HUGS 2018
Jefferson Lab, Newport News, VA
May 29- June 15 2018

# Fundamental Symmetries - 3

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# Plan of the lectures

- Review symmetry and symmetry breaking

- Introduce the Standard Model and its symmetries

- Beyond the SM:
  - hints from current discrepancies?
  - effective theory perspective

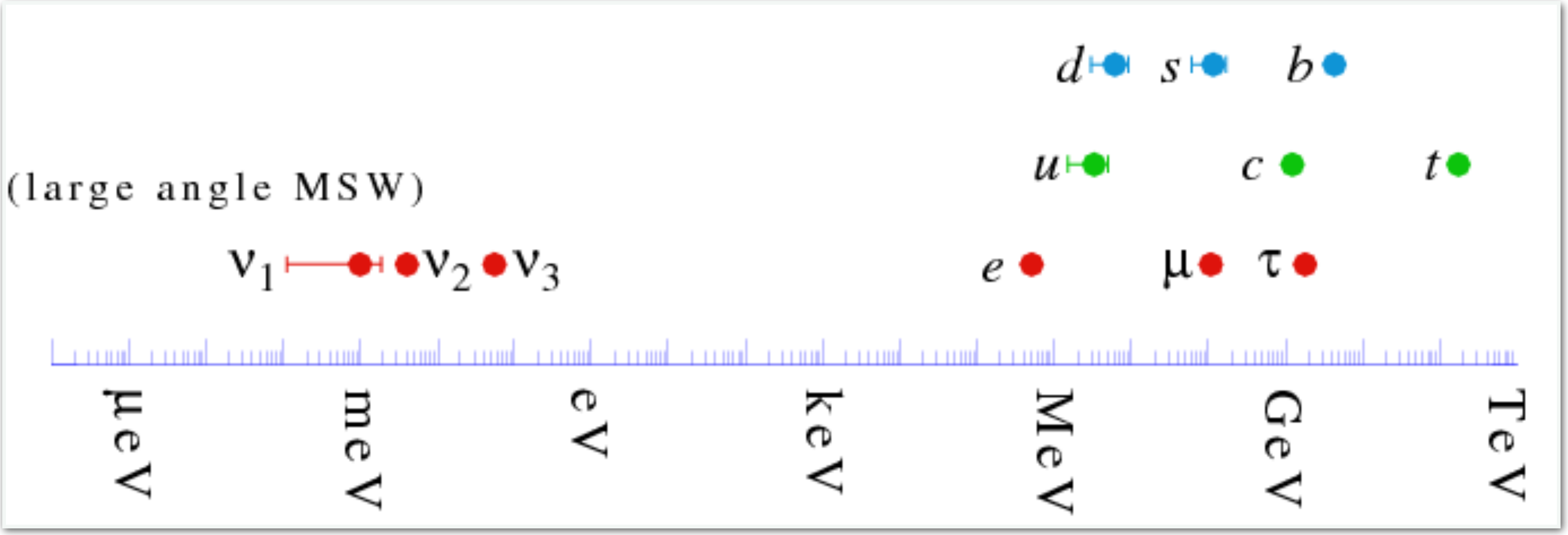
- Discuss a number of "worked examples"
  - Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
  - Symmetry tests: CP (T) violation and EDMs; Lepton Number violation and neutrino-less double beta decay.

# Status of the Standard Model

- Tested at the loop level in both electroweak and flavor sector

- Experimental hints pointing to new physics:
    - Neutrino mass
        - Sterile neutrinos?
    - Few-sigma discrepancies in precision physics
        - Muon g-2
        - Lepton universality in B meson decays
        - Neutron lifetime:  beam vs bottle
        - …

# What about neutrino masses?



arXiv:1010.4131

# What about neutrino masses?

- Neutrino mass requires new degrees of freedom
  - Lorentz invariant “mass terms” for fermions

(1)

$$m_D \, \overline{\psi_L} \, \psi_R \; + \; \text{h.c.}$$

(2)

$$m_M \, \psi_L^T \, C \psi_L \; + \; \text{h.c.}$$

  - In the case of neutrinos:
    - option (1) requires introducing $\nu_R$ and using Higgs to make it SU(2) gauge invariant (as for other fermions)
    - option (2) is not SU(2) gauge invariant

# What about neutrino masses?

- Neutrino mass requires new degrees of freedom
- Simple / natural option: three R-handed neutrinos $\nu_{Ri}$ (gauge singlets)

$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\frac{1}{2}\nu_R^T C M_R \nu_R + \bar{\ell} Y_\nu \nu_R \tilde{\varphi} + \text{h.c.}\right)$$

Both allowed by gauge symmetry

Mass term breaks $U(1)_L$

$$\ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e \qquad \nu_R \to e^{i\alpha}\nu_R$$

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$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left( \xcancel{\frac{1}{2}\nu_R^T C M_R \nu_R} + \bar{\ell}\, Y_\nu\, \nu_R\, \tilde{\varphi} + \text{h.c.} \right)$$

- Dirac neutrinos: $M_R = 0$. Complete analogy to quark sector (B → L), except for tiny ($O(10^{-10})$) Yukawa couplings

$$Y_e = V_{e_L}^\dagger Y_e^{\text{diag}} V_{eR}$$

$$Y_\nu = V_{\nu_L}^\dagger Y_\nu^{\text{diag}} V_{\nu R}$$

$$\Rightarrow \boxed{\frac{g}{\sqrt{2}} W_\mu^- \; \bar{e}_L^\alpha \, \gamma^\mu U^{\alpha i} \, \nu_L^i}$$

$$U = V_{e_L} V_{\nu_L}^\dagger$$

Unitary mixing in CC vertex: 3 angles, 1 phase

- Majorana neutrinos: $M_R \neq 0$. L not conserved

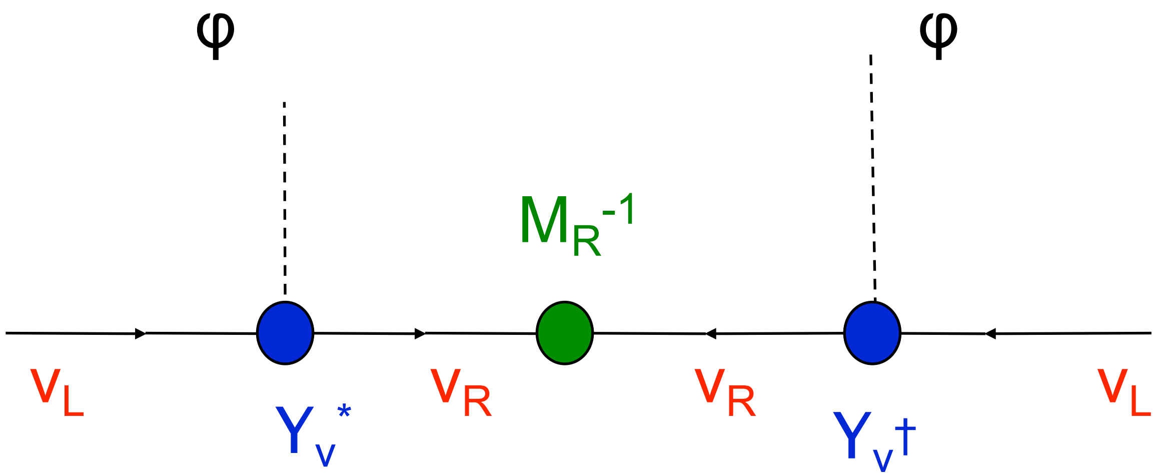
$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\frac{1}{2}\nu_R^T C M_R \nu_R + \bar{\ell}\, Y_\nu\, \nu_R \tilde{\varphi} + \text{h.c.}\right)$$

- In general 6x6 mass matrix for $\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$: six Majorana ($\nu=\nu^c$) eigenstates
- If $M_R >> vY_\nu$: 3 light ($\nu_L \rightarrow \nu_i$) and 3 heavy ($\nu_R \rightarrow N_i$) eigenstates

$$\mathcal{L}_{\nu SM} \supset -\frac{1}{2}\nu_L^T\, C\, m_\nu\, \nu_L$$

$$m_\nu = v^2\, Y_\nu^*\, M_R^{-1}\, Y_\nu^\dagger$$

We could have written this term without reference to $\nu_R$ and in SU(2) gauge-invariant form (more later)



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- If $M_R >> vY_\nu$: 3 light ($\nu_L \rightarrow \nu_i$) and 3 heavy ($\nu_R \rightarrow N_i$) eigenstates
- Mixing of 3 light Majorana neutrinos: $$\mathcal{L}_{\nu SM} \supset -\frac{1}{2}\nu_L^T C\, m_\nu\, \nu_L$$

$$m_\nu = V_{\nu_L}^T m_\nu^{\text{diag}} V_{\nu_L}$$

$$Y_e = V_{e_L}^\dagger Y_e^{\text{diag}} V_{e_R}$$

$$\Rightarrow$$

$$\boxed{\frac{g}{\sqrt{2}} W_\mu^- \, \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \, \nu_L^i}$$

$$U = V_{e_L} V_{\nu_L}^\dagger$$

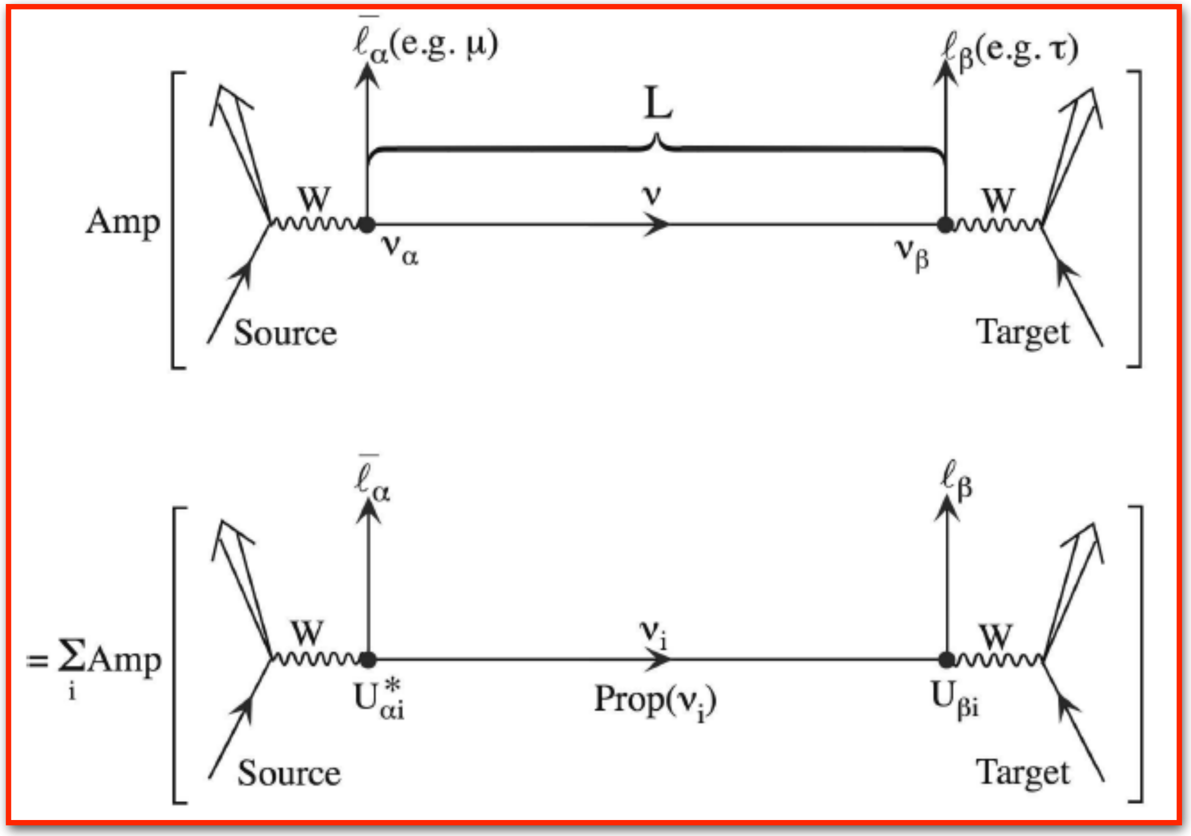
Unitary mixing in CC vertex: 3 angles, 1+2 phases

$$U = U_{\text{Dirac}} \times \begin{pmatrix} 1 & & \\ & e^{i\alpha_1} & \\ & & e^{i\alpha_2} \end{pmatrix}$$

# Neutrino phenomenology

- $\mathcal{L}_{\nu\mathrm{SM}}$ probed at the Intensity Frontier (accelerator, reactor) and Cosmic Frontier (solar, atmospheric, astro)
- Oscillation experiments sensitive to mass splittings and mixing angles

Image credit: B. Kayser



$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix},$$

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \times \frac{1}{2}\left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

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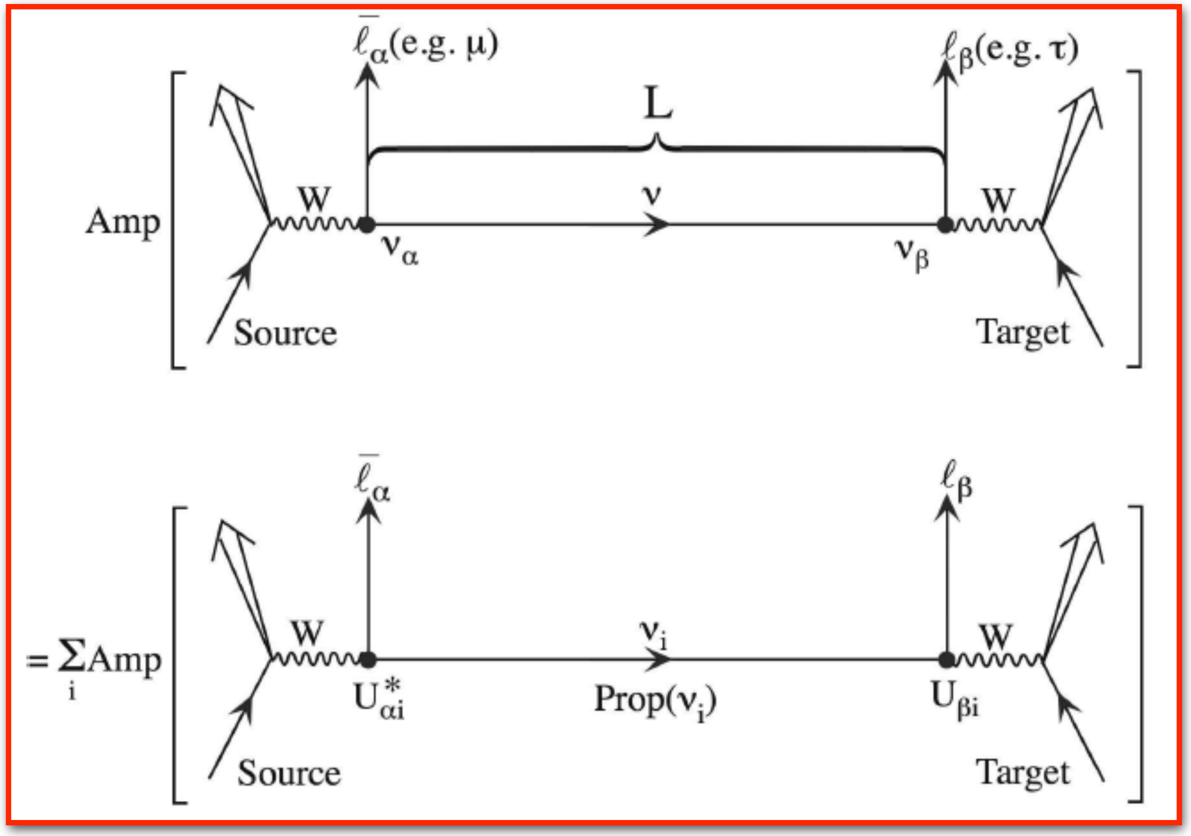

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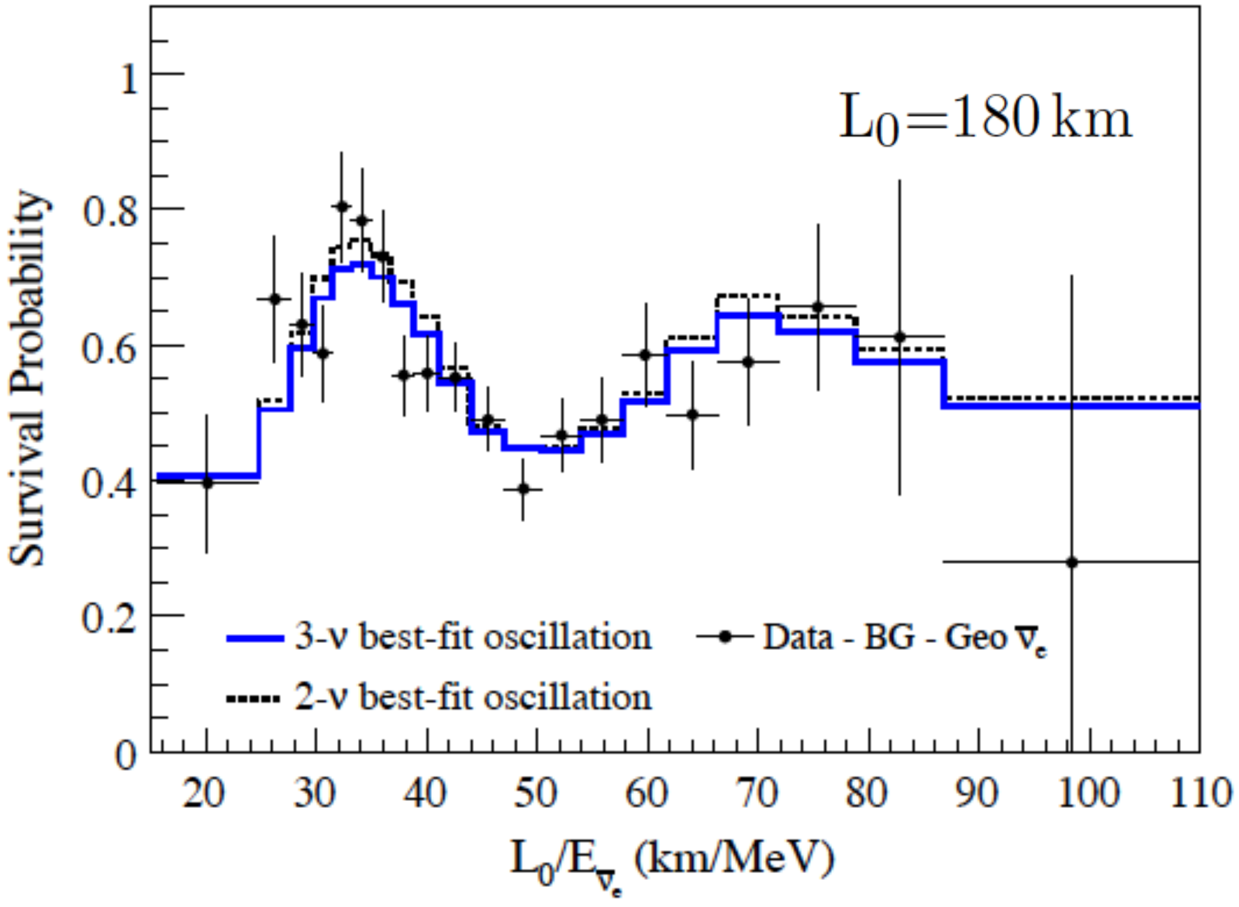
**KAMLAND 2011**



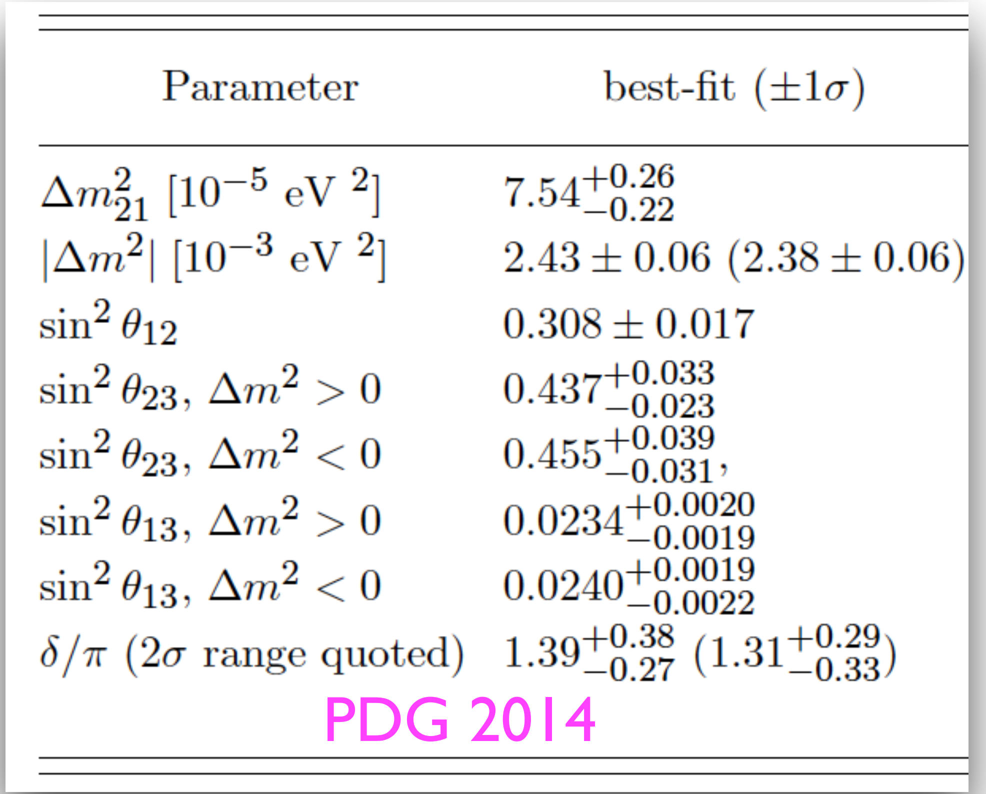
**Reactor electron anti-neturino survival probability**

# Neutrino phenomenology

- $\mathcal{L}_{\nu SM}$ probed at the Intensity Frontier (accelerator, reactor) and Cosmic Frontier (solar, atmospheric, astro)
- Oscillation experiments sensitive to mass splittings and mixing angles

World data consistent with 3 light states,
but other light ν not excluded

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

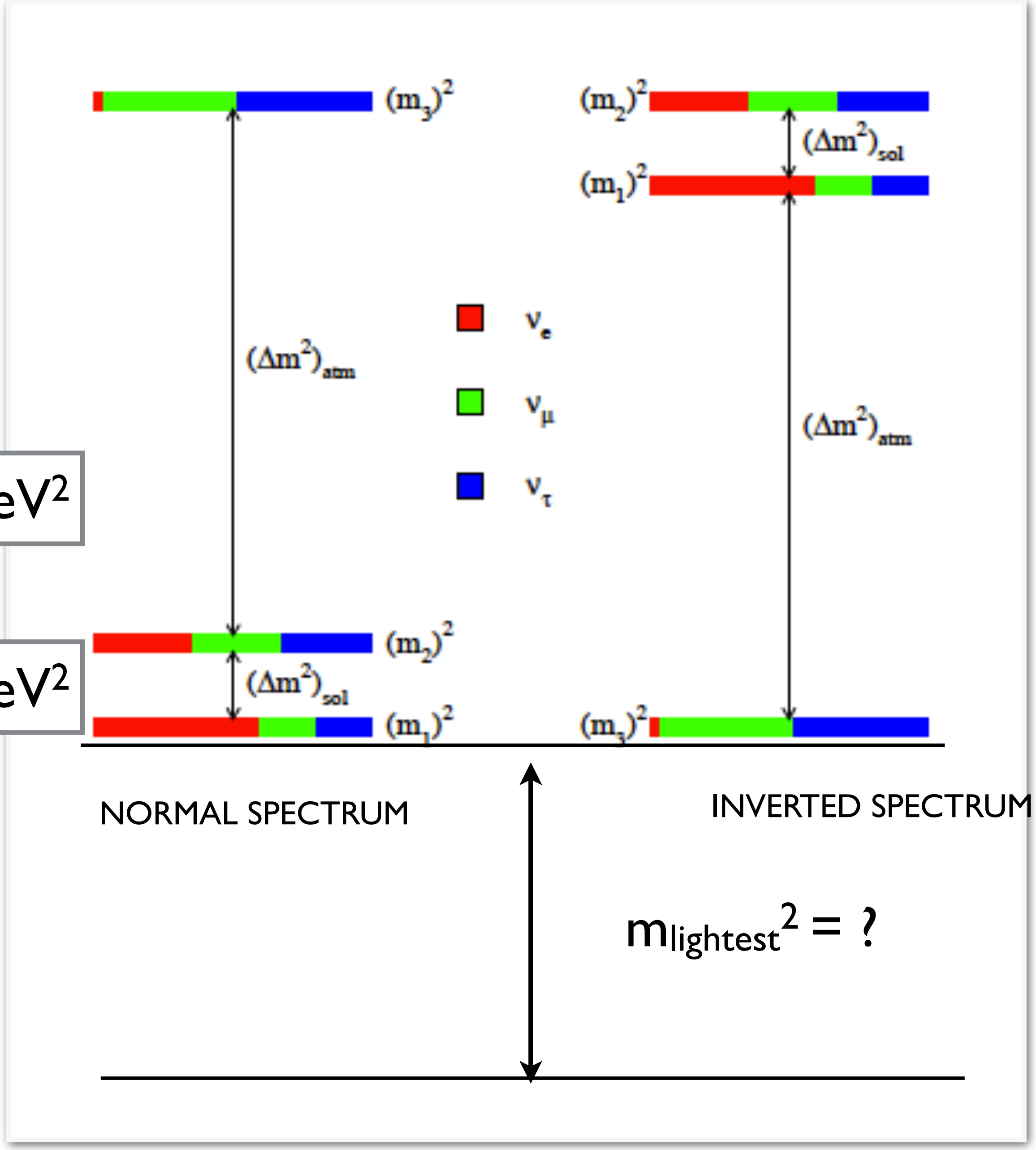


| Parameter | best-fit (±1σ) |
|---|---|
| $\Delta m^2_{21}$ [$10^{-5}$ eV $^2$] | $7.54^{+0.26}_{-0.22}$ |
| $\|\Delta m^2\|$ [$10^{-3}$ eV $^2$] | $2.43 \pm 0.06$ $(2.38 \pm 0.06)$ |
| $\sin^2\theta_{12}$ | $0.308 \pm 0.017$ |
| $\sin^2\theta_{23}$, $\Delta m^2 > 0$ | $0.437^{+0.033}_{-0.023}$ |
| $\sin^2\theta_{23}$, $\Delta m^2 < 0$ | $0.455^{+0.039}_{-0.031}$, |
| $\sin^2\theta_{13}$, $\Delta m^2 > 0$ | $0.0234^{+0.0020}_{-0.0019}$ |
| $\sin^2\theta_{13}$, $\Delta m^2 < 0$ | $0.0240^{+0.0019}_{-0.0022}$ |
| $\delta/\pi$ ($2\sigma$ range quoted) | $1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$ |

PDG 2014

~2.4 $10^{-3}$ eV$^2$

~7.5 $10^{-5}$ eV$^2$



# Neutrino phenomenology

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World data consistent with 3 light states,
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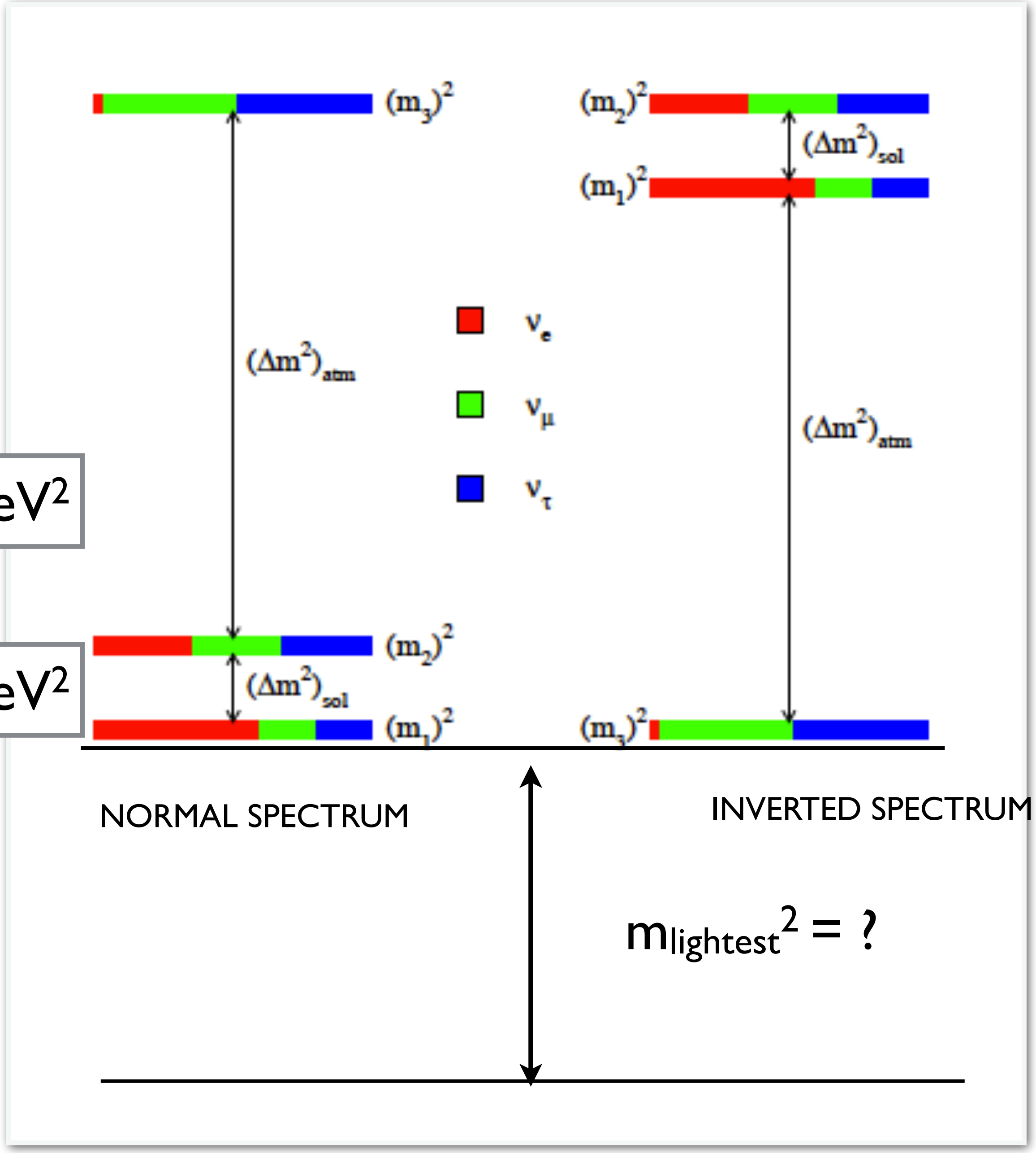
$$U \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

A. de Gouvea

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$



~2.4 $10^{-3}$ eV$^2$

~7.5 $10^{-5}$ eV$^2$

# Open questions

- Many key aspects of ν dynamics remain unknown, and will be explored by experiments in the next decade

- Symmetries / particle content:
  - Is lepton number (L) broken? (Dirac vs Majorana) (0νββ)
  - Are there light sterile ν's? (short-baseline anomalies, cosmo)

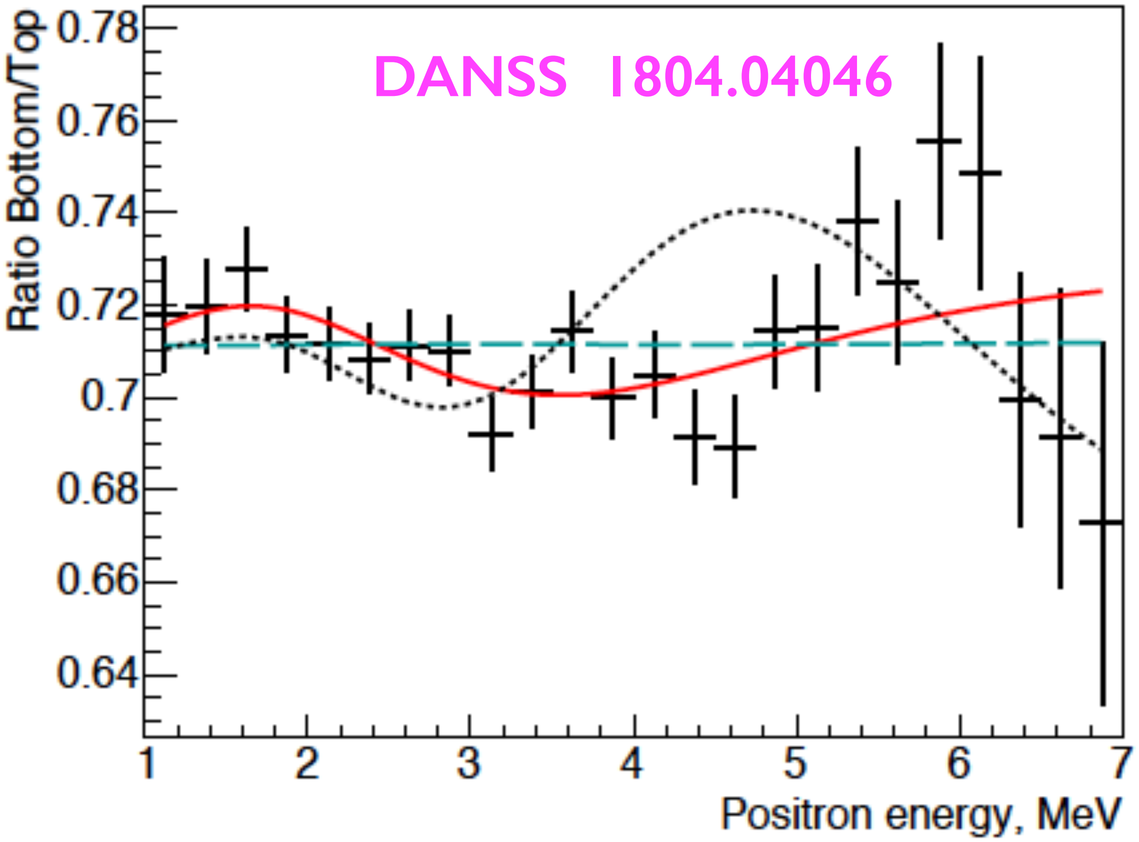
- Determine parameters of mass matrix (regardless its origin):
  - Absolute mass scale (beta decay, 0νββ*, cosmology*)
  - Mass ordering
  - Mixing angles (✔), CPV phase

(oscillation experiments)

# Sterile neutrinos?

- Anomalies in $\nu_e$ disappearance $\nu_e$ to $\nu_\mu$ appearance data

- Reactor anomaly: $\overline{\nu}_e$ to $\overline{\nu}_e$ (~$3\sigma$),
  now independent of calculated flux



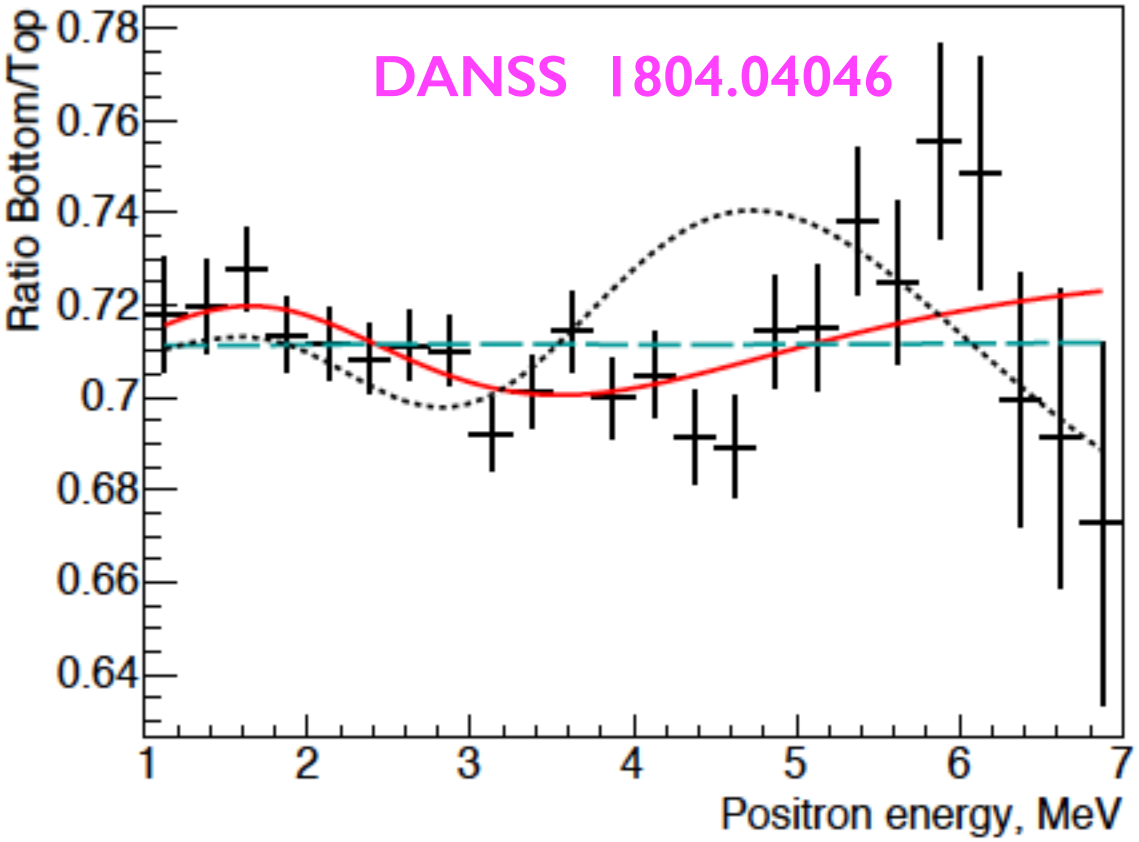
DANSS 1804.04046

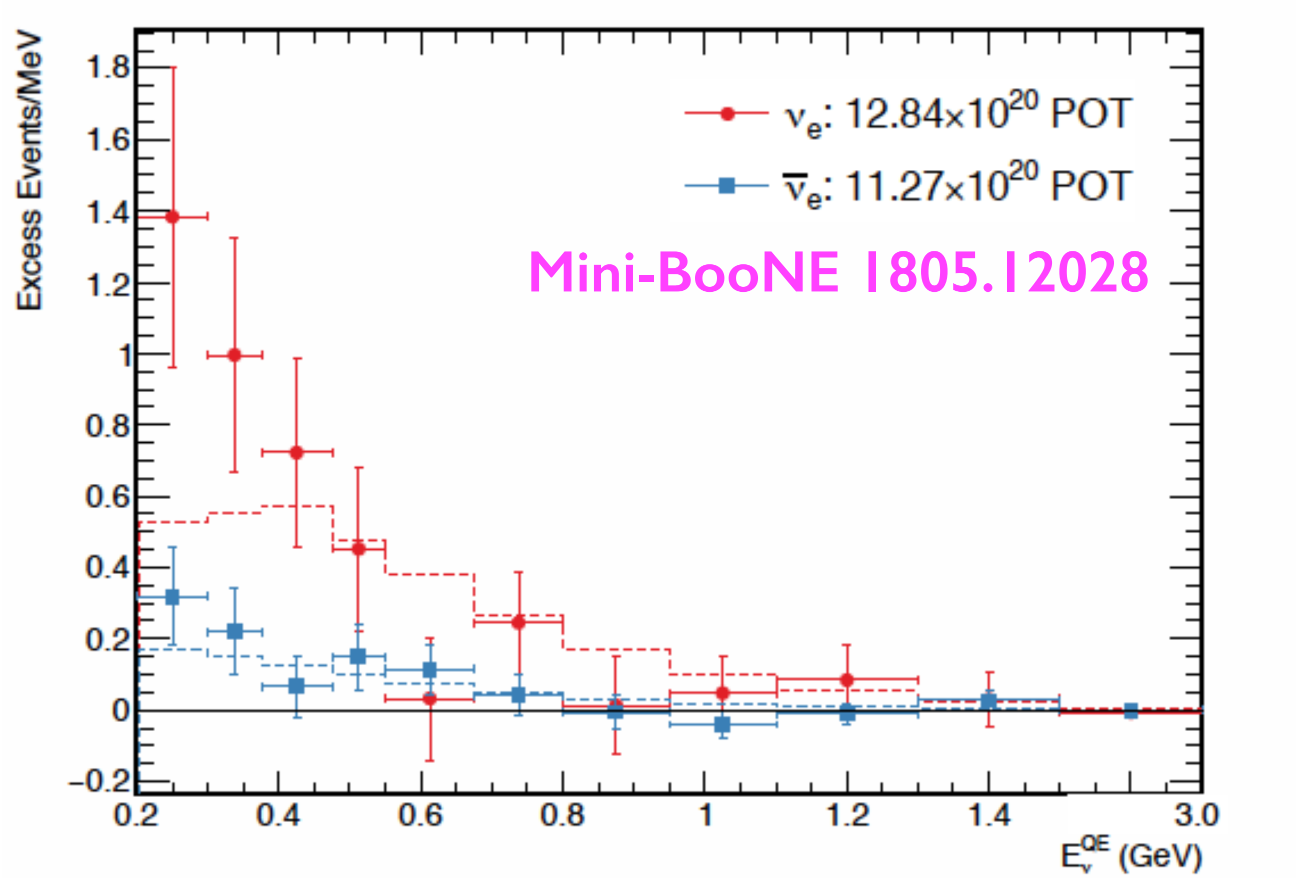
# Sterile neutrinos?

- Anomalies in $\nu_e$ disappearance $\nu_e$ to $\nu_\mu$ appearance data

- Reactor anomaly: $\bar{\nu}_e$ to $\bar{\nu}_e$ (~3$\sigma$), now independent of calculated flux

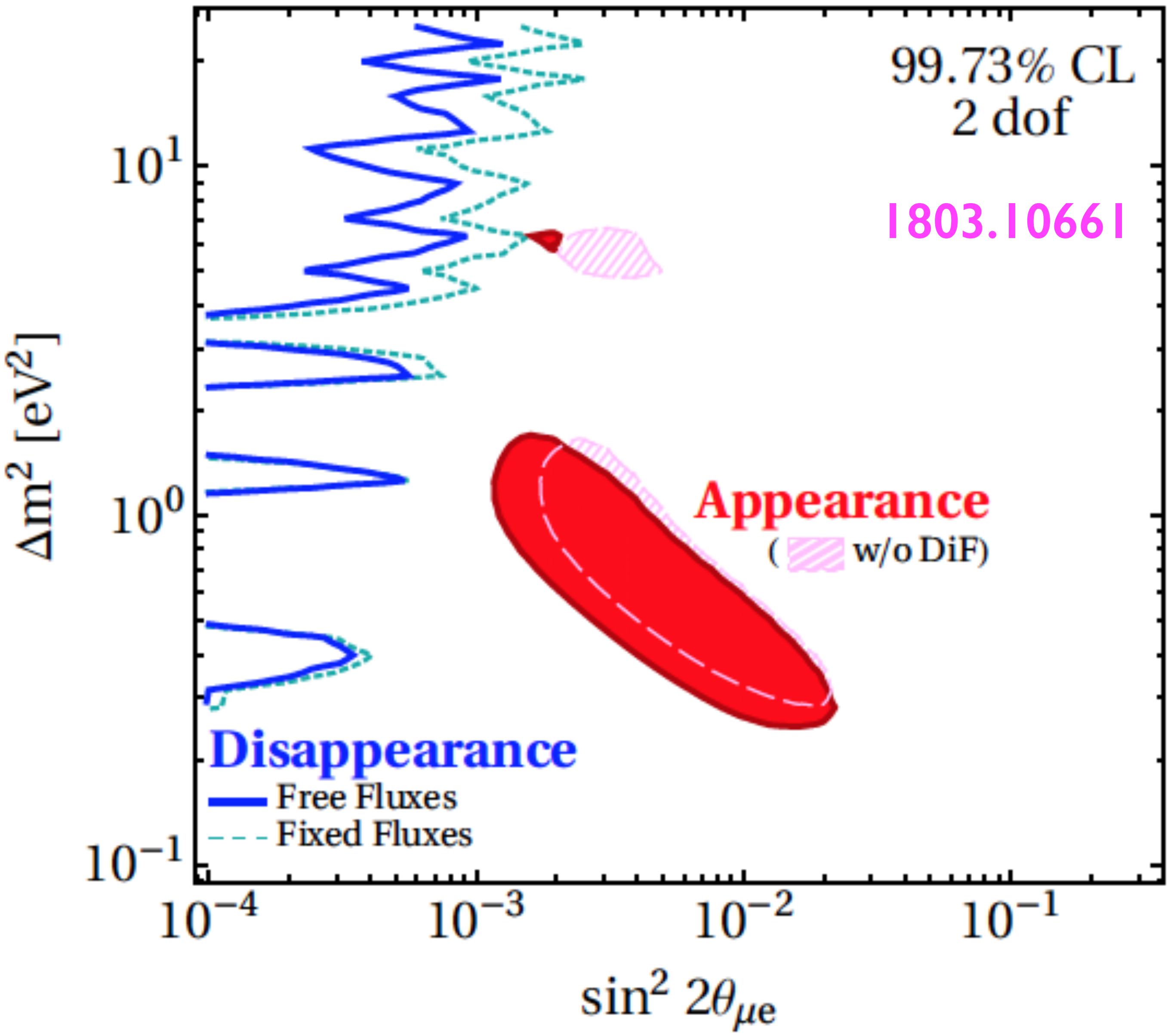
- Short-baseline anomaly: $\nu_\mu$ to $\nu_e$ excess (4.8$\sigma$)


DANSS 1804.04046


Mini-BooNE 1805.12028

# Sterile neutrinos?

- Anomalies in $\nu_e$ disappearance $\nu_e$ to $\nu_\mu$ appearance data
- Global analysis in 3+1 scheme, using increasingly strong bounds on $\nu_\mu$ disappearance (MINOS+, …)



$P(\nu_e \text{ to } \nu_e) \sim 1 - 4|U_{e4}|^2 \sin^2(\text{phase})$

$P(\nu_\mu \text{ to } \nu_\mu) \sim 1 - 4|U_{\mu4}|^2 \sin^2(\text{phase})$

$P(\nu_\mu \text{ to } \nu_e) \sim 1 - \underbrace{4|U_{e4}U_{\mu4}|^2}_{\sin^2(2\theta_{\mu e})} \sin^2(\text{phase})$

$$\text{phase} = \left(\frac{\Delta m^2_{41} L}{4E}\right)$$

4.7σ tension between different data sets!

MicroBooNE at FNAL will shed light on MiniBooNE excess (e vs γ discrimination)

# Status of the Standard Model

- Tested at the loop level in both electroweak and flavor sector

- Experimental hints pointing to new physics:
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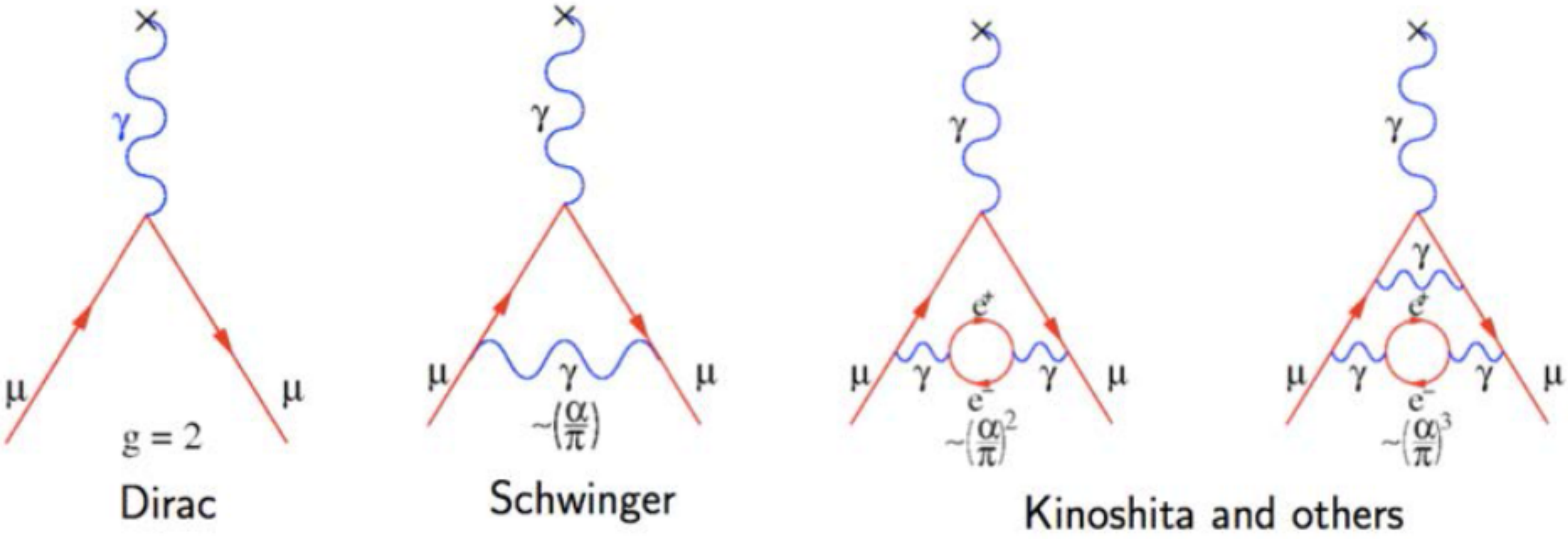
    - Sterile neutrinos?
  - Few-sigma discrepancies in precision physics
    - Muon g-2
    - Lepton universality in B meson decays
    - Neutron lifetime: beam vs bottle
    - …

# Muon anomalous magnetic moment

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}, \qquad \vec{s} = \frac{\hbar}{2}\vec{\sigma}$$

- Dirac predicts g=2 in 1928
- 1947: Measurements find $g_e \neq 2$
- Schwinger calculated $g_e = 2(1 + a_e) \qquad a_e = \frac{(g_e - 2)}{2} = \frac{\alpha}{2\pi} \approx 0.00116$



Great success of QED

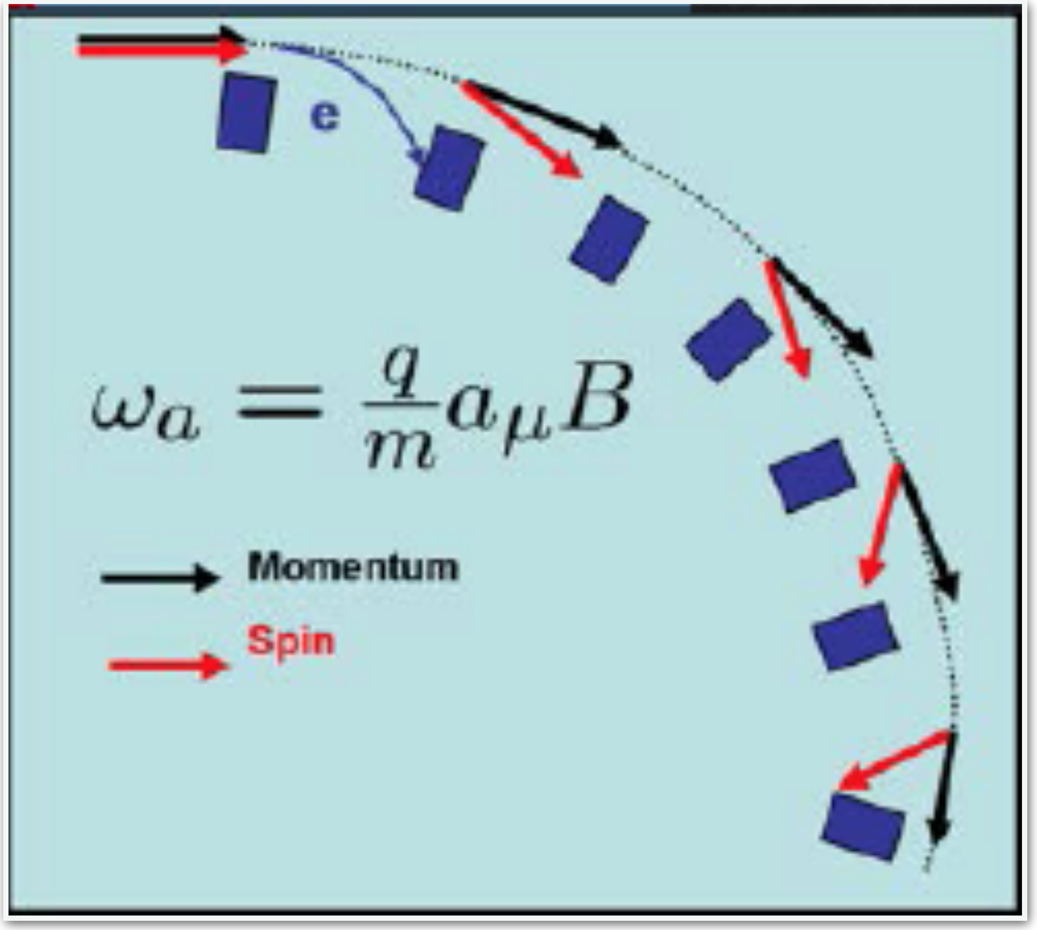
D. Kawall

D. Hertzog

- Current experimental precision: $\Delta g_e = 5.2\times10^{-13}$ and $\Delta g_\mu = 1.2\times10^{-9}$
  - $g_e$ used to determine the electromagnetic coupling
  - $g_\mu$ used to challenge the SM!

- How is $g_\mu$ ($a_\mu$) measured?
  - Exploit the fact that momentum and spin do not precess in the same way in a B field
  - Relative frequency $\omega_a$ proportional to (g-2)*B

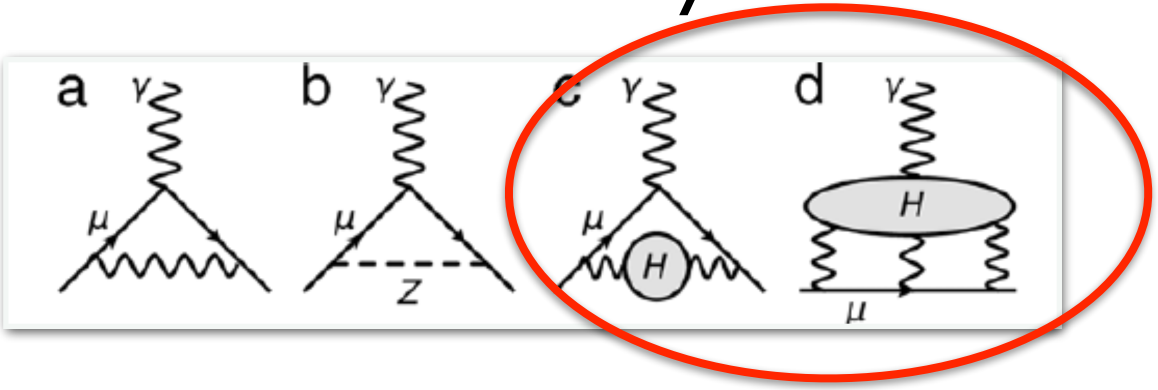
$$\omega_C = \frac{eB}{mc\gamma}$$



$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

- Where are we?

SM theory



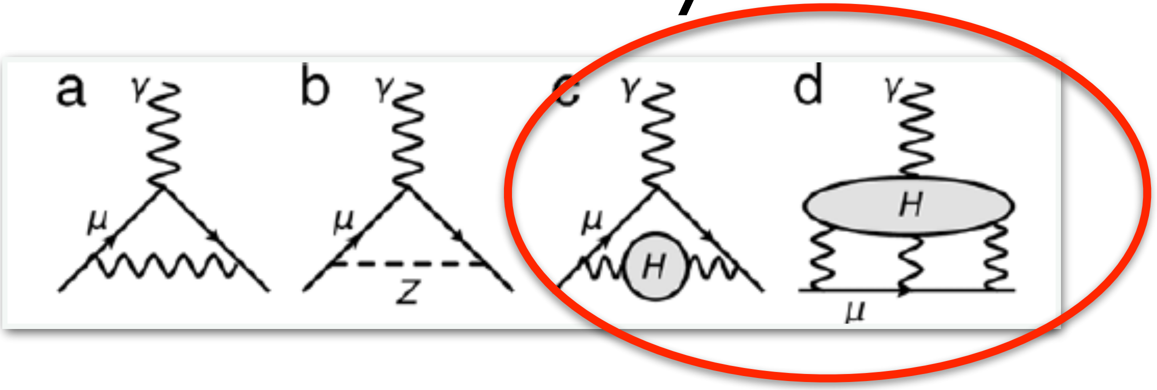
vs

Experiment

Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

- Where are we?

SM theory



Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

vs

Experiment

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}$$

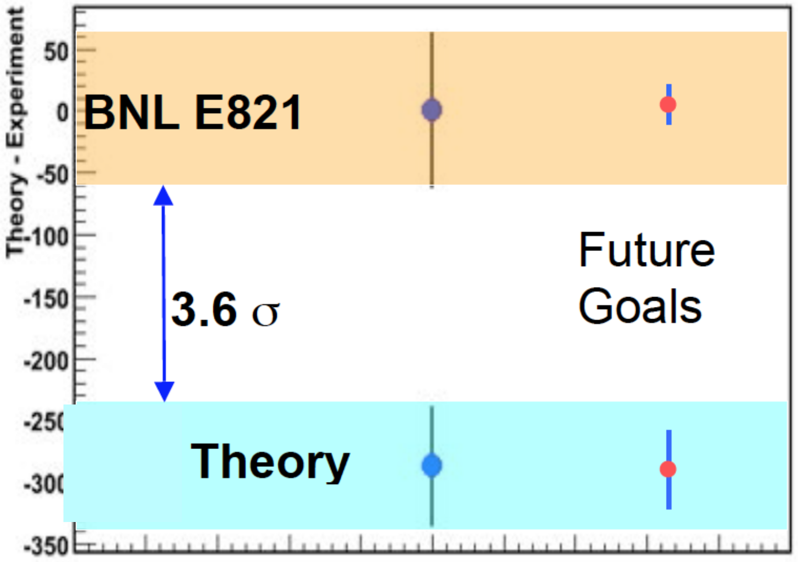
$$a_\mu = (g_\mu - 2)/2$$

$$\begin{aligned} a_\mu(\text{Expt}) &= 116\,592\,089\,(54)(33) \times 10^{-11} \\ a_\mu(\text{SM}) &= 116\,591\,802\,(42)(26)(02) \times 10^{-11} \end{aligned}$$

BNL E821 (2006)

$$\Rightarrow \quad \Delta a_\mu = 287(80) \times 10^{-11}$$

$3.6\sigma$ discrepancy



Goal: 0.14 ppm

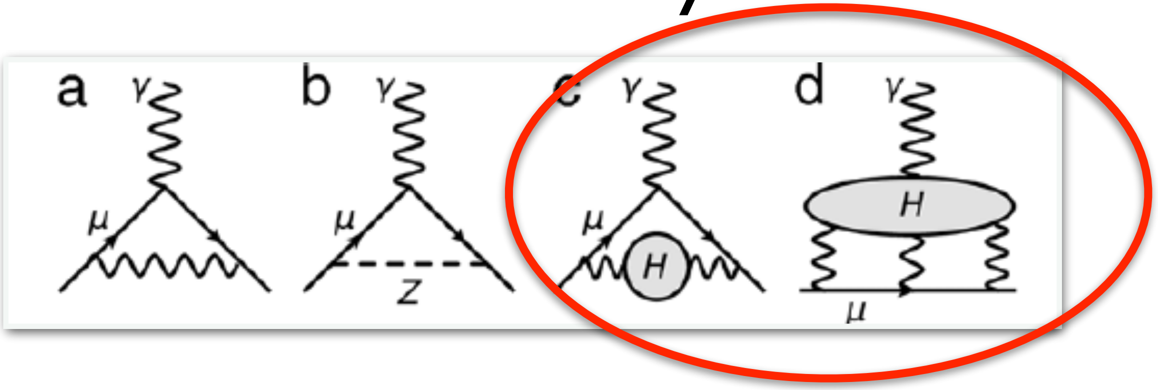
New g-2 at Fermilab (FNALE989) and J-PARCE34 will improve uncertainty factor of 4

Establish confidence in error bar

D. Hertzog

- Where are we?

## SM theory



Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

vs

## Experiment

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}$$

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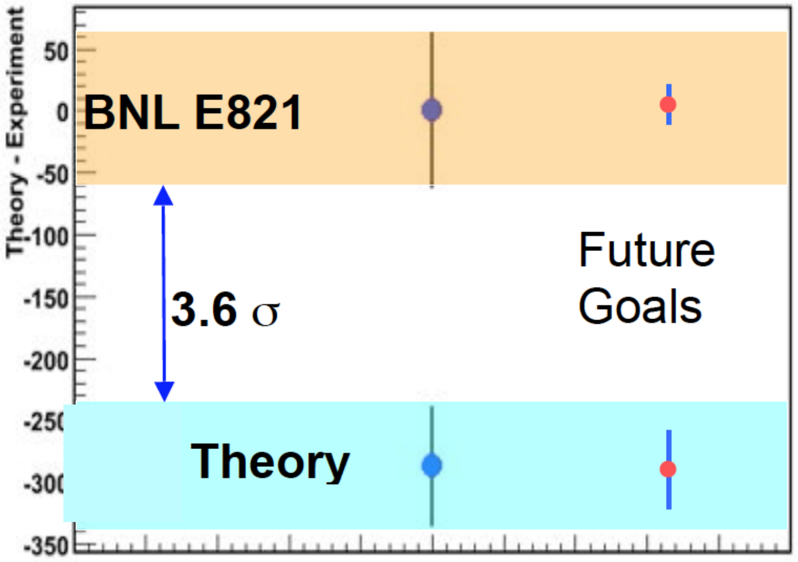
D. Hertzog



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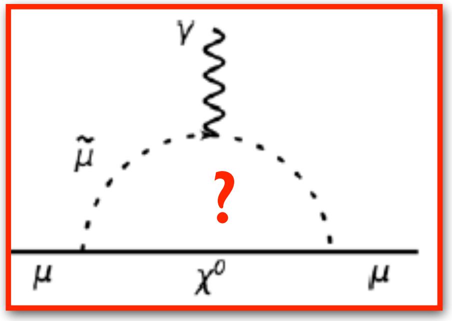


New physics?

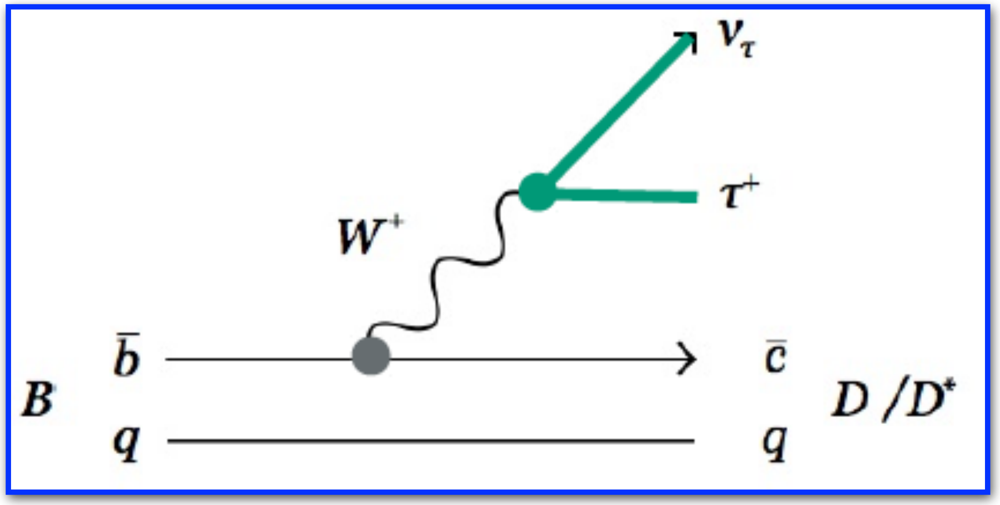
# Lepton universality in B decays

**Tree level, b → c ℓ ν**

abundant

well known in SM

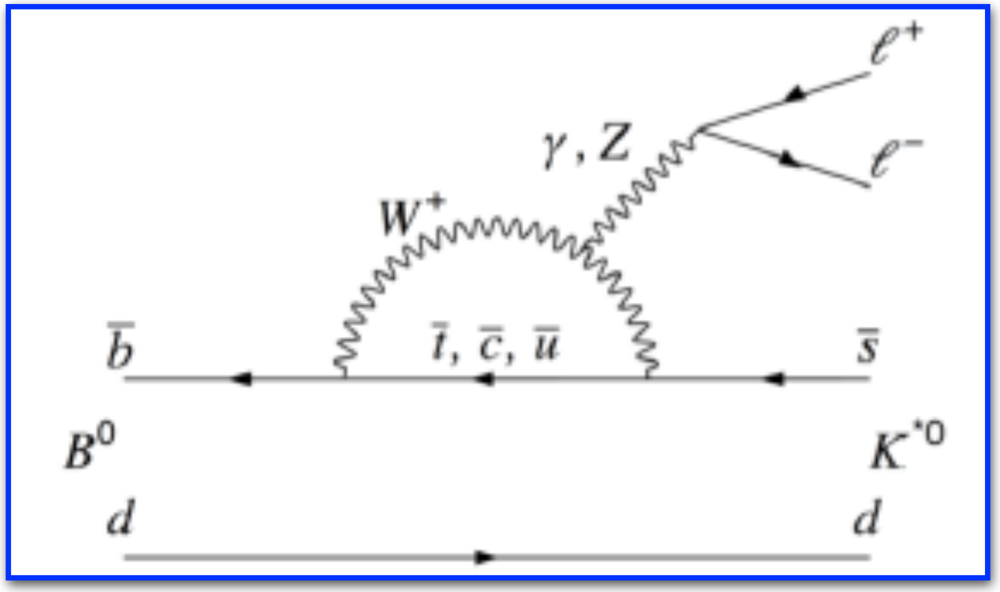
**possible new physics in 3rd gen.**



**Loop level, b → s ℓ ℓ**

FCNC forbidden at tree-level in SM

**sensitive to new physics in loops**



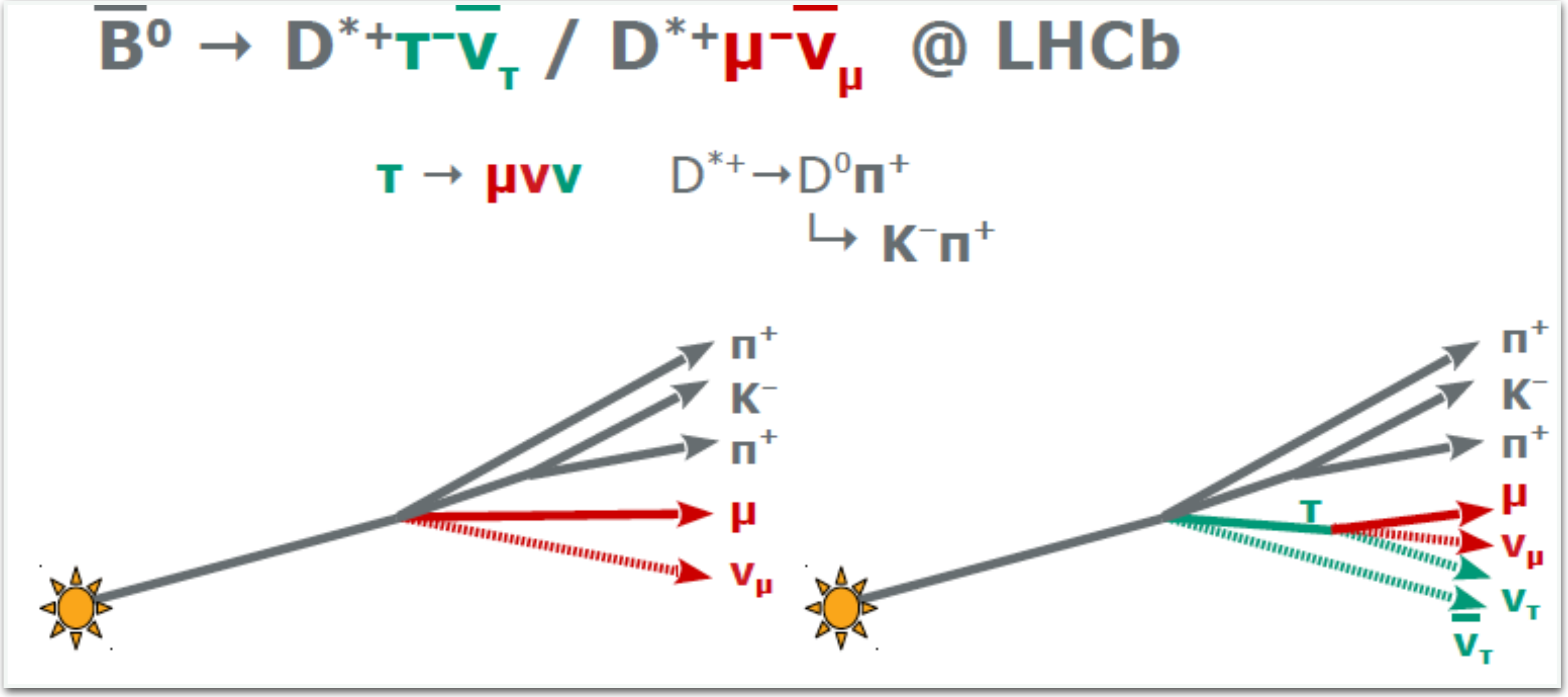
**Approach : determine ratio of branching fractions**

experimentally clean → many systematics cancel

theoretically clean → many QCD effects cancel

# Lepton universality in B decays

**R(D*)**



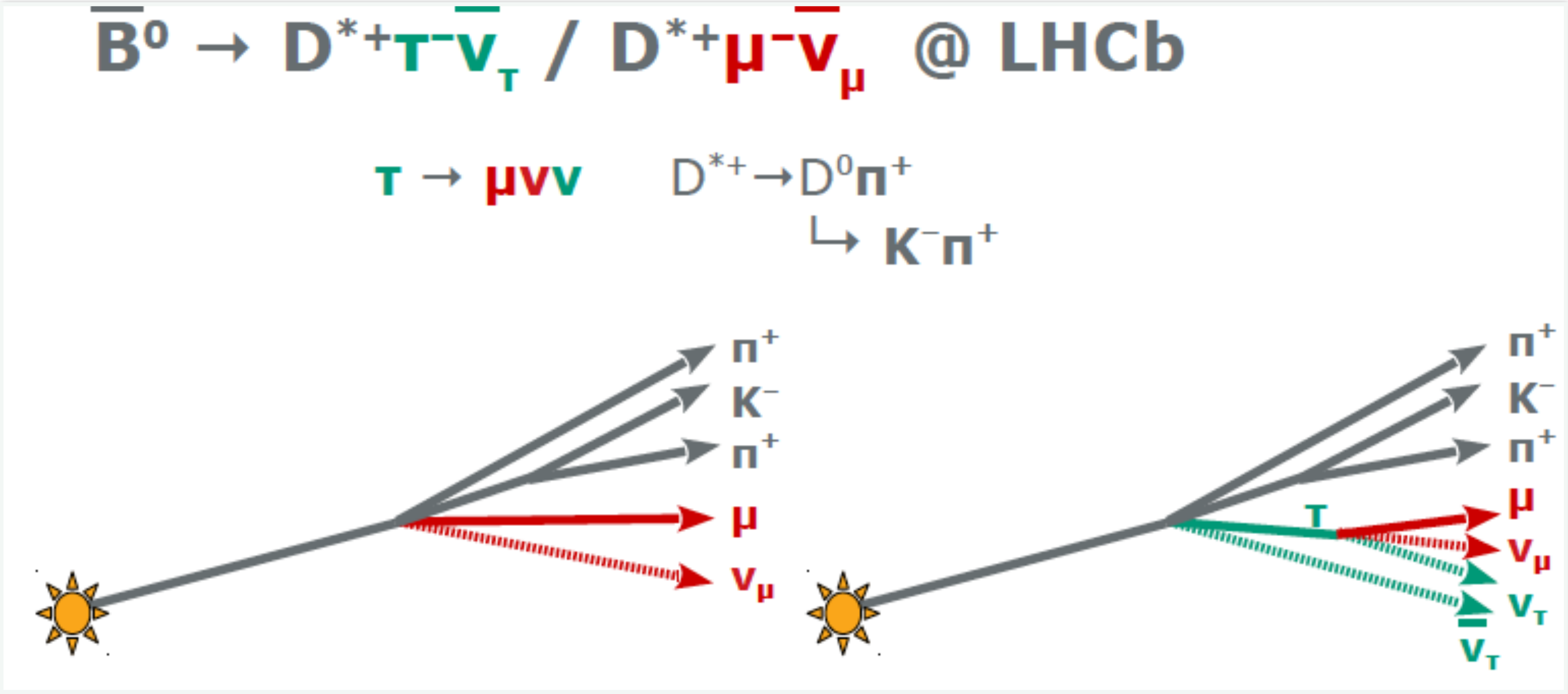
$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ / $D^{*+}\mu^-\bar{\nu}_\mu$ @ LHCb

$\tau \to \mu\nu\nu$ $D^{*+} \to D^0\pi^+$

$\hookrightarrow K^-\pi^+$

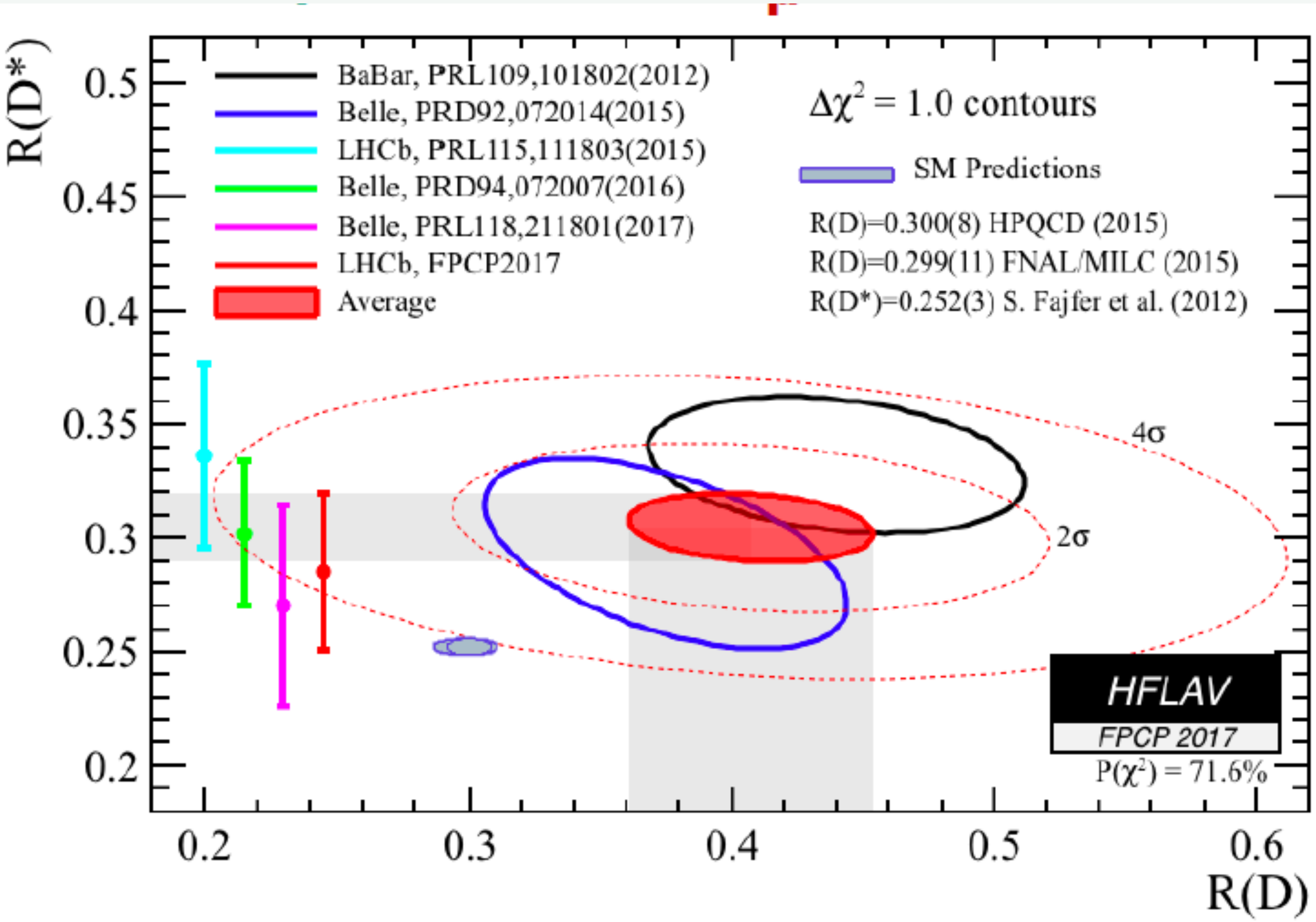
# Lepton universality in B decays

**R(D*)**



$$R_{K^{*0}} = \boxed{\frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}} \Big/ \boxed{\frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}}$$

# Lepton universality in B decays



**Violates Universality @ $10^{-2}$ level by 4.1σ**

RD(*) (**e**,**μ**,**τ**) > prediction : **4.1σ tension**

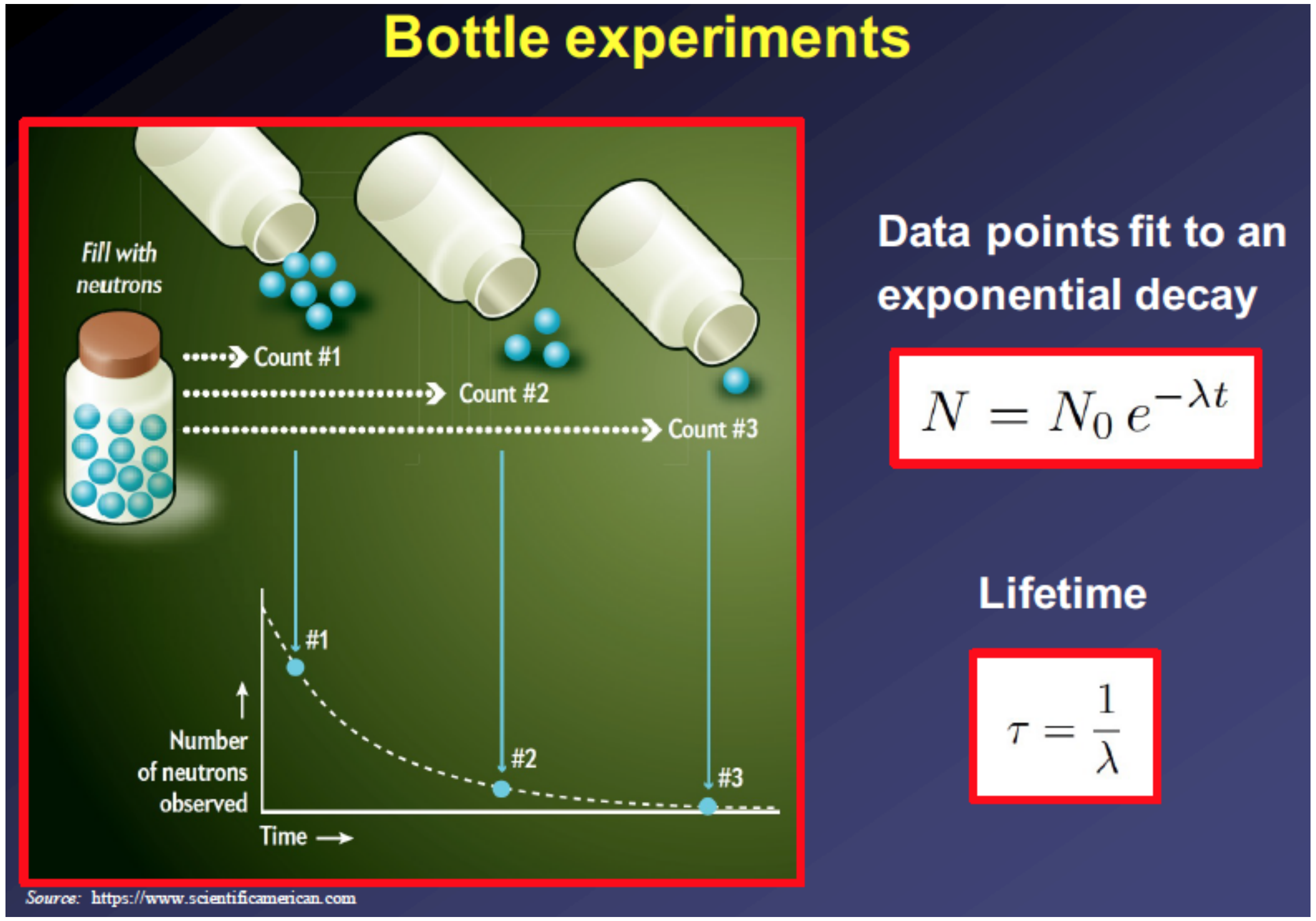
RK(*) (**e**,**μ**) < prediction : **~4σ tension**

(not shown here)

G. Onderwater, CIPANP 2018

# Neutron lifetime puzzle

$$n \to p + e^- + \bar{\nu}_e$$



**Bottle experiments**

Data points fit to an exponential decay

$$\boxed{N = N_0\, e^{-\lambda t}}$$

Lifetime

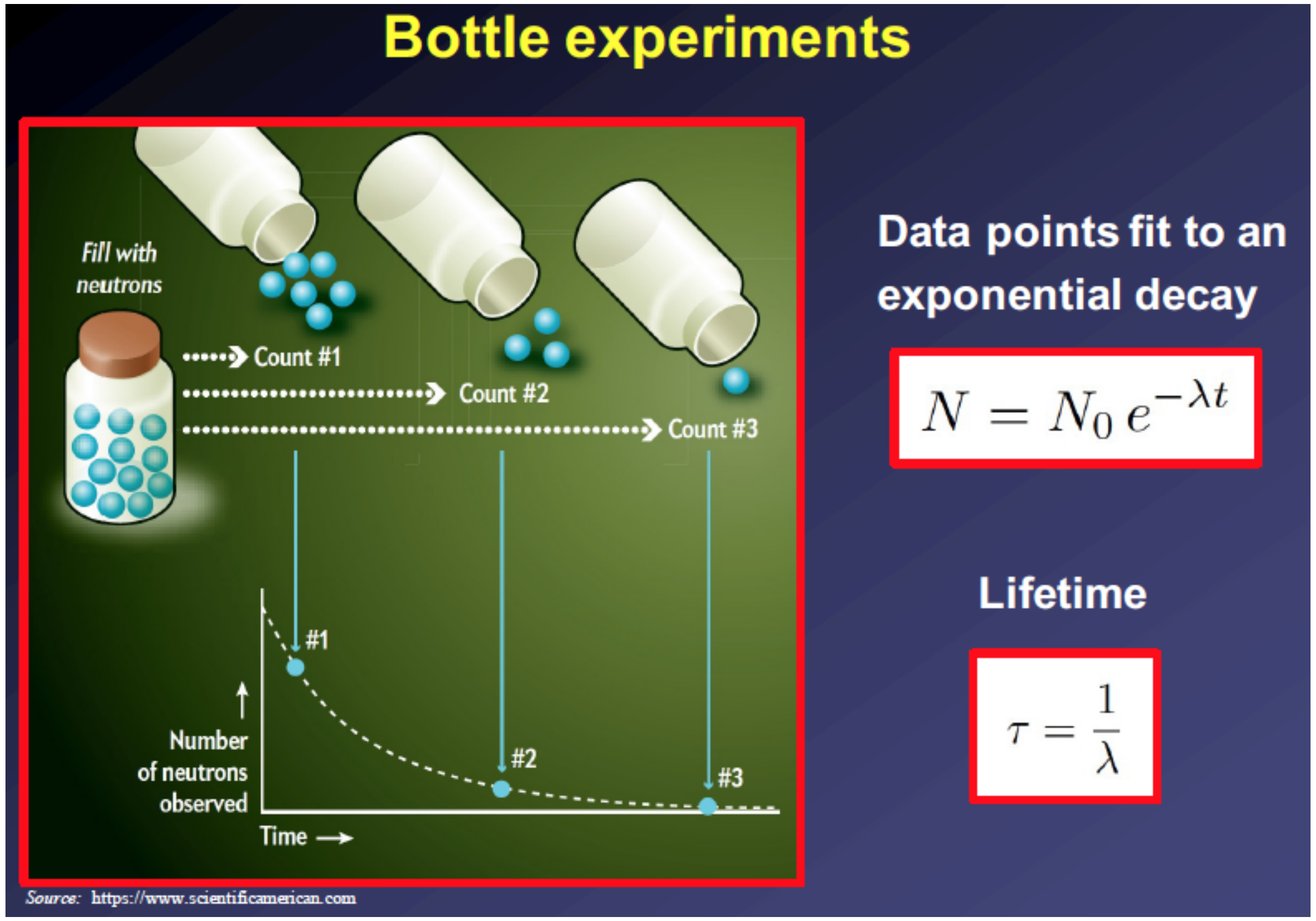
$$\boxed{\tau = \frac{1}{\lambda}}$$

*Source:* https://www.scientificamerican.com

Count the living

# Neutron lifetime puzzle

$$n \to p + e^- + \bar{\nu}_e$$



## Bottle experiments

Data points fit to an exponential decay

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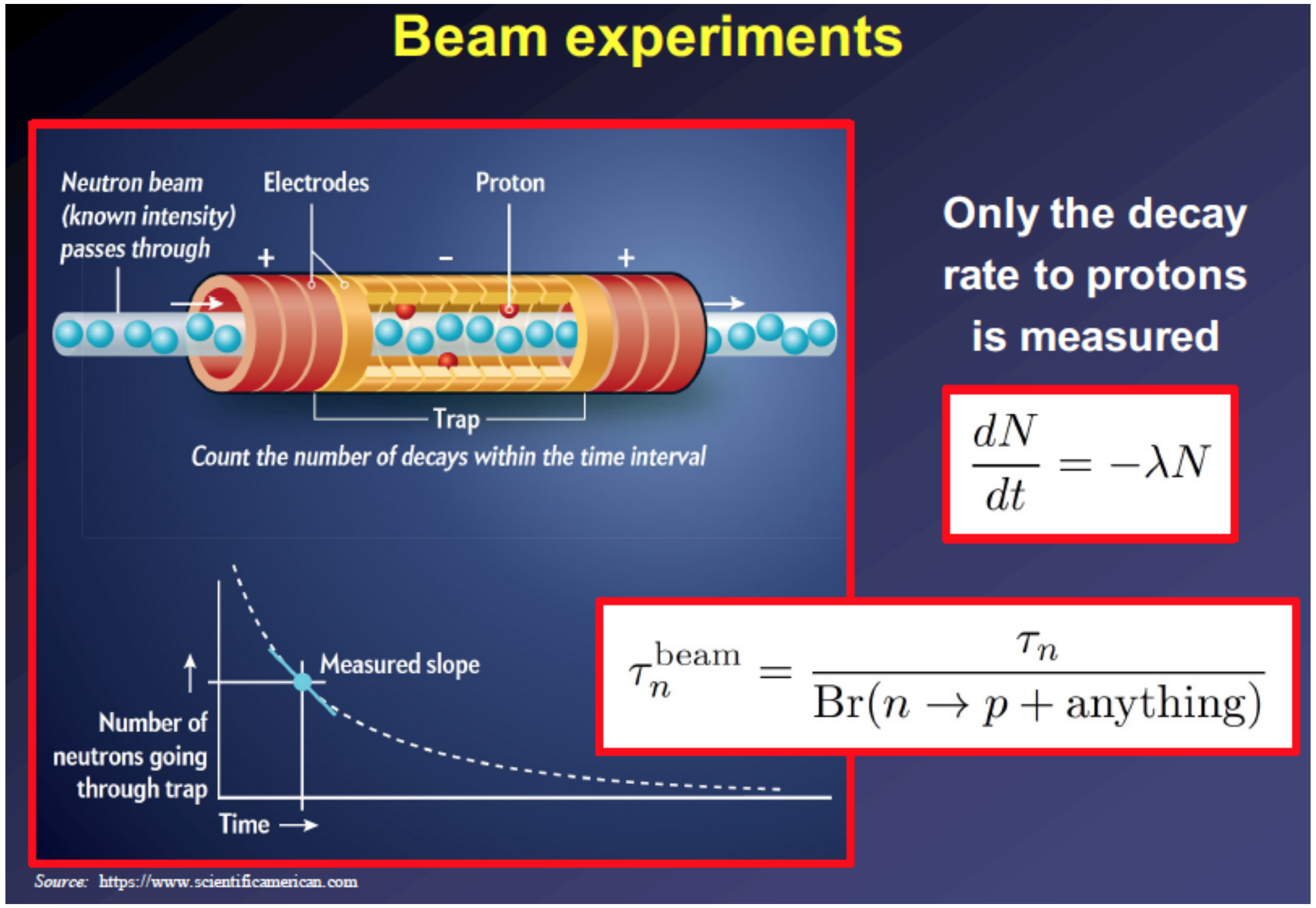
Lifetime

$$\boxed{\tau = \frac{1}{\lambda}}$$

*Source:* https://www.scientificamerican.com



## Beam experiments

Only the decay rate to protons is measured

$$\boxed{\frac{dN}{dt} = -\lambda N}$$

$$\boxed{\tau_n^{\text{beam}} = \frac{\tau_n}{\mathrm{Br}(n \to p + \text{anything})}}$$

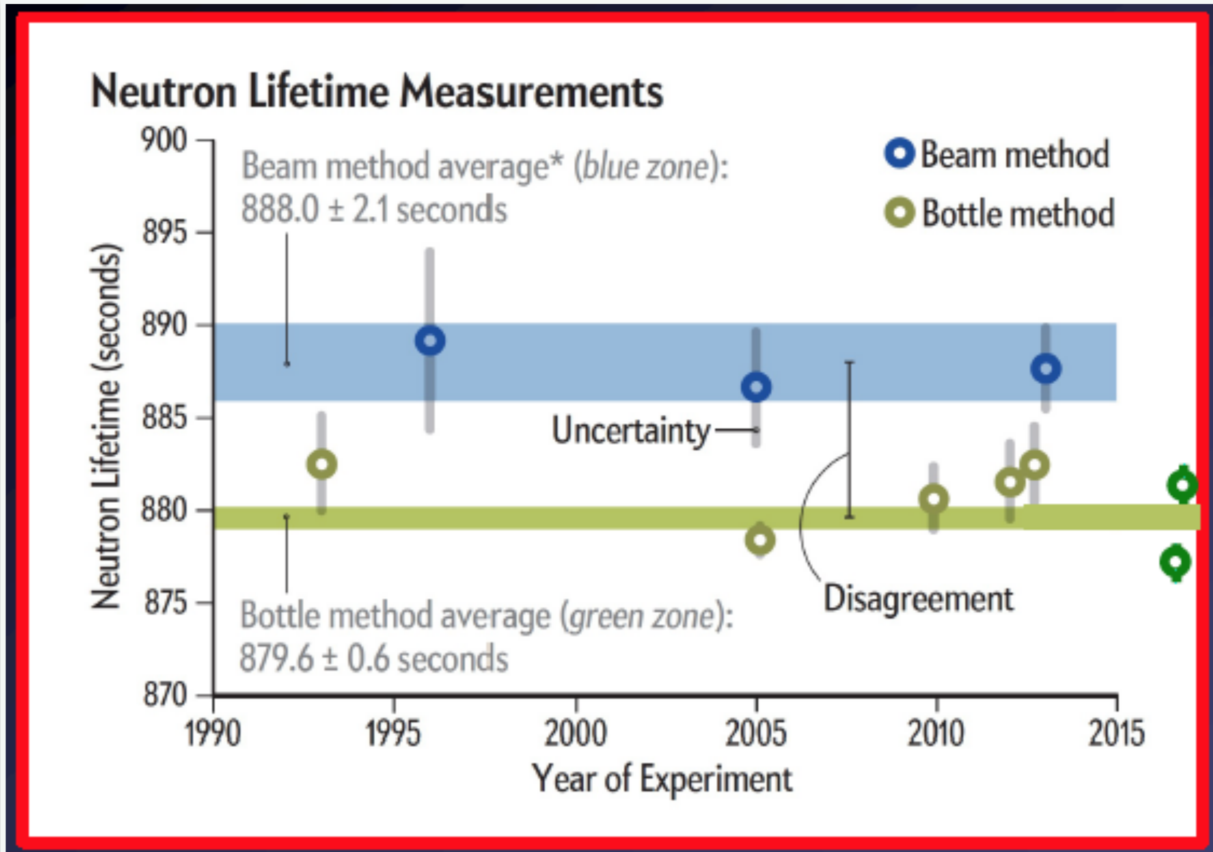
*Source:* https://www.scientificamerican.com

Count the living

Count the dead

B. Fornal, CIPANP 2018

# Neutron lifetime puzzle



*Source:* https://www.scientificamerican.com, modified

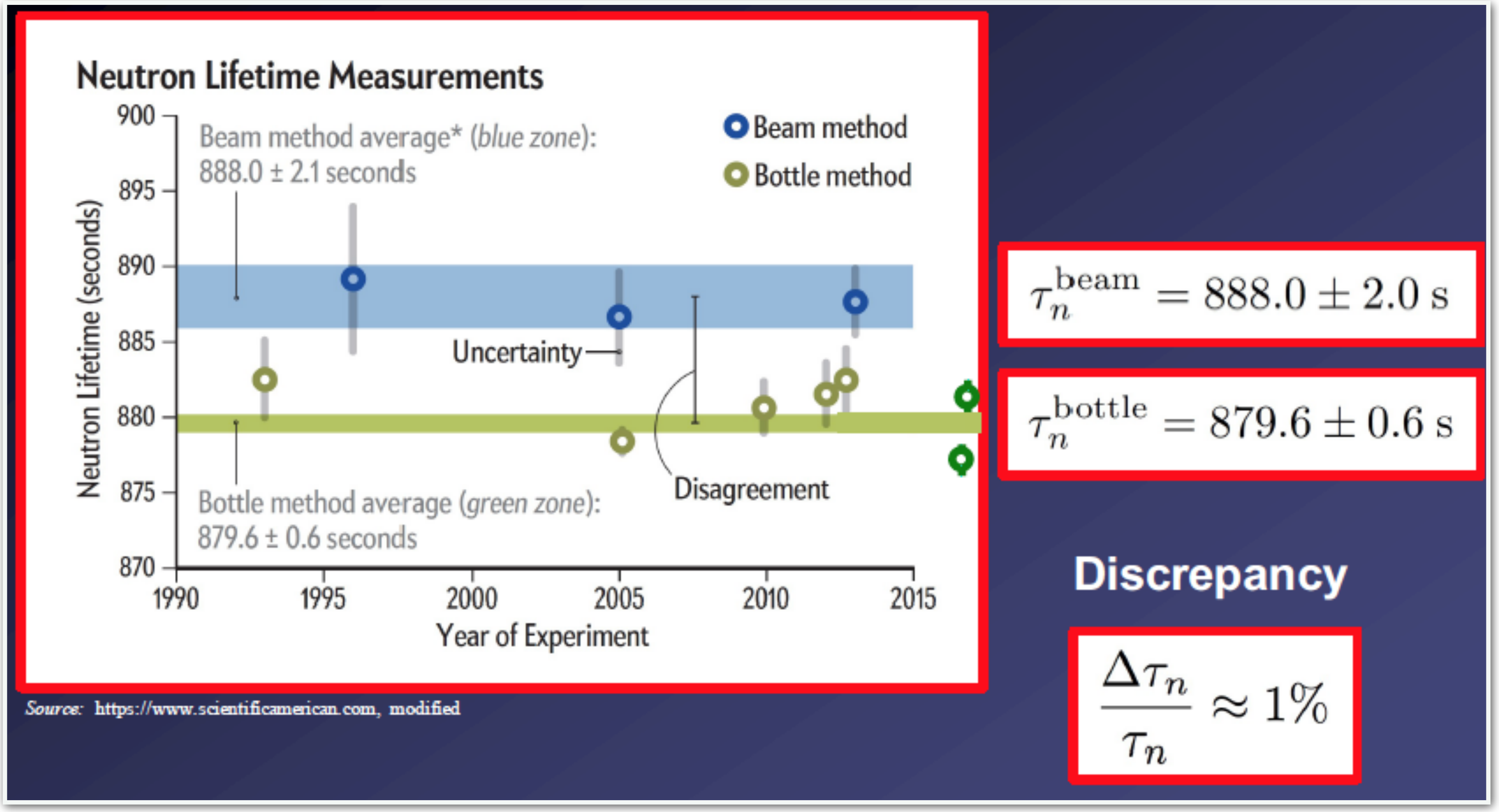
$$\tau_n^{\text{beam}} = 888.0 \pm 2.0\ \text{s}$$

$$\tau_n^{\text{bottle}} = 879.6 \pm 0.6\ \text{s}$$

**Discrepancy**

$$\frac{\Delta\tau_n}{\tau_n} \approx 1\%$$

# Neutron lifetime puzzle



*Source:* https://www.scientificamerican.com, modified

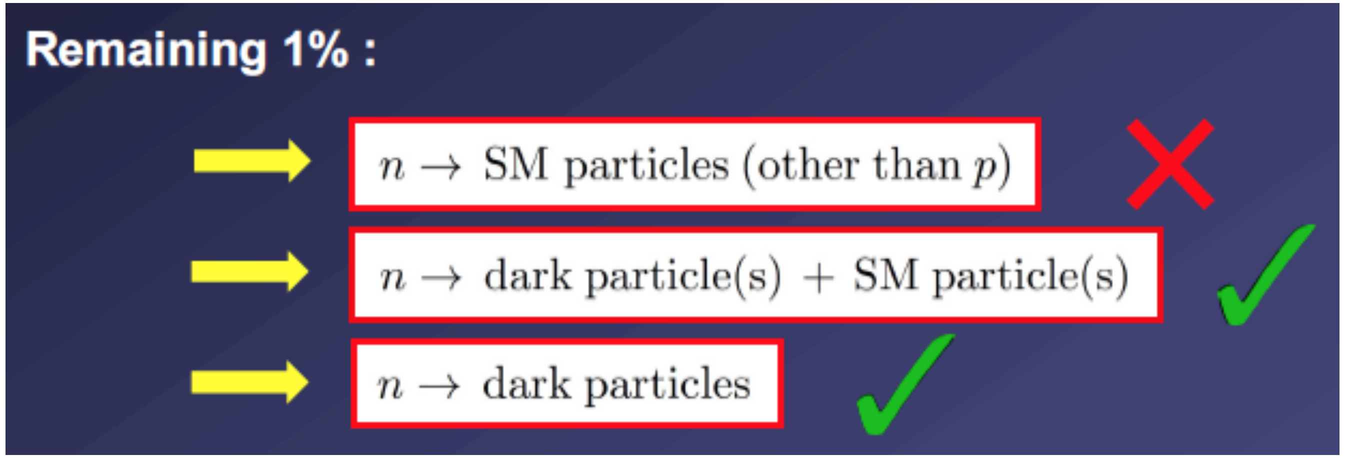
$$\tau_n^{\text{beam}} = 888.0 \pm 2.0\ \text{s}$$

$$\tau_n^{\text{bottle}} = 879.6 \pm 0.6\ \text{s}$$

**Discrepancy**

$$\frac{\Delta\tau_n}{\tau_n} \approx 1\%$$

$$\text{Br}(n \to p + \text{anything}) \approx 99\%$$



**Remaining 1% :**

- $n \to$ SM particles (other than $p$) ✗
- $n \to$ dark particle(s) + SM particle(s) ✓
- $n \to$ dark particles ✓

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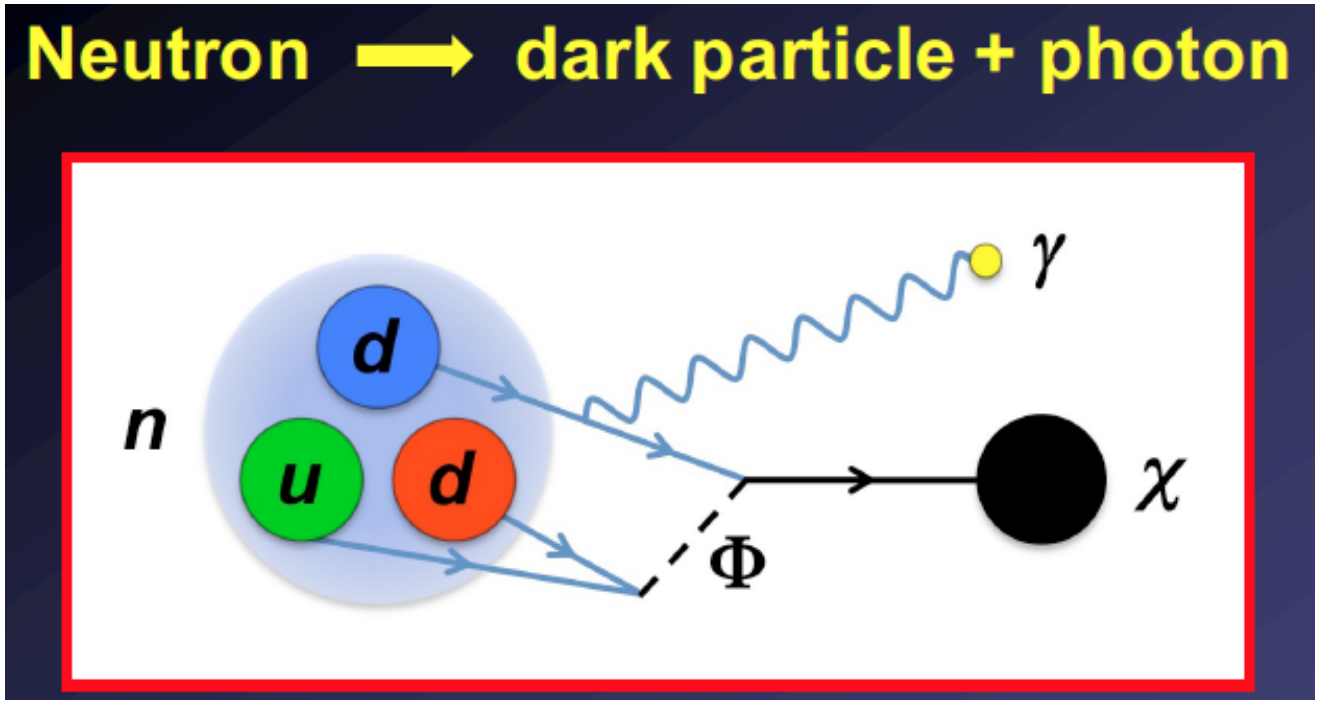
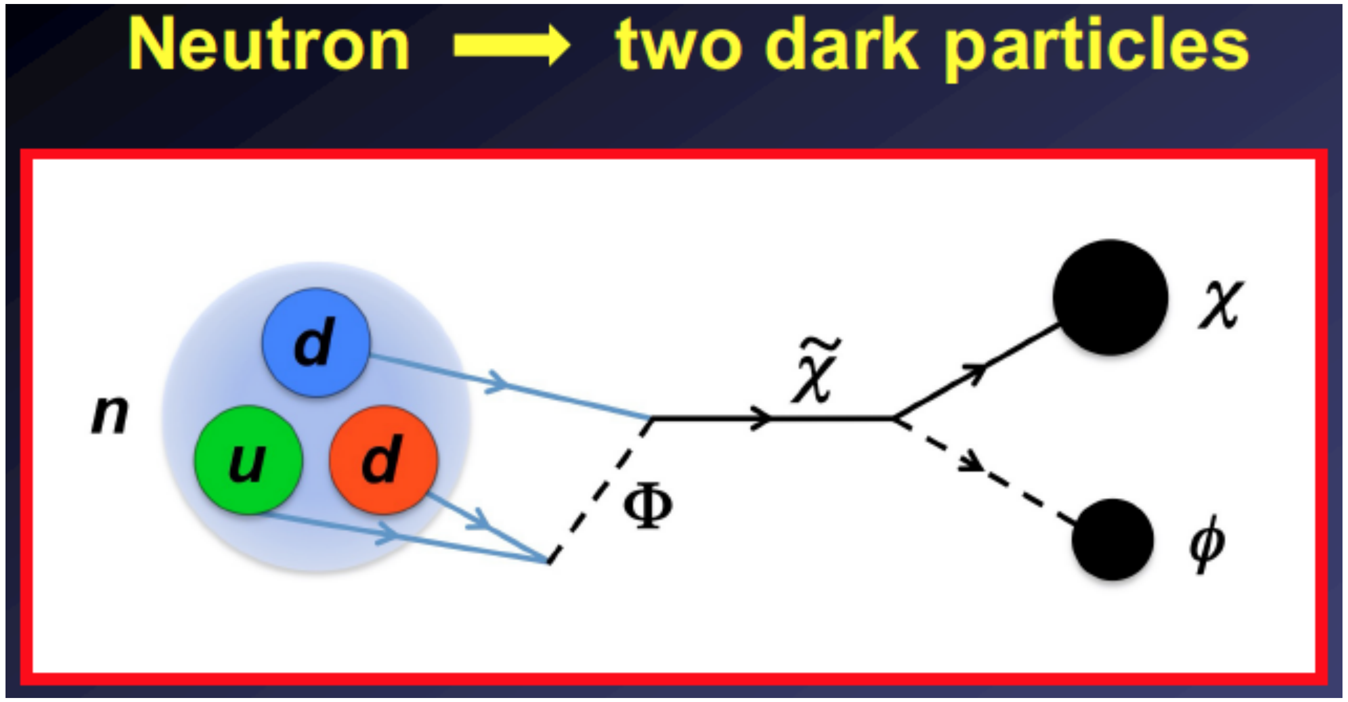
# Neutron lifetime puzzle

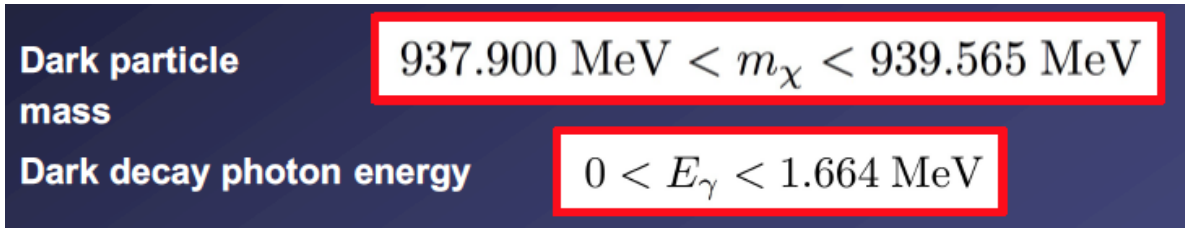


**Neutron ⟶ dark particle + photon**



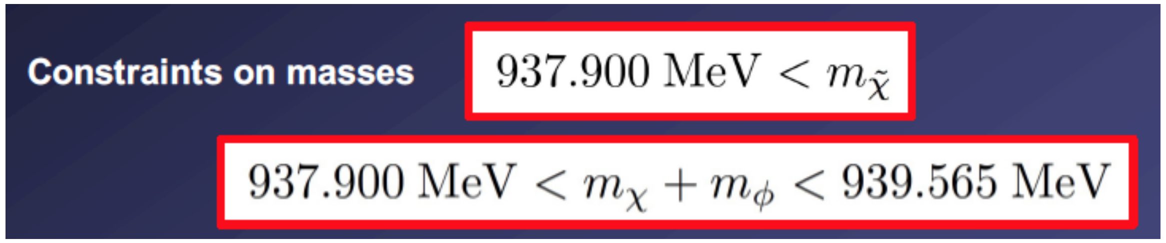
**Neutron ⟶ two dark particles**

From $^9$Be stability



**Dark particle mass** $937.900\ \text{MeV} < m_\chi < 939.565\ \text{MeV}$

**Dark decay photon energy** $0 < E_\gamma < 1.664\ \text{MeV}$



**Constraints on masses** $937.900\ \text{MeV} < m_{\tilde{\chi}}$

$937.900\ \text{MeV} < m_\chi + m_\phi < 939.565\ \text{MeV}$

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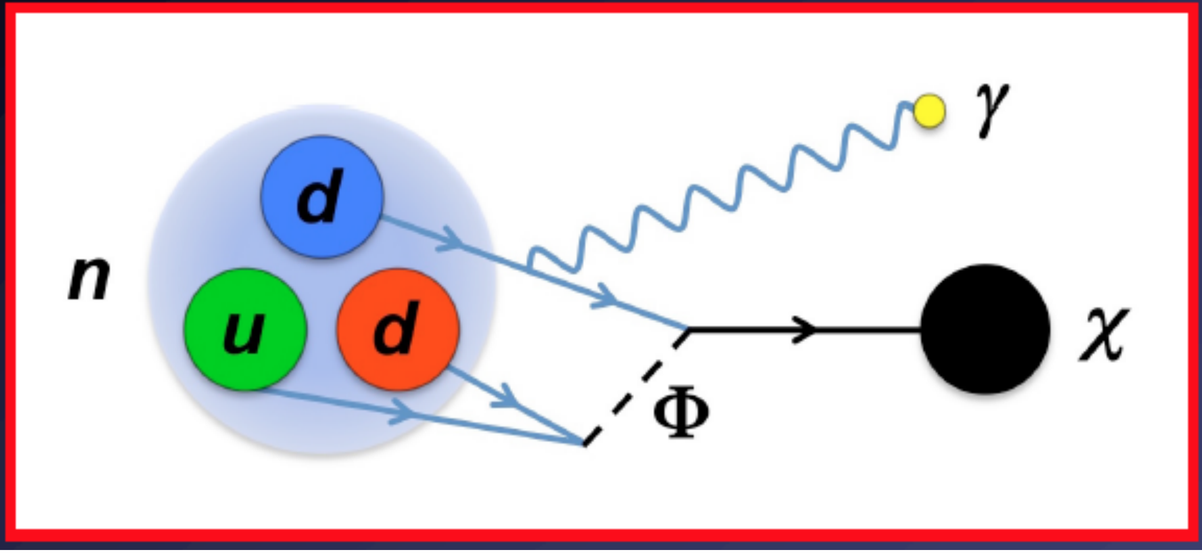
# Neutron lifetime puzzle

**Neutron ⟶ dark particle + photon**



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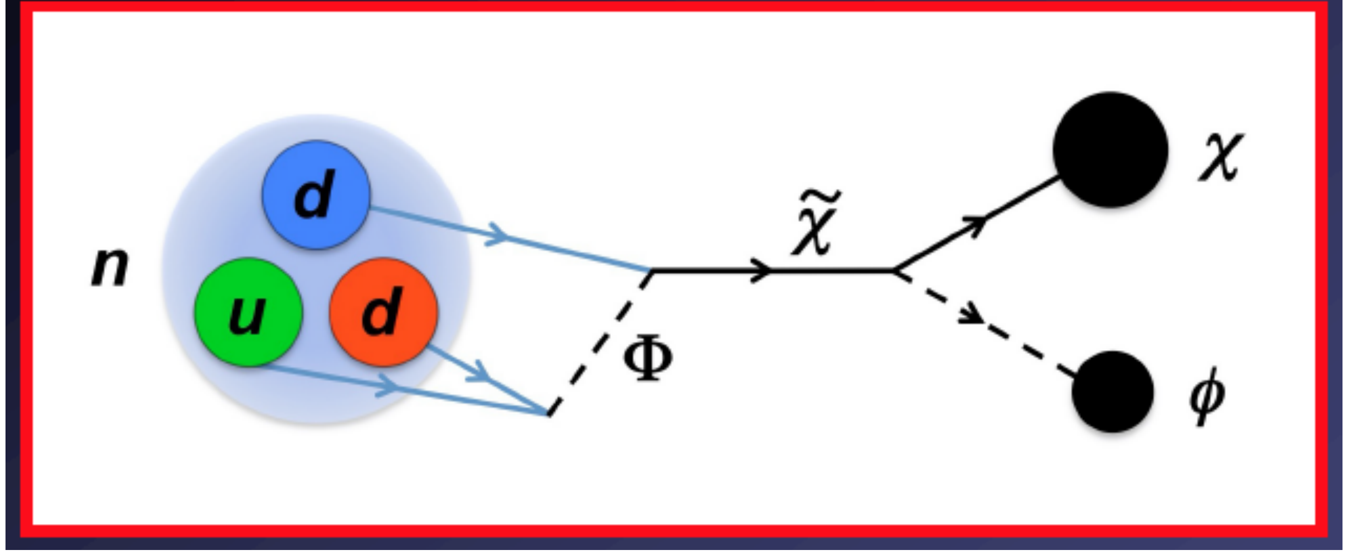

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⟶ ***"Missing Neutrons May Lead a Secret Life as Dark Matter",***

C. Moskowitz, Scientific American (January 29, 2018)

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