The X17 boson?

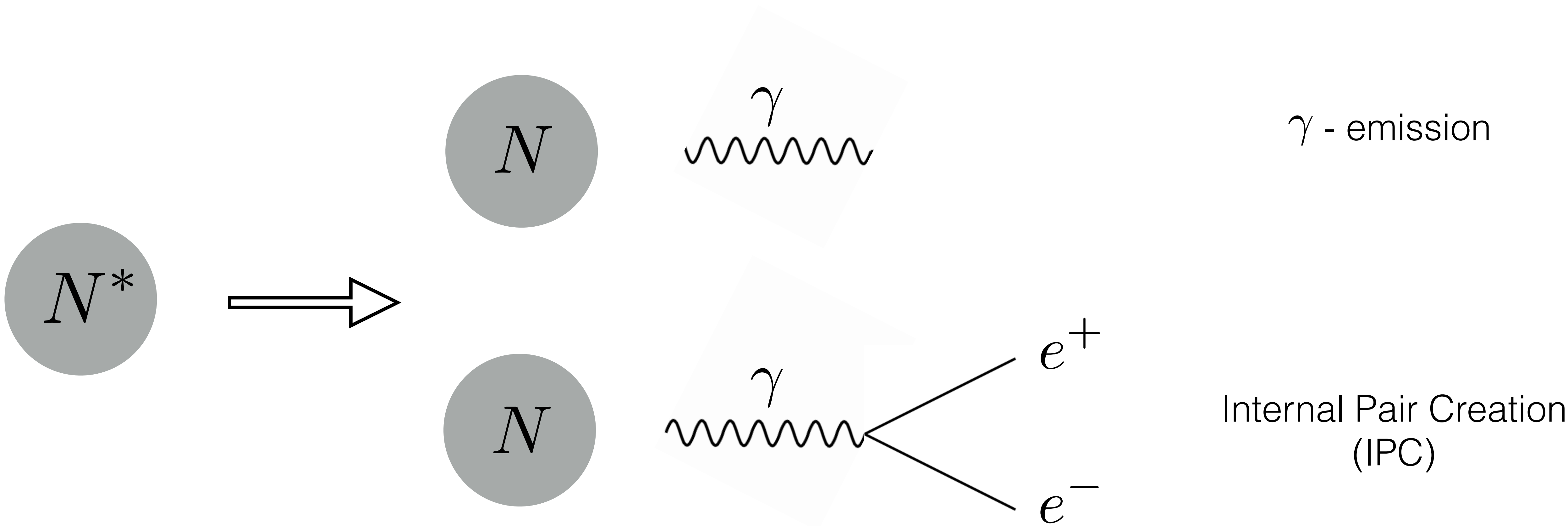
Daniele Barducci

w/ Claudio Toni 2212.06453

TPPC Kick-off meeting 2024

- Nuclear transitions are decays of an excited nucleus into its ground state

- Two ways in which they can occur within the Standard Model



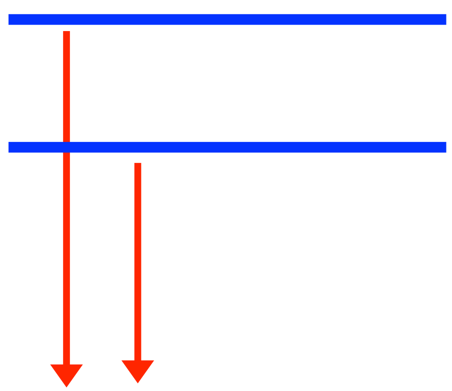
- Nuclear excitation energies are $\mathcal{O}(\mathrm{MeV})$

- Rare nuclear transitions can test for light and weakly coupled new physics

- In 2015 ATOMKI studied IPC processes for the decay of excited beryllium energy states

$^8\mathrm{Be}^*(18.15)$ $\quad J^\pi = 1^+ \quad T = 0 \quad \Gamma = 138\ \mathrm{KeV} \quad \mathrm{BR}_\gamma \sim 1.4 \times 10^{-5}$

$^8\mathrm{Be}^*(17.64)$ $\quad J^\pi = 1^+ \quad T = 1 \quad \Gamma = 10.7\ \mathrm{KeV} \quad \mathrm{BR}_\gamma \sim 1.4 \times 10^{-3}$



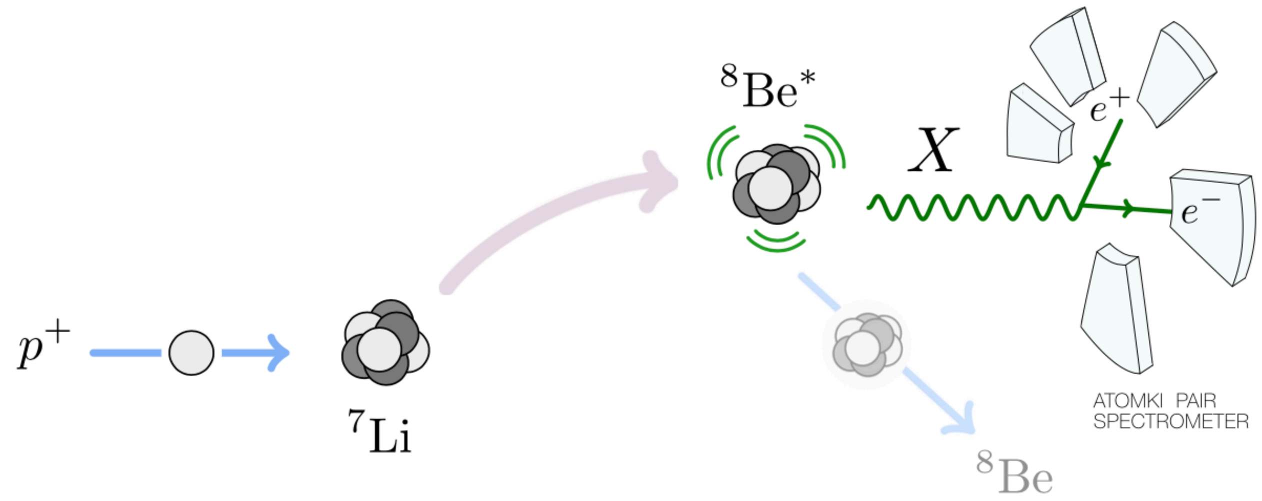
Ground state $m_{^8\mathrm{Be}} = 7454.85\ \mathrm{MeV} \quad J^\pi = 0^+\ , \quad T = 0$

- The experiment consists in a proton beam colliding $^7\mathrm{Li}$ target nuclei at rest

- They measure the IPC process

$$p + A \to N^* \to N + e^+ e^-$$

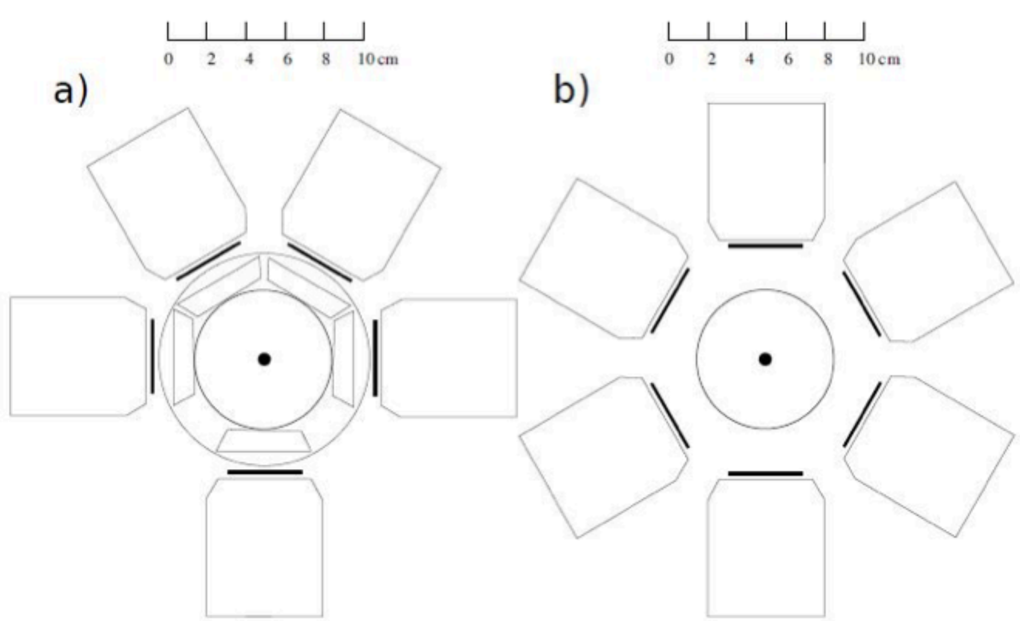
- Varying the proton energy they were able to scan across the $^8\mathrm{Be}$ resonances

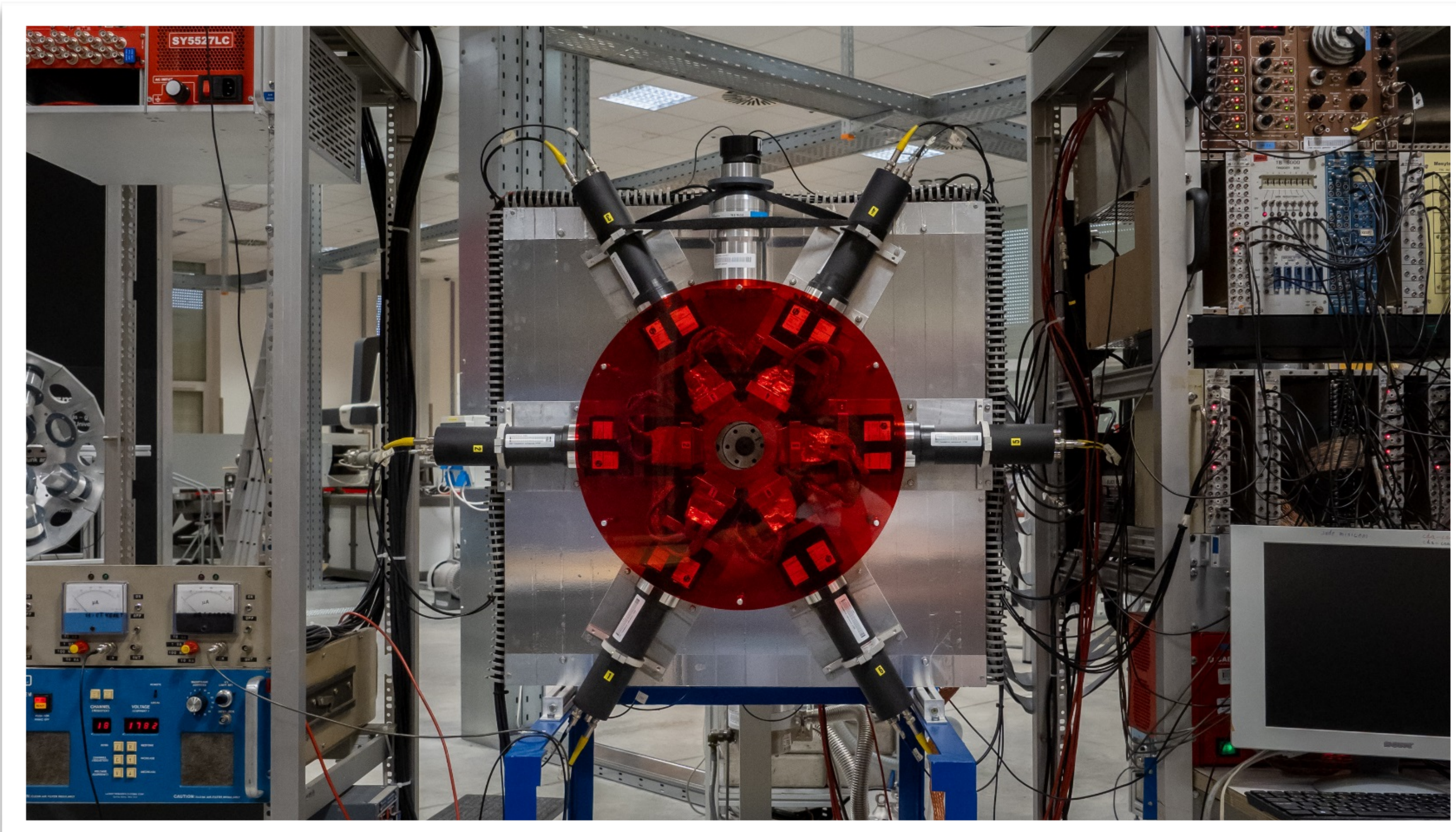


$$E_{beam} = \frac{m_{N_*}^2 - (m_A + m_p)^2}{2m_A}$$

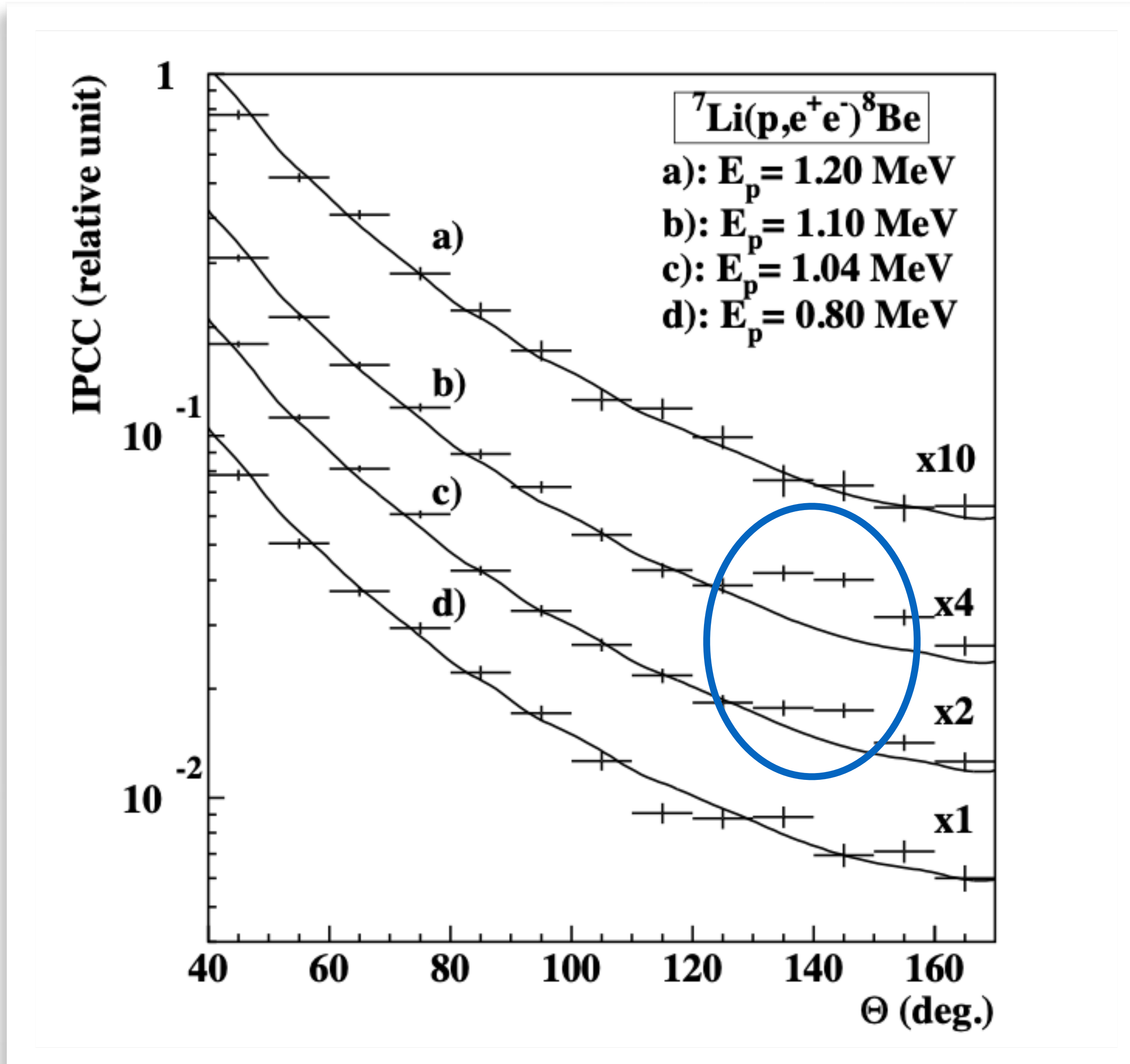
E_{beam}(MeV)	A	m_A(MeV)	N_*	m_{N_*}(MeV)
1.03	^{7}Li	6533.83	^{8}Be(18.15)	7473.01
0.45	^{7}Li	6533.83	^{8}Be(17.64)	7472.50

- The e^+e^- pairs are detected by detectors perpendicular to the beam directions



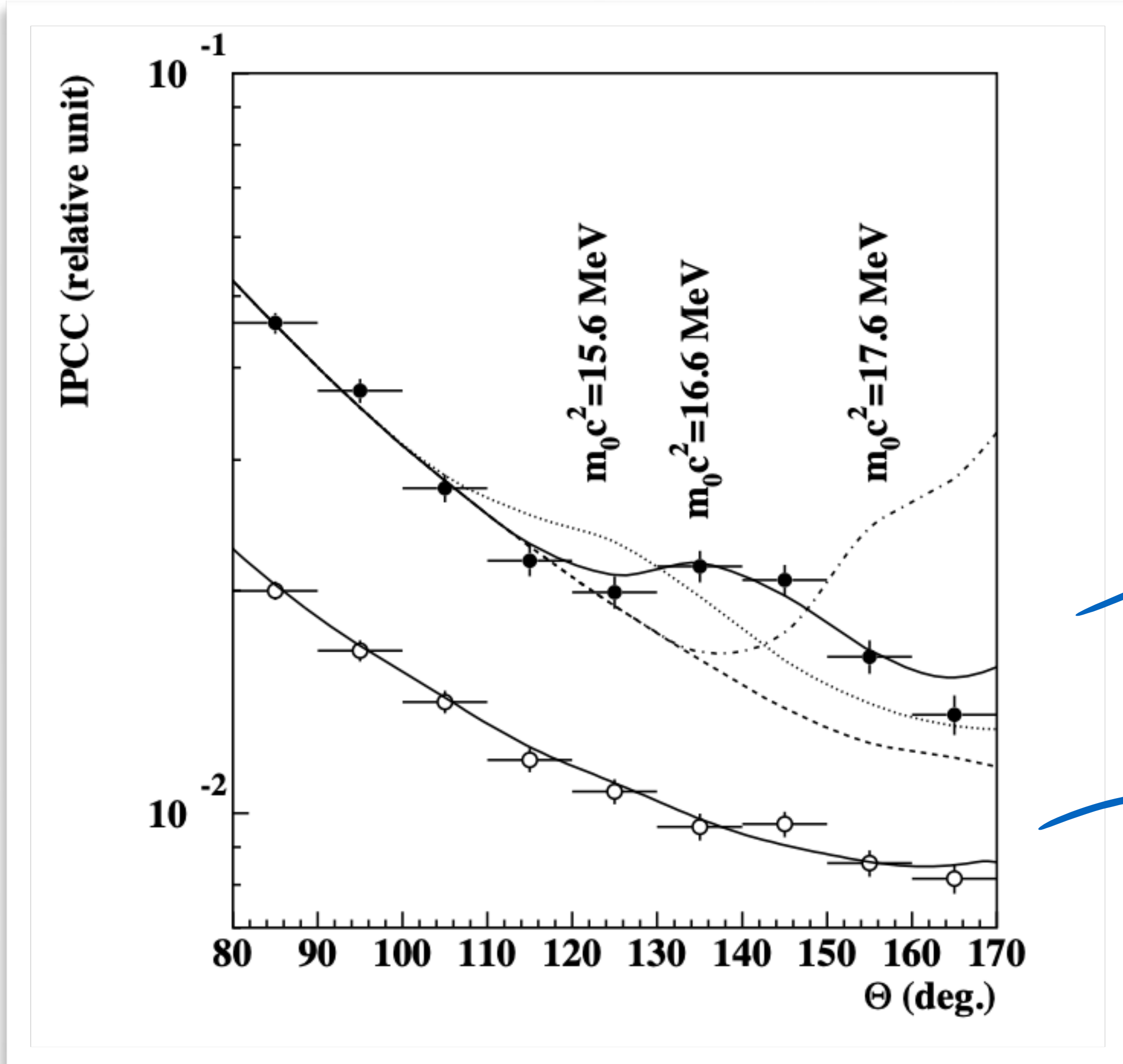

SY5527LC

- They observed an anomalous peak at an opening angle of ~ 140° for the e^+e^- pairs
- The anomaly vanishes outside the $^8\mathrm{Be}$ resonances [ATOMKI: 1504.01527]



- They measured was later confirmed with an improved experimental setup
[ATOMKI: *J.Phys.Conf.Ser.* 1056 (2018) 1, 012028]

- ATOMKI speculate on the anomaly origin from the decay of the excited $^{8}\mathrm{Be}(18.15)$ state



$$|y| \equiv \left|\frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}\right| < 0.5$$

$$|y| \equiv \left|\frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}\right| > 0.5$$

- The deviation has a significance of $\sim 7\sigma$

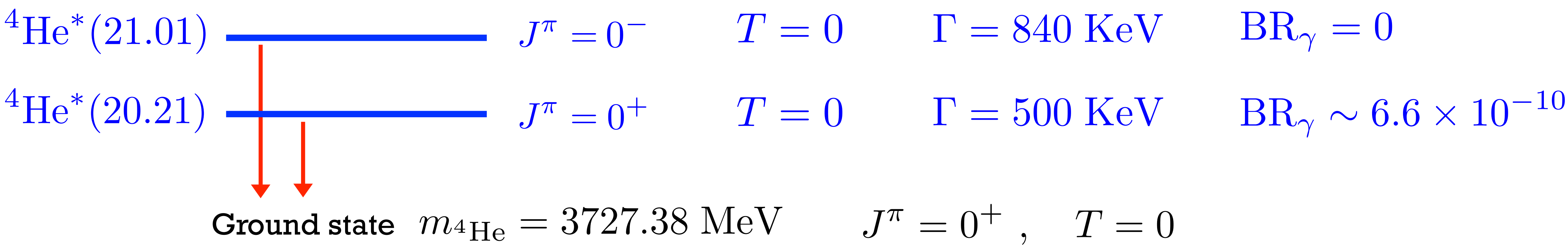
- The signal can be explained with the production of a new particle from $^{8}\mathrm{Be}(18.15)$ decay

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

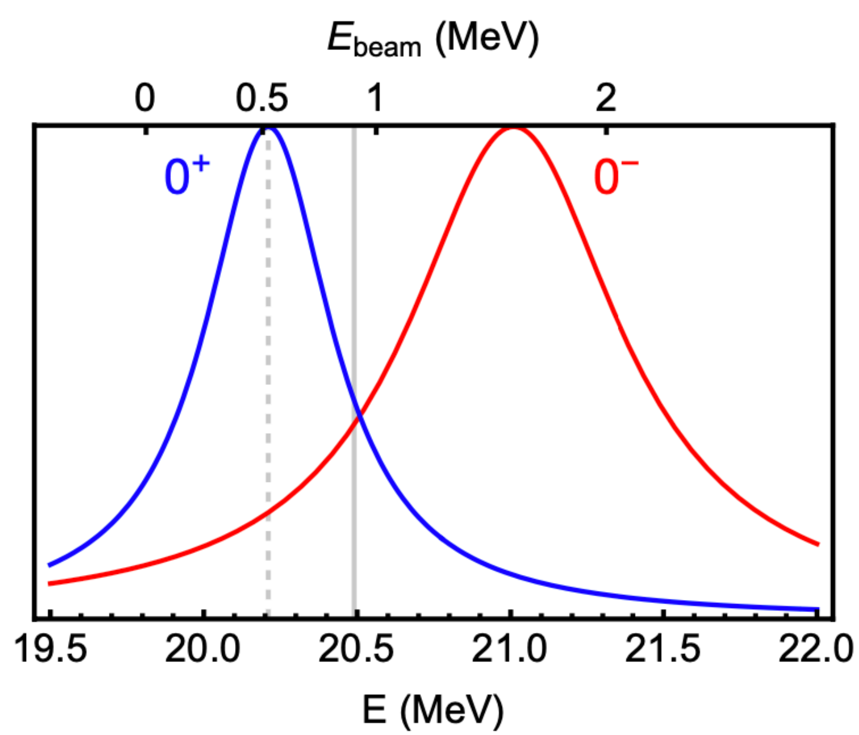
$$\frac{\Gamma(^{8}\mathrm{Be}(18.15) \to {}^{8}\mathrm{Be} + X)}{\Gamma(^{8}\mathrm{Be}(18.15) \to {}^{8}\mathrm{Be} + \gamma)}\,\mathrm{BR}(X \to e^+e^-) = (6 \pm 1) \times 10^{-6}$$

- In 2019 ATOMKI repeated the experiment with $^4\mathrm{He}$ excited nuclei with p on tritium

E_{beam}(MeV)	A	m_A(MeV)	N_*	m_{N_*}(MeV)
1.59	^{3}H	2808.92	^{4}He(21.01)	3748.39
0.52	^{3}H	2808.92	^{4}He(20.21)	3747.59

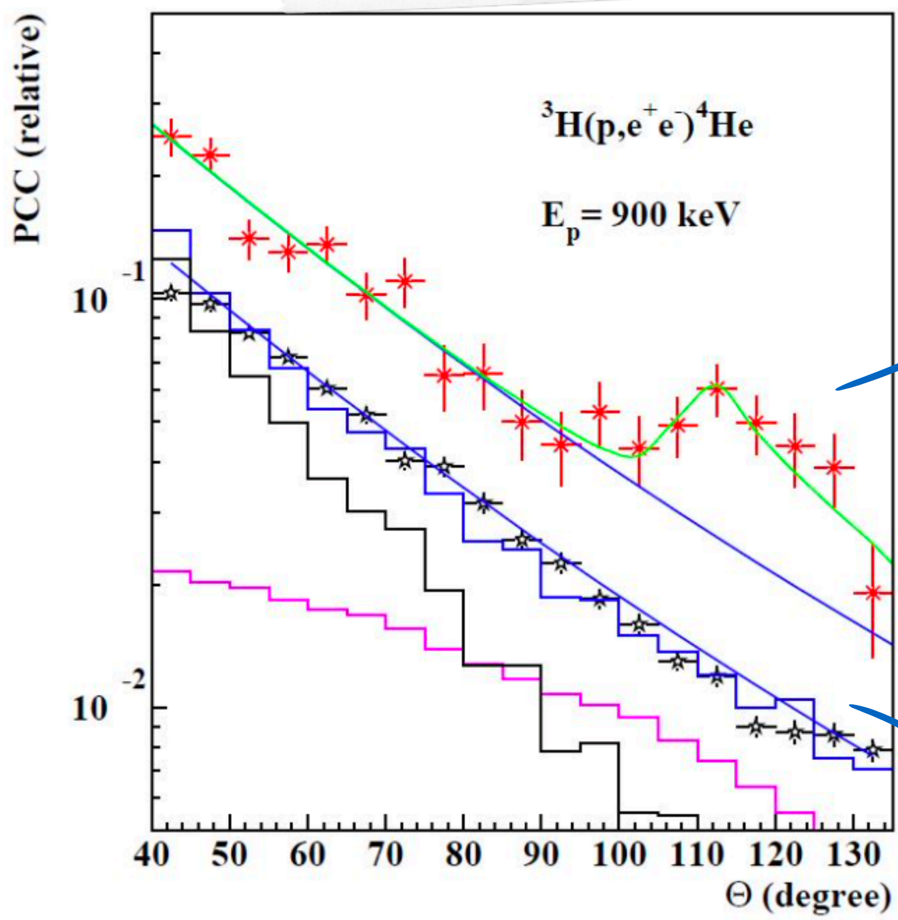


- Proton energy chosen between the two resonances, both states populated



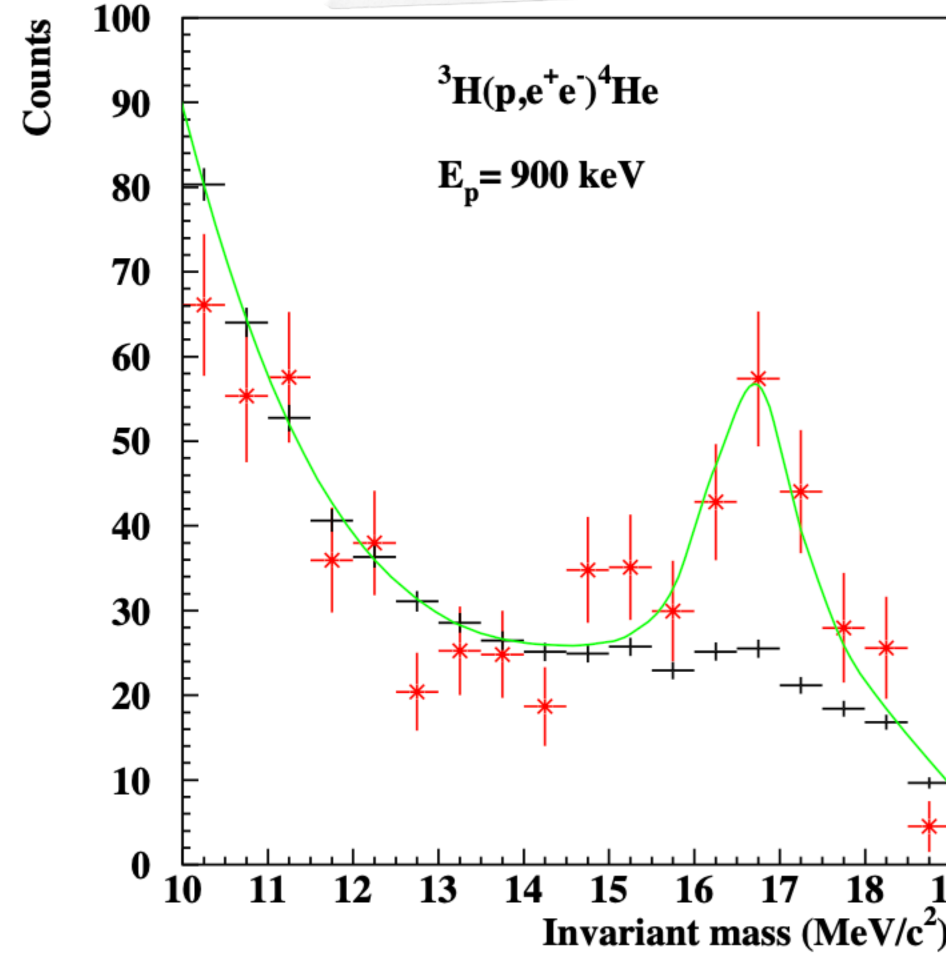
- IPC only possible for $^4\mathrm{He}(20.21)$ because of parity conservation

- They again find a bump in the e^+e^- opening angle at $\theta \sim 115^\circ$



$$|y| \equiv \left|\frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}\right| < 0.5$$

$$|y| \equiv \left|\frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}\right| > 0.5$$



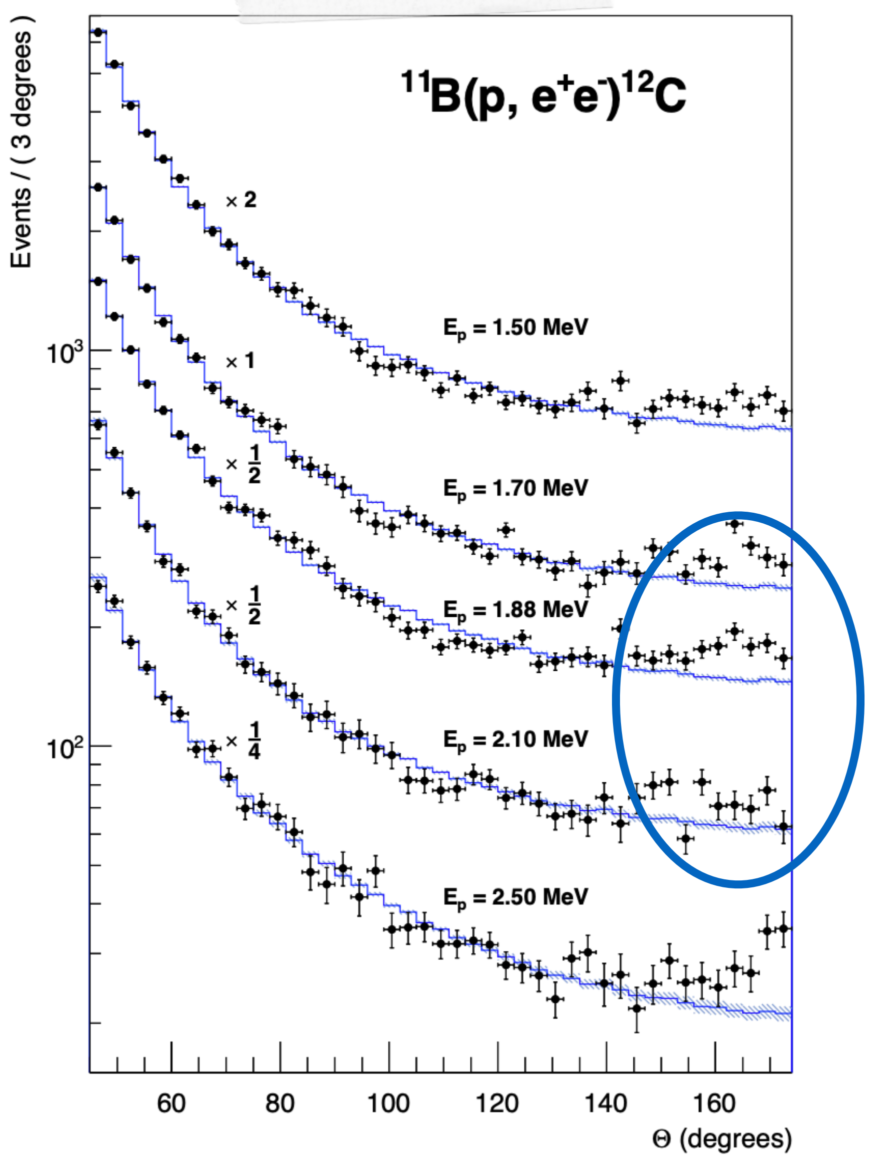
- Best-fit mass $m_X = 16.84 \pm 0.16\ (\text{stat}) \pm 0.20\ (\text{syst})\ \text{MeV}$

[ATOMKI: 1910.10459, 2104.10075]

- In 2020 it was suggested to search for the same effect in $^{12}\mathrm{C}$ nuclei [Feng+ 2006.01151]
- This is the heaviest nucleus with enough excitation energy
- Excited carbon state produced with protons on a boron target

$^{12}\mathrm{C}^*(17.23)$ $J^\pi = 1^-$ $T = 1$ $\Gamma = 1150$ KeV $\mathrm{BR}_\gamma \sim 3.8 \times 10^{-5}$

Ground state $m_{^{12}\mathrm{C}} = 11174.86$ MeV $J^\pi = 0^+$, $T = 0$



- Data agree with predictions for $\theta < 140^\circ$
- Less evident deviations for $\theta > 140^\circ$

$$m_X = 17.03 \pm 0.11\ (\mathrm{stat}) \pm 0.2\ (\mathrm{syst})\ \mathrm{MeV}$$

$$\frac{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + X)}{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + \gamma)}\ \mathrm{BR}(X \to e^+e^-) = 3.6(3) \times 10^{-6}$$

[ATOMKI 2209.10795]

- The experimental results are not due to a statistical fluctuations
- Only three possibilities are left

***i)* Unaccounted experimental systematics and/or error ?**

***ii)* Unaccounted standard nuclear physics effects?**

***iii)* Unaccounted beyond the Standard Model physics?**

- The experimental results are not due to a statistical fluctuations
- Only three possibilities are left

_i)_ Unaccounted experimental systematics and/or error ?

_ii)_ Unaccounted standard nuclear physics effects?

iii) Unaccounted beyond the Standard Model physics?

- The anomaly is seen in three different nuclear decays and different setups have been used
- It seems solid… but an independent experiment is needed

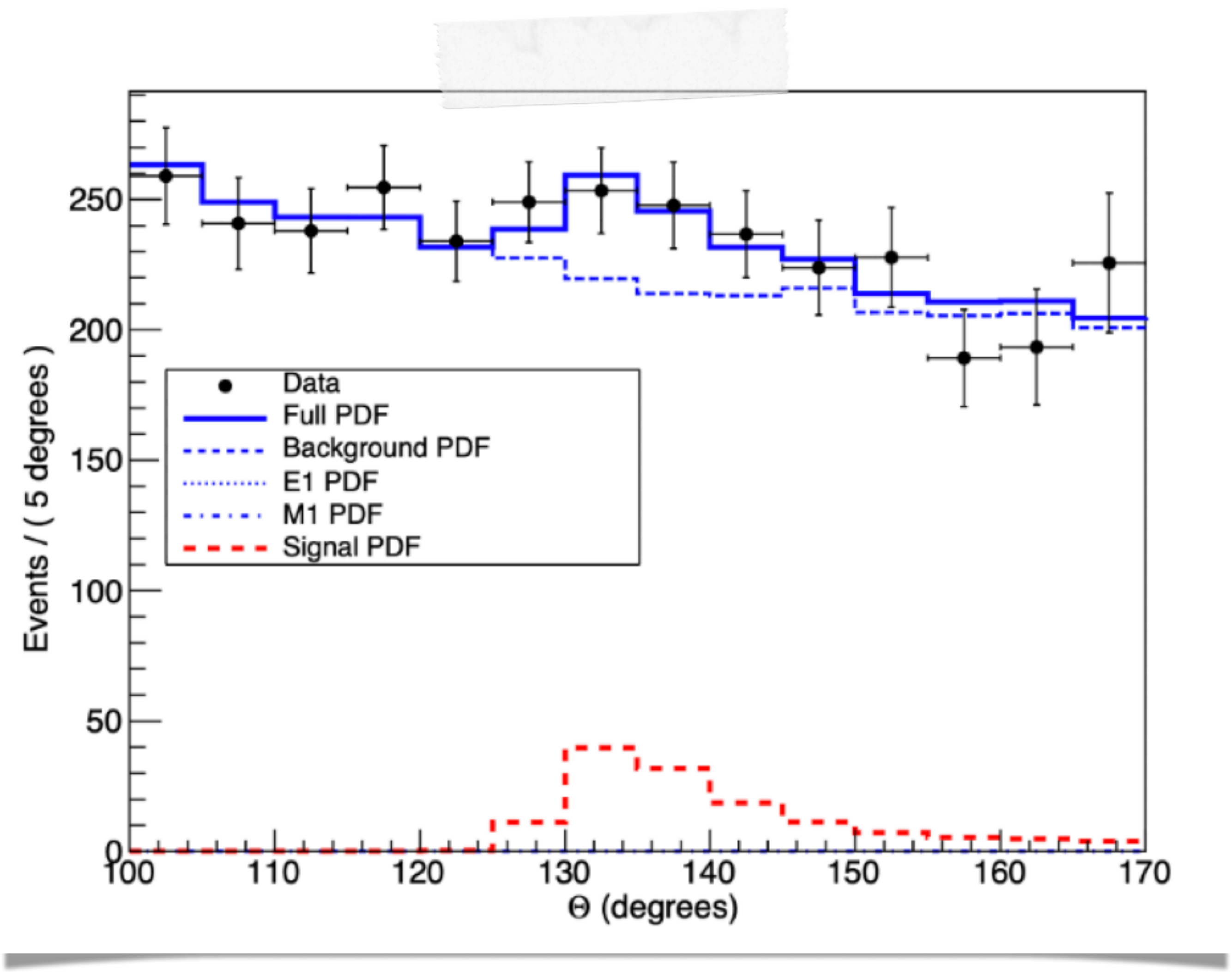
Meg-II @ PSI can replicate the measurement. Data taking over, analysis ongoing

Tandem @ Montreal
Van-de-Graaf @ Prague } can also replicate the measurement. Status unclear…

PADME @ LNF seems to provide the most promising and closer in time update

Already an independent (?) confirmation (?)

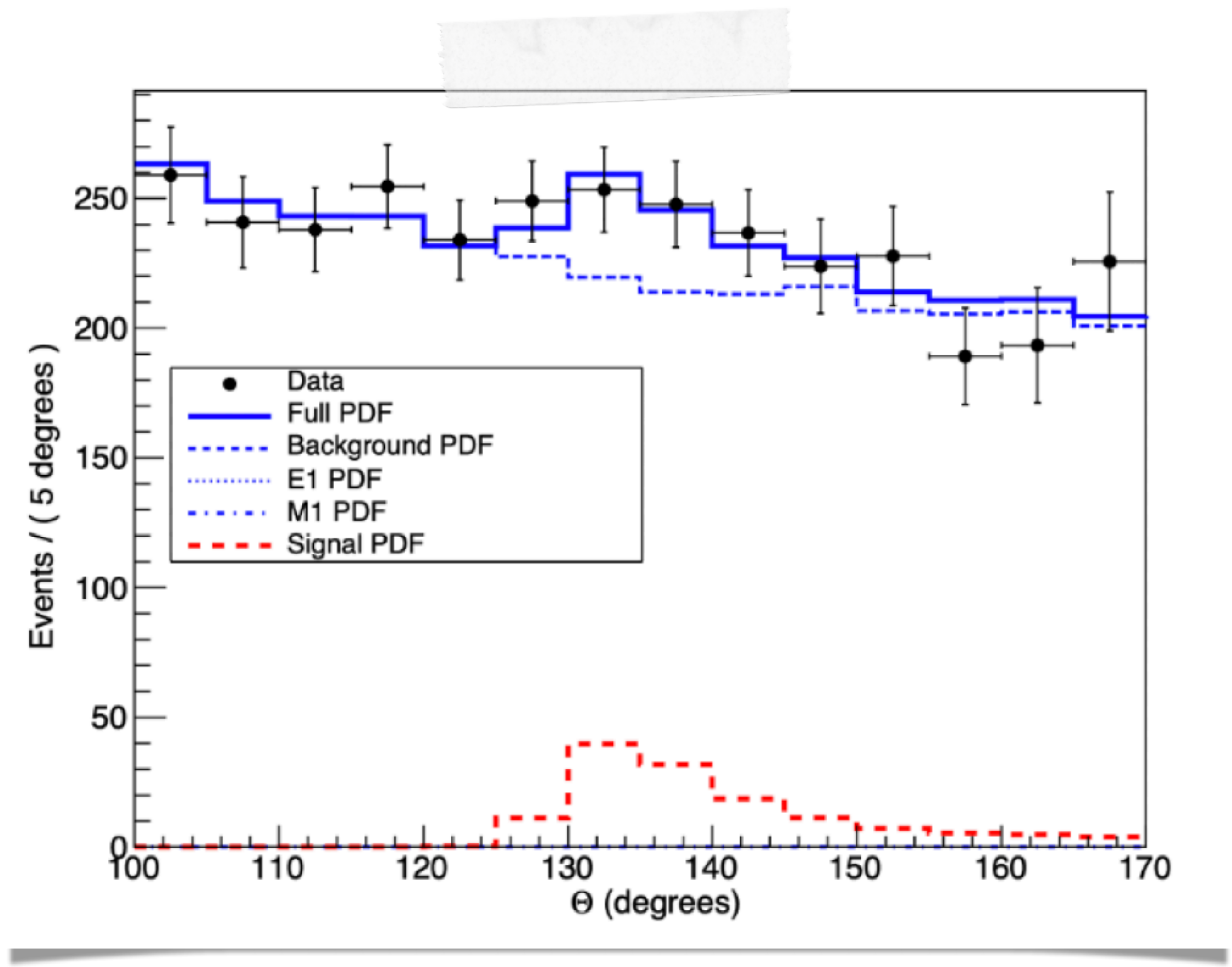
- A few weeks ago an experiment in Hanoi repeated the measurement [2401.11676]
- They observed the same anomalous peak in the e^+e^- angular opening at $^8\mathrm{Be}(18.15)$



$$m_X = 16.7 \pm 0.47\ (\mathrm{stat}) \pm 0.35\ (\mathrm{syst})\ \mathrm{MeV}$$

Already an independent (?) confirmation (?)

- A few weeks ago an experiment in Hanoi repeated the measurement [2401.11676]
- They observed the same anomalous peak in the e^+e^- angular opening at $^8\mathrm{Be}(18.15)$



$$m_X = 16.7 \pm 0.47\ (\mathrm{stat}) \pm 0.35\ (\mathrm{syst})\ \mathrm{MeV}$$

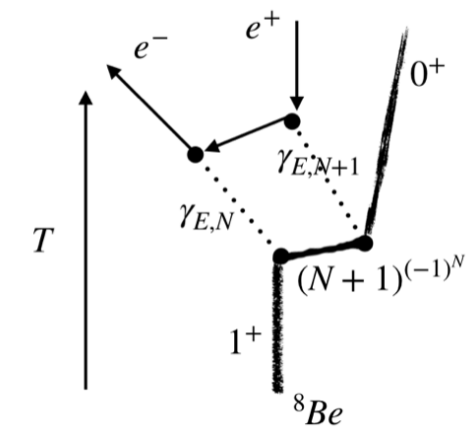
- Is it really ''independent'' ? Strong input from the ATOMKI group, which signed the work

Possible Standard Model & nuclear physics solutions

- Possible nuclear physics effects have been investigated.
  Authors indicate that known processes cannot explain the ATOMKI results
  [Zhang & Miller 1703.04588, 2008.11288]

- Double conversion of photon pairs [Koch 2003.05722]

  Thus, it has to be concluded that the process studied in this paper does not give a completely satisfying explanation of the "X17 puzzle".



- Exotic QCD bound states
  - Tetraquark hypothesis, predicts a second unobserved resonance [Chen 2006.01018]
  - Hexadiquark hypothesis, can only explain the He result [Kubarovsky+ 2206.14441]

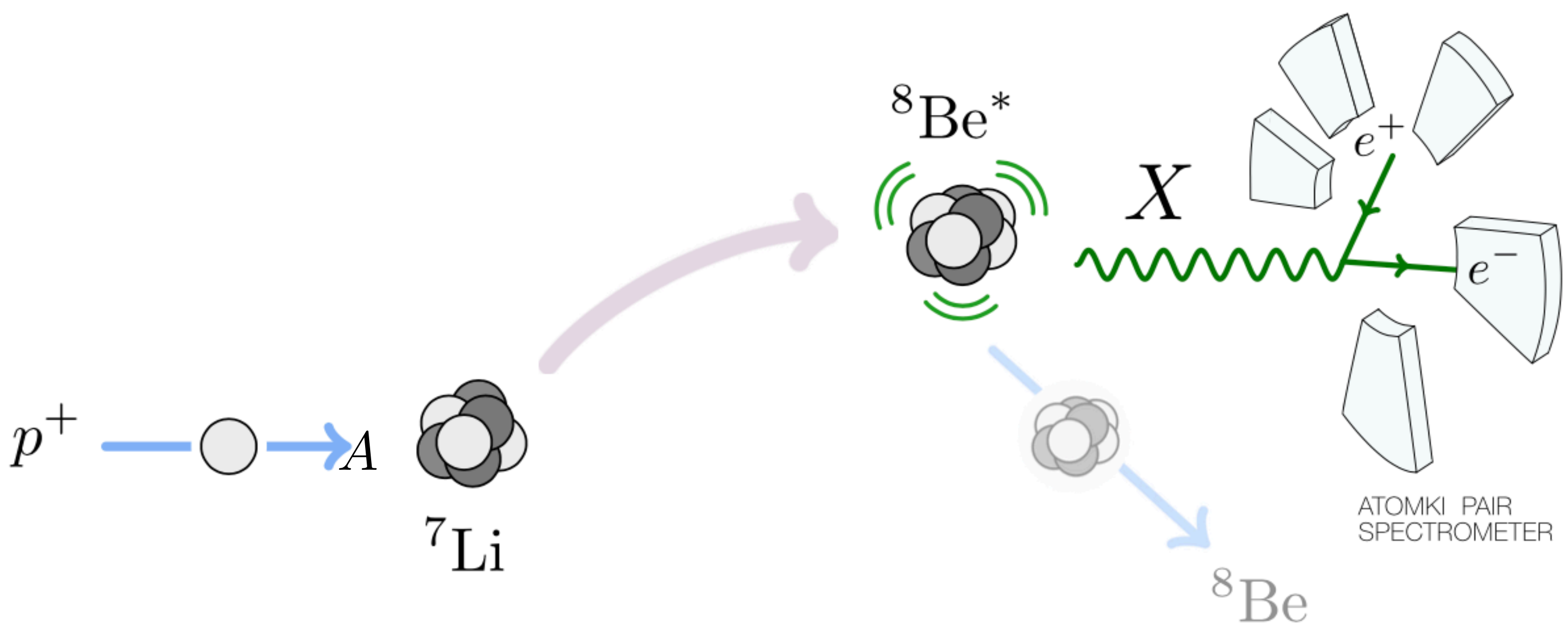
- Higher order corrections to and interference terms with Born amplitude
  [Aleksejevs 2102.01127]

No firm explanation in terms of SM effects has been established

Lets assume is a BSM state

Process kinematics

- The features of the excess are
  - Resonant bumps at the same invariant mass for all the nuclear transitions
  - e^+e^- opening angle peaks at $140°, 115°$ and $160°$ for $^8\mathrm{Be}$,$^4\mathrm{He}$ and $^{12}\mathrm{C}$
  - Signal in $^8\mathrm{Be}$ and $^4\mathrm{He}$ for small lepton energy asymmetry $|y| < 0.5$



- Center of mass energy $E_{\rm CM} = \sqrt{(m_p + m_A)^2 + 2 m_A E_b} \simeq m_p + m_A + \frac{m_{pA}}{m_p} E_b$
- Excited state produced almost at rest in the lab frame
- The energy of the X boson in the CM frame is $\omega = \frac{E_{\rm CM}^2 + m^2 - m_N^2}{2 E_{\rm CM}} \simeq E_{\rm th} + \frac{m_{pA}}{m_p} E_b$

$E_{\rm th} = m_p + m_A - m_N$

- Angular opening in function of the energy asymmetry and kinematical variables

$$\theta_{\pm} = \cos^{-1}\left(\frac{-1 - y^2 + \delta^2 + 2v^2}{\sqrt{(1 - \delta^2 + y^2)^2 - 4y^2}}\right)$$

$$\begin{cases} y = \dfrac{E_+ - E_-}{E_+ + E_-} \\ \delta = 2m_e/\omega \\ v = \sqrt{1 - \left(\dfrac{m}{\omega}\right)^2} \end{cases}$$

- Angular opening in function of the energy asymmetry and kinematical variables

$$\theta_{\pm} = \cos^{-1}\left(\frac{-1 - y^2 + \delta^2 + 2v^2}{\sqrt{(1-\delta^2+y^2)^2 - 4y^2}}\right)$$

$$\begin{cases} y = \dfrac{E_+ - E_-}{E_+ + E_-} \\ \delta = 2m_e/\omega \\ v = \sqrt{1 - \left(\dfrac{m}{\omega}\right)^2} \end{cases}$$

- Maximum asymmetry and minimal opening angle are

$$y_{\text{max}} \simeq v_X \qquad \text{and} \qquad \theta_{\pm}^{\text{min}} \simeq \cos^{-1}(2v_X^2 - 1)$$

N_*	$v_X\,/\,c$
^{8}Be(18.15)	0.350
^{8}Be(17.64)	0.267
^{4}He(21.01)	0.588
^{4}He(20.21)	0.541
^{12}C(17.23)	0.163

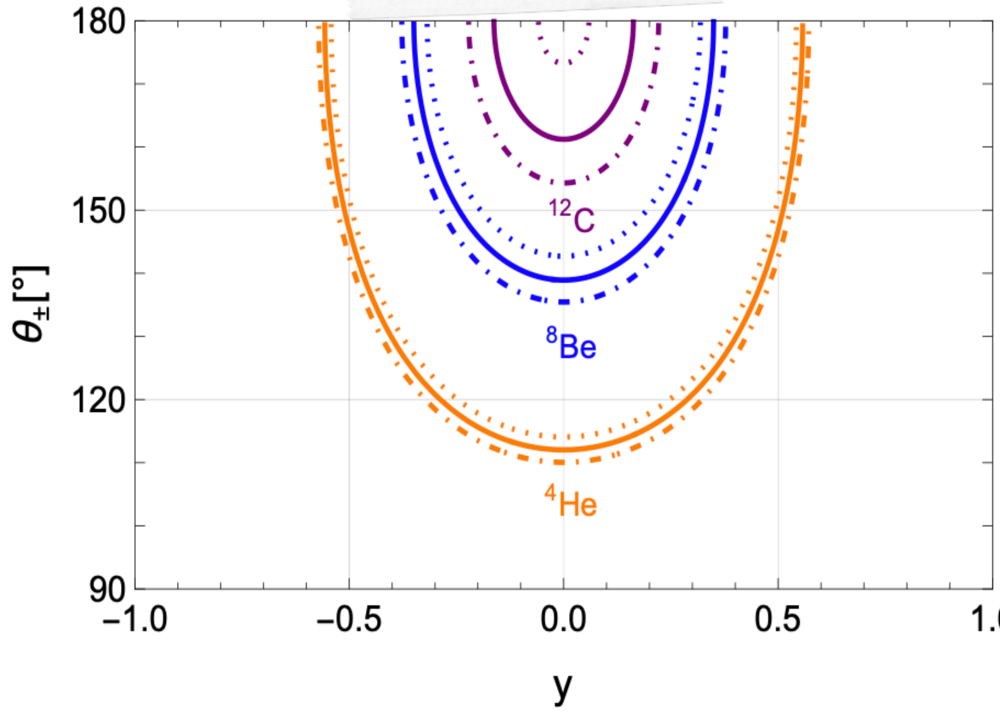
- Angular opening in function of the energy asymmetry and kinematical variables

$$\theta_\pm = \cos^{-1}\left(\frac{-1 - y^2 + \delta^2 + 2v^2}{\sqrt{(1-\delta^2+y^2)^2 - 4y^2}}\right)$$

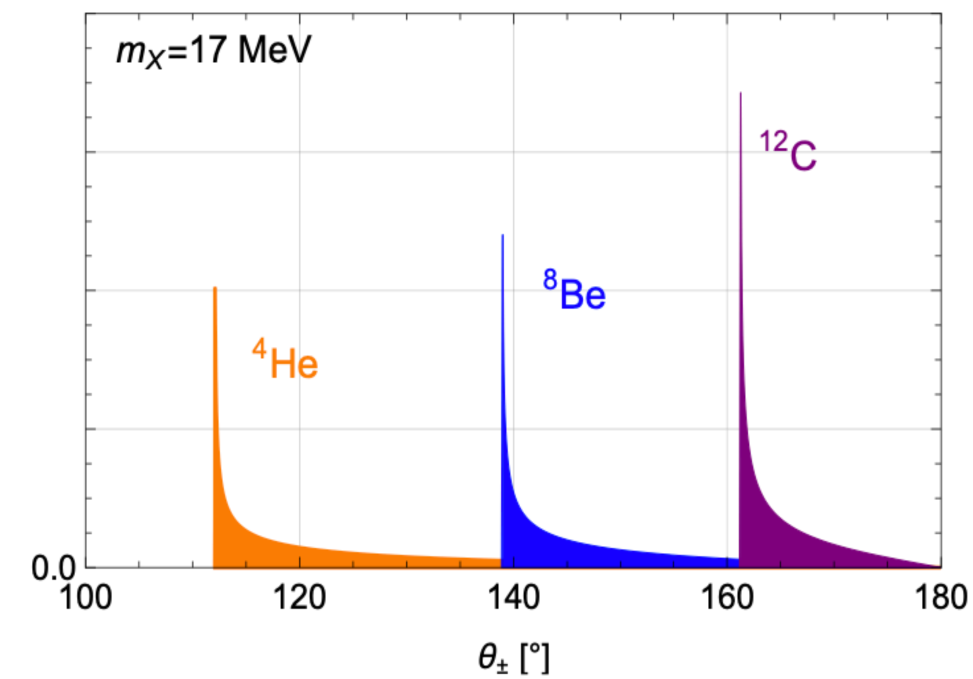
$$\begin{cases} y = \dfrac{E_+ - E_-}{E_+ + E_-} \\ \delta = 2m_e/\omega \\ v = \sqrt{1 - \left(\dfrac{m}{\omega}\right)^2} \end{cases}$$

- Maximum asymmetry and minimal opening angle are

$$y_{\max} \simeq v_X \quad \text{and} \quad \theta_\pm^{\min} \simeq \cos^{-1}(2v_X^2 - 1)$$



N_*	v_X / c
^{8}Be(18.15)	0.350
^{8}Be(17.64)	0.267
^{4}He(21.01)	0.588
^{4}He(20.21)	0.541
^{12}C(17.23)	0.163



- Distributions peak at the minimum opening angle
- ^{8}Be , ^{4}He and ^{12}C openings compatible with a single mass value
- No contribution for $|y| > 0.5$ as observed in the ^{8}Be and ^{4}He measurements

Single particle hypothesis might explain all anomalous measurements

Process dynamics

- Spin and parity conservation restrict the possible quantum number of the X boson
- Consider the $^8\mathrm{Be}(18.15)$ decay into a spin-0 state

$$\begin{matrix} ^8\mathrm{Be}^*(18.15) & ^8\mathrm{Be} & X \end{matrix}$$

$$1^+ \to 0^+ + 0^\pi$$

- Orbital angular momentum should be $l = 1$
- Parity conservations fixes $(-1)^{l=1} \times \pi_X = 1$ which excludes a CP-even scalar state

Process dynamics

- Spin and parity conservation restrict the possible quantum number of the X boson
- Consider the $^8\mathrm{Be}(18.15)$ decay into a spin-0 state

$$\begin{array}{ccc} {}^8\mathrm{Be}^*(18.15) & {}^8\mathrm{Be} & X \end{array}$$

$$1^+ \to 0^+ + 0^\pi$$

- Orbital angular momentum should be $l = 1$
- Parity conservations fixes $(-1)^{l=1} \times \pi_X = 1$ which excludes a CP-even scalar state

Process $N^* \to N$	X boson spin parity $S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
$^8\mathrm{Be}(18.15) \to {}^8\mathrm{Be}$	1	0, 2	1	/
$^8\mathrm{Be}(17.64) \to {}^8\mathrm{Be}$	1	0, 2	1	/
$^4\mathrm{He}(21.01) \to {}^4\mathrm{He}$	/	1	0	/
$^4\mathrm{He}(20.21) \to {}^4\mathrm{He}$	1	/	/	0
$^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C}$	0, 2	1	/	1

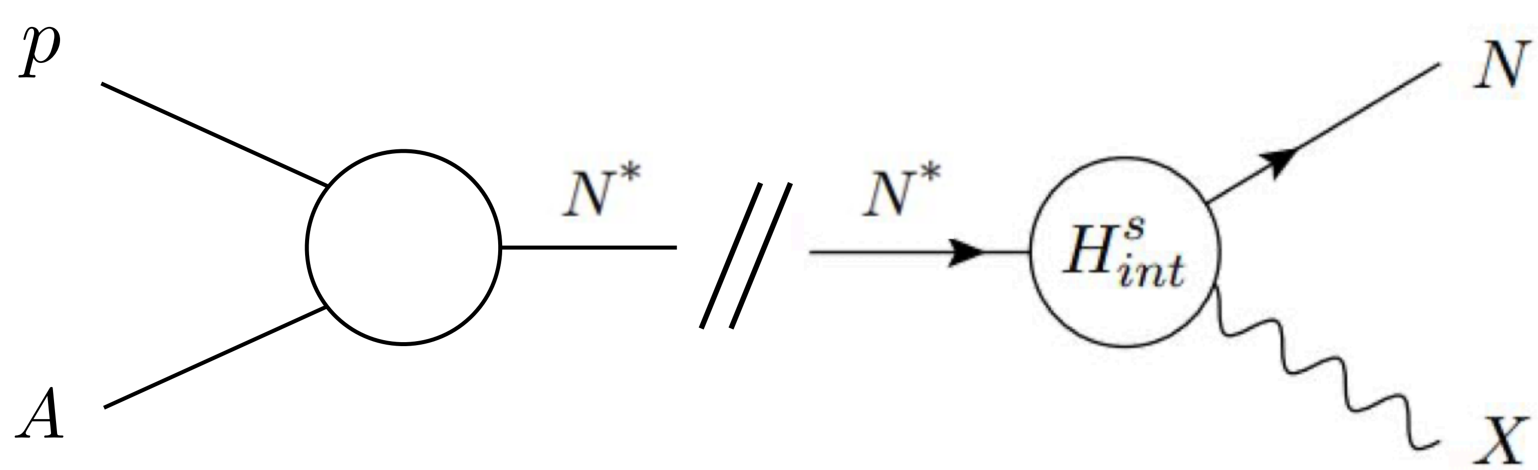
- Vector and axial vector can explain all three anomalies (with different $^4\mathrm{He}$ transitions)
- Pseudoscalar state can explain $^8\mathrm{Be}$ and $^4\mathrm{He}$, but need a pure scalar contribution to $^{12}\mathrm{C}$

Can a combined explanation be found?

- We describe the interaction of the X boson to nuclear matter via the Hamiltonian

$$H^s_{\text{int}} = \begin{cases} \int d^3\vec{r}\, \mathcal{S}(\vec{r}) X(\vec{r}) & \text{if } s = 0 \\ \int d^3\vec{r}\, \mathcal{J}_\mu(\vec{r}) X^\mu(\vec{r}) & \text{if } s = 1 \end{cases}$$

- Factorize excited nucleus production and decay



- Compute the decay width for real X emission from N_* decay

$$\mathcal{T}^s_{fi} = \langle f, X| H^s_{\text{int}} |i\rangle = \begin{cases} \langle f| \int d^3\vec{r}\, \mathcal{S}(\vec{r}) e^{-i\vec{k}\cdot\vec{r}} |i\rangle & \text{if } s = 0 \\ \langle f| \int d^3\vec{r}\, [\epsilon^\mu_a(\vec{k})]^* \mathcal{J}_\mu(\vec{r}) e^{-i\vec{k}\cdot\vec{r}} |i\rangle & \text{if } s = 1 \end{cases}$$

- We expand the nuclear matrix elements in terms of spherical tensor operators

Scalar case | **Vector case**

$$\mathcal{G}_{JM} = \int d^3\vec{r}\, j_J(kr) Y_{JM}(\hat{r}) \mathcal{S}(\vec{r})$$

$$\mathcal{M}_{JM} = \int d^3\vec{r}\, j_J(kr) Y_{JM}(\hat{r}) \mathcal{J}^0(\vec{r}) \ ,$$

$$\mathcal{L}_{JM} = \frac{i}{k}\int d^3\vec{r}\, \vec{\nabla}[j_J(kr) Y_{JM}(\hat{r})] \cdot \vec{\mathcal{J}}(\vec{r}) \ ,$$

$$\mathcal{T}^{\rm el}_{JM} = \frac{1}{k}\int d^3\vec{r}\, \vec{\nabla} \times [j_J(kr) \mathbf{Y}_{JJM}(\hat{r})] \cdot \vec{\mathcal{J}}(\vec{r}) \ ,$$

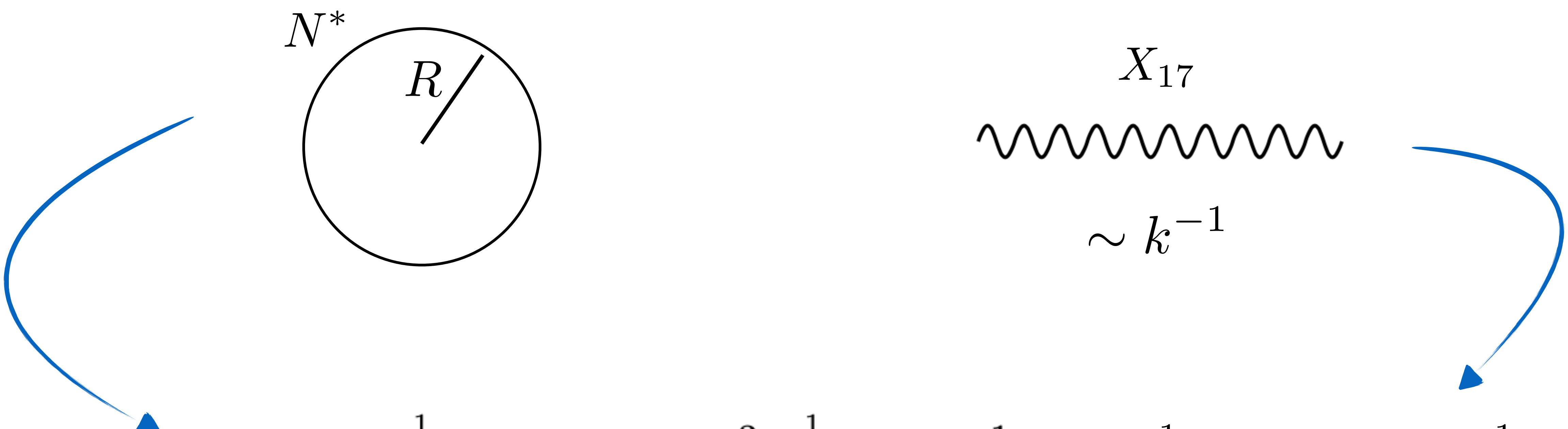
$$\mathcal{T}^{\rm mag}_{JM} = \int d^3\vec{r}\, [j_J(kr) \mathbf{Y}_{JJM}(\hat{r})] \cdot \vec{\mathcal{J}}(\vec{r}) \ ,$$

- The decay rates can be expressed as

Spin-0 $$\Gamma_X^{s=0} = \frac{2k}{2J_*+1}\left\{\sum_{J\geq 0} |\langle f||\mathcal{G}_J||i_*\rangle|^2\right\}$$

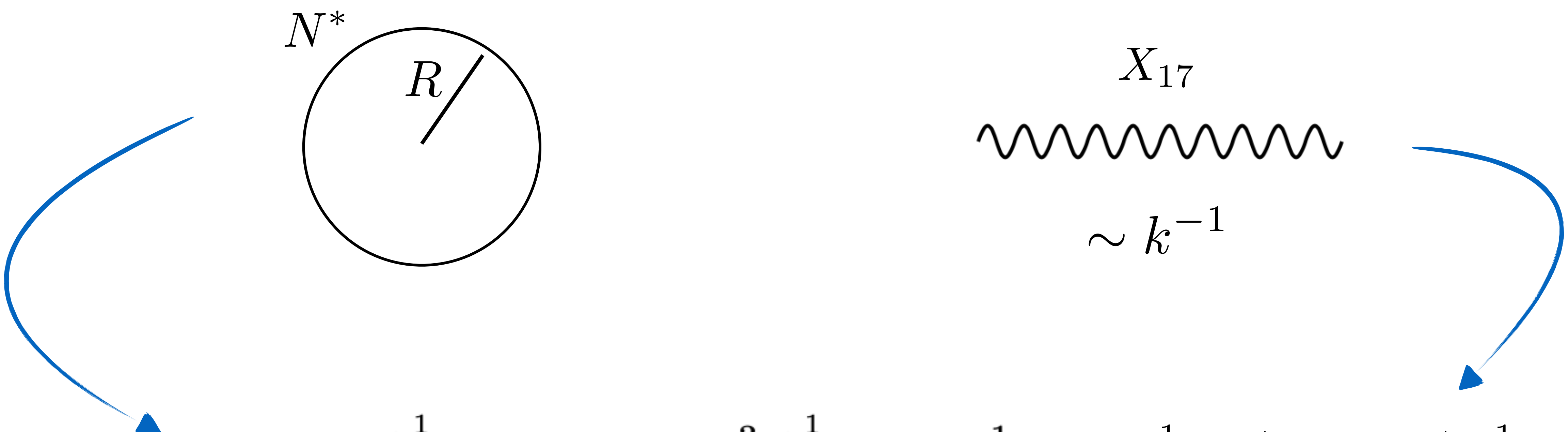
Spin-1 $$\Gamma_X^{s=1} = \frac{2k}{2J_*+1}\left\{\underbrace{\sum_{J\geq 0}\left|\langle f||\left[\frac{k}{m}\mathcal{M}_J - \frac{\omega}{m}\mathcal{L}_J\right]||i_*\rangle\right|^2}_{=\ \left(\frac{m}{k}\right)^2 \sum_{J\geq 0} |\langle f||\mathcal{M}_J||i_*\rangle|^2 \text{ for a conserved current}} + \sum_{J\geq 1}\left[\left|\langle f||\mathcal{T}^{el}_J||i_*\rangle\right|^2 + \left|\langle f||\mathcal{T}^{mag}_J||i_*\rangle\right|^2\right]\right\}$$

- Long wave-length approximation, expand the spherical operators for small kr



$$R \simeq R_0 A^{\frac{1}{3}} \simeq 6.1 \times 10^{-3} A^{\frac{1}{3}}\ \mathrm{MeV}^{-1} \ll k^{-1} \sim (10\ \mathrm{MeV})^{-1}$$

- Long wave-length approximation, expand the spherical operators for small kr



$$R \simeq R_0 A^{\frac{1}{3}} \simeq 6.1 \times 10^{-3} A^{\frac{1}{3}} \ \mathrm{MeV}^{-1} \ll k^{-1} \sim (10 \ \mathrm{MeV})^{-1}$$

- Parametrize the effective interaction of the X boson with the following Lagrangians

only relevant for 4He and 12C

$$\mathcal{L}_{S^\pi=0^+} = z_p \bar{p} p X + z_n \bar{n} n X \qquad \mathcal{L}_{S^\pi=1^-} = C_p \bar{p} \gamma^\mu p X_\mu + C_n \bar{n} \gamma^\mu n X_\mu$$

$$\mathcal{L}_{S^\pi=0^-} = i h_p \bar{p} \gamma^5 p X + i h_n \bar{n} \gamma^5 n X \qquad \mathcal{L}_{S^\pi=1^+} = a_p \bar{p} \gamma^\mu \gamma^5 p X_\mu + a_n \bar{n} \gamma^\mu \gamma^5 n X_\mu$$

- Maximal kinetic energy per nucleon $\sim 30 \ \mathrm{MeV}$, take the non-relativistic limit of nuclear operators
- Compute the decay rated for the various J^π assignments in terms of known nuclear matrix elements

- Decay rates for various J^π assignments in terms of known nuclear matrix elements

	^{8}**Be**	^{4}**He**	^{12}**C**
0^+	/	^{4}**He(20.21)** $2k(z_p+z_n)^2\left\lvert \frac{k^2}{6e}\langle\rho^{(\gamma)}\rangle + \frac{1}{2m_N}\langle\hat{K}\rangle\right\rvert^2$	$\frac{2k^3}{27}(z_p-z_n)^2\lvert\langle\lvert\lvert d^{(\gamma)}\rvert\rvert\rangle\rvert^2$
0^-	$\frac{k^3}{72\pi m_N^2}\lvert\langle h_p\hat{\sigma}^{(p)}+h_n\hat{\sigma}^{(n)}\rangle\rvert^2$	^{4}**He(21.01)** $\frac{k^5}{228\pi m_N^2}(h_p+h_n)^2\lvert\langle\hat{d}_0^\sigma\rangle\rvert^2$	/
1^-	$\frac{4\mu_N^2\omega^3}{27}\lvert\langle\mu^{(X)}\rangle\rvert^2$	^{4}**He(20.21)** $\frac{m^2k^3\alpha}{18}\lvert\langle\rho^{(X)}\rangle\rvert^2$	$\frac{16\pi\alpha\omega^3}{27}\left(1+\frac{m^2}{2\omega^2}\right)\lvert\langle d^{(X)}\rangle\rvert^2$
1^+	$\frac{k}{18\pi}\left(2+\frac{\omega^2}{m^2}\right)\lvert\langle a_p\hat{\sigma}^{(p)}+a_n\hat{\sigma}^{(n)}\rangle\rvert^2$	^{4}**He(21.01)** $\frac{\omega^2k^3}{72\pi m^2}(a_p+a_n)^2\lvert\langle\hat{d}_0^\sigma\rangle\rvert^2$	$\frac{k^3}{144\pi}(a_p-a_n)^2\lvert\langle\hat{D}_3^\sigma\rangle\rvert^2$

$\sum_{\ell=1}^{A}\tau_3^{(\ell)}(\vec{r}\times\vec{\sigma})_\ell$ unknown

Beryllium

$$\frac{\Gamma(^8\text{Be}(18.15)\to{}^8\text{Be}+X)}{\Gamma(^8\text{Be}(18.15)\to{}^8\text{Be}+\gamma)}\,\text{BR}(X\to e^+e^-)=(6\pm1)\times10^{-6}$$

Helium

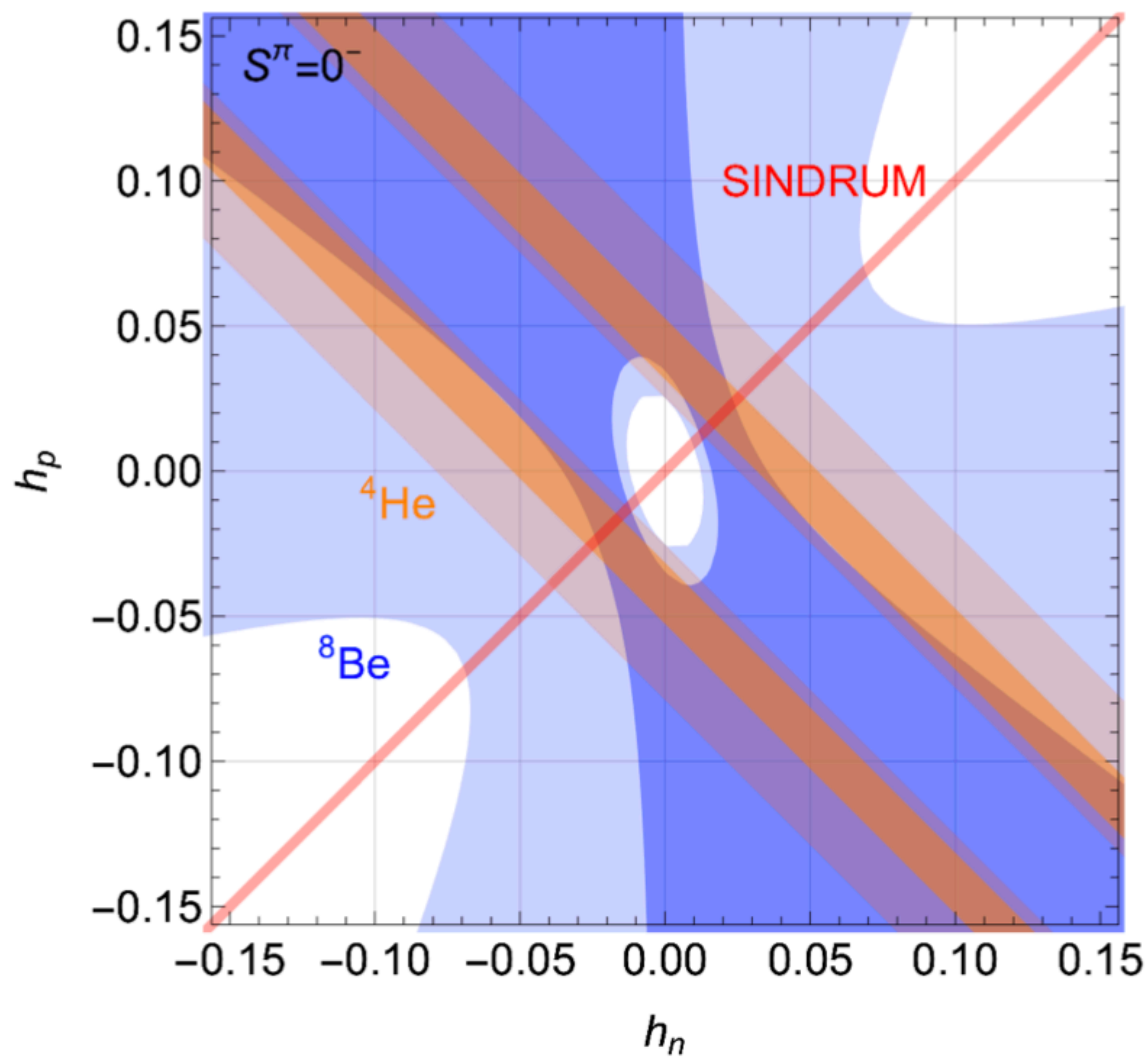
$$\frac{\Gamma(^4\text{He}(20.21)\to{}^4\text{He}+X)}{\Gamma(^4\text{He}(20.21)\to{}^4\text{He}+e^+e^-)}\,\text{BR}(X\to e^+e^-)=0.20\pm0.03$$

$$\frac{\Gamma(^4\text{He}(21.01)\to{}^4\text{He}+X)}{\Gamma(^4\text{He}(20.21)\to{}^4\text{He}+e^+e^-)}\,\text{BR}(X\to e^+e^-)=0.87\pm0.14$$

Carbon

$$\frac{\Gamma(^{12}\text{C}(17.23)\to{}^{12}\text{C}+X)}{\Gamma(^{12}\text{C}(17.23)\to{}^{12}\text{C}+\gamma)}\,\text{BR}(X\to e^+e^-)=3.6(3)\times10^{-6}$$

Pseudoscalar state



- $^8\mathrm{Be}$ and $^4\mathrm{He}$ data can both be fitted with nucleon couplings of $\mathcal{O}(10^{-2})$
- Pseudoscalar/pion mixing angle $\theta_{X\pi} = \dfrac{f_\pi (h_p - h_n)}{2 g_A m_{p,n}}$ has strong bounds from SINDRUM search for $\pi^+ \to e^+ \nu_e X$ which gives $|\theta_{X\pi}| \lesssim \dfrac{10^{-4}}{\sqrt{\mathrm{BR}(X \to e^+ e^-)}}$
- $^{12}\mathrm{C}$ data cannot be explained via a pure CP-odd scalar. Mixed parity state?

- The CP-even component doesn't contribute to the $^8\mathrm{Be}$ decay
- It mediates the decay of the $^4\mathrm{He}(20.21)$ states
- For similar value of scalar couplings the rate is larger than the $^4\mathrm{He}(21.01)$ one

$$\Gamma_{^4\mathrm{He}(20.21)} \simeq 6\times 10^{-4}\mathrm{eV}\left(\frac{z_p+z_n}{10^{-2}}\right)^2 \qquad \Gamma_{^4\mathrm{He}(21.01)} \simeq 9.7\times 10^{-6}\mathrm{eV}\left(\frac{h_p+h_n}{10^{-2}}\right)^2$$

- The CP-even component doesn't contribute to the $^{8}\mathrm{Be}$ decay
- It mediates the decay of the $^{4}\mathrm{He}(20.21)$ states
- For similar value of scalar couplings the rate is larger than the $^{4}\mathrm{He}(21.01)$ one

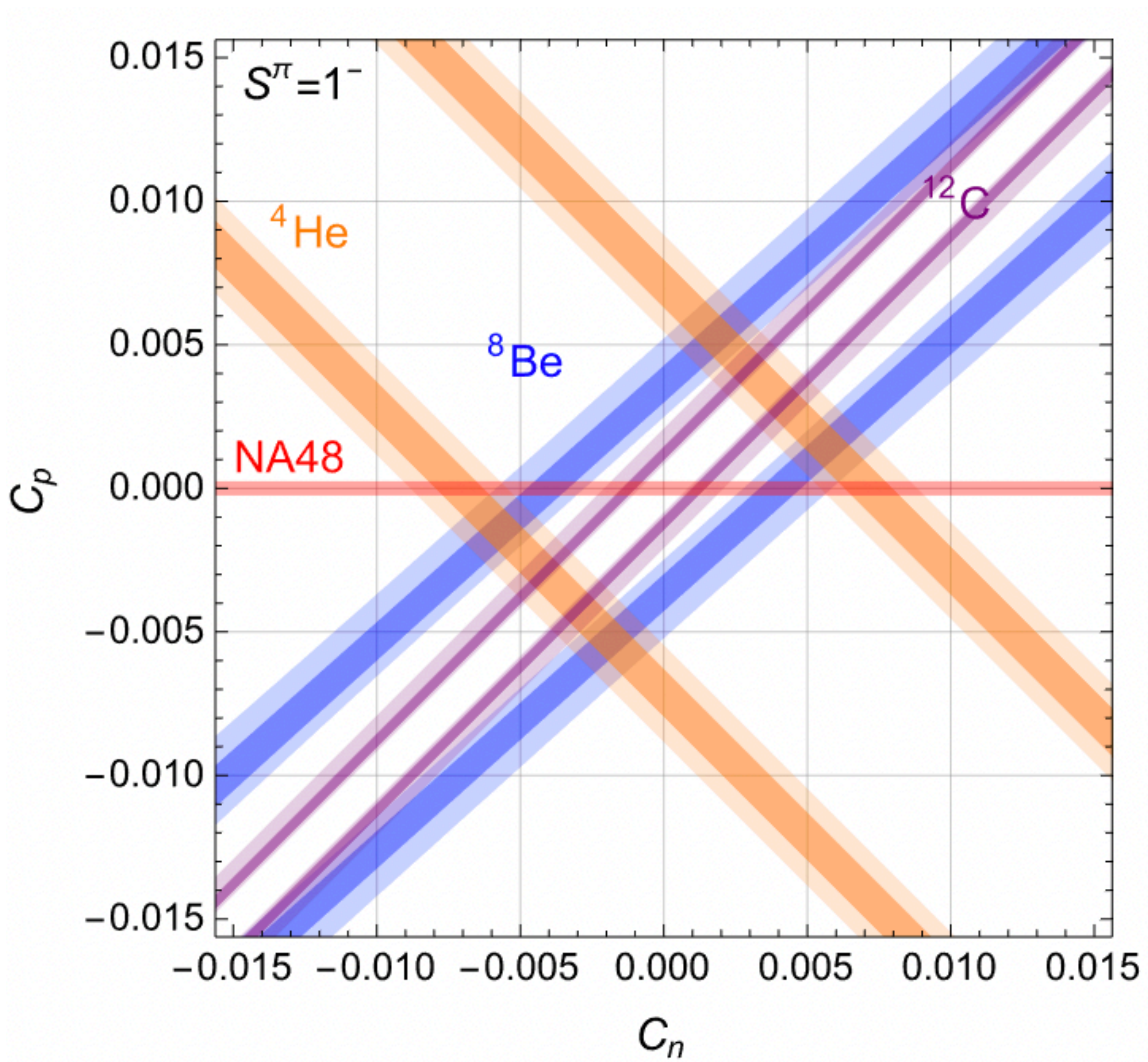
$$\Gamma_{^4\mathrm{He}(20.21)} \simeq 6 \times 10^{-4}\mathrm{eV} \left(\frac{z_p + z_n}{10^{-2}}\right)^2 \qquad \Gamma_{^4\mathrm{He}(21.01)} \simeq 9.7 \times 10^{-6}\mathrm{eV} \left(\frac{h_p + h_n}{10^{-2}}\right)^2$$

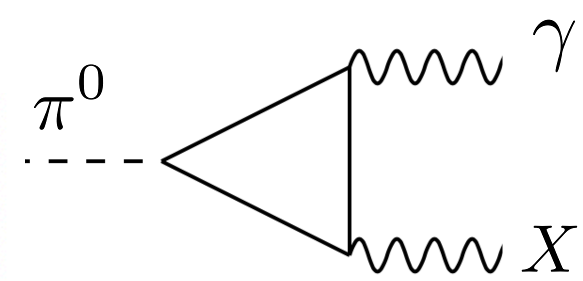
- Tune a cancellation of the scalar iso-scalar $z_p + z_n$ coupling
- The $^{12}\mathrm{C}$ rate can be fitted with a $\mathcal{O}(10^{-2})$ scalar iso-vector coupling

$$\frac{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + X)}{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + \gamma)} \simeq 2.4 \times 10^{-6} \left(\frac{z_p - z_n}{10^{-2}}\right)^2$$

Mixed parity state can potentially fit the three measurements

Vector state



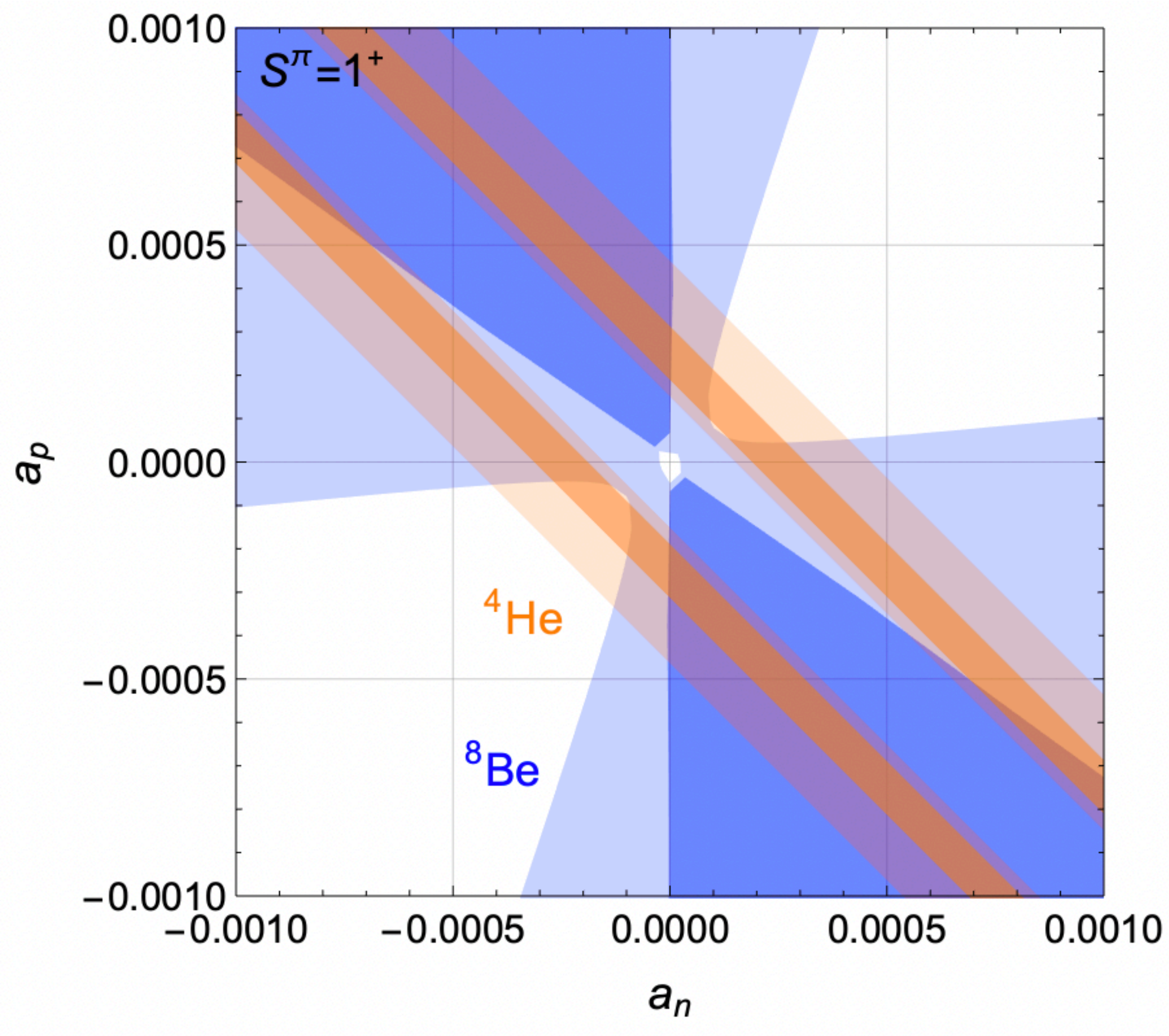


$\simeq (Q_u C_u - Q_d C_d) \ll 1$

Protophobic to avoid NA48 bound on $\pi^0 \to \gamma X$

- Protophobia strongly constrain a combined vector explanation for $^{8}\mathrm{Be}$ and $^{4}\mathrm{He}$
- No combined explanation seems possible when considering also the $^{12}\mathrm{C}$ data

Axial vector state



- $^8\mathrm{Be}$ and $^4\mathrm{He}$ can be satisfied, no relevant constraint on the parameter space
- The relevant matrix-element for the $^{12}\mathrm{C}$ transition is unknown… Rough estimate

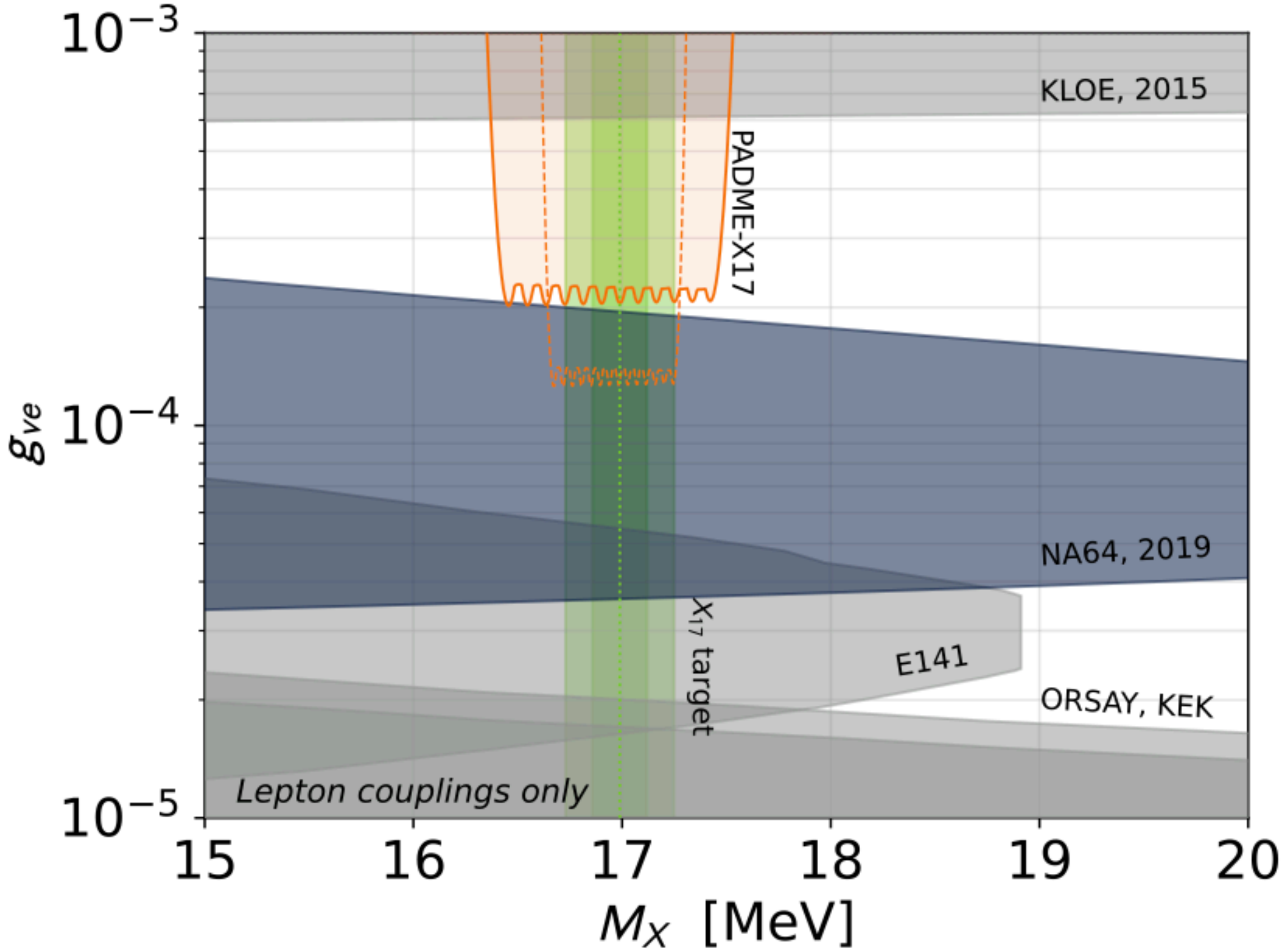
$$\langle ^{12}\mathrm{C}||\hat{D}_3^\sigma||^{12}\mathrm{C}(17.23)\rangle \simeq A \times R \simeq 12 \times 2.75\,\mathrm{fm} \simeq 1.7 \times 10^{-1}\,\mathrm{MeV}^{-1}$$

- For $\mathcal{O}(10^{-4})$ nucleon couplings $\dfrac{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + X)}{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + \gamma)} \simeq \mathcal{O}(10^{-6})$ in the ATOMKI ballpark

Axial state can potentially fit all three measurements

The PADME search

- The X boson must couple to electrons and can be produced in e^+e^- scattering
- Electron coupling of a light boson constrained by a multitude of experiments
- It has been proposed to search for X in production via resonant annihilation of positron beam on atomic electrons in a fixed target [Nardi+ 1802.04756, Darme'+ 2209.09261]
-



- Data taking over, data analysis ongoing. Results expected in Summer 2024
- See also PADME talk at WIFAI-2023 conference
-

Possible UV completion ?

- Minimal possibility for a light vector is to assume the SM Lagrangian to be invariant under a $U(1)_X$ symmetry
- The $U(1)_X$ charges are then a combination of B, L_i, Y
- After EWSB the *X* charges acquire a contribution from weak isospin T^3
- The axial coupling are given by

$$C_A^u = -C_A^d = -C_A^e \equiv C_A$$

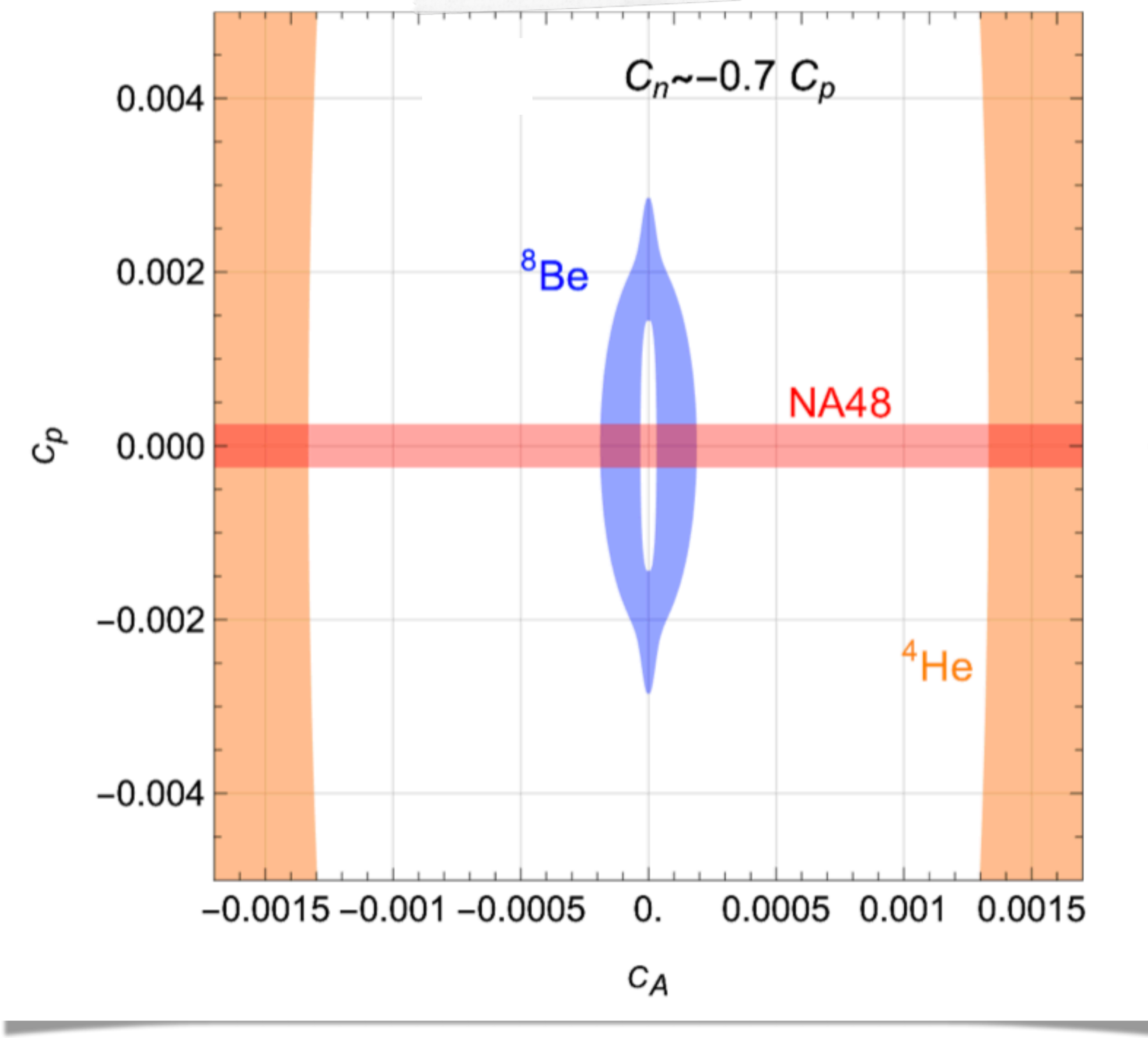
- The vector coupling to up and down quarks are independent combinations of B and Q
- Atomic parity violation experiments enforce a strong bound

$$|C_A^e| \left| \frac{188}{399} C_V^u + \frac{211}{399} C_V^d \right| \lesssim 1.8 \times 10^{-12}$$

- It can be satisfied by tuning $C_V^d = -\frac{188}{211} C_V^u$ which gives $C_V^n \sim -0.7 C_V^p$
- However the $^8\mathrm{Be}$ and the $^4\mathrm{He}$ anomalies cannot be simultaneously satisfied

Possible UV completion ?

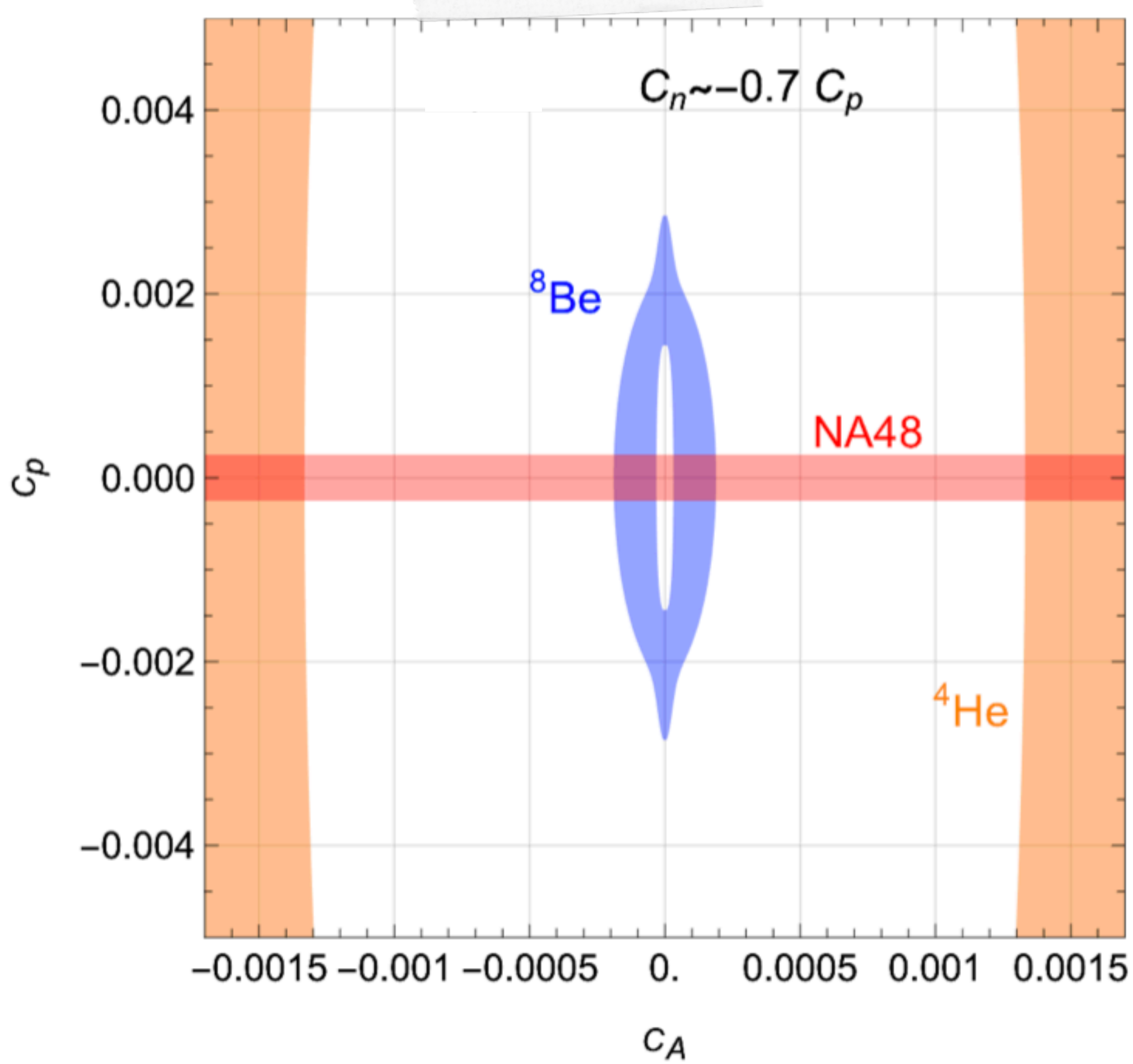
- Minimal possibility for a light vector is to assume the SM Lagrangian to be invariant under a $U(1)_X$ symmetry
- The $U(1)_X$ charges are then a combination of B, L_i, Y
- After EWSB the X c[illegible] $_3$
- The axial coupling a[illegible]



- The vector couplin[illegible]tions of B and Q
- Atomic parity violati[illegible]
- It can be satisfied b[illegible] C_V^p
- However the $^8\mathrm{Be}$ a[illegible] satisfied

Possible UV completion ?

- Minimal possibility for a light vector is to assume the SM Lagrangian to be invariant under a $U(1)_X$ symmetry
- The $U(1)_X$ charges are then a combination of B, L_i, Y
- After EWSB the X c ... 3
- The axial coupling ...



- The vector couplinç ... tions of B and Q
- Atomic parity violati ...
- It can be satisfied b ... C_V^p
- However the $^8\mathrm{Be}$ ... satisfied

- Non minimal possibility have been attempted, tightly constrained
  [Feng+ 1608.03591, Delle Rose+ 1704.03436 , 1811.07953, Kozaczuk 1612.01525]

Conclusions

- Three anomalies in nuclear transitions of $^{8}\mathrm{Be}$, $^{4}\mathrm{He}$ and $^{12}\mathrm{C}$ excited nuclei

- Statistical significance is very strong $\gtrsim 7\sigma$

- No clear SM explanation in terms of nuclear physics effects

- Present data are from a single experiment, need an independent confirmation

- The kinematic of the 3 anomalies points to the possibility of a single particle explanation, a new boson with mass of $\sim 17\ \mathrm{MeV}$

- Effective theories for different spin/parity assignments seem to favor axial and pseudoscalar candidates over the vector one, after the latest Carbon measurements

- PADME experiment at LNF will soon release results of a dedicated searches; other experiments have planned to do similar analyses

Non-relativistic expansion of nucleon operators

Spin-1 case

	$\mathcal{J}^0(\vec{r})$	$\vec{\mathcal{J}}_{\rm irr}(\vec{r})$	$\vec{\mu}(\vec{r})$
$C_p\bar{p}\gamma^\mu p + C_n\bar{n}\gamma^\mu n$	$\sum_{j=1}^A C_j\delta_{\vec{r},\vec{r}_j}$	$\sum_{j=1}^A \frac{C_j}{2m_j}\{\vec{p}_j,\delta_{\vec{r},\vec{r}_j}\}$	$\sum_{j=1}^A \frac{C_j}{2m_j}\vec{\sigma}_j\delta_{\vec{r},\vec{r}_j}$
$a_p\bar{p}\gamma^\mu\gamma^5 p + a_n\bar{n}\gamma^\mu\gamma^5 n$	$\sum_{j=1}^A \frac{a_j}{2m_j}\{\vec{\sigma}_j\cdot\vec{p}_j,\delta_{\vec{r},\vec{r}_j}\}$	$\sum_{j=1}^A a_j\vec{\sigma}_j\delta_{\vec{r},\vec{r}_j}$	/
$\frac{\kappa_p}{2m_p}\partial_\nu(\bar{p}\sigma^{\mu\nu}p) + \frac{\kappa_n}{2m_n}\partial_\nu(\bar{n}\sigma^{\mu\nu}n)$	/	/	$\sum_{j=1}^A \frac{\kappa_j}{2m_j}\vec{\sigma}_j\delta_{\vec{r},\vec{r}_j}$

Spin-0 case

	$\mathcal{S}(\vec{r})$
$z_p\bar{p}p + z_n\bar{n}n$	$\sum_{j=1}^A z_j\delta_{\vec{r},\vec{r}_j}$
$h_p i\bar{p}\gamma^5 p + h_n i\bar{n}\gamma^5 n$	$\sum_{j=1}^A \frac{h_j}{2m_j}\vec{\sigma}_j\cdot\vec{\nabla}[\delta_{\vec{r},\vec{r}_j}]$

Table 3. Leading term of the non relativistic expansion for the relativistic vector current, the relativistic axial current and the anomalous magnetic moment terms (upper table) and for the scalar and pseudoscalar density (lower table). $\delta_{\vec{r},\vec{r}_j}=\delta(\vec{r}-\vec{r}_j)$.

Nuclear operators matrix elements

Vector case $S^\pi = 1^-$

$$\mathcal{M}_{00} \simeq -\frac{k^2}{6}\frac{1}{\sqrt{4\pi}}\sum_{s=1}^{A} C_s r_s^2 \equiv -\frac{ek^2}{6}\rho^{(X)} \ ,$$

$$\mathcal{M}_{1M} \simeq \frac{k}{3}\sqrt{\frac{3}{4\pi}}\sum_{s=1}^{A} C_s \vec{r}_s \cdot \hat{e}_M \equiv \frac{ek}{3} d_M^{(X)} \ ,$$

$$\mathcal{T}^{el}_{1\mathrm{M}} \simeq \frac{\sqrt{2}\omega}{3}\sqrt{\frac{3}{4\pi}}\sum_{s=1}^{A} C_s \vec{r}_s \cdot \hat{e}_M \equiv \frac{\sqrt{2}e\omega}{3} d_M^{(X)} \ ,$$

$$\mathcal{T}^{\mathrm{mag}}_{1M} \simeq \frac{i\sqrt{2}k}{3}\frac{1}{2m_{\mathcal{N}}}\sqrt{\frac{3}{4\pi}}\sum_{s=1}^{A}[C_s(\vec{r}_s \times \vec{p}_s) + (C_s + \kappa_s)\vec{\sigma}_s]\cdot \hat{e}_M \equiv \frac{i\sqrt{2}k\mu_{\mathcal{N}}}{3}\mu_M^{(X)}$$

Axial vector case $S^\pi = 1^+$

$$\mathcal{M}_{00} \simeq \mathcal{M}_{1M} \simeq 0\,,$$

$$\mathcal{L}_{00} \simeq -\frac{ik}{3}\frac{1}{\sqrt{4\pi}}\sum_{s=1}^{A} a_s(\vec{r}_s \cdot \vec{\sigma}_s) \equiv -\frac{ik}{6}\frac{1}{\sqrt{4\pi}}[(a_p + a_n)\hat{d}_0^\sigma + (a_p - a_n)\hat{d}_3^\sigma]\,,$$

$$\mathcal{L}_{1M} \simeq \frac{i}{3}\sqrt{\frac{3}{4\pi}}\sum_{s=1}^{A} a_s \vec{\sigma}_s \cdot \hat{e}_M \equiv \frac{i}{3}\sqrt{\frac{3}{4\pi}}[a_p \hat{\sigma}_M^{(p)} + a_n \hat{\sigma}_M^{(n)}]\,,$$

$$\mathcal{T}^{\mathrm{el}}_{1M} \simeq \frac{i\sqrt{2}}{3}\sqrt{\frac{3}{4\pi}}\sum_{s=1}^{A} a_s \vec{\sigma}_s \cdot \hat{e}_M \equiv \frac{i\sqrt{2}}{3}\sqrt{\frac{3}{4\pi}}[a_p \hat{\sigma}_M^{(p)} + a_n \hat{\sigma}_M^{(n)}]\,,$$

$$\mathcal{T}^{\mathrm{mag}}_{1M} \simeq \frac{ik}{3\sqrt{2}}\sqrt{\frac{3}{4\pi}}\sum_{s=1}^{A} a_s(\vec{r}_s \times \vec{\sigma}_s)\cdot \hat{e}_M \equiv \frac{ik}{6\sqrt{2}}\sqrt{\frac{3}{4\pi}}[(a_p + a_n)\hat{D}^\sigma_{0M} + (a_p - a_n)\hat{D}^\sigma_{3M}]\,.$$

Nuclear operators matrix elements

Scalar case $S^\pi = 0^+$

$$\mathcal{G}_{00} \simeq \frac{1}{\sqrt{4\pi}} \sum_{s=1}^{A} z_s \left[1 - \frac{p_s^2}{2m_\mathcal{N}^2} - \frac{k^2 r_s^2}{6}\right]$$

$$\mathcal{G}_{1M} \simeq \frac{k}{3}\sqrt{\frac{3}{4\pi}} \sum_{s=1}^{A} z_s \vec{r}_s \cdot \hat{e}_M,$$

Pseudoscalar case $S^\pi = 0^-$

$$\mathcal{G}_{00} \simeq \frac{k^2}{6m_\mathcal{N}} \frac{1}{\sqrt{4\pi}} \sum_{s=1}^{A} h_s(\vec{r}_s \cdot \vec{\sigma}_s) \equiv \frac{k^2}{12m_\mathcal{N}} \frac{1}{\sqrt{4\pi}} [(h_p + h_n)\hat{d}_0^\sigma + (h_p - h_n)\hat{d}_3^\sigma] \ ,$$

$$\mathcal{G}_{1M} \simeq -\frac{k}{6m_\mathcal{N}} \sqrt{\frac{3}{4\pi}} \sum_{s=1}^{A} h_s \vec{\sigma}_s \cdot \hat{e}_M \equiv -\frac{k}{6m_\mathcal{N}} \sqrt{\frac{3}{4\pi}} [h_p \hat{\sigma}_M^{(p)} + h_n \hat{\sigma}_M^{(n)}] \ ,$$

Atomic parity violation

Atomic parity violation

In atomic system, parity violation can be observed in the case, *e.g*, of and electric dipole transition between two atomic states with the same parity. The X_μ gives additional contributions to these transitions due to the interaction between atomic electrons and the nucleus. In the effective operator

$$\mathcal{L} \supset -\frac{1}{m_X^2}\left[C_V^u C_A^e (\bar{u}\gamma^\mu u)(\bar{e}\gamma_\mu\gamma^5 e) + C_A^u C_V^e (\bar{u}\gamma^\mu\gamma^5 u)(\bar{e}\gamma_\mu e) + u \leftrightarrow d\right] \ , \tag{F.7}$$

where only the $V \times A$ part have been kept, only the $A_e \times V_{u,d}$ interaction give a relevant effect for parity violation observables. This is due to the fact this part of the interaction between the electron and the nucleus is coherent, and thus proportional to the total weak charge of the nucleus itself, while the $A_q \times V_e$ interaction adds incoherently. This effect is thus suppressed for heavy enough nuclei [82]. The BSM contribution to $A_e \times V_{u,d}$ can be expressed as a modification to the weak nuclear charge Q_W [83]

$$\delta Q_W = -\frac{2\sqrt{2}}{G_F} 3(Z+N)\frac{C_A^e C_V^{q,\text{eff}}}{m_X^2} \ , \qquad C_V^{q,\text{eff}} = \frac{C_V^u(2Z+N) + C_V^d(Z+2N)}{3(Z+N)} \ . \tag{F.8}$$

The most accurate prediction comes from transition of ${}^{133}_{55}\text{Cs}$ [68] which, combined with the SM theoretical prediction [84], yields [85] $|\delta Q_W| \lesssim 0.6$ hence the bound reads

$$|C_A^e|\left|\frac{188}{399}C_V^u + \frac{211}{399}C_V^d\right| \lesssim 1.8 \times 10^{-12} \ . \tag{F.9}$$

- One can then compute the relevant spherical operators and, finally, the BSM decay rates

	^{8}**Be**	^{4}**He**	^{12}**C**
0^+	/	^{4}**He(20.21)** $2k(z_p+z_n)^2\left\lvert\frac{k^2}{6e}\langle\rho^{(\gamma)}\rangle+\frac{1}{2m_\mathcal{N}}\langle\hat{K}\rangle\right\rvert^2$	$\frac{2k^3}{27}(z_p-z_n)^2\lvert\langle\lvert\lvert d^{(\gamma)}\rvert\rvert\rangle\rvert^2$
0^-	$\frac{k^3}{72\pi m_N^2}\lvert\langle h_p\hat{\sigma}^{(p)}+h_n\hat{\sigma}^{(n)}\rangle\rvert^2$	^{4}**He(21.01)** $\frac{k^5}{228\pi m_N^2}(h_p+h_n)^2\lvert\langle\hat{d}_0^\sigma\rangle\rvert^2$	/
1^-	$\frac{4\mu_N^2\omega^3}{27}\lvert\langle\mu^{(X)}\rangle\rvert^2$	^{4}**He(20.21)** $\frac{m^2k^3\alpha}{18}\lvert\langle\rho^{(X)}\rangle\rvert^2$	$\frac{16\pi\alpha\omega^3}{27}\left(1+\frac{m^2}{2\omega^2}\right)\lvert\langle d^{(X)}\rangle\rvert^2$
1^+	$\frac{k}{18\pi}\left(2+\frac{\omega^2}{m^2}\right)\lvert\langle a_p\hat{\sigma}^{(p)}+a_n\hat{\sigma}^{(n)}\rangle\rvert^2$	^{4}**He(21.01)** $\frac{\omega^2k^3}{72\pi m^2}(a_p+a_n)^2\lvert\langle\hat{d}_0^\sigma\rangle\rvert^2$	$\frac{k^3}{144\pi}(a_p-a_n)^2\lvert\langle\hat{D}_3^\sigma\rangle\rvert^2$

- E.g. for $^4\mathrm{He}$ transition with vector state $J^\pi=1^-$ only $\mathcal{M}_{00}$ contributes

$$\mathcal{M}_{00}\simeq-\frac{k^2}{6}\int d^3\vec{r}\,r^2Y_{00}\mathcal{J}^0(\vec{r})=-\frac{k^2}{6\sqrt{4\pi}}\sum_i C_ir_i^2\equiv-\frac{e^2k^2}{6}\rho^{(X)}$$

- The matrix elements of $\hat{K}=\sum_s p_s^2/2m_s$ and $\hat{D}_3^\sigma=\sum_{\ell=1}^{A}\tau_3^{(\ell)}(\vec{r}\times\vec{\sigma})_\ell$ are not known