New physics in rare decays

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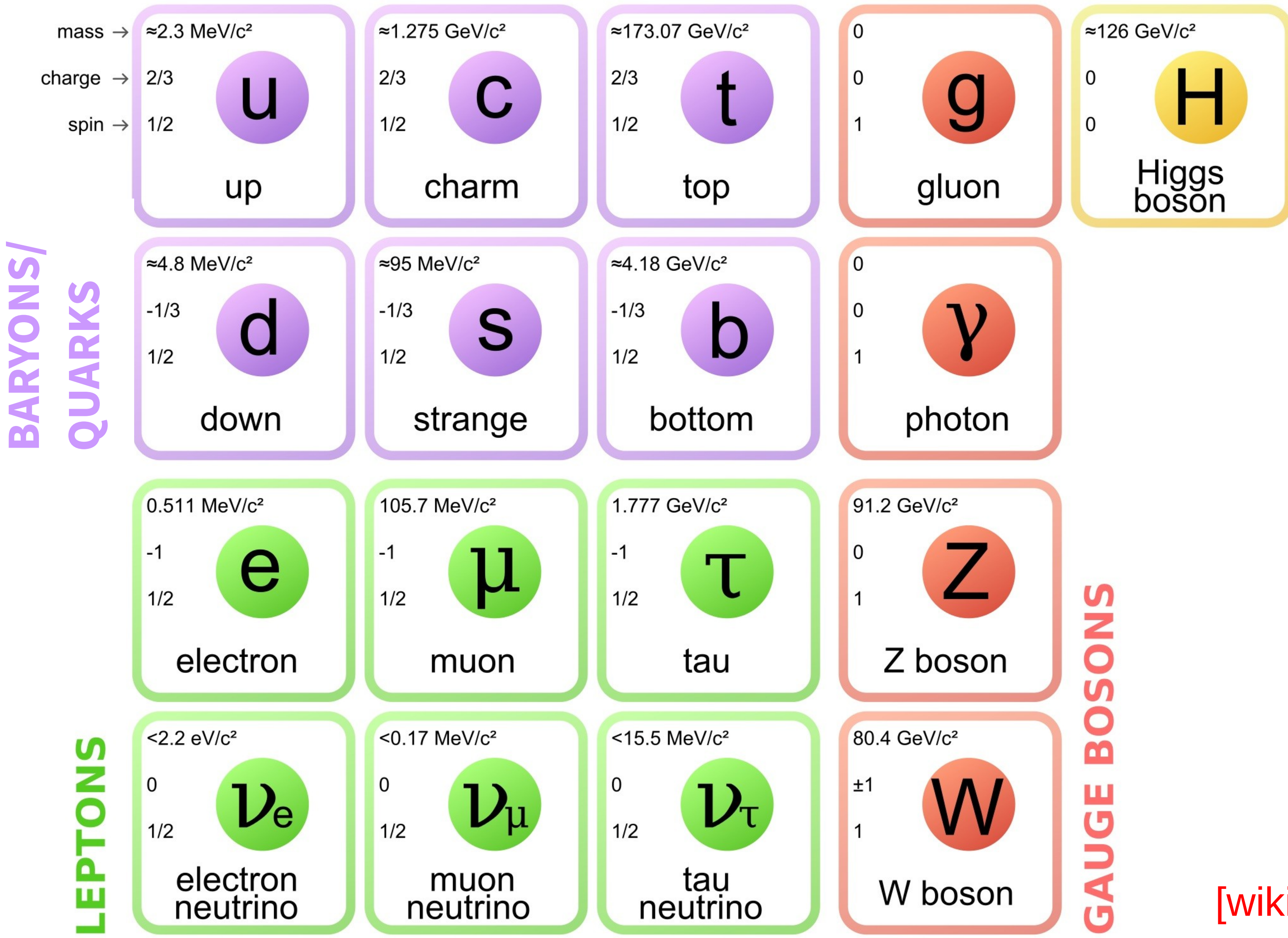
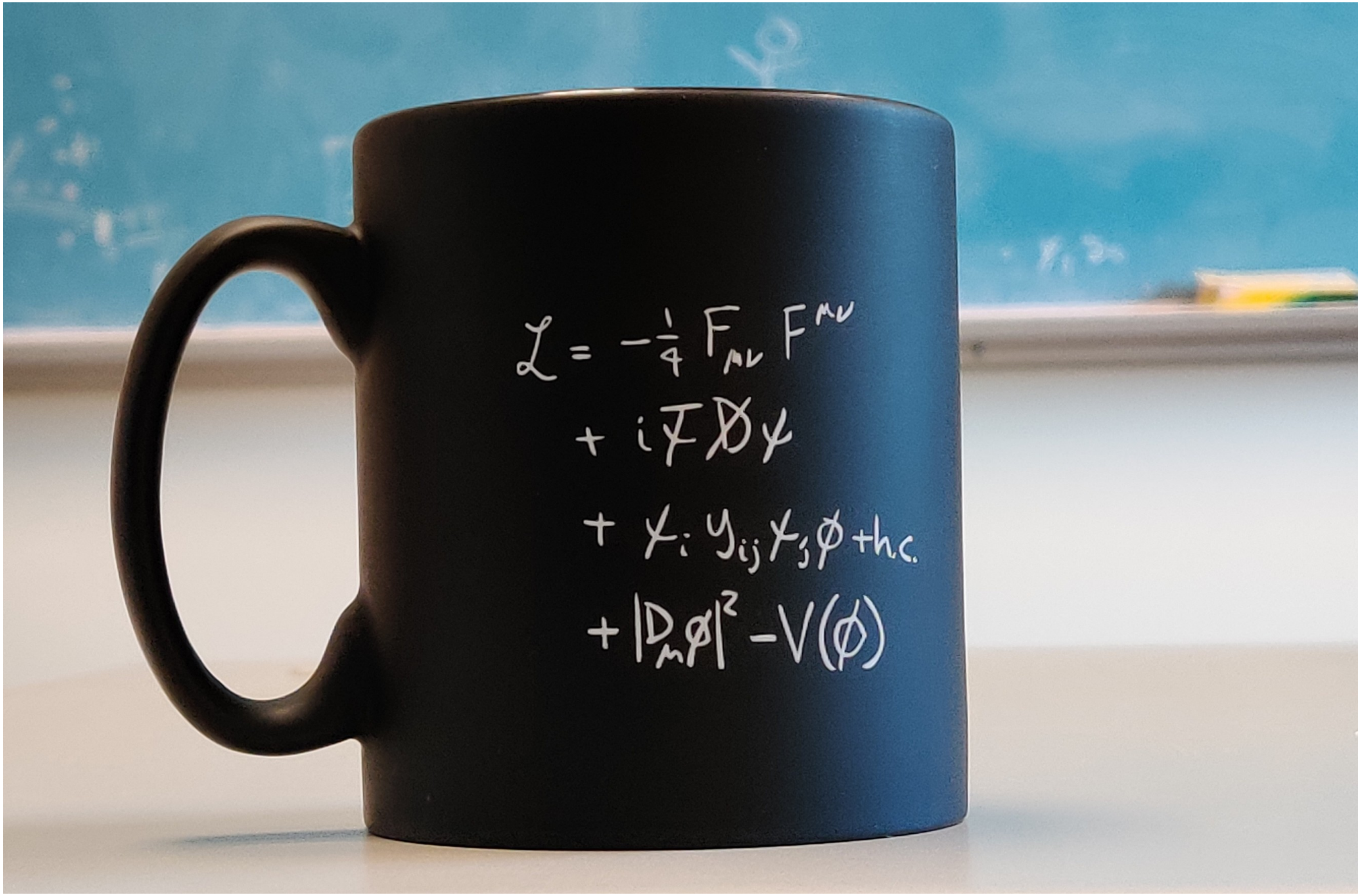
Elementary particles



[wikipedia]

Interactions



Standard Model

$$
\begin{aligned}
\mathcal{L} = &-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
&\tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
&W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - \\
&A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + \\
&4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2 + \\
&2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&\tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + \\
&m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + \\
&(\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2-1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \\
&\tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + \\
&i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \\
&\tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \\
&\bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \\
&\partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^- X^-) - \tfrac{1}{2}gM[\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \tfrac{1}{2}igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]
\end{aligned}
$$

[Courtesy of T.D. Gutierrez]

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_{\mathrm{L}_e} \times \mathrm{U}(1)_{\mathrm{L}_\mu} \times \mathrm{U}(1)_{\mathrm{L}_\tau} \, .$$

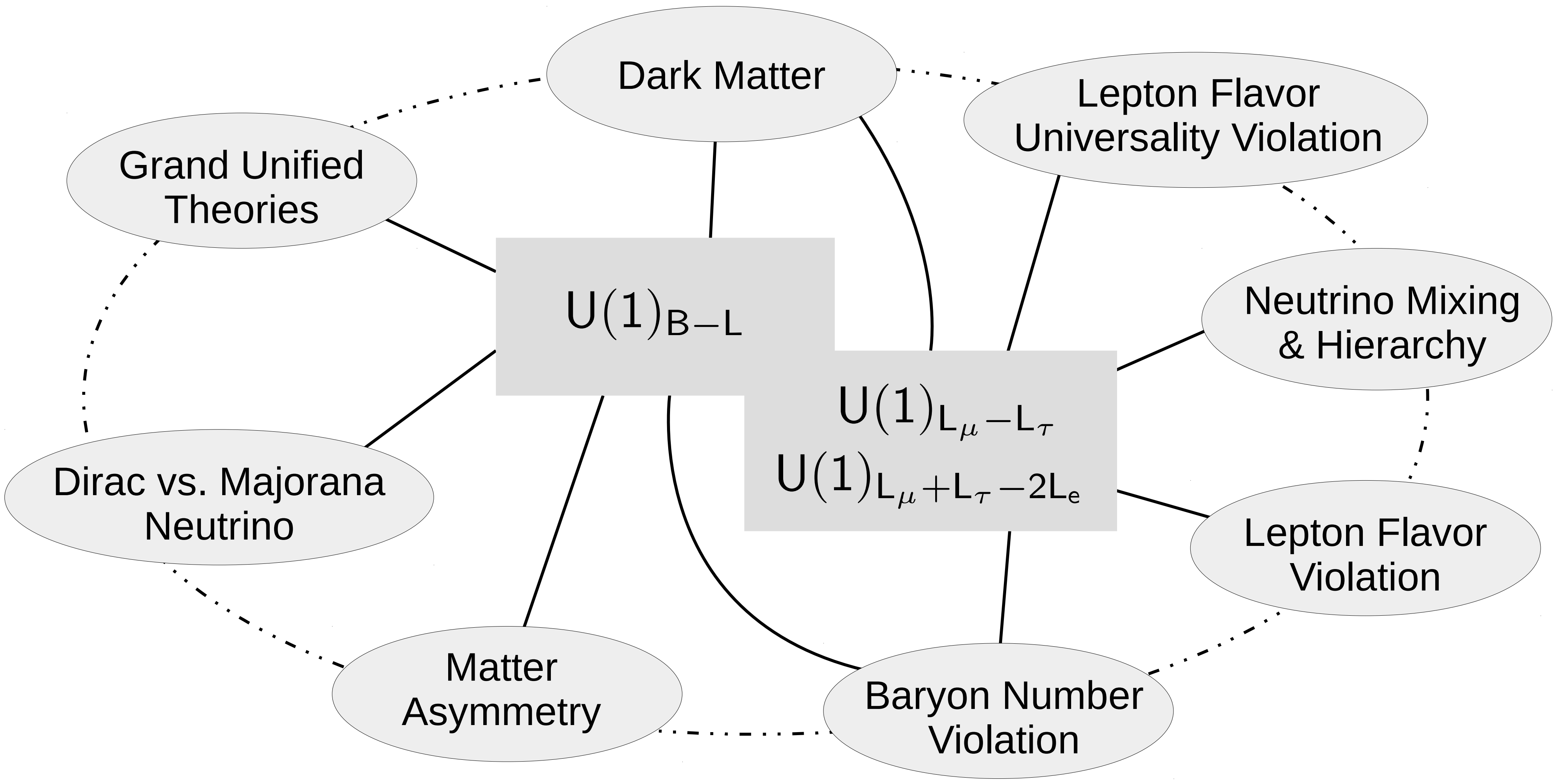
- $U(1)_{B+L}$ broken non-perturbatively to $\mathbb{Z}_3$,

$$\Delta \mathrm{B} = 3 \quad \wedge \quad \Delta \mathrm{L}_e = \Delta \mathrm{L}_\mu = \Delta \mathrm{L}_\tau = 1 \, ,$$

  but unobservable at low temperatures. ['t Hooft, PRL '76]

- True accidental global symmetry:

$$\mathbb{Z}_3^{(\mathrm{B+L})/2} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \, .$$



Dark Matter
Lepton Flavor Universality Violation
Grand Unified Theories
Neutrino Mixing & Hierarchy
$U(1)_{B-L}$
$U(1)_{L_\mu - L_\tau}$
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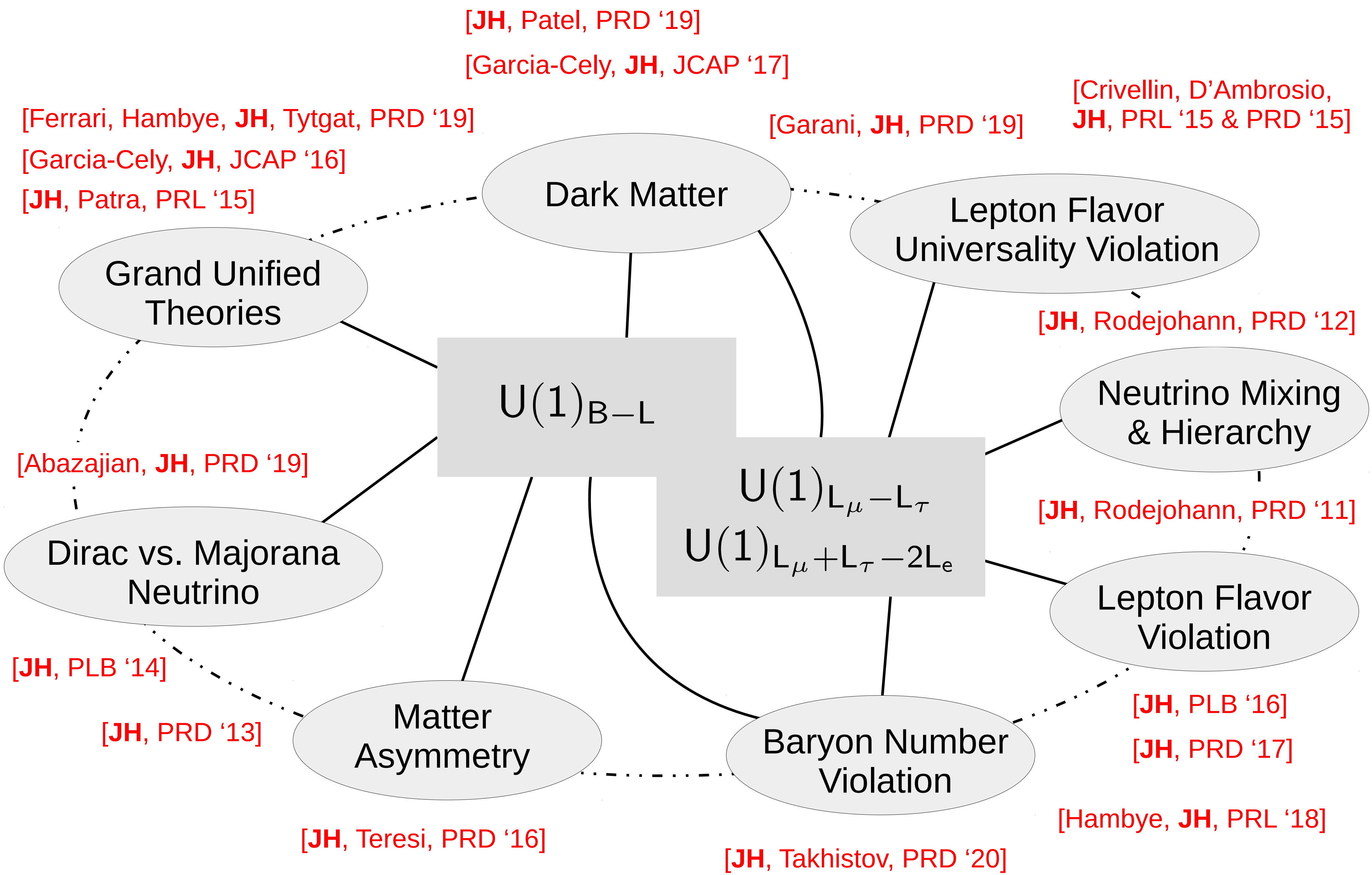
Dirac vs. Majorana Neutrino
Lepton Flavor Violation
Matter Asymmetry
Baryon Number Violation


[JH, Patel, PRD ‘19]
[Garcia-Cely, JH, JCAP ‘17]
[Ferrari, Hambye, JH, Tytgat, PRD ‘19]
[Garcia-Cely, JH, JCAP ‘16]
[JH, Patra, PRL ‘15]
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[Crivellin, D’Ambrosio, JH, PRL ‘15 & PRD ‘15]
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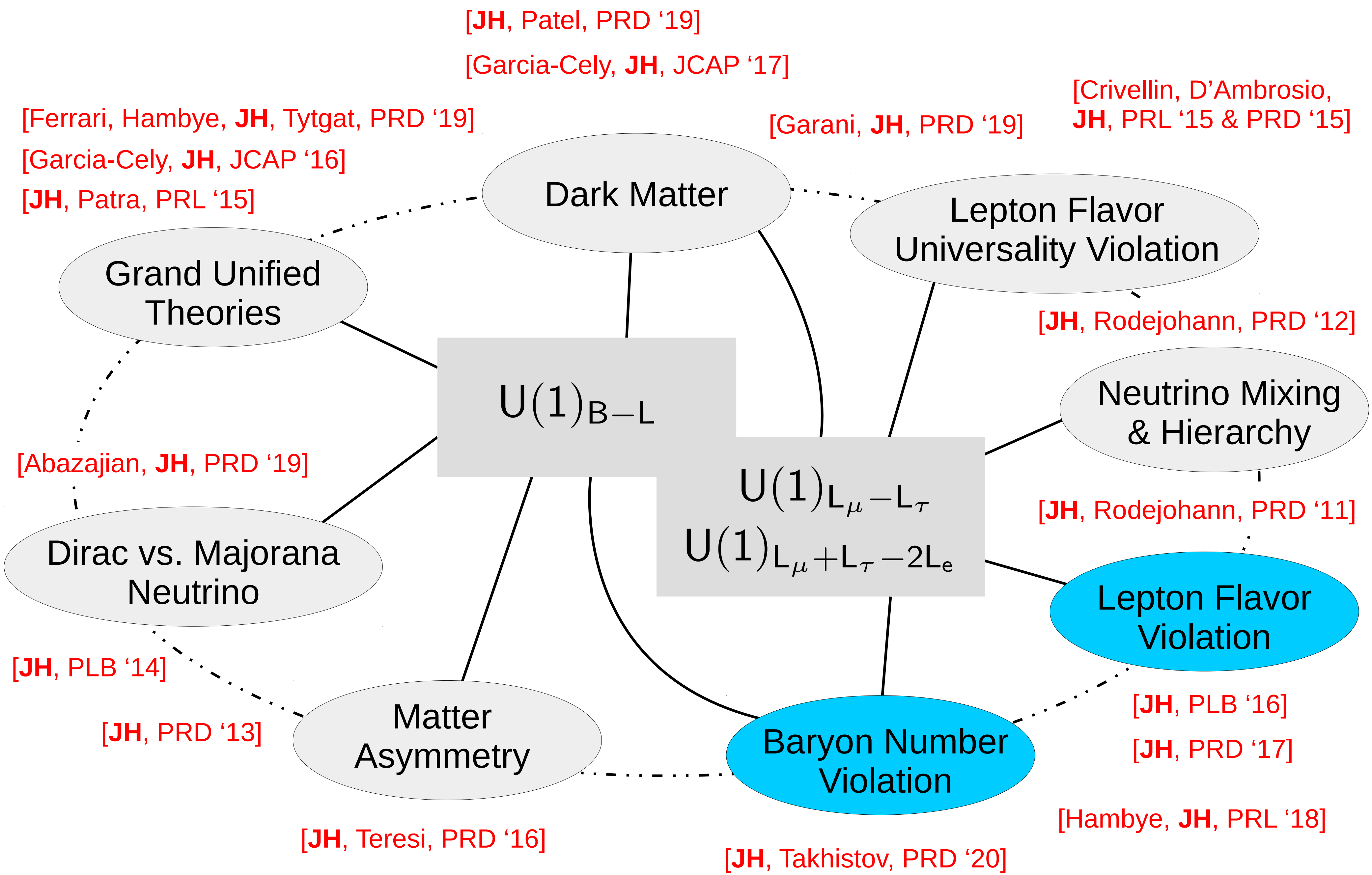
[Hambye, JH, PRL ‘18]
[JH, Teresi, PRD ‘16]
[JH, Takhistov, PRD ‘20]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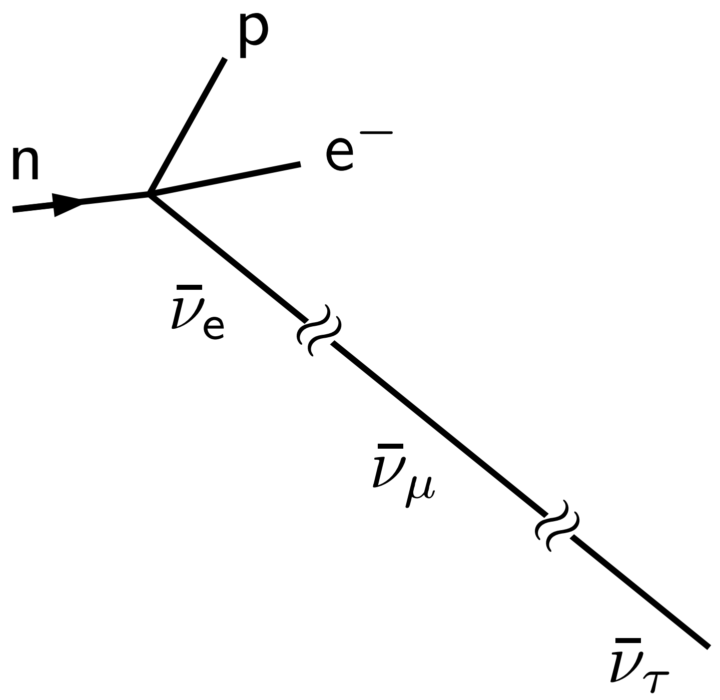
Neutrino oscillations = flavor violation

- Observations of $\nu_\alpha \to \nu_\beta$ prove that $M_\nu \neq 0$ and

  $$U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$$

  is broken!



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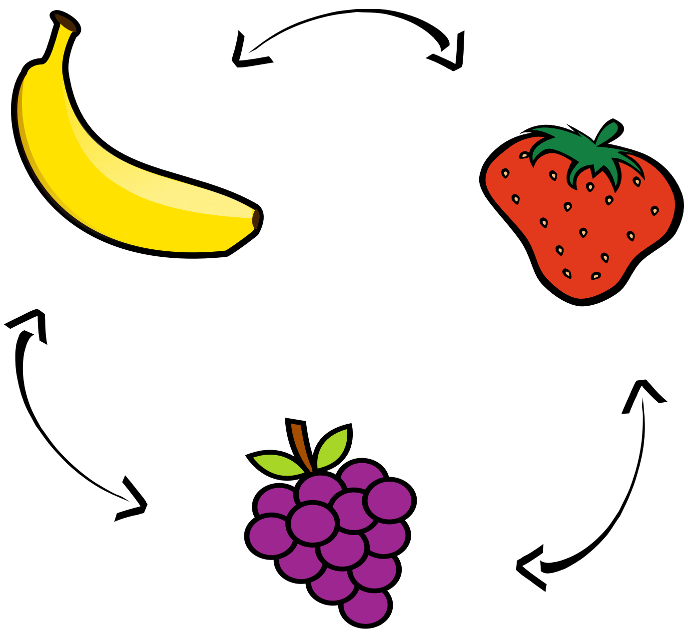
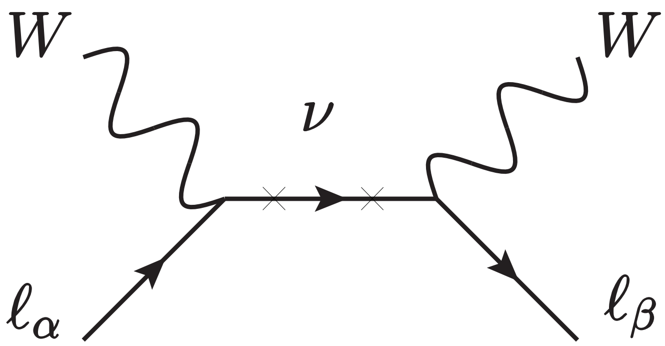
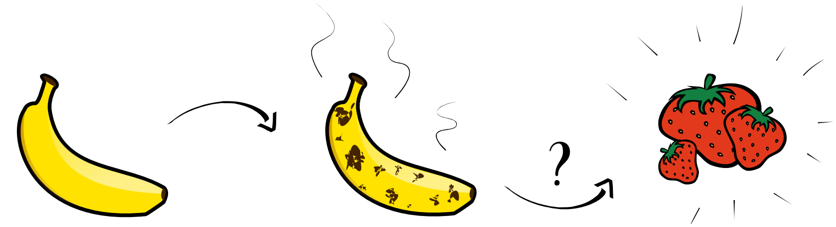
  is broken!
- Amplitudes for charged lepton flavor violation are suppressed:





$$\mathcal{A}(\ell_\alpha^- \to \ell_\beta^-) \propto \frac{(M_\nu M_\nu^\dagger)_{\alpha\beta}}{M_W^2} < 10^{-24}\,.$$

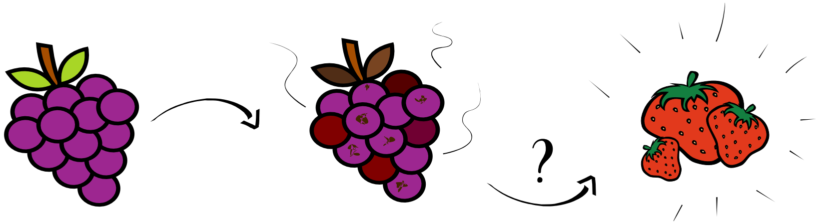
Flavor violating decays



- Prime example: $\mu \to e\gamma$ @ MEG.
- Observation = new particles (beyond SM *and* M_ν).
- $\mu^- \to e^- e^+ e^-$ @ Mu3e will probe scales up 10^6 GeV.

LFV	process	current	future	exp
$\lvert\Delta L_e\rvert = \lvert\Delta L_\mu\rvert = 1$	$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14}	MEG-II
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}	Mu3e
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-18}	Mu2e, COMET
	$h \to e\bar{\mu}$	6.1×10^{-5}	10^{-5}	LHC
	$Z \to e\bar{\mu}$	7.5×10^{-7}	10^{-10}	FCC-ee
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}	NA62

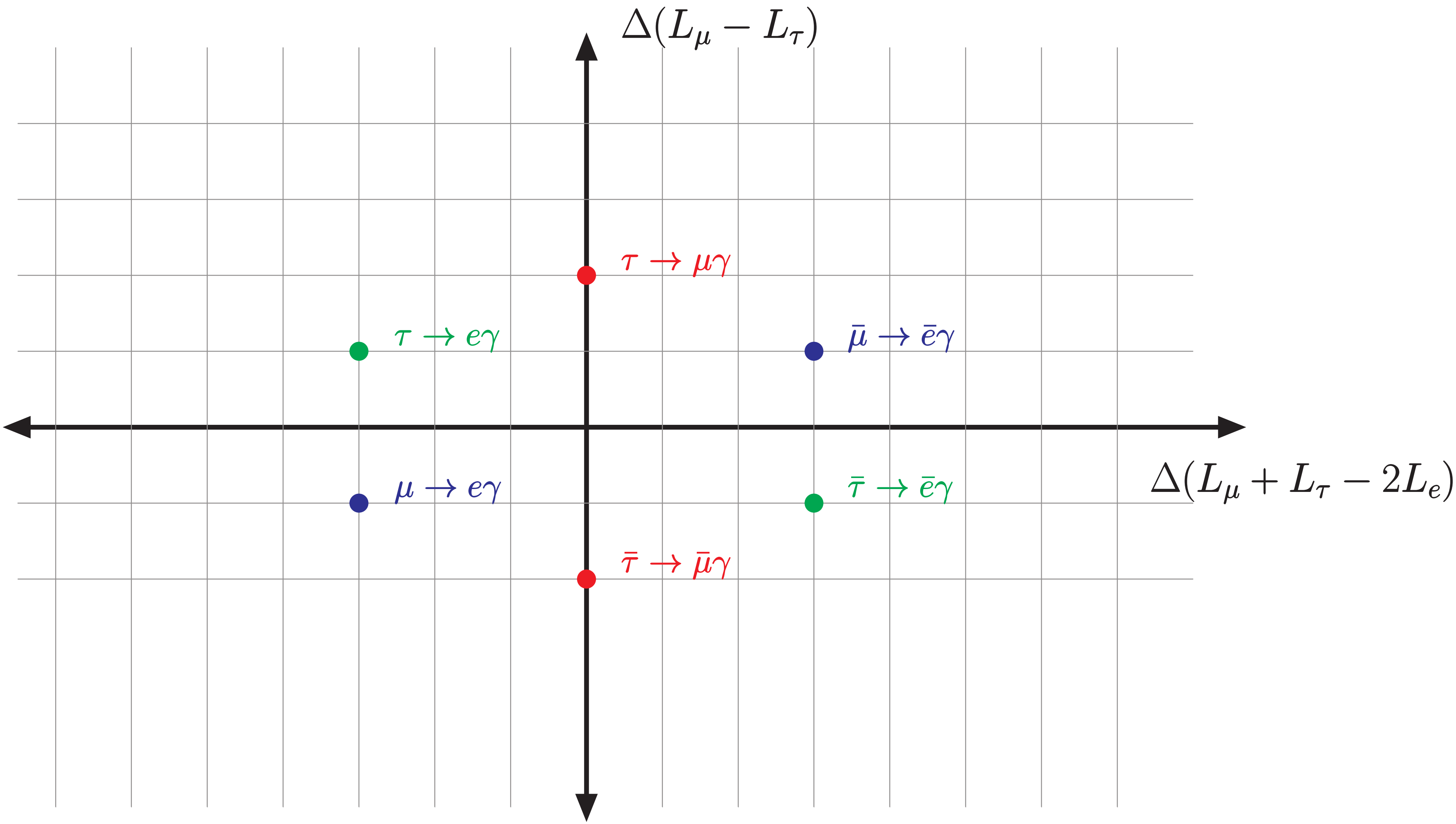
Flavor violating decays



- Produce tauons at B factories (BaBar, Belle, LHCb).
- Observation = new particles (beyond SM *and* M_ν).
- $\tau^- \to e^- e^+ e^-$ @ Belle II will probe scales up to $2 \times 10^4\,\mathrm{GeV}$.

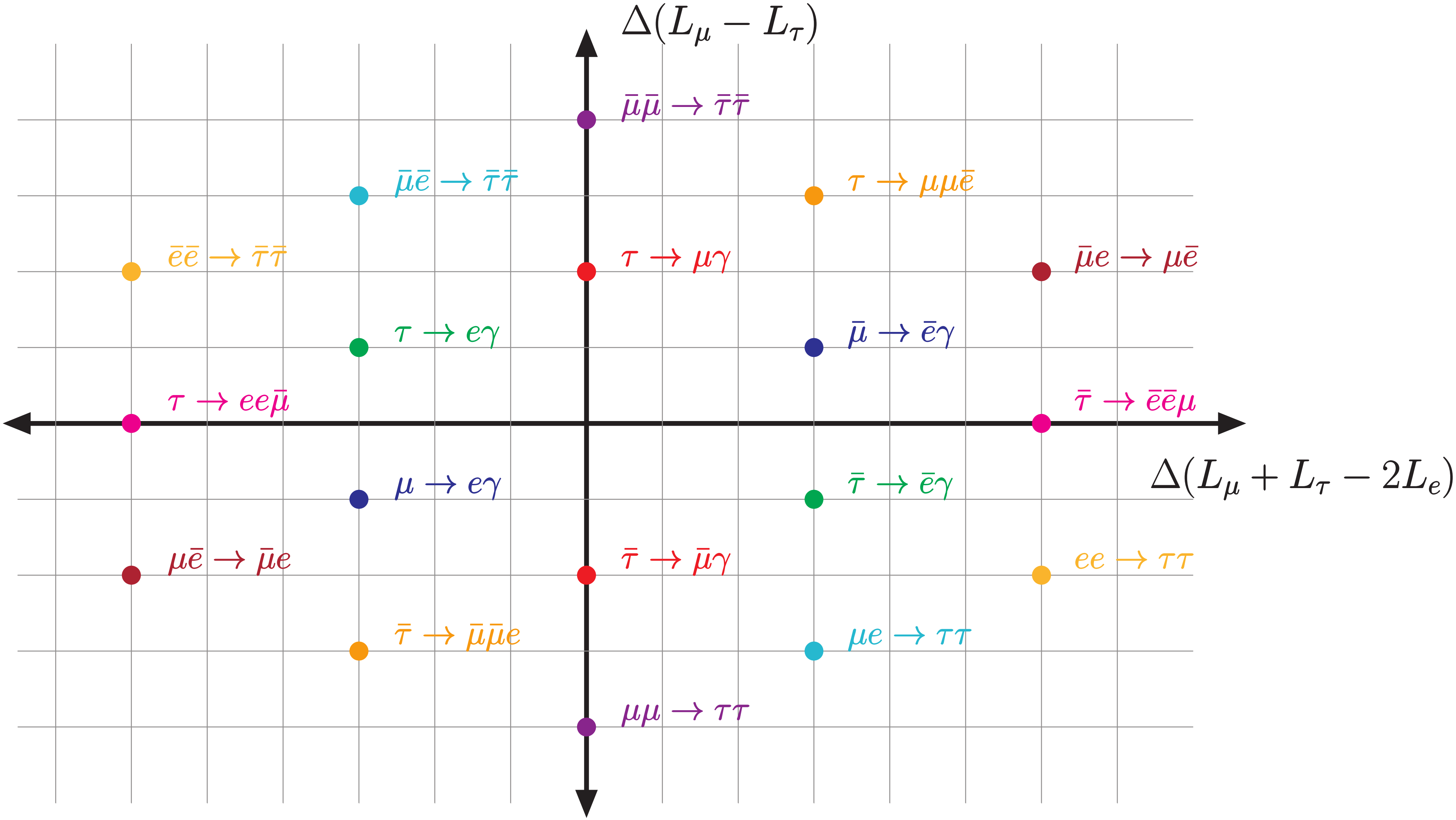
LFV	process	current	future	exp
$\lvert\Delta L_e\rvert = \lvert\Delta L_\tau\rvert = 1$	$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}	Belle II
	$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	10^{-9}	Belle II
	$\tau \to e\,\mathrm{had}$	$\mathcal{O}(10^{-8})$	10^{-9}	Belle II
	$h \to e\bar{\tau}$	4.7×10^{-3}	10^{-4}	LHC
	$Z \to e\bar{\tau}$	9.8×10^{-6}	10^{-9}	FCC-ee
	had $\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$	–	Belle II

LFV = breaking of $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$



[**JH**, PRD ‘17]

LFV = breaking of $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$



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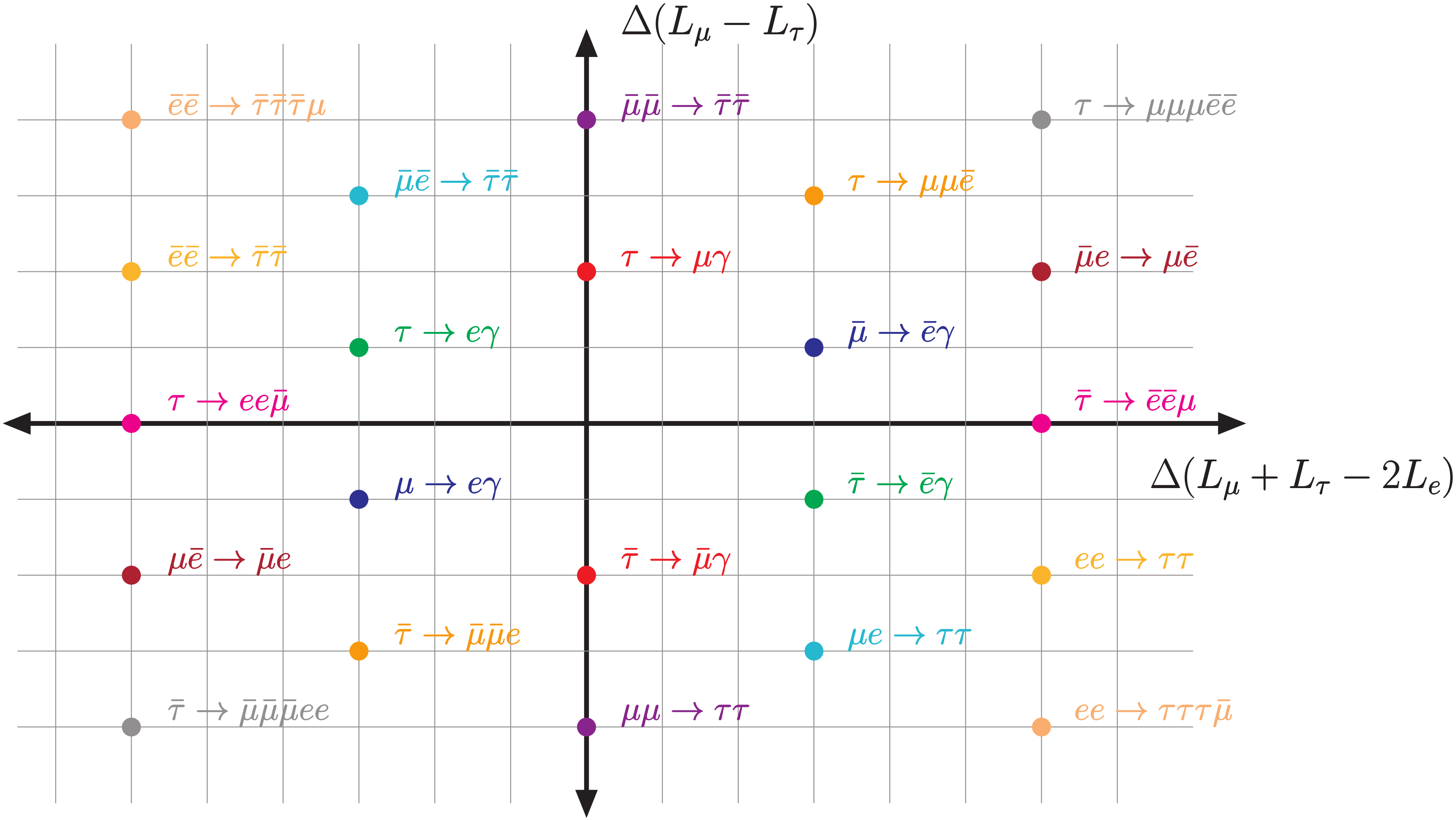
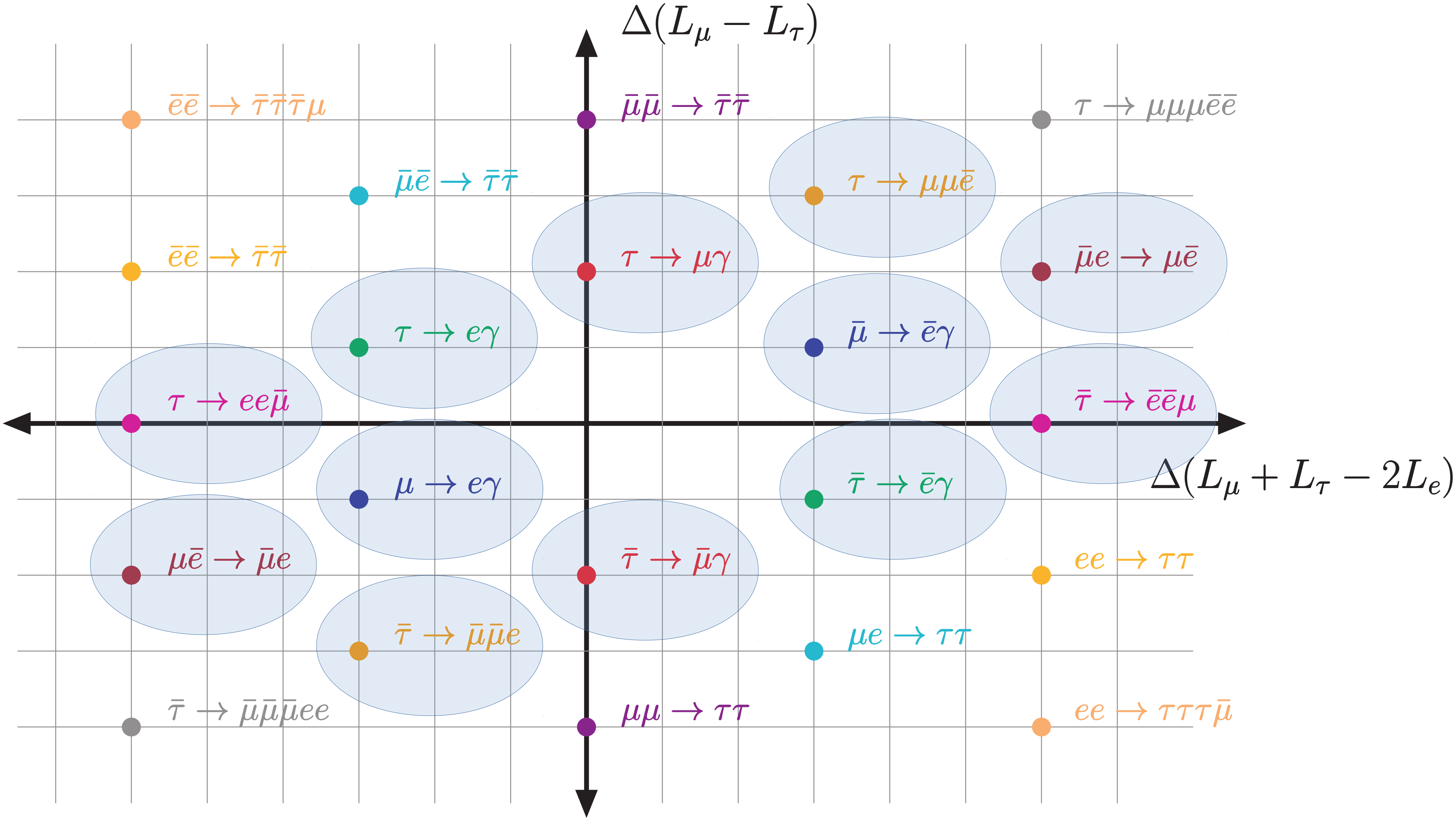


[**JH**, PRD '17]

Currently being probed



[**JH**, PRD ‘17]

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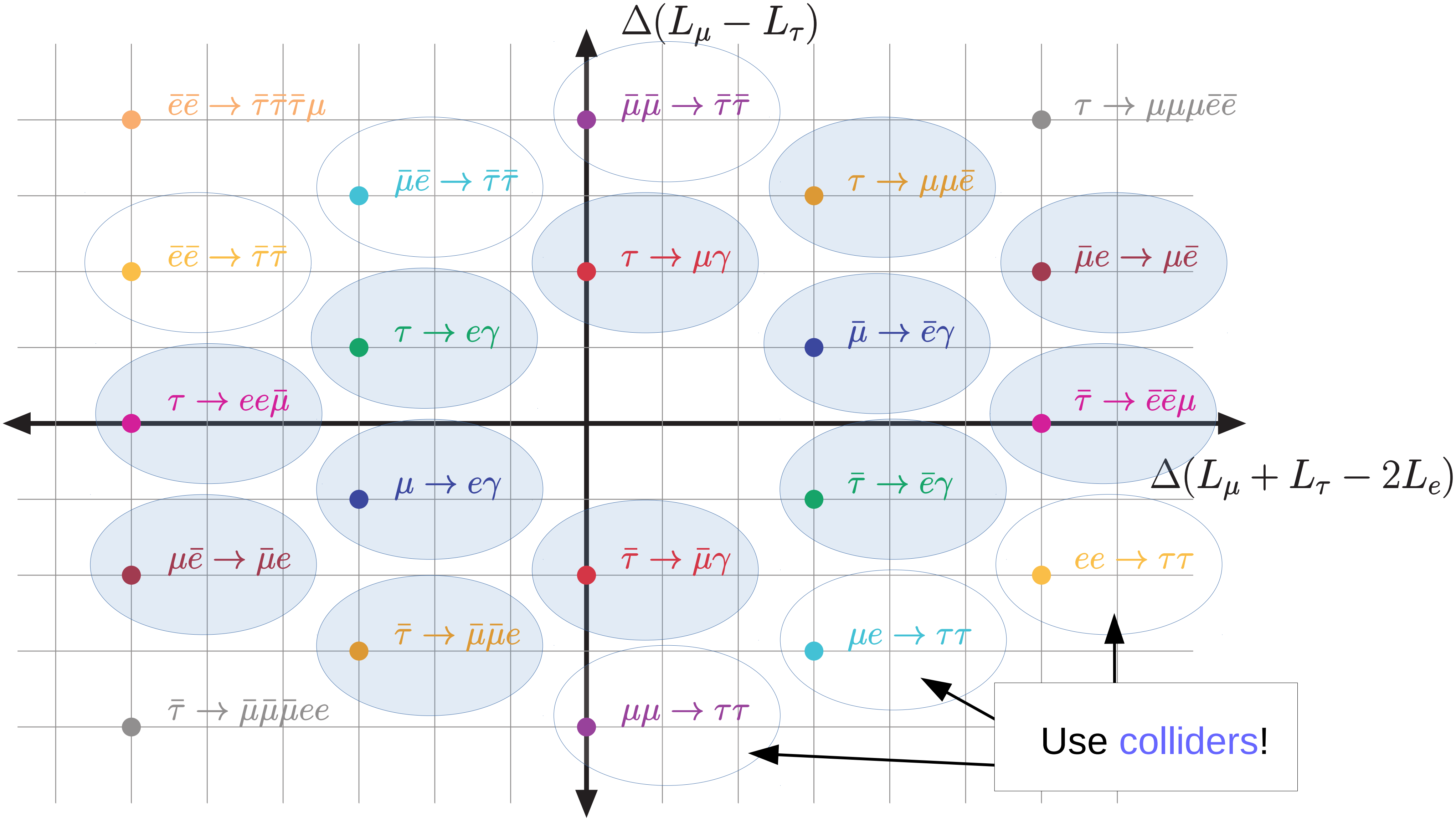
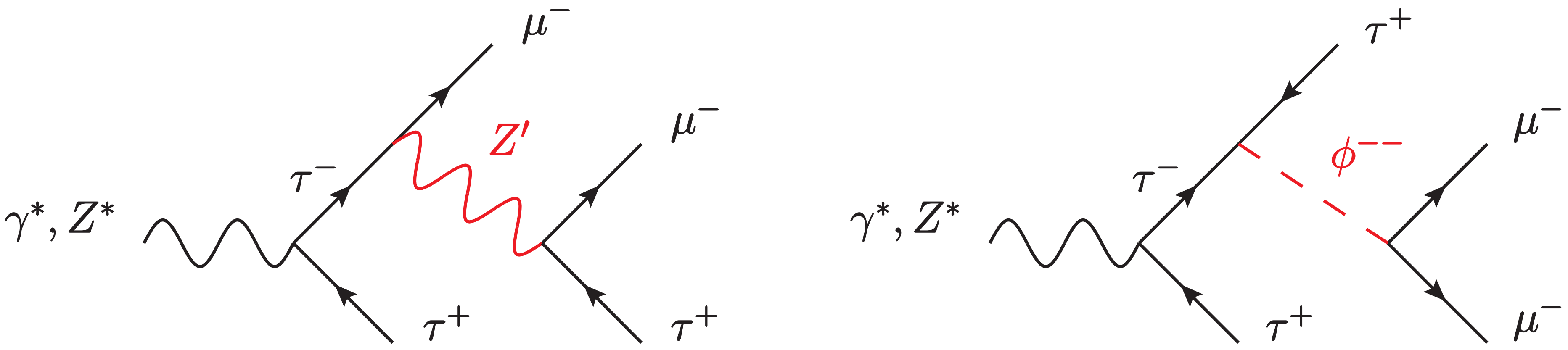


[JH, PRD '17]



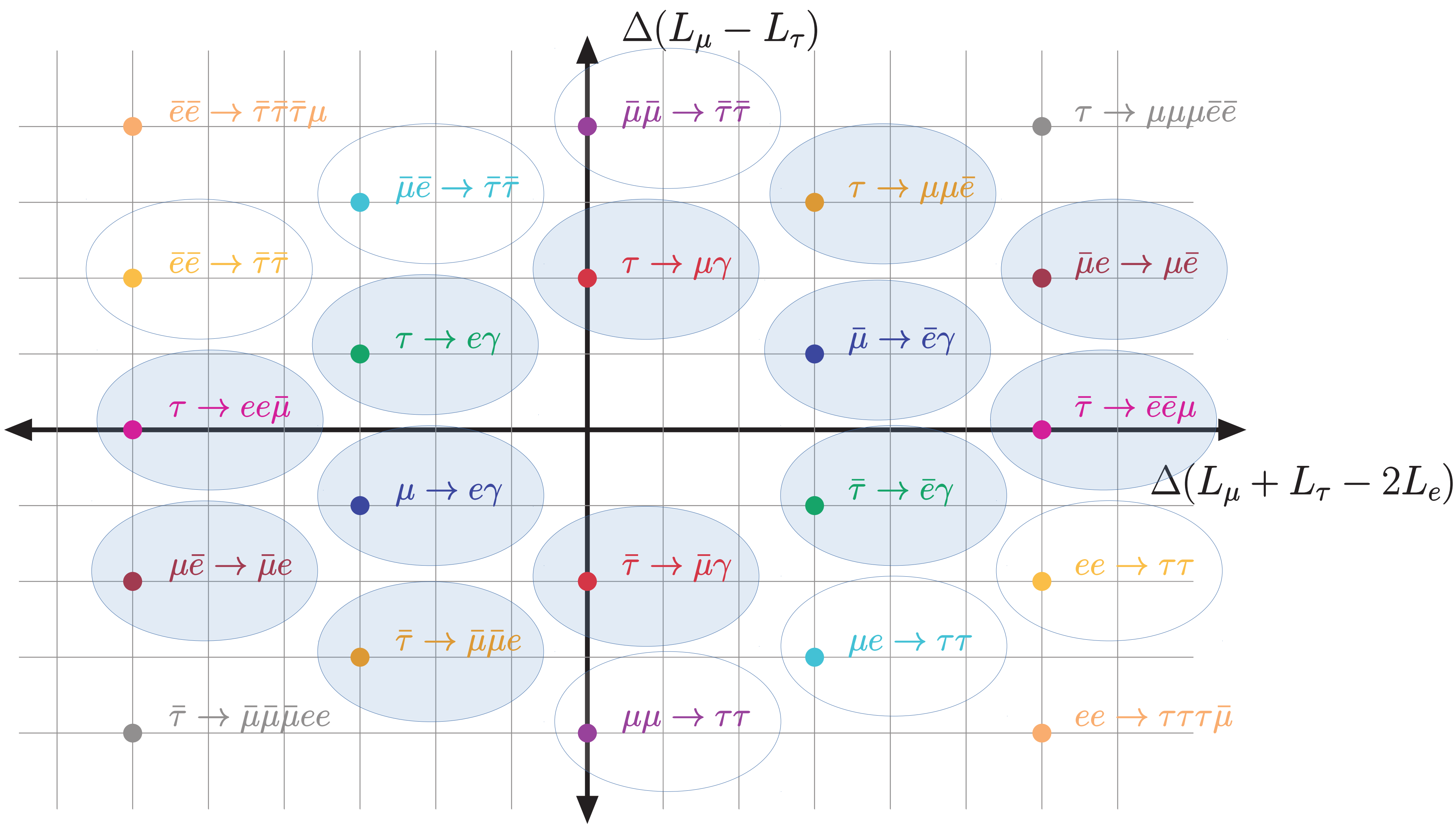
- $Z \to \tau^+ \tau^+ \mu^- \mu^-$ via neutral or doubly-charged boson.
- ϕ^{--} better constrained from $pp \to \phi^{--}\phi^{++} \to \mu^-\mu^-\mu^+\mu^+$.
- Z' testable if $m_{Z'} < \sqrt{s}$ (HL-LHC) or $m_{Z'} < m_Z$ (FCC-ee).

[Altmannshofer, Chen, Dev, Soni, PLB '16]

- Can resolve $(g-2)_\mu$.
- More general $Z \to \tau^+ \tau^+ \ell^- \ell'^-$? [**JH**, in progress]

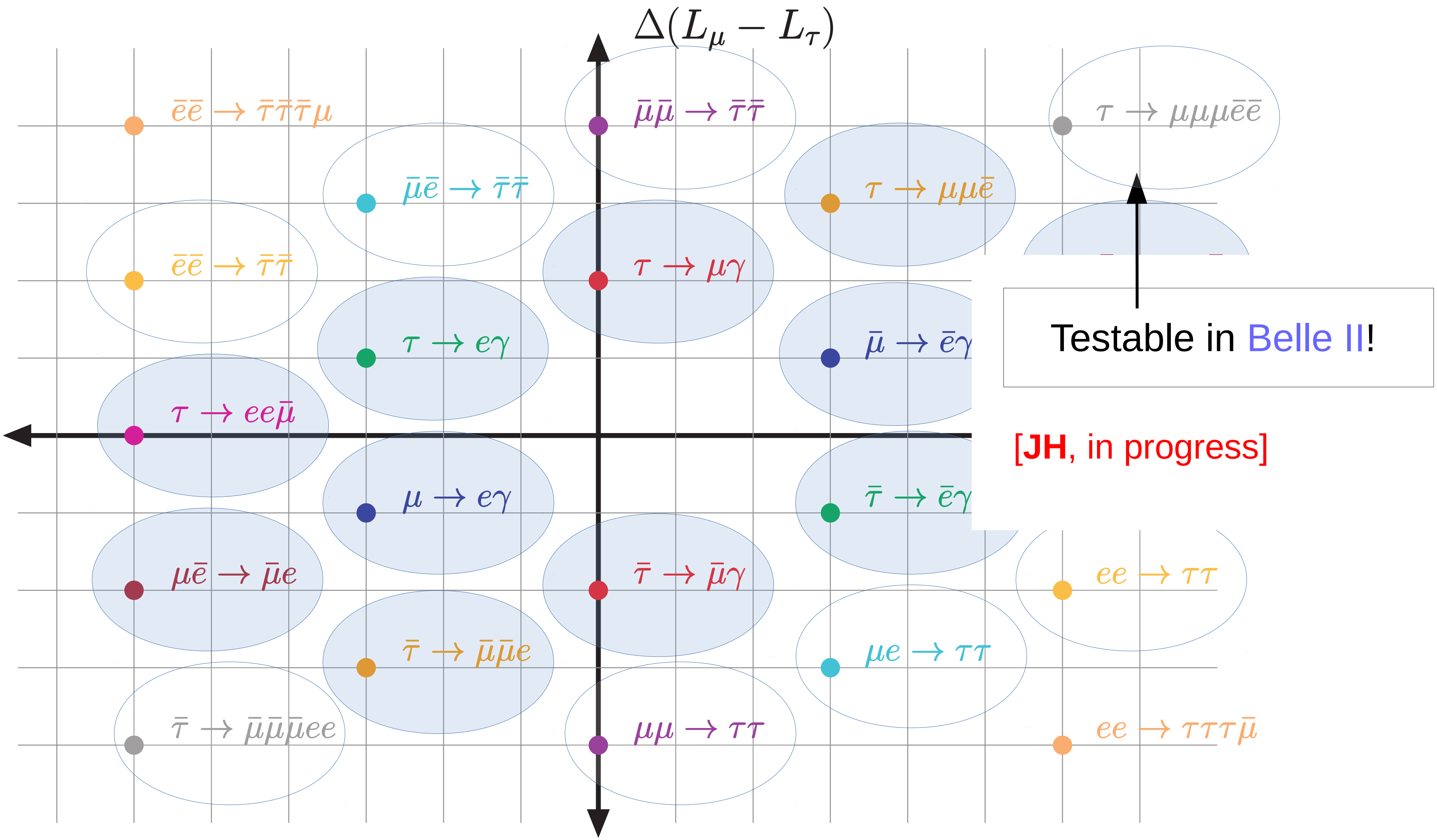
Lepton flavor violation at the energy frontier!

Currently being probed: Doable:



[**JH**, PRD ‘17]

Currently being probed: (shaded ellipse) Doable: (empty ellipse)



[JH, PRD ‘17]

Probing light particles

- Mu3e: BR($\mu \to e\, X$) from 10^{-6} to 10^{-8}.
- Belle II: BR($\tau \to \ell\, X$) from 10^{-3} to 10^{-5}. [**JH**, PLB '16]
- Followed by (displaced) $X \to \ell^+\ell^-$, $\gamma\gamma$? [**JH**, Rodejohann, PLB '17]

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- Mu3e: BR($\mu \to e\, X$) from 10^{-6} to 10^{-8}.
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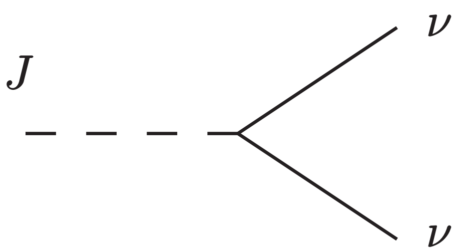
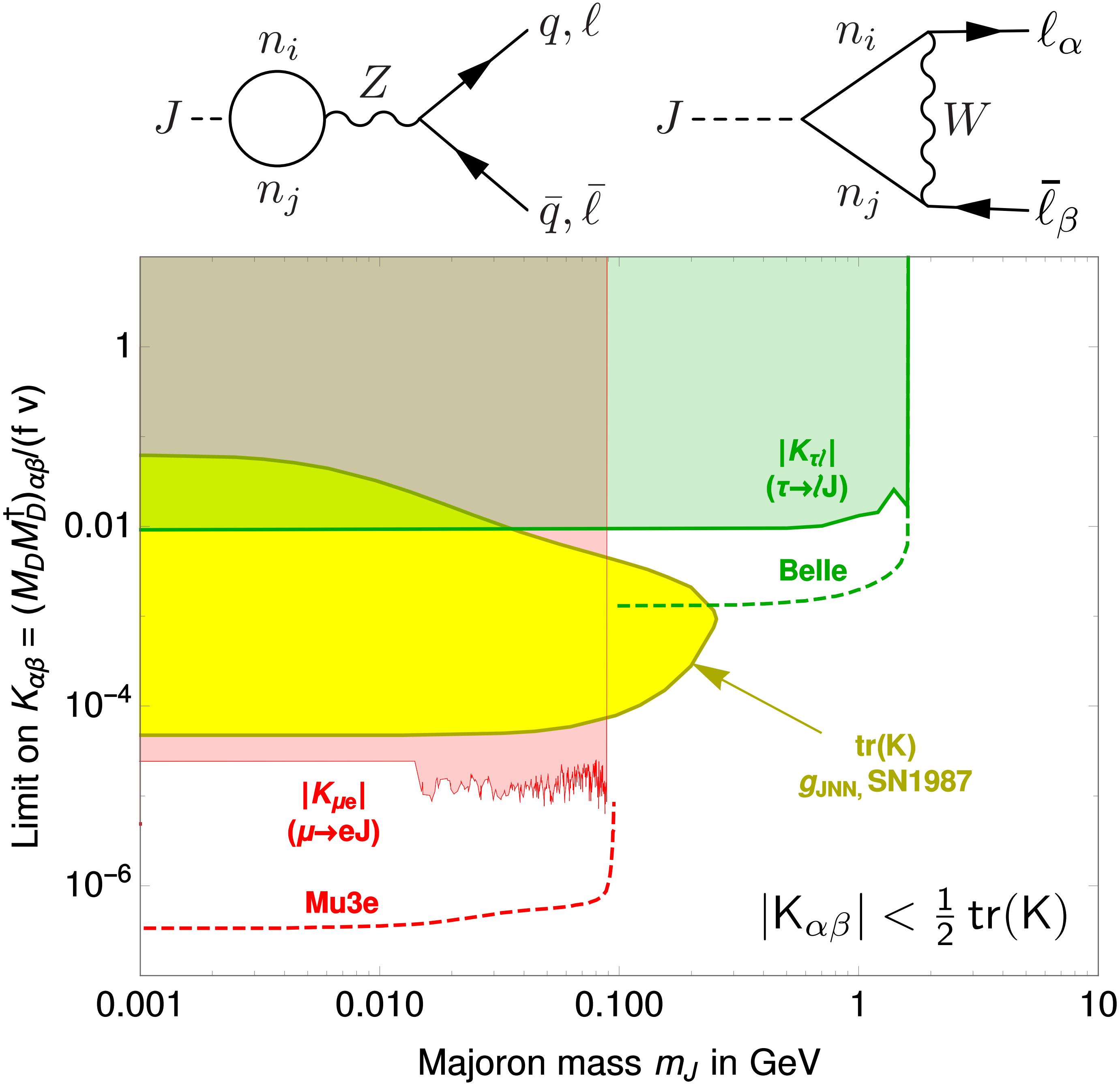
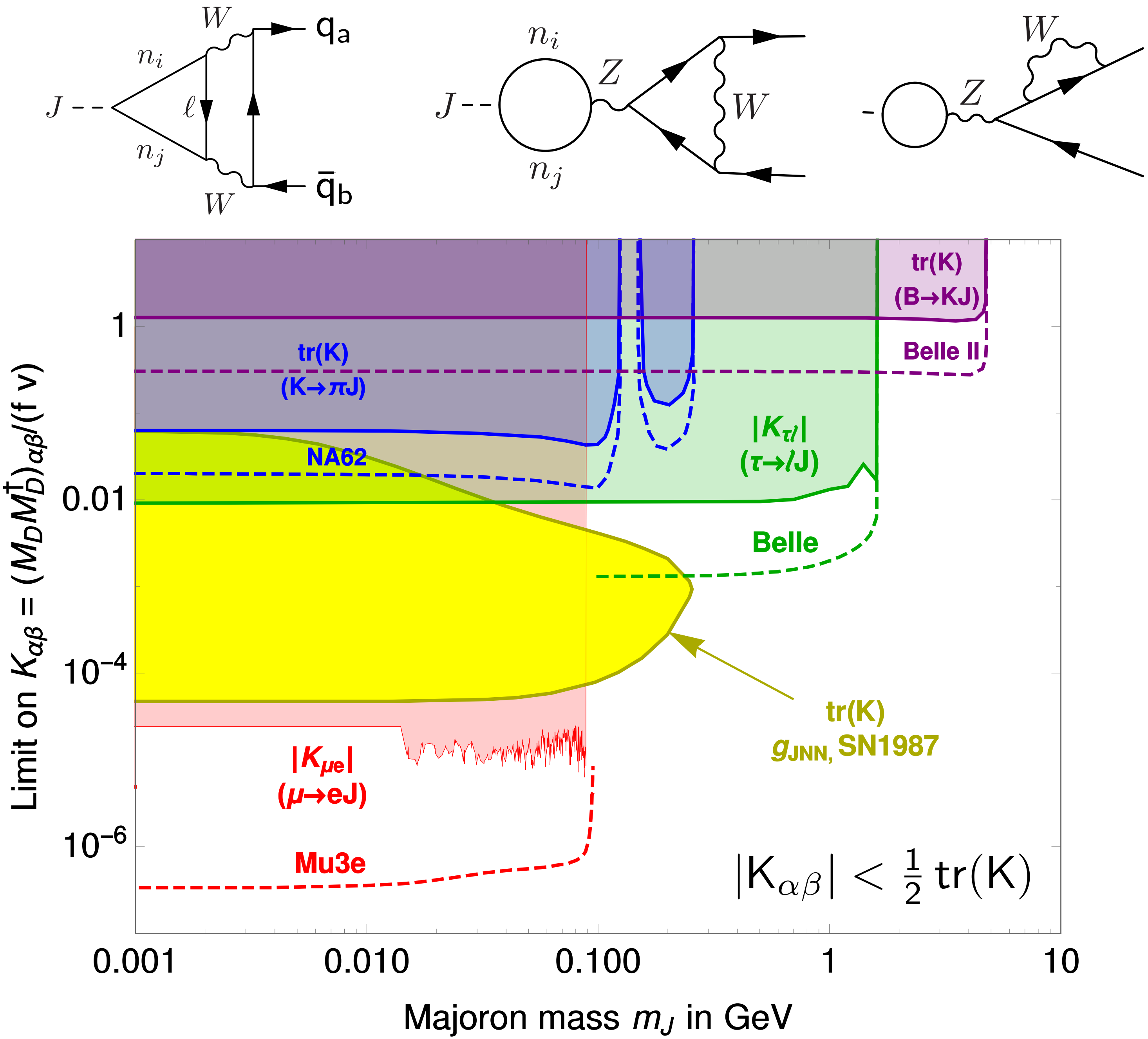
- Followed by (displaced) $X \to \ell^+\ell^-, \gamma\gamma$? [**JH**, Rodejohann, PLB ‘17]
- Example: Majoron.
  - Pseudo-Goldstone boson of lepton number.
  - Potential dark matter candidate. [**JH**, Garcia-Cely, JHEP ‘17]
  - Tree-level coupling only to neutrinos.





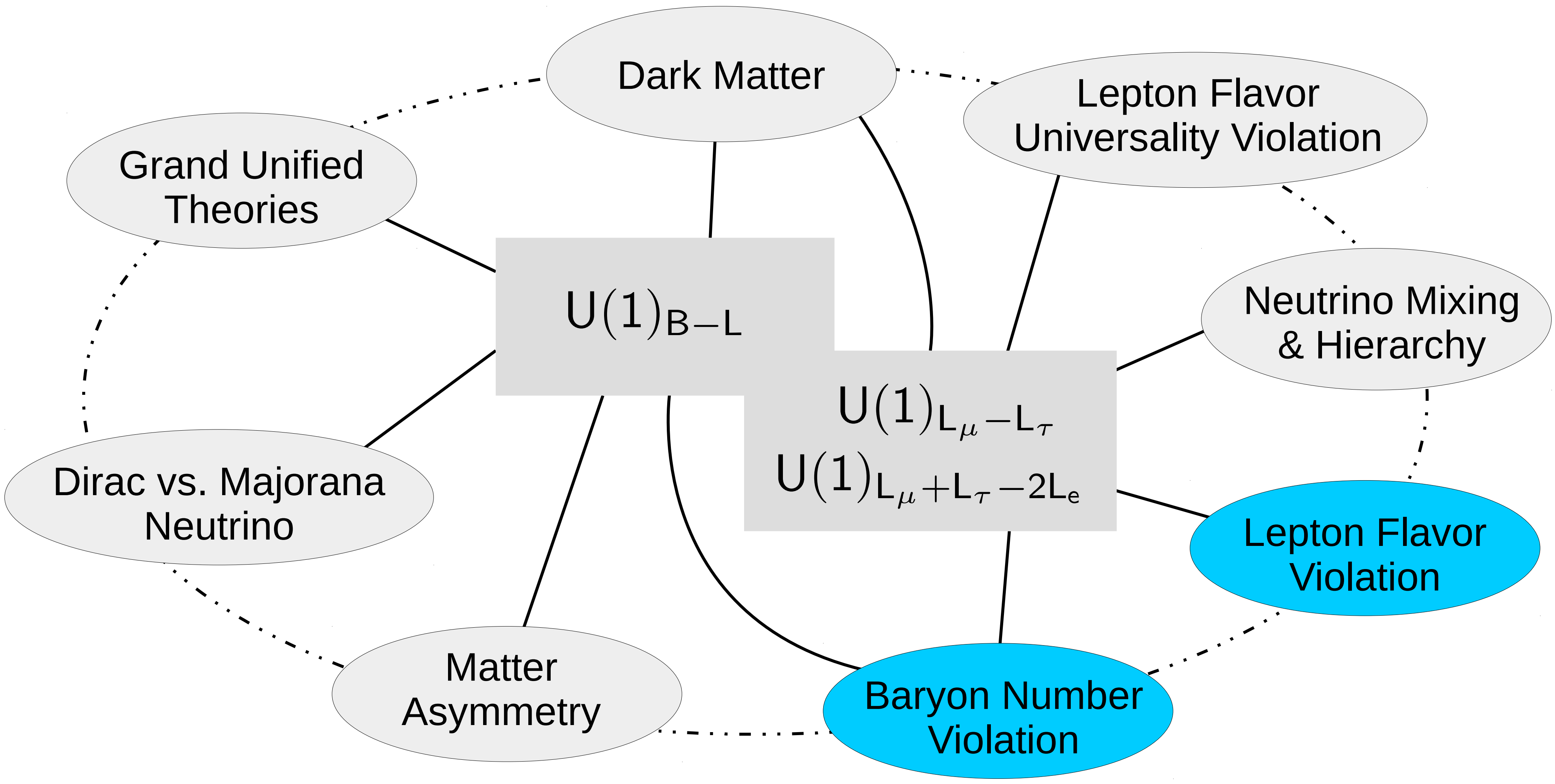
[**JH**, Garcia-Cely, JHEP '17]



[**JH**, Patel, PRD '19]

Lepton flavor violation

- Powerful probe of new physics with mass up to 10^6 GeV.
- More data soon: Mu3e, Mu2e, COMET, Belle II,…
- Full coverage requires colliders: $Z \to \tau^+ \tau^+ \ell^- \ell'^-$.
- More signatures with light new particles!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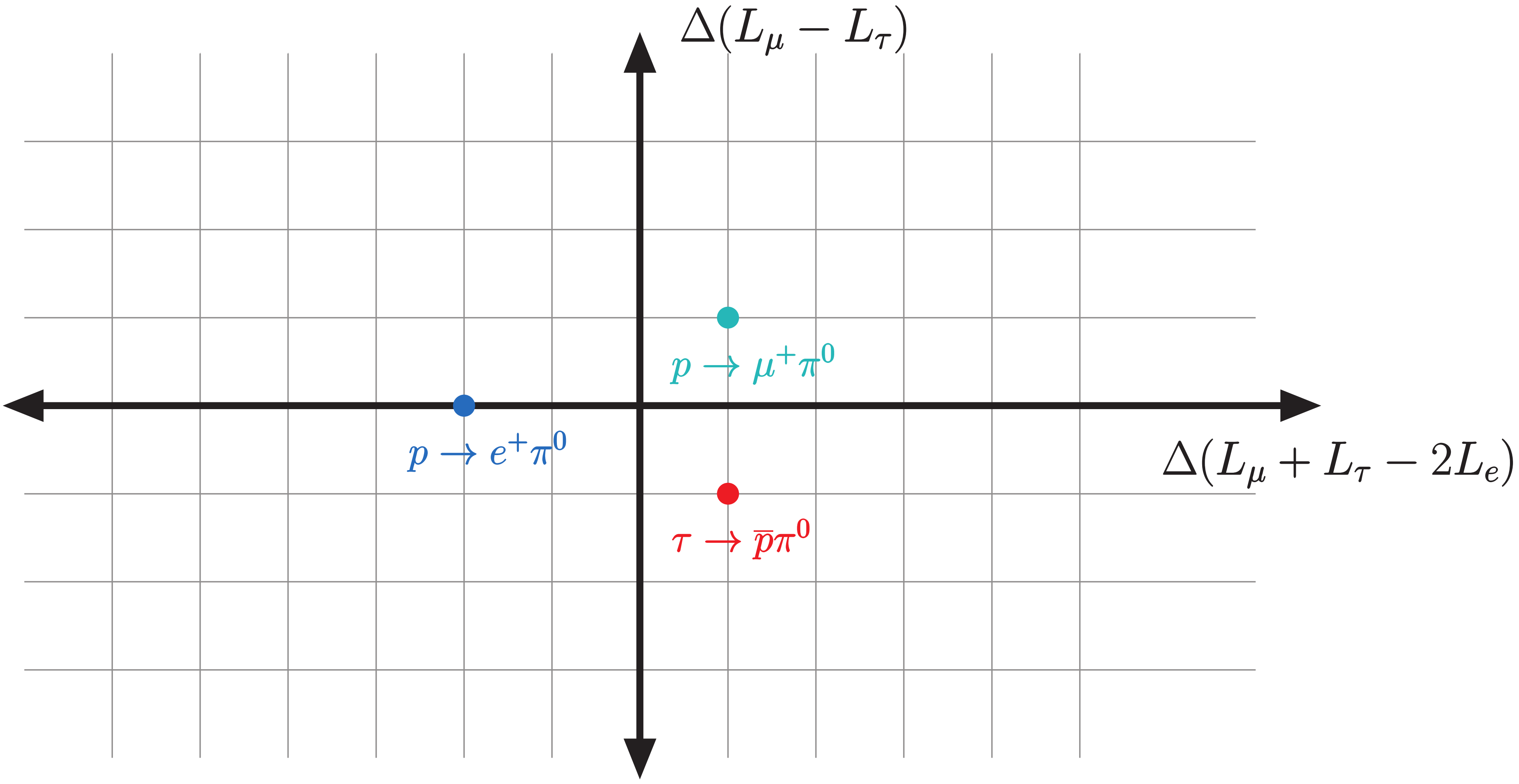
Matter Asymmetry
Baryon Number Violation

Baryon number violation

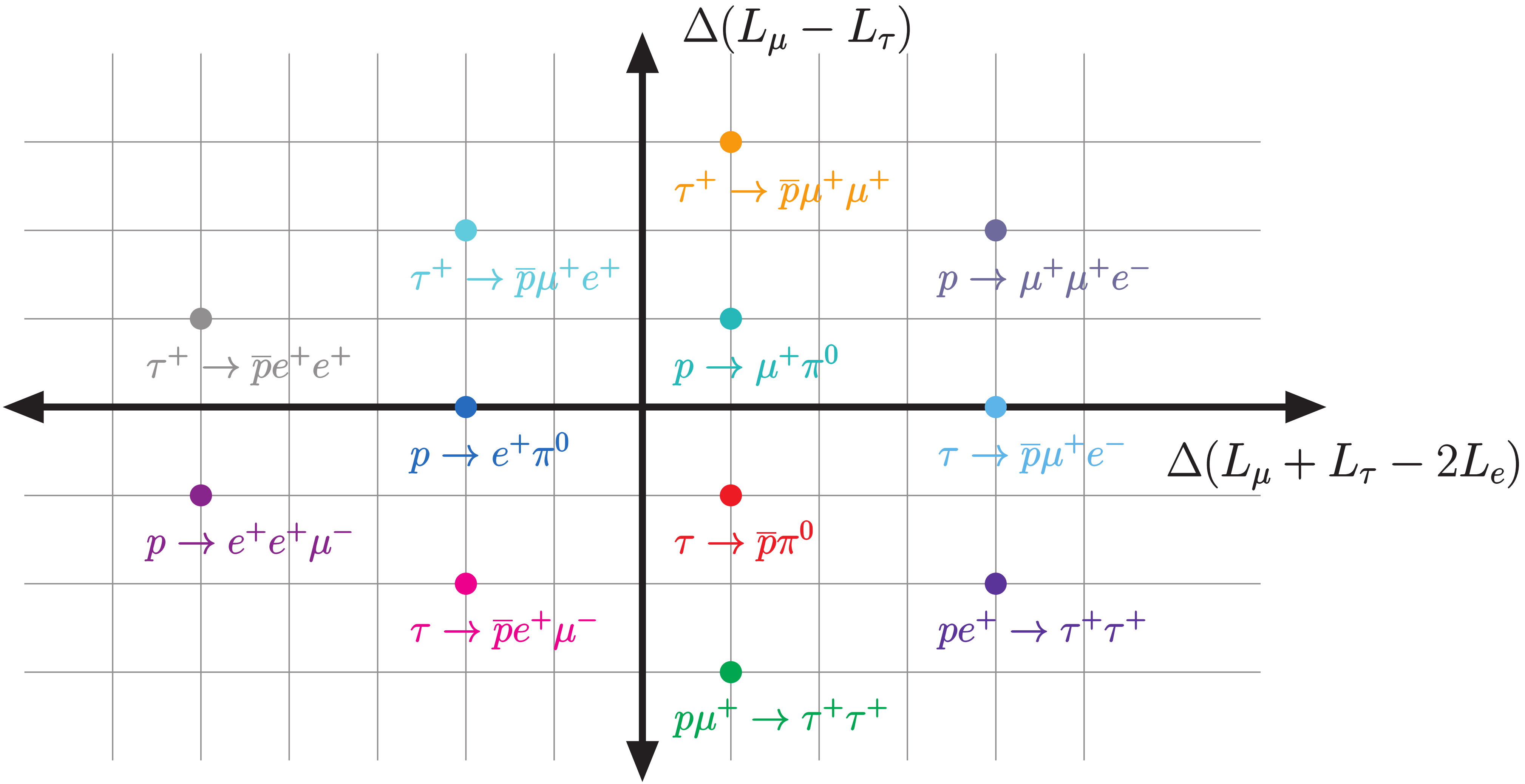
- So far assumed $\Delta B = 0$, but can also do LFV with $\Delta B \neq 0$.
- Example: proton decay ($\Delta B = 1$).
- Super-K limits on $p \to e^+\pi^0$, $\mu^+\pi^0$ are 10^{34} years!
- Probes scales up to 10^{15} GeV!
- Future: JUNO (China), DUNE (US), Hyper-K (Japan).

ΔB = ΔL = 1



$\Delta(L_\mu - L_\tau)$
$p \to \mu^+\pi^0$
$p \to e^+\pi^0$
$\Delta(L_\mu + L_\tau - 2L_e)$
$\tau \to \overline{p}\pi^0$

ΔB = ΔL = 1



$\Delta(L_\mu - L_\tau)$
$\tau^+ \to \overline{p}\mu^+\mu^+$
$\tau^+ \to \overline{p}\mu^+e^+$
$p \to \mu^+\mu^+e^-$
$\tau^+ \to \overline{p}e^+e^+$
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$p \to e^+\pi^0$
$\tau \to \overline{p}\mu^+e^-$
$\Delta(L_\mu + L_\tau - 2L_e)$
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$pe^+ \to \tau^+\tau^+$
$p\mu^+ \to \tau^+\tau^+$

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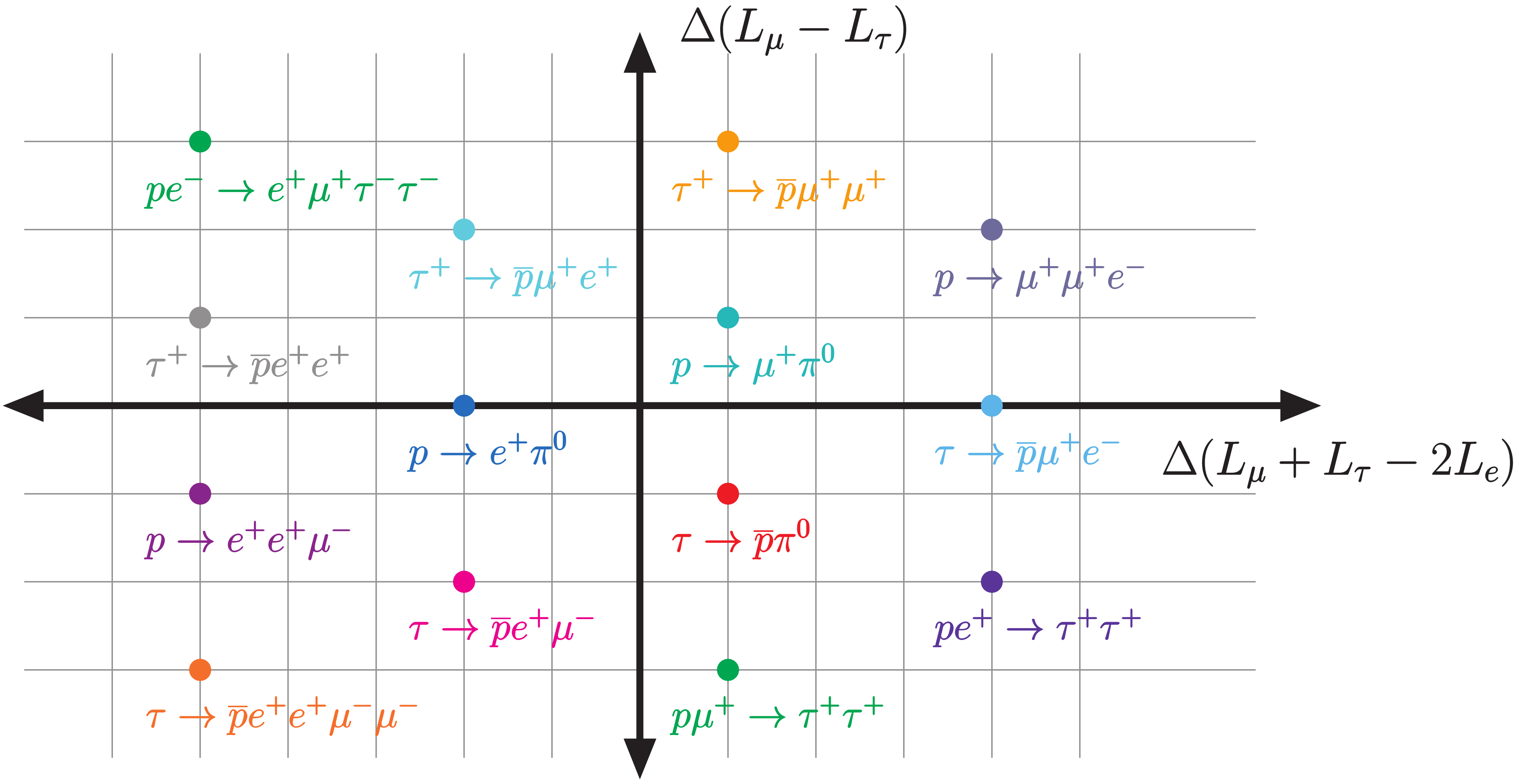

$\Delta(L_\mu - L_\tau)$
$\Delta(L_\mu + L_\tau - 2L_e)$
$pe^- \to e^+\mu^+\tau^-\tau^-$
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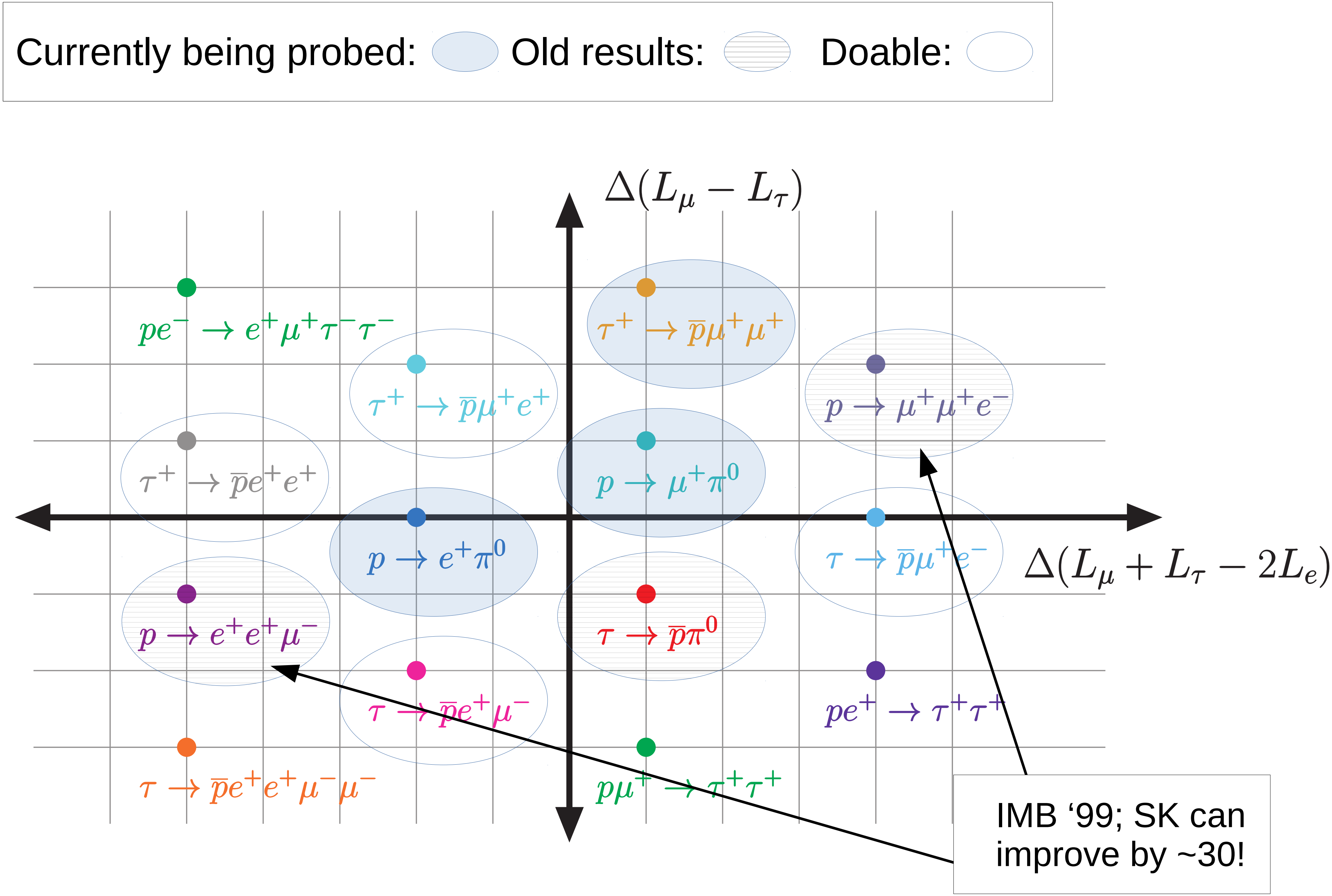


[Hambye, **JH**, PRL '18]

p → μ⁺μ⁺e⁻

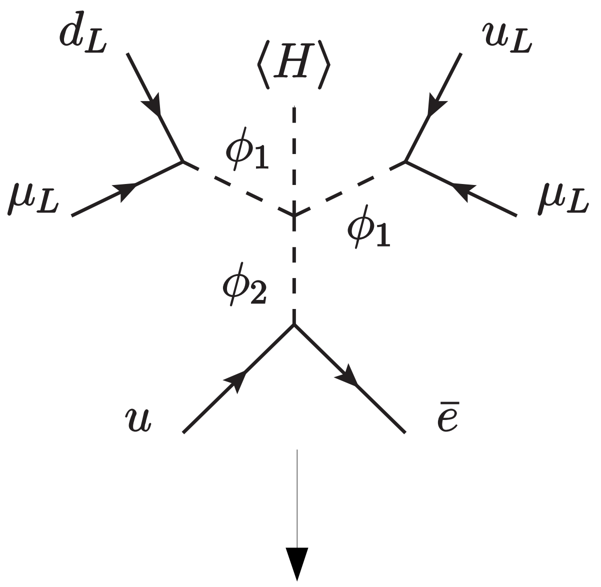
- Minimal leptoquark example:

$$\phi_1 \sim (\mathbf{3}, \mathbf{3}, -2/3)\,,\ \phi_2 \sim (\mathbf{3}, \mathbf{2}, 7/3)\,.$$

- $L_\mu + 2L_e - 3L_\tau$ ensures simple structure

$$y_j \overline{L}_\mu \phi_1 Q^c_j + f_j \overline{u}_j \phi_2 L_e + \lambda \phi_1^2 \phi_2 H\,.$$

- Final ΔB=1 operator: $\frac{1}{\Lambda^6} Q Q u L_\mu L_\mu \overline{L}_e H$.
- Lattice QCD input: $\langle 0 | uud | p \rangle$.



$$\frac{1}{\Lambda^6} \sim \frac{\lambda y_1^2 f_1}{m^4_{\phi_1} m^2_{\phi_2}}$$

$$\Gamma(p \to \mu^+ \mu^+ e^-) \simeq \frac{\langle H \rangle^2 \beta^2 m_p^5}{6144 \pi^3 \Lambda^{12}} \simeq \frac{(100\,\mathrm{TeV}/\Lambda)^{12}}{10^{33}\,\mathrm{yr}}$$

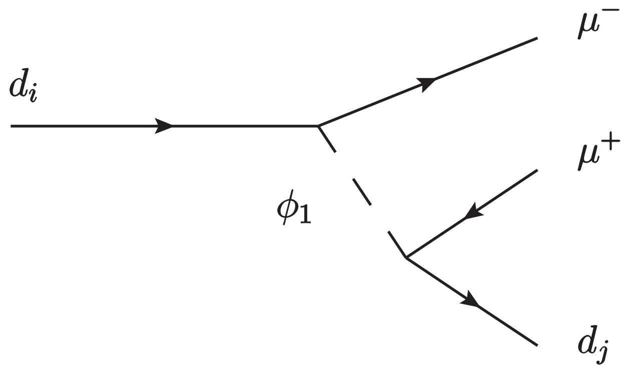
[Hambye, **JH**, PRL '18]

Lepton universality in $b \to s\mu^-\mu^+$

- $\frac{y_j \bar{y}_i}{m^2_{\phi_1}} (\overline{L}_\mu Q^c_j)(Q_i L_\mu)$.

- Modifies $b \to s\mu^-\mu^+$:

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



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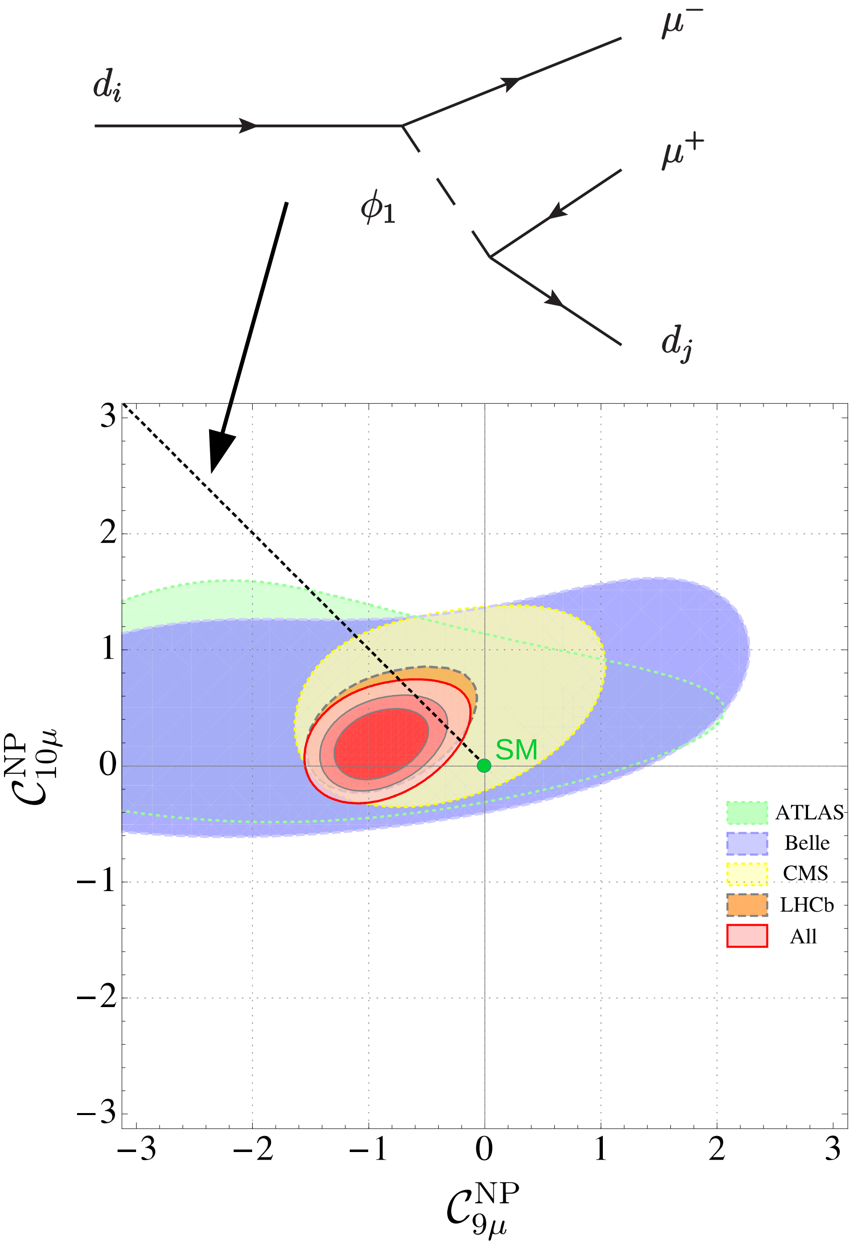
- LHCb: R(K)~0.85, R(K*)~0.67.

- Improve fit with

$$m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3} .$$

[Alok+, PRD '17; Dorsner+, JHEP '17; Capdevila+, JHEP '18, Algueró+, EPJC '19]



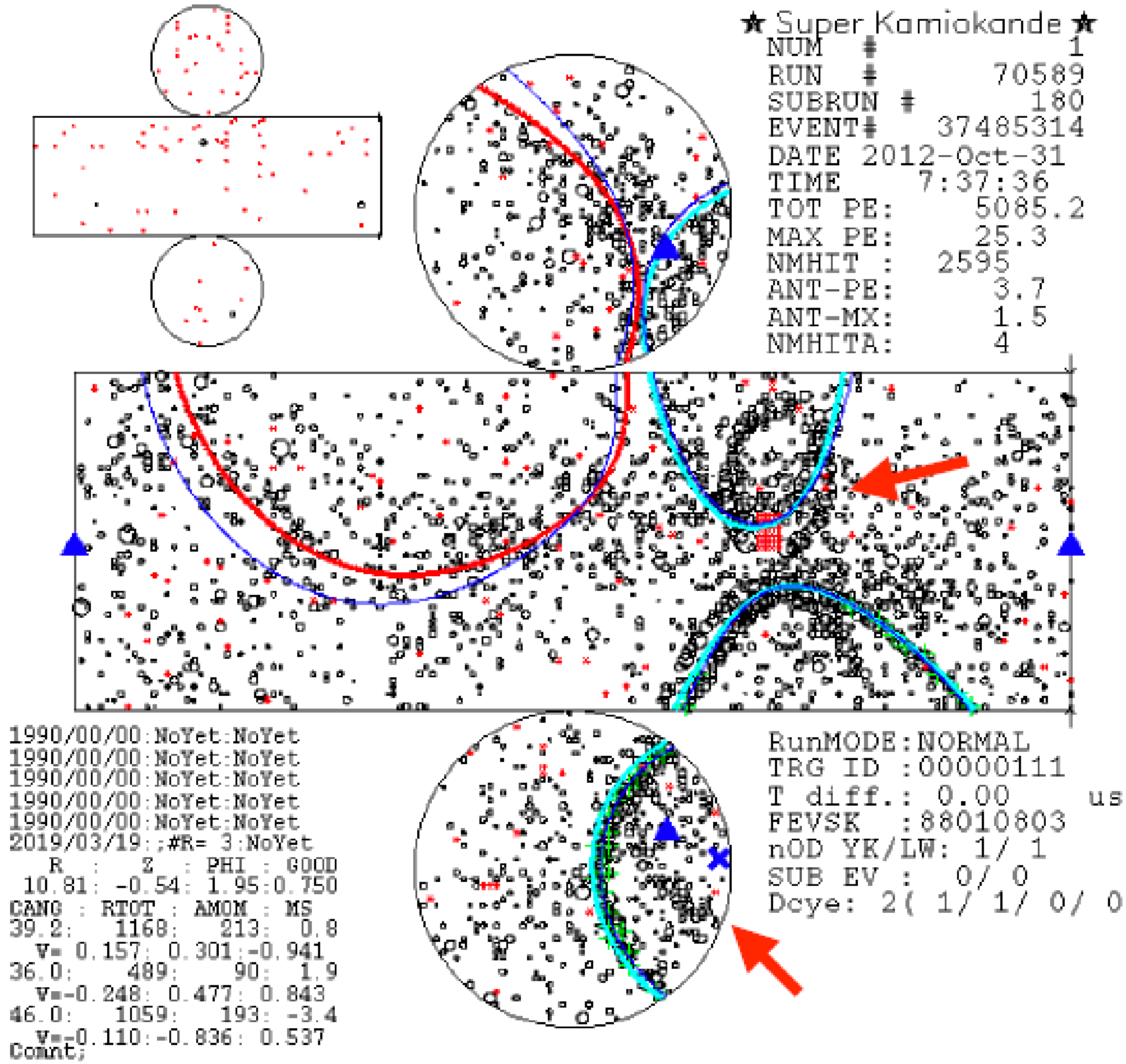
[Algueró+, EPJC '19]

Preliminary!

p→eμμ

- Super-K searched for p → ℓℓℓ!
- Presented by Makoto Miura at BLV 2019 in Madrid.

[full paper: arXiv:2001.08011]



Preliminary!

- Super-K searched for $p \to \ell\ell\ell$!
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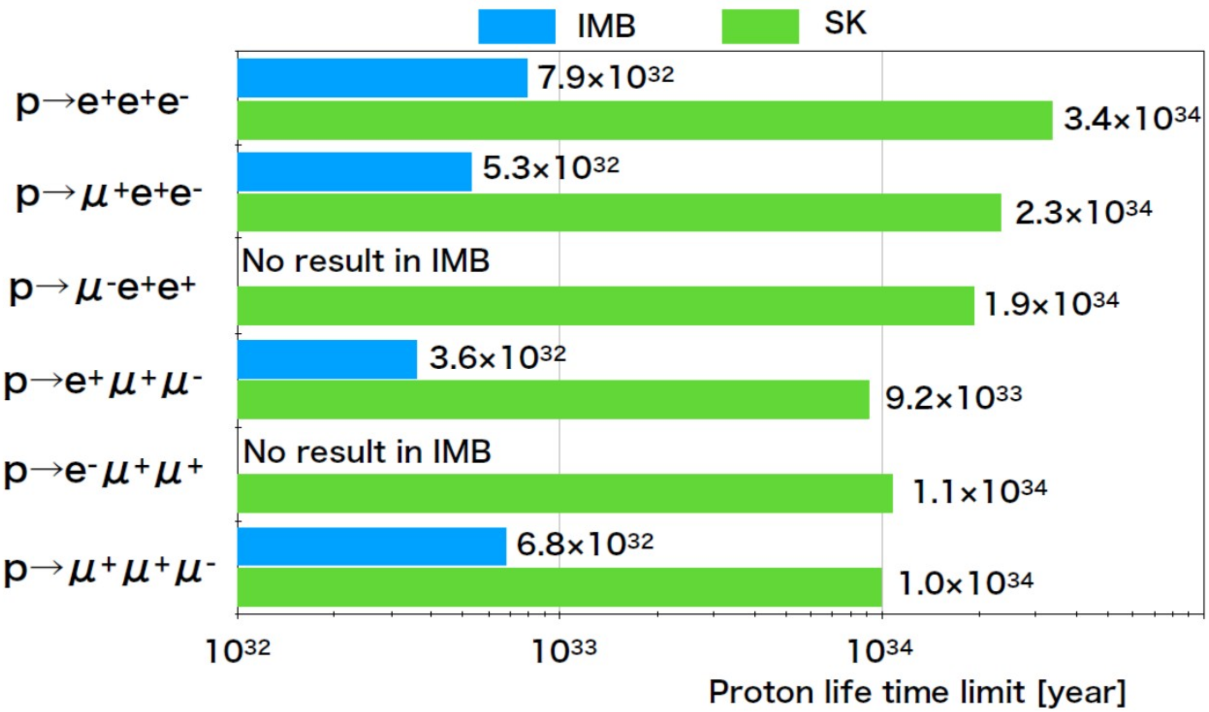
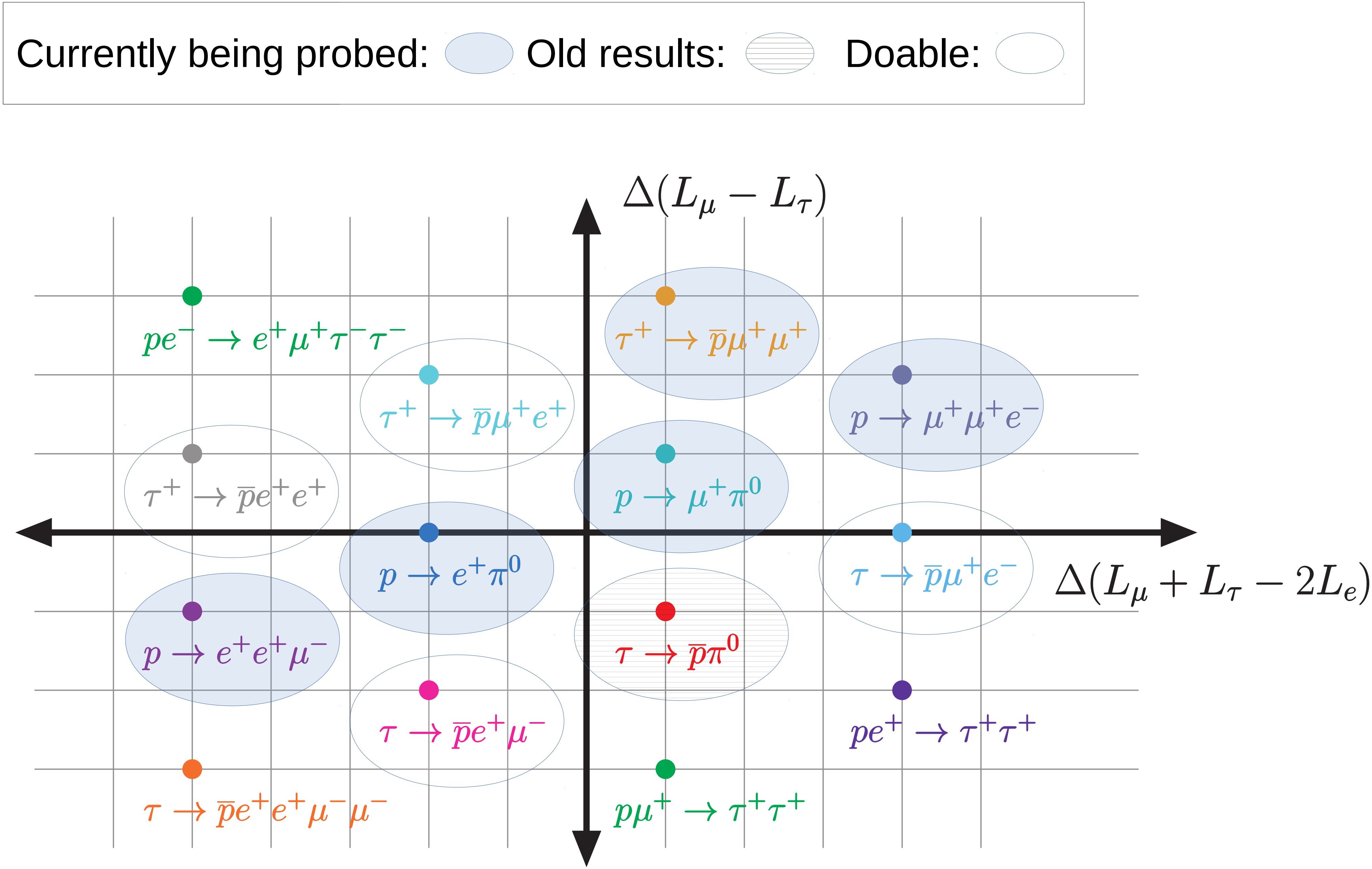
[full paper: arXiv:2001.08011]



Compatible with background, limits around 10^{34} yr.



Currently being probed:
Old results:
Doable:
$\Delta(L_\mu - L_\tau)$
$\Delta(L_\mu + L_\tau - 2L_e)$
$pe^- \to e^+\mu^+\tau^-\tau^-$
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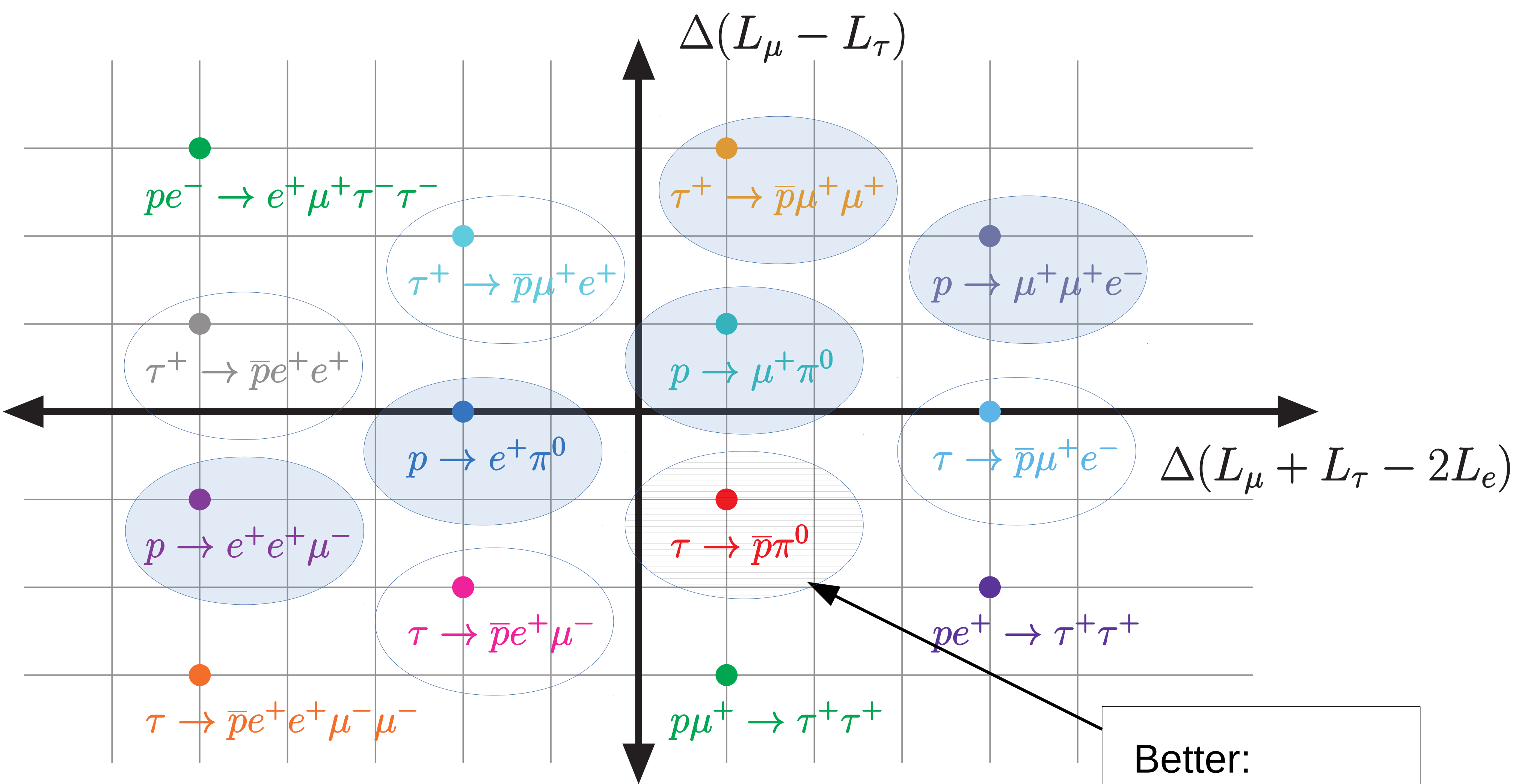
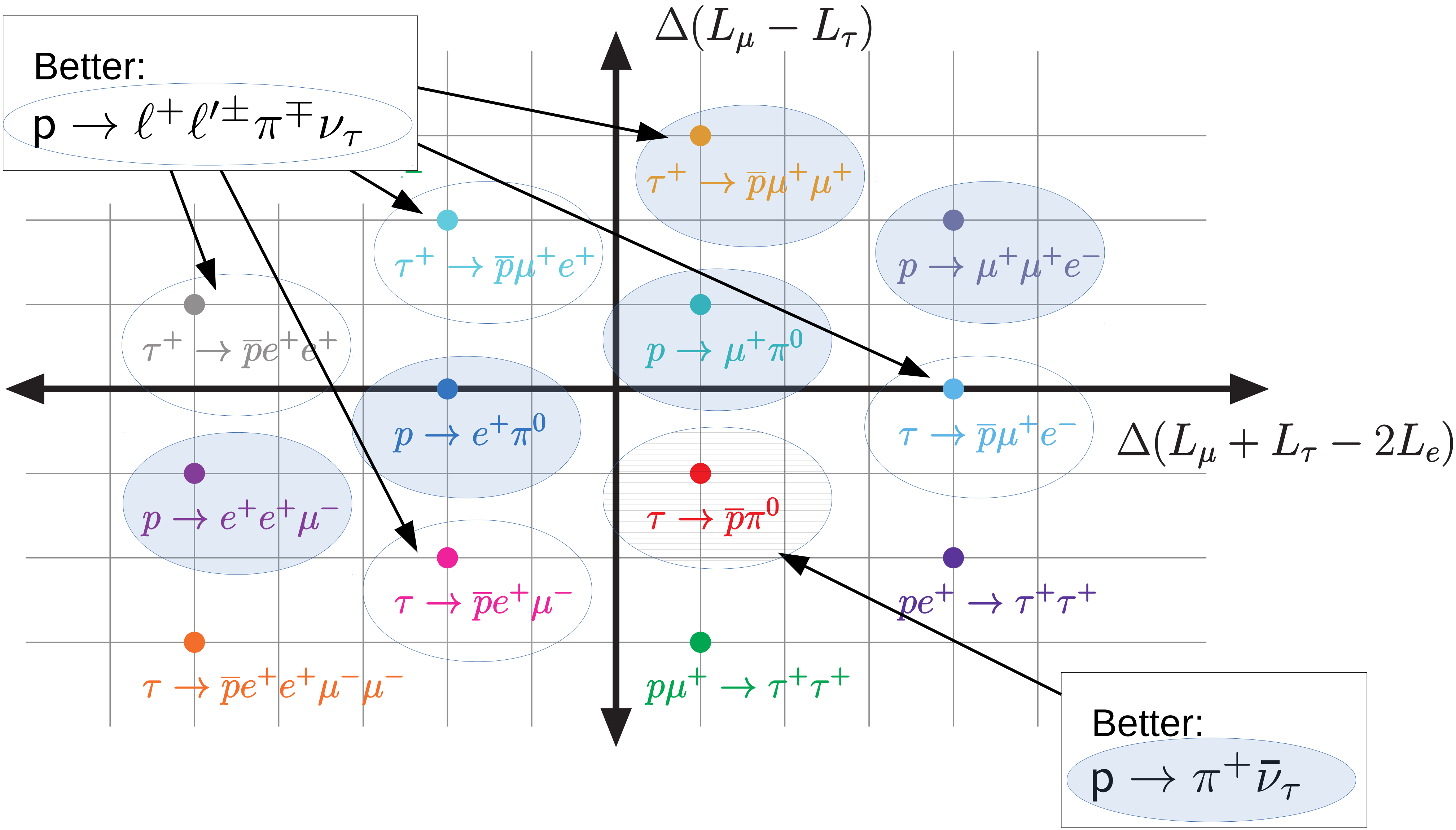


Better:
$p \to \pi^+\bar{\nu}_\tau$

[Marciano, NPB '95]

Currently being probed: Old results: Doable:



[Marciano, NPB '95]

Full coverage

- Super-K cannot to go through all $\Delta B > 0$ decays:
  - 38 two-body $\Delta B = 1$ modes: $N \to A B$.
  - 76 three-body $\Delta B = 1$ modes: $N \to A B C$.
  - 118 two-body $\Delta B = 2$ modes: $N N \to A B$…
- Exclusive searches reach $t \sim 10^{34}$ yr.

Full coverage

- Super-K cannot to go through all $\Delta B > 0$ decays:
  - 38 two-body $\Delta B = 1$ modes: $N \rightarrow AB$.
  - 76 three-body $\Delta B = 1$ modes: $N \rightarrow ABC$.
  - 118 two-body $\Delta B = 2$ modes: $NN \rightarrow AB$…
- Exclusive searches reach $t \sim 10^{34}$ yr.
- Inclusive, e.g. $p \rightarrow e^+ +$ anything, could reach 10^{32} yr.
  - E.g. $\Gamma^{-1}(p \to e^+ \nu\nu) > 1.7 \times 10^{32}$ yr. [Super-K, PRL '14]
- Also probes $\Delta B > 1$ and *light new physics*!

[**JH**, Takhistov, PRD '20]

ΔB & light new physics

- Light new fermion χ:
  - $\frac{udd\chi}{\Lambda^2}$: sterile neutron.
  - $m_\chi \ll m_n : n \to \pi^0 \bar{\chi}$.

    [Davoudiasl, PRL '15]
  - $m_\chi \gtrsim m_n : B^+ \to p\chi$, $\chi \to \bar{p}\pi^+$

- Light new boson φ:
  - $\frac{QQQL\varphi}{\Lambda^3}$.
  - $m_\varphi \ll m_p : p \to e^+ \bar{\varphi}$.
  - $m_\varphi \gtrsim m_p : B^0 \to \bar{p}\, e^+ \bar{\varphi}$,

    $t \to \bar{u}\, \bar{b}\, \mu^+ \bar{\varphi}, \ldots$

- Brings baryon number violation to the energy frontier!
- χ or φ as (asymmetric) dark matter?

[**JH**, in progress]

Summary

- Standard Model symmetry/prediction:

$$\mathbb{Z}_3^{(\mathsf{B+L})/2} \times \mathsf{U}(1)_{\mathsf{B-L}} \times \mathsf{U}(1)_{\mathsf{L}_\mu - \mathsf{L}_\tau} \times \mathsf{U}(1)_{\mathsf{L}_\mu + \mathsf{L}_\tau - 2\mathsf{L}_e} \,.$$

- Violated? New particles! How? New structure!
- Exciting data is coming:
  - LFV: Mu3e, Mu2e, COMET, Belle II.
  - ΔB: JUNO, DUNE, Hyper-Kamiokande.
- Still untapped potential:
  - Inclusive searches increase coverage.
  - Light new physics ($\ell \to \ell' + X$, $p \to \ell^+ + X$, $B^+ \to p + X$,…).
- Connected to dark matter or baryon asymmetry?

Road map to new physics