The X17 anomaly: status and prospect

Enrico Nardi

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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Anomalies in nuclear transitions observed by the Atomki experiment

Summary:

- 2015: First anomaly observed in the angular correlation of e^+e^- pairs emitted in nuclear transition of $^8Be^*$(18.15 MeV) -> ground state (g.s.) [Phys. Rev. Lett. 116, 042501 (2016)]

- 2017: With improved exp. setup, similar anomaly in $^8Be^*$(17.64 MeV) decay to g.s. (previously not observed). Reported in Messina symposium (Oct 2016) and Bormio meeting (Jan 2017) [EPJ Web Conf. 142 (2017) 01019; PoS BORMIO 2017 (2017)]

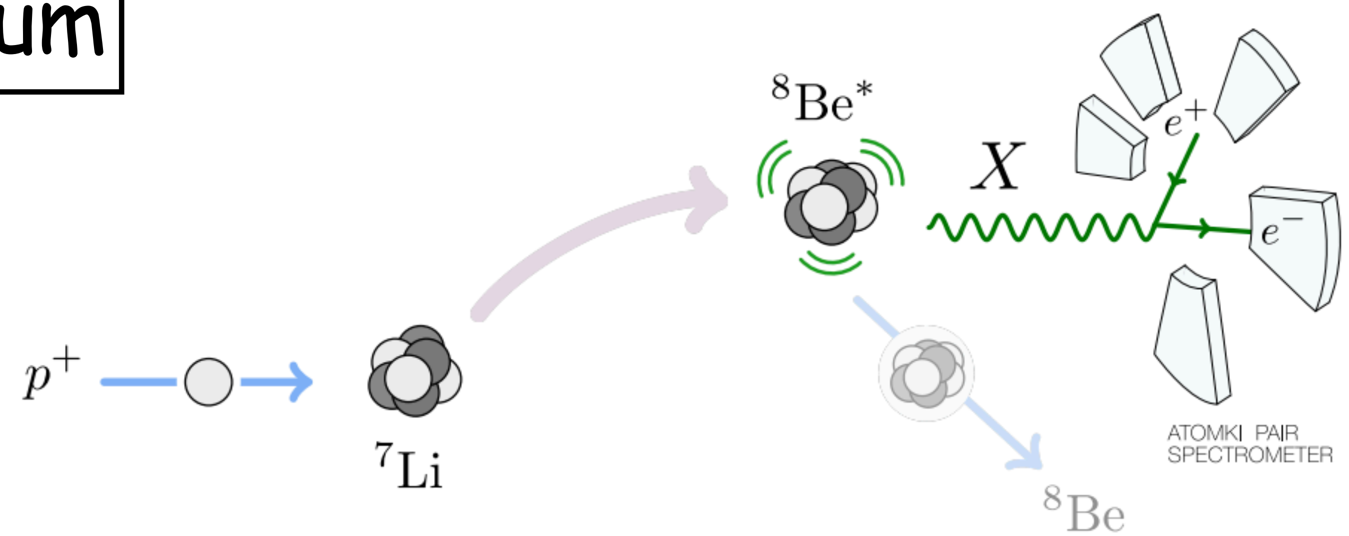
- 2018: Confirmation of ^8Be result (thinner target, 5+1 telescopes) first hint of similar anomaly in $^4He^*$(21 MeV) transition [Zakopane Conf., Acta Phys.Polon.B 50 (2019) 3, 675]

- 2019: Confirmation of ^4He bump (7.2σ) consistent with M_X~17MeV interpretation [Phys.Rev.C 104 (2021) 4, 044003 • (received 27 October 2019) - e-Print: 2104.10075 supersedes 1910.10459]

- 2021: Preliminary results for $^{12}C^*$(17.2 MeV) decaying to g.s.: excess of e^+e^- pairs at large angles (~ 160^o). [A.J. Krasznahorkay, "Shedding light on X17" workshop, Centro Fermi, Rome, Sept. 2021]

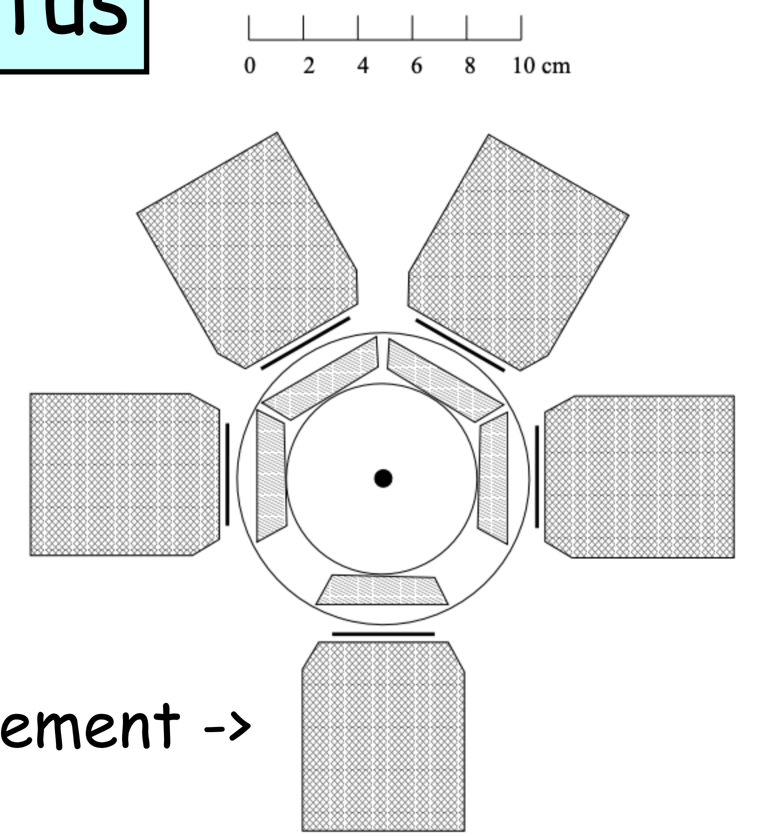
The Atomki experimental apparatus

Berillium



Feng+, 1608.0359

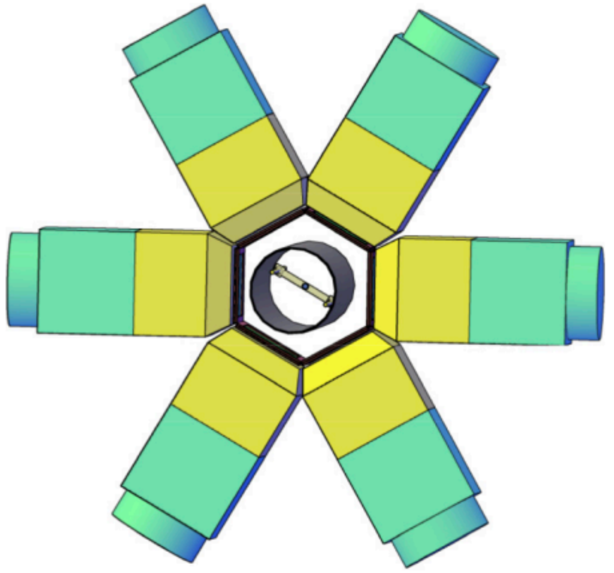
Five telescopes arrangement ->

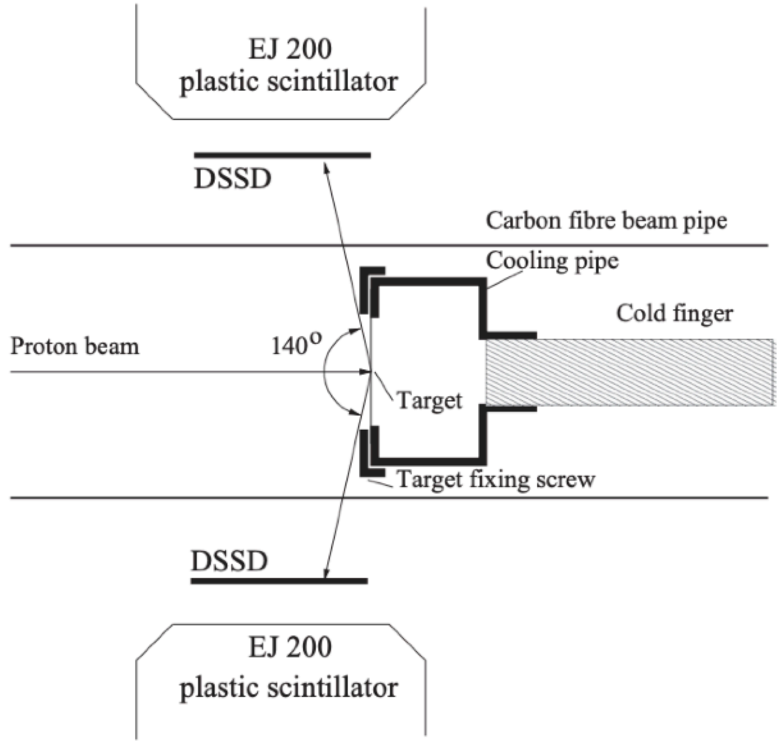


During the years, several improvements in the apparatus (accelerator, detectors, electronics)

Helium

Six telescopes arrangement ->

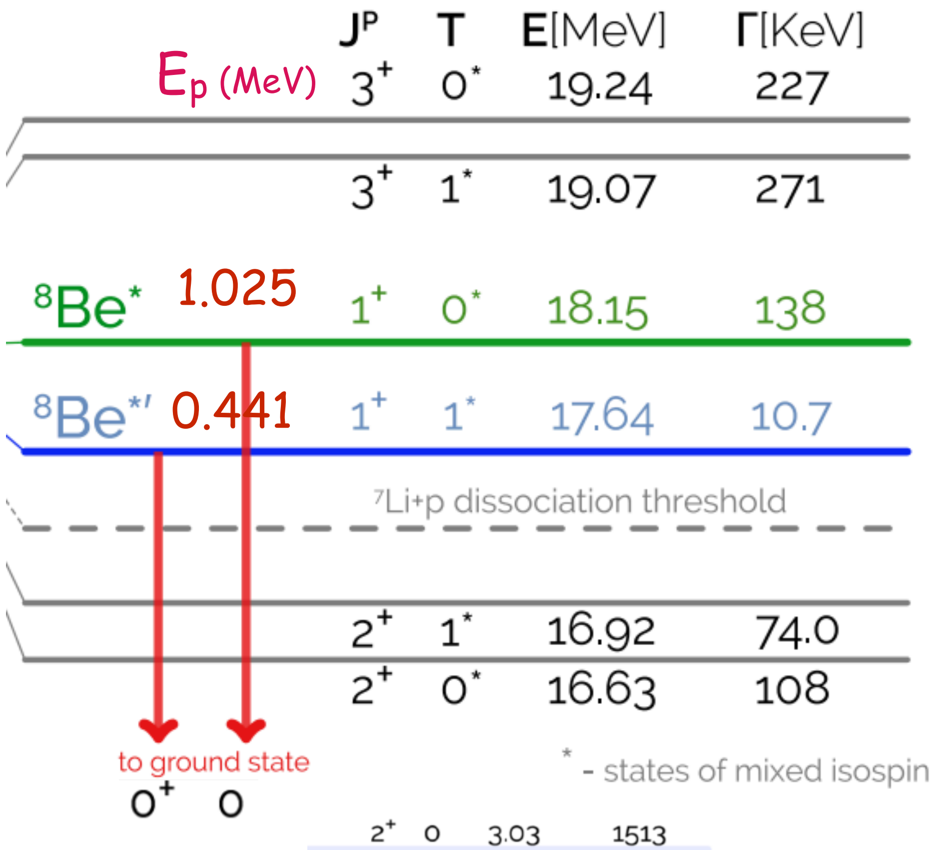




Atomki e^+e^- pairs measurements:

1. energy-sum spectrum $E_\pm = E_{e+}+E_{e-}$
2. e^+e^- angular correlations θ

Berillium nuclear transitions



Resonant transition $p+{}^7Li \to {}^8Be^* \to \dots$

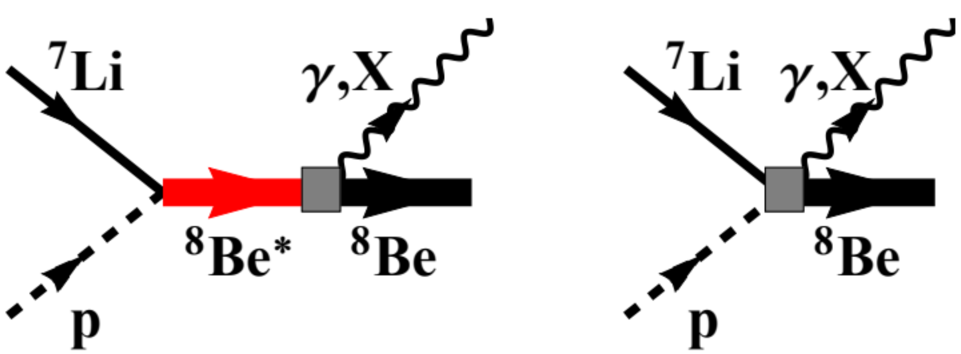
$^8Be^* \to p + {}^7Li$ (mostly)

$^8Be^* \to {}^8Be + \gamma$ $(B_\gamma = 1.4 \times 10^{-5})$

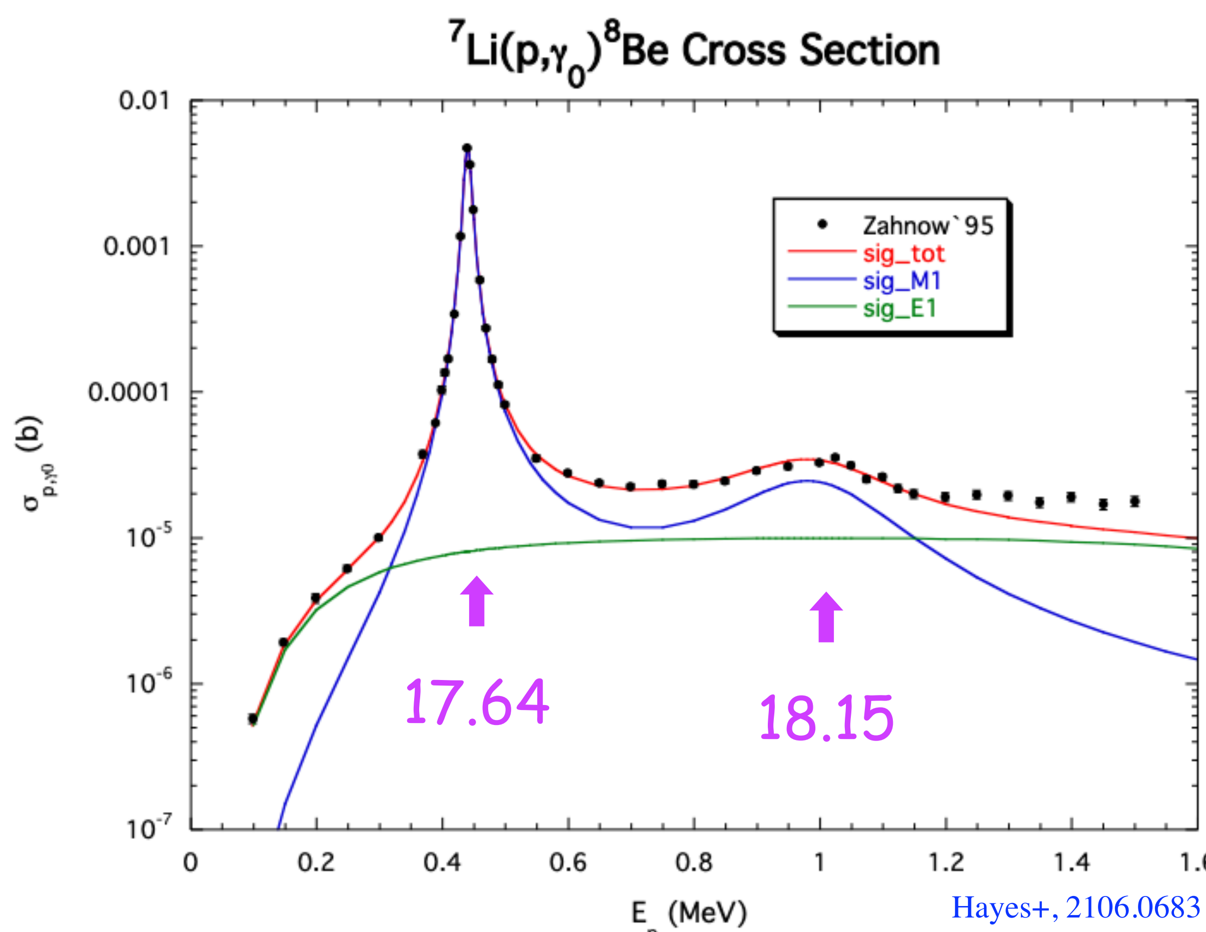
$^8Be^* \to {}^8Be + e^+e^-$ $(B_\pm = 4 \times 10^{-3}\, B_\gamma)$

$[{}^8Be^* \to {}^8Be + X_{17}$ $(B_X = 6 \times 10^{-6}\, B_\gamma)]$

Radiative $p + {}^7Li \to {}^8Be + \gamma$

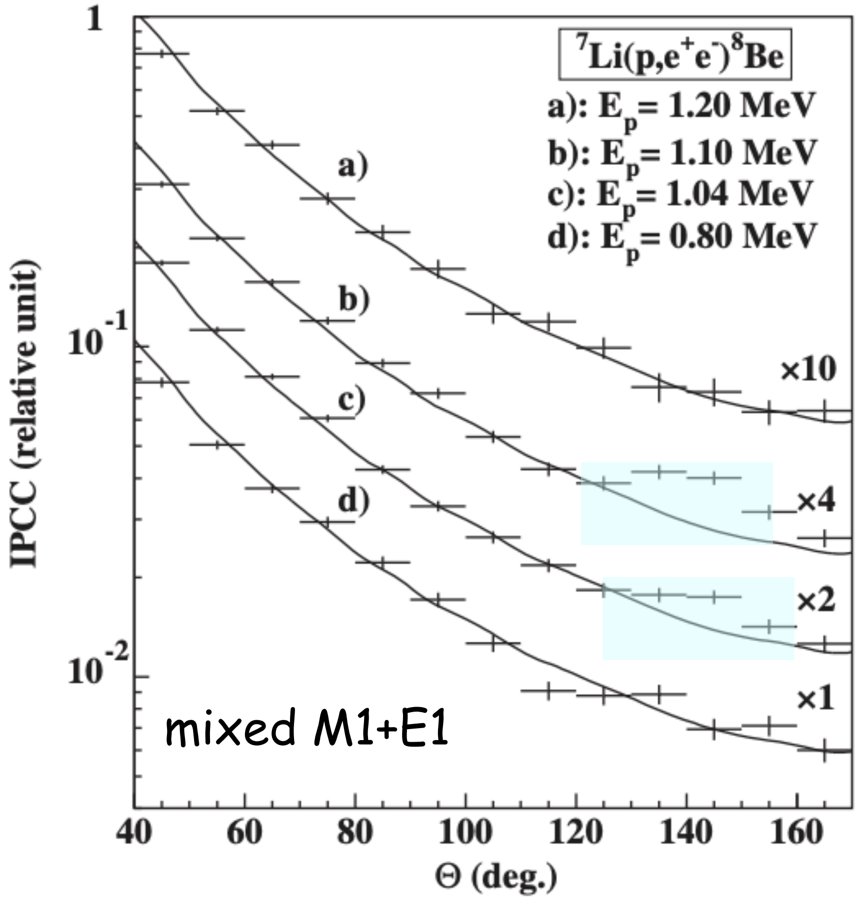


M1 resonant transition - E1 direct p capture
(valid also for a Vector X_{17})



Atomki results for ^{8}Be [PRL 116, 042501 (2016)]

Angular correlation



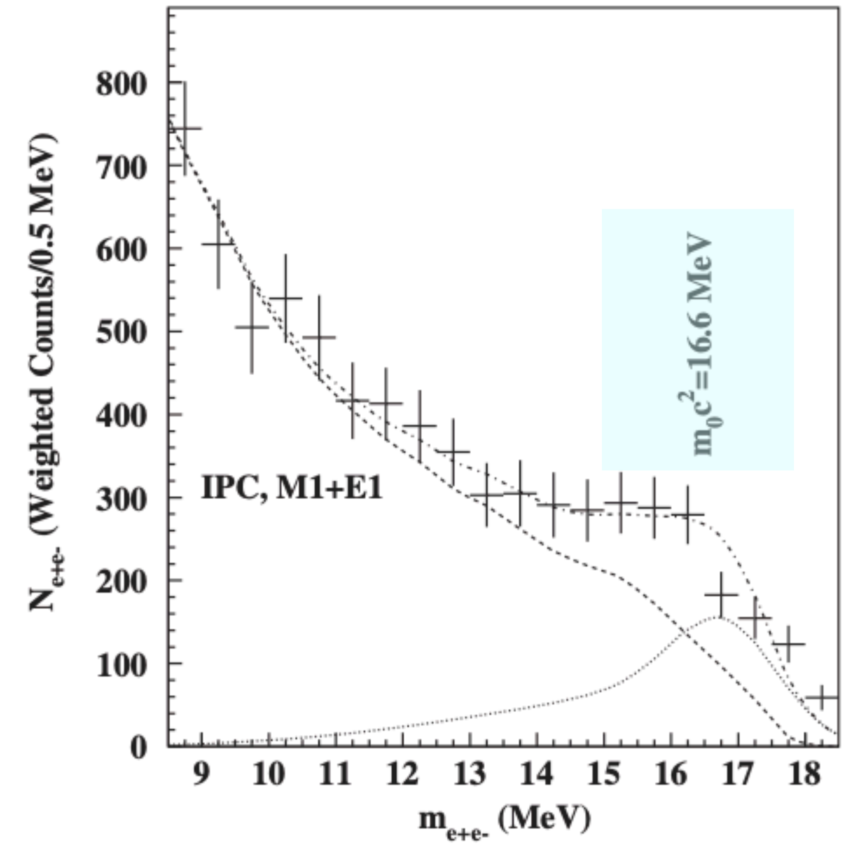
^{8}Be*(18.15MeV) IS

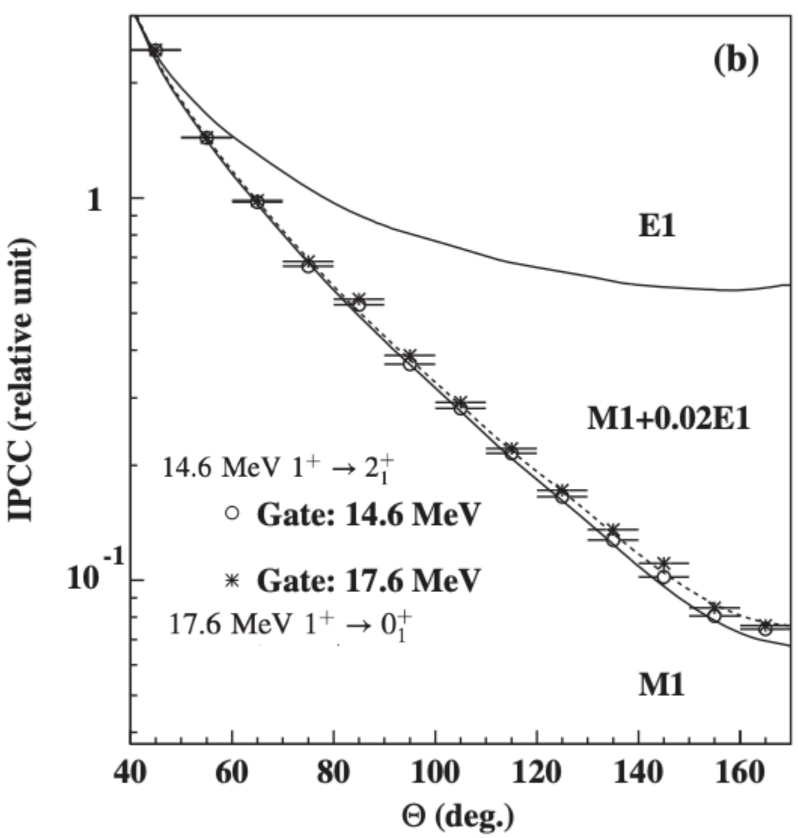
Energy gate: $E_\pm$ > 18 MeV

$y=\Delta E_\pm/E_\pm$ < 0.5

$$m_\pm^2 \simeq (1-y^2)\, E_\pm^2\, \sin^2\theta/2$$

Invariant mass distribution





^{8}Be*(17.64MeV) IV

The contribution of the direct capture depends on the target thickness if the energy loss of the beam in the target is larger than the width of the resonance. The dashed simulated curve in Fig. 1(b) is obtained by fitting a small (2.0%) $E1$ contribution to the dominant $M1$ one, which describes the experimental data reasonably well.

One important theoretical input [Feng+, PRL 1604.07411 [hep-ph]; PRD 1608.03591 [hep-ph]]

As noted above, the decay $^8\text{Be}^{*\prime} \to {}^8\text{Be}\, X$ is not seen. The protophobic gauge boson can mediate isovector transitions, so there is no dynamical suppression of this decay. However, its mass is near the 17.64 MeV threshold, so the decay is kinematically suppressed. For $m_X = 17.0\ (17.4)$ MeV, the $|\vec{p}_X|^3/|\vec{p}_\gamma|^3$ phase space suppression factor is 2.3 (5.2) times more severe for the $^8\text{Be}^{*\prime}$ decay than for the $^8\text{Be}^*$ decay. In particular,

Feng+, PRL 1604.07411 [hep-ph];

If the observed anomaly in $^8\text{Be}^*$ decays originates from a new particle, then the absence of new particle creation in the $^8\text{Be}^{*\prime}$ decay combined with the isospin mixing discussed in Sec. IV strongly suggest that such decays are kinematically—not dynamically—suppressed and that the new particle mass is in the upper part of the range given in Eq. (1). It also suggests that with more data, a similar, but more phase space-suppressed, excess may appear in the IPC decays of the 17.64 state.

Feng+, PRD 1608.03591 [hep-ph];

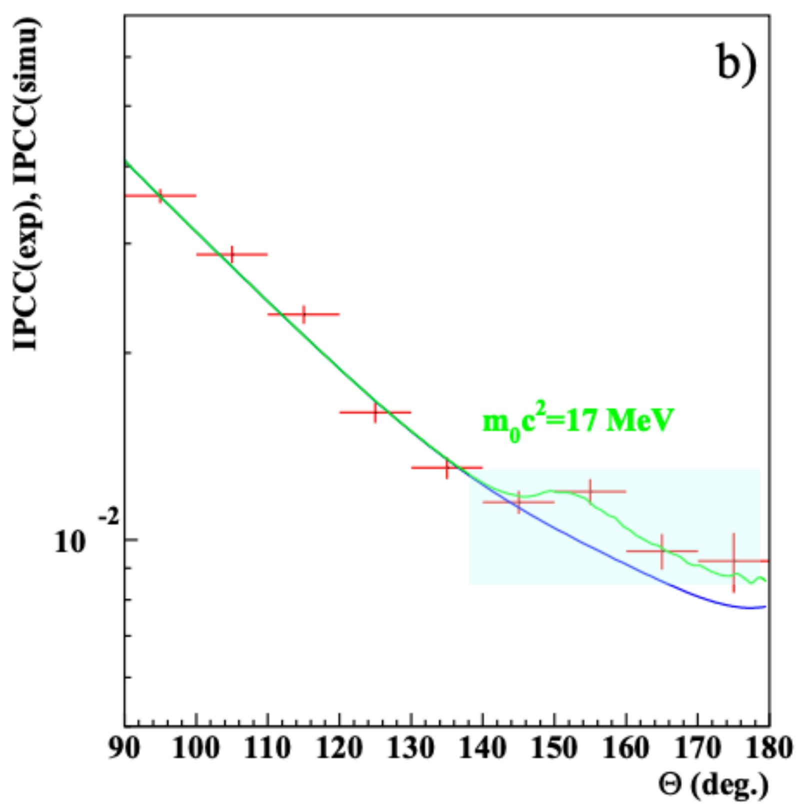
New Atomki results for $^8\text{Be}^*(17.64)$

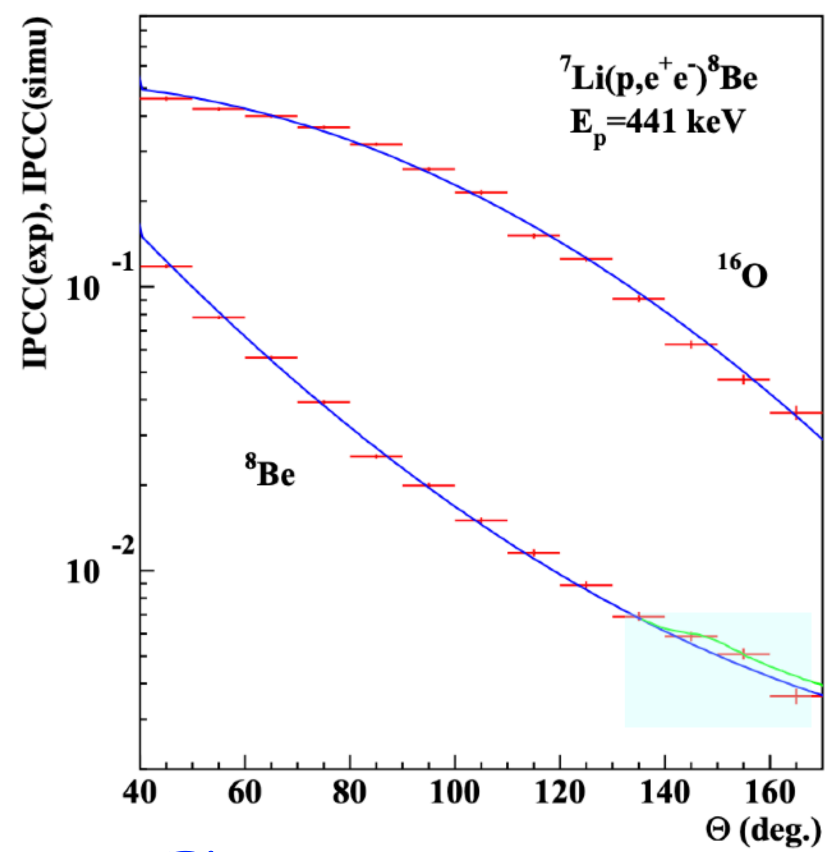
Messina symposium (Oct 2016)

Bormio meeting (Jan 2017)

our experimental setup has been moved to a new accelerator laboratory and has also been improved.

we observed some smaller deviation also for the 17.6 MeV transition as was predicted by Feng et al., but which we did not see before





Bump location:
150° (17.64 MeV) vs.
140° (18.15 MeV)

Axial vector boson

Calculation of relevant Nucl. Matrix Elements:
Kozaczuk+, PRD 1612.01525 [hep-ph]

the $^8\text{Be}^{*\prime} \to {}^8\text{Be}+X$ transition rate can be suppressed relative to that of the $^8\text{Be}^* \to {}^8\text{Be}+X$ mode for an axial vector. This effect is dynamical,

^{8}Be anomaly: Standard Model explanations ?

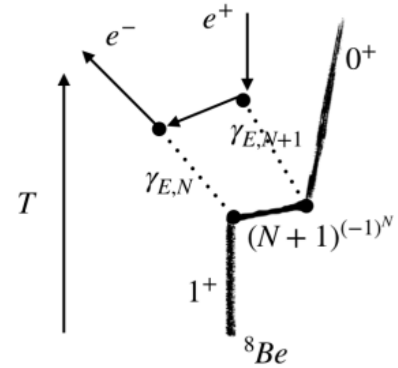
Zhang & Miller PLB, arXiv:1703.04588 [nucl-th]

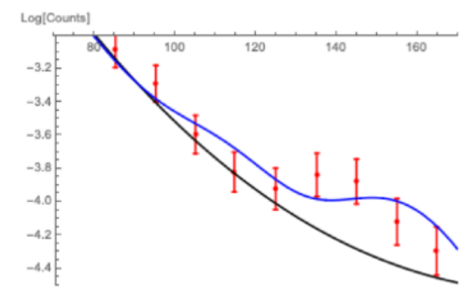
Interferences between different multipoles. Possibility of using the nuclear transition form factor to explain the anomaly

We find that the model improvements are not able to explain the anomaly.

Koch, NPB, arXiv:2003.05722 [hep-ph]

Hypothesises nuclear chain reaction and conversion of two resulting highly energetic γs into an electron–positron pair.





The kinematics fits perfectly the experimental result. No explanation for the isospin structure can be given. The process does not give a satisfying explanation of X17.

Kálmán & Keszthelyi EPJA, arXiv:2005.10643 [nucl-th]

Higher order processes, in which strong and electromagnetic interactions are coupled and govern jointly the system from the definite initial state to the definite final one [Analyzed ^{8}Be and (qualitatively) also ^{4}He]

Enhancement can be generated by higher order processes. Lower energy nucl. transitions can cause peaked angle dependence in angular correlations.

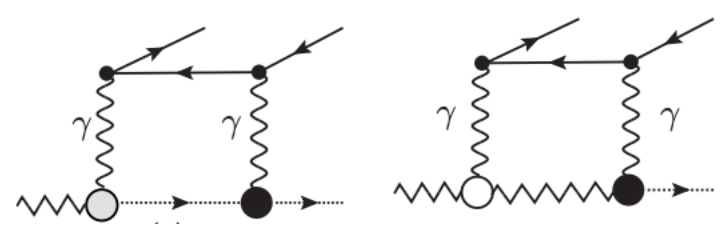
Zhang & Miller PLB, arXiv:2008.11288 [hep-ph]

Derived isospin relation between photon and (protophobic) X couplings to nucleons. X production dominated by direct transitions with a smooth energy dependence occurring for all proton beam energies above threshold

X bremsstrahlung occurs at all beam energies above threshold. The enhancement should have been seen at all four Atomki p-energies. The explanation of the anomaly in terms of protophobic vector boson cannot be correct.

Aleksejevs+, arXiv:2102.01127 [nucl-th]

Full second-order calculation of ^{8}Be* → ^{8}Be e^+e^- process: interferences second-order corrections and the interference terms to the Born-level decay amplitudes



The observed ^{8}Be experimental structure can be reproduced within the Standard Model.

Hayes+, arXiv:2106.06834 [nucl-th]

Study of e^+e^- angular distributions for nuclear decay for several multipoles M1,E1 dominate, but the ratio of M1 to E1 strength strong function of energy (Atomki: M1/E1 assumed constant over the energy region Ep = 0:8-1:2 MeV)

The evidence of a new particle emitted from the 18.15 MeV resonance in ^{8}Be seems to be strongly dependent on the assumptions about the nuclear structure of this resonance. Atomki surplus events at large angles could be an artefact of the Atomki analysis nuclear structure assumptions.

About theoretical interpretation [Feng+, PRL 1604.07411 [hep-ph]; PRD 1608.03591 [hep-ph]]

X_{17} particle: Some simple possibilities are excluded:

Scalar: $J^P = 1^+(^8Be^*) \to 0^+(^8Be)\ 0^+(X)$ => $L=1$; $P = +1 = (-1)^L$

Vector with no definite parity (Z'): APV constraints

$U(1)_{B-L}$ vector boson: ν-e scattering ($g_{B-L} \lesssim 10^{-5}$)

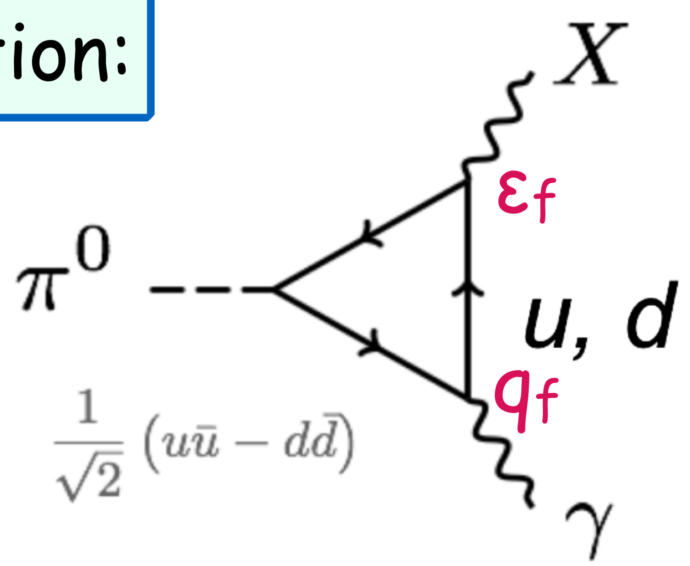
Kinetically mixed V': $g_f = \varepsilon Q_f$ NA48/2 limit $\pi^0 \to X\gamma$

Pionphobic/Protophobic vector particle interpretation:

$\pi^0 \to X\gamma$: $|2\varepsilon_u + \varepsilon_d| <$ 8×10^{-4} (NA48/2)

$B_X/B_\gamma \propto (\varepsilon_p+\varepsilon_n)^2 (p_X/p_\gamma)^3 \approx 6 \times 10^{-6}$ (Atomki)

=> $|\varepsilon_u + \varepsilon_d| \approx$ 4×10^{-3}



$\varepsilon_d \approx -2\ \varepsilon_u$ (±10%) ==> $\varepsilon_p = 2\varepsilon_u + \varepsilon_d \approx 0$; $\varepsilon_n = 2\varepsilon_d + \varepsilon_u \approx 1.2 \times 10^{-2}$

[Feng+, 1608.0359 [hep-ph] (Aug. 2016)]

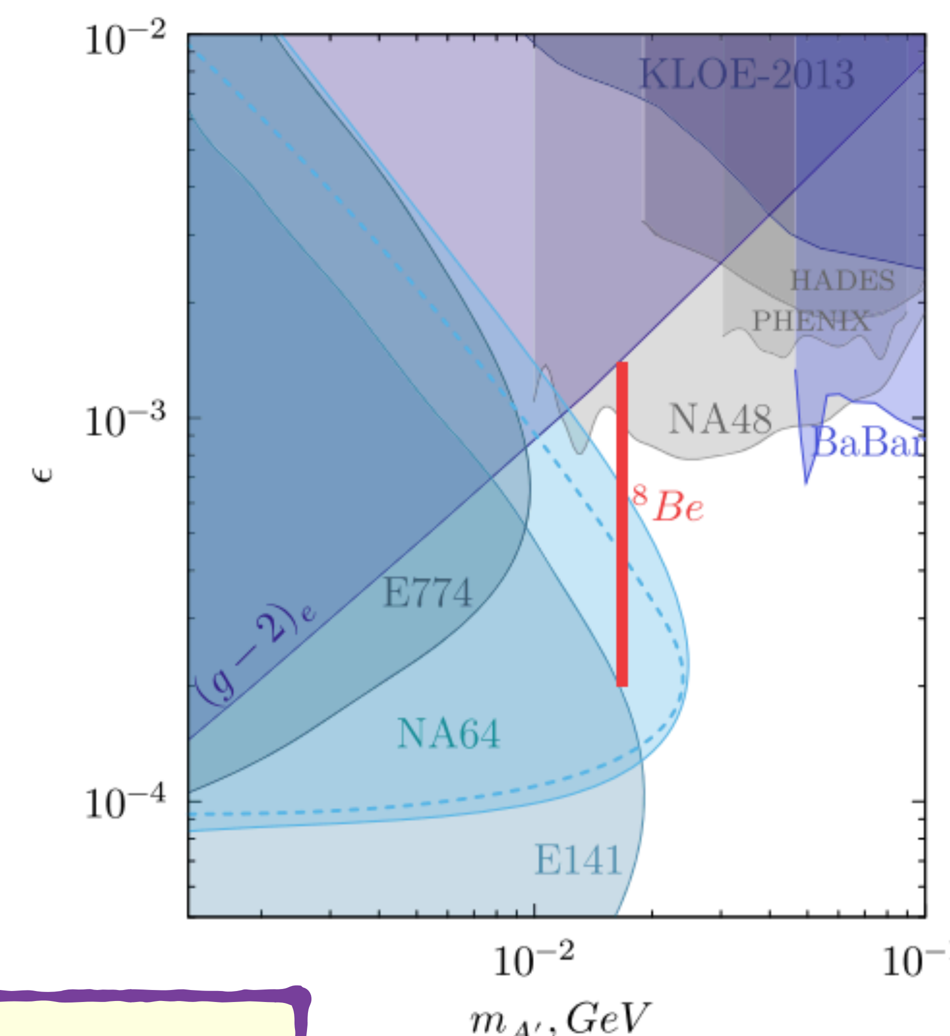
For protophobic vector, ^{8}Be data can be explained with:

$\varepsilon_u = -\varepsilon_n/3 \approx \pm\ 3.7 \times 10^{-3}$; $\varepsilon_d = 2\varepsilon_n/3 \approx \mp\ 7.4 \times 10^{-3}$; $|\varepsilon_e| \in [2,14] \times 10^{-4}$

Current limits on X17

[NA64@ CERN, 1912.11389 [hep-ex] (Dec. 2019)]

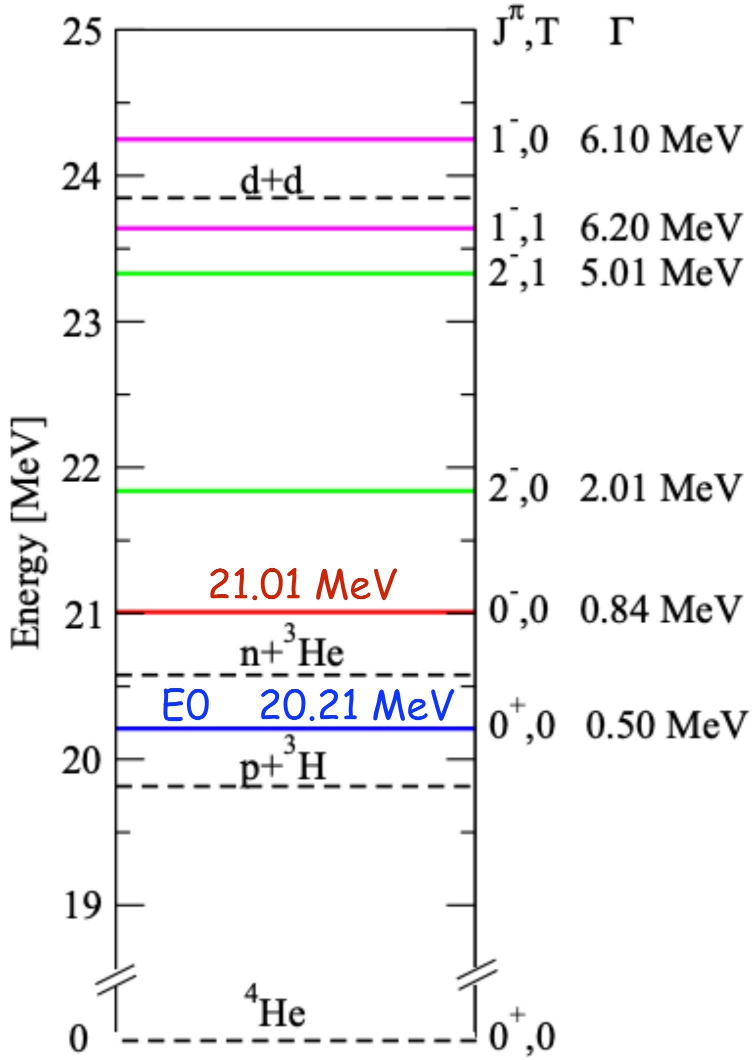
The X17 boson could be produced in the bremsstrahlung reaction $e^- Z \rightarrow e^- Z\ X$ by a high energy beam (150 GeV) of electrons incident on the active target in the NA64 experiment, and observed through its decay $X \rightarrow e^+e^-$



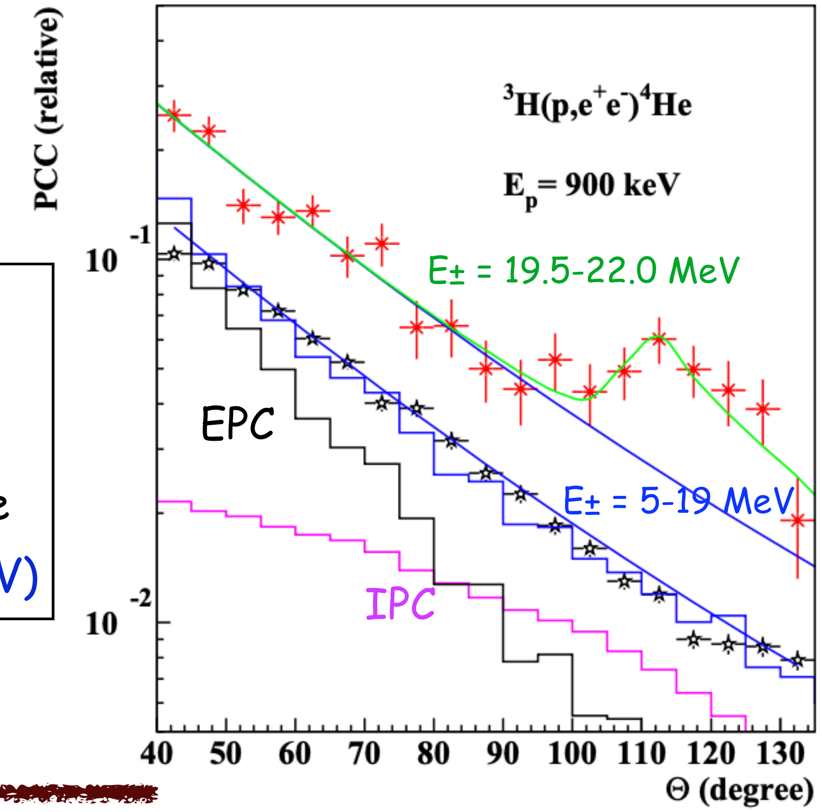
$|\varepsilon_e| \in [2.0,6.8] \times 10^{-4}$ for M_X =16.7 MeV

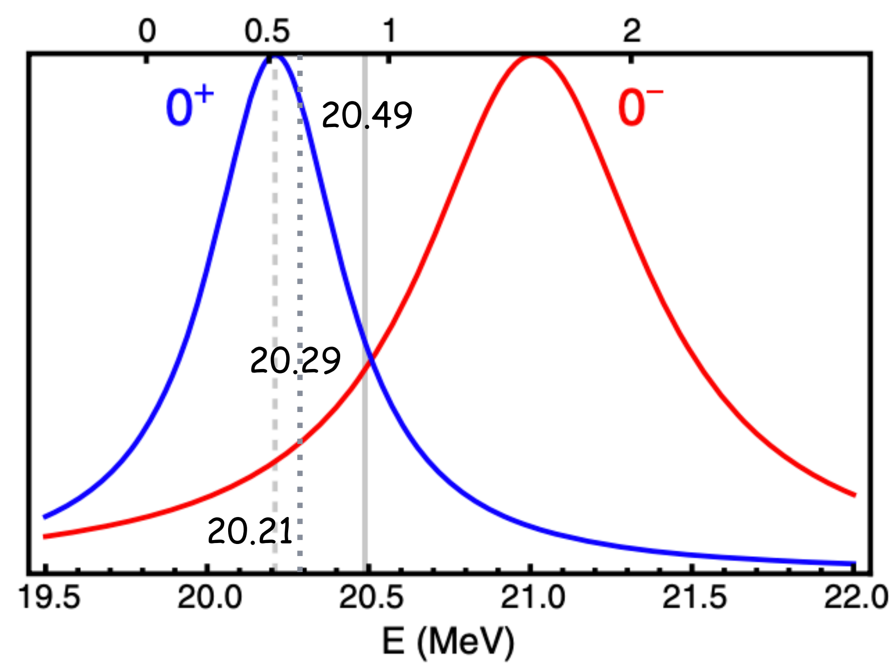
(In the meanwhile: M_X (^{8}Be) = (17.1 ± 0.16) MeV)

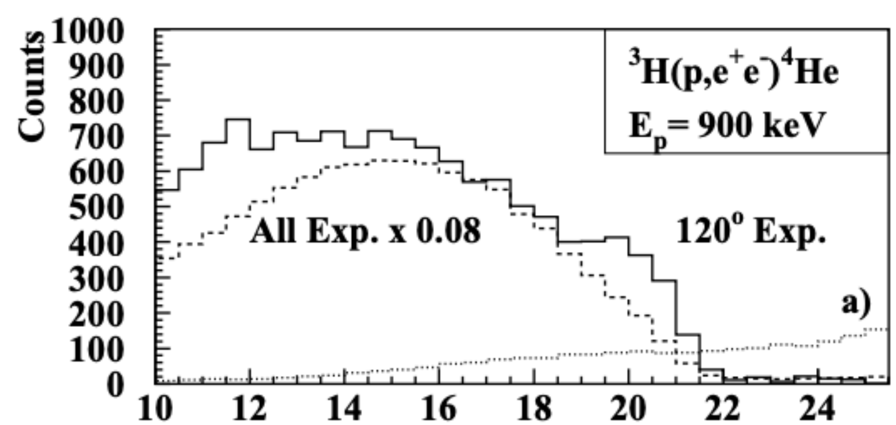
Helium 4 nuclear transitions

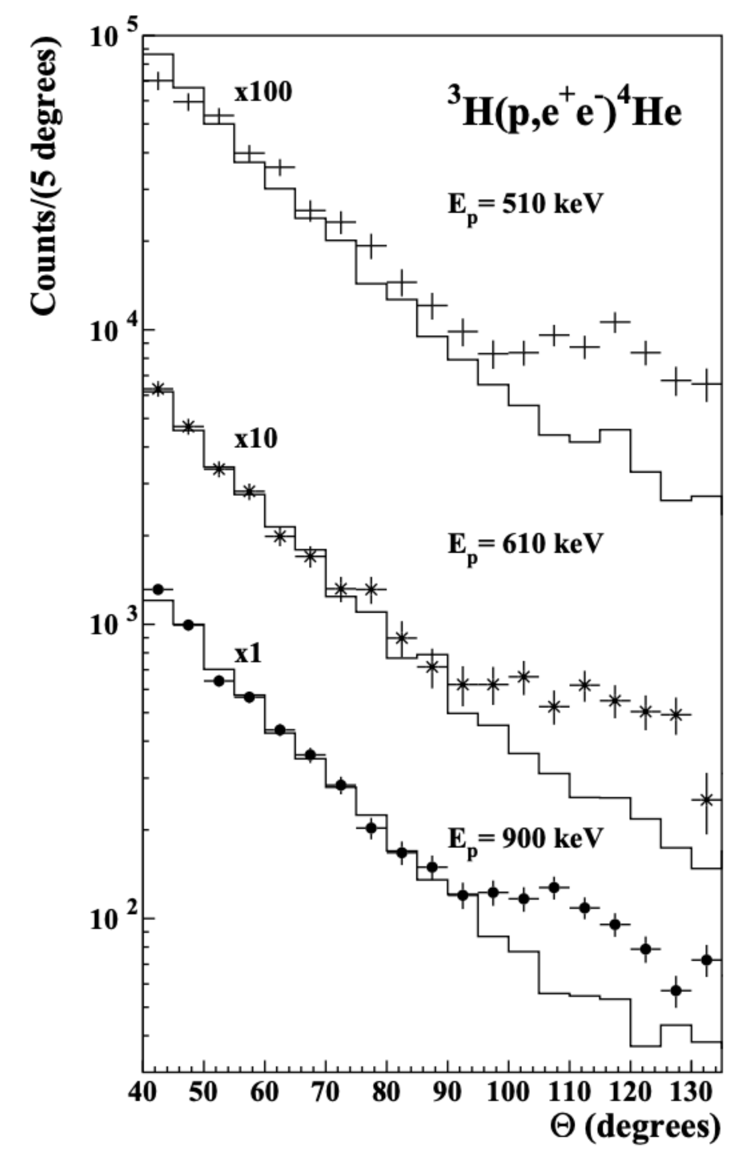


arXiv:1910.10459 [nucl-ex] E_p=900 keV
(below E(p,n) = 1.018 keV threshold)
excites the ^{4}He nucleus to E*=20.49 MeV
and populates the second ^{4}He excited state
0^-(21.01 MeV) overlapped with 0^+(20.21 MeV)







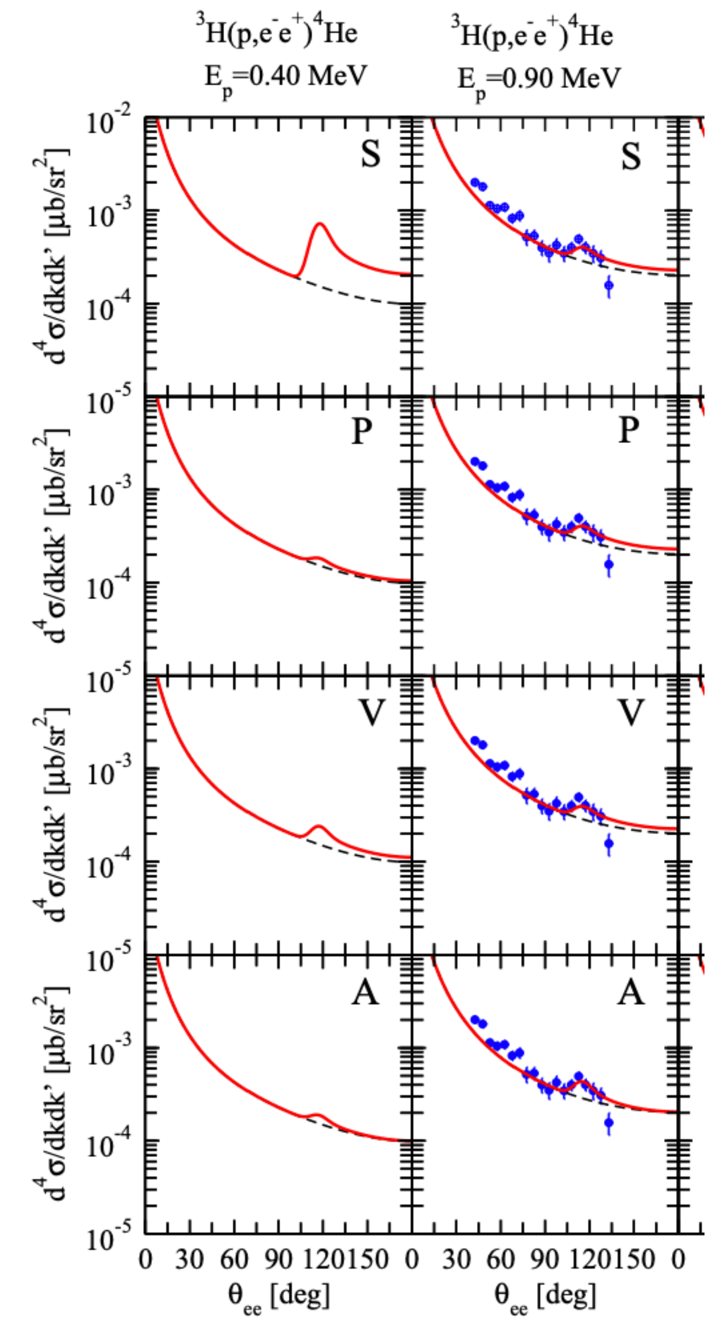


PRC (2021) [arXiv:2104.1075 [nucl-ex]]
E_p = 510, 610, 900 keV to induce direct
& resonant radiative capture ^{3}H (p,γ) ^{4}He
and populate the overlapping 1st 0^+ and
2nd 0^- ^{4}He excited states

^{4}He anomaly: Standard Model explanations ?

The X17 boson and the ^{3}H(p,e$^+$e$^-$)^{4}He and ^{3}He(n,e$^+$e$^-$)^{4}He processes: a theoretical analysis [Viviani+, PRD 2104.04808 [nucl-th]]

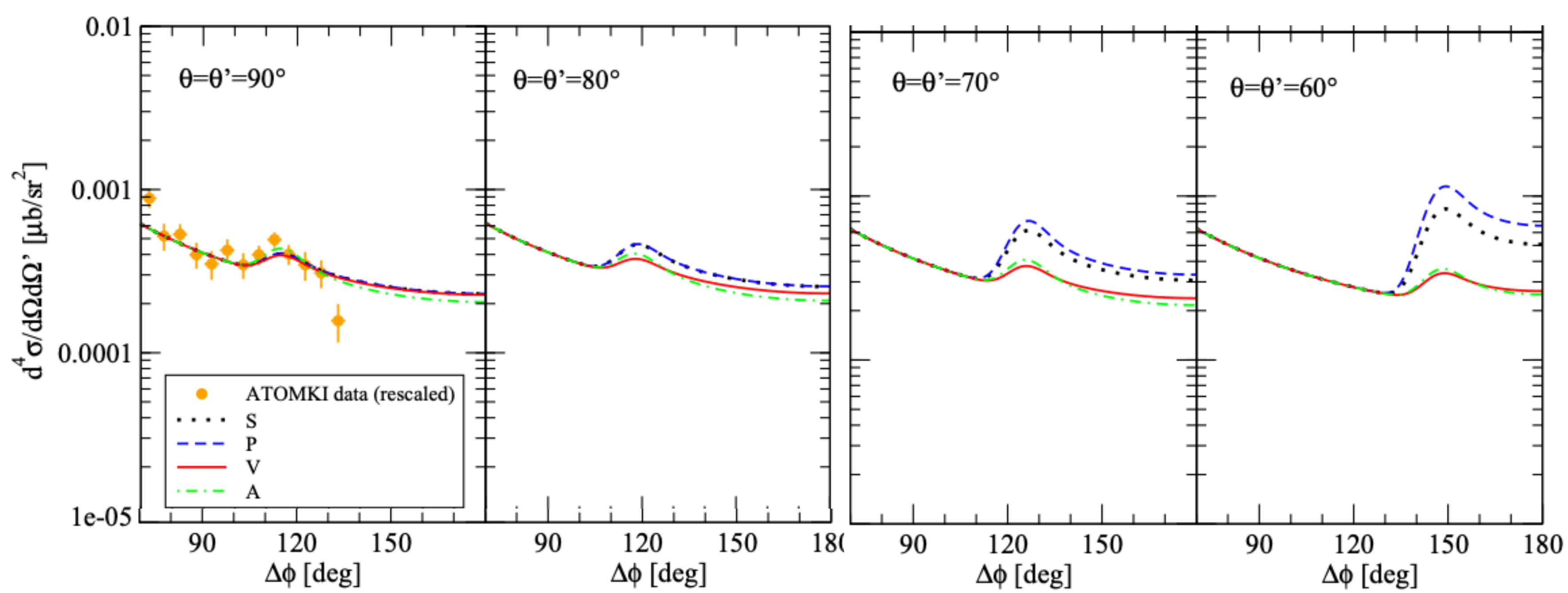
- Analysis of the process in the standard theory (ab initio nuncl. phys. calculations)
- Study of how the exchange of X_{17}(V,A,S,P) would impact such a process
- Beyond the resonance-saturation approach (justified for ^{8}Be but not for ^{4}He)
- Detailed study of the behaviour of the (V,A,S,P) induced angular correlations



Main results:

- The predicted cross sections are monotonically decreasing as function of the e$^+$e$^-$ opening angle.
- Absence of any resonance-like structure
- Measurements at $\theta_{\nu p} \neq 90^o$ can discriminate X=V,A,S,P

M_X=17MeV
$\theta_{\nu p}$ = 90^o



^{8}Be vs. ^{4}He: kinematic consistency [Feng+, PRD 2006.01151 [hep-ph]]

For M_X=17MeV and uniform distrib. in cos φ($e^\pm$ c.o.m. axis vs. v_X) the Lab. opening angle distrib. will be strongly peaked near their minimal values (when $e^\pm$ axis ⊥ v_X)

The theor. values are: $\theta^{min}_\pm$ = 112° [^{4}He(20.49)]; 139°[^{8}Be(18.15)]; 161° [^{12}C(17.23)].

[Exact for spin 0, approximate for spin 1]

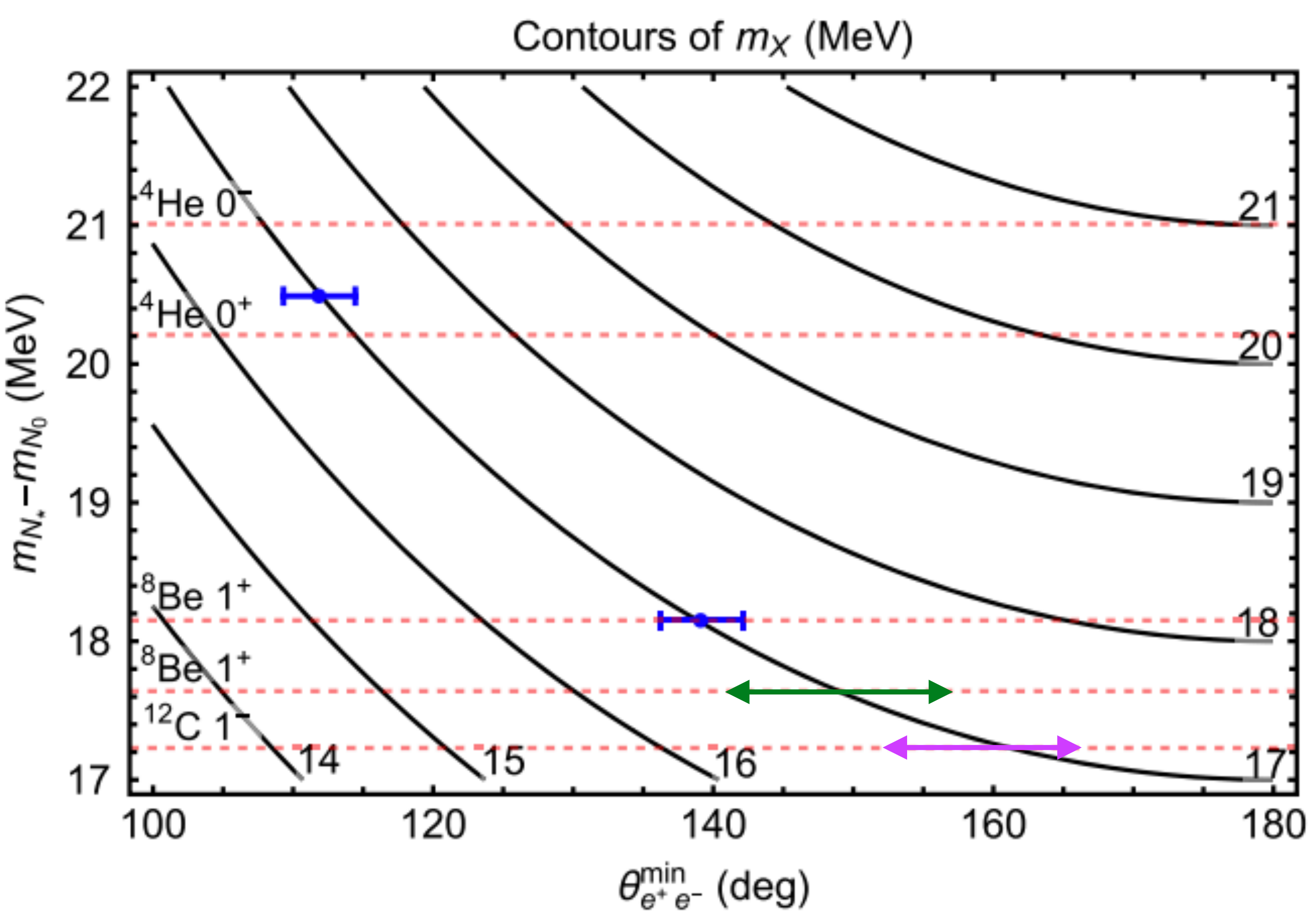
^{4}He: M_X = 16.94 ± 0.24, θ ~ 115°

^{8}Be: M_X = 17.01 ± 0.16, θ ~ 140° [θ(17.64 MeV)~150°]

^{12}C: M_X broadly consistent, θ ~ 160°

N_*	$J_*^{P_*}$	T_*	Γ_{N_*} [keV]	$B(N_* \to N_0\gamma)$
^{8}Be(18.15)	1^+	0	138	1.4×10^{-5}
^{8}Be(17.64)	1^+	1	10.7	1.4×10^{-3}
^{12}C(17.23)	1^-	1	1150	3.8×10^{-5}
^{4}He(21.01)	0^-	0	840	0
^{4}He(20.21)	0^+	0	500	6.6×10^{-10} (E0)

(^{8}Be, ^{12}C, ^{4}He)$_{gs}$ 0^+ 0

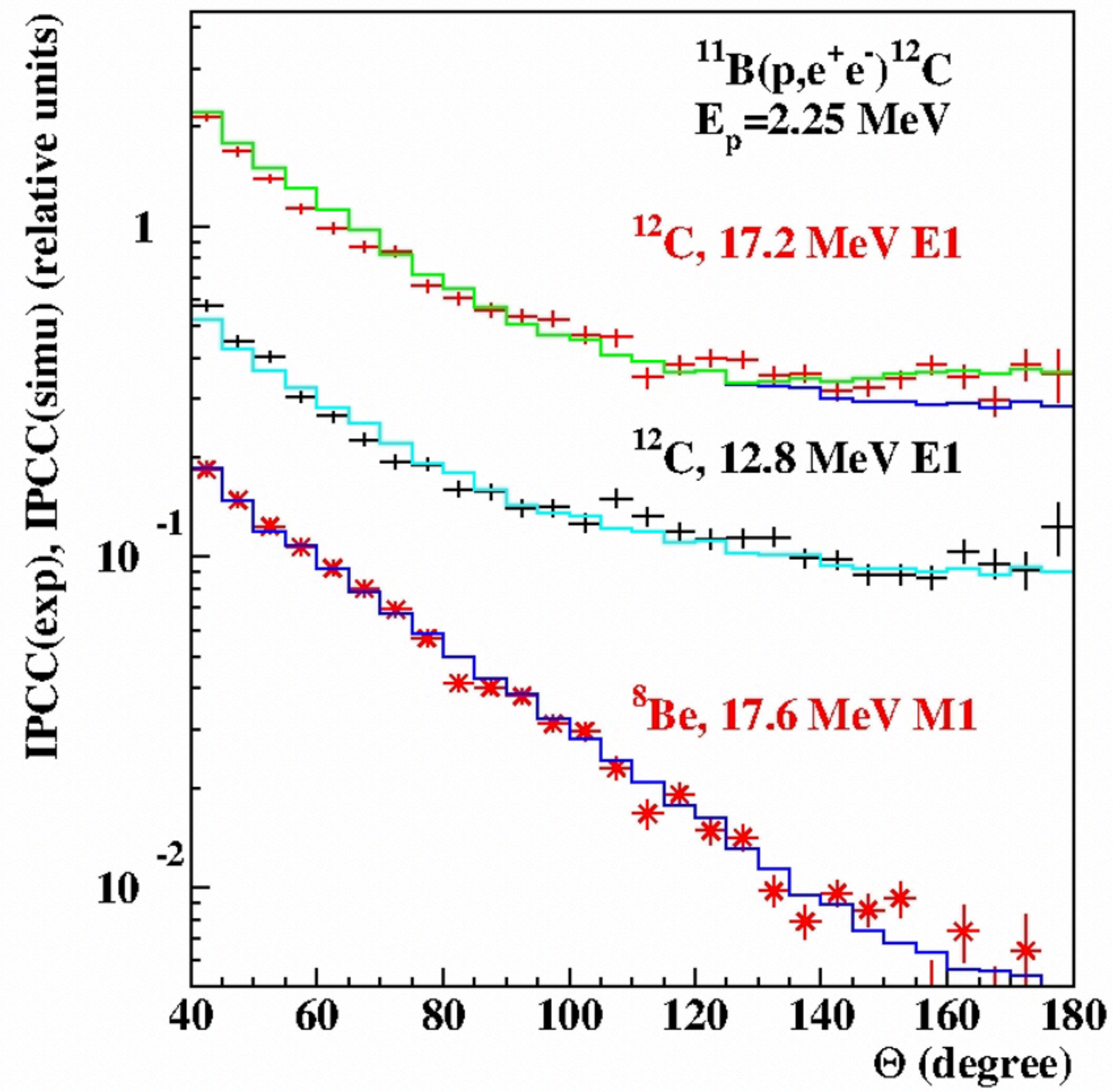


Preliminary results for ^{12}C

Nuclear reaction: $p + {}^{11}B \longrightarrow {}^{12}C^{*}(17.23\ \mathrm{MeV}) \longrightarrow {}^{12}C + e^{+}e^{-}$

$E_p = 2.25$ MeV $\qquad J^P({}^{12}C^{*}) = 1^{-}$

A. Krasznahorkay
Shedding light on X17 Workshop
Rome, September 6-8, 2021



^{8}Be vs. ^{4}He: dynamical consistency [Feng+, PRD 2006.01151 [hep-ph]]

Allowed nuclear transitions and X17 mediators

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	✘	✔	✔	✔
^{12}C(17.23)	1^-	✔	✘	✔	✔
^{4}He(21.01)	0^-	✘	✔	✘	✔
^{4}He(20.21)	0^+	✔	✘	✔	✘

Selection rules:
$J^* = L \oplus J_X$
$P^* = (-1)^L P_X$

Measured X17 production rates

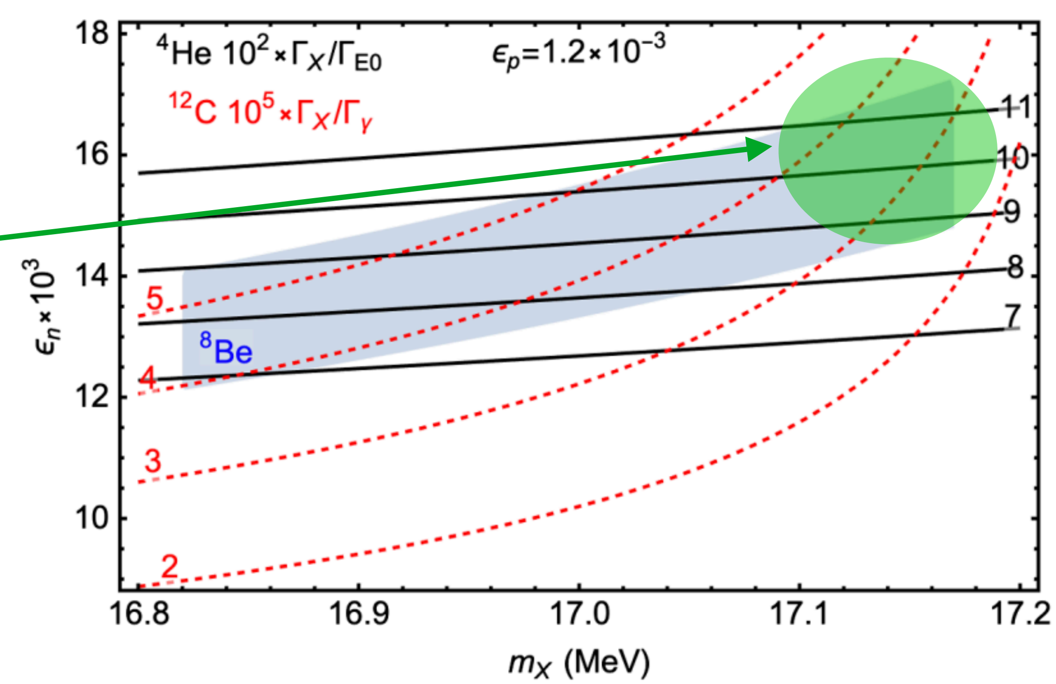
$$\frac{\Gamma_X^{\rm Be}}{\Gamma_\gamma^{\rm Be}} \equiv \frac{\Gamma(^8{\rm Be}^* \to {}^8{\rm Be} + X)}{\Gamma(^8{\rm Be}^* \to {}^8{\rm Be} + \gamma)} \simeq 6 \times 10^{-6} \qquad {}^8{\rm Be}^*(18.15)$$

$$\frac{\Gamma_X^{\rm He}}{\Gamma_\pm^{\rm He}} \equiv \frac{\Gamma(^4{\rm He}' \to {}^4{\rm He} + X)}{\Gamma(^4{\rm He}^* \to {}^4{\rm He}\, e^+e^-)} \simeq 4 \times 10^{-5} \qquad {}^4{\rm He}'(20.49),\ {}^4{\rm He}^*(20.21)$$

Are these branchings consistent with a single set of X17 couplings ?

Protophobic Vector: ^{8}Be - ^{4}He dynamical consistency region

Axial vector: might also explain ^{8}Be - ^{4}He (with more difficulties)



Summarising:

- Both anomalies $\gtrsim 7\sigma$, not a statistical fluctuation
- Bumps, not general excesses. Not a last bin effect
- By Introducing a new particle, remarkable improvement of the fits
- SM explanation seems disfavoured ^{8}Be [Zhang+, (2017)]; ^{4}He [Viviani+, (2021)]
- ^{8}Be - ^{4}He anomalies kinematically & dynamically consistent for V and A
- Analogous effect predicted for ^{12}C, and is supported by preliminary data

Experimental perspective

MEGII @ PSI: (search for CLFV $\mu^+ \to e^+ \gamma$)

^{8}Be: CW accelerator E_p = 1.1 MeV, MEGII spectrometer, Li_2O target

Measurement during main HIPA 2022 shutdown (?) (5σ, 50h DAQ)

LUNA-MV @ LNGS: high intensity proton beam and very low background

^{4}He via $^3H(p,e^+e^-)^4He$ reaction. (RICH detector under study)

Measurements: 2023-5 (LoI in preparation)

n_ToF @ CERN: pulsed neutron beam in a wide energy range.

^{4}He via $^3He(n,e^+e^-)^4He$. Measurements: 2022-24 (CERN LoI approved)

AN2000 @ LNL (INFN): Focus on ^{8}Be and, possibly, ^{12}C cases (timescale ?)

Validation/confutation from a particle physics experiment

PHYSICAL REVIEW D **97,** 095004 (2018)

Resonant production of dark photons in positron beam dump experiments

Enrico Nardi,[1,*] Cristian D. R. Carvajal,[2] Anish Ghoshal,[1,3] Davide Meloni,[3,4] and Mauro Raggi[5]

Since $X_{17} \to e^+ e^-$,
then $e^+ e^- \to X_{17}$
via positron-electron **resonant** annihilation (early 2017)

BTF@LNF: $E_+ \sim$ 250 - 500 MeV
$\sqrt{s} \sim$ 15.8 - 22.4 MeV

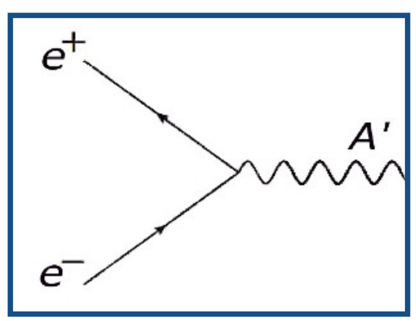
M_X=17 MeV E_+=289 MeV

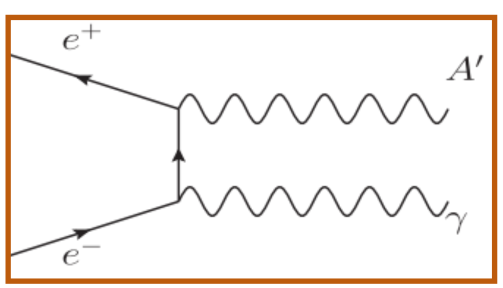
$$\sigma_{\rm res} = \sigma_{\rm peak}\frac{\Gamma_X}{2m_X}\delta\left(1-\frac{\sqrt{s}}{M_X}\right)$$

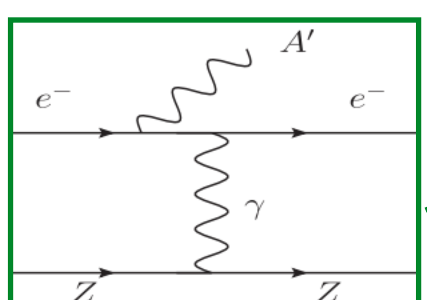
$$\Gamma_X = 0.05\left(\frac{\epsilon}{10^{-3}}\right)^2 \text{eV}$$

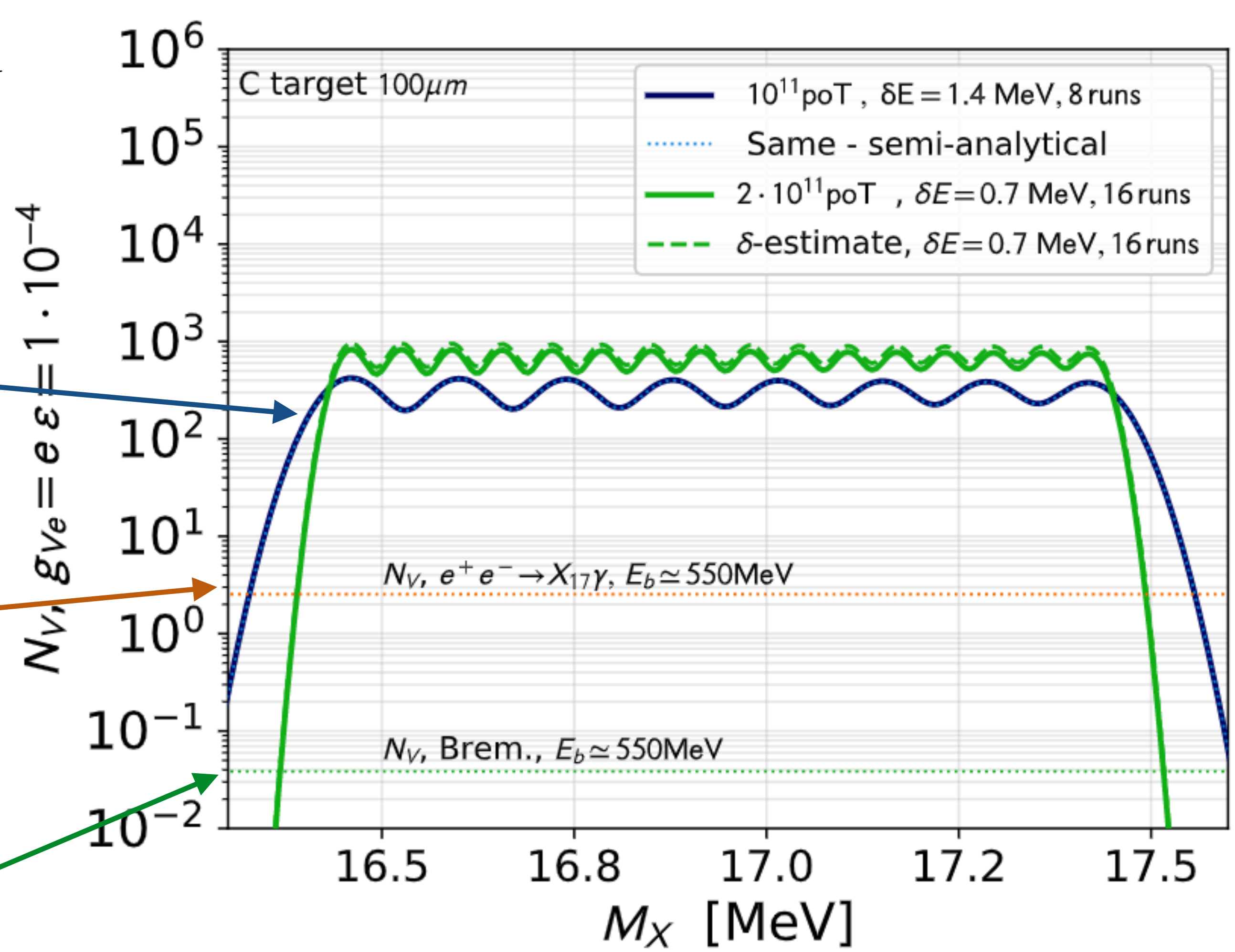
$$\sigma_{\rm peak} \sim 50\text{b}$$

"Huge" cross section !



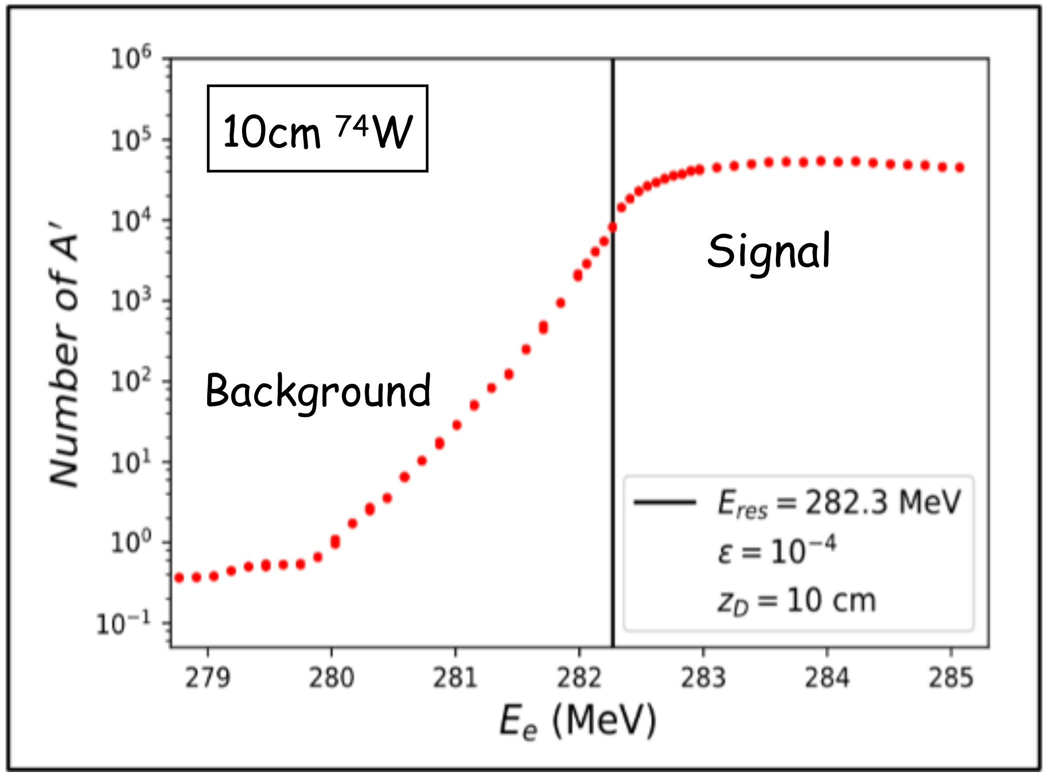






Several other advantages, as e.g. measurement of background

- E_{beam} below/above resonance
- Shoot with an e^- beam



- Although not optimal for X —> e^+e^- detection/reconstruction (conceived for $e^+ e^-$ —> γ $X_{invis.}$) the existing PADME detector can be used (with minor upgrades)
- Beam tests at 280-290 MeV will be performed soon (weeks)
- Physics run most probably only after the summer 😠

Conclusions

- The anomalies observed in nuclear transitions appear to be consistent with a particle physics interpretation (X_{17})
- Present data are from a single experiment. Independent verifications are needed.
- Intense effort for new experiments is ongoing. First new data expected in the next 1-2 years.
- Explanations via higher order nuclear physics effects, interferences, higher multipoles contributions, are (strongly) disfavoured, but…
- Being of a completely different nature, a particle physics experiment can be decisive to validate the X_{17} hypothesis.