# New Physics @ Nanjing Proton Source

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9th Workshop on Hadron Physics in China and Opportunities Worldwide

Nanjing University

2017-07-26

# Nanjing Proton Source (NPS)

**A high-current superconducting proton source has been proposed to be built for a number of science researches and also for health/industry applications.**

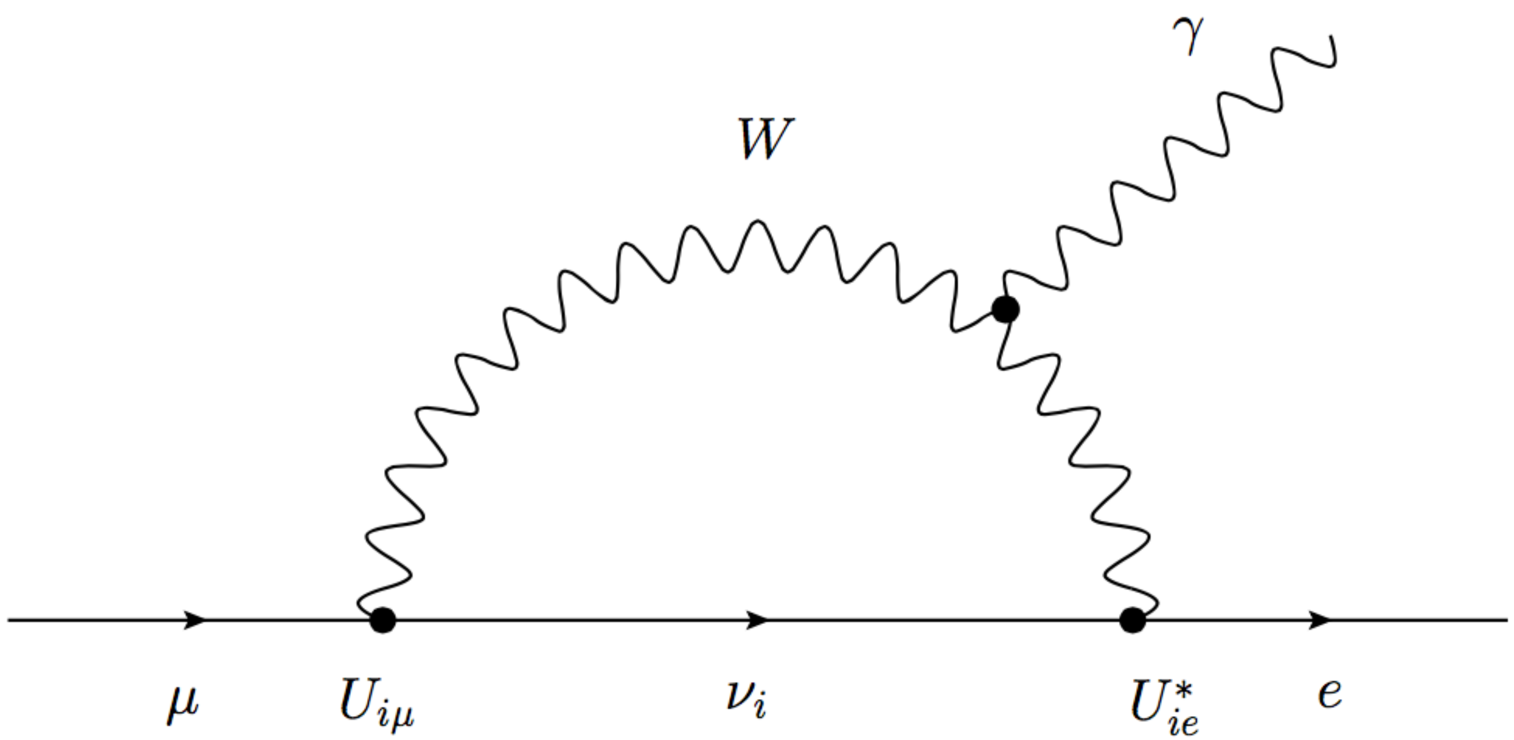
- **Beam energy range: 3.5 MeV to 1000 MeV**
- **Beam current range: 10 μA to 26 mA**

**An Sun's talk on July 28**

# (Possible) new physics topics that could be probed with the NPS

- Lepton flavor violation
- Muon g-2
- Proton radius puzzle
- Light boson search

# Charged lepton flavor violation (cLFV) in SM




**SM** $$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 \sim 10^{-54}$$

**suppressed by the tiny neutrino masses**

**Bernstein & Cooper, Physics Reports 2013**

# Current cLFV limits on muon

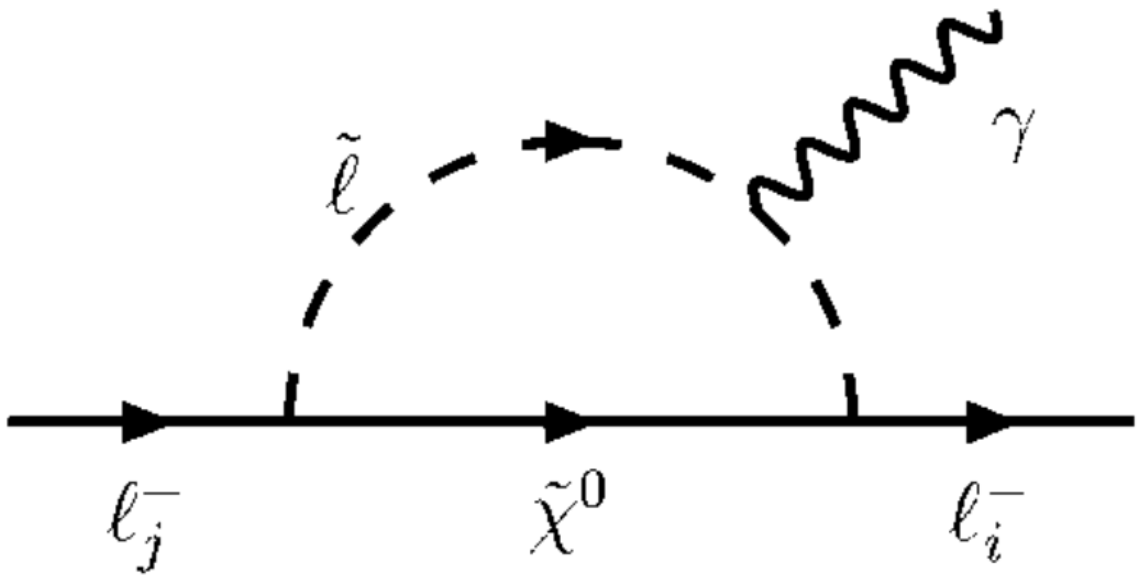
| $\mu^-$ DECAY MODES | | | Fraction $(\Gamma_i/\Gamma)$ | | Confidence level | $p$ (MeV/$c$) |
|---|---|---|---|---|---|---|
| $e^- \overline{\nu}_e \nu_\mu$ | | | $\approx 100\%$ | | | 53 |
| $e^- \overline{\nu}_e \nu_\mu \gamma$ | | [d] | $(6.0\pm0.5) \times 10^{-8}$ | | | 53 |
| $e^- \overline{\nu}_e \nu_\mu e^+ e^-$ | | [e] | $(3.4\pm0.4) \times 10^{-5}$ | | | 53 |
| **Lepton Family number (*LF*) violating modes** | | | | | | |
| $e^- \nu_e \overline{\nu}_\mu$ | *LF* | [f] | $< 1.2$ | % | 90% | 53 |
| $e^- \gamma$ | *LF* | | $< 4.2$ | $\times 10^{-13}$ | 90% | 53 |
| $e^- e^+ e^-$ | *LF* | | $< 1.0$ | $\times 10^{-12}$ | 90% | 53 |
| $e^- 2\gamma$ | *LF* | | $< 7.2$ | $\times 10^{-11}$ | 90% | 53 |

$\mu \to e\gamma$ is 40 orders of magnitude larger than SM

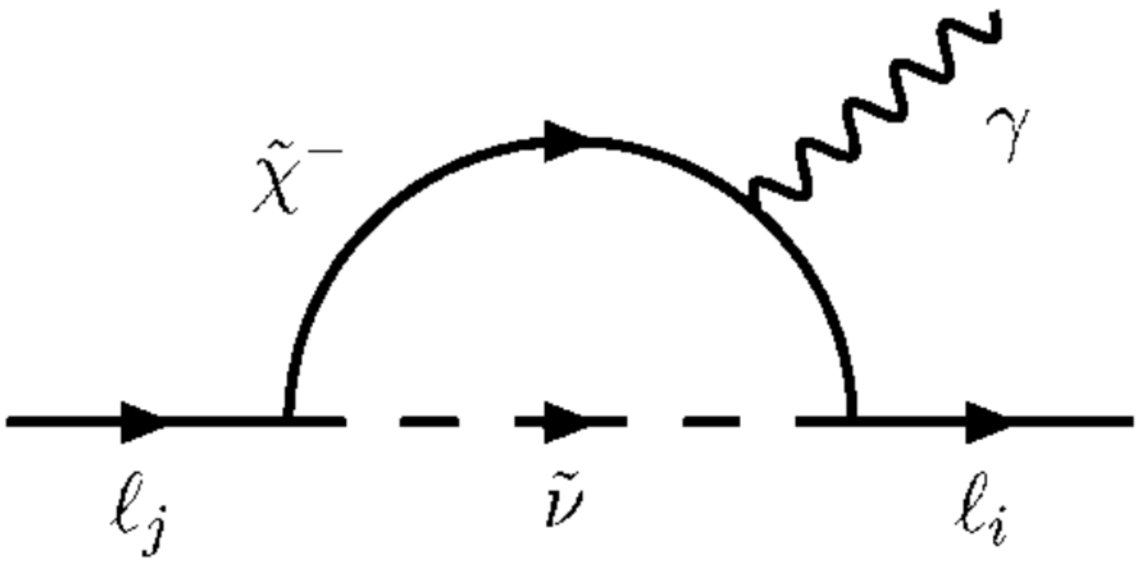
**MEG Collab. 2016** **PDG 2017**

# cLFV in SUSY

Albright & Chen, PRD 2008




neutralino-slepton

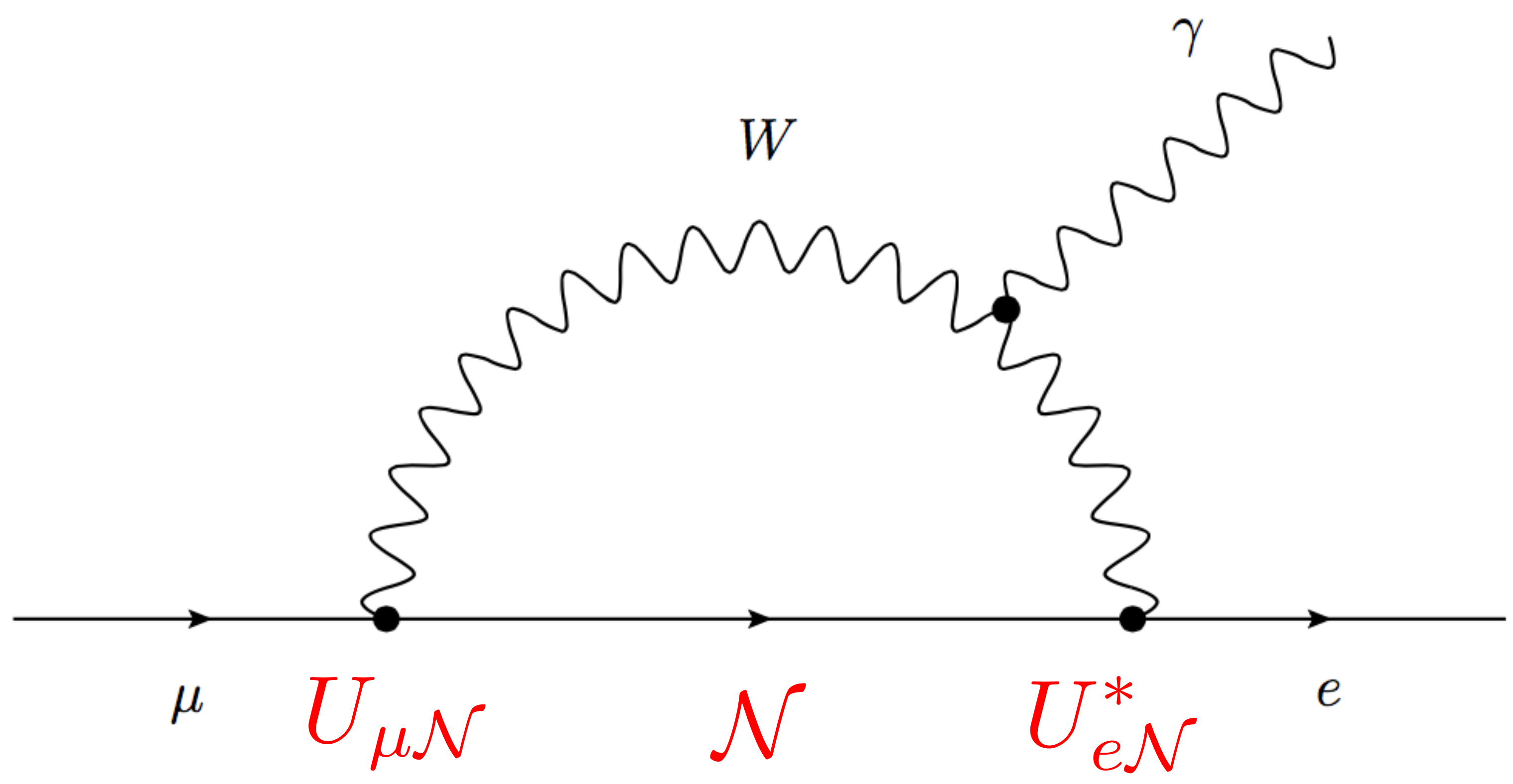



sneutrino-wino

Sparticles ~ TeV and above (thanks to LHC)

sizable contribution to cLFV that can be probed now

# cLFV w/ heavy neutrinos



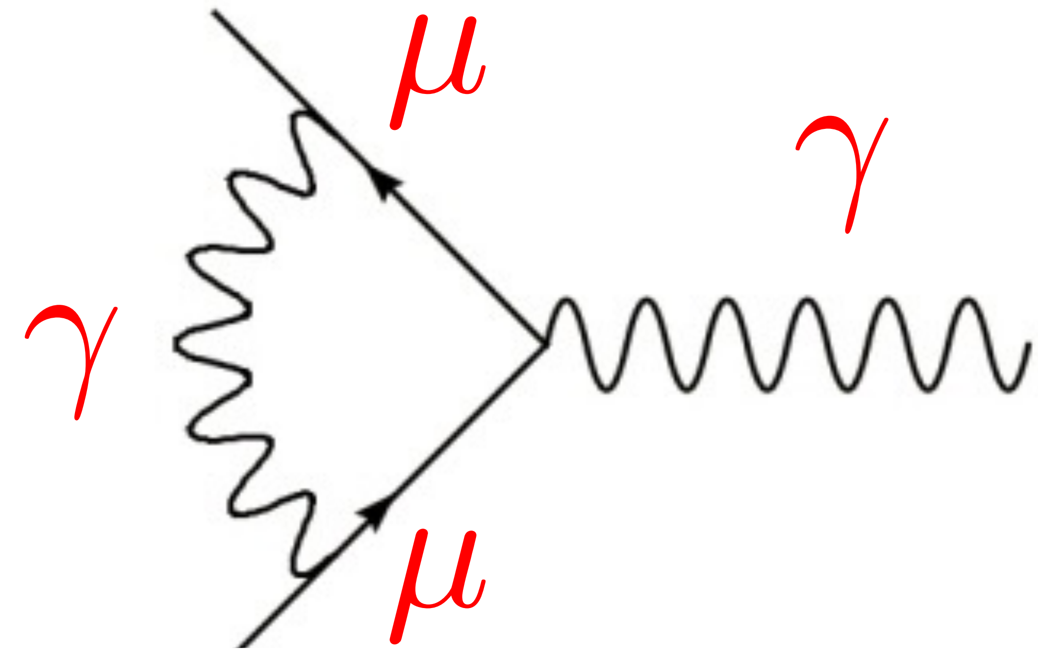

**For a fourth generation w/ a heavy neutrino**

$$\mathcal{B}(\mu^+ \to e^+\gamma) \simeq \frac{3\alpha}{32\pi} |U^*_{e\mathcal{N}} U_{\mu\mathcal{N}}|^2 \frac{m^4_{\mathcal{N}}}{m^4_{W}}.$$

**For** $m_{\mathcal{N}} \simeq m_W$, $|U^*_{e\mathcal{N}} U_{\mu\mathcal{N}}| < 10^{-4}$.

**Marciano, Mori & Roney ARNPS 2008**

# muon g-2




$$a_\mu^{\rm EXP} = (11\ 659\ 208.9 \pm 6.3) \times 10^{-10}$$

**Muon g-2 Collab. PRD 73 (2006) 072003**

$$a_\mu^{\rm SM} = (11\ 659\ 182.8 \pm 4.9) \times 10^{-10}$$

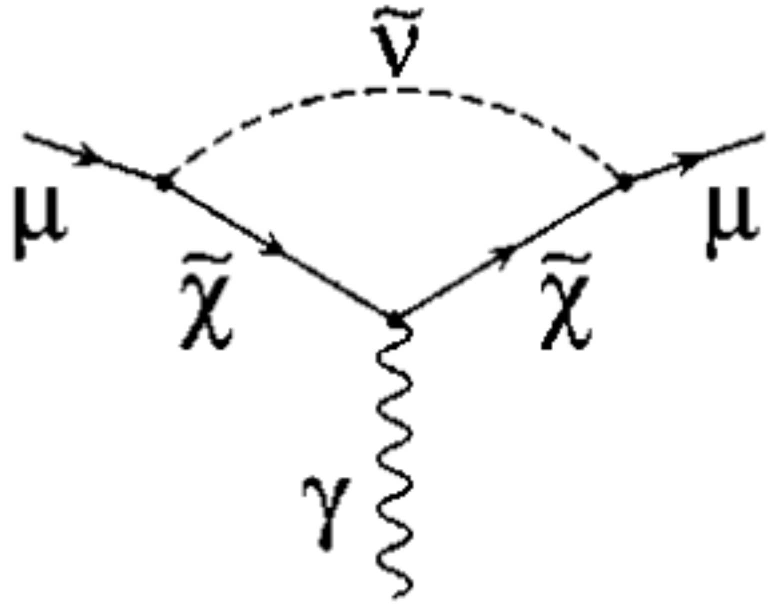
**Hagiwara, Liao, Martin Nomura, Teubner, 2010**

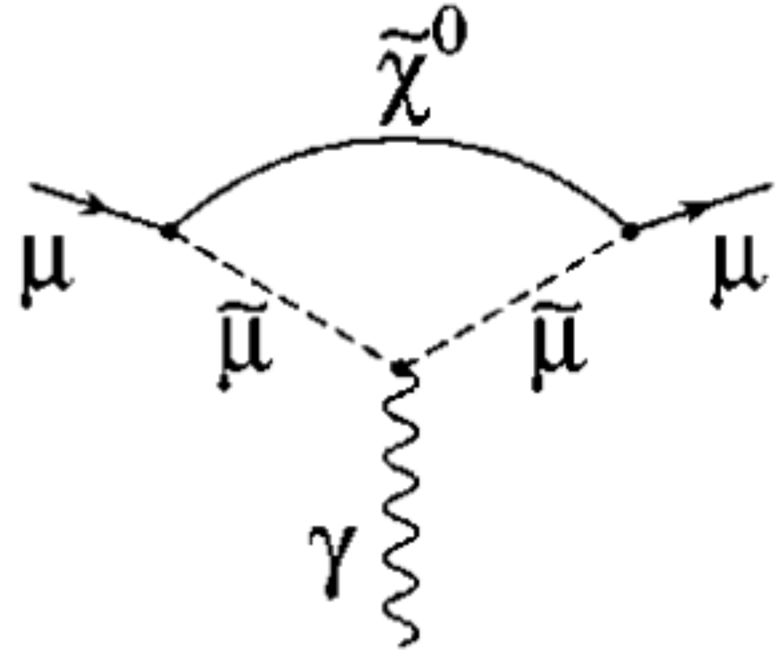
$$a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

**Hagiwara, Ma, Mukhopadhyay, 1706.09313**

**3.3 σ discrepancy!**

# muon g-2 in SUSY




**sneutrino-chargino** **smuon-neutralino**

$$a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

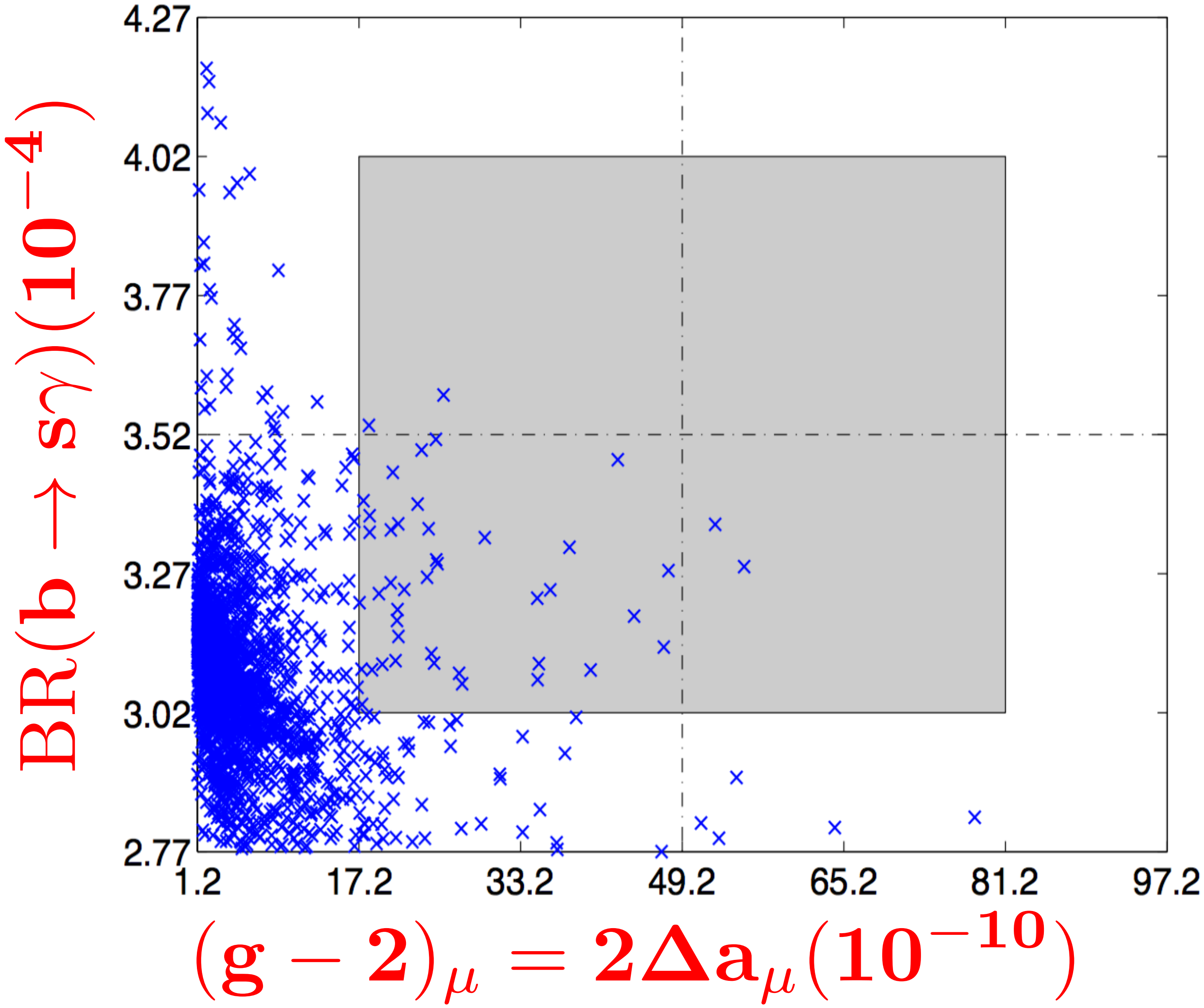
$$a_\mu({\rm SUSY}) \simeq {\rm sgn}\,(\mu)\ 130 \times 10^{-11}\ \tan\beta\ \left(\frac{100\ {\rm GeV}}{\Lambda}\right)^2$$

**Czarnecki & Marciano, 2001**

# muon g-2 in SUGRA

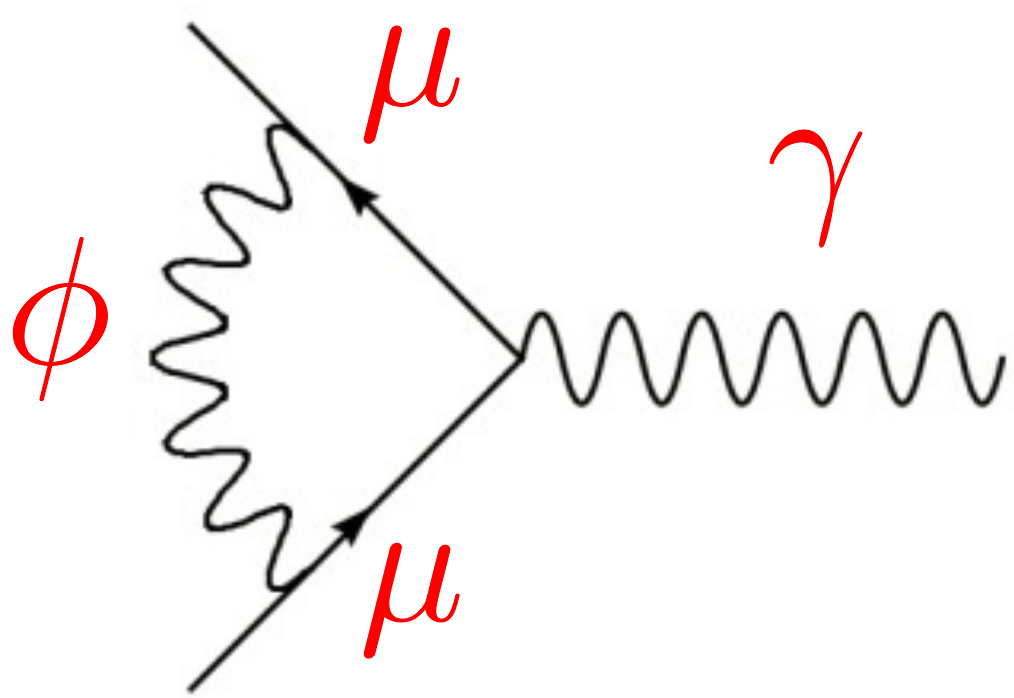
A scan in the SUGRA models with 3-million model points.

Improvements on muon g-2 measurements can further probe the NP models.




Chen, Feldman, ZL, Nath 2009

# muon g-2 w/ a new boson



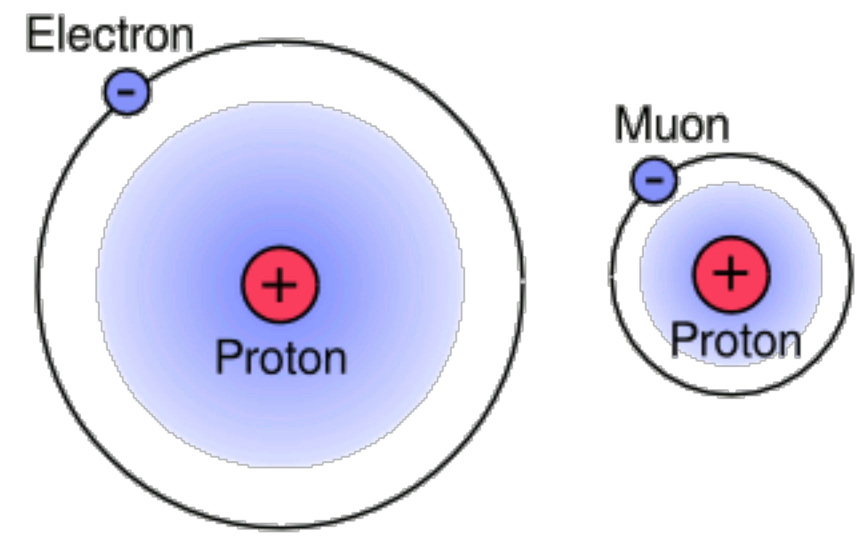

$$\Delta a_l = \frac{\alpha}{2\pi}\left(\frac{g_\mu}{e}\right)^2 \xi\left(m_\phi/m_l\right)$$

$$\xi(x)_{\text{scalar}} = \int_0^1 \frac{(1-z)^2(1+z)}{(1-z)^2+x^2 z}dz$$

$$\xi(x)_{\text{vector}} = \int_0^1 \frac{2z(1-z)^2}{(1-z)^2+x^2 z}dz$$

**Tucker-Smith & Yavin, 1011.4922**

# Proton radius puzzle




**Lamb shift in the muonic hydrogen atom**

$$r_p = 0.84087(39)\ \text{fm}$$

**CREMA Collab., Nature 466:213 (2010)**
**CREMA Collab., Science 339:417 (2013)**

**Electronic hydrogenate atom & electron-proton scattering**

$$r_p = 0.8775(51)\ \text{fm}$$

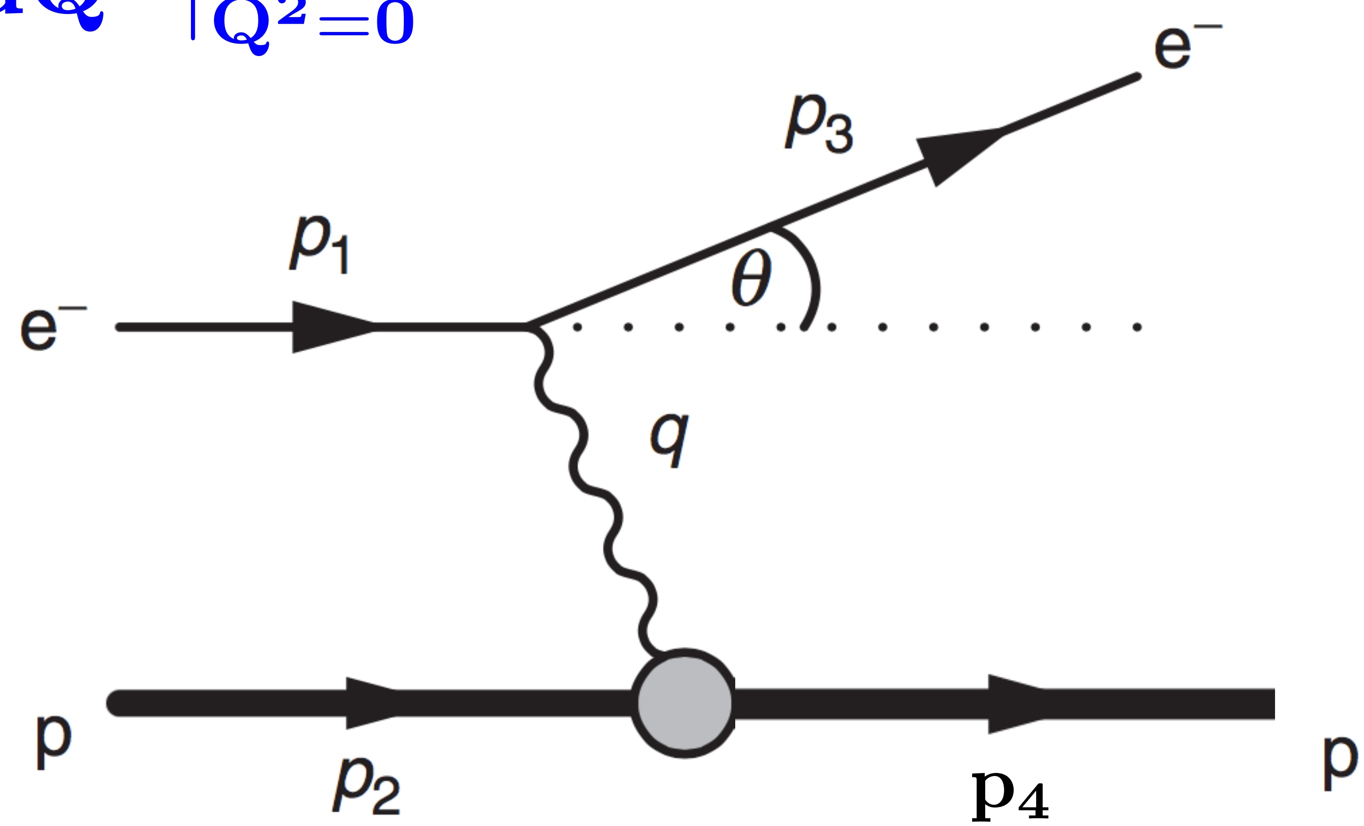
**Mohr, Taylor & Newell, RMP 2012**
**A1 Collab., PRL 2010**

**7 σ discrepancy!**

# Proton radius in e-p scattering

**Proton radius definition: the mean-square value of the radius in e-p scattering**

$$\mathbf{r_p \equiv \sqrt{\langle r_p^2 \rangle} = \sqrt{-6\frac{dG_E}{dQ^2}\bigg|_{Q^2=0}}}$$



# Atomic energy levels

**Coulomb potential correction due to proton radius**

$$\delta V(\mathbf{r}) \equiv V_C(\mathbf{r}) - V_C^{\mathrm{pt}}(\mathbf{r}) = -4\pi\alpha \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \frac{[G_\mathrm{E}(\mathbf{q}^2) - 1]e^{-i\mathbf{q}\cdot\mathbf{r}}}{\mathbf{q}^2}$$

**An accurate approximation:** $G_\mathrm{E}(\mathbf{q}^2) - 1 \approx -\mathbf{q}^2 r_p^2/6$

**because in atomic physics** $r_p q \sim r_p/a_B \sim 10^{-5}$

**The resulting energy shift for atomic S-states**

$$\Delta E = \langle \Psi_S | \delta V | \Psi_S \rangle = \frac{2}{3}\pi\alpha \left|\Psi_S(0)\right|^2 r_p^2.$$

**Pohl et al., Annu. Rev. Nucl. Part. Sci. 2013**

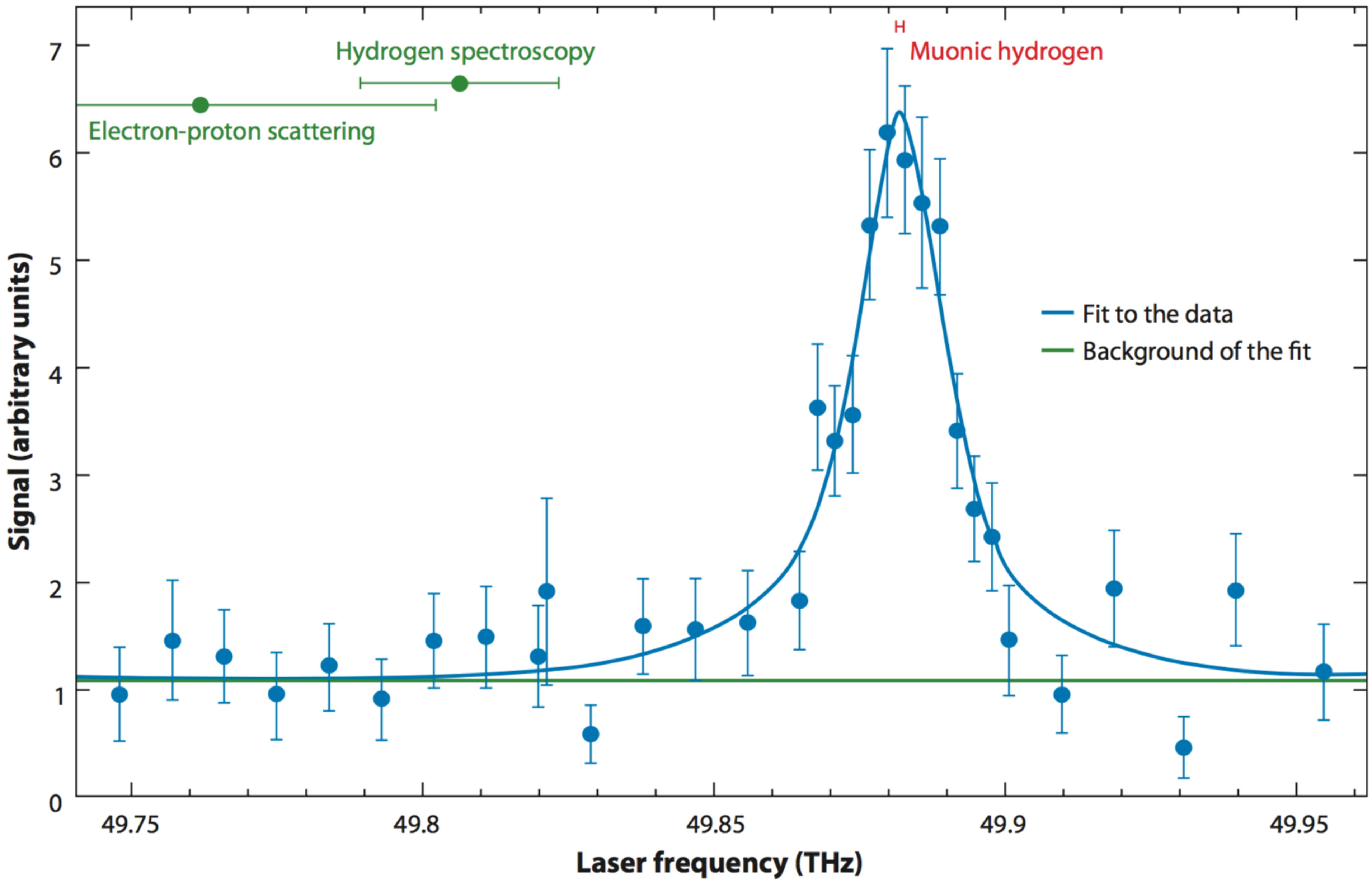
# Lamb shift in muonic hydrogen

The leading contribution to 2S-2P splitting is the Uehling potential

Including the effects from proton radius, the lamb shift is

$$\Delta\tilde{E} = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV} \quad \text{for} \quad 2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$$

$r_p$ in fm




**Pohl et al., Annu. Rev. Nucl. Part. Sci. 2013**

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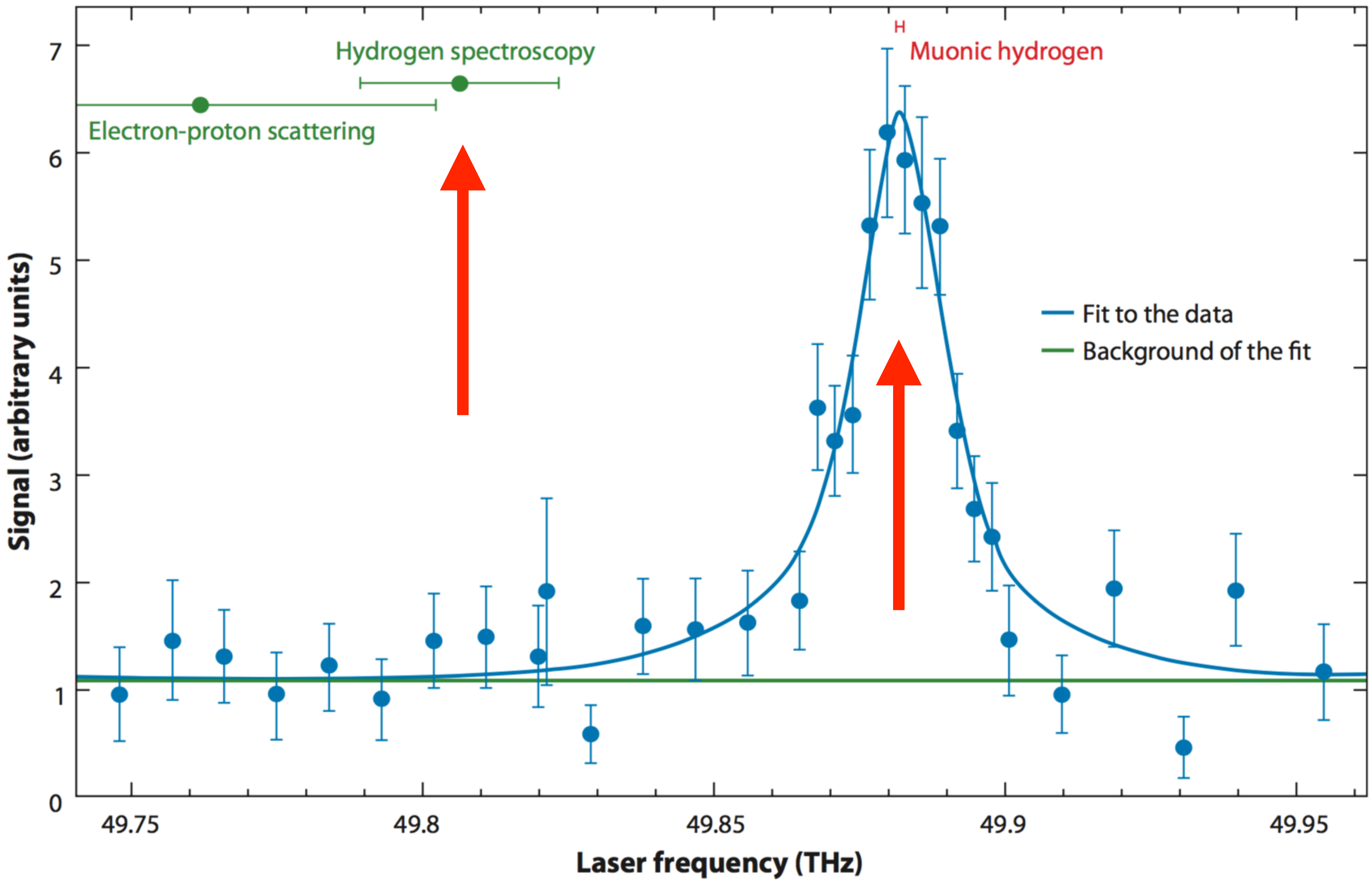
$r_p$ in fm




**Pohl et al., Annu. Rev. Nucl. Part. Sci. 2013**

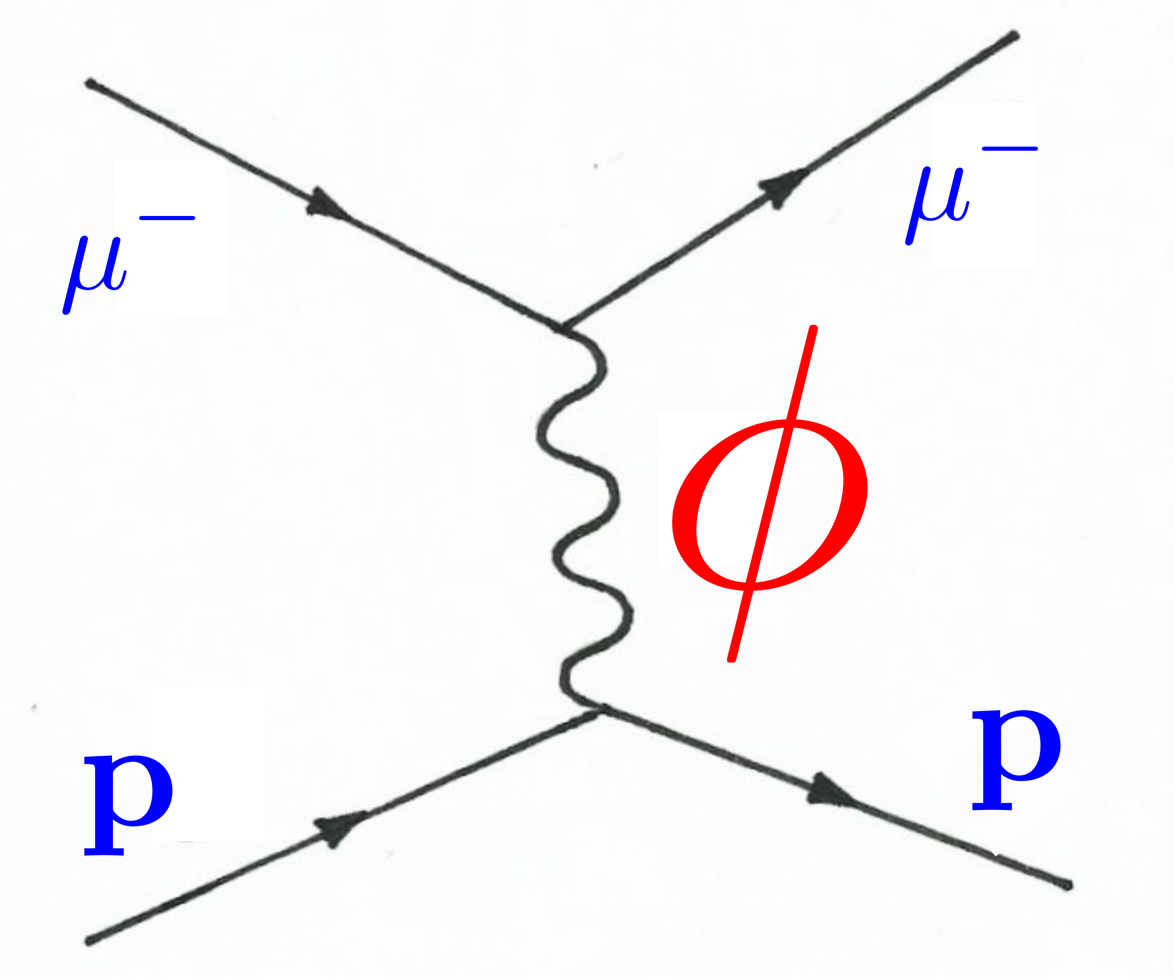
$$\Delta E_{\mathbf{exp}} - \Delta E_{\mathbf{th}} = 0.3\ \mathbf{meV}$$

# New physics explanation

**New potential term (Yukawa)**

$$V_\phi(r) = (-)^{s+1}\left(\frac{g_\mu g_p}{e^2}\right)\frac{\alpha e^{-m_\phi r}}{r}$$

**s is spin and m is mass**




$$\langle 2P|V_\phi|2P\rangle - \langle 2S|V_\phi|2S\rangle = 0.3\ \mathbf{meV}$$

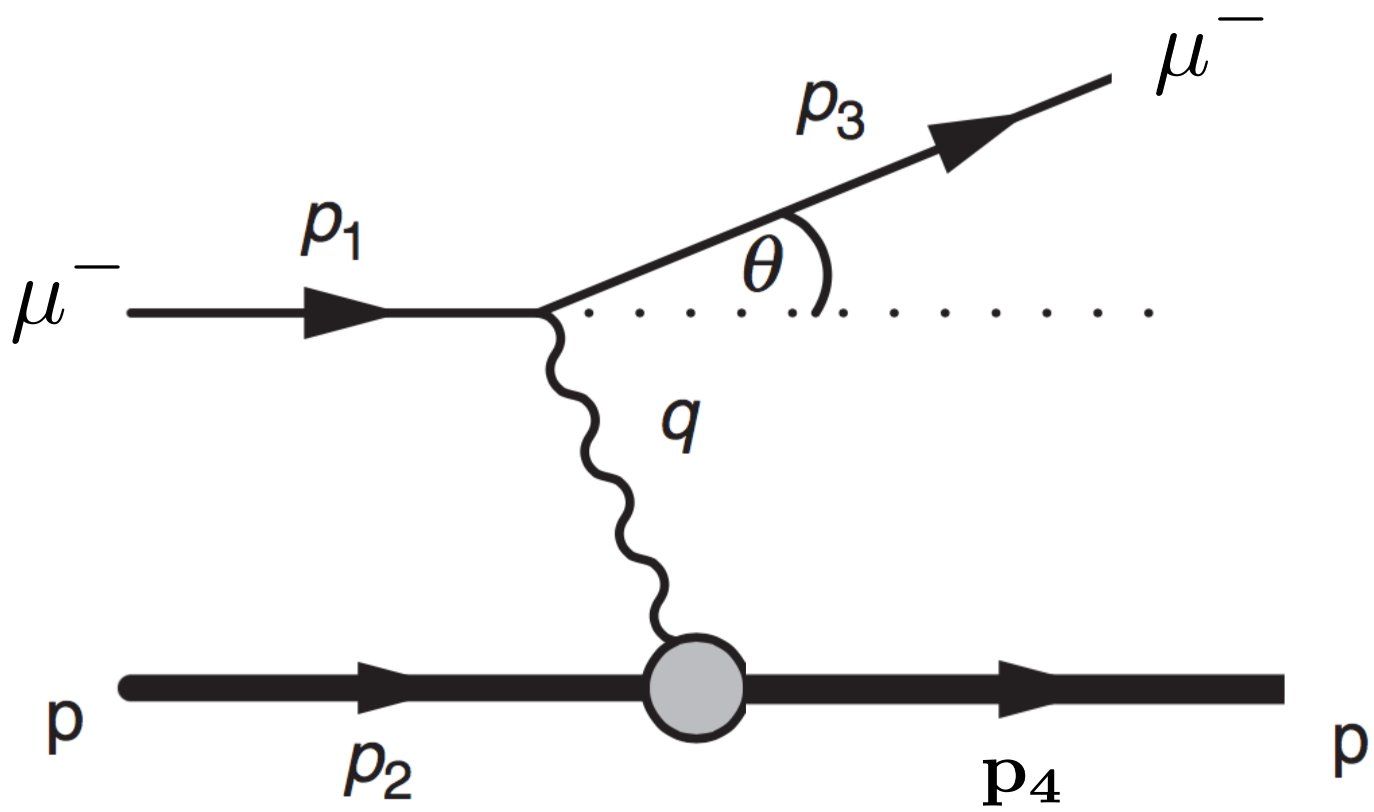
**Such a new MeV boson can also explain the muon g-2 anomaly**

**Liu, McKeen, Miller PRL 2016**

**Tucker-Smith & Yavin, 1011.4922**

# muon-proton scattering

**Maybe muon interacts differently with proton**




**Form factor measurement in muon-proton scattering**

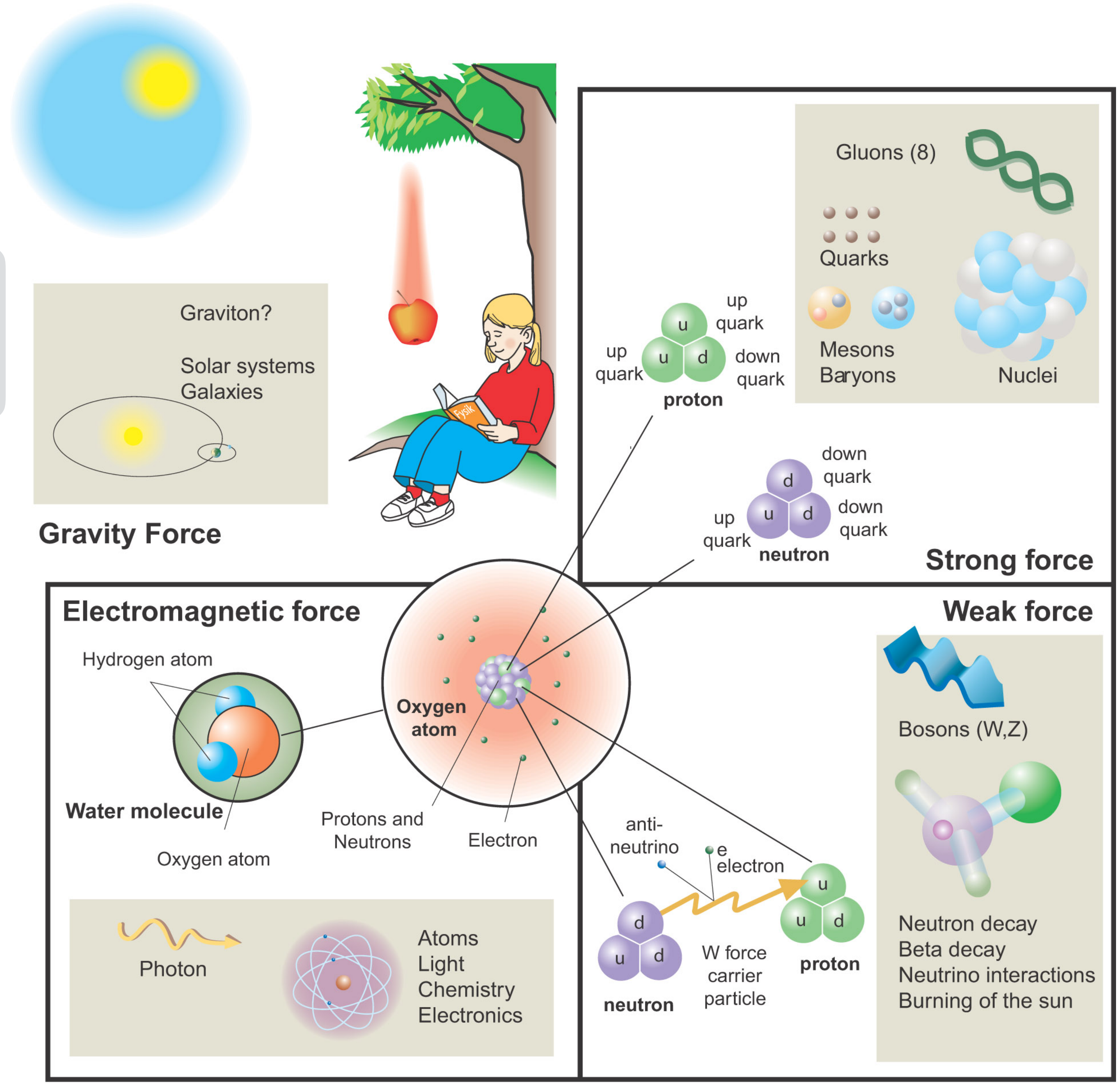
# A new type of interaction?

Gravity

Strong

EM

Weak

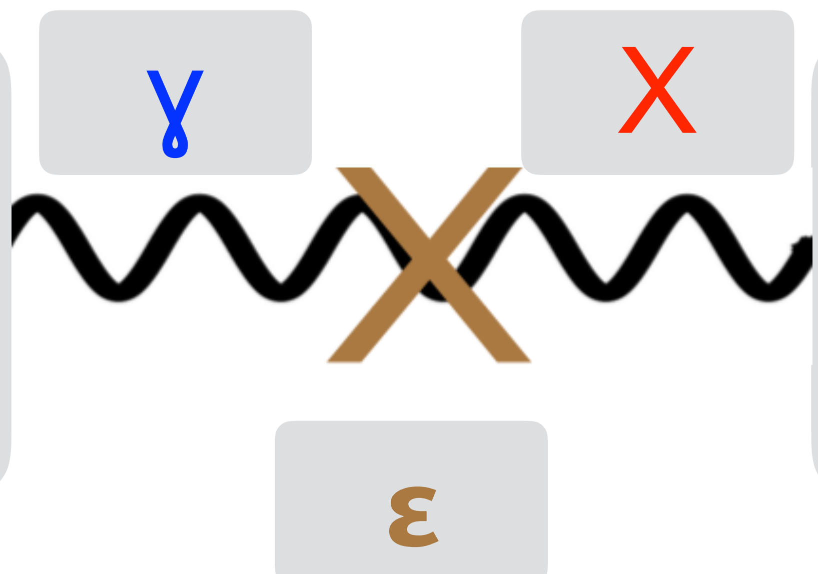



A new interaction (or a 5th force)

# Dark Photon

Photon mixes w/ X boson

SM
g, W/Z, γ




Hidden sector
X boson

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F_Y^{\mu\nu} X_{\mu\nu}$$

‘Kinetic Mixing’

Holdom, PLB 1986

# Stueckelberg boson

## Generate gauge boson masses w/o Higgs

$$\Delta\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}(\partial_\mu\sigma + M_1 X_\mu + M_2 B_\mu)^2$$

invariant under the following gauge transformations

$$\delta_Y B_\mu = \partial_\mu \lambda_Y, \delta_Y \sigma = -M_2 \lambda_Y, \quad U(1)_Y$$

$$\delta_X C_\mu = \partial_\mu \lambda_X, \delta_X \sigma = -M_1 \lambda_X, \quad U(1)_X$$

boson mass $M_X \simeq M_1$

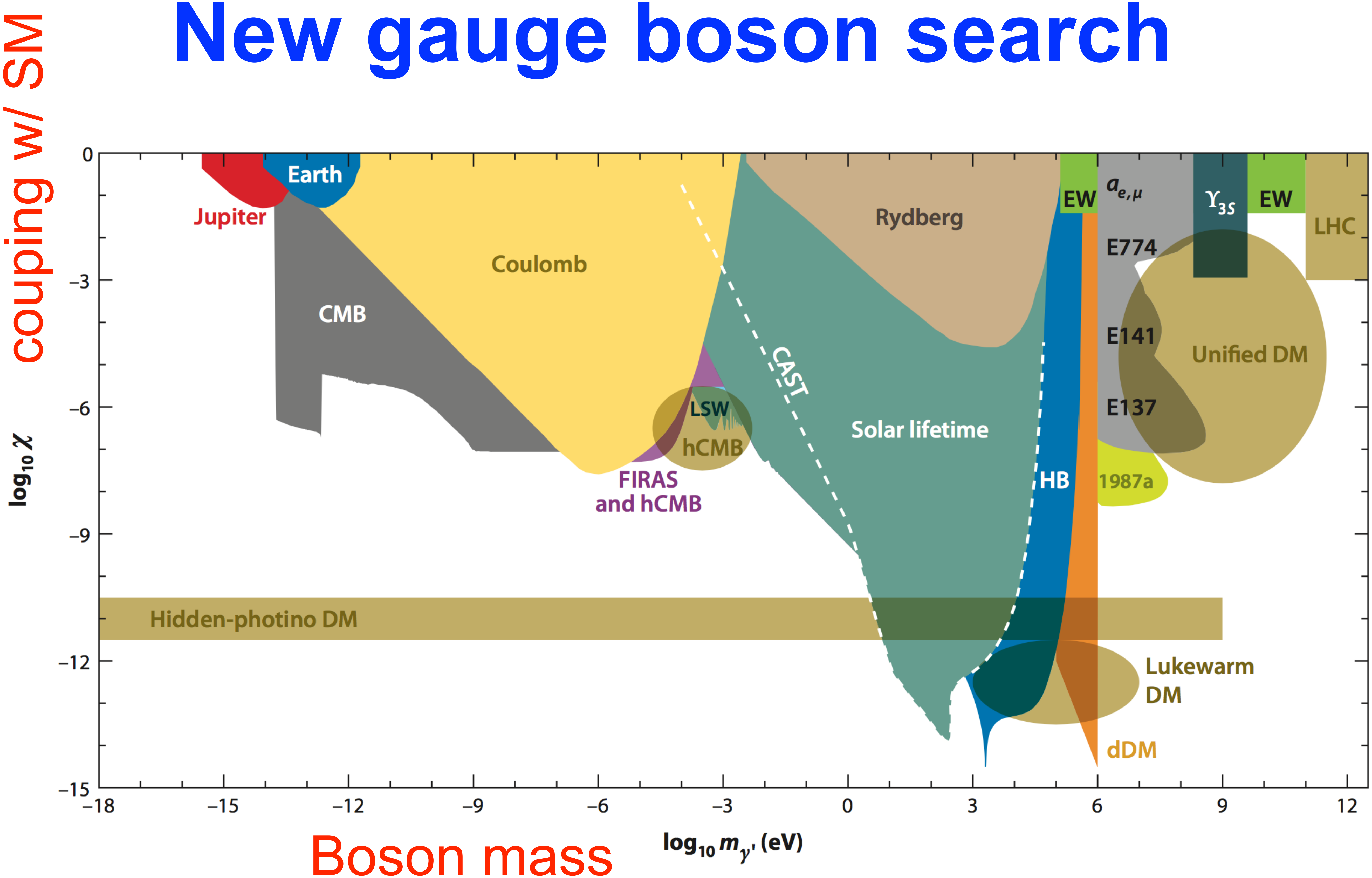
coupling w/ SM

$$\epsilon \equiv \frac{M_2}{M_1} \text{ or } \frac{M_1}{M_2} \ll 1$$

Kors & Nath, PLB 2004

Feldman, Liu, Nath, PRL 2006

# New gauge boson search




Jaeckel & Ringwald, Annu. Rev. Nucl. Part. Sci. 2010

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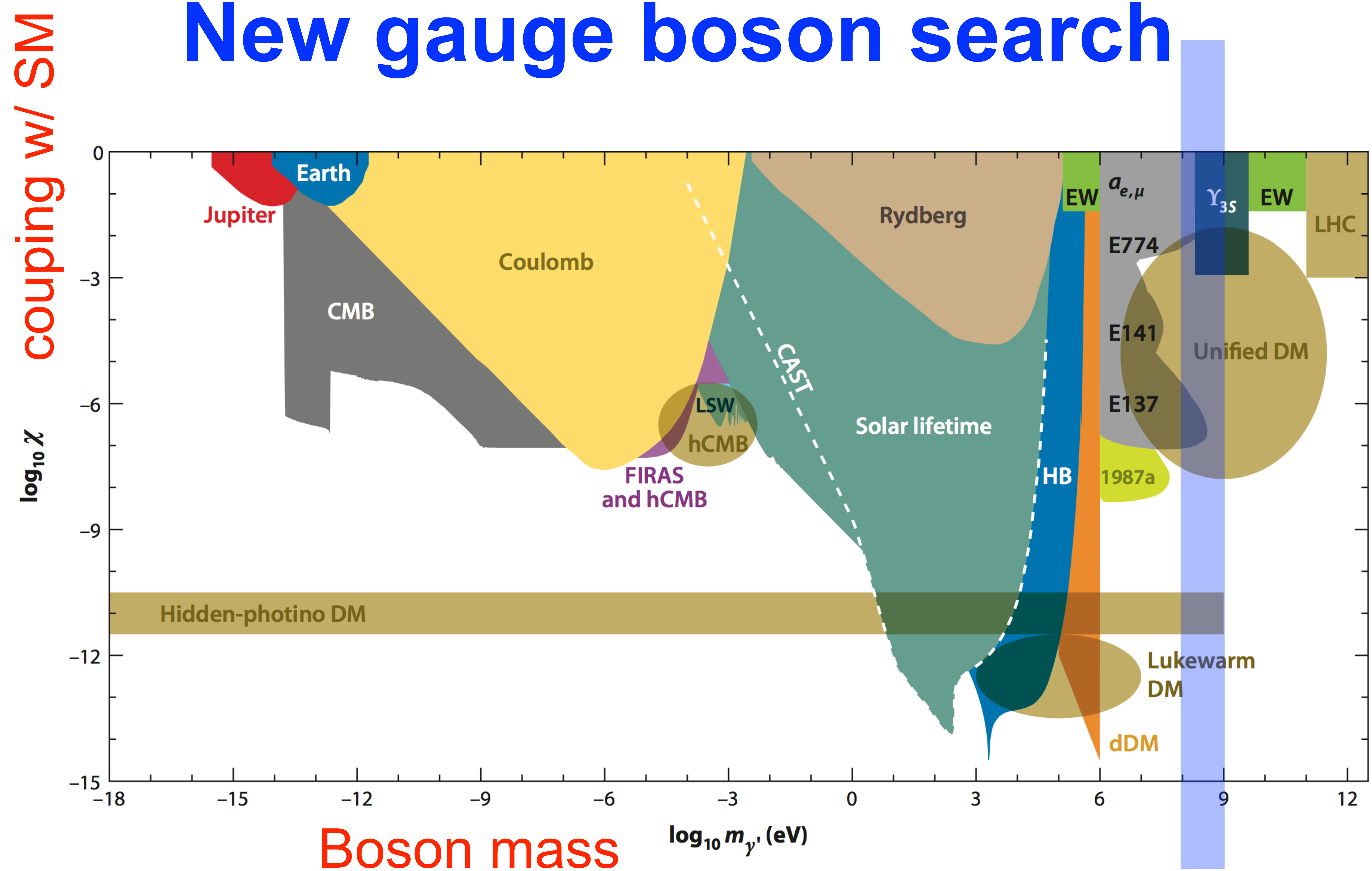
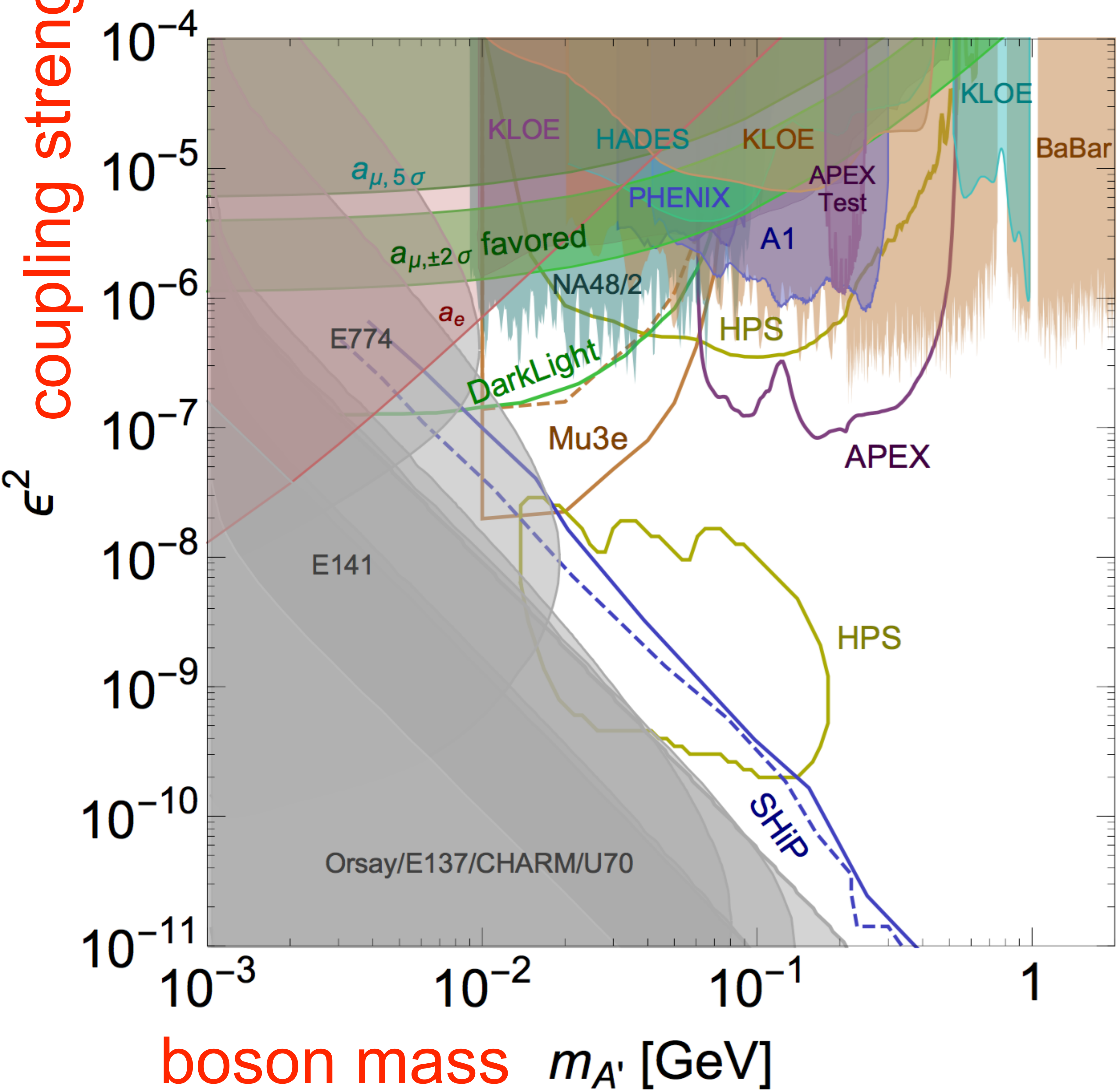



Jaeckel & Ringwald, Annu. Rev. Nucl. Part. Sci. 2010

# Intensity frontier efforts




APEX @ JLab

SHiP @ CERN

DarkLight @ JLab

HPS @ JLab

Mu3e @ PSI

Essig 2015

# 6.8σ anomaly in Be-8 decays

Anomalous events in both the opening angle and invariant mass distributions of electron-positron pairs in the Be-8 transitions.

Hungarian Atomki Collab.

Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

# Be-8 decays

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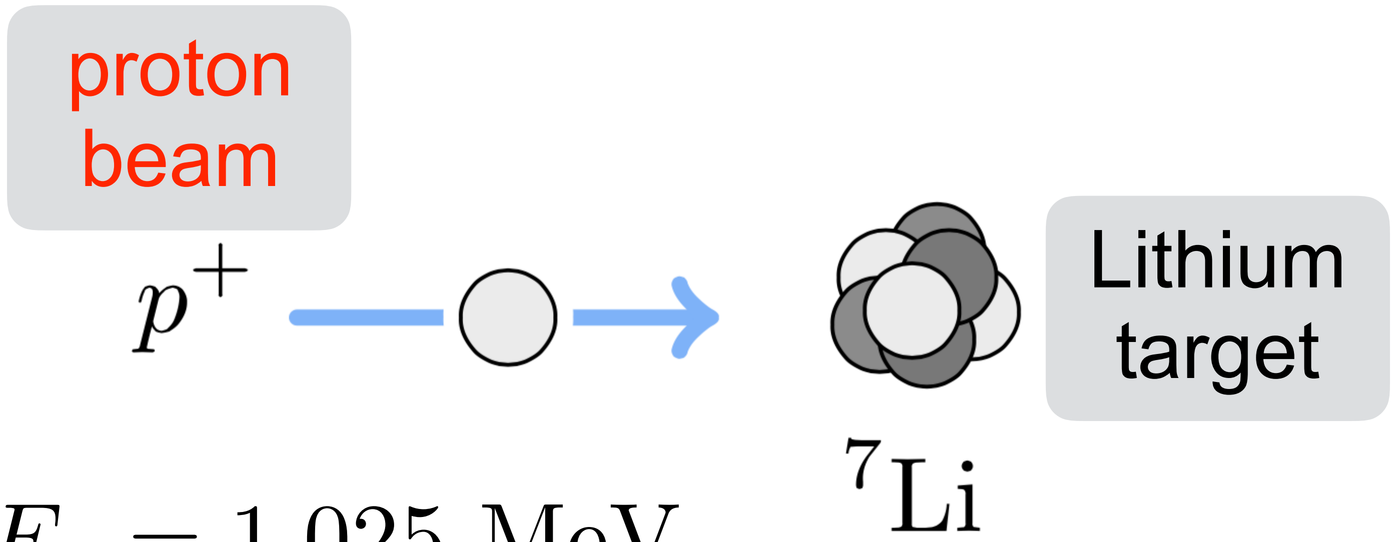
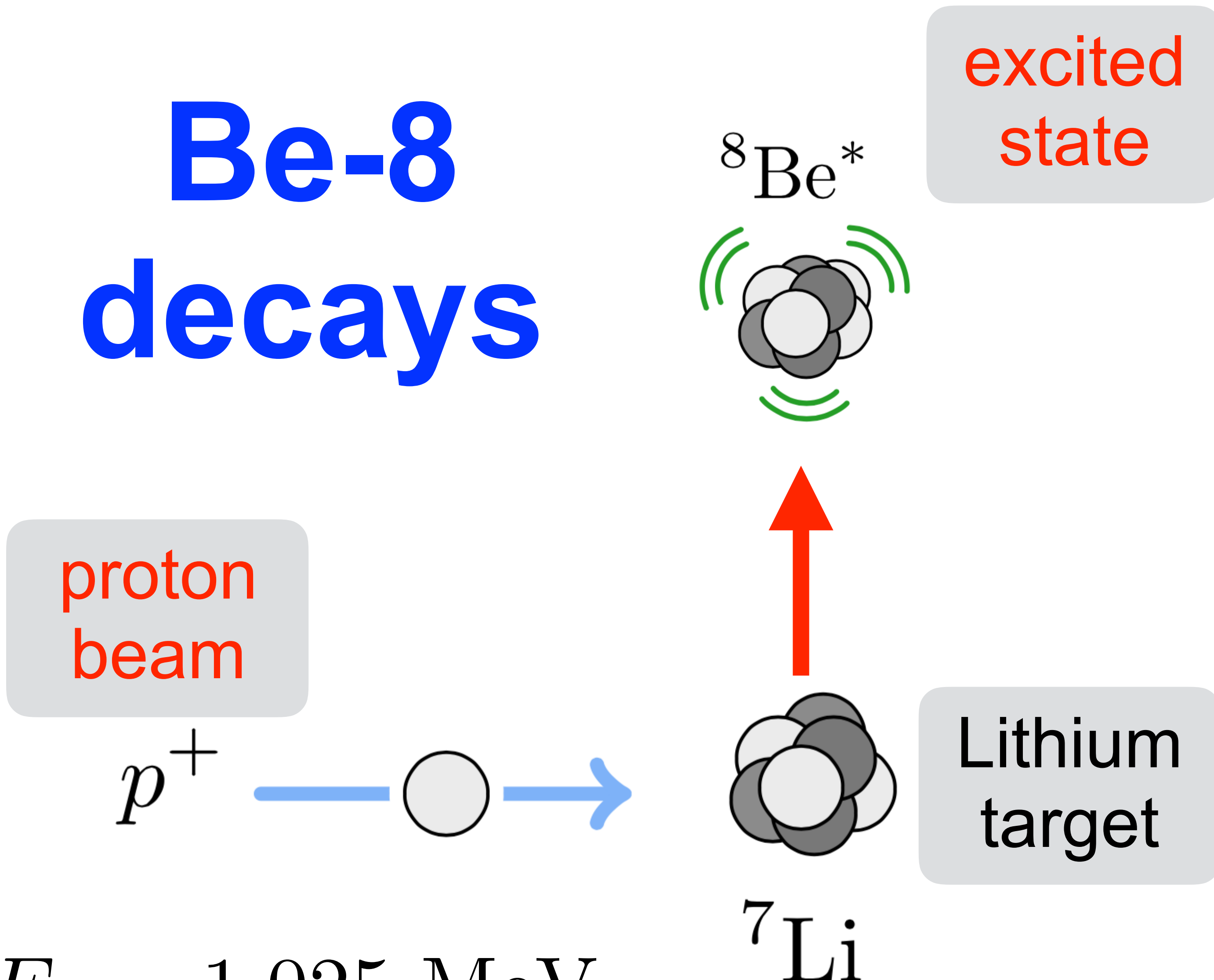



$$E_p = 1.025 \text{ MeV}$$

# Be-8 decays

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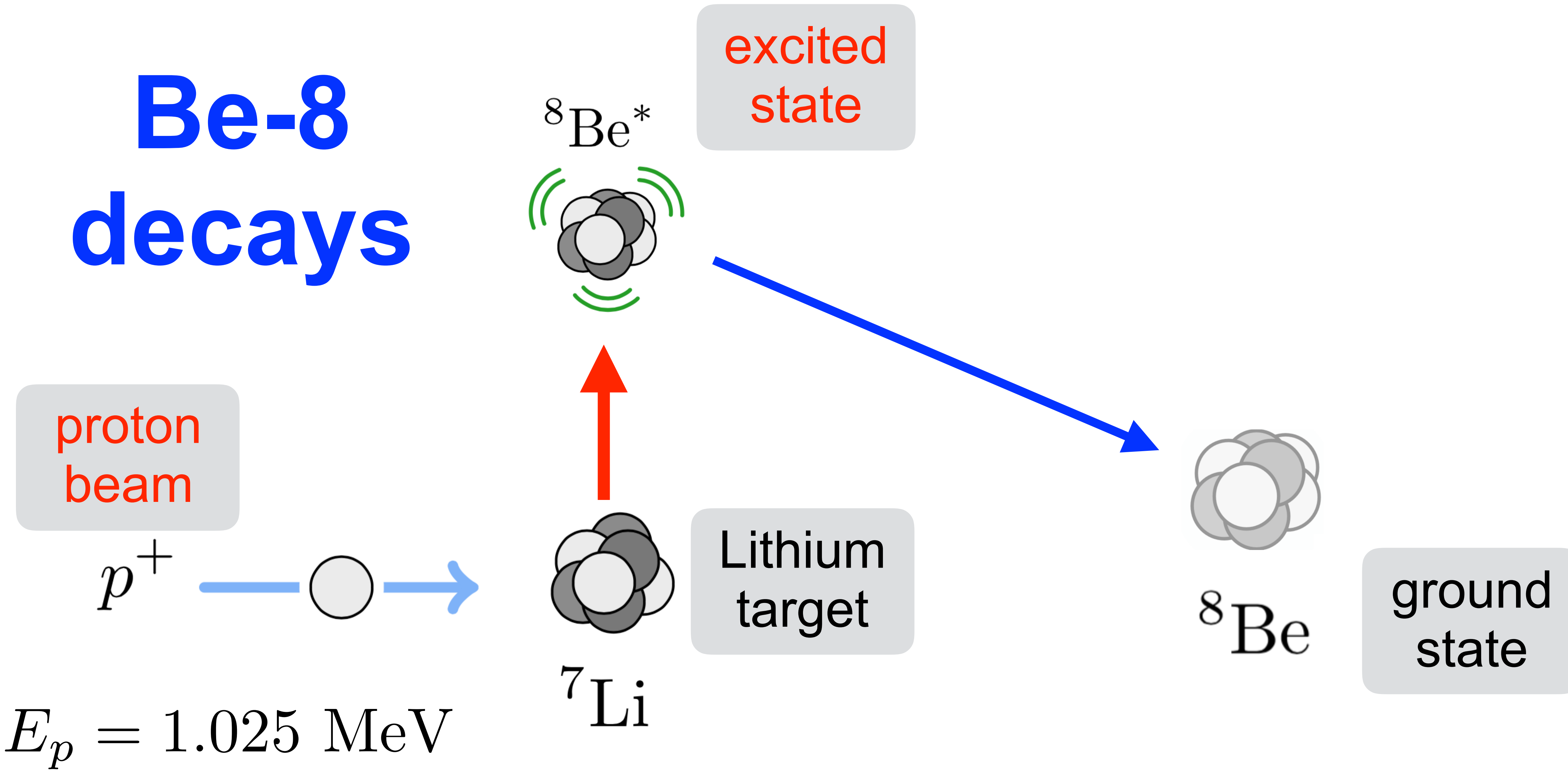
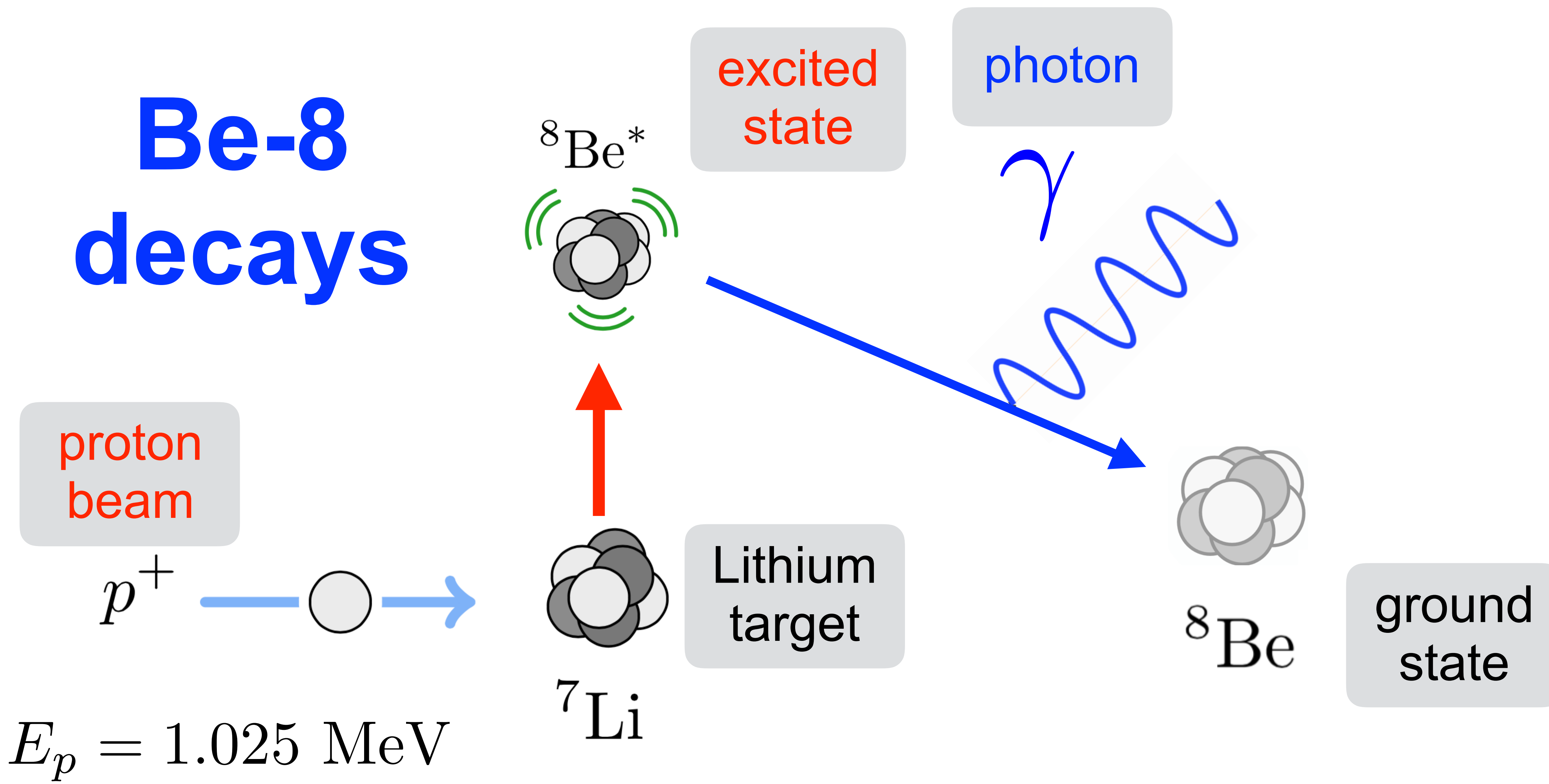


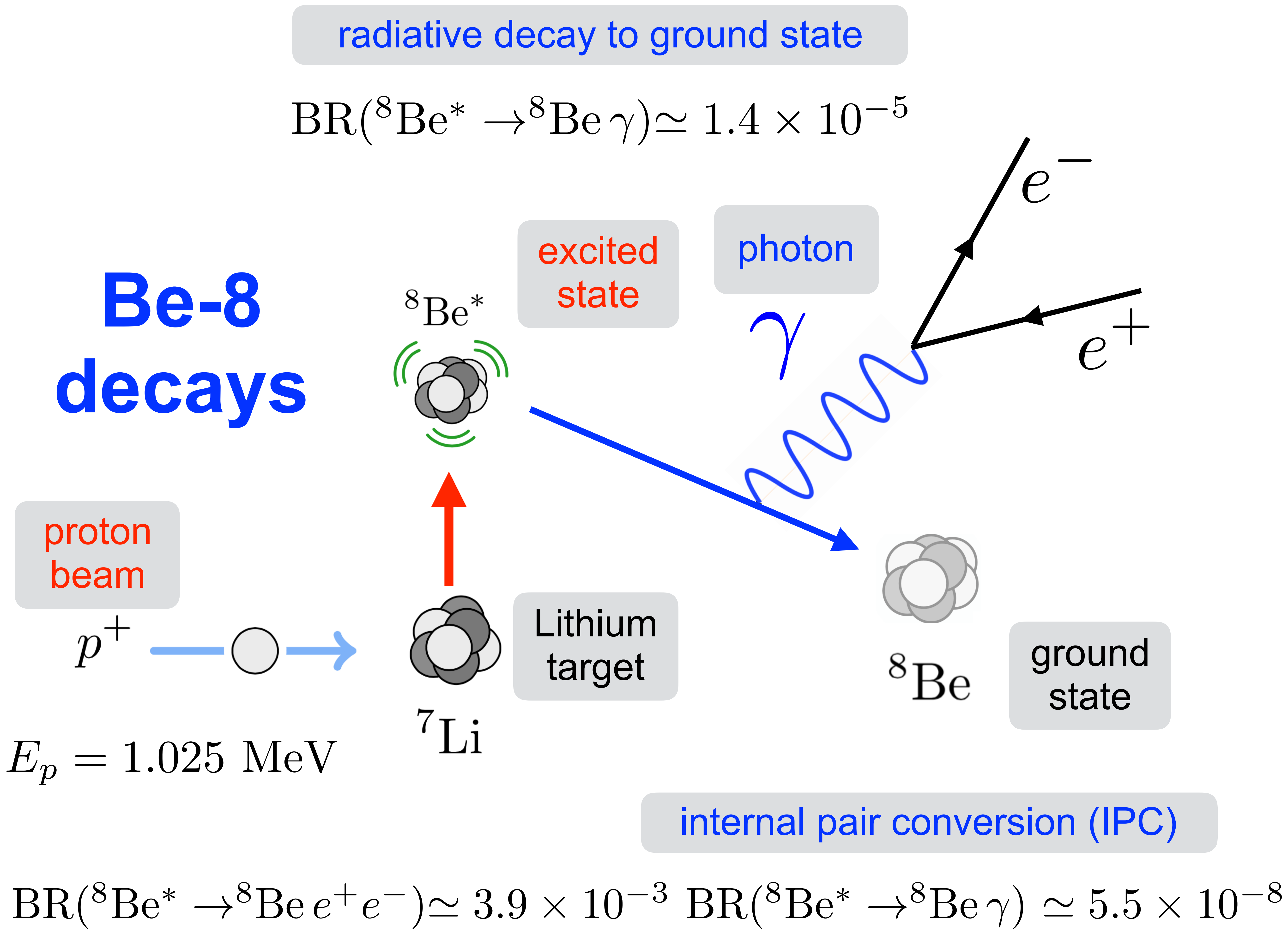
$^8\text{Be}^*$
excited state
proton beam
$p^+$
Lithium target
$^7\text{Li}$
$^8\text{Be}$
ground state
$E_p = 1.025\ \text{MeV}$

radiative decay to ground state

$$\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma) \simeq 1.4 \times 10^{-5}$$

# Be-8 decays




radiative decay to ground state
$\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma) \simeq 1.4 \times 10^{-5}$
Be-8 decays
excited state
photon
$\gamma$
$e^-$
$e^+$
$^8\mathrm{Be}^*$
proton beam
$p^+$
Lithium target
$^7\mathrm{Li}$
$^8\mathrm{Be}$
ground state
$E_p = 1.025\ \mathrm{MeV}$
internal pair conversion (IPC)
$\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,e^+e^-) \simeq 3.9 \times 10^{-3}$
$\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma) \simeq 5.5 \times 10^{-8}$

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radiative decay to ground state

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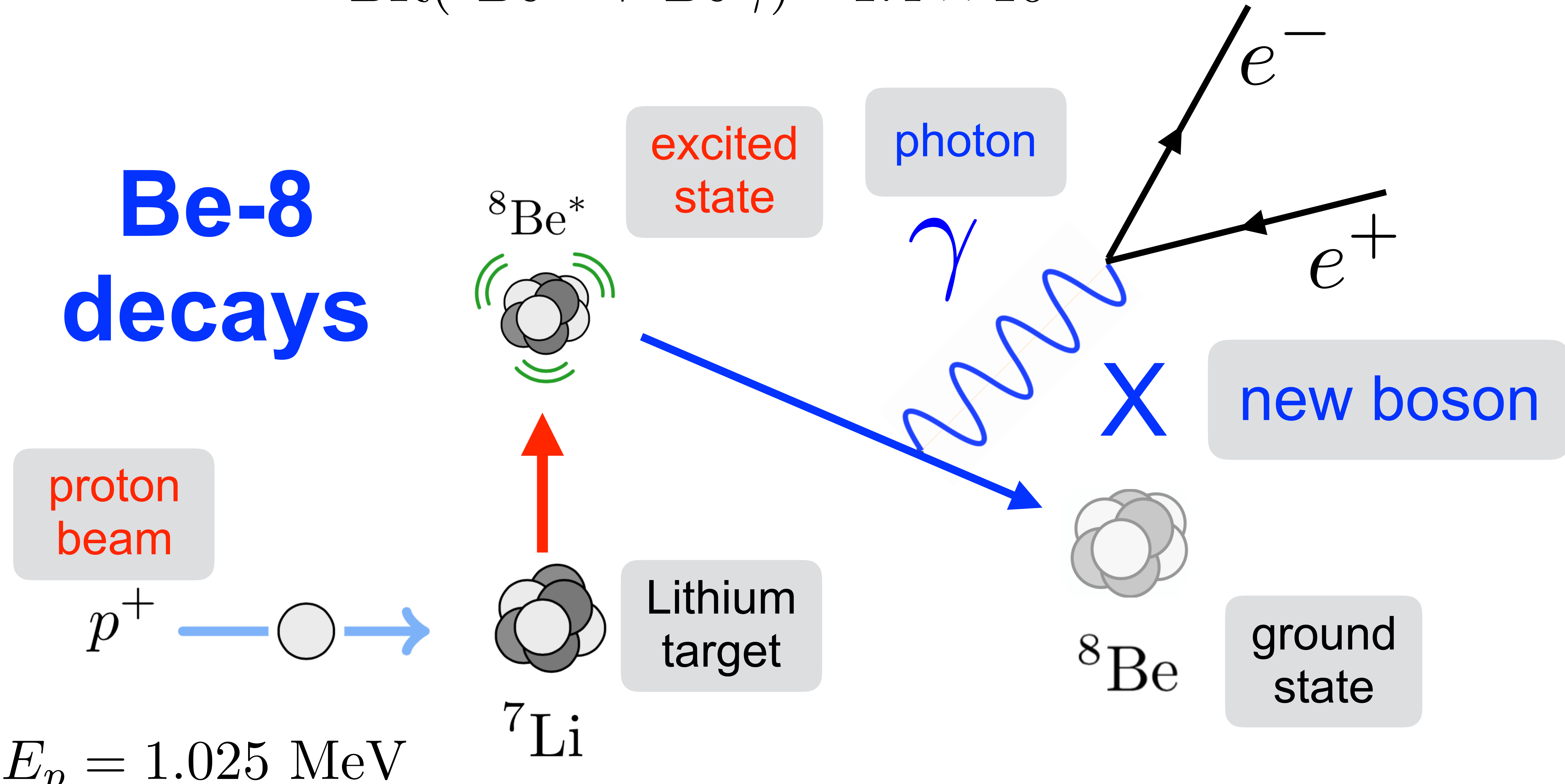


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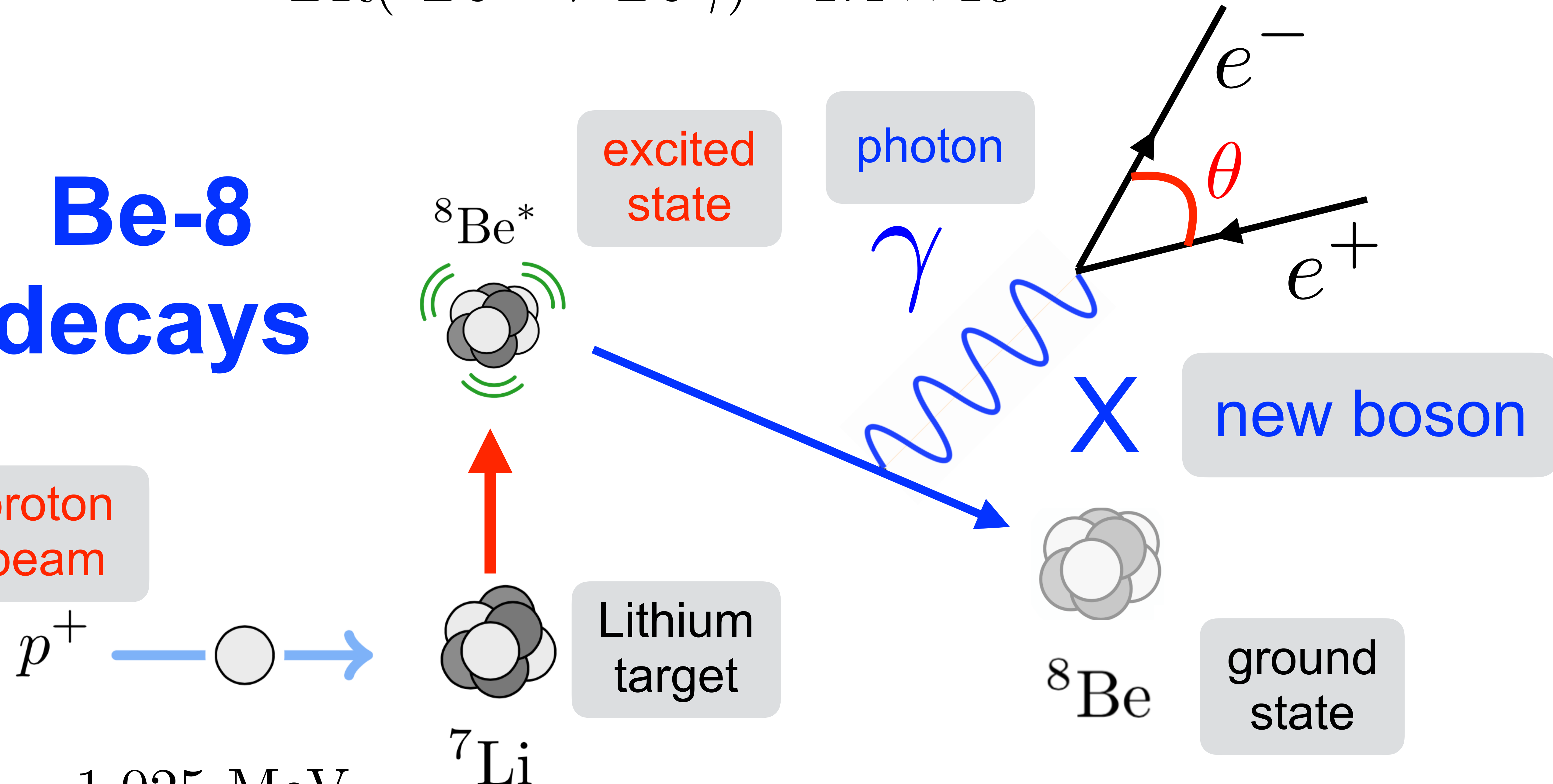


$$E_p = 1.025\ \mathrm{MeV}$$

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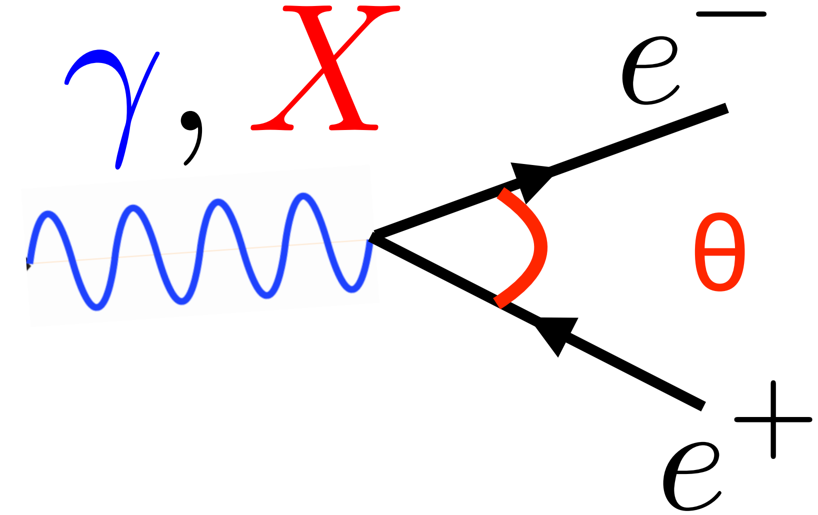
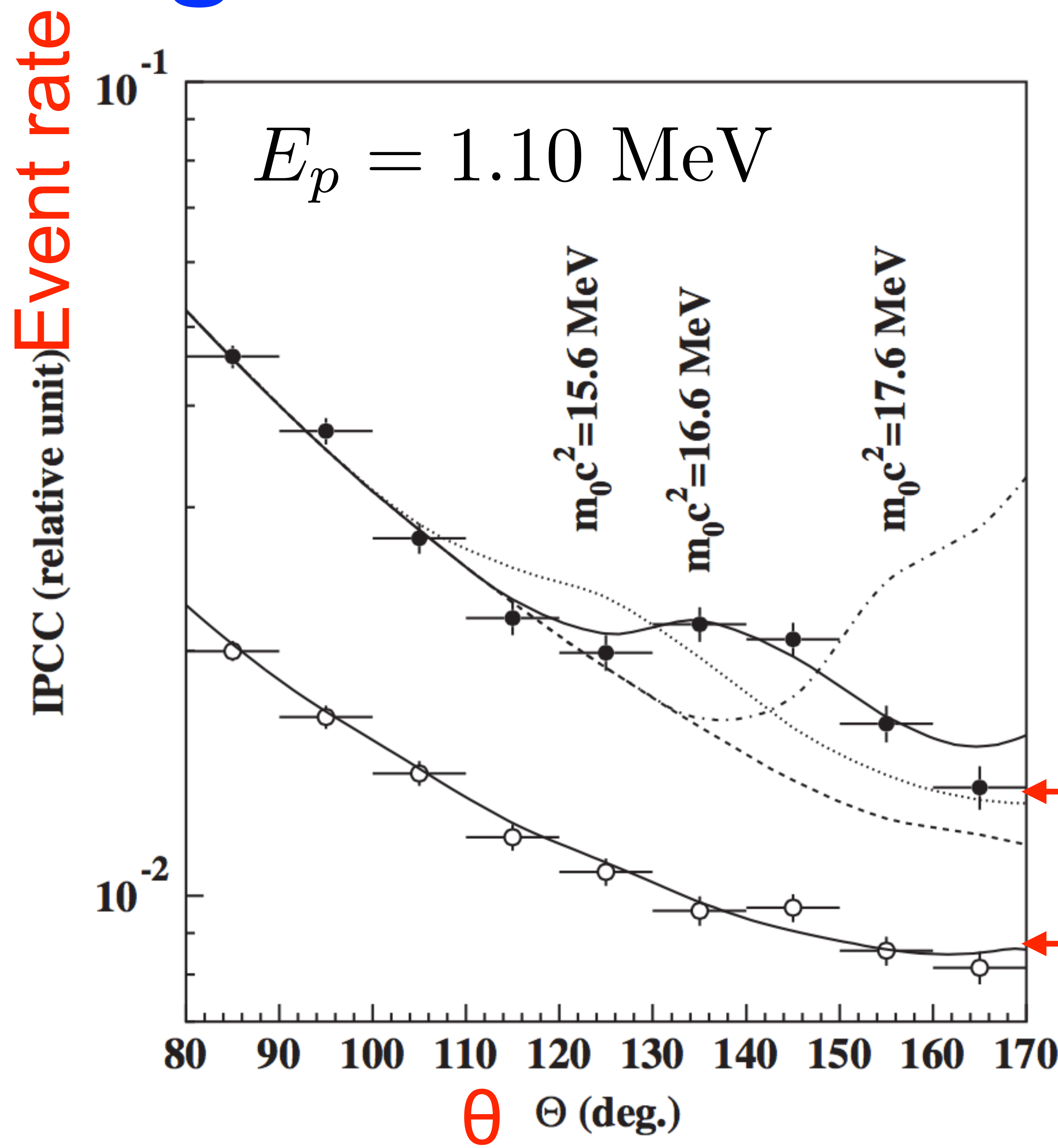
# Angular correlation

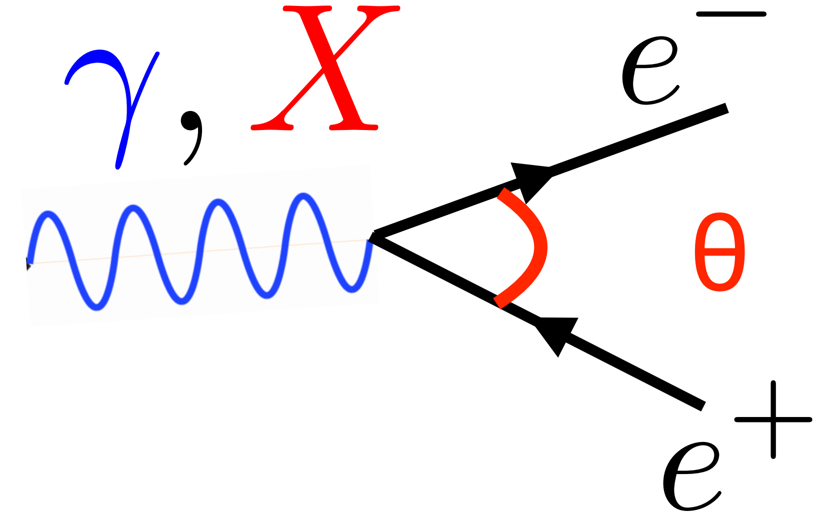


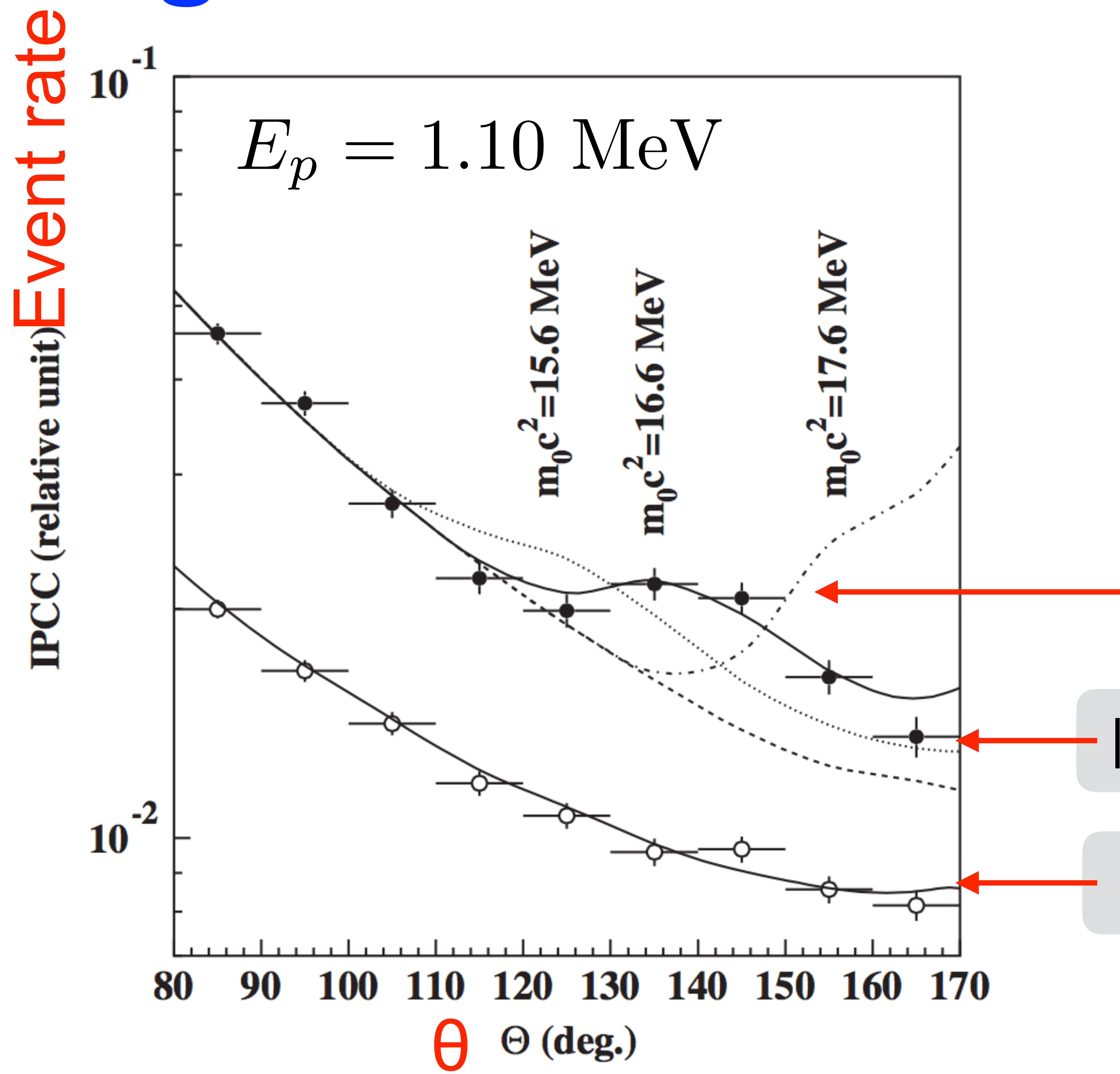




$$y = \frac{E_{e^-} - E_{e^+}}{E_{e^-} + E_{e^+}}$$

Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

# Angular correlation

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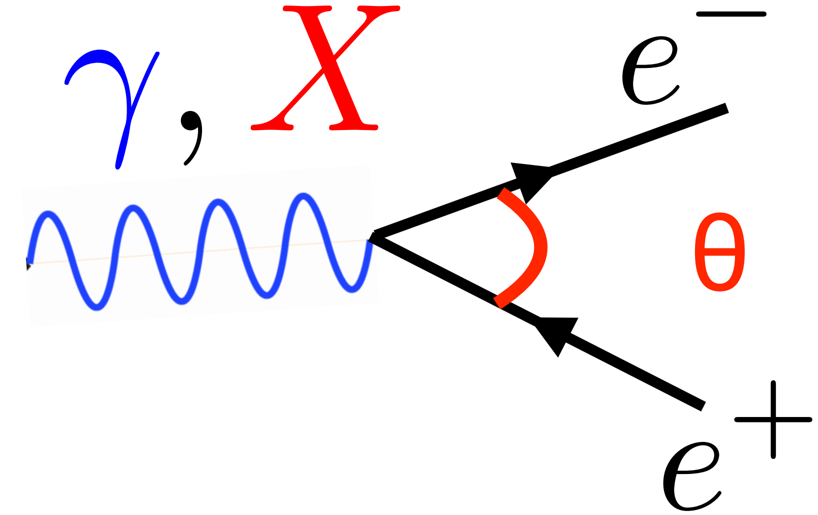


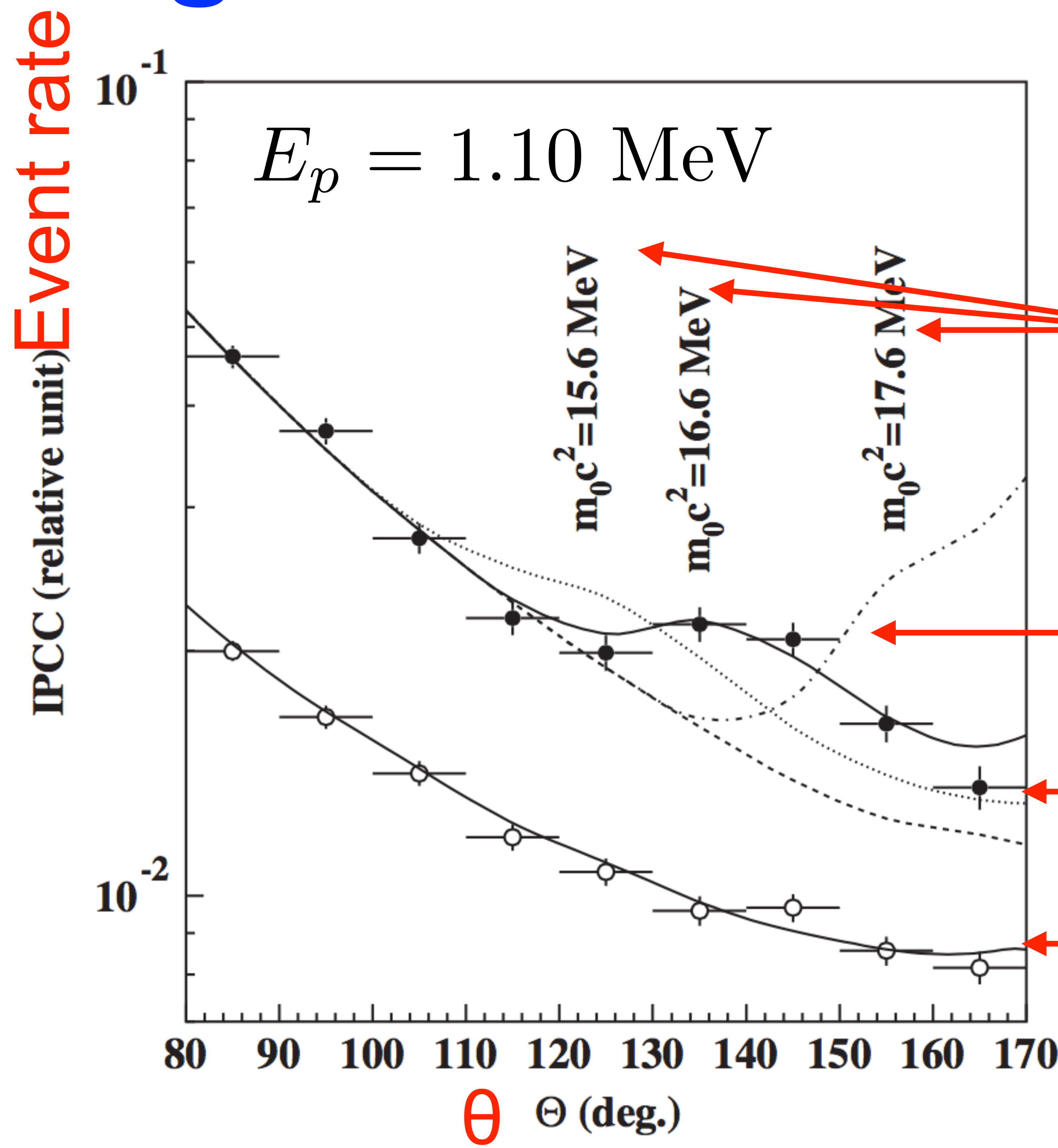


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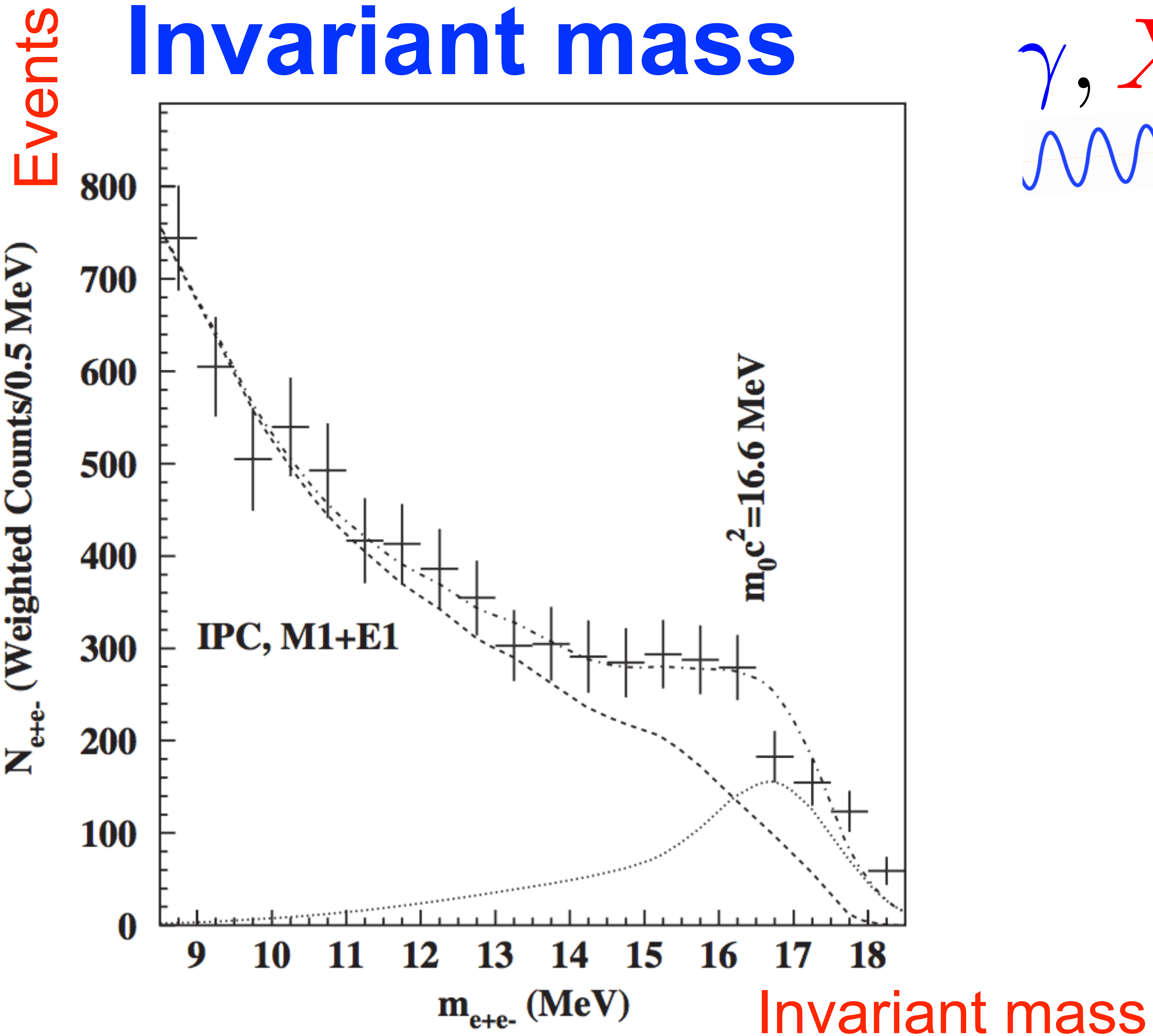
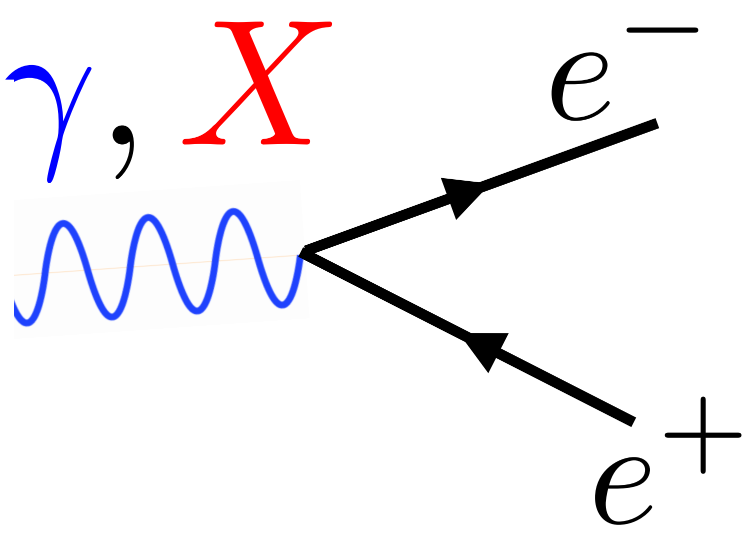
Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

# Invariant mass




Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

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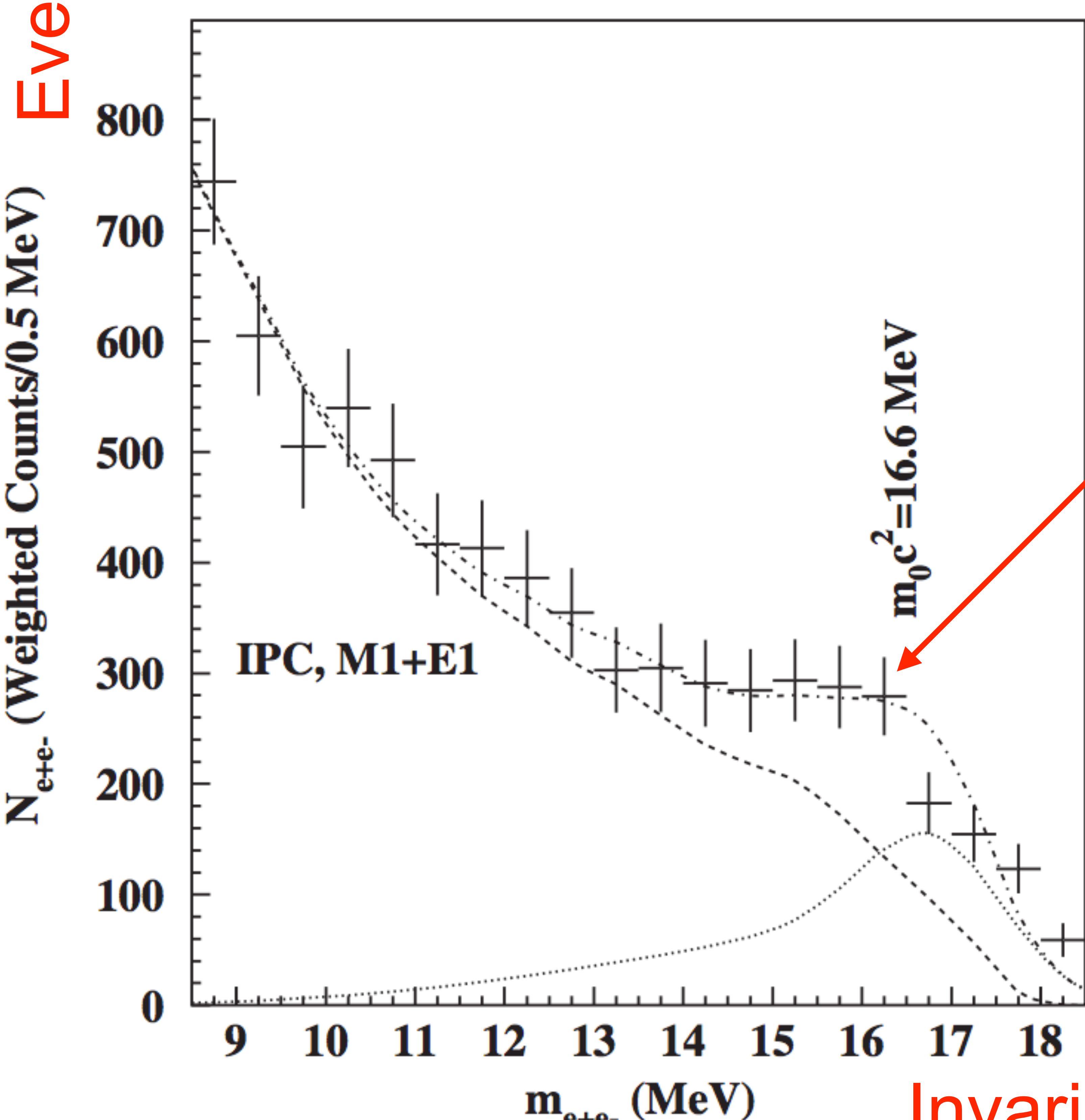
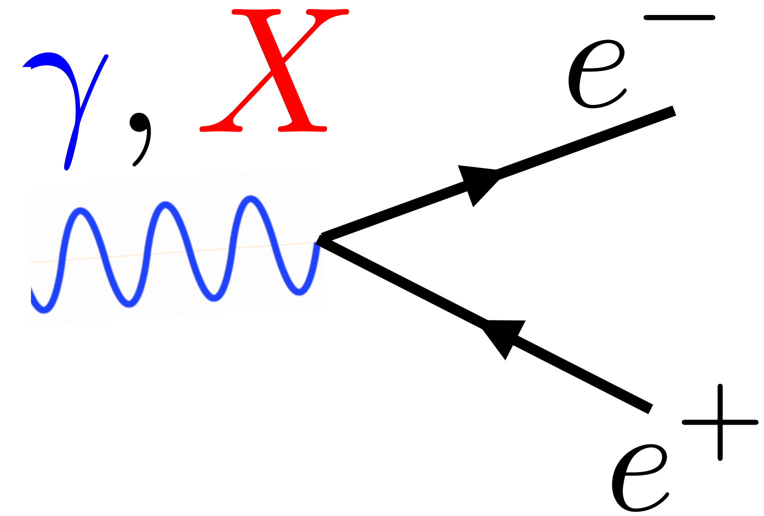
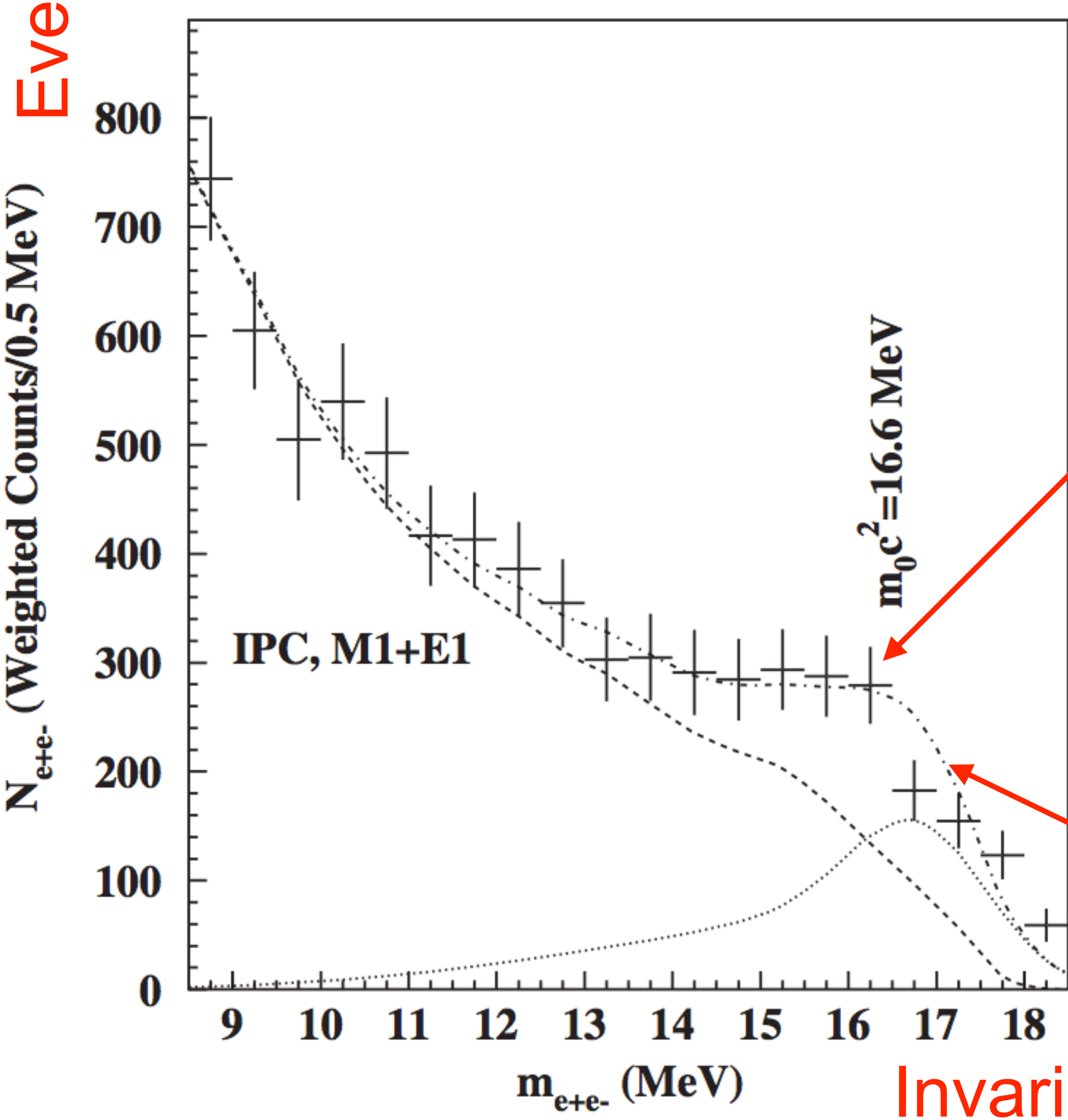


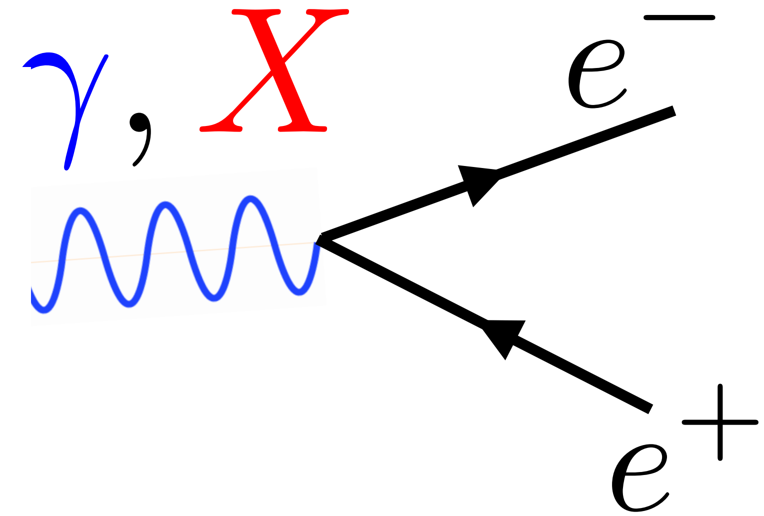




Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

# Invariant mass

Events




excess

Simulation w/ 16.6 MeV boson fits data

Invariant mass

Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

# Best-fit model

Excess events occur at both angular and invariant mass distributions which point to the same mass.

Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

$$m_X = 16.7 \pm 0.35\,(\mathrm{stat}) \pm 0.5\,(\mathrm{sys})\ \mathrm{MeV}$$

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X)}{\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma)} = 5.8 \times 10^{-6}$$

assuming $\mathrm{BR}(X \to e^+e^-) = 1$

$\chi^2/\mathrm{dof} = 1.07$

Atomki Collab.

# Summary

- **A number of interesting new physics searches can be studied with the Nanjing Proton Source (NPS), including cLFV, muon g-2, mu-p scattering, and new gauge boson search.**
- **You are welcome to collaborate with us.**

**Thank you!**