Charged Lepton Flavor Violation & Lepton/Baryon Number Violation at Belle II

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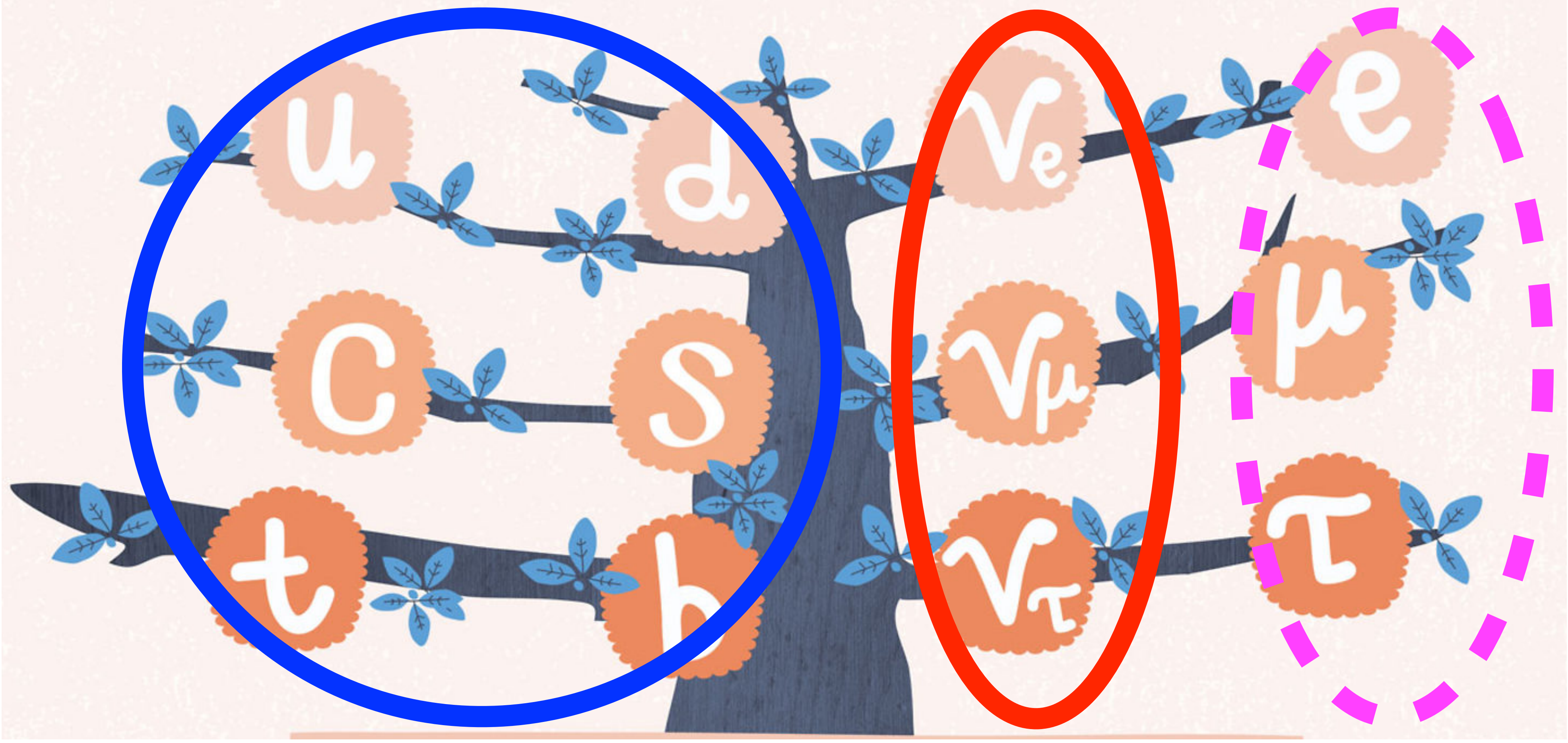
On behalf of the Belle II Collaboration

Snowmass - cLFV tau workshop
23 July 2020

3 generations of matter

Quark-mixing:

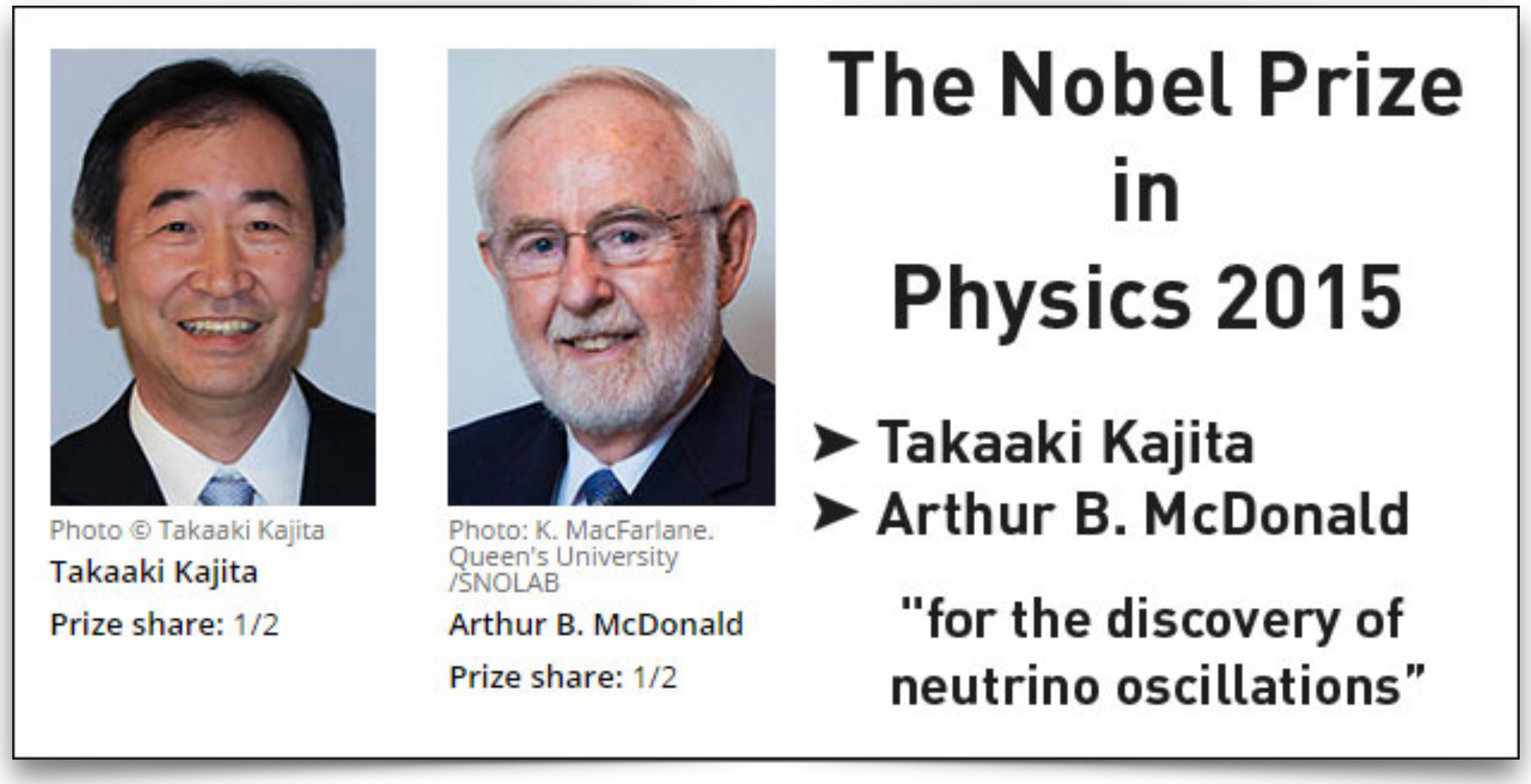
The Nobel Prize in Physics 2008



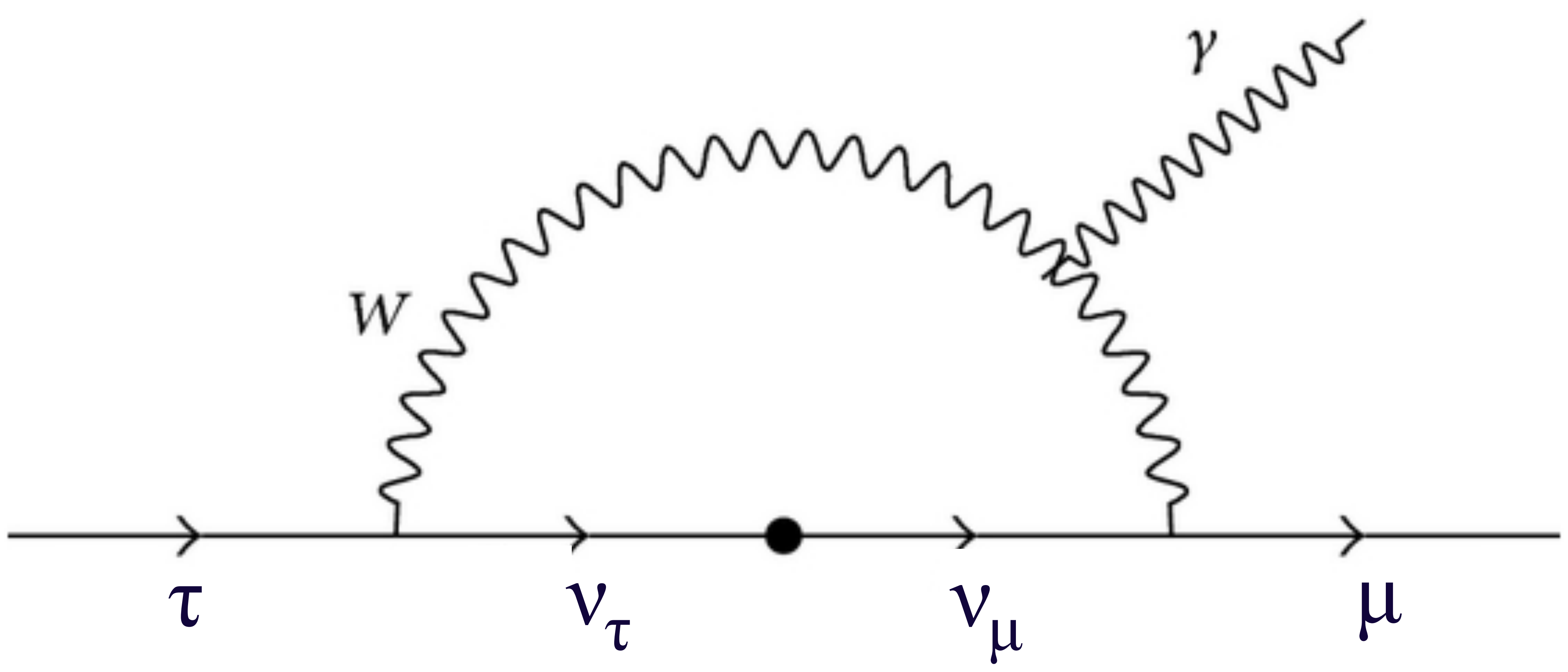
Lepton number violation (LNV) / Charged lepton flavor violation (LFV):

?

Neutrino-oscillations:



cLFV/LNV/BNV



$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma)$ [Lee-Shrock, Phys. Rev. D **16**, 1444 (1977)]

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

many orders below experimental sensitivity!

cLFV/LNV/BNV is NOT forbidden by any continuous symmetry

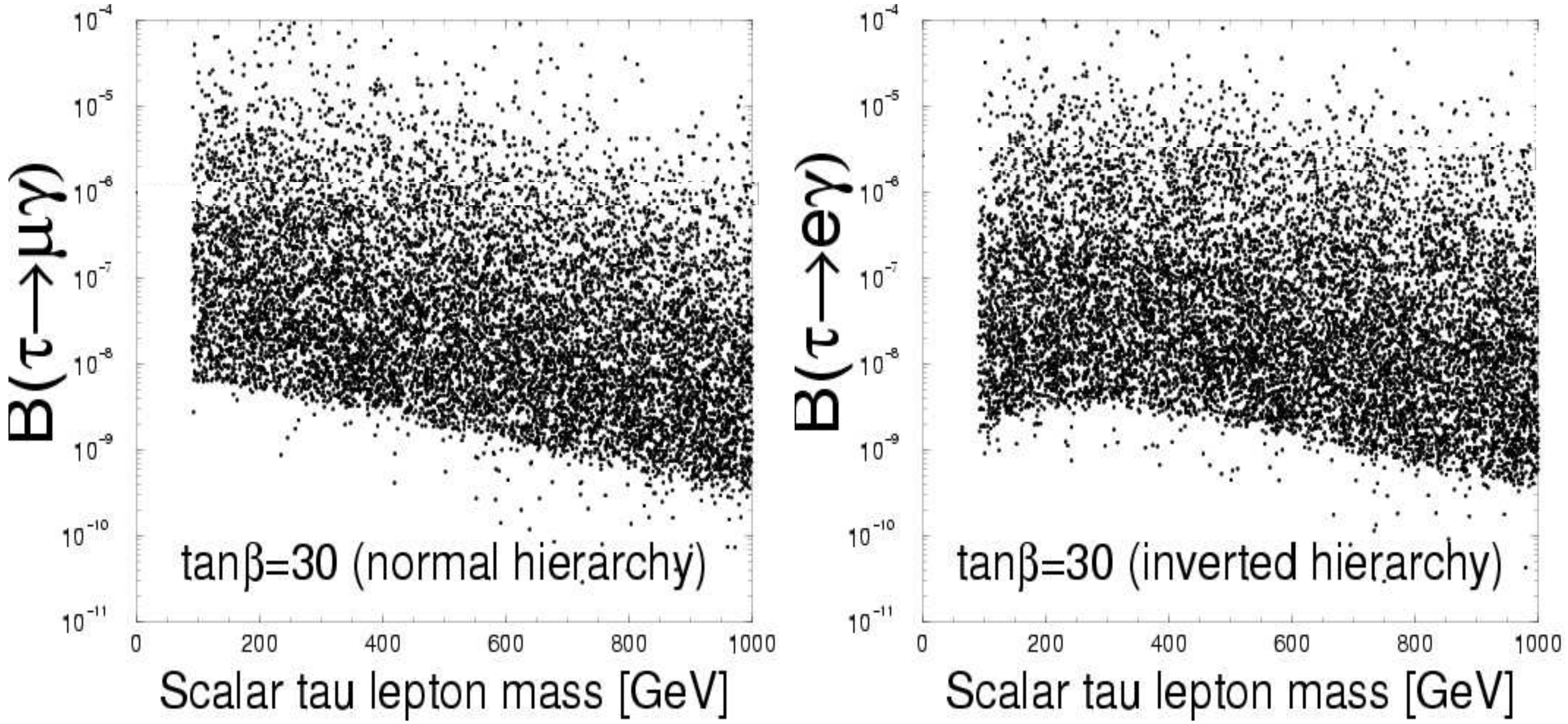
$\Rightarrow$ most New Physics (NP) models naturally include such processes

Any observation of cLFV/LNV/BNV

$\Rightarrow$ unambiguous signature of NP

NP predictions

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons
- Some models predict LFV up to existing experimental bounds
- eg. SUSY models: non-diagonal slepton mass matrix $\Rightarrow \mathrm{LFV}$
- Normal (Inverted) hierarchy for slepton $\Rightarrow \tau \to \mu\gamma$ ($\tau \to e\gamma$)



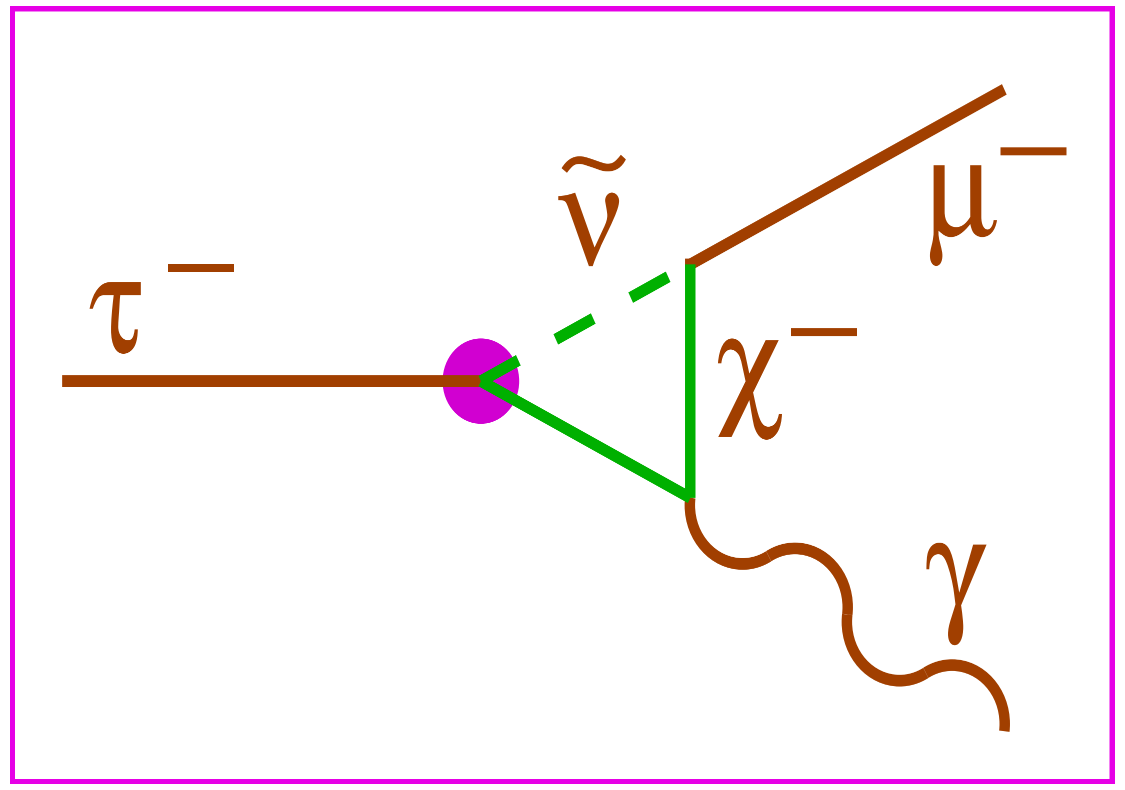
(J. Ellis, J. Hisano, M. Raidal and Y. Shimizu, Phys. Rev. D **66** (2002) 115013)

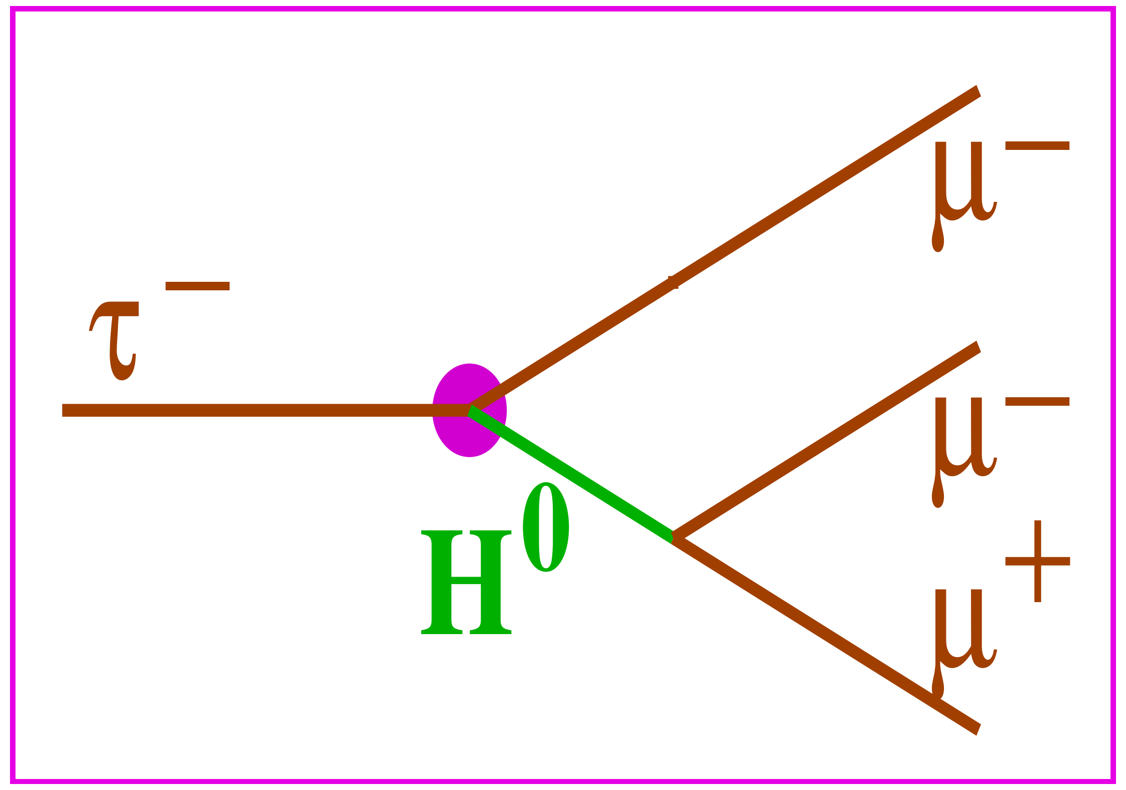
NP predictions

- Neutrinoless 2 and 3 body τ decays have different sensitivity

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
Non-Universal Z' (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}

Illustrative scenarios ...





☞ Search for $\tau \to \ell\gamma/P^0$, $\tau \to \ell\ell\ell$, $\tau \to \ell hh'$ decays $(\ell = e, \mu; h = \pi, K)$

Probing NP at electron-positron colliders

- **Lepton flavor violation (charge conjugate modes implied)**
  - **$\tau \to e/\mu\ \gamma$ (BaBar, Belle)**
  - **$\tau \to e/\mu$ (scalar/pseudoscalar/vector mesons) (BaBar, Belle)**
  - **$\tau \to e\ e\ e$ (BaBar, Belle)**
  - **$\tau \to \mu\ \mu\ \mu$ (BaBar, Belle)**
  - **$\tau \to e\ \mu\ \mu$, $\mu\ e\ e$ (BaBar, Belle)**
  - **$\tau \to e/\mu\ h\ h$ (non-resonant final states with $h=\pi/K$) (BaBar, Belle)**

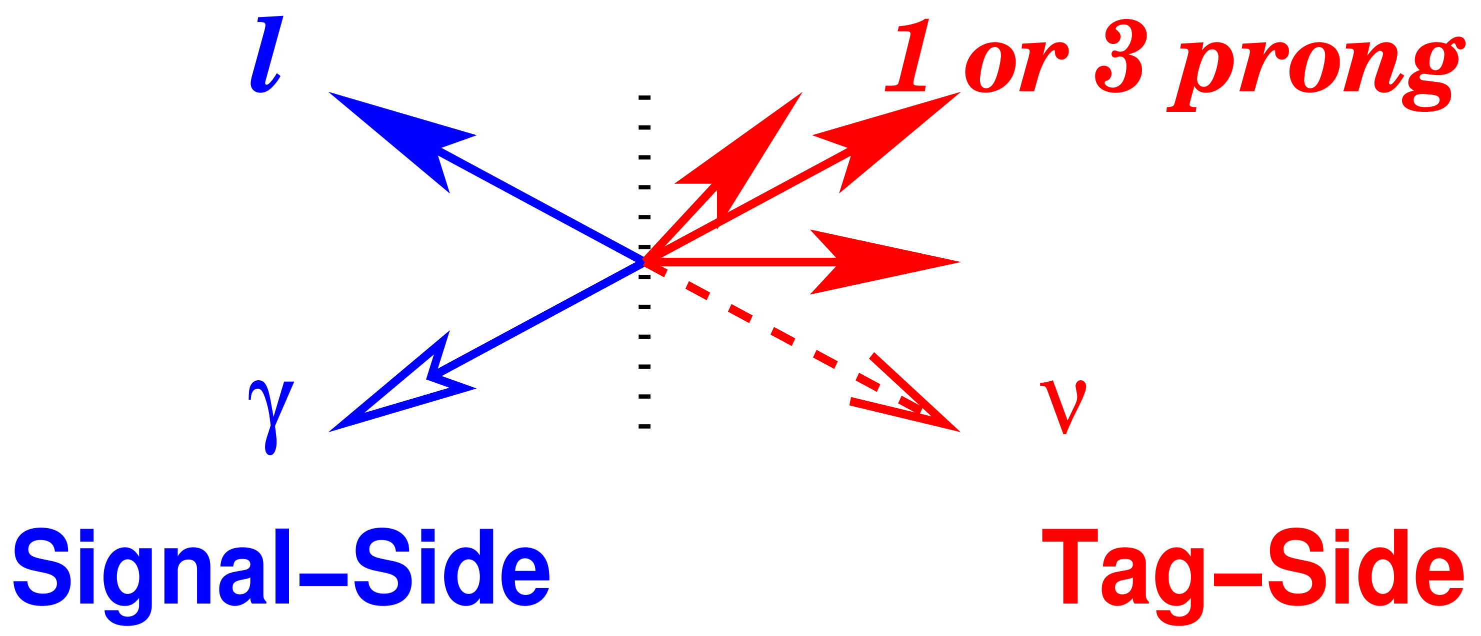
- **Lepton number violation**
  - **$\tau^- \to e^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (BaBar, Belle)**
  - **$\tau^- \to \mu^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (BaBar, Belle)**

- **Baryon number violation**
  - **$\tau^- \to \Lambda\ \pi^-$, $\bar{\Lambda}\ \pi^-$ (Belle)**
  - **$\tau^- \to \bar{p}\ \gamma/\pi/\eta$ (CLEO)**

Electron-positron colliders

- Known initial conditions (beam energy constraint)
- Clean environment (less backgrounds)

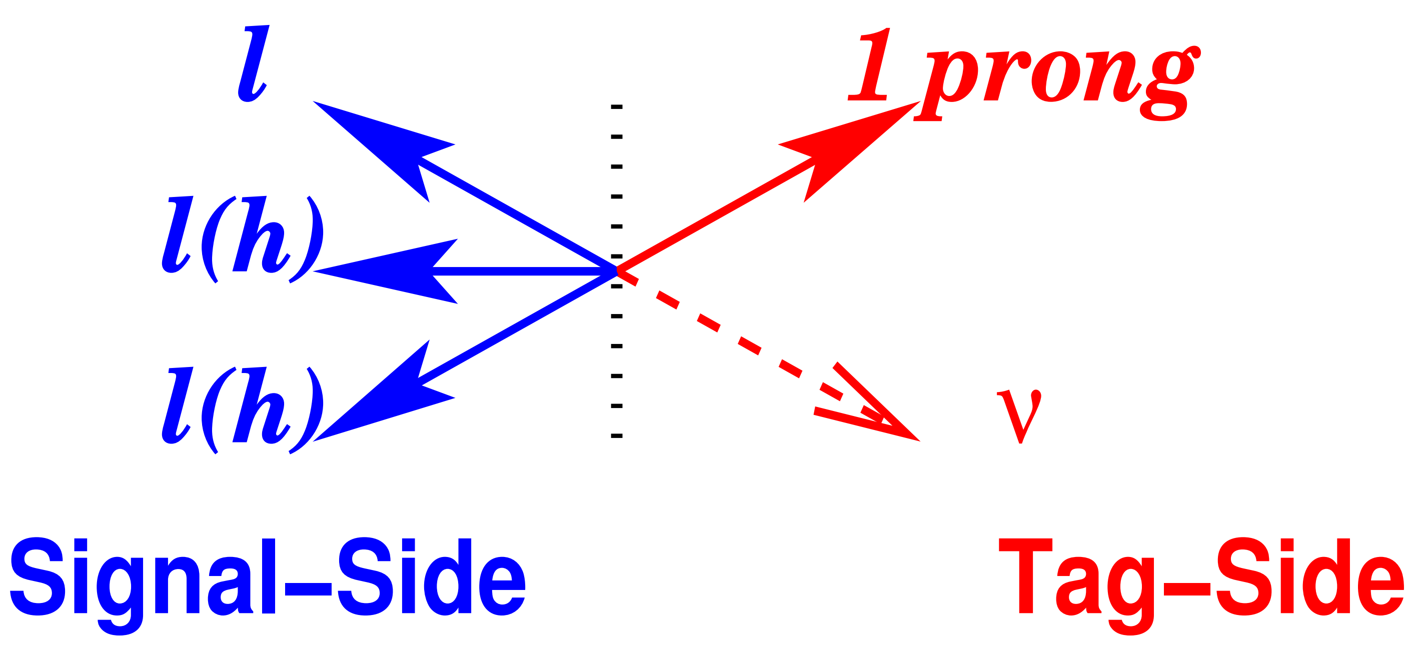
$\boxed{\tau \to \ell\gamma}$



Backgrounds:

- $\tau \to e\gamma$ $(\tau \to \mu\gamma)$:
  - Radiative Bhabha (di-muon)
  - $\tau^+\tau^-\gamma(\tau \to \ell\nu\overline{\nu})$
  - $q\overline{q}$ (γ)

$\boxed{\tau \to \ell\ell\ell\ (\tau \to \ell h h')}$



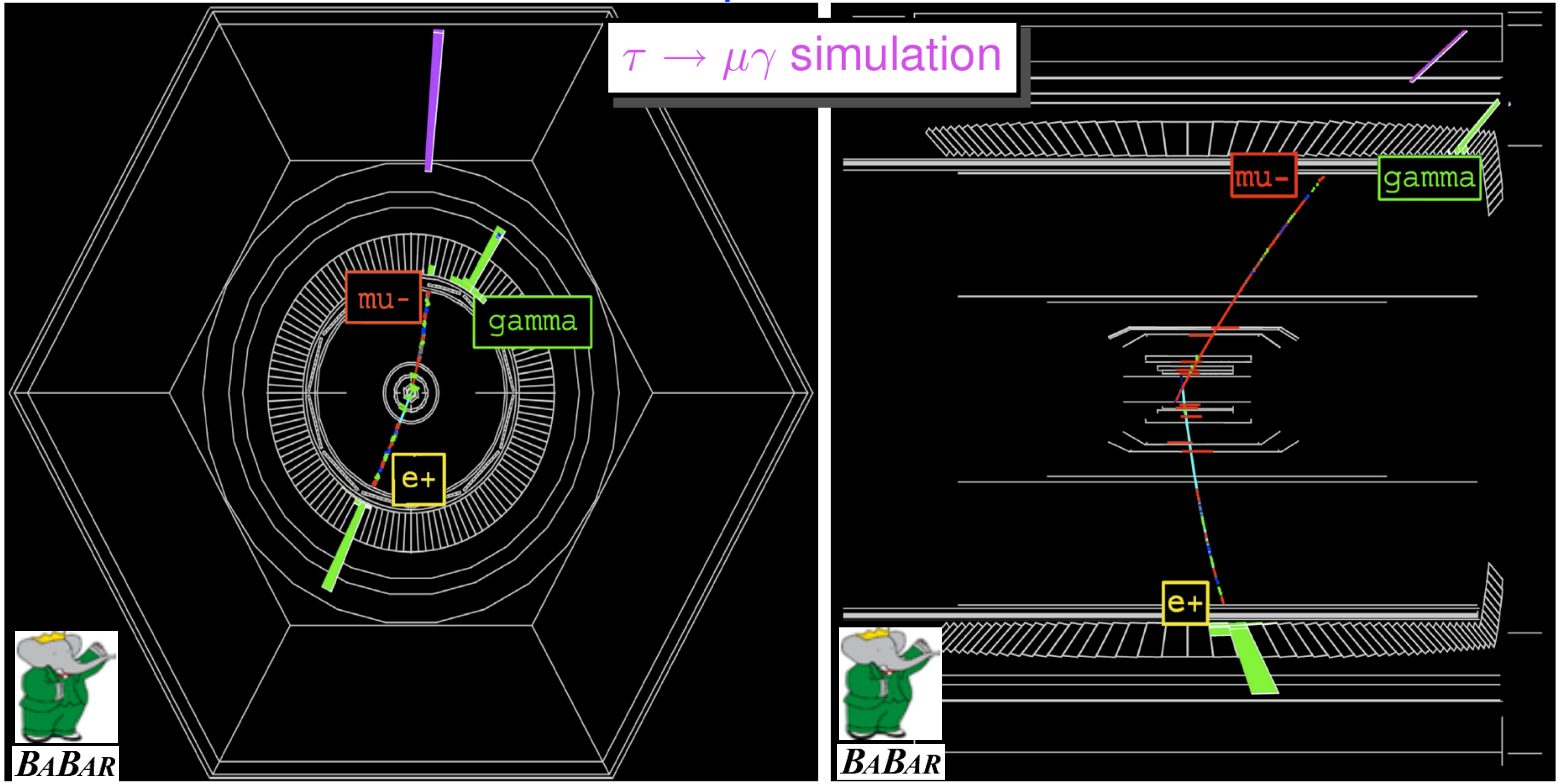
Backgrounds:

- $\tau^- \to \ell'^-\ell^+\ell^-$:
  - Bhabha, di-muon
- $\tau^- \to \ell^+\ell'^-\ell'^-$, $\tau \to \ell h h'$:
  - $\tau^+\tau^-$, $q\overline{q}$

# of ν(s) in Signal-side	Signal: 0	$\tau^+\tau^-$: 1-2	Bhabha, di-muon, $q\overline{q}$: 0
# of ν(s) in Tag-side	Signal: 1-2	$\tau^+\tau^-$: 1-2	Bhabha, di-muon, $q\overline{q}$: 0

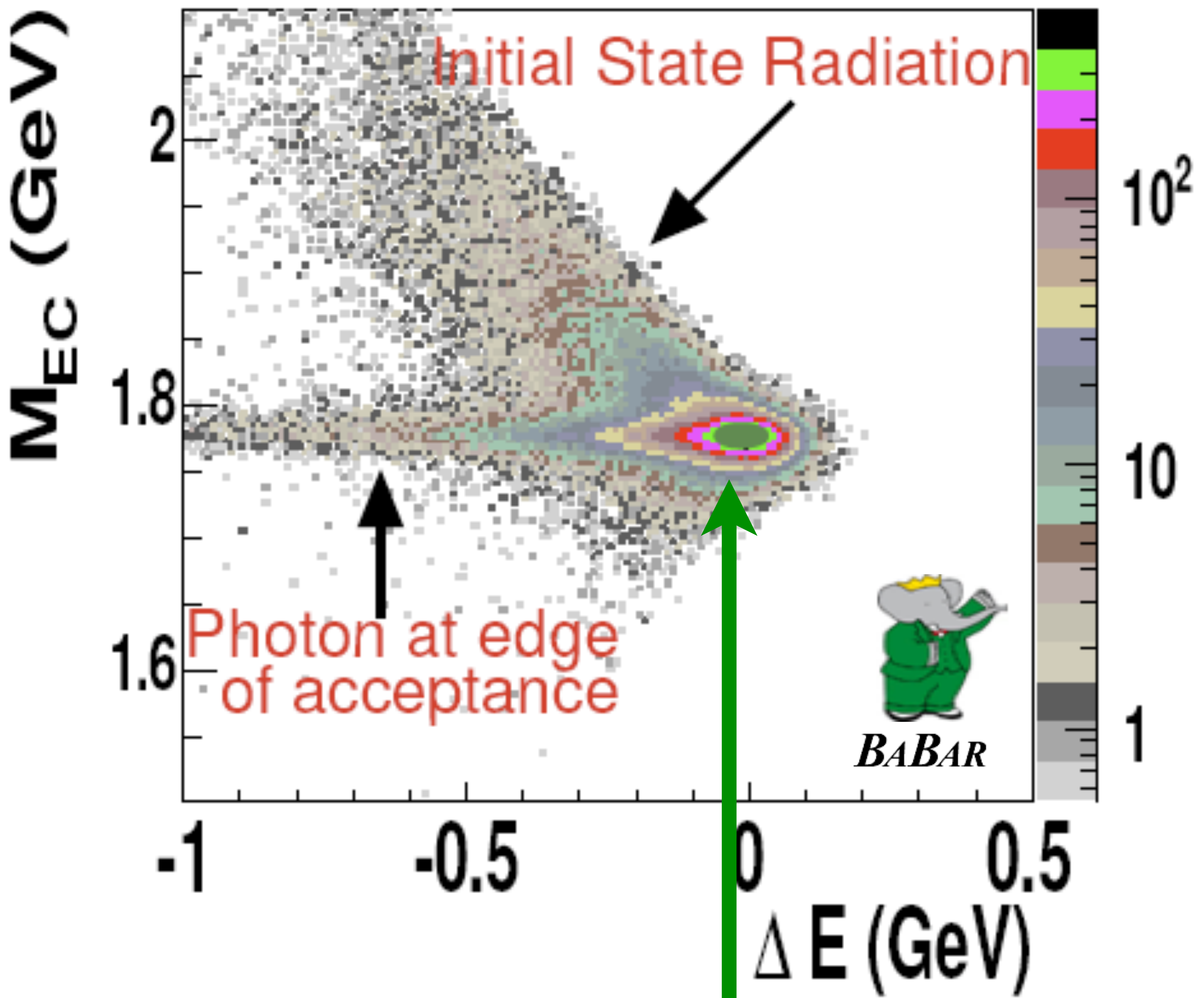
τ → μ γ : signal characteristics in e⁺e⁻ colliders

- $m_{\mu\gamma} \sim m_\tau$
- CM Frame: $\Delta E = \sqrt{P_\mu^2 + m_\mu^2} + E_\gamma - \sqrt{s}/2 \sim 0$



$\tau \to \mu\,\gamma$: signal characteristics in e^+e^- colliders

- (Energy, Mass)$_{\text{daughters}} \sim (\frac{\sqrt{s}}{2}, m_\tau)$ (upto resolution & radiation)



$\tau \to \mu\gamma$ simulation

$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$

$\sigma(\Delta E) \sim 40\,\text{MeV}$

M_{EC} ($\sigma \sim 9$ MeV)

Beam energy constrained mass after vertexing

γ at μ POCA(XY)

[Inv. mass: $\sigma \sim 24$ MeV]

☞ Signal Region: $\pm$ 2 σ around ($\langle\Delta E\rangle$, $\langle M_{EC}\rangle$)

$\tau \rightarrow \mu\, \gamma$: signal characteristics in e^+e^- colliders

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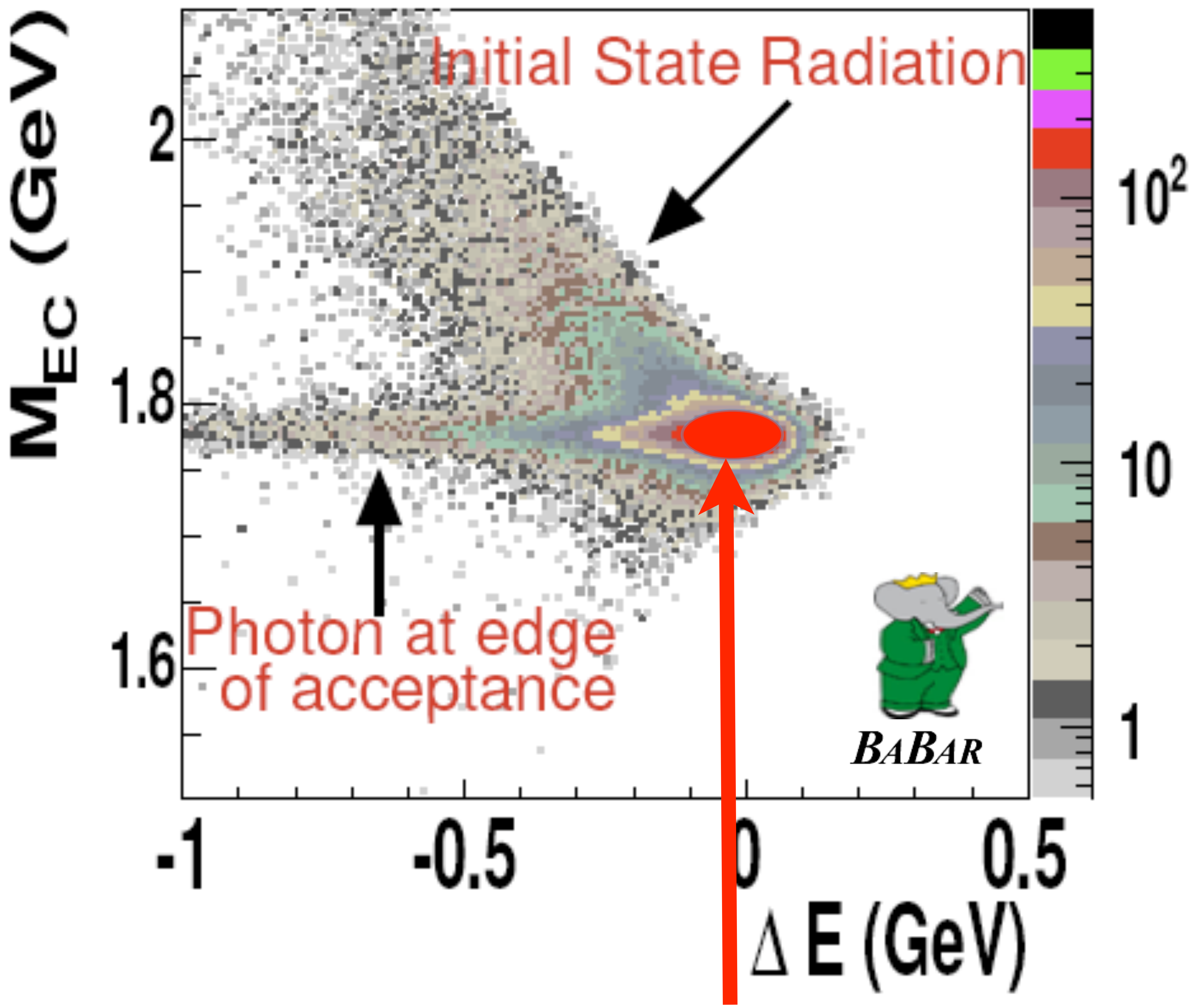

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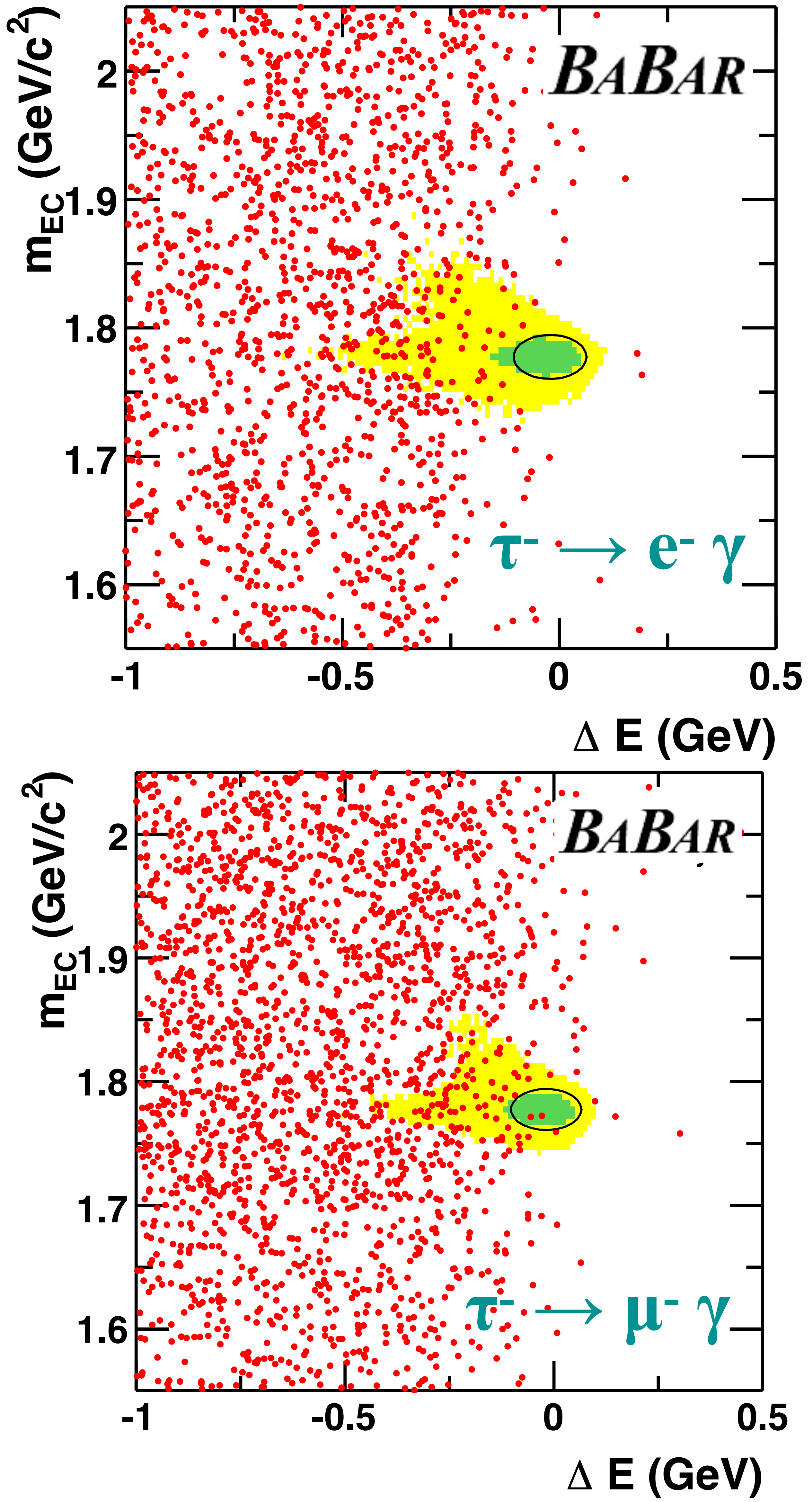
Beam energy constrained mass after vertexing

γ at μ POCA(XY)

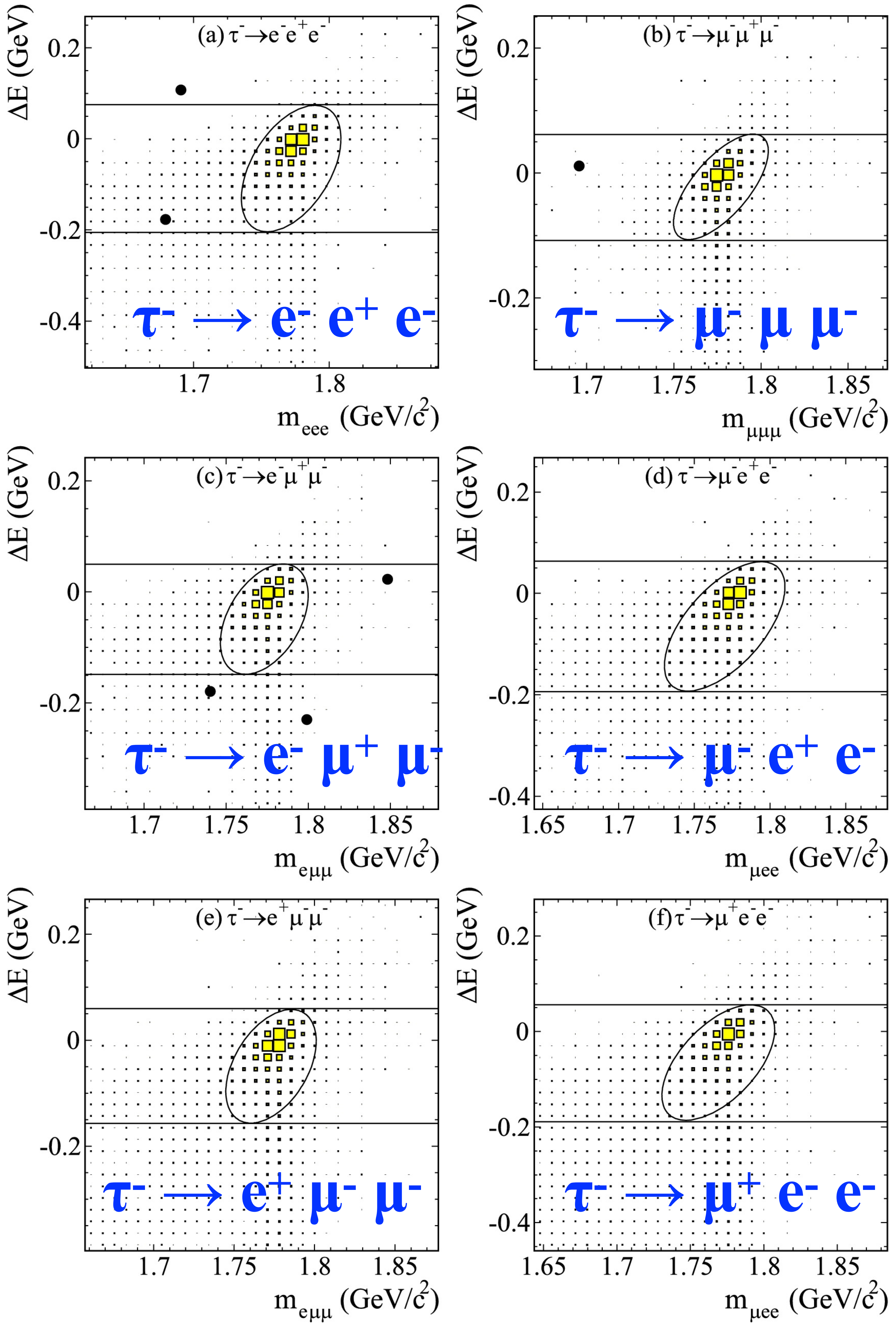
[Inv. mass: $\sigma \sim 24$ MeV]

☛ Blinded Region: $\pm\, 3\, \sigma$ around $(\langle \Delta E \rangle, \langle M_{EC} \rangle)$

$\tau \to \ell\gamma, \ell\ell\ell$: signal regions



Phys. Rev. Lett. 104 (2010) 021802



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Upper Limit

$$B_{\mathrm{UL}}^{90} = N_{\mathrm{UL}}^{90} / (N_\tau \times \varepsilon)$$

- ε: high statistics signal MC simulated for different Data-taking periods

ε =	Trigger	Reco	Topology	PID	Cuts	Signal–Box
	90%	70%	70%	50%	50%	50%

Cumulative:

90%	63%	44%	22%	11%	~5%

Decay modes	2σ signal ellipse obs	exp	ε (%)	UL ($\times 10^{-8}$) obs	exp
$\tau^\pm \to e^\pm\gamma$	0	1.6 ± 0.4	3.9 ± 0.3	3.3	9.8
$\tau^\pm \to \mu^\pm\gamma$	2	3.6 ± 0.7	6.1 ± 0.5	4.4	8.2

BABAR

Phys. Rev. Lett. 104 (2010) 021802

$N_\tau = 963$ M

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

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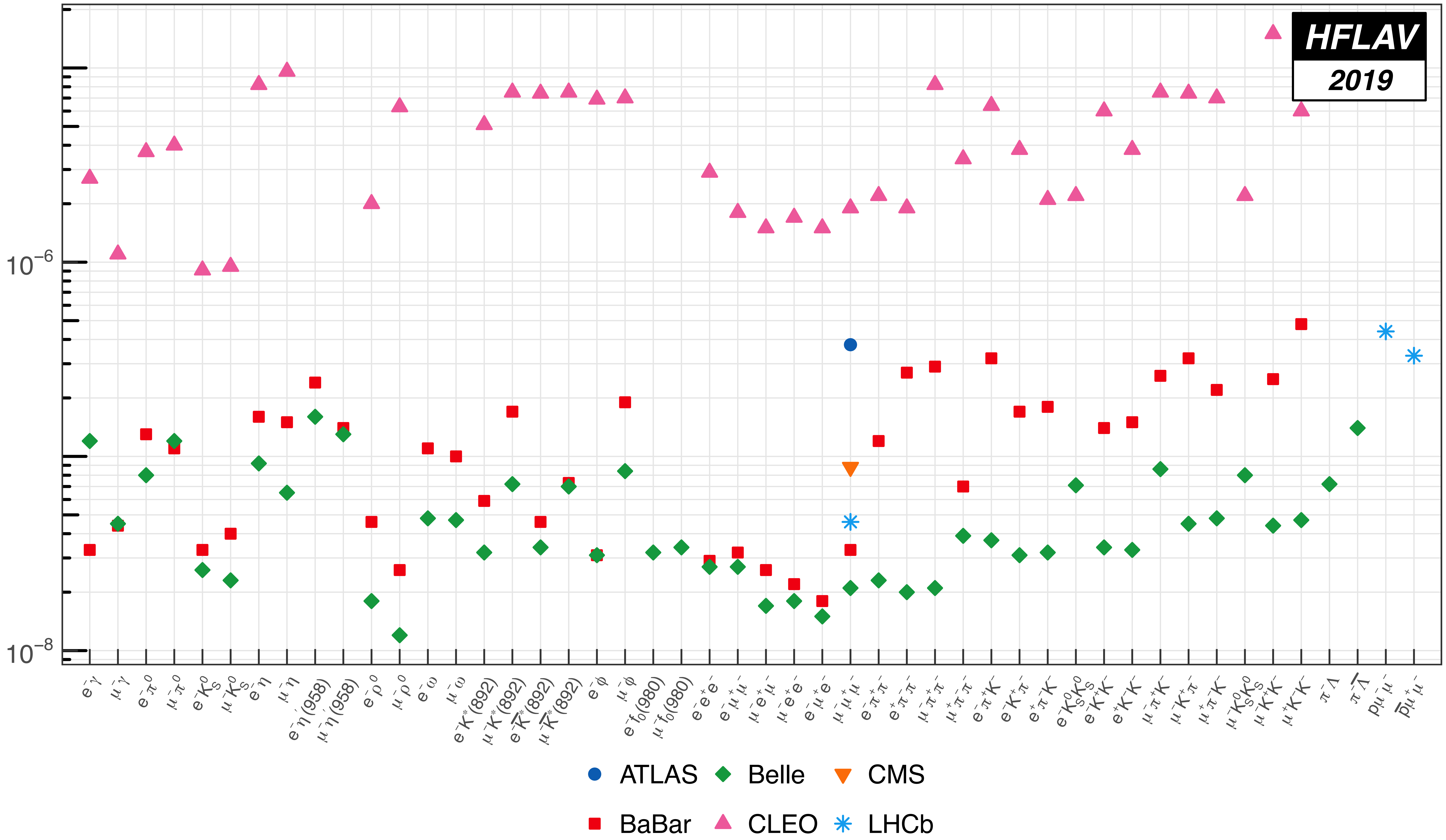
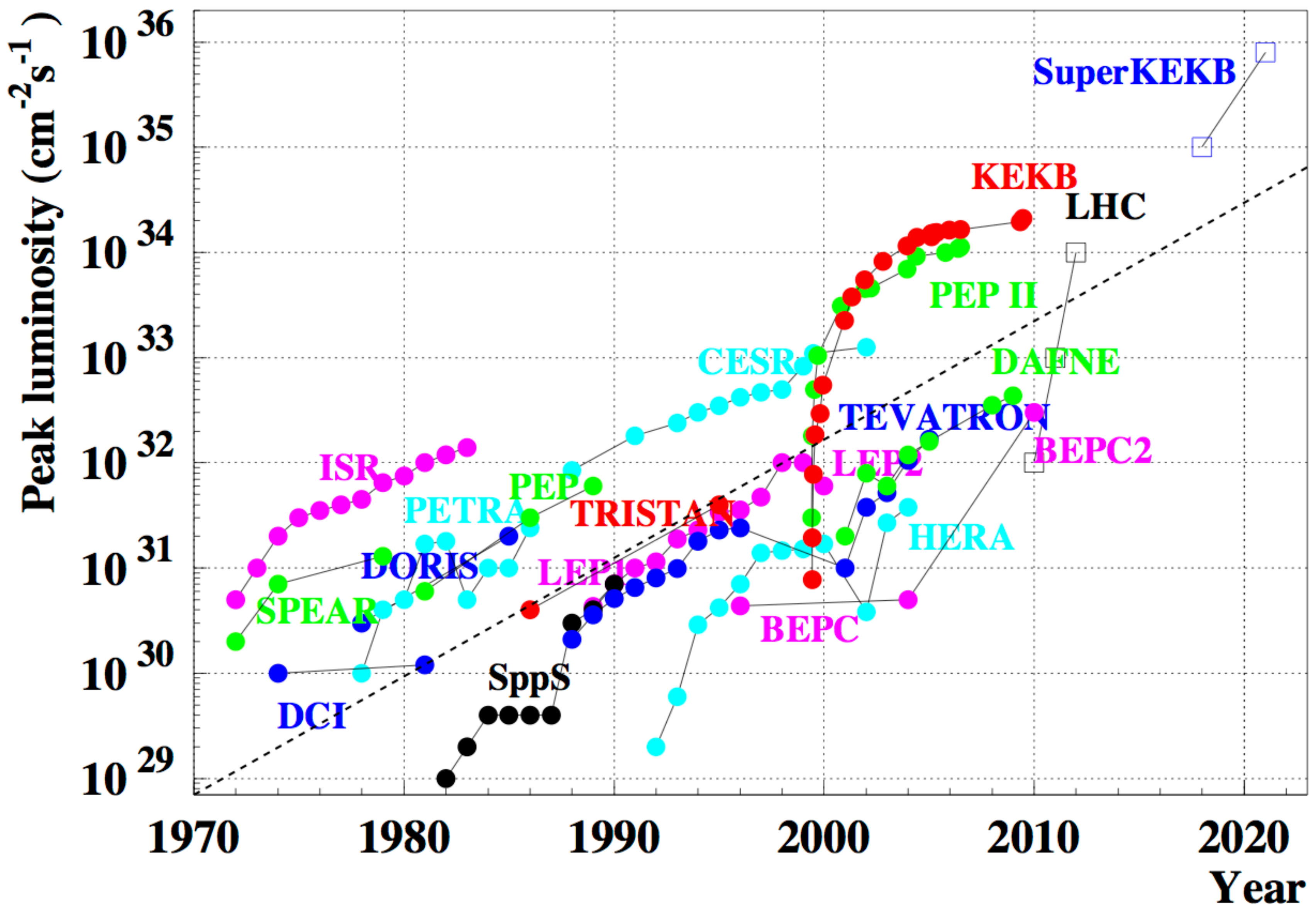
$N_\tau = 1438$ M

Summary of present limits

90% CL upper limits on τ LFV decays

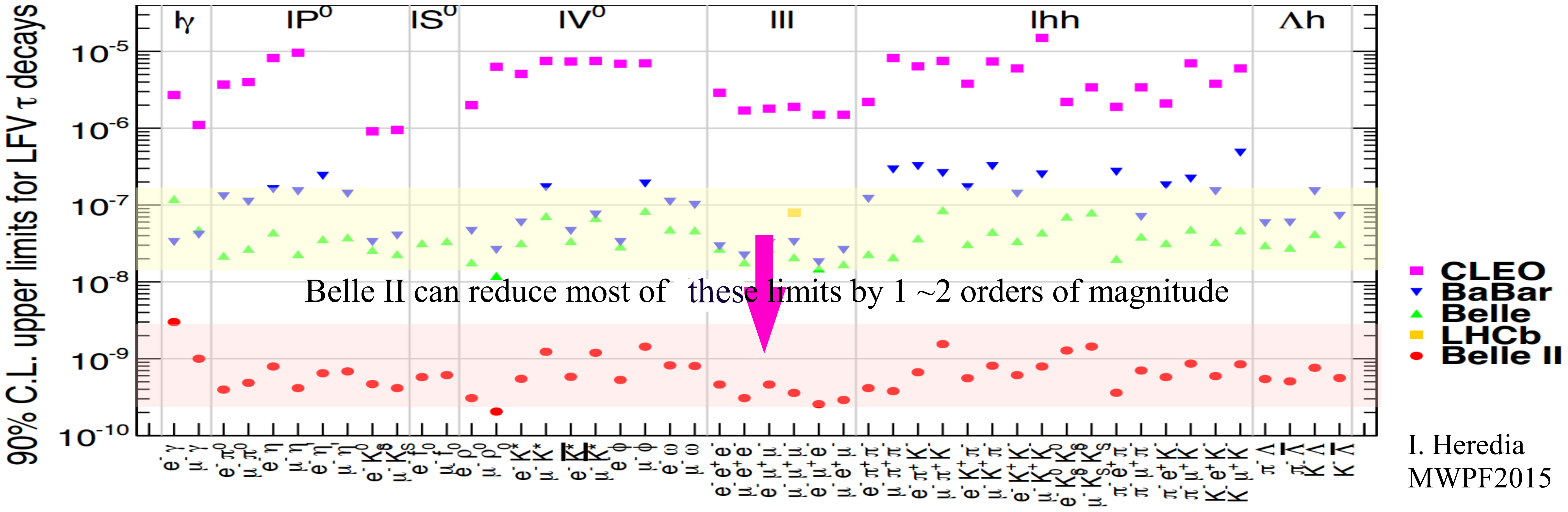


Future prospects at e^+e^- colliders



Cross Section at 10.58 GeV
$\sigma(\tau^+\tau^-)=(0.919\pm0.003)$nb

	Luminosity (L)	$N_\tau = 2L\sigma$
CLEO	14 fb^{-1}	$2*10^7$
BaBar	500 fb^{-1}	$1*10^9$
Belle	1 ab^{-1}	$2*10^9$
Belle II	50 ab^{-1}	$1*10^{11}$



I. Heredia
MWPF2015

Summary

- **Observation of LFV/LNV/BNV in the charged lepton sector would completely change our understanding of Nature and herald a new era of discovery in elementary particle physics.**
- **Now is a very interesting era in the searches for cLFV/LNV/BNV in decays of the tau lepton, as the current limits will improve by an order of magnitude in the next decade at the next generation Belle II experiment.**
- **Branching fractions up to few parts in 10^{-9} will be probed in neutrino-less 2-body and 3-body decays of the tau lepton.**
- **Colliders provide complementary information to cLFV/LNV/BNV searches at fixed target experiments, e.g. MEG, Mu2e, COMET, Mu3e, etc.**