Lepton Flavor Violation in τ decays

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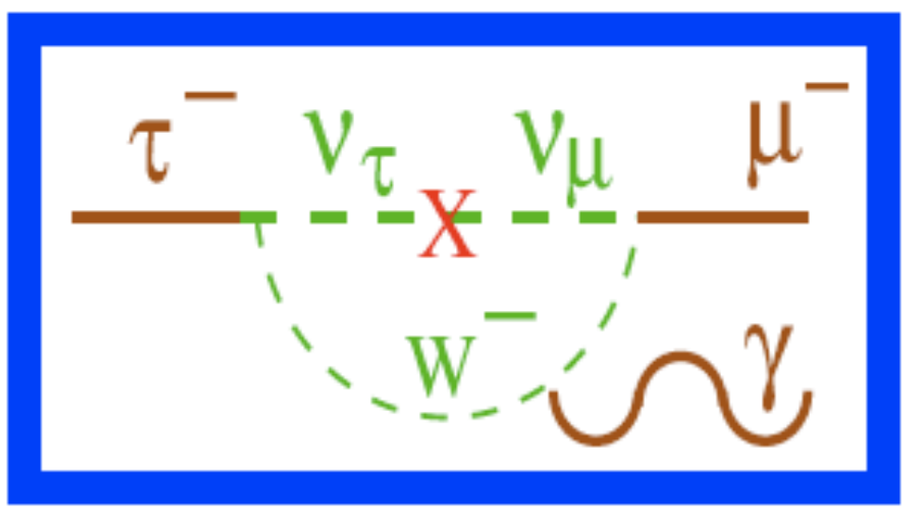
LFV in τ decays

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν's have finite mass
  $\Rightarrow$ Lepton Flavor is violated in Nature: but by how much?
- SM extended to include finite ν mass and mixing predicts LFV



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

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

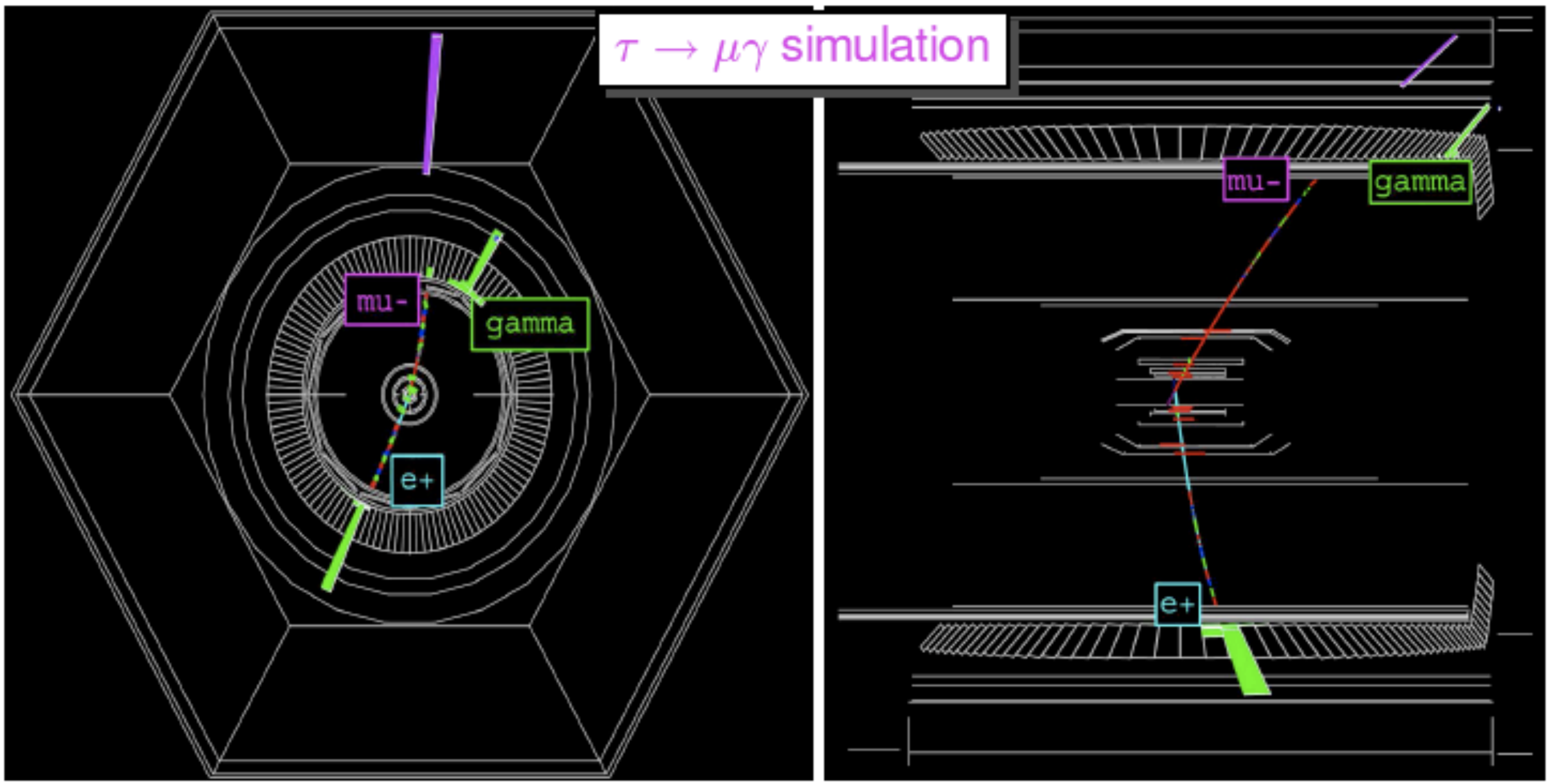
With $\Delta \sim 10^{-3}\,{\rm eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,{\rm eV}$

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

... many orders below experimental sensitivity!

In e^-e^+ colliders, if we saw ...

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



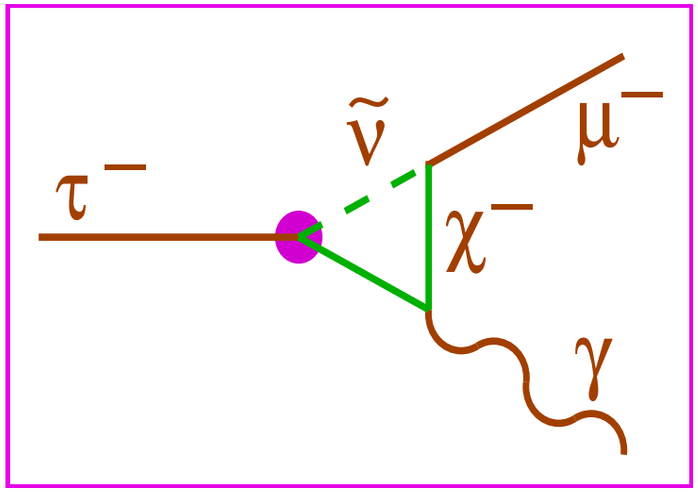
...unambiguous signature of new physics!

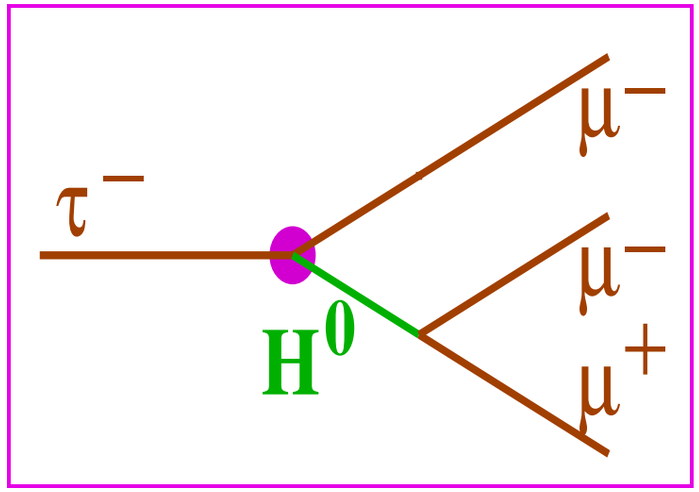
LFV in τ decays

- 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 $\nu_{\rm R}$ (PRD66(2002)034008)	10^{-9}	10^{-10}

Illustrative scenarios ...



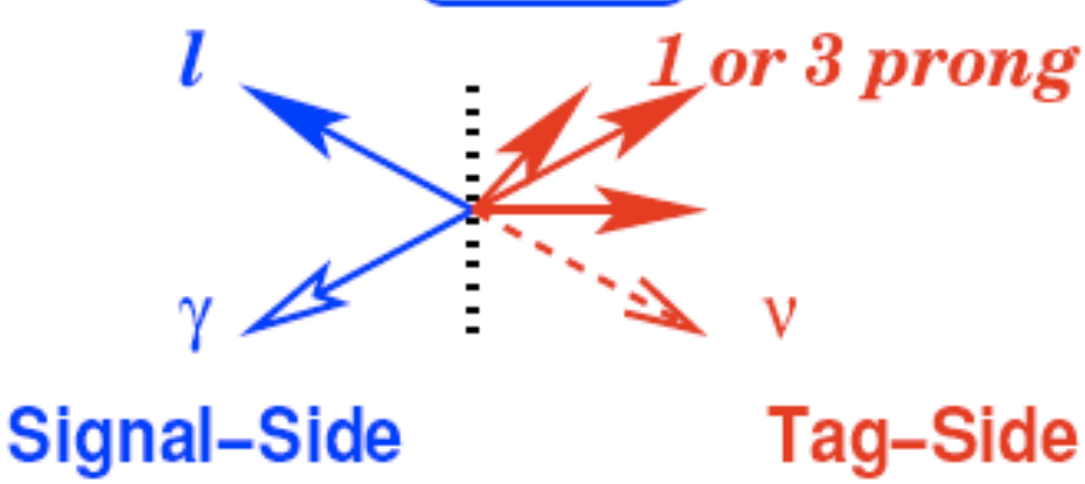


☞ Search for $\tau \to \ell\gamma/P^0$, $\tau \to \ell\ell\ell$, $\tau \to \ell hh'$ decays $(\ell = e, \mu; h = \pi, K)$

$e^-e^+ \to \tau^-\tau^+$ (Clean Environment)

- Divide τ-pair event $\perp$ to thrust axis (CM frame) in 2 hemispheres

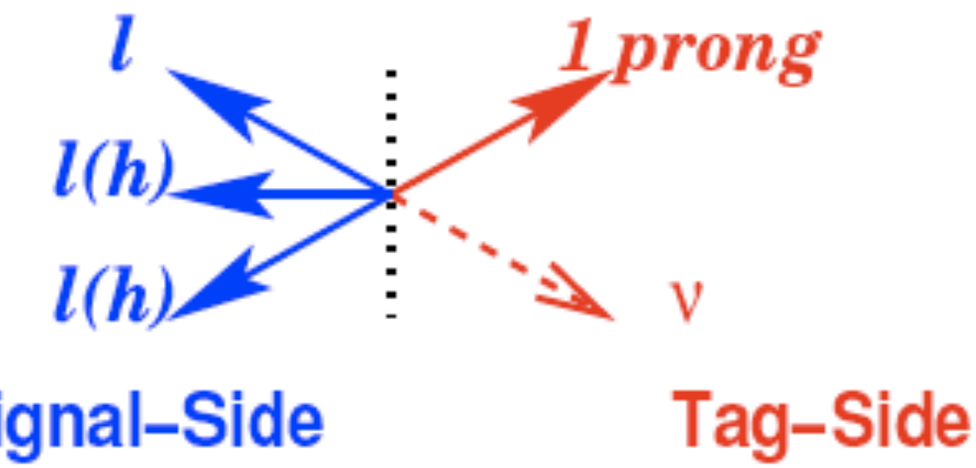
$\tau \to \ell\gamma$



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)

$\tau \to \ell\ell\ell$ ($\tau \to \ell hh'$)

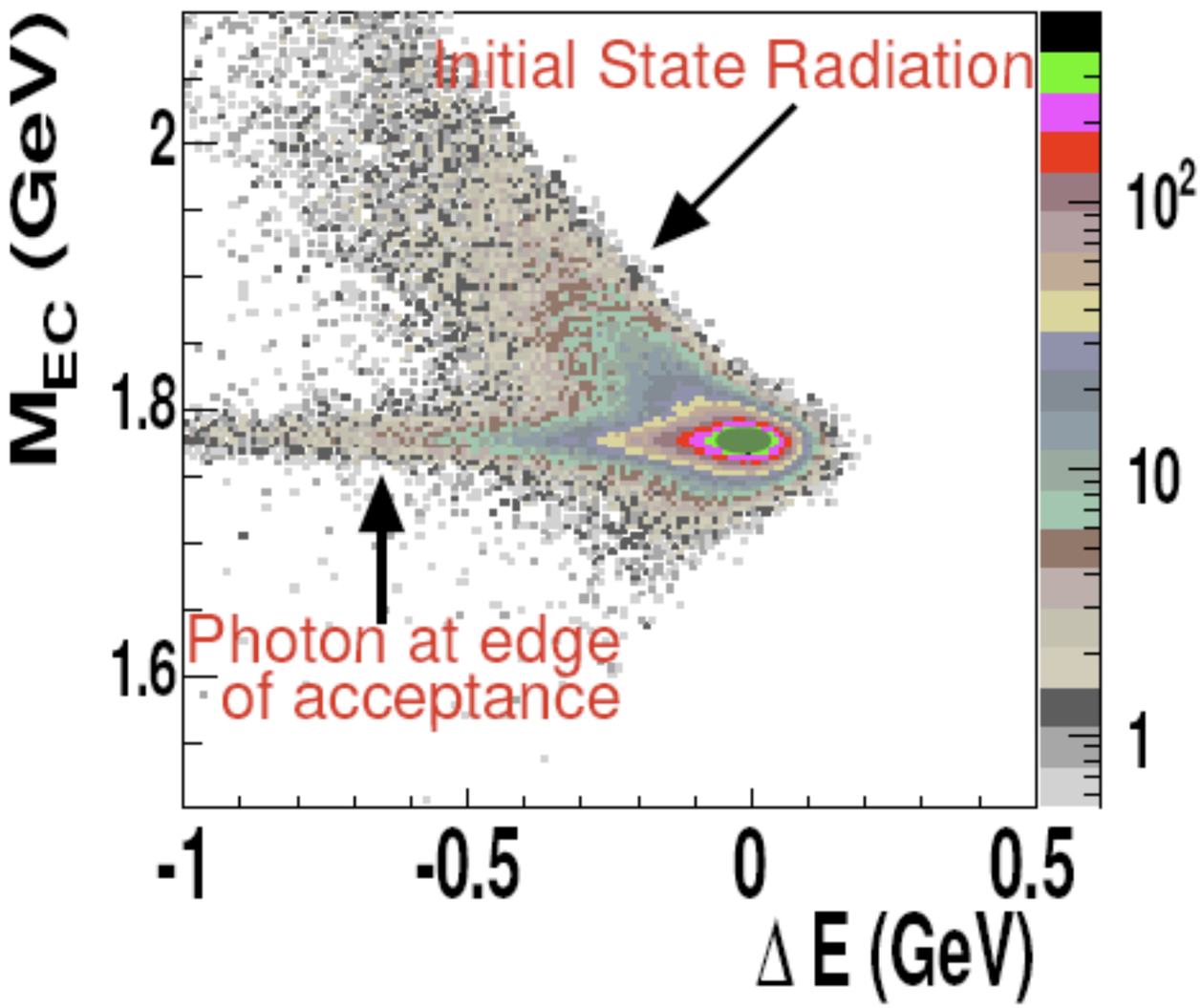


Backgrounds:

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

$\tau \to \mu\gamma$ in e^-e^+ colliders

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



$\tau \to \mu\gamma$ simulation

$$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$$
$$\sigma(\Delta E) \sim 50\,\text{MeV}$$

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

Beam energy constrained mass after vertexing

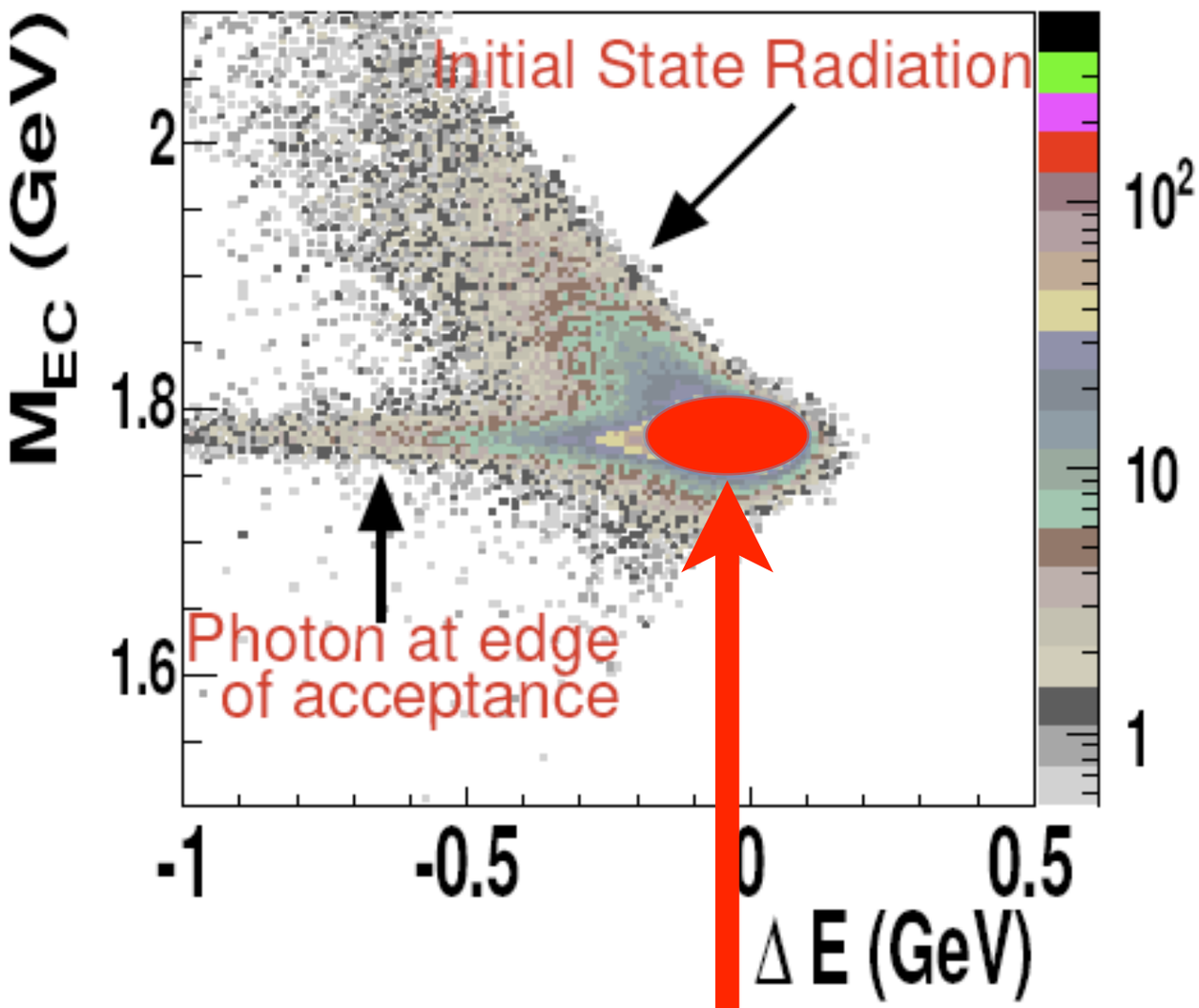
γ at μ POCA(XY)

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

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

$\tau \to \mu\gamma$ in e^-e^+ colliders

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



$\tau \to \mu\gamma$ simulation

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

Beam energy constrained mass after vertexing

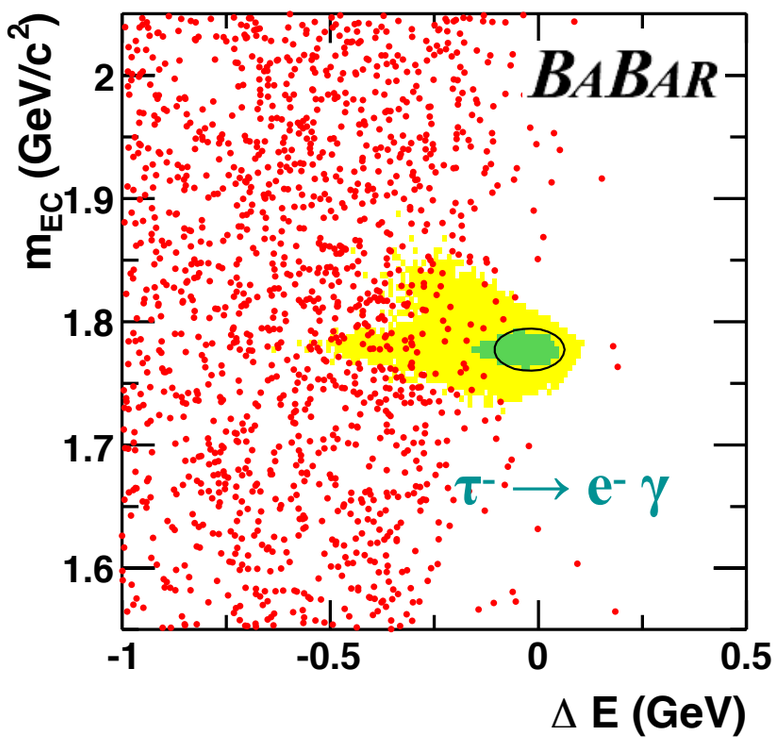
γ at μ POCA(XY)

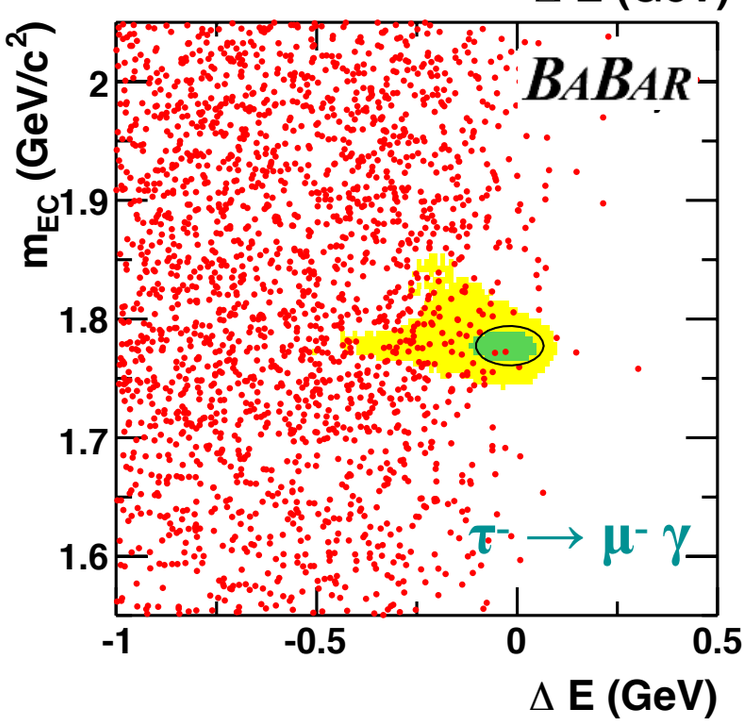
[Inv. mass: $\sigma \sim 24$ MeV]

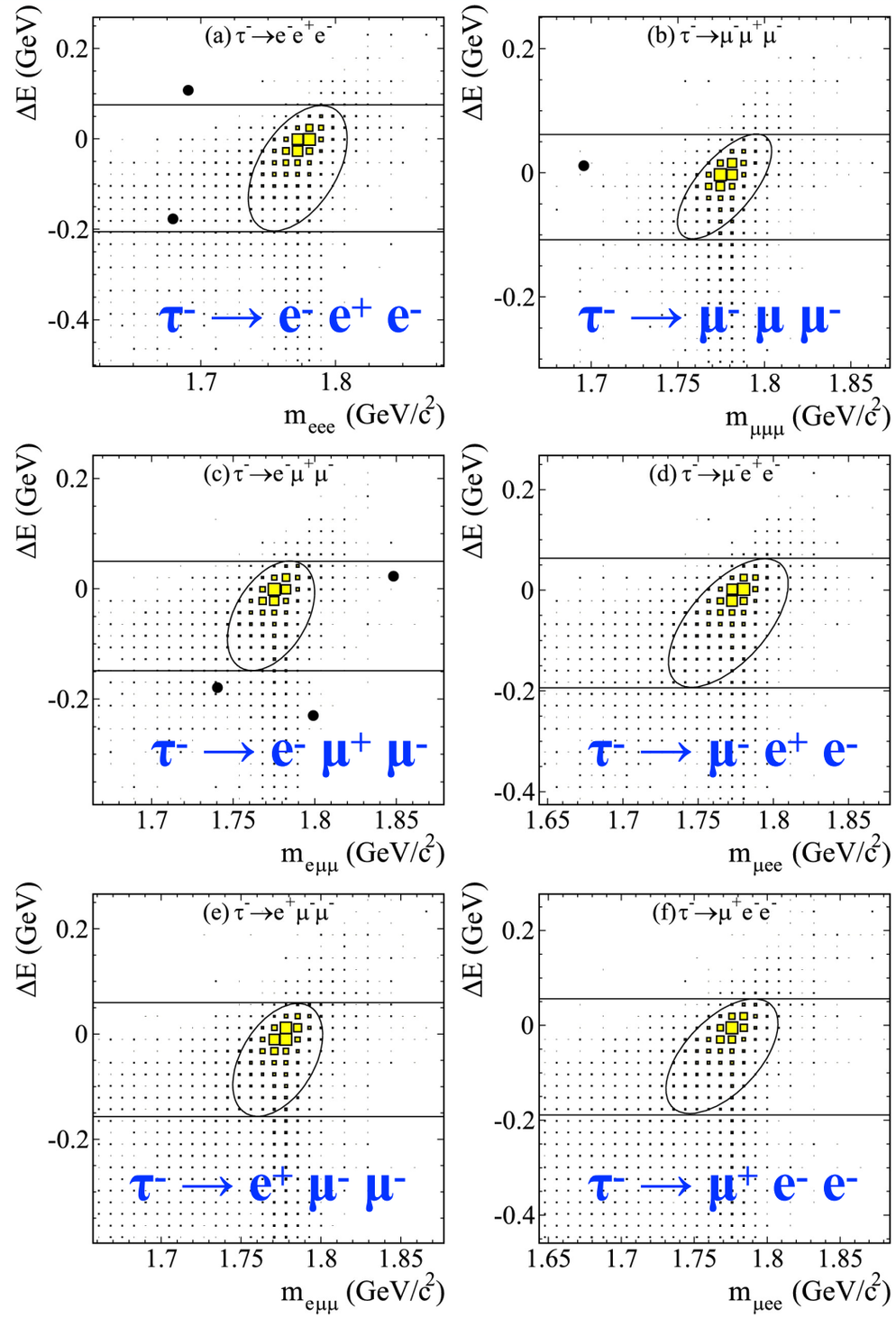
☞ Signal Region: $\pm 2\,\sigma$ around ($\langle\Delta E\rangle$, $\langle M_{EC}\rangle$)

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

$\tau \to l\gamma$, $\tau \to lll$ in e^-e^+ colliders







Phys. Rev. Lett. 104 (2010) 021802

Phys. Lett. B687 (2010) 139

BELLE

$\tau \to l\gamma$, $\tau \to lll$ in e^-e^+ colliders

$$B^{90}_{\rm UL} = N^{90}_{\rm UL}/(N_\tau \times \varepsilon)$$

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

$\varepsilon =$	Trigger	Reco	Topology	PID	Cuts	Signal–Box
	90%	70%	70%	50%	50%	50%
Cumulative:						
	90%	63%	44%	22%	11%	~5%

$N_\tau = 963$ M

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

Phys. Rev. Lett.
104 (2010) 021802

$N_\tau = 1438$ M

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^-e^+e^-$	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

Phys. Lett.
B687 (2010) 139

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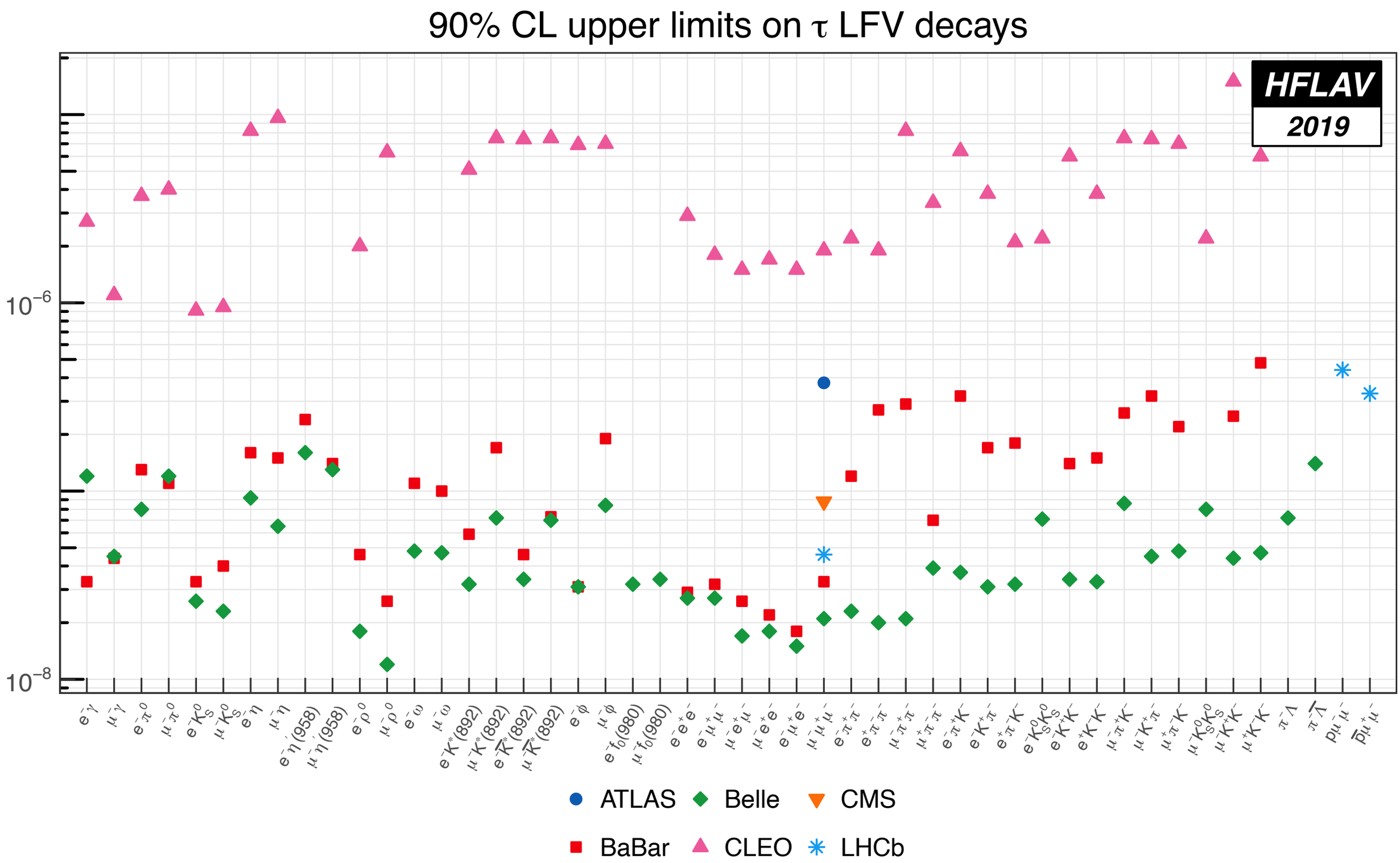
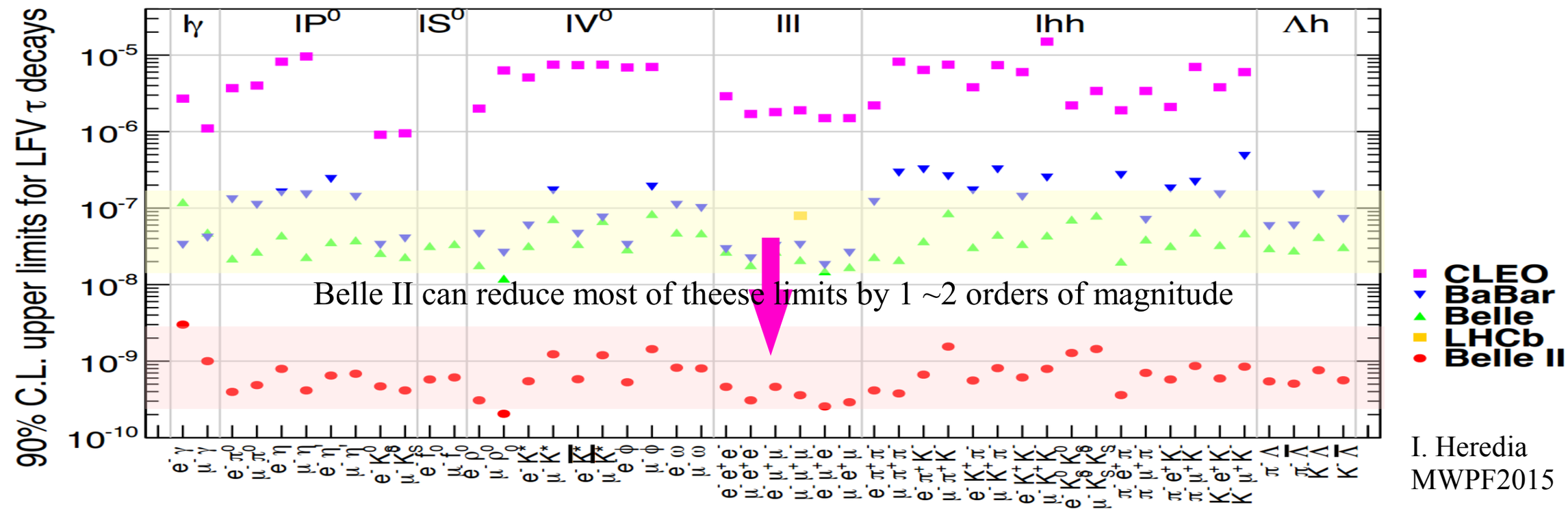
Summary of present limits



Future prospects at Belle II (2019-2031)

	Luminosity	$N_\tau = 2L\sigma$
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

"Tau Physics and Precision Electroweak Physics with Polarized Beams at SuperKEKB/Belle II" (RF/SNOWMASS21-RF0_RF0-EF4_EF0-AF5_AF0_Banerjee_Roney-046.pdf)

Beam polarization enhances the sensitivity (https://arxiv.org/pdf/0810.1312.pdf)

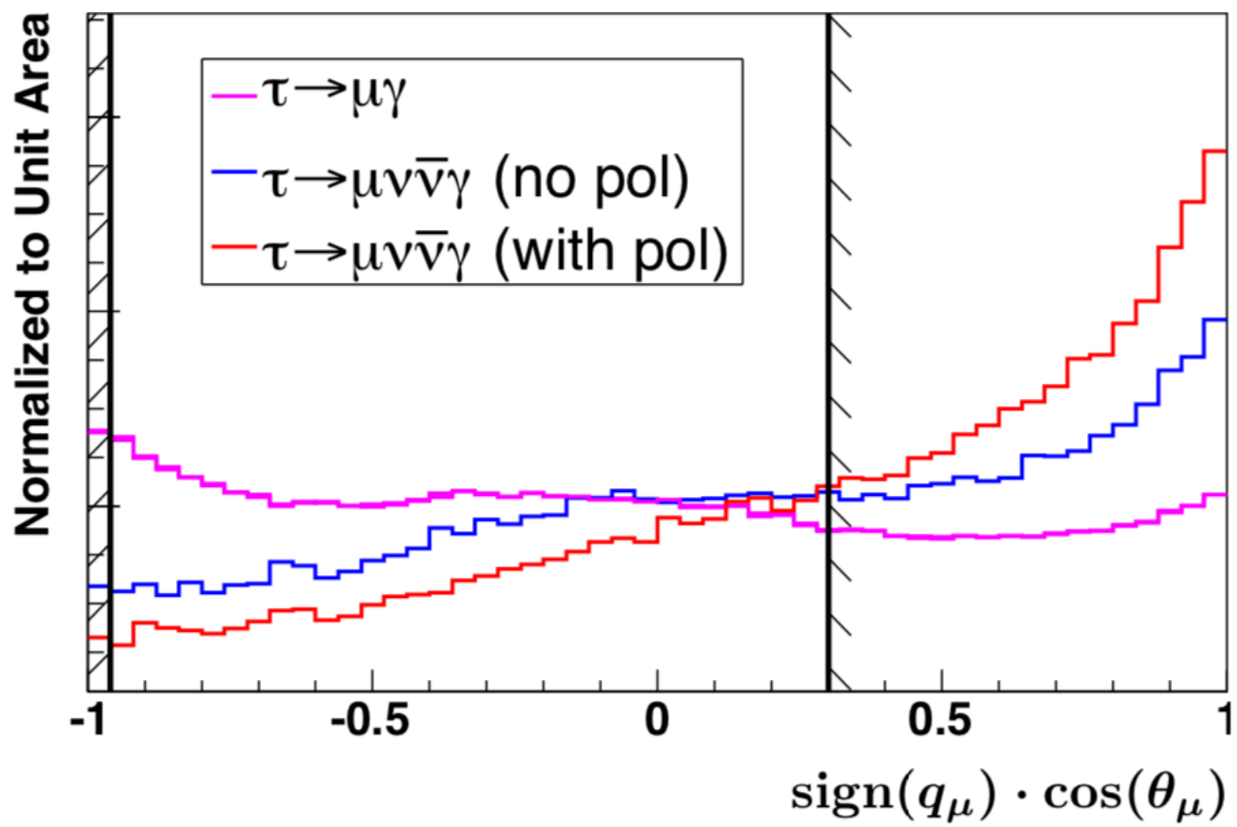


FIG. 15: Distribution of the cosine of the signal-side muon multiplied by the muon charge for signal and background events with and without electron beam polarization in the $\tau^{\pm} \to \mu^{\pm}\gamma$ search analysis at Super$B$.

The "irreducible background" would be cut by 70% for a 39% loss in signal efficiency. This would result in approximately a 10% improvement in the sensitivity.

Helicity structure of LFV coupling (https://arxiv.org/pdf/1609.04617.pdf)

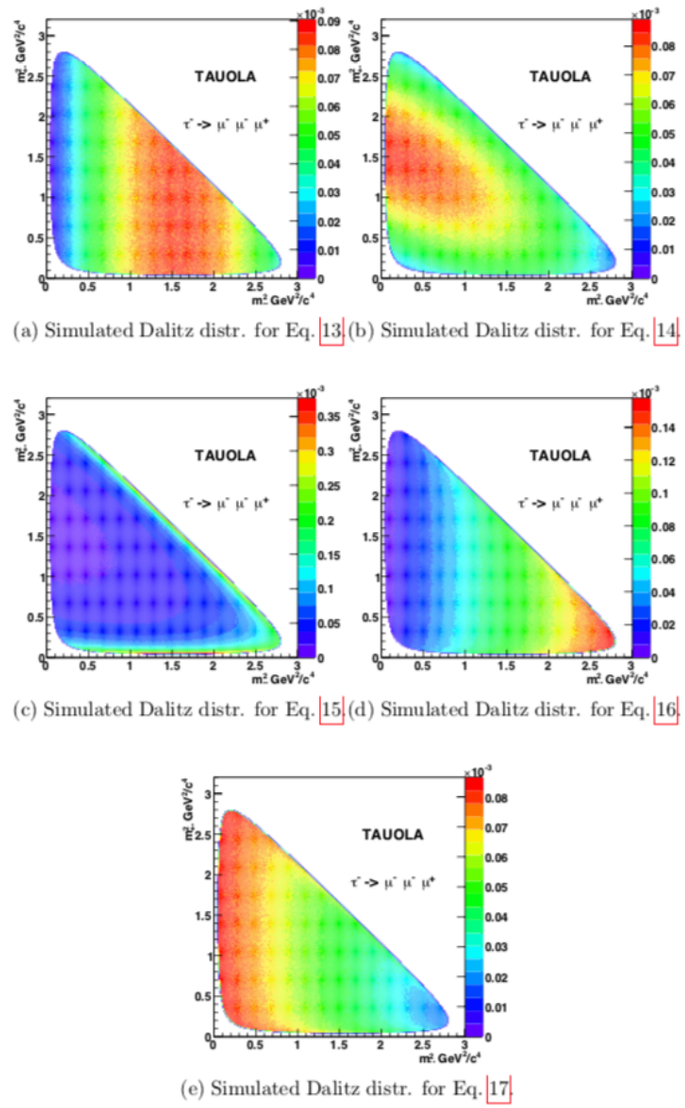
Four left-handed leptons (O1 operator)

Two left-handed, two right-handed leptons (O4 operator)

Radiative right-handed leptons (R1 operator)

Interference between O1 and R1 operators

Interference between O4 and R1 operators



(a) Simulated Dalitz distr. for Eq. 13 (b) Simulated Dalitz distr. for Eq. 14

(c) Simulated Dalitz distr. for Eq. 15 (d) Simulated Dalitz distr. for Eq. 16

(e) Simulated Dalitz distr. for Eq. 17

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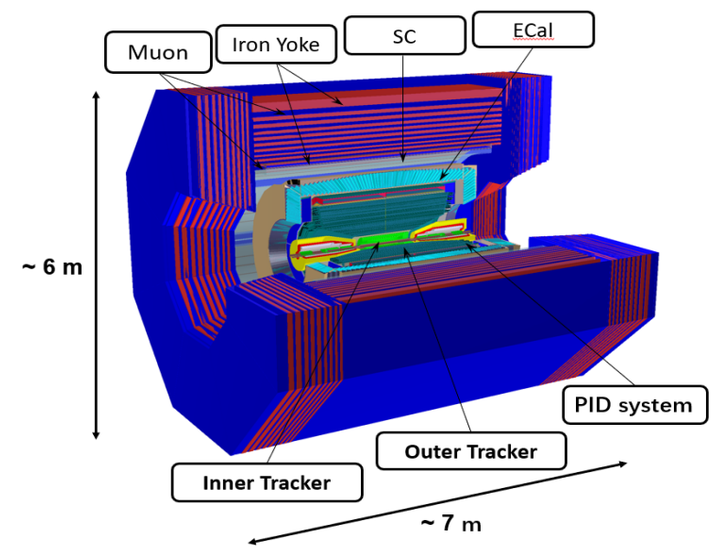
Figure 1: Dalitz distributions simulated in the effective field approach for the five different BSM operators corresponding to different lepton chirality structures [25]. The normalized to unit area distributions, implemented in the TAUOLA package.

The most important aspect of having the polarization is the possibility to determine the helicity structure of the LFV coupling from the final state momenta distributions.

Beyond 2030: Chinese proposal

Proposed STCF in China

- Peaking luminosity (0.5-1)×10^{35} $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity and realize beam polarization

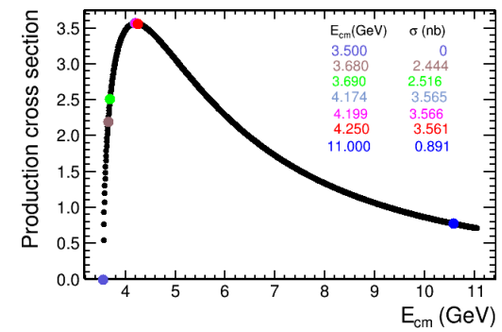


"Physics Potential of a Super tau-Charm Facility"
(RF/SNOWMASS21-RF7_RF1_STCF-013.pdf)

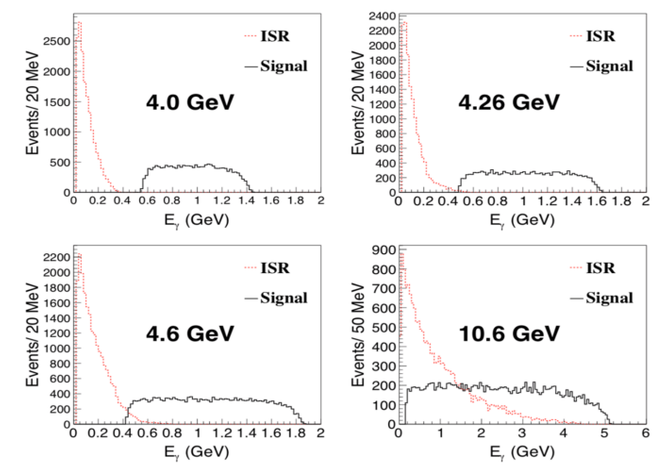
Beyond 2030: Chinese proposal

- **Advantage**:
  - **Threshold** production
  - **Peaking cross section** in 4-5 GeV
  - At 4.26 GeV, number of tau pairs per year:

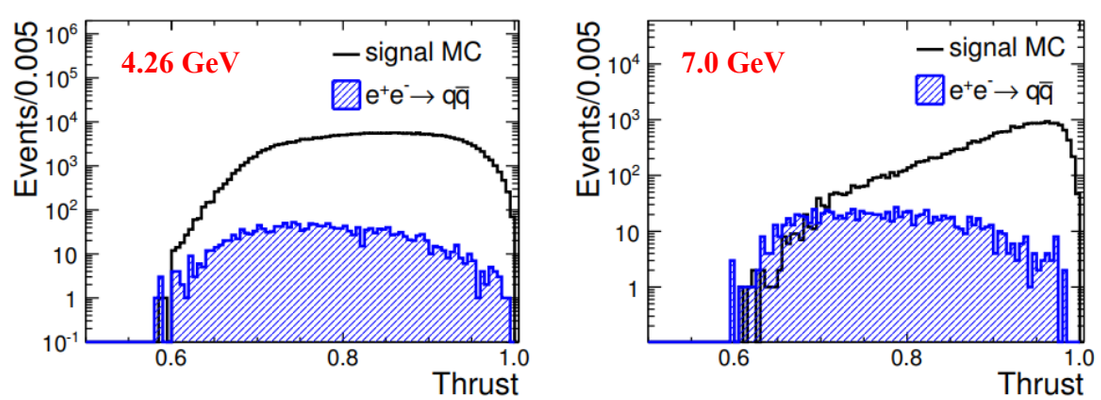
    $N_{\tau\tau}$~ 1.0 ab^{-1} ×3.5 nb = 3.5 × 10^9
  - $e^+e^- \to \gamma\tau^+\tau^-$ is **not** the main background
  - Improved π/μ misid rate at STCF



- **Disadvantage**:
  - **Entangled topology** of $e^+e^- \to \tau^+\tau^-$
  - Large **hadronic** backgrounds at low c.m.e



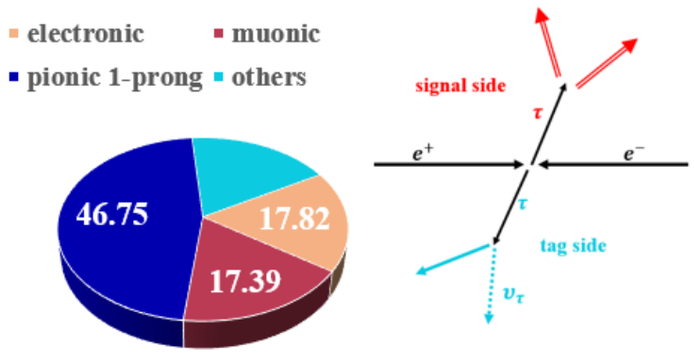
$$T \equiv max_{\vec{n}} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$



"Physics Potential of a Super tau-Charm Facility" (RF/SNOWMASS21-RF7_RF1_STCF-013.pdf)

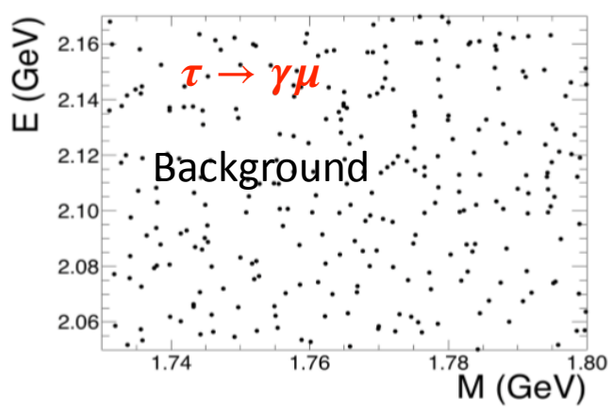
Beyond 2030: Chinese proposal

LFV decay of τ at STCF



- Signal side $\tau \to \gamma\mu$
- Tag side: $\tau \to e\upsilon\bar{\upsilon}$, $\pi\upsilon$, $\pi\pi^0\upsilon(\mathscr{B}r = 54\%)$
- **Dominant background**: $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-, \tau^+ \to \pi\pi^0\upsilon, \tau^- \to \mu\upsilon\bar{\upsilon}$

- **Stringent** selection criteria applied to remove the backgrounds
- Efficiency: 4.2%~8.5% depending on loose/strict cut **(include tag branching fraction)**
- **The sensitivity: $\mathscr{B}^{90}_{UL}(\tau \to \gamma\mu)$~$1/\sqrt{\mathscr{L}}$**



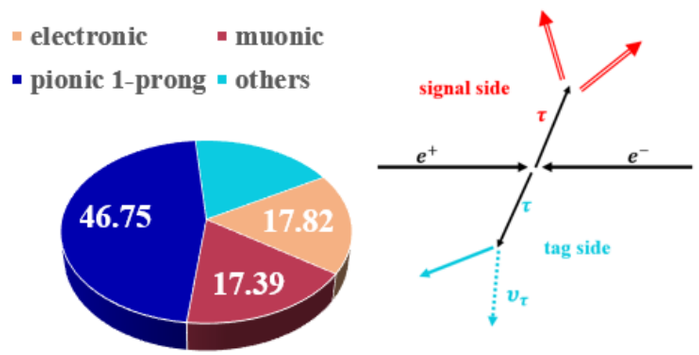
- **STCF with 1ab^{-1}:**

$$\mathscr{B}^{90}_{UL}(\tau \to \gamma\mu) < \frac{N^{90}_{UL}}{2\varepsilon N_{\tau\tau}} \sim 3.2 \times 10^{-8}$$

"Physics Potential of a Super tau-Charm Facility" (RF/SNOWMASS21-RF7_RF1_STCF-013.pdf)

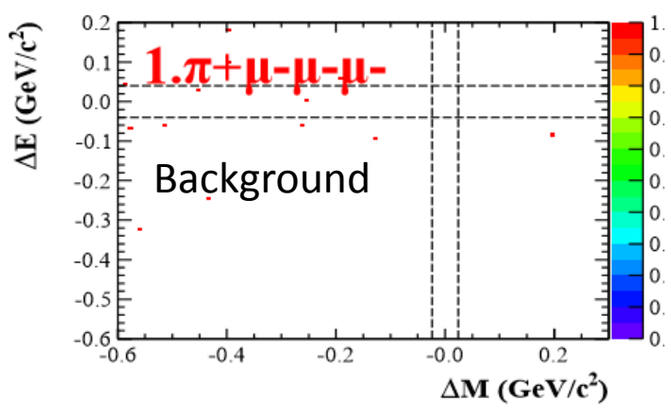
Beyond 2030: Chinese proposal

LFV decay of τ at STCF



- Precisely known kinematics of initial state
- Full reconstruction of signal side
- Neutrino in tag side is missing

- Signal side: $\tau \to 3leptons$
- Tag side: $\tau \to e\upsilon\bar{\upsilon}$, $\mu\upsilon\bar{\upsilon}$, $\pi\upsilon + n\pi^0$ ($\mathscr{B}r = 82\%$)
- Almost background free, **the sensitivity : $\mathscr{B}^{90}_{UL}\left(\tau \to \mu\mu\mu\right)$~$1/\mathscr{L}$**
- Best efficiency ($\tau \to \mu\mu\mu$): 22.5% **(including tag branching fraction)**



- **STCF with 1ab^{-1}:**

$$\mathscr{B}^{90}_{UL}\left(\tau \to \mu\mu\mu\right) < \frac{N^{90}_{UL}}{2\varepsilon N_{\tau\tau}} \sim 1.4 \times 10^{-9}$$

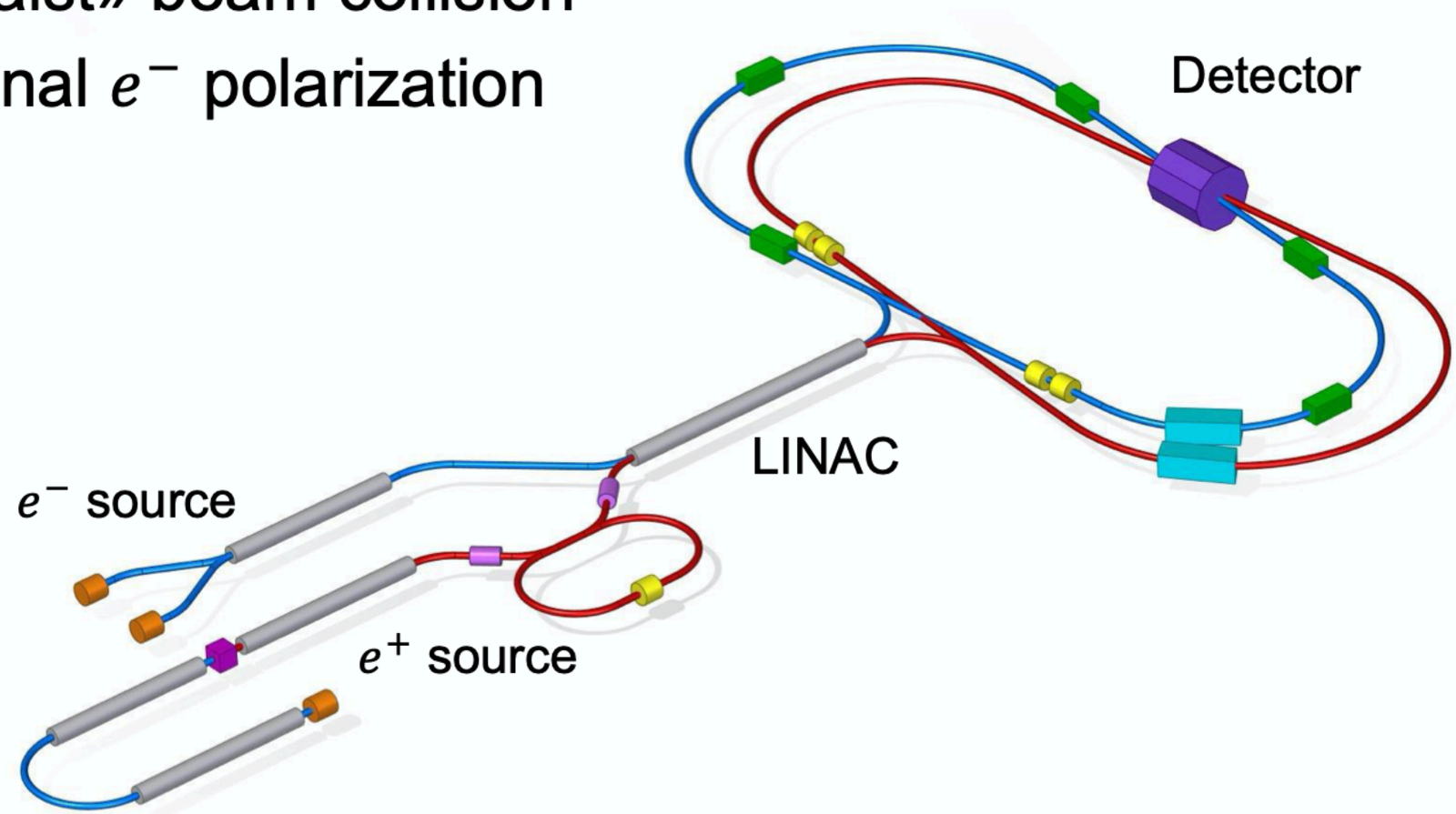
"Physics Potential of a Super tau-Charm Facility"
(RF/SNOWMASS21-RF7_RF1_STCF-013.pdf)

Beyond 2030: Russian proposal

Super Charm-tau factory @BINP

- Symmetric e^+e^- collider, $2E = 2 \div 6$ ГэВ
- Luminosity $10^{35}\ 1/cm^2s$
- «Crab Waist» beam collision
- Longitudinal e^- polarization

Factory of c, τ, J/ψ



"Precision experiments at Super Charm-Tau Factory"
(RF/SNOWMASS21-RF1_RF7_BINP-019.pdf)

Beyond 2030: Russian proposal

Nuclear Physics B - Proceedings Supplements
Volumes 253–255, August–October 2014, Pages 199-201

Feasibility study for a search for $\tau \to \mu + \gamma$ decay at Super $\mathbf{c} - \tau$ factory

A.V. Bobrov [a, b], A.E. Bondar [a, b]

Show more

https://doi.org/10.1016/j.nuclphysbps.2014.09.048

Abstract

A Monte Carlo study of possible background processes in a search for $\tau \to \mu\gamma$ decay has been performed for conditions of the Super $c - \tau$ factory (SCTF) at a center-of-mass energy 3.686 GeV, 3.77 GeV and 4.17 GeV. The background from $\tau^+\tau^-$ events has been analysed. Selection criteria for background suppression are suggested and necessary requirements on the detector characteristics have been found. A possible upper limit for $\mathscr{B}_{\tau\to\mu\gamma}$ at SCTF is about $(1.5 \div 2.5) \times 10^{-10}$. The SCTF can successfully compete with the Super B-factory in a search for $\tau \to \mu\gamma$ decay.

"Precision experiments at Super Charm-Tau Factory" (RF/SNOWMASS21-RF1_RF7_BINP-019.pdf)

Summary

- **Observation of LFV 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 LFV 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. Polarized beams can further improve the sensitivity.**

- **Branching fractions up to few parts in 10^{-9} to 10^{-10} will be probed in neutrino-less 2-body and 3-body decays of the tau lepton.**

- **Proposed experiments at "Super Tau Charm Factory" will provide complementary information to searches for LFV in tau decays, also with possibility of beam polarization.**