inv}
- ΔE & M_{inv} as main variables
  - $\pm 5\sigma$ for background estimation
  - $\pm 3\sigma$ ellipse: blinded
  - $\pm 2\sigma$ ellipse: for signal counting
- Results

Physics Letters B 666 (2008) 16–22

$$\mathcal{B}(\tau^- \to \mu^- \gamma) < 4.5 \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to e^- \gamma) < 12.0 \times 10^{-8}$$

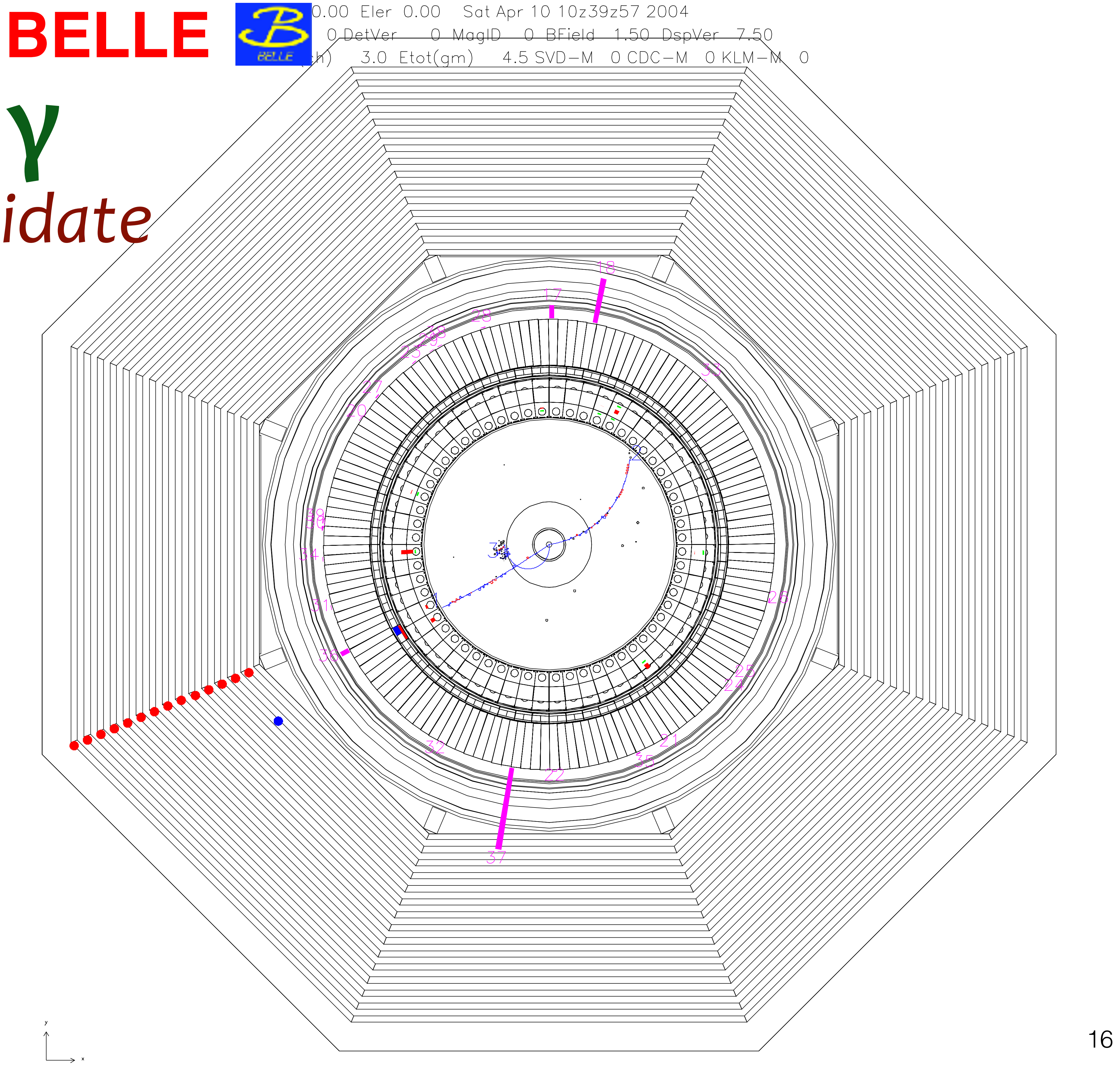
at 90% CL





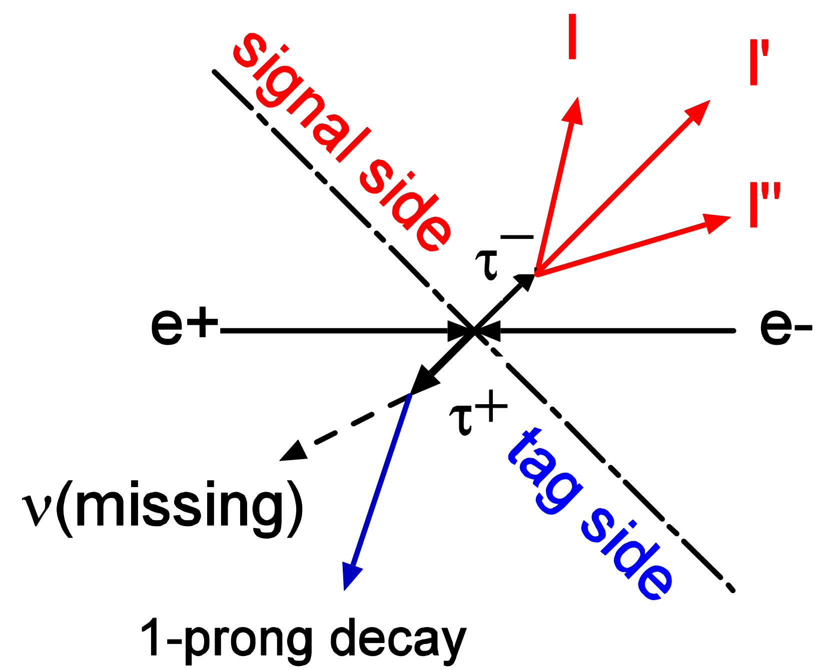
$\tau^+ \rightarrow \ell^+ \gamma$

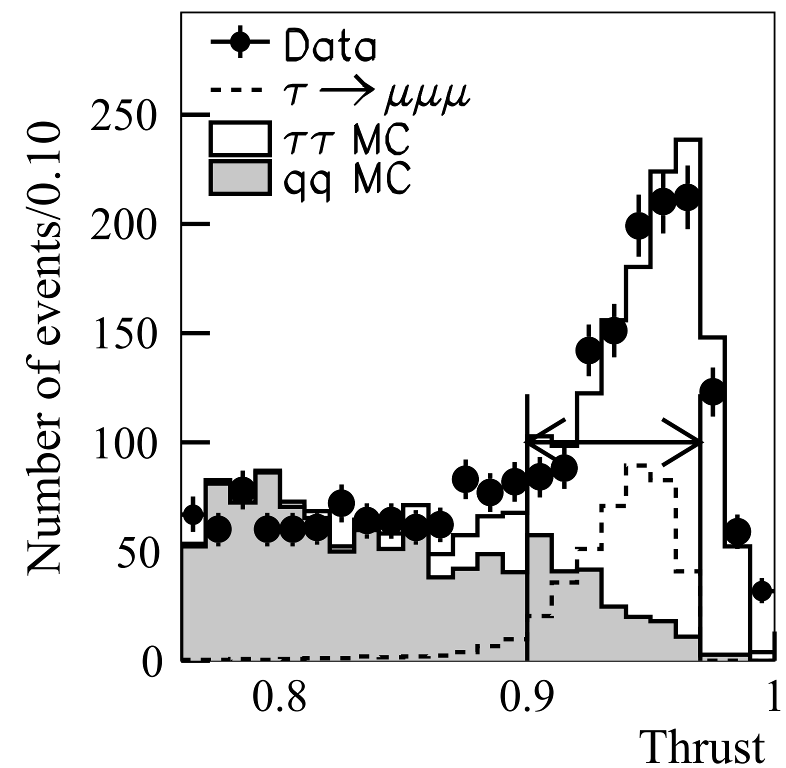
a signal candidate



$\tau^+ \rightarrow \ell^+ \ell^- \ell^+$

- Event selection $\int \mathcal{L} dt = 782\ \mathrm{fb}^{-1}$
  - 1-vs-3 event topology
  - two hemispheres: "signal" side and "tag" side
  - $\vec{p}_{\mathrm{miss}}$ within the tag side & $p_{\mathrm{miss}} > 0.4\ \mathrm{GeV}/c$
  - use **thrust** for $q\bar{q}$ suppression
  - $\gamma \rightarrow e^+e^-$ veto: $M_{ee} > 0.2\ \mathrm{GeV}/c^2$
  - generic $\tau^+\tau^-$ event suppression by 2D cut on p_{miss}-vs.-m^2_{miss}

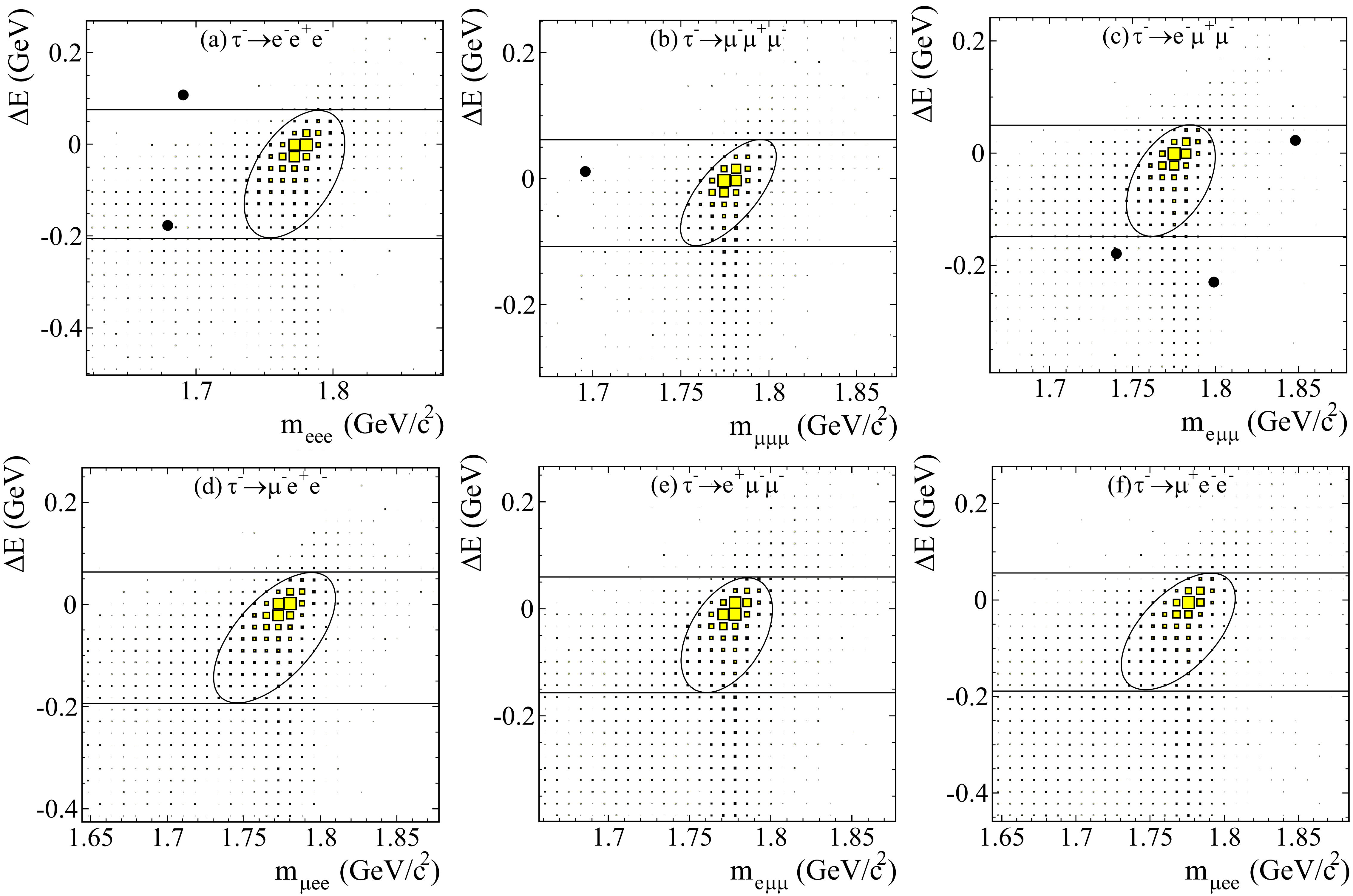




- ΔE & M_{3l} as main variables
  - $\pm 20\sigma$ for analysis
  - blinded analysis
  - background estimation in the M_{3l} side-band

$\tau^+ \rightarrow \ell^+ \ell^- \ell^+$

elliptical signal region was blinded



Physics Letters B 687 (2010) 139–143

$\tau^+ \rightarrow \ell^+ \ell^- \ell^+$

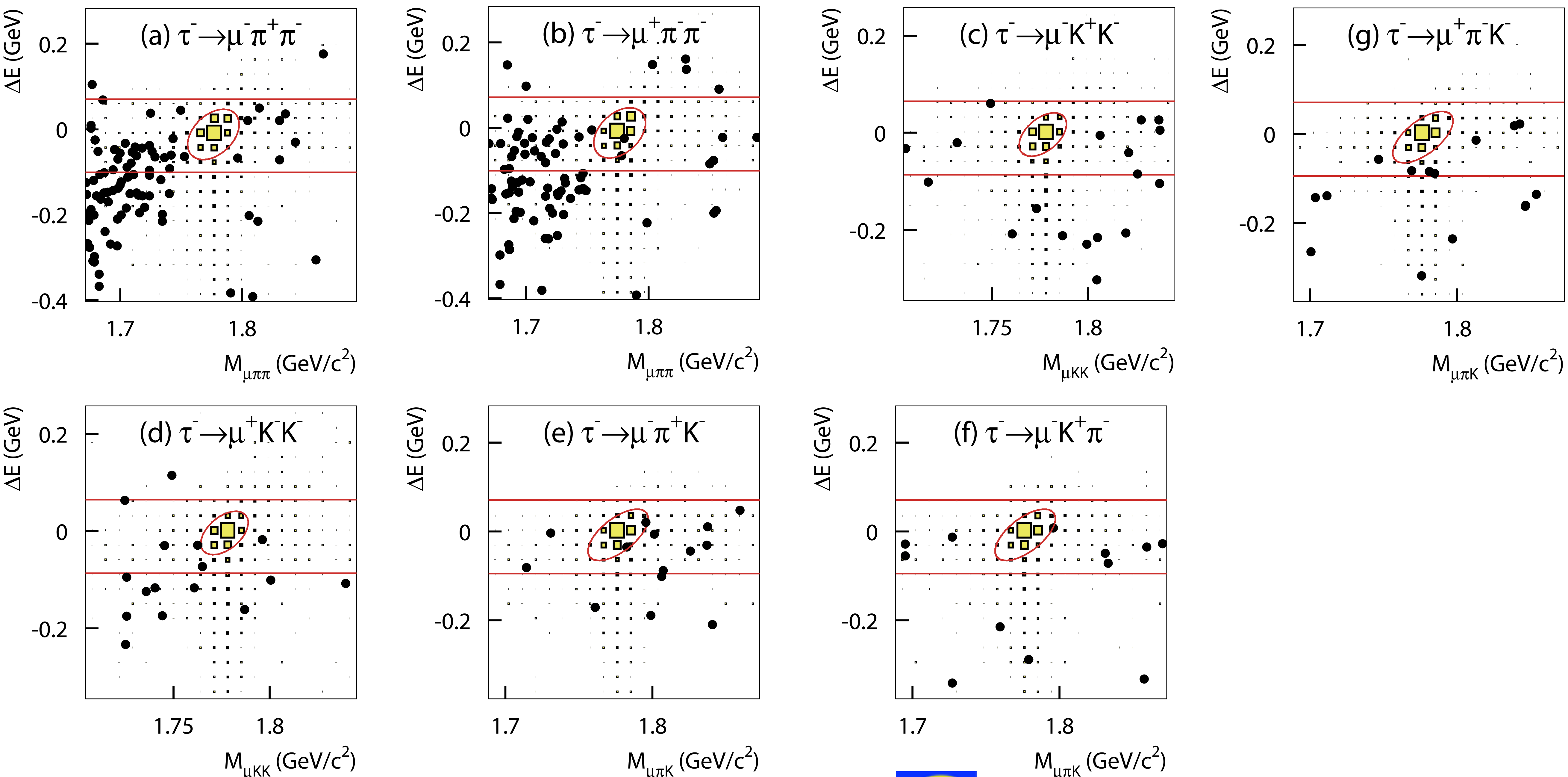
- Results

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^- e^+ e^-$	6.0	0.21 ± 0.15	9.8	0	< 2.7
$\tau^- \to \mu^- \mu^+ \mu^-$	7.6	0.13 ± 0.06	7.4	0	< 2.1
$\tau^- \to e^- \mu^+ \mu^-$	6.1	0.10 ± 0.04	9.5	0	< 2.7
$\tau^- \to \mu^- e^+ e^-$	9.3	0.04 ± 0.04	7.8	0	< 1.8
$\tau^- \to e^+ \mu^- \mu^-$	10.1	0.02 ± 0.02	7.6	0	< 1.7
$\tau^- \to \mu^+ e^- e^-$	11.5	0.01 ± 0.01	7.7	0	< 1.5

$$\mathcal{B}(\tau^- \to \ell^- \ell^+ \ell^-) < \frac{s_{90}}{2 N_{\tau\tau} \varepsilon}$$

$$N_{\tau\tau} = 719 \times 10^6$$

(LFV) $\tau^+ \to \ell^+ h^- h'^+$ and (LNV) $\ell^- h^+ h'^+$ $(h = \pi,\ K)$



Physics Letters B 719 (2013) 346–353

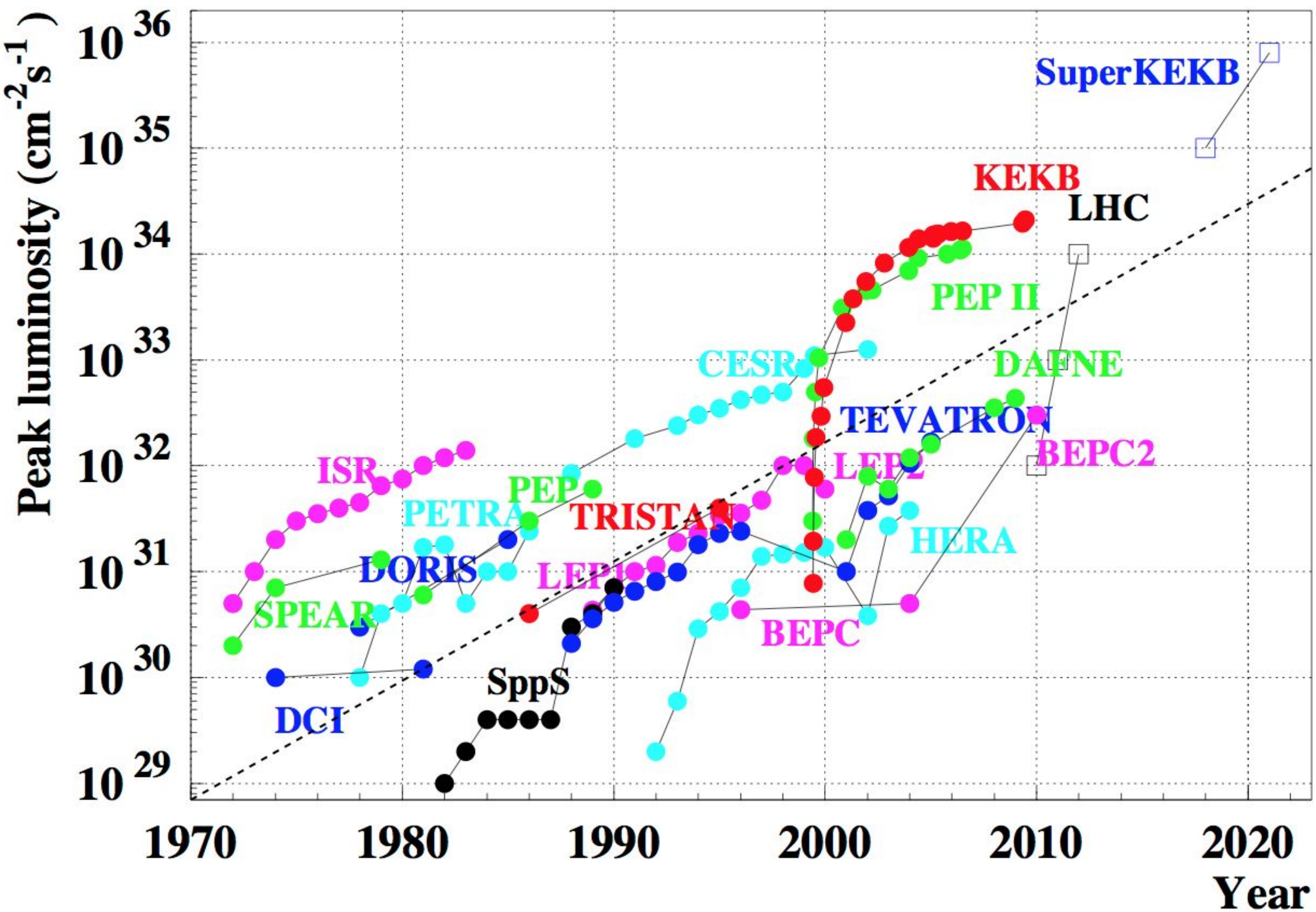
$\tau^+ \to \ell^+ h^- h'^+$ and $\ell^- h^+ h'^+$

(LFV) (LNV)

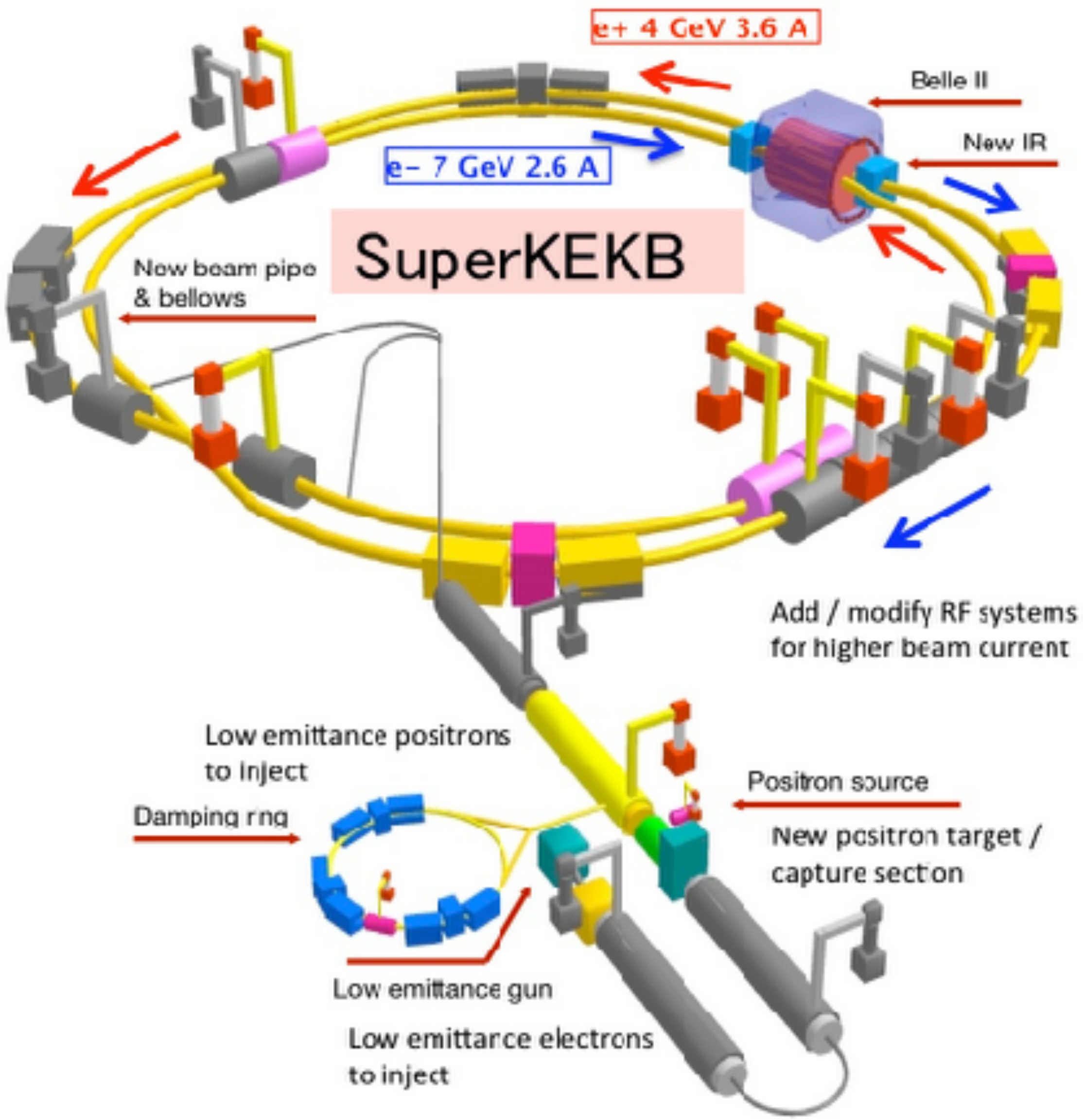
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.7	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.6	1	4.01	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.7	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.19	5.5	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.19	6.1	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	6.2	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.7	0	2.29	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.5	0	2.39	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.28	6.2	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	6.4	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.7	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	6.2	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	6.1	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	6.2	0	2.03	3.2

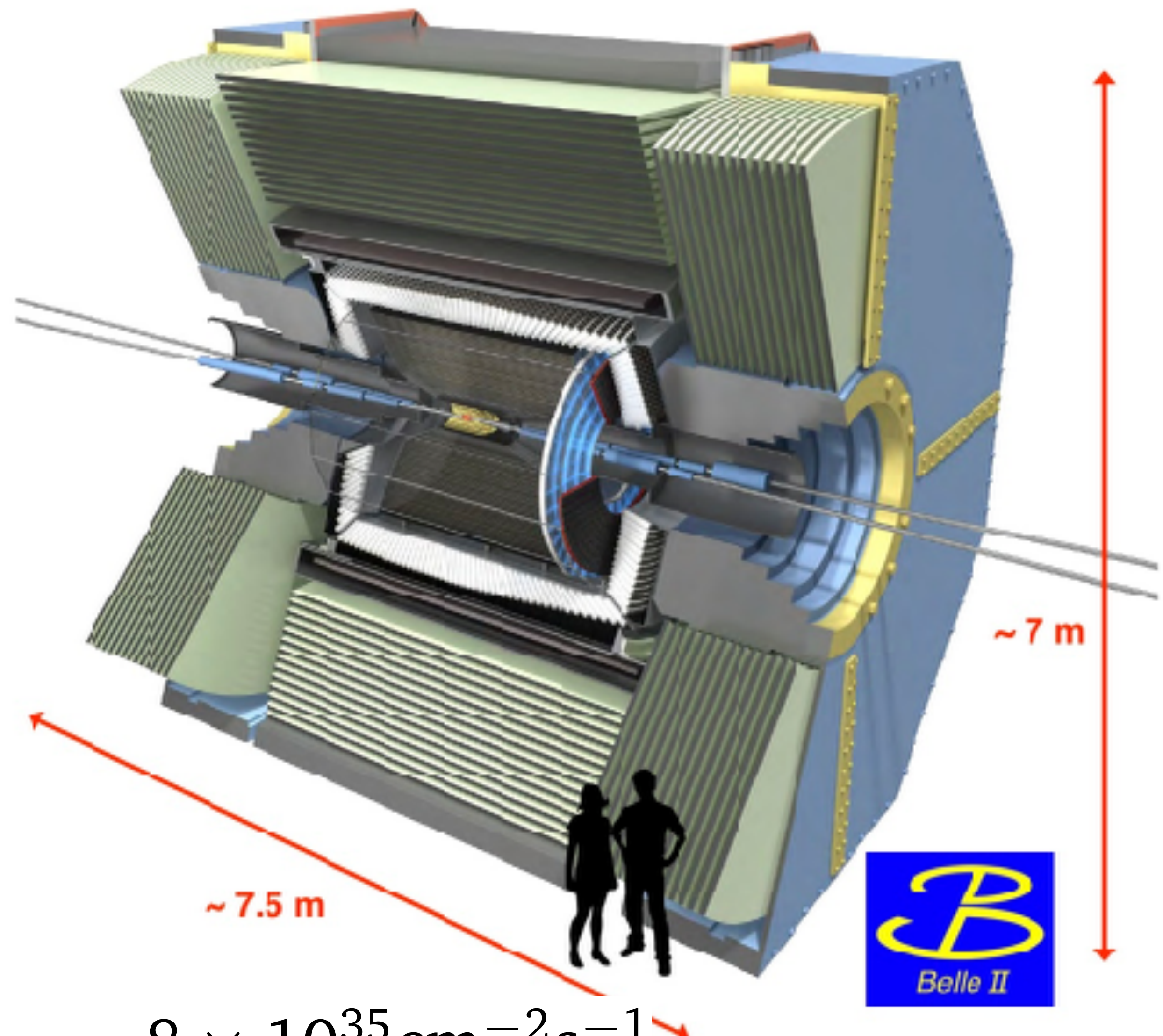
Physics Letters B 719 (2013) 346–353

Next step: Luminosity upgrade



SuperKEKB & Belle II





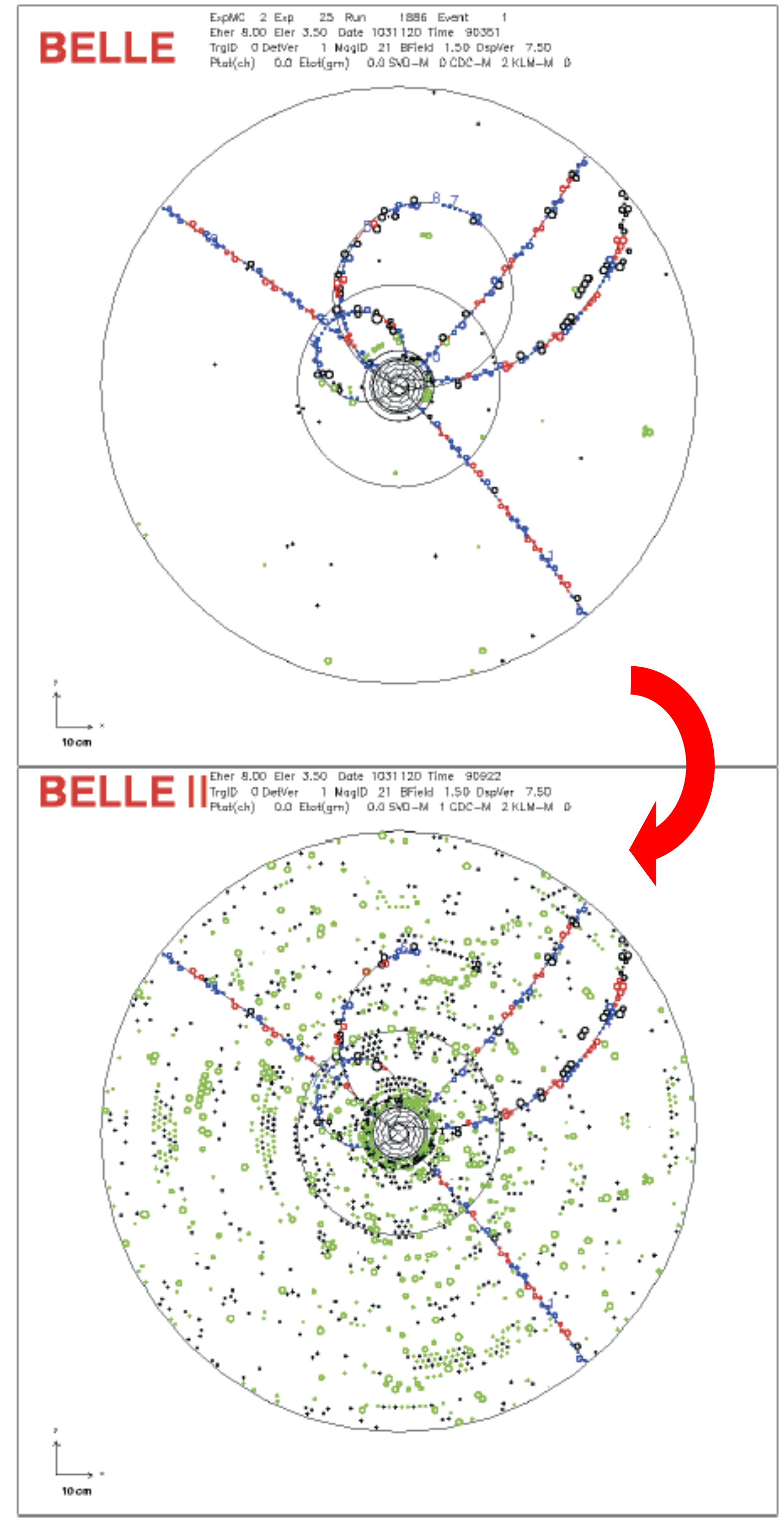
$$e^- \xrightarrow{7\ \text{GeV}} (\star) \xleftarrow{4\ \text{GeV}} e^+$$

$$\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

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

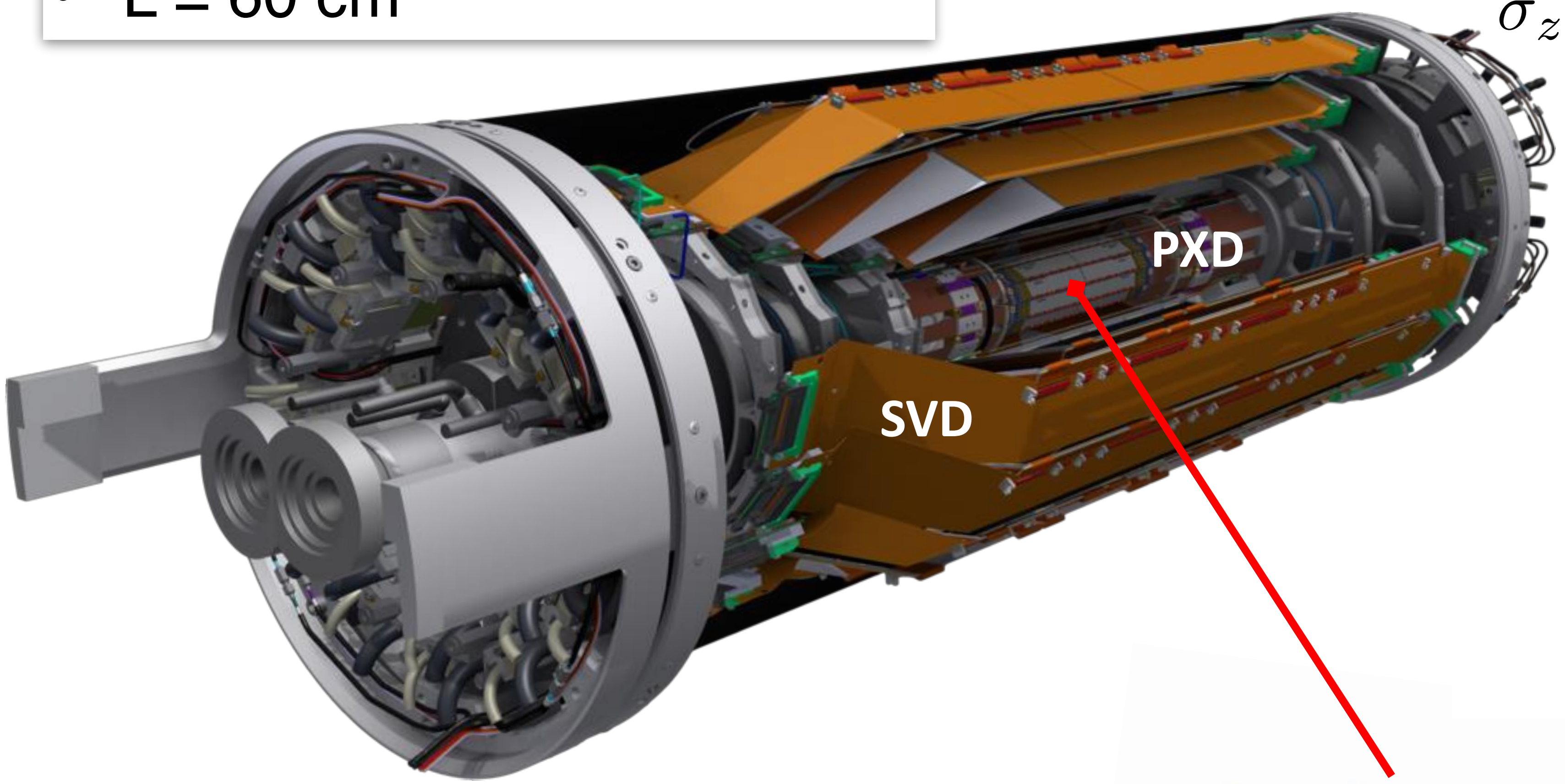
Challenges & responses for Belle II

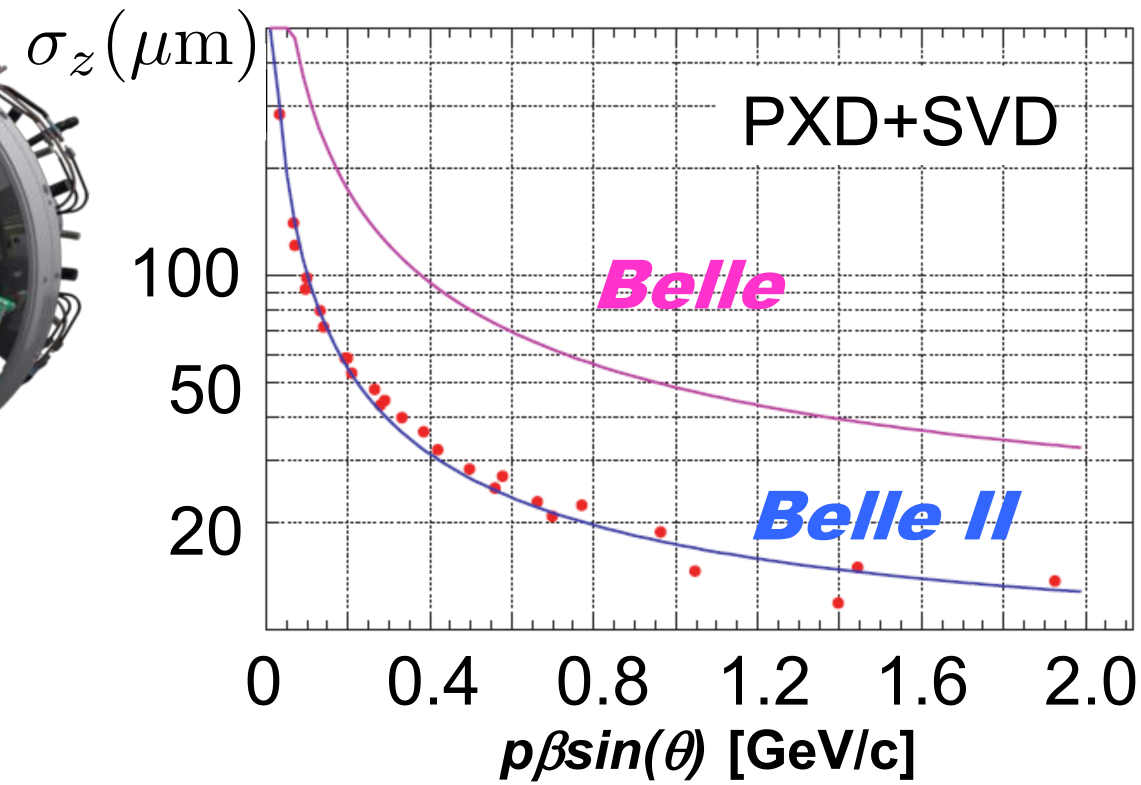
- Severe beam background
  - due to ×40 increase in $\mathcal{L}_{\text{peak}}$
  - fine segmentation and fast readout ➔ reduce occupancy
  - replace detector components
- Some big changes
  - vertex: SVD (4 layers) ➔ **PXD (2) + SVD (4)**
  - hadron identification: binary Cherenkov ➔ **iTOP** ("imaging Time-of-Propagation")



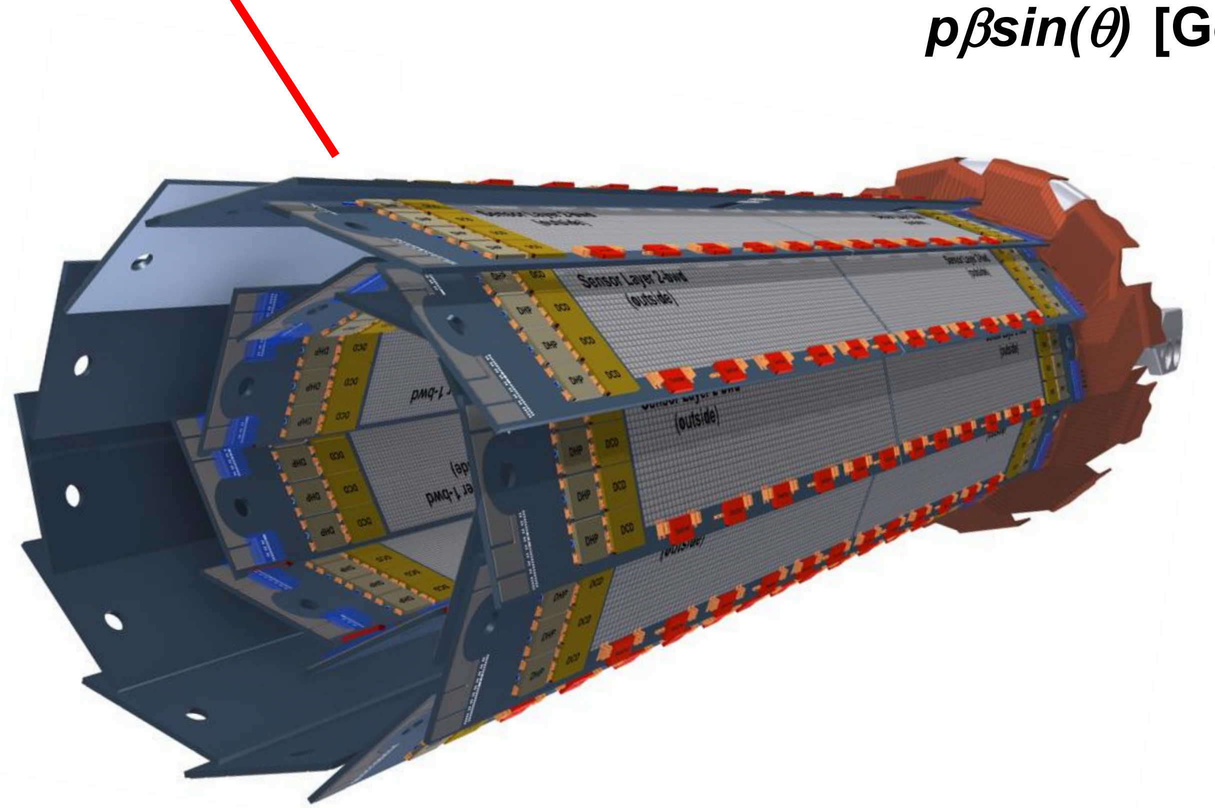
Vertexing for Belle II

SVD
- 4 layers of DSSD
- r = 3.8, 8.0, 11.5, 14.0 (cm)
- L = 60 cm

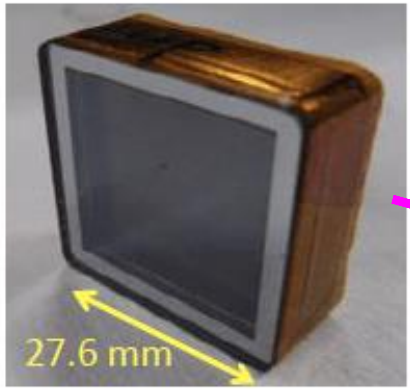




PXD (pixel detector)
- 2 layers of DEPFET
- r = 1.4, 2.2 (cm)
- L = 12 cm

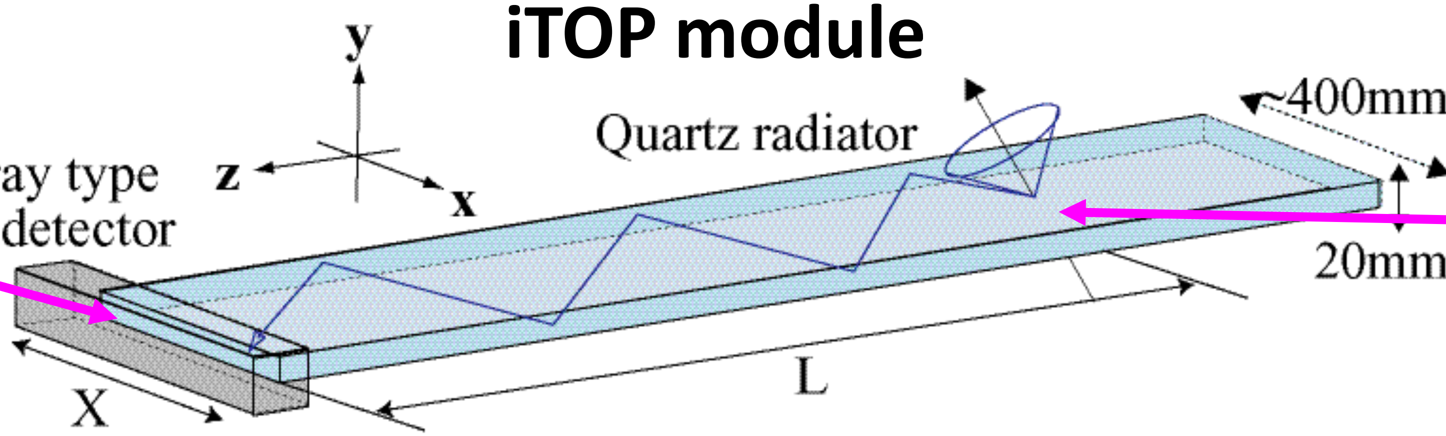


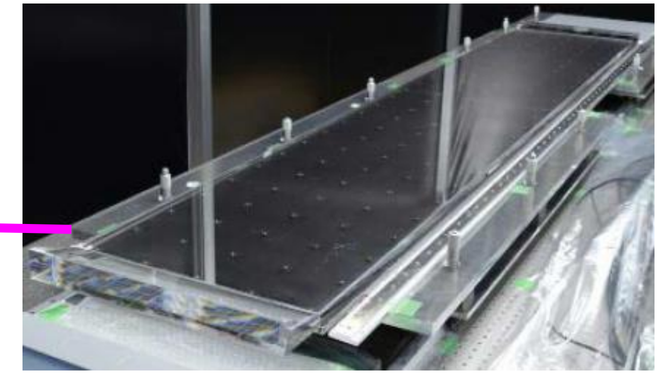
hadron ID for Belle II



512 Hamamatsu 4 x 4 MCP-PMT

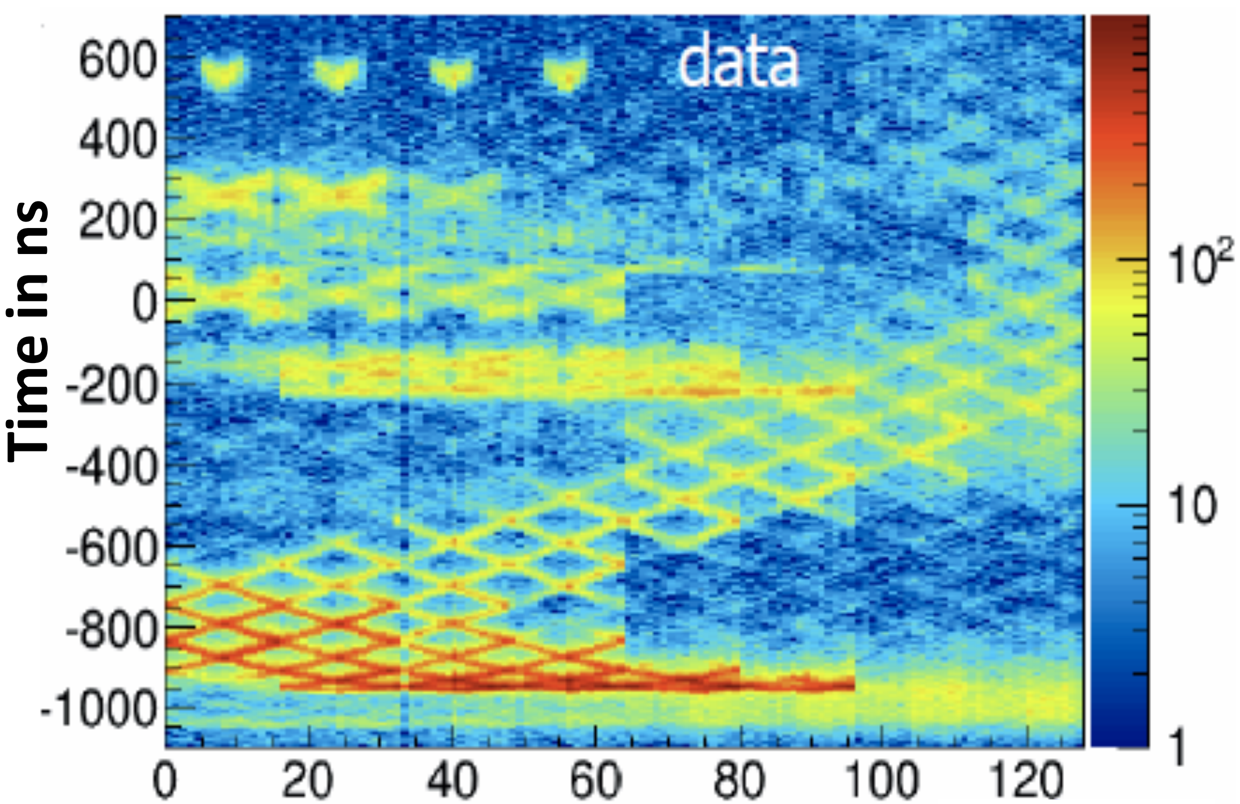
iTOP module

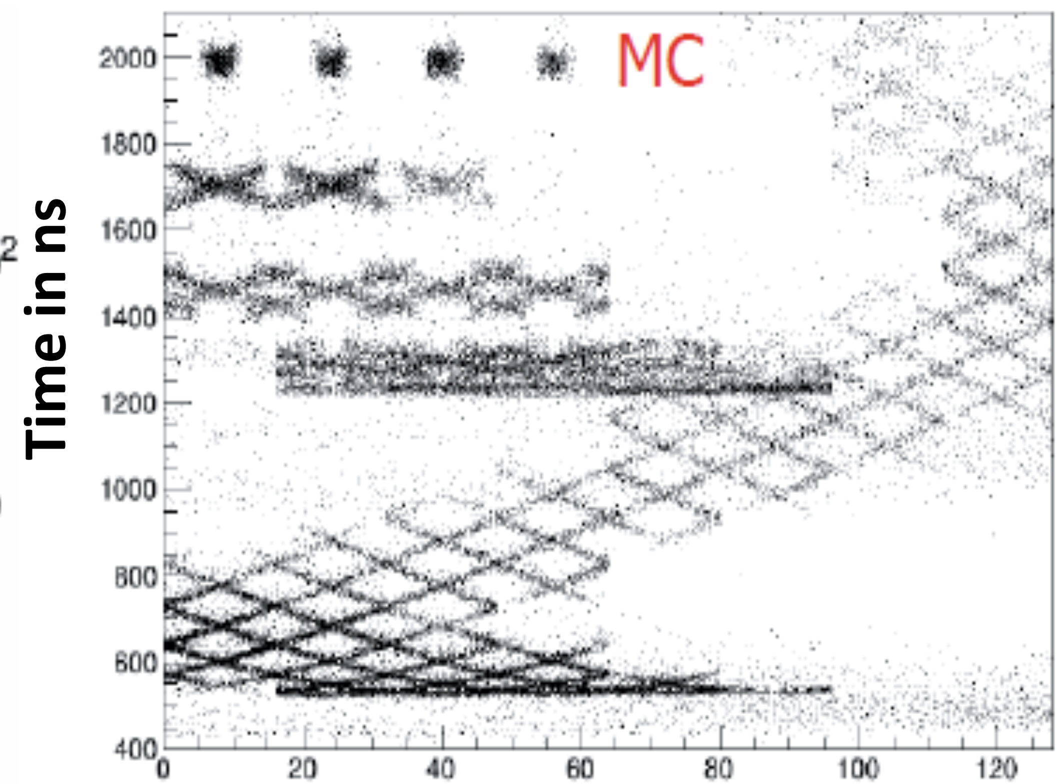




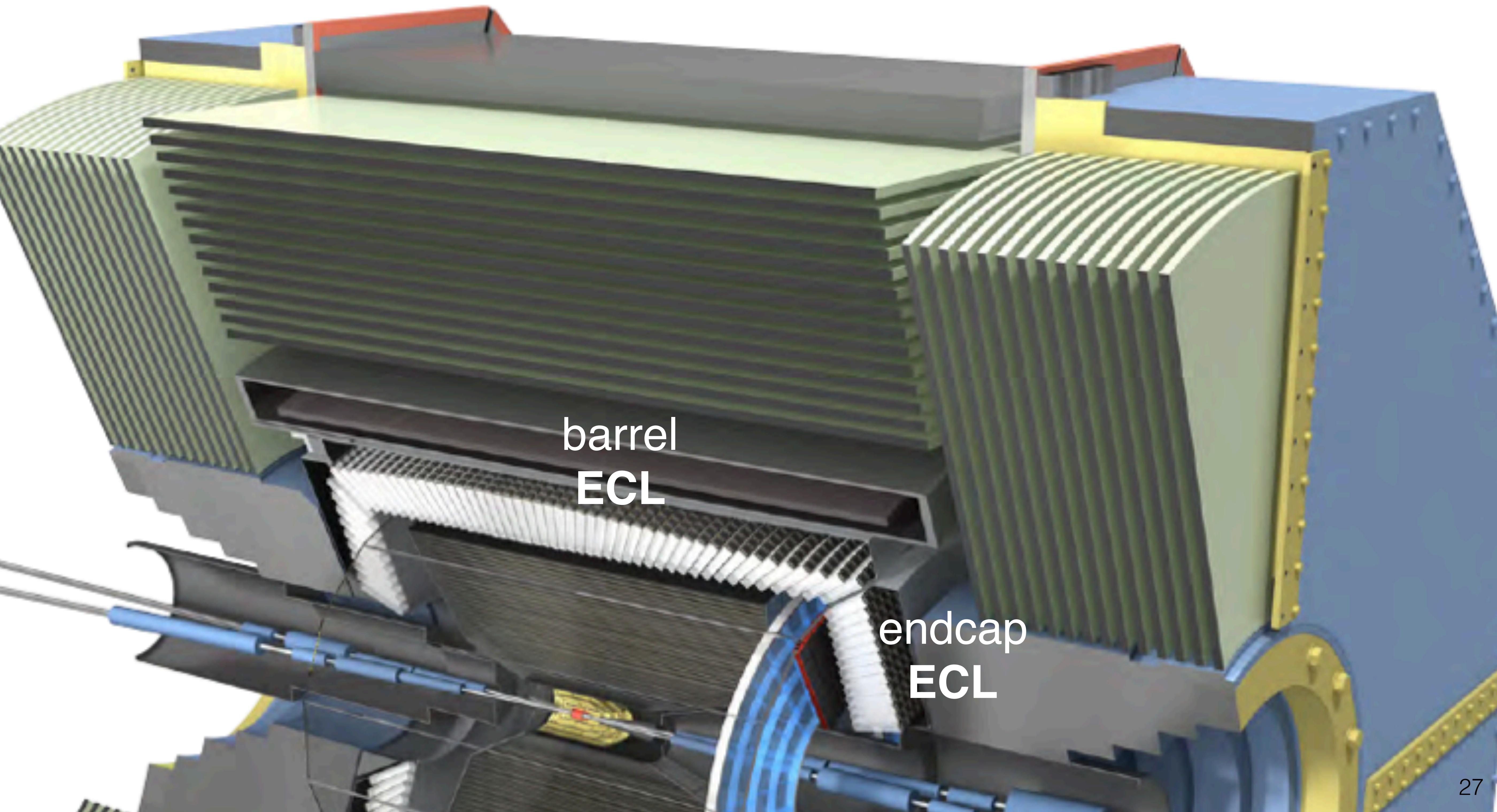
Quartz radiator

TOP test beam data





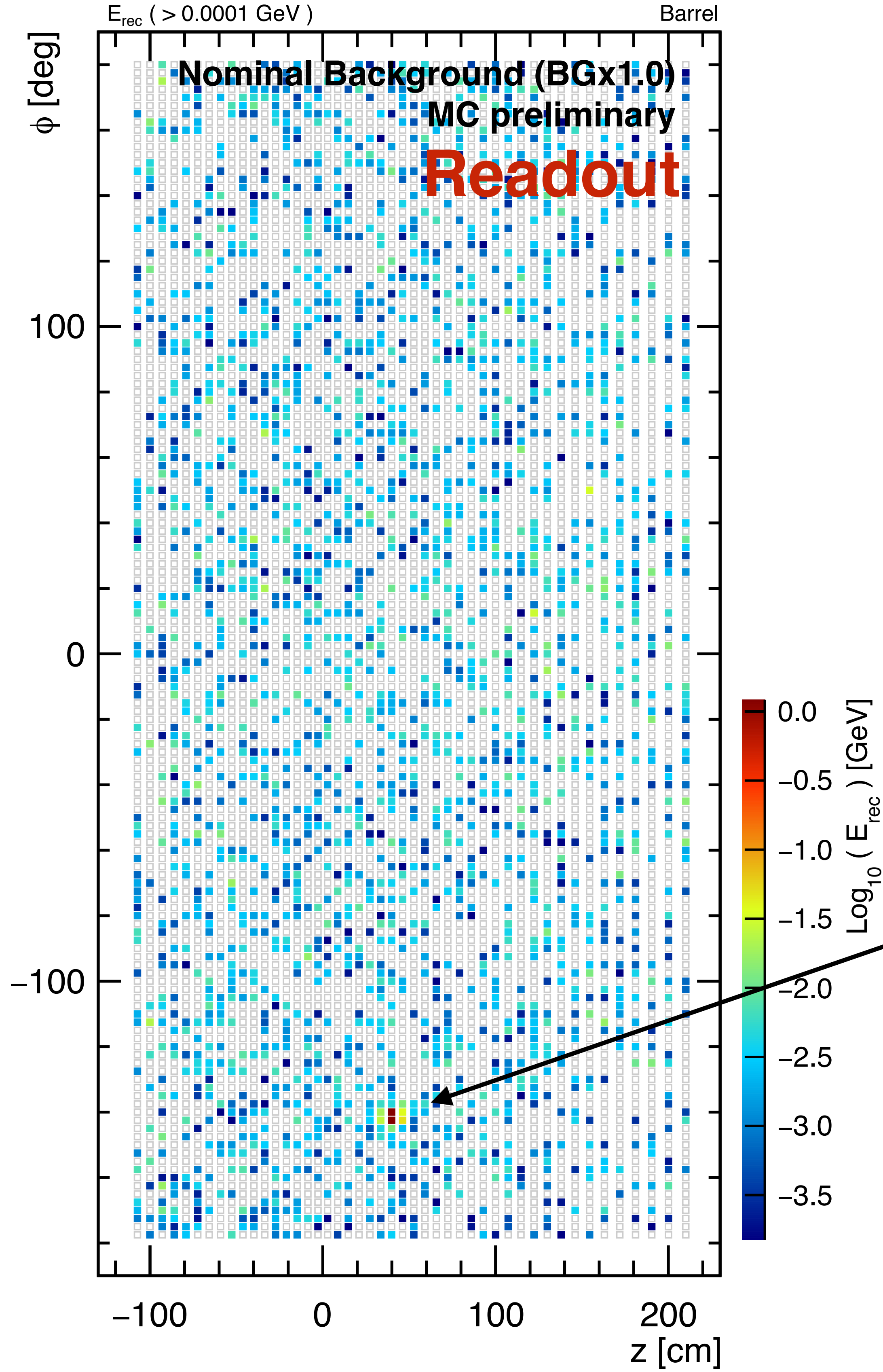
Challenges & responses: ECL

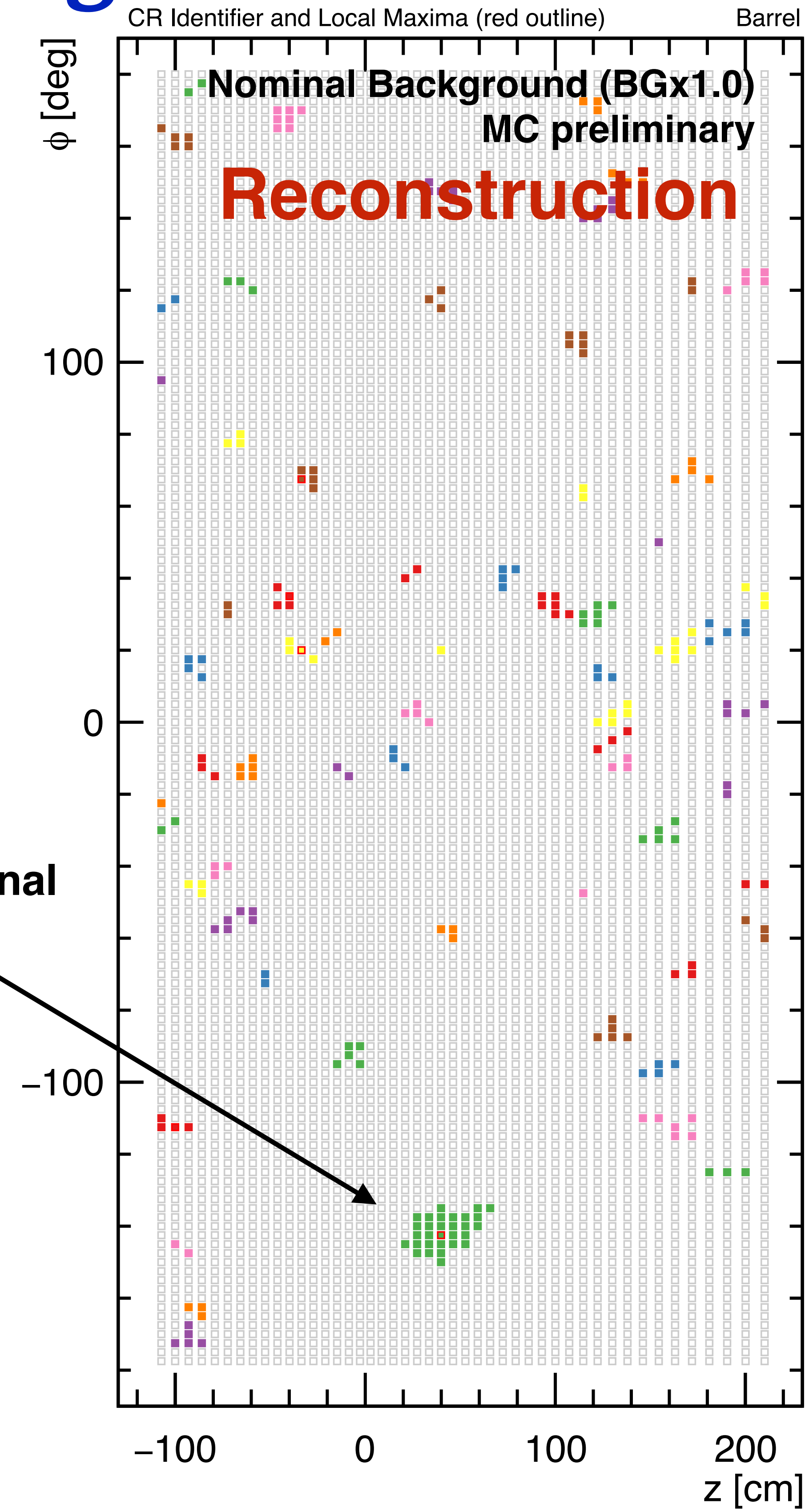


Challenges & responses: ECL

- ECL is essential for γ and $e^{\pm}$ detection
  - hence indispensable for τ LFV ($\tau^{\pm} \to e^{\pm}\gamma,\ \ell^{\pm}\ell^{+}\ell^{-}$ etc.)
- Belle ECL
  - CsI(Tl) crystals with PIN photodiode
- Belle II ECL
  - upgrade is needed due to higher rates & radiation load
  - waveform sampling in new readout electronics
    - timing resolution $<$ 4.5 ns in cosmic-ray test of barrel ECL
  - use of pure-CsI for endcap crystals being considered

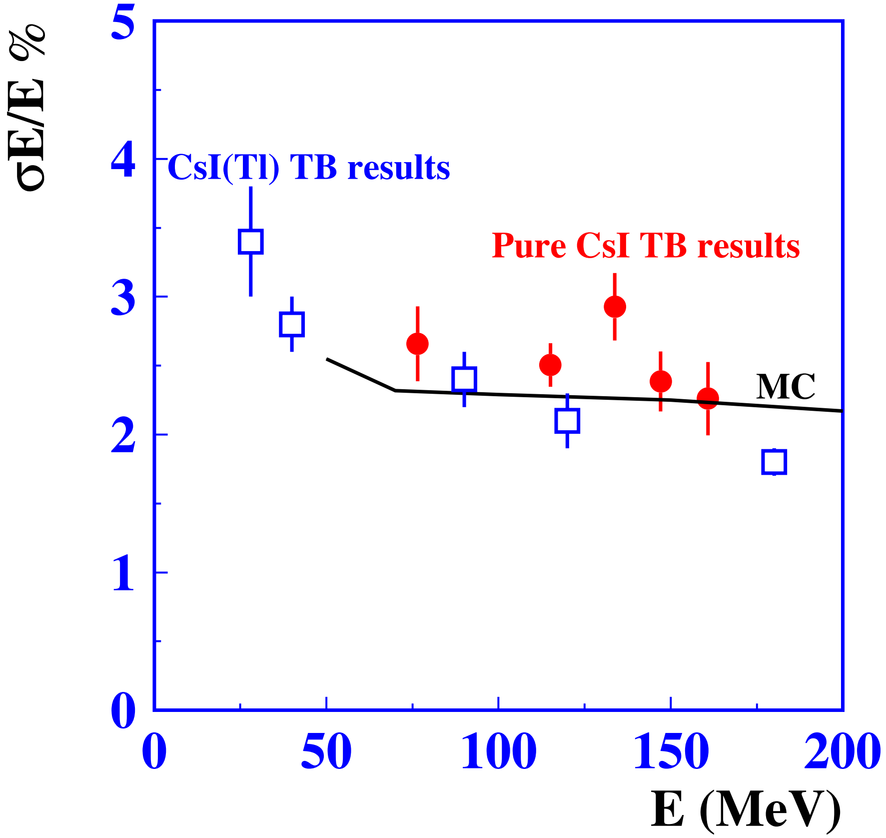
Belle II ECL with background



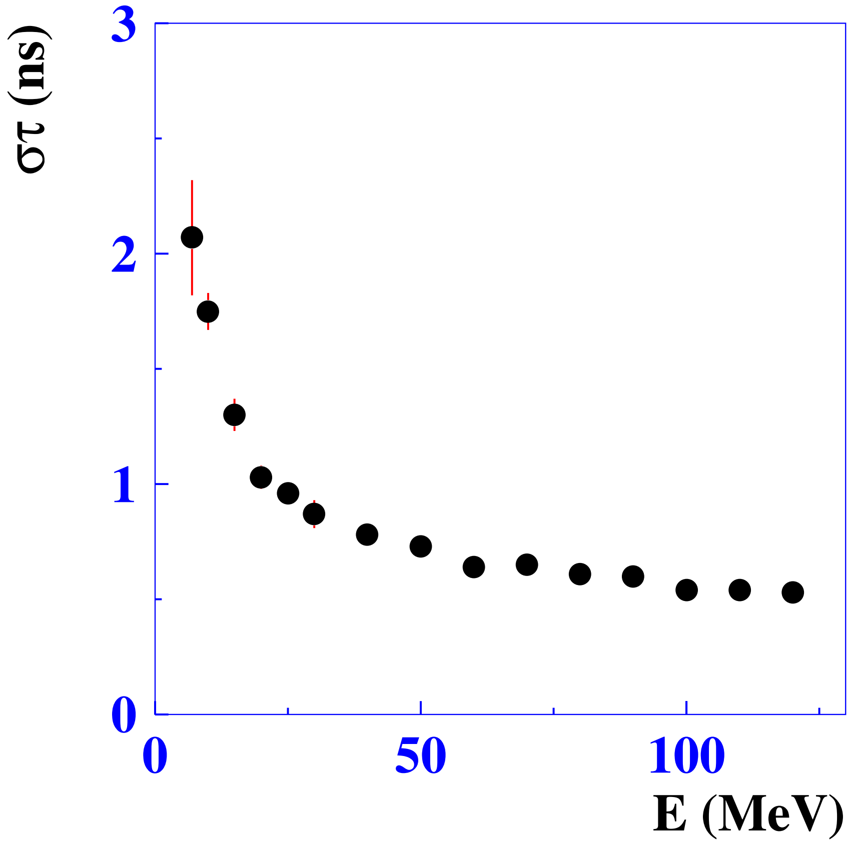


3 GeV γ Signal

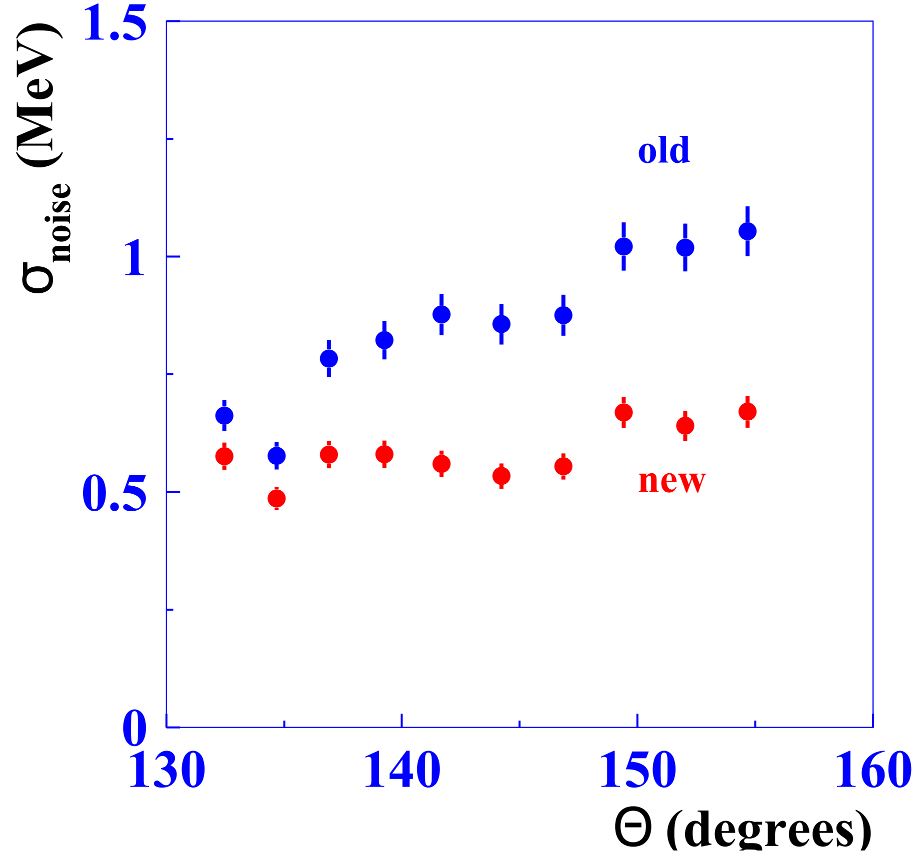
Belle II ECL performances (TB)



energy resolution

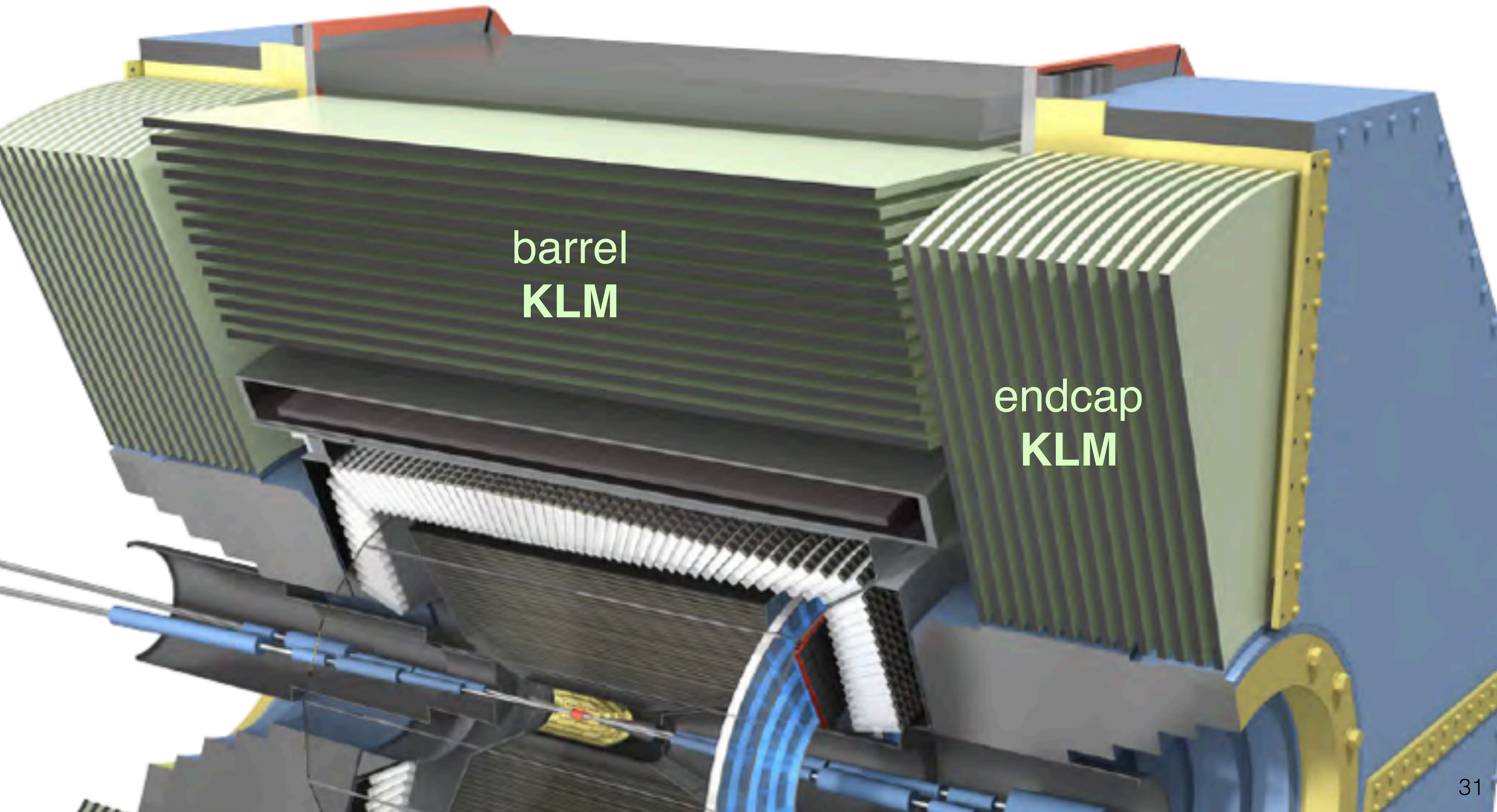


timing resolution



pile-up noise suppression
w/ new electronics

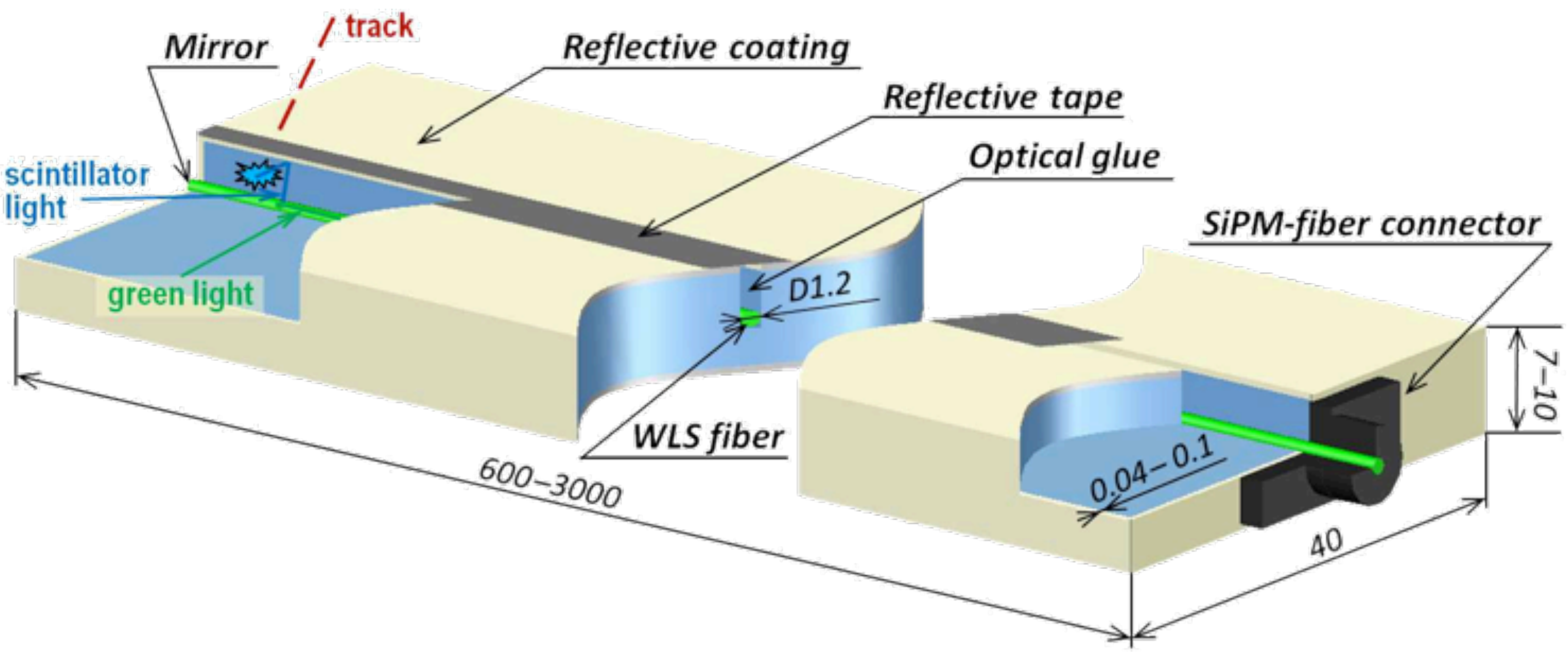
Challenges & responses: KLM

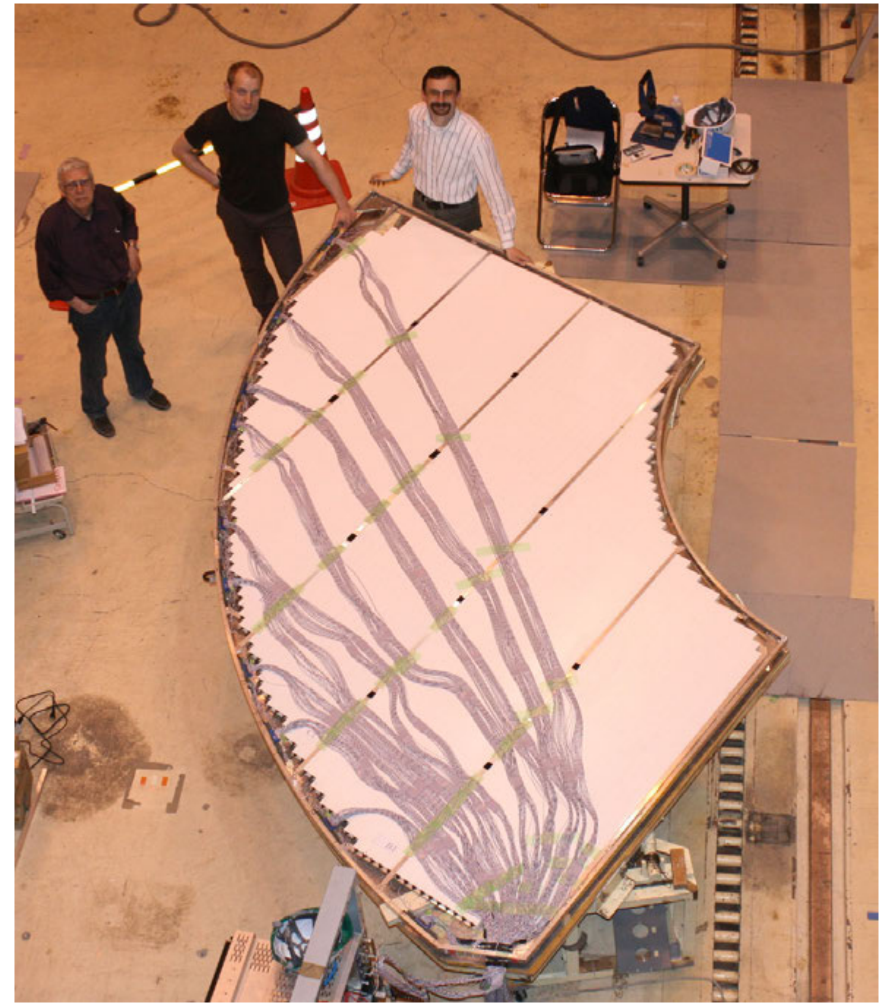


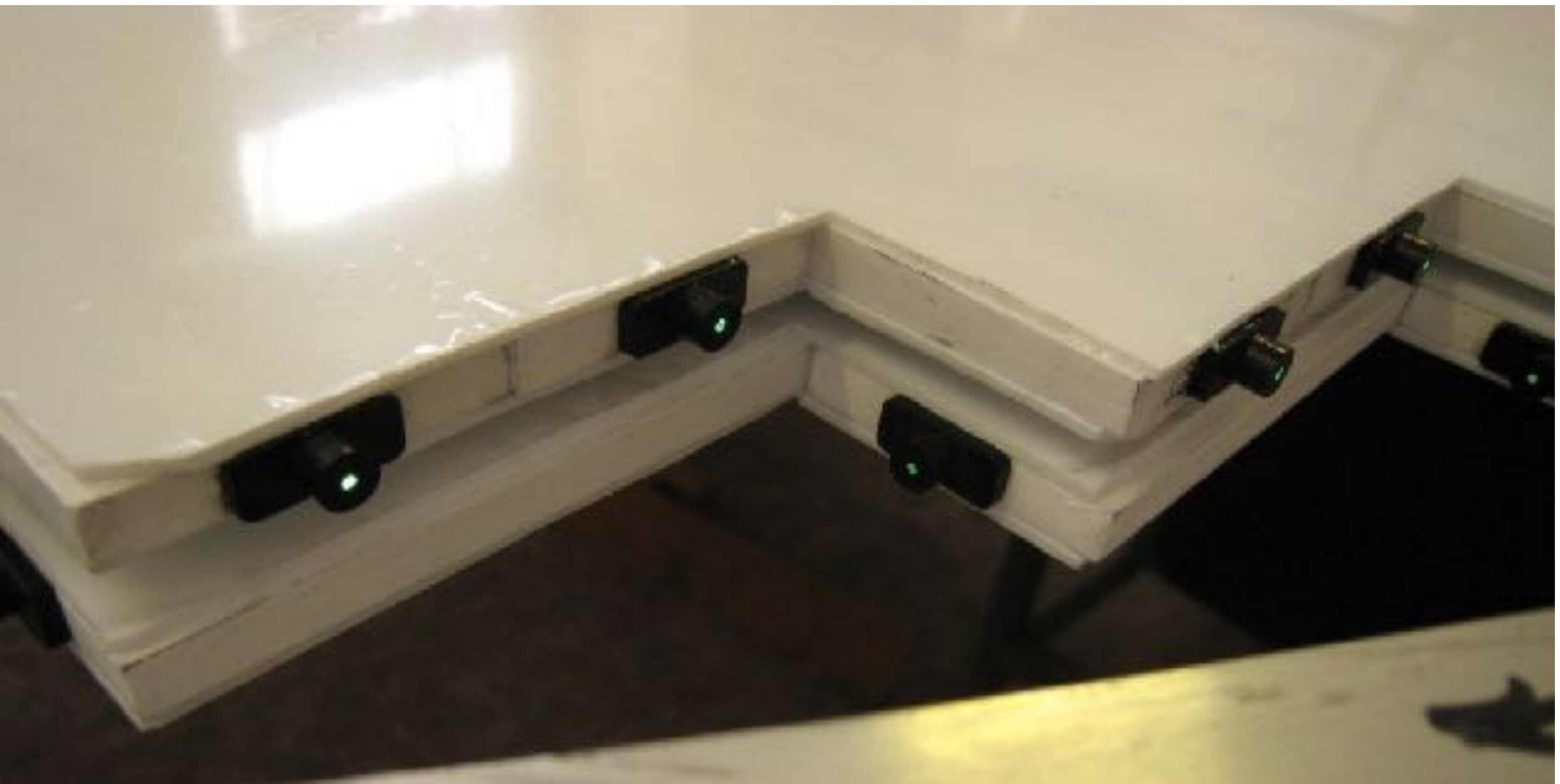
Challenges & responses: KLM

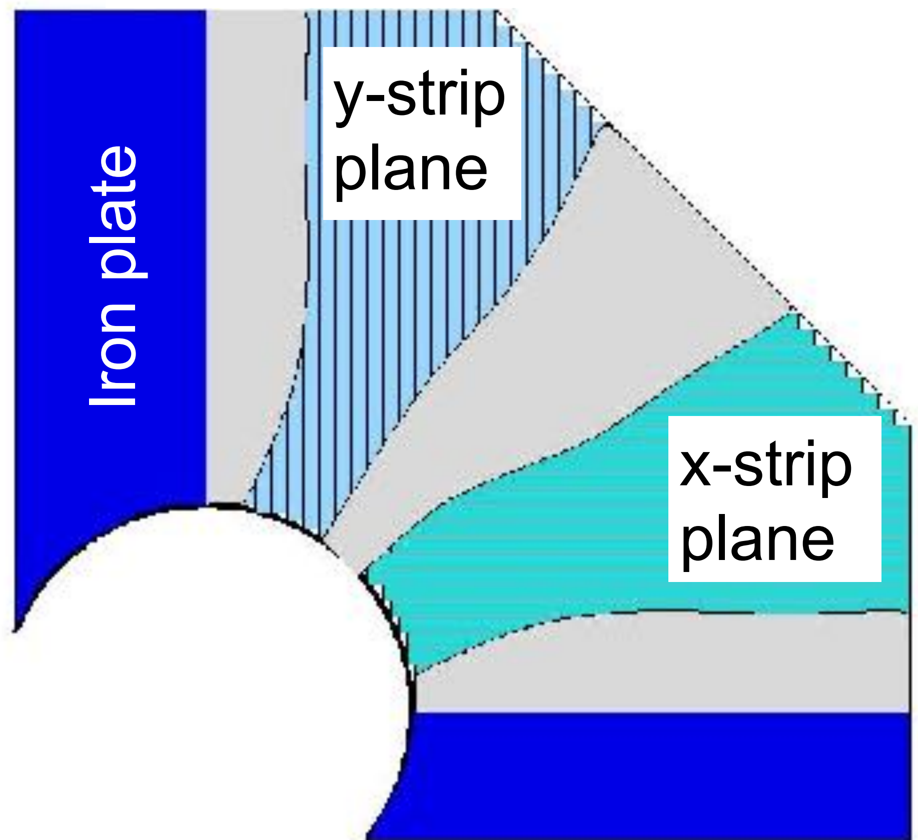
- KLM is essential for $\mu^{\pm}$ detection
  - hence indispensable for τ LFV ($\tau^{\pm} \to \mu^{\pm}\gamma,\ \ell^{\pm}\ell^{+}\ell^{-}$ etc.)
- Belle KLM
  - alternating layers of iron plates (partly for flux return) and RPC
- Belle II KLM
  - Belle's RPC system cannot handle high background rates
  - all RPC's in endcaps and 2 innermost barrel layers are replaced with scintillators
  - readout electronic under production (will be ready by summer 2017)

Scintillator-KLM (Belle II)



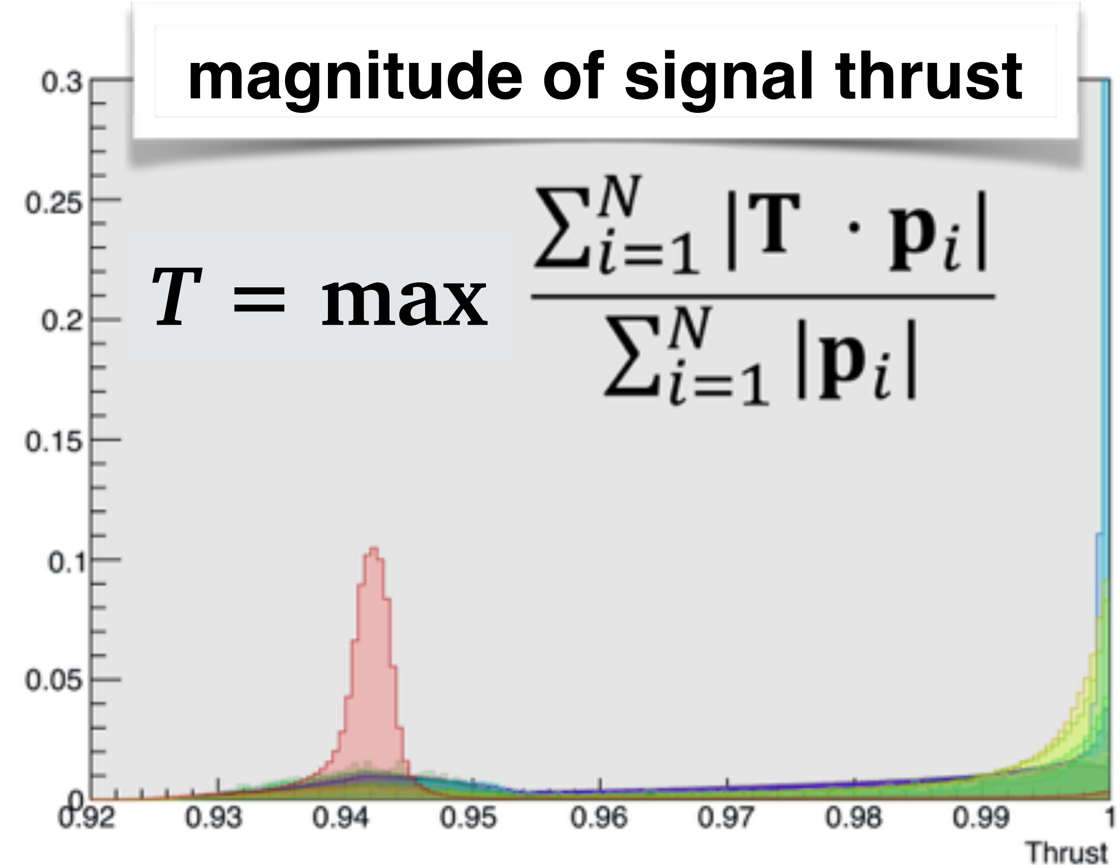


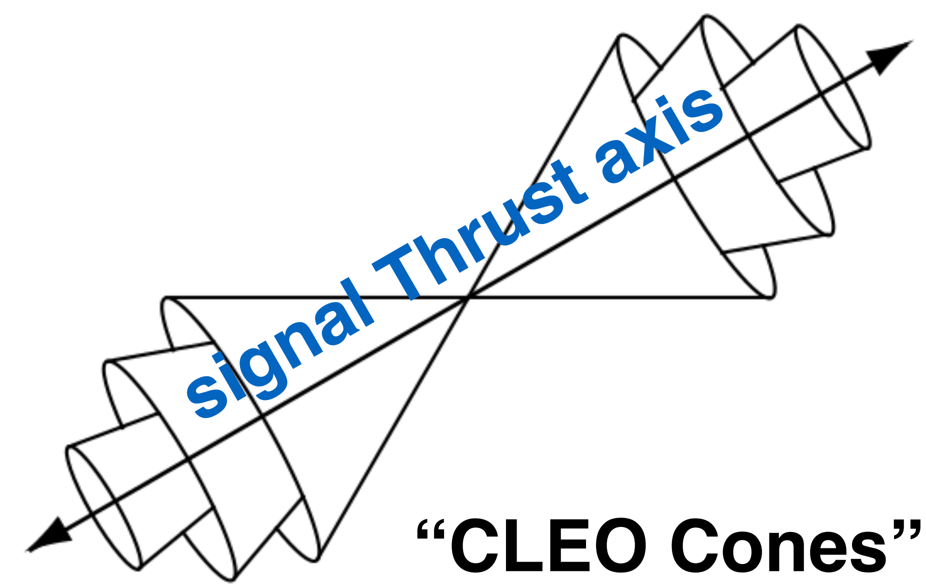




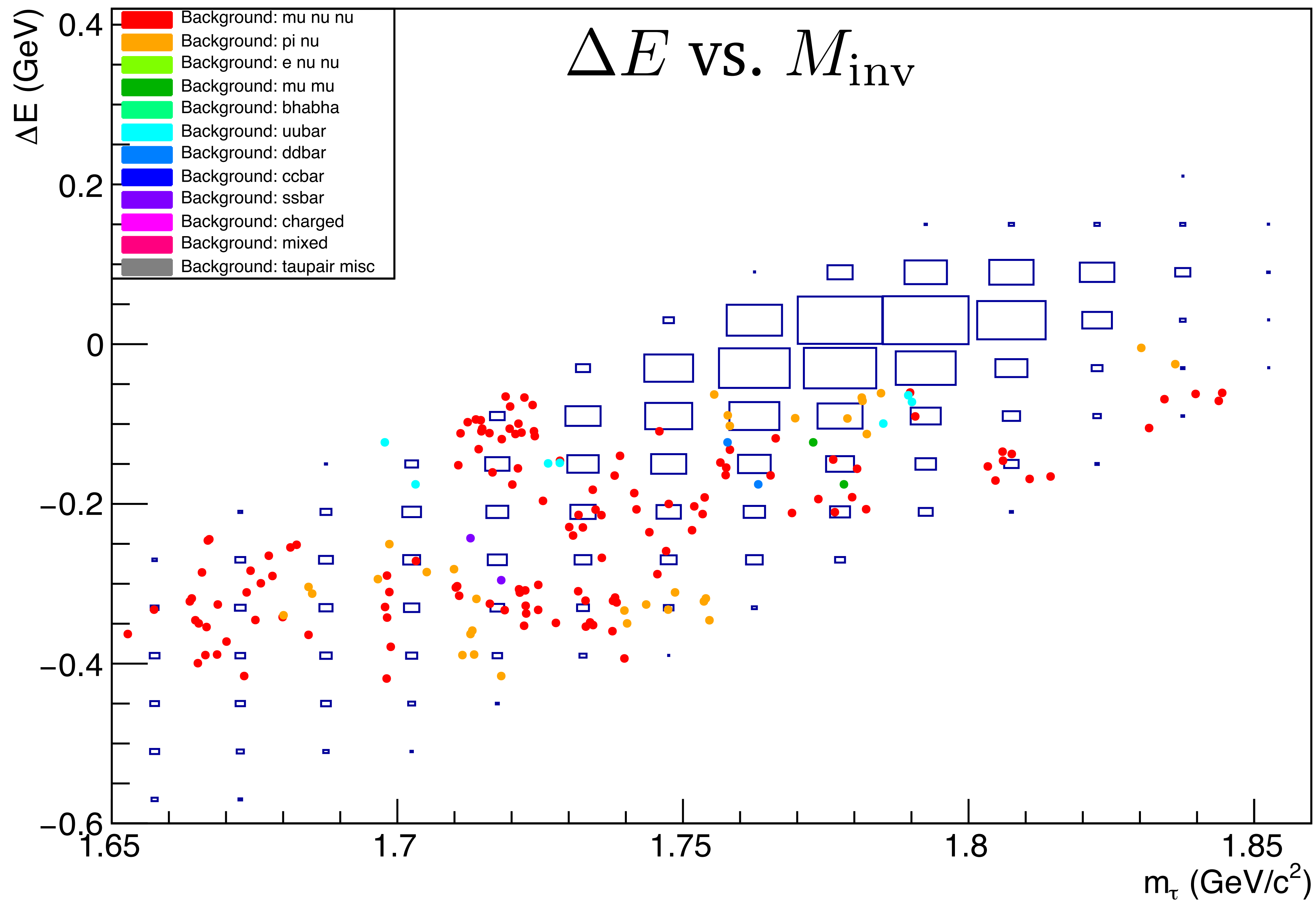
$\tau \to \mu\gamma$ in Belle II (MC study)

- sensitivity study using Belle II MC incl. beam background simulation
  - MS thesis work by B. Moore (U. Melbourne)
  - for sensitivity comparison with Belle (with $\int \mathcal{L} dt = 1\ \mathrm{ab}^{-1}$)
- Background rejection by
  - event shape variables — thrust, Fox-Wolfram moments, momentum flow distributions ("CLEO cones"), etc.
- Signal extraction by (ΔE, M_{inv})

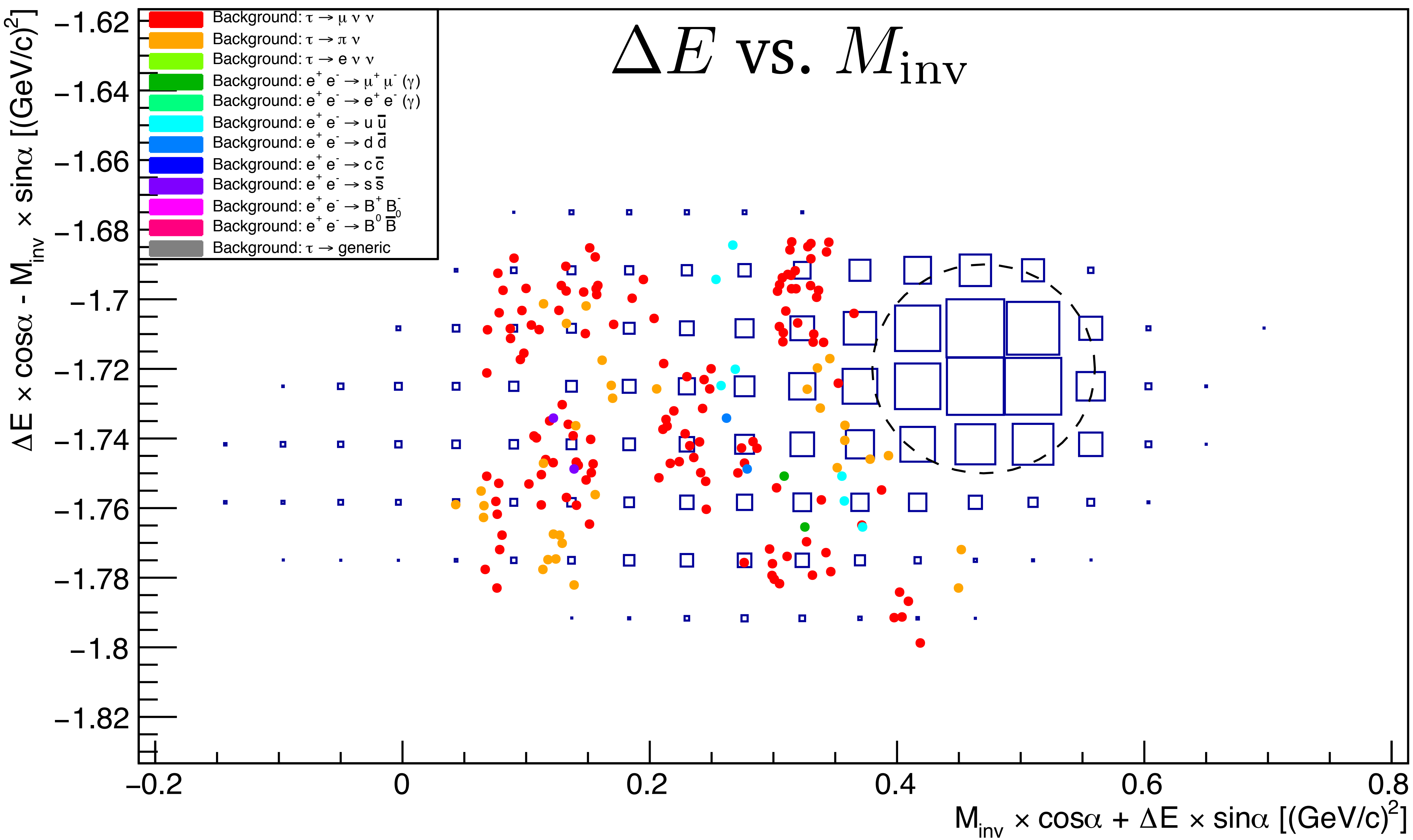




$\tau \rightarrow \mu\gamma$ in Belle II (MC study)



τ → μγ in Belle II (MC study)



- rotating $(M_{\rm inv}, \Delta E)$ to minimize correlation
- $\varepsilon_{\rm sig} = 4.59\%$ with zero background

$\tau \rightarrow \mu\gamma$ sensitivity (Belle vs. Belle II)

	Belle (535 fb^{-1})	Belle II (1 ab^{-1})
$\mathcal{L}$ (cm^2/s)	2.11×10^{34}	80×10^{34}
ε_{signal}	5.09%	4.59%
n_{BG}	10	-
$B_{90}(\tau \rightarrow \mu\gamma)$	**4.5×10^{-8}**	**2.7×10^{-8}**

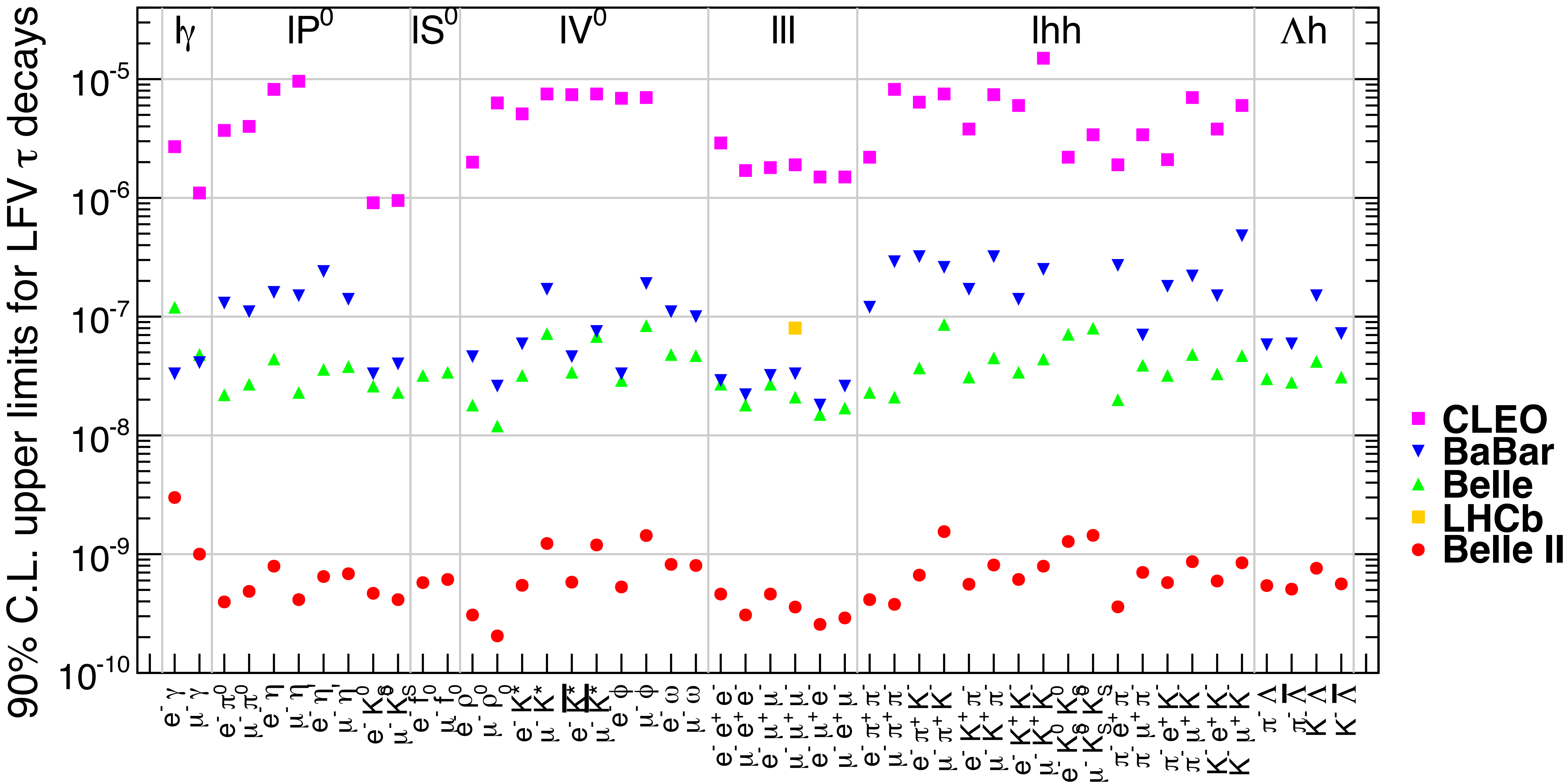
→

Belle II (50 ab^{-1})
5.5×10^{-10}

a naive extrapolation by luminosity

- First τ LFV sensitivity study at Belle II
  - even with much higher beam background, the sensitivity is comparable to that of Belle (scaled by luminosity)
  - signal region is background-free

τ LFV summary & prospects



HFAG summary plot for τ LFV decays,
overlaid with Belle II extrapolation to 50 ab^{-1} assuming zero background

Other related subjects in Belle II

- LFUV involving B decays to τ
  - $R(D), R(D^*)$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- LFUV, LFV involving EW penguin *B* decays
  - $R(K), R(K^*)$ for LFUV
  - $B \to K^{(*)}\ell^{\pm}\tau^{\mp},\ K^{(*)}e^{\pm}\mu^{\mp}$, etc. for LFV

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- With 50 times increase of data and detector improvement, these too will provide exciting opportunities for Belle II

Belle II milestones

- Phase 1 (Feb. 2016): beam commissioning + beam background measurements
  - ✓ circulate beams; no collision
  - ✓ BEAST II (in place of Belle II) as a commissioning detector
- Recent highlights
  - ✓ Final Quads installed in Feb. 2017
  - ✓ Belle II roll-in on Apr. 11, 2017
- Phase 2 (Dec. 2017): Detector in place without SVD + PXD
  - ✓ *Dark-sector search can start!*
- Phase 3 (Nov. 2018): Start physics run with full Belle II detector

Closing remarks

- Belle, being an e^+e^- B-factory experiment, is a τ-factory experiment at the same time.
- With nearly 1 billion $\tau^+\tau^-$ sample, Belle has obtained most stringent upper limits in most of the τ LFV, LNV and BNV decays, with 90% UL of $O(10^{-8})$.
- With ~50 billion $\tau^+\tau^-$ events expected in the upgraded Belle II experiment, these searches will be greatly improved.
- For very clean modes (e.g. $\tau^+ \to \ell^+\ell^-\ell^+$), the upper limit is expected to improve linearly with luminosity. And it will be a very powerful probe for new physics beyond the SM.