The X17 anomaly: status and prospect

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Silafae XIV - USFQ - Nov. 14-18, 2022

A nuclear physics anomaly: in $^{8}Be^{*}$ de-excitation process

$^{8}Be^{*}$ (17.6 MeV)

^{8}Be ^{8}Be

$^{8}Be^{*}$ -> p + ^{7}Li (mostly)

$^{8}Be^{*}$ -> ^{8}Be + γ (B_{γ} = 1.4 x 10^{-5})

$^{8}Be^{*}$ -> ^{8}Be + $e^{+}e^{-}$ ($B_{e\pm}$ = 4 x 10^{-3} B_{γ})

[$^{8}Be^{*}$ -> ^{8}Be + X_{17}

↳ $e^{+}e^{-}$ (B_{X} = 6 x 10^{-6} B_{γ})]

Anomaly first observed in ^{8}Be Nuclear Transitions =>

Anomalies in nuclear transitions observed by the Atomki experiment

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The Atomki experimental apparatus

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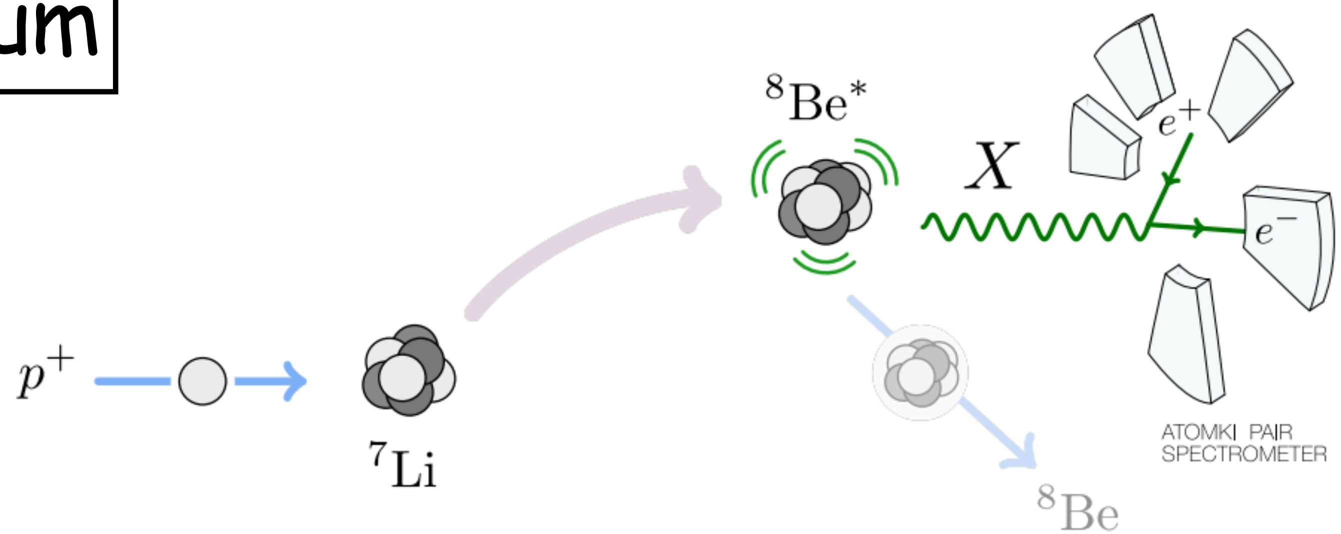
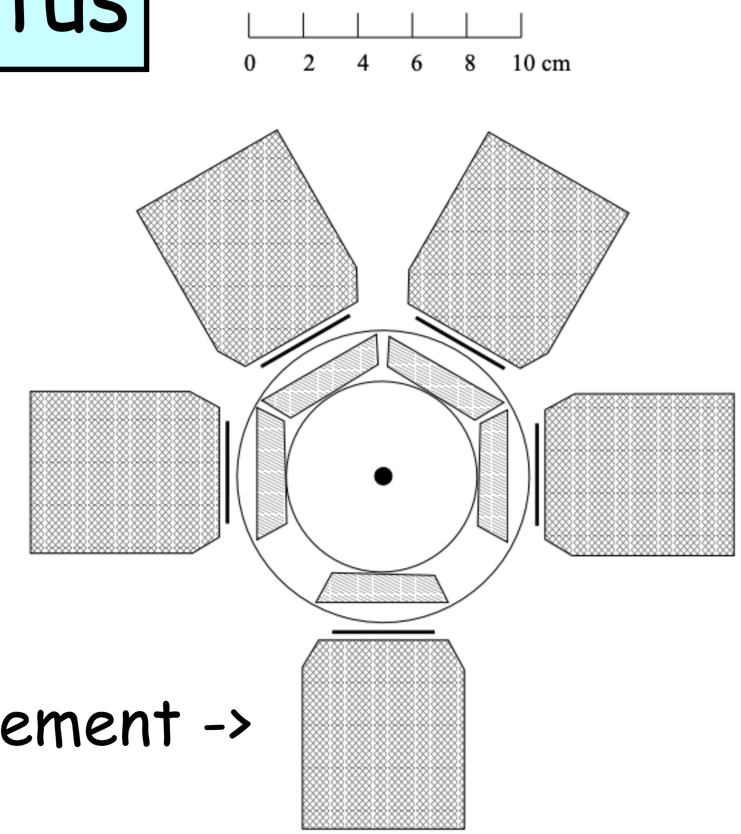
Berillium



Feng+, 1608.0359

Five telescopes arrangement ->



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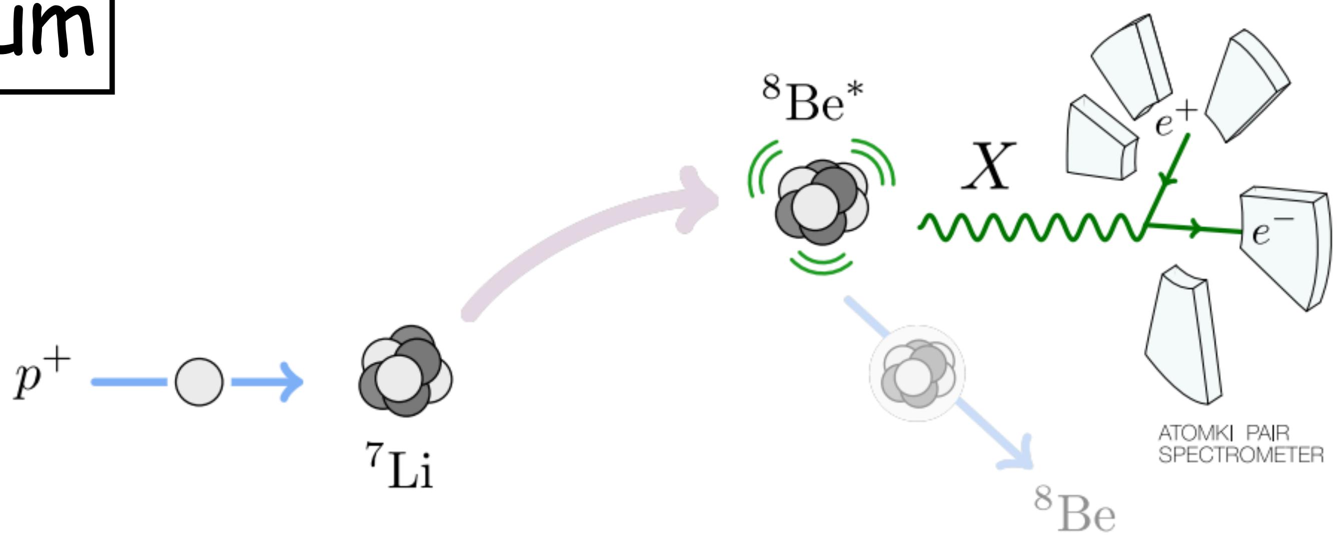

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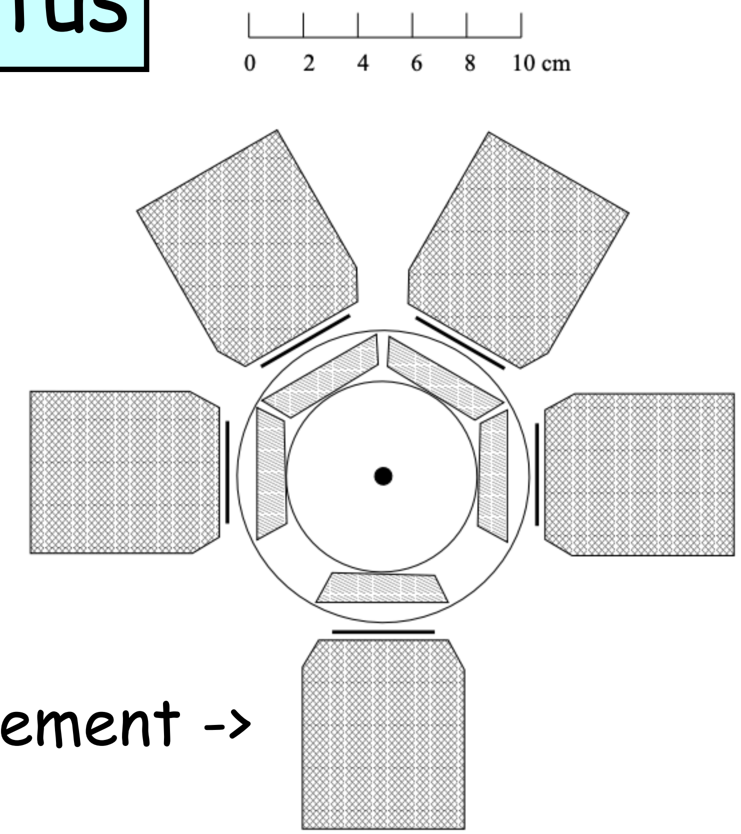

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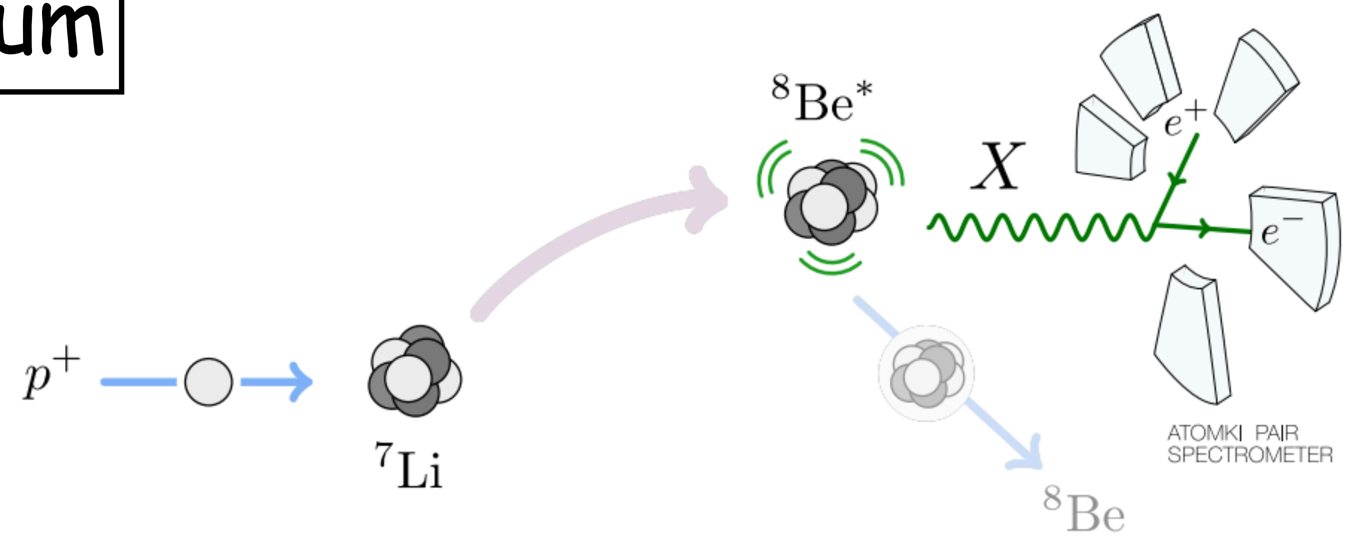

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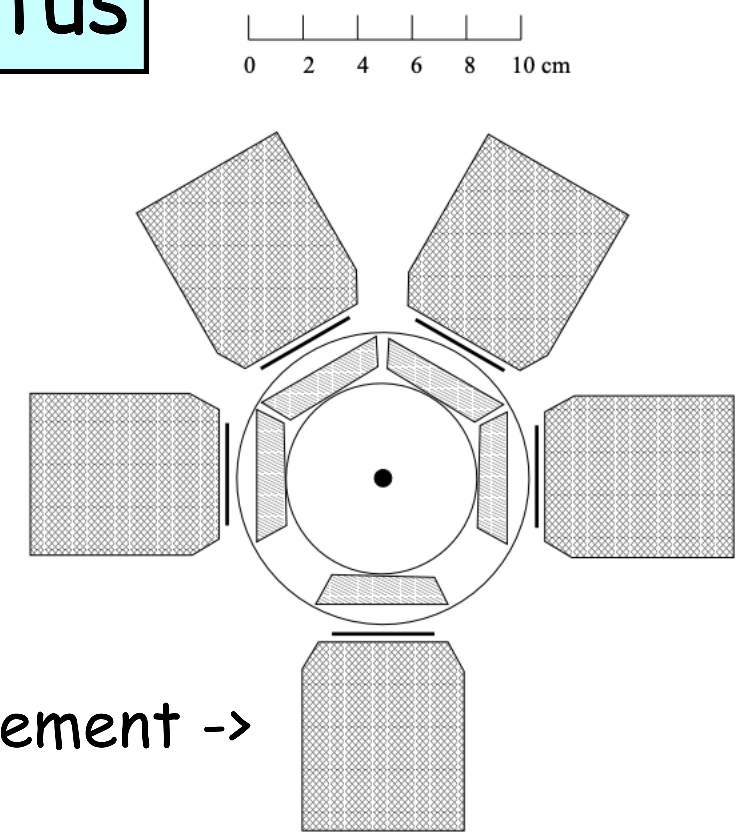

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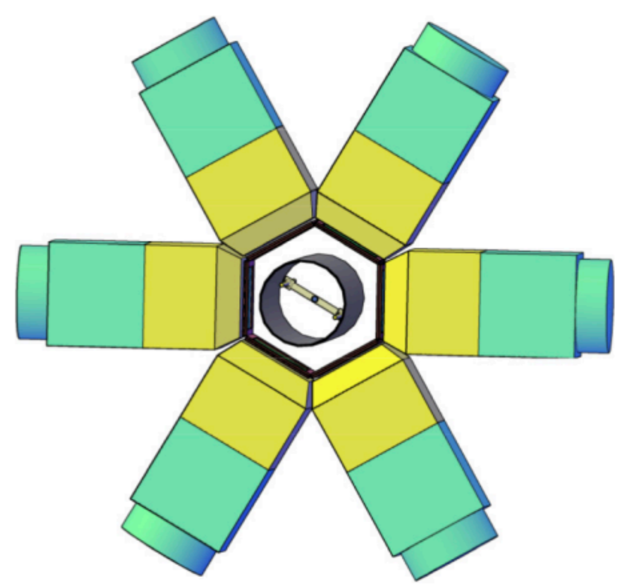
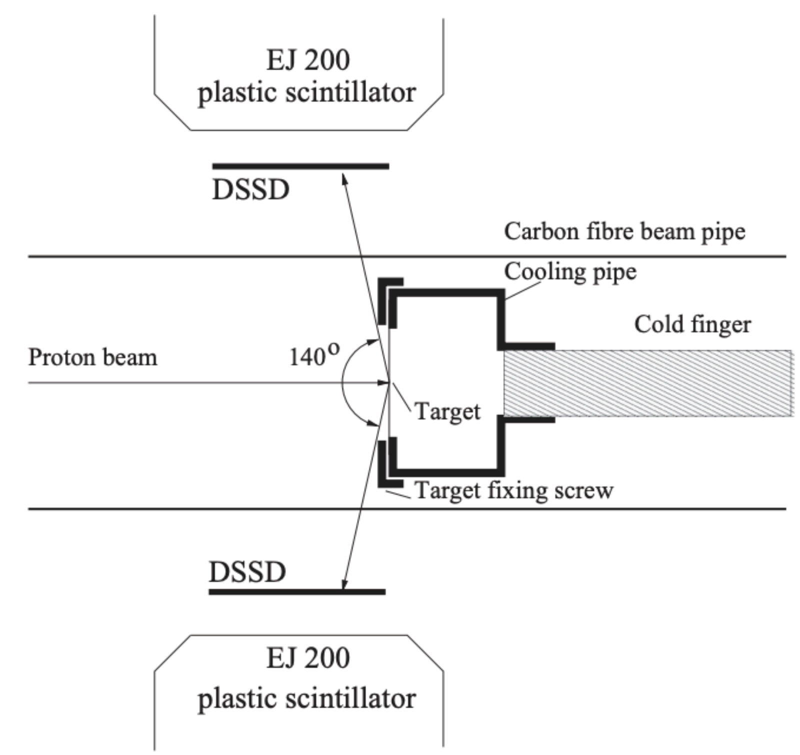
Helium

Six telescopes arrangement ->





<u>Atomki e^+e^- pairs measurements:</u>

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

Berillium nuclear transitions

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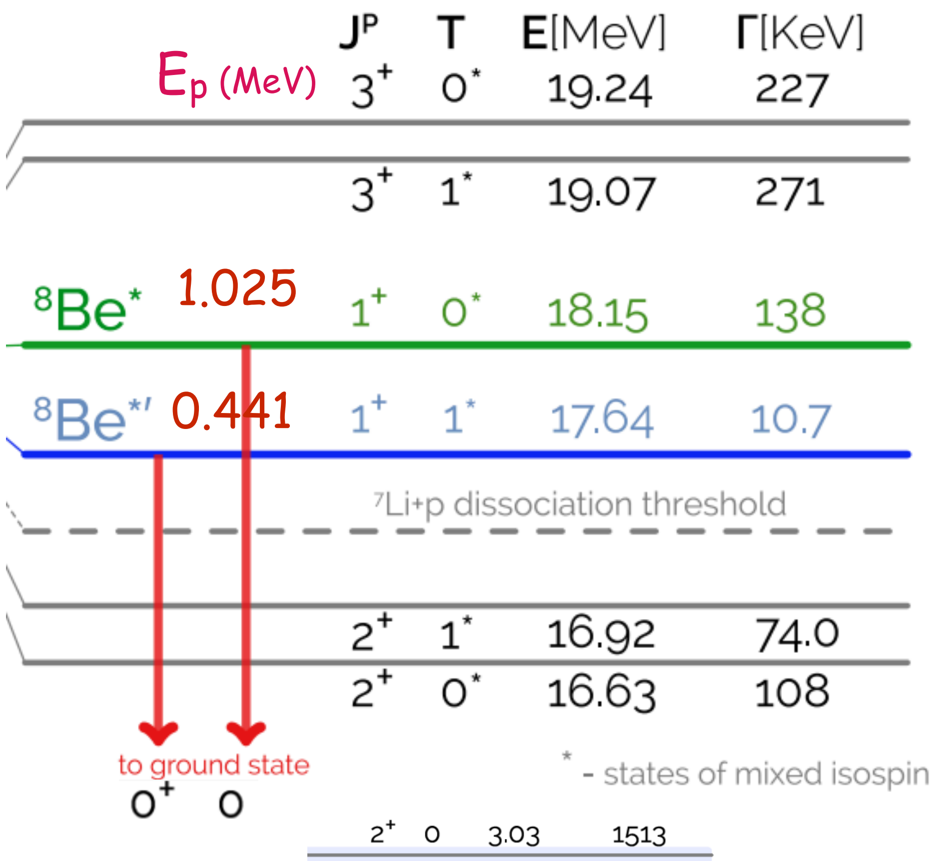
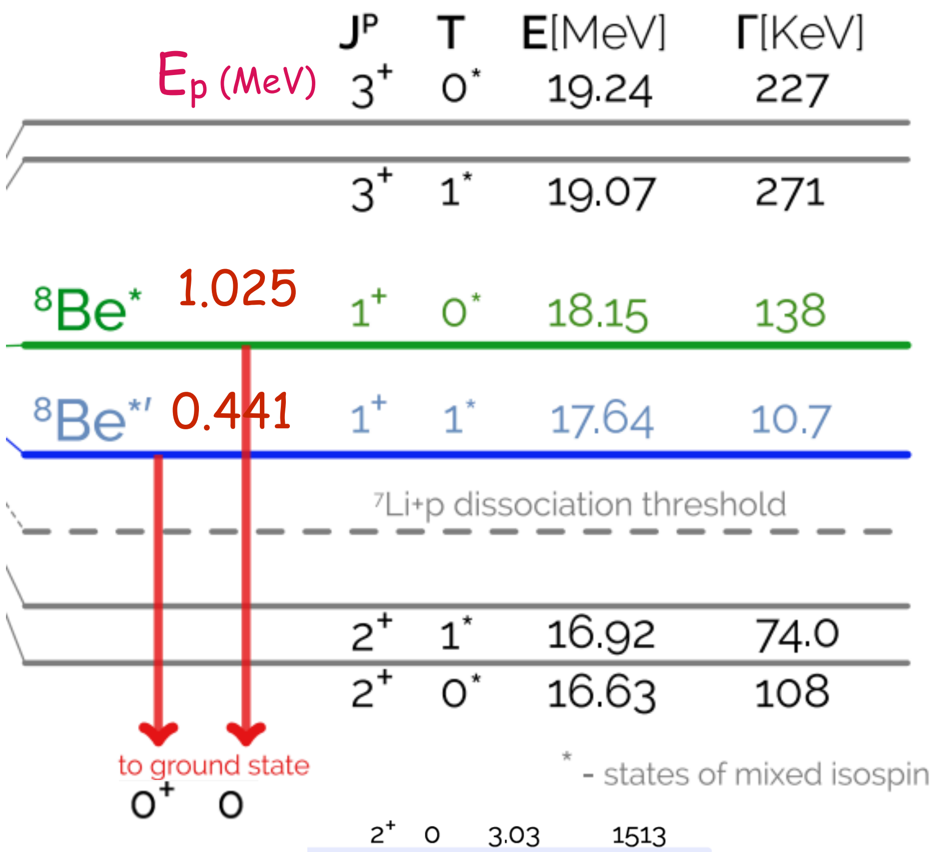
Resonant transition $p + {}^{7}Li \rightarrow {}^{8}Be^{*} \rightarrow \ldots$

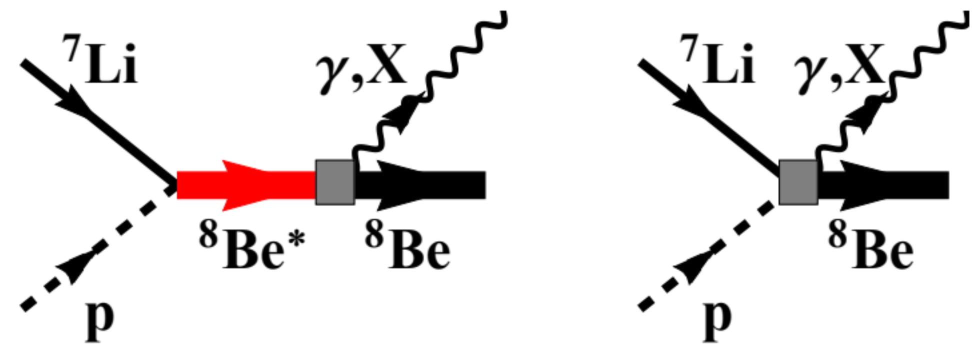


Berillium nuclear transitions

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

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





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

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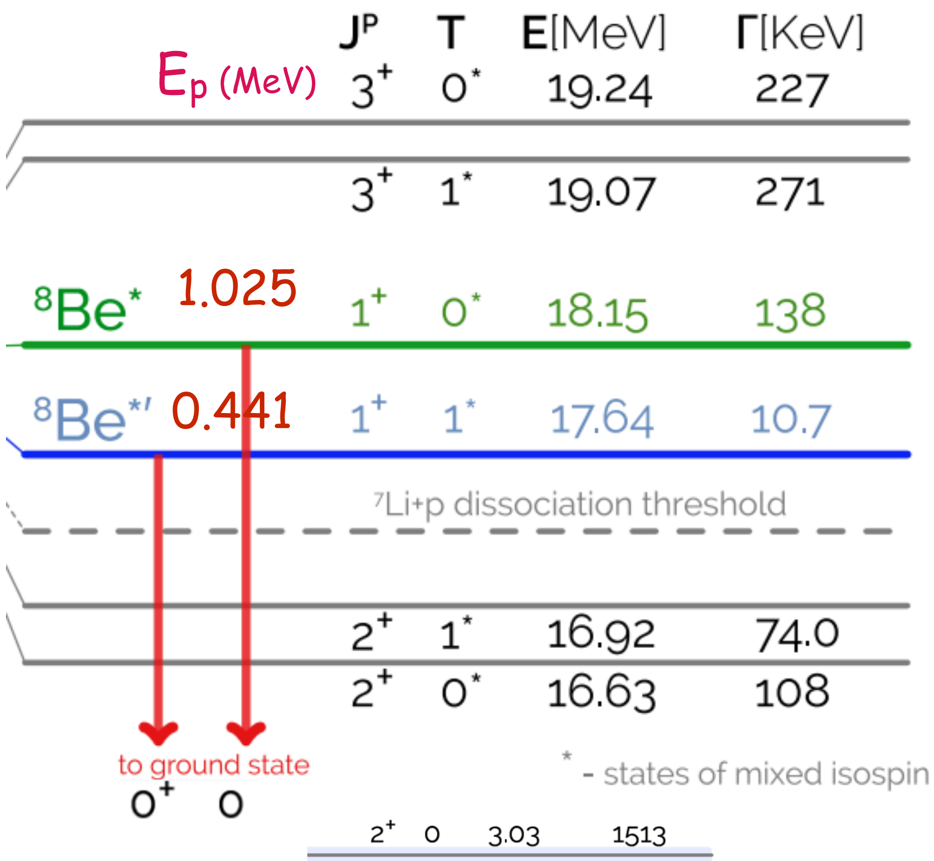

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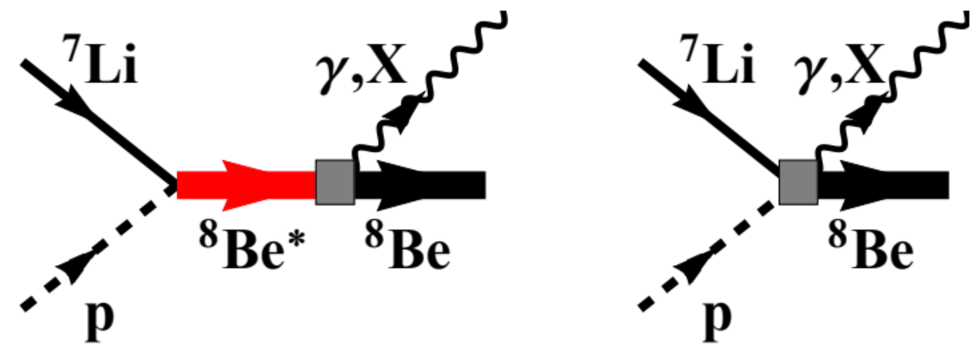

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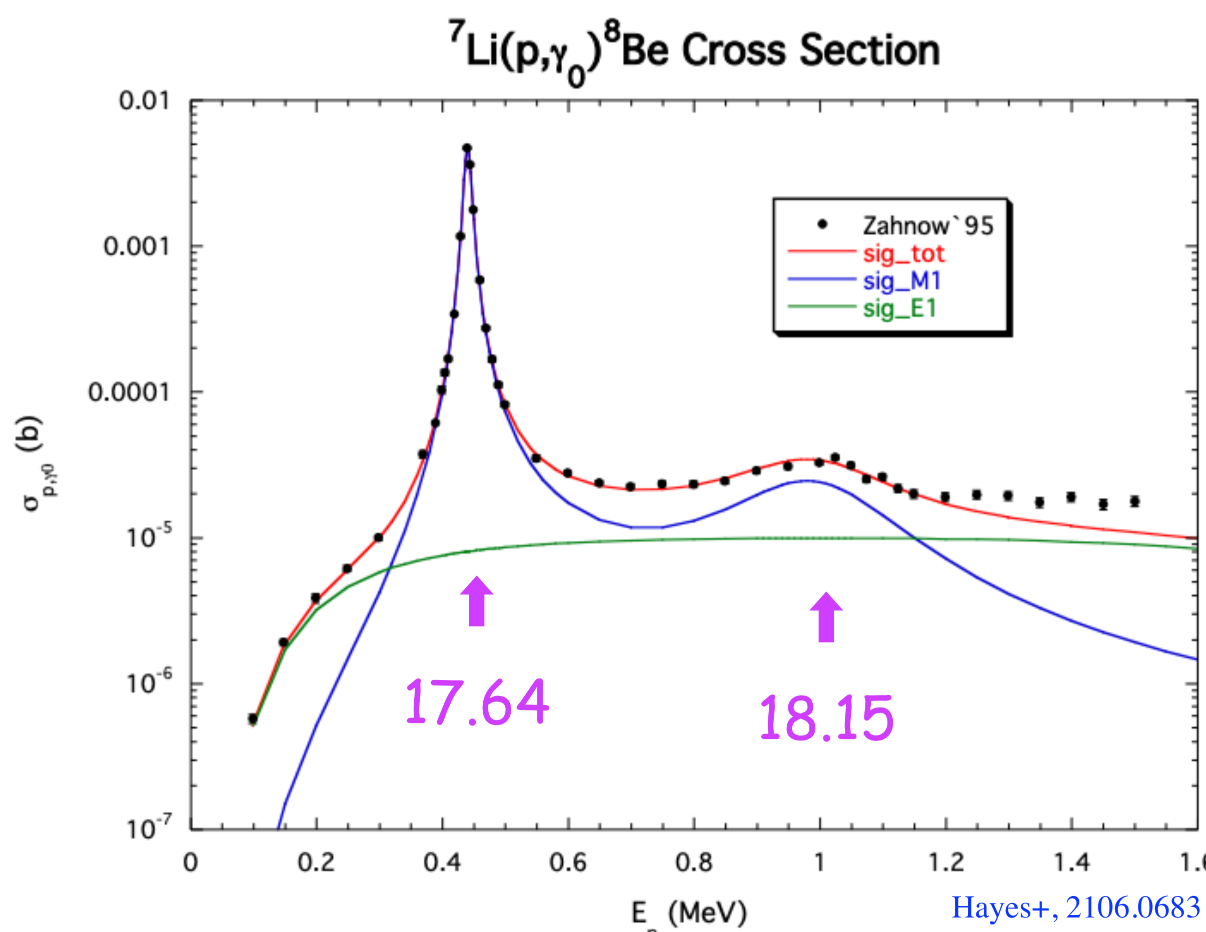

Hayes+, 2106.0683

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

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^{8}Be*(18.15MeV) IsoS

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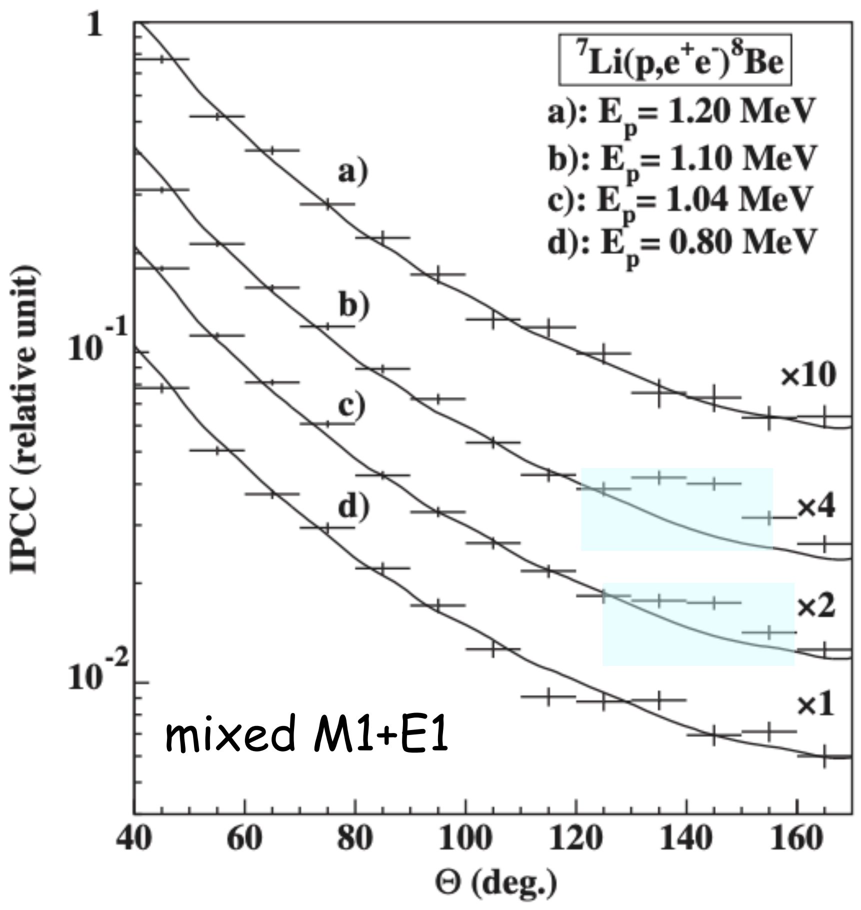
Angular correlation



$^8Be^*$(18.15MeV) IsoS

Energy gate: $E_\pm$ > 18 MeV

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

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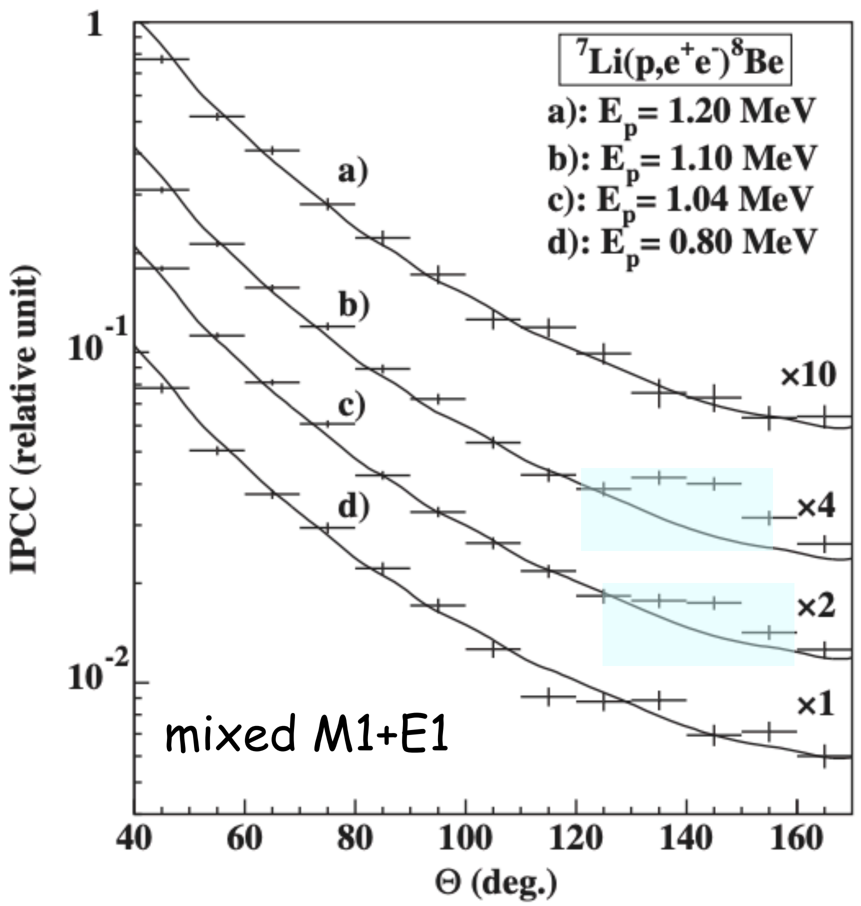

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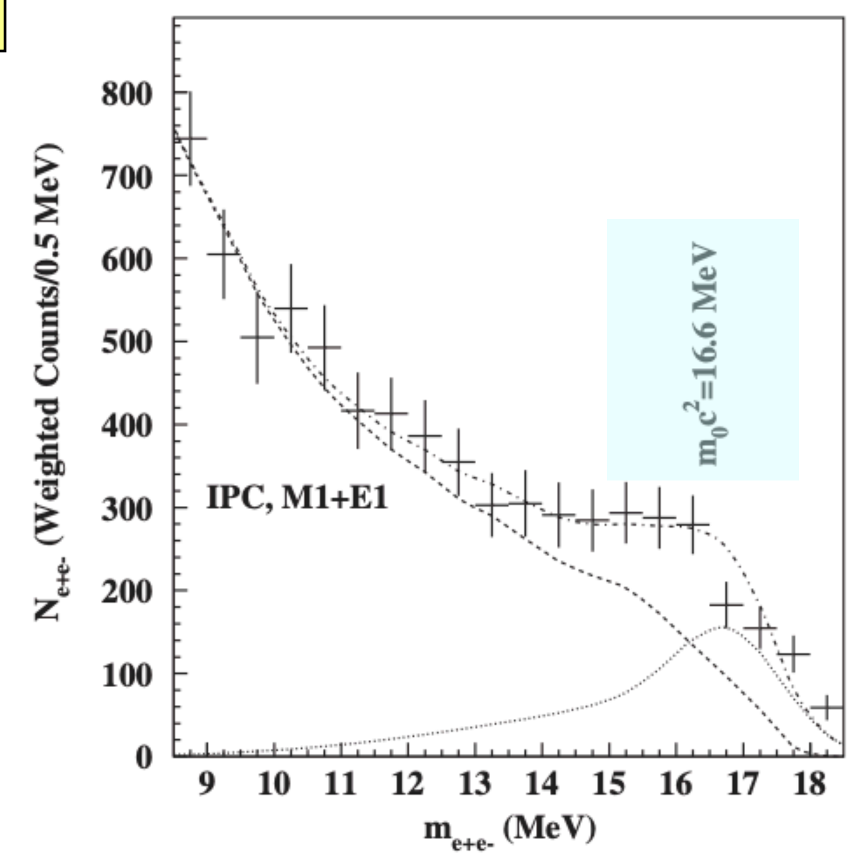
Invariant mass distribution



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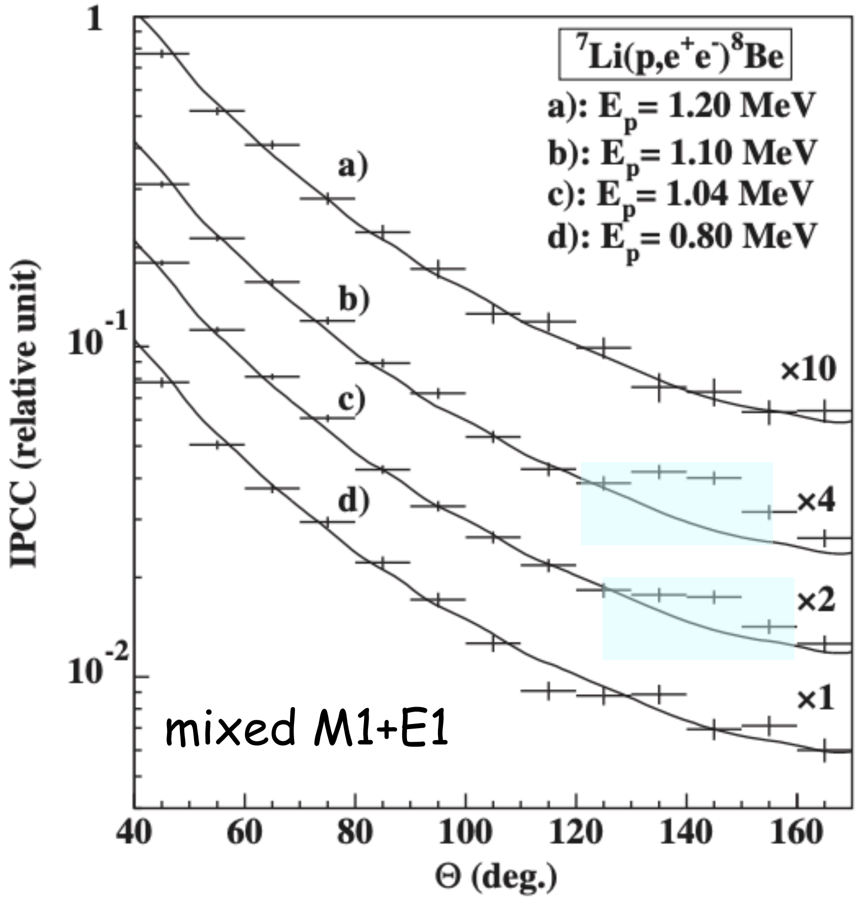

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^{8}Be*(17.64MeV) IsoV

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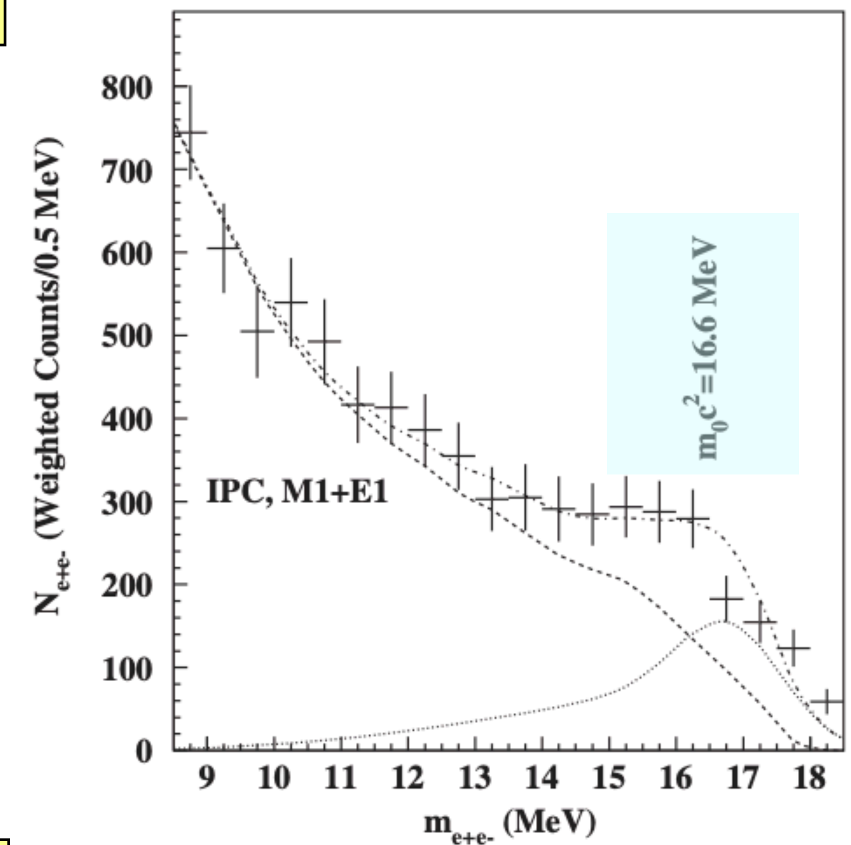

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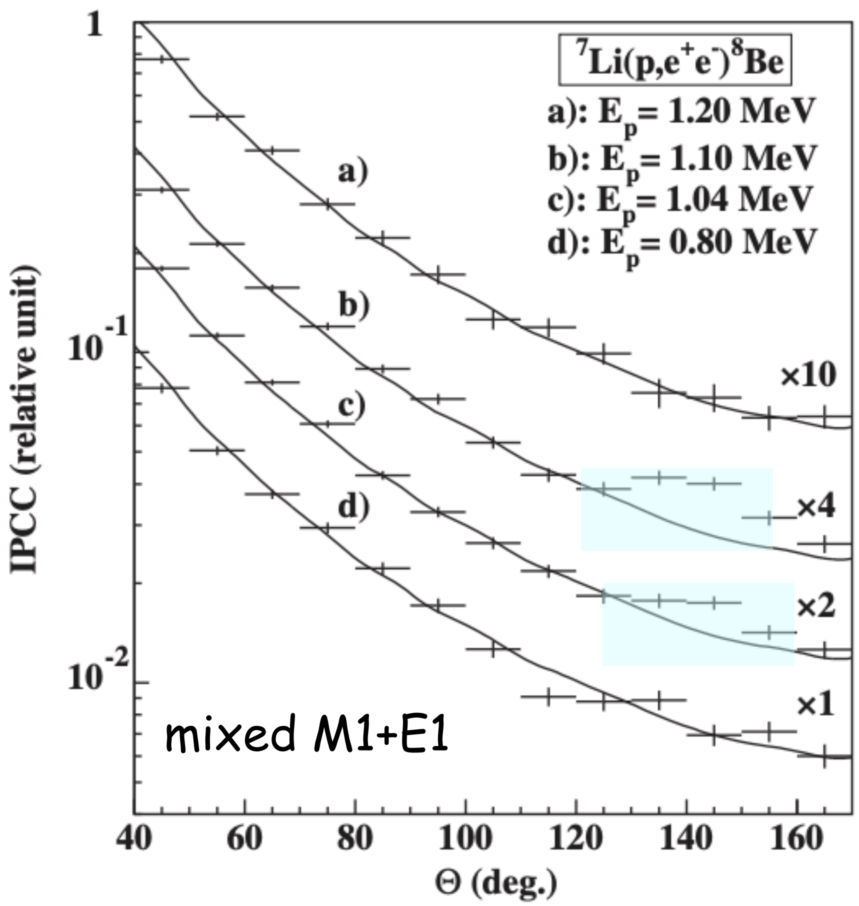

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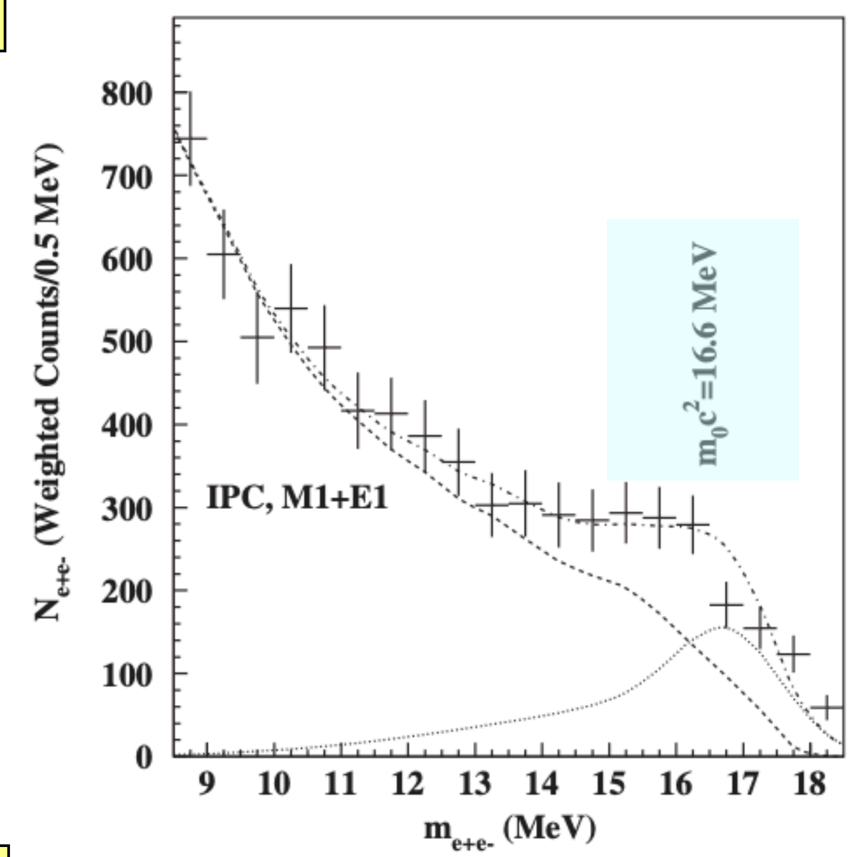

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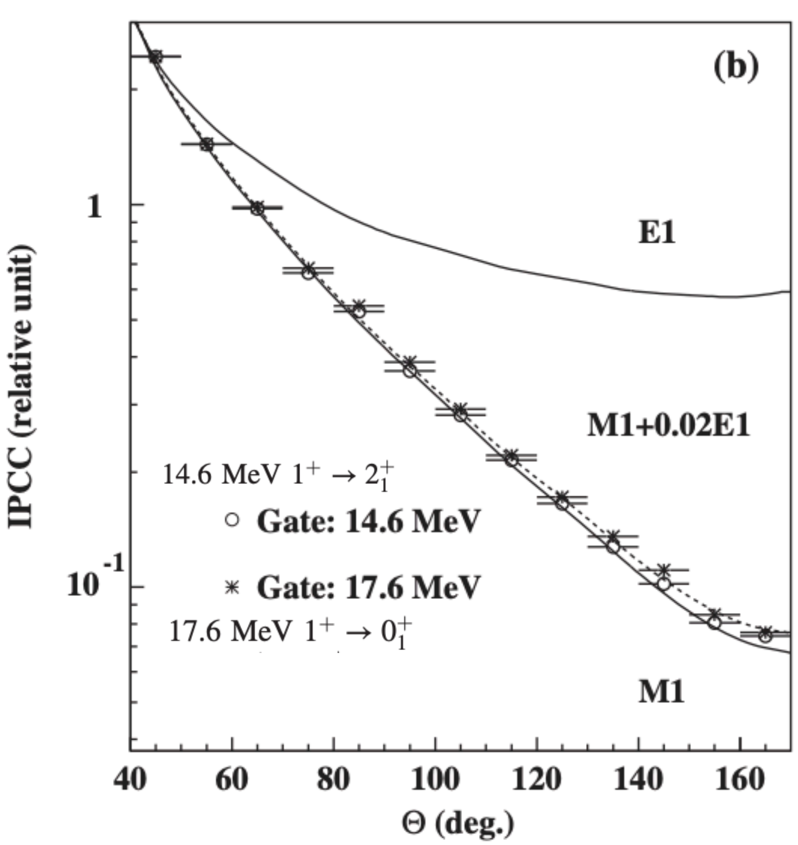

The contribution of the direct capture depends on the target thickness if the energy loss of the beam in the target is larger than the width of the resonance. The dashed simulated curve in Fig. 1(b) is obtained by fitting a small (2.0%) $E1$ contribution to the dominant $M1$ one, which describes the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

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

As noted above, the decay $^8\mathrm{Be}^{*\prime} \to {}^8\mathrm{Be}\,X$ 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 $^8\mathrm{Be}^{*\prime}$ decay than for the $^8\mathrm{Be}^*$ decay. In particular,

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If the observed anomaly in $^8\mathrm{Be}^*$ decays originates from a new particle, then the absence of new particle creation in the $^8\mathrm{Be}^{*\prime}$ 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.

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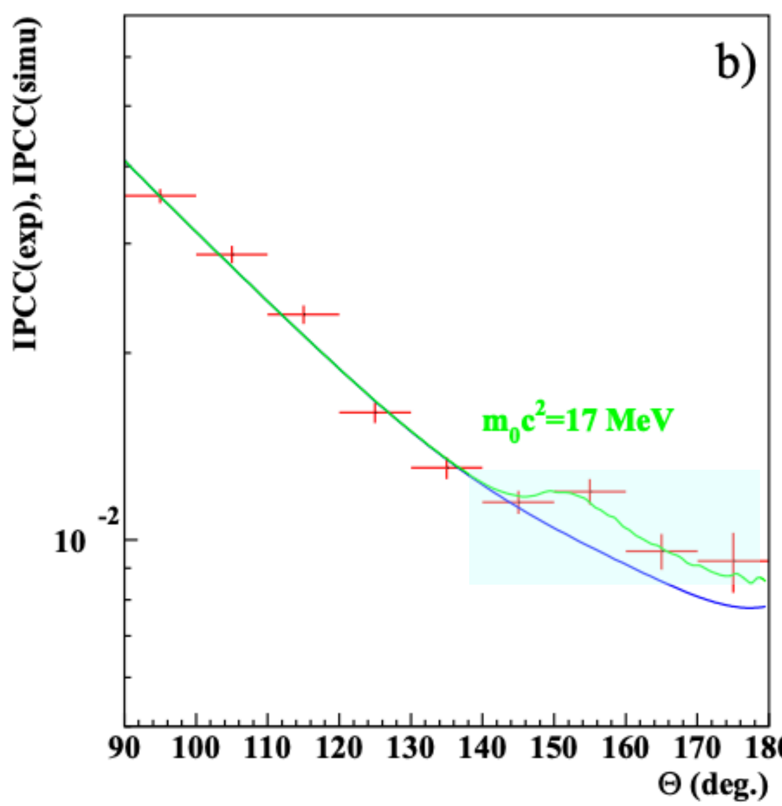
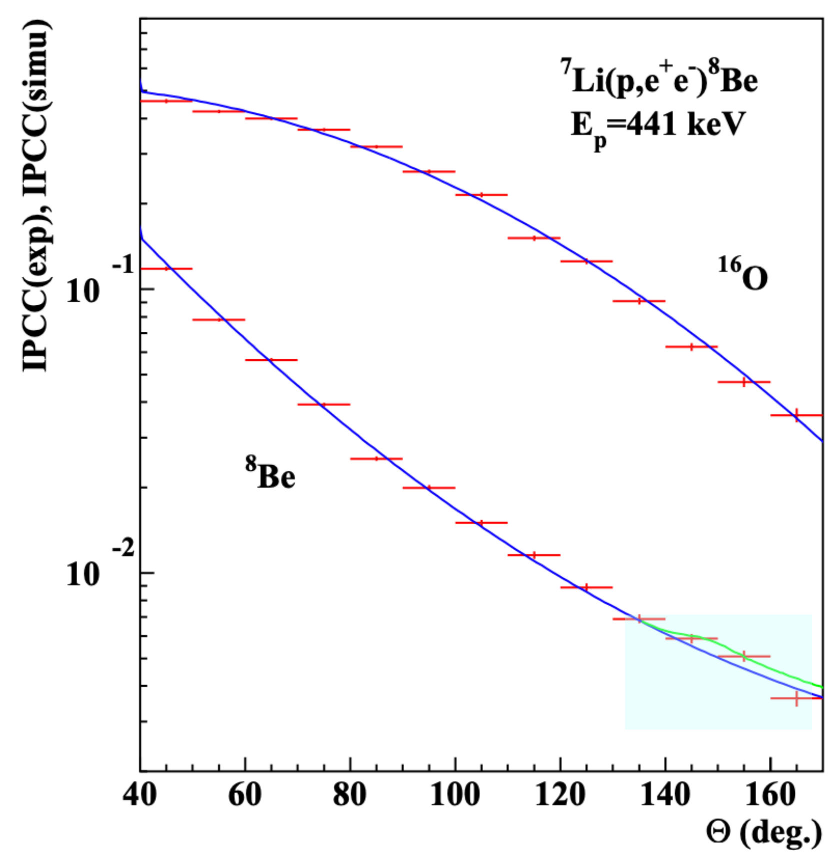
Bump location:
150° (17.64 MeV) vs.
140° (18.15 MeV)

Messina symposium (Oct 2016)



Bormio meeting (Jan 2017)



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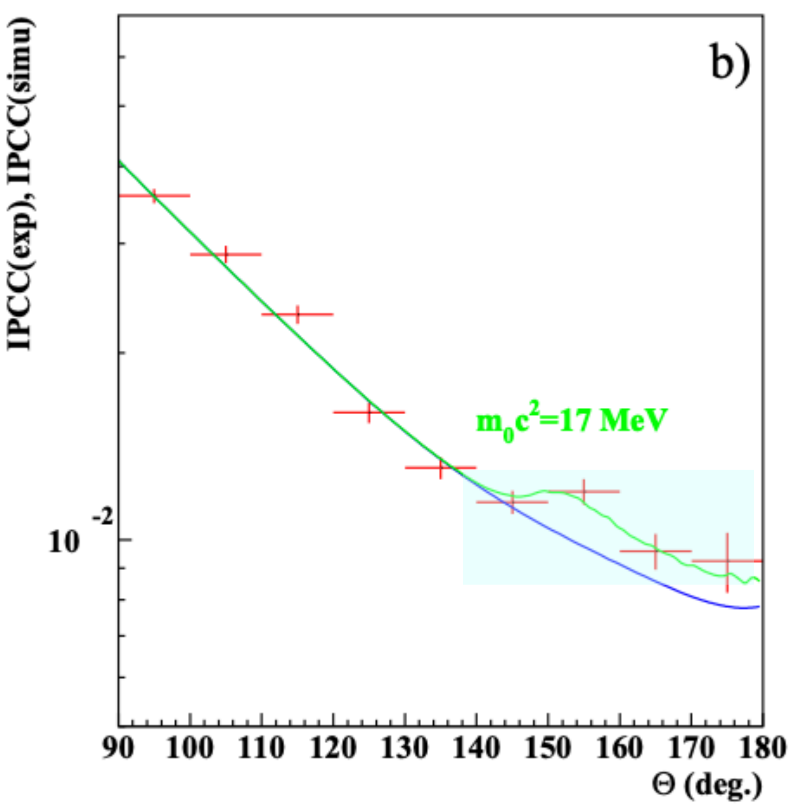

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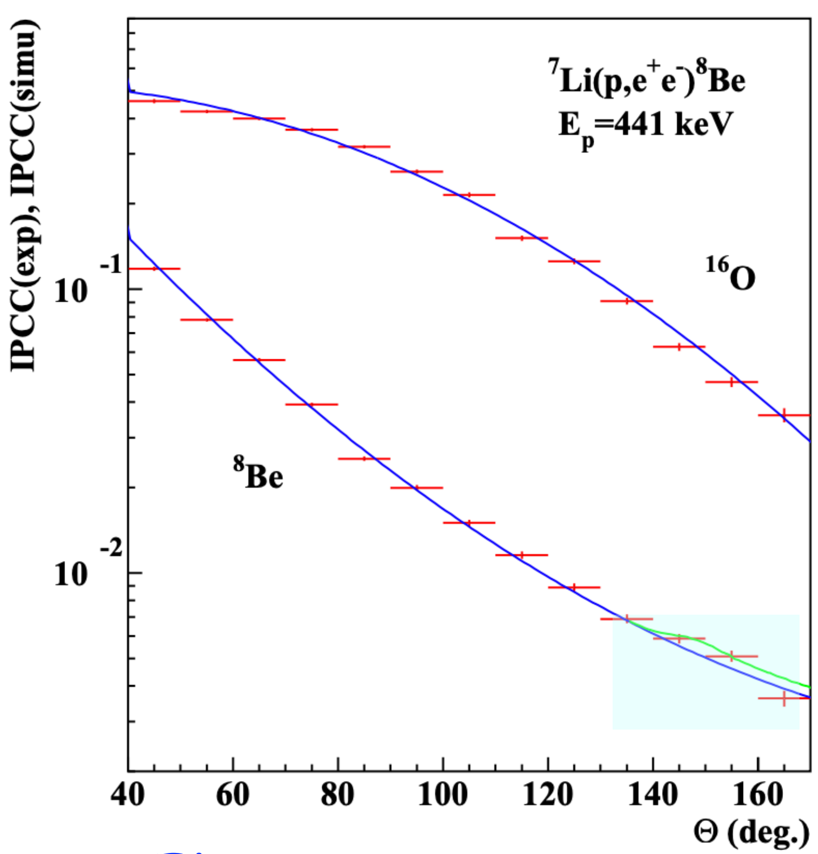

Bump location:
150° (17.64 MeV) vs.
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Axial vector boson

Calculation of relevant Nucl. Matrix Elements:

Kozaczuk+, PRD 1612.01525 [hep-ph]

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

^{8}Be anomaly: Standard Model explanations ?

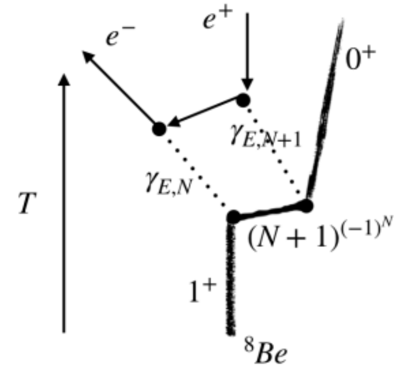
Zhang & Miller PLB, arXiv:1703.04588 [nucl-th]

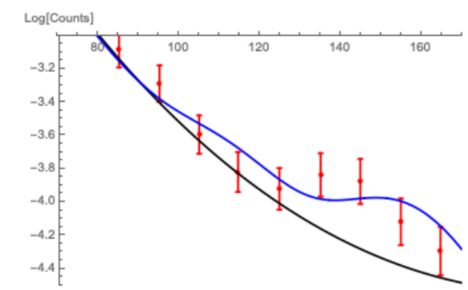
Interferences between different multipoles. Possibility of using the nuclear transition form factor to explain the anomaly

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.

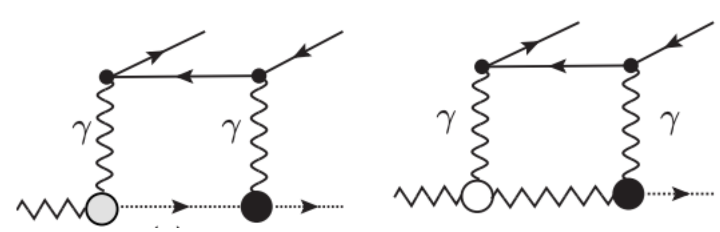
Zhang & Miller PLB, arXiv:2008.11288 [hep-ph]

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]]

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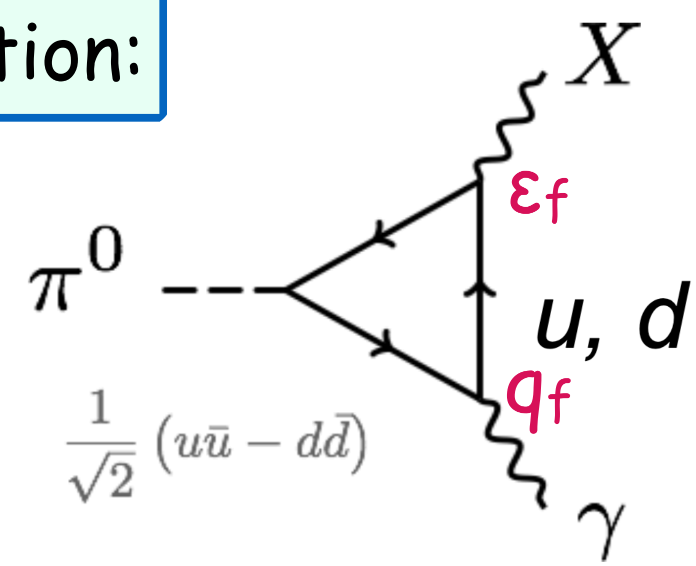

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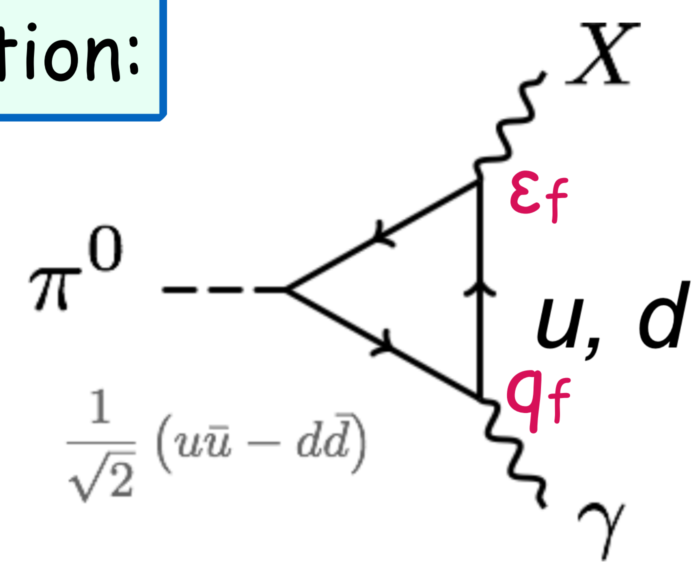
$B_X/B_\gamma \propto (\varepsilon_p+\varepsilon_n)^2 (p_X/p_\gamma)^3 \approx 6 \times 10^{-6}$ (Atomki)

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



$\varepsilon_d \approx -2\, \varepsilon_u$ (±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:

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

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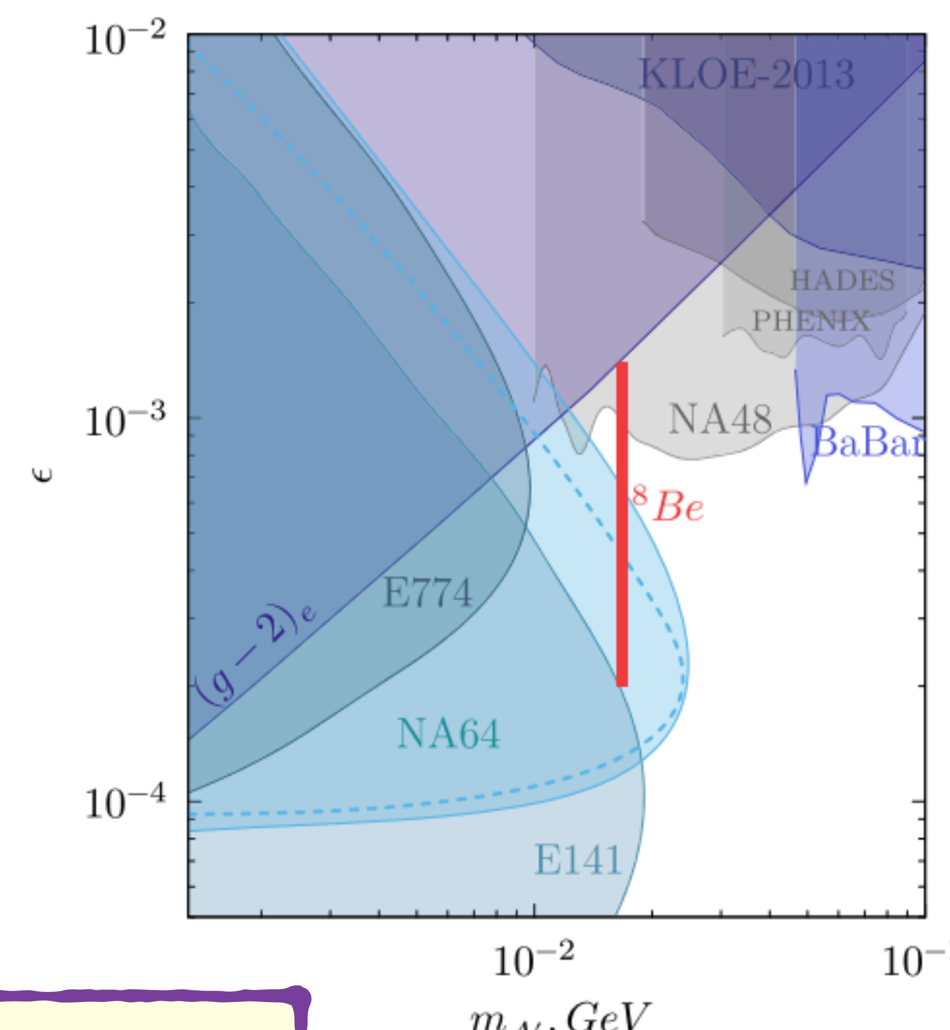
Current limits on X17

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

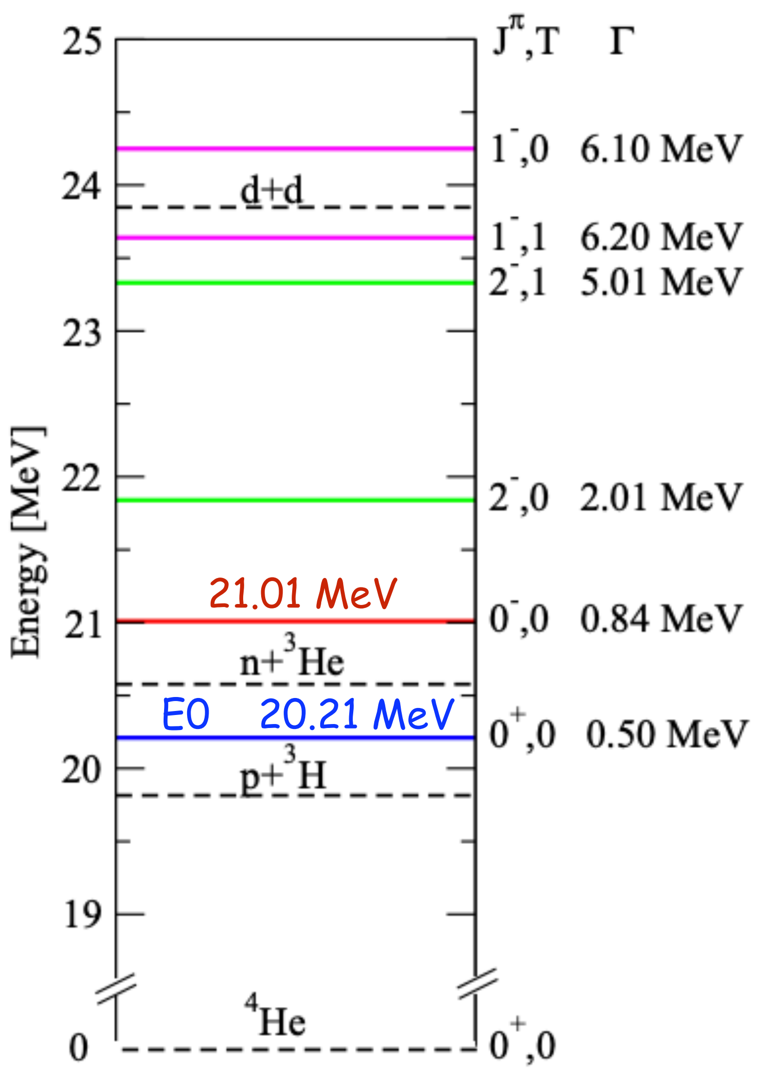
The X17 boson could be produced in the bremsstrahlung reaction $e^- Z \to e^- Z\, X$ by a high energy beam (150 GeV) of electrons incident on the active target in the NA64 experiment, and observed through its decay $X \to e^+e^-$



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

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

Helium 4 nuclear transitions



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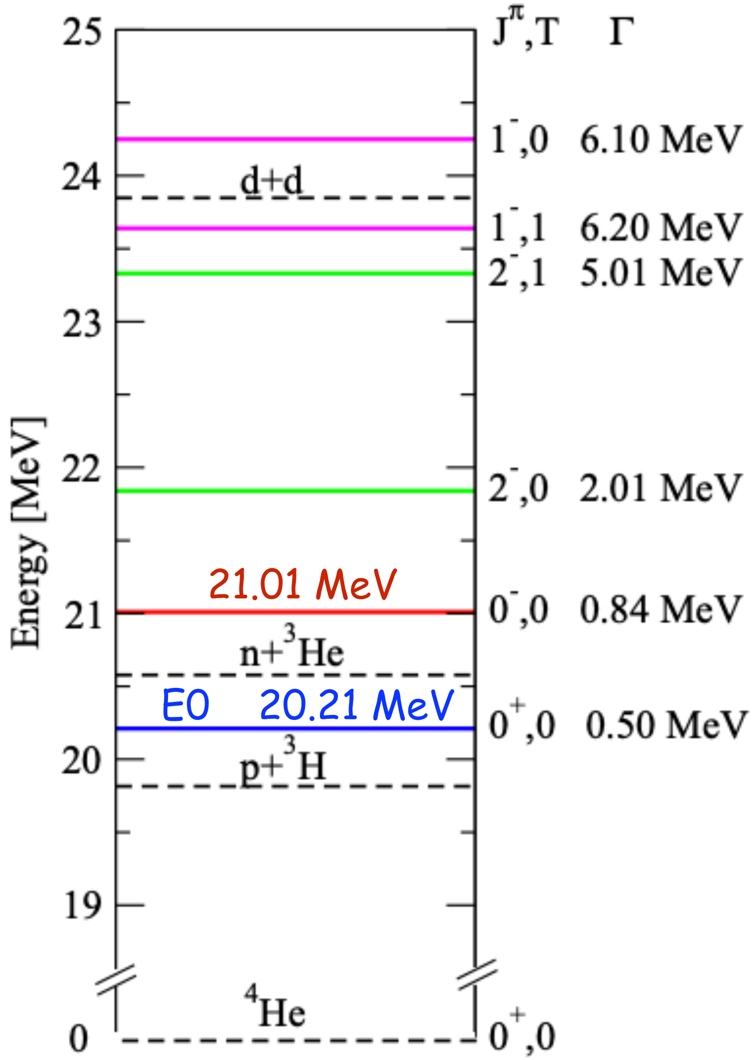
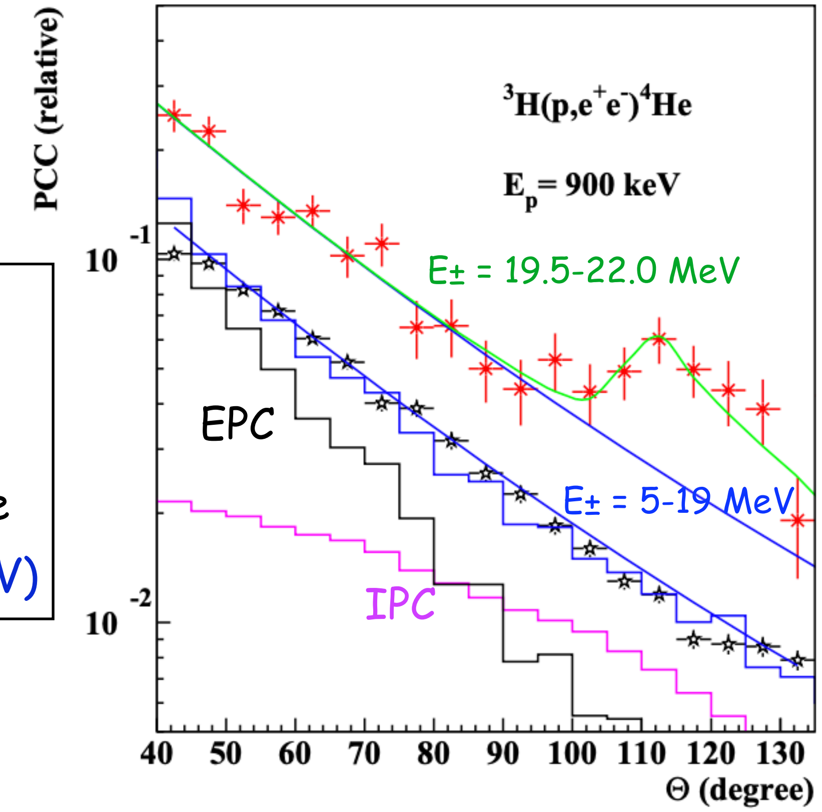
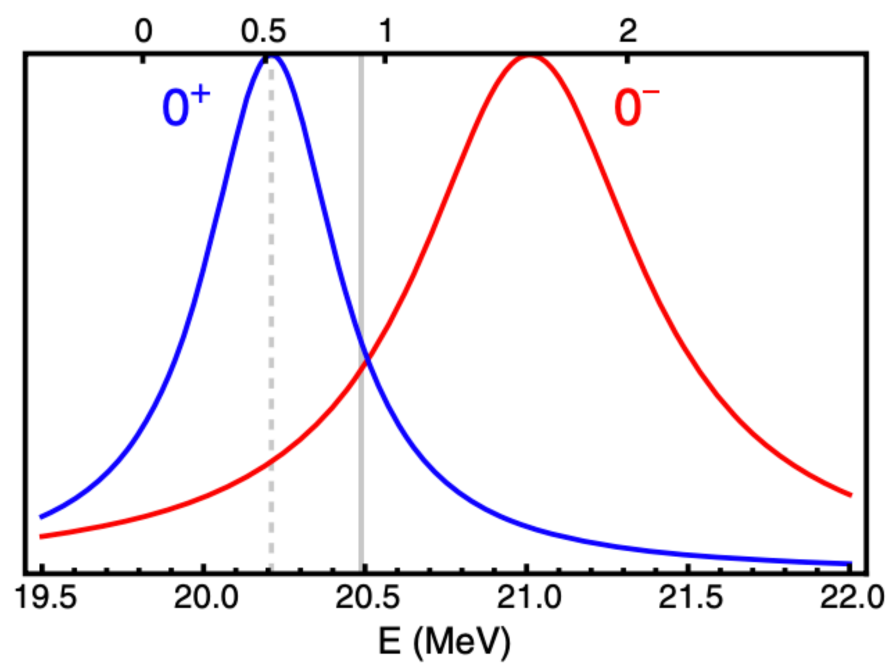


arXiv:1910.10459 [nucl-ex] E_p=900 keV
(below E(p,n) = 1.018 keV threshold)
excites the ^{4}He nucleus to E*=20.49 MeV
and populates the second ^{4}He excited state
0^-(21.01 MeV) overlapped with 0^+(20.21 MeV)





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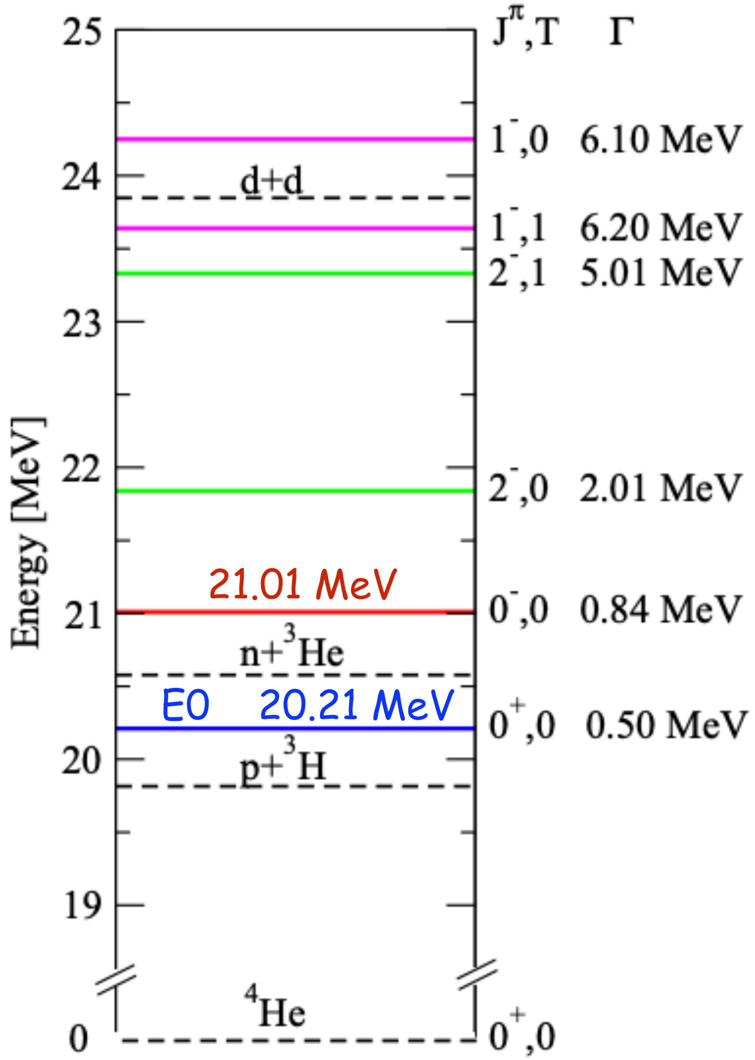

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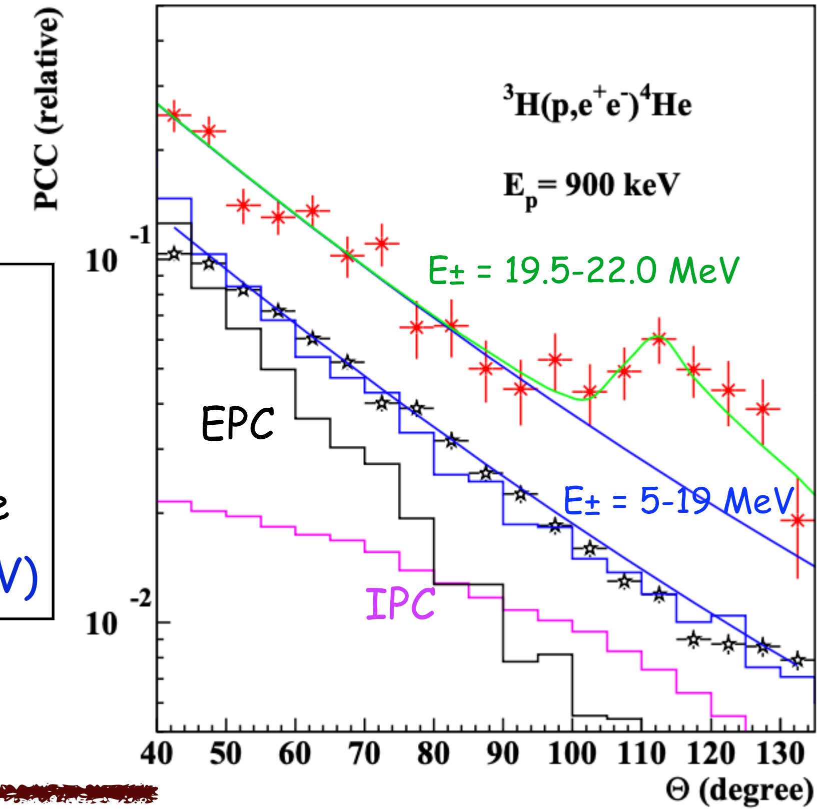

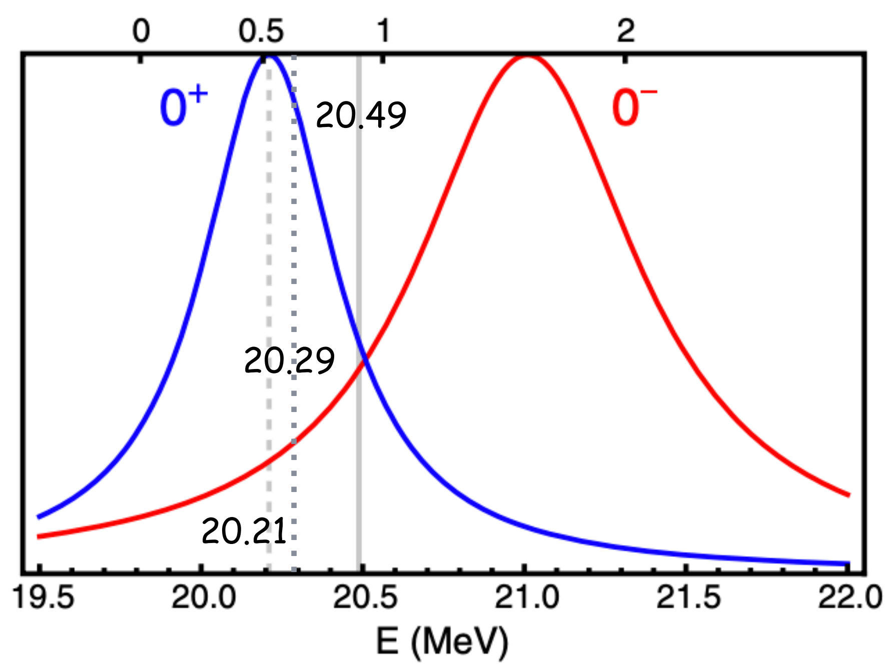

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E_p = 510, 610, 900 keV to induce direct
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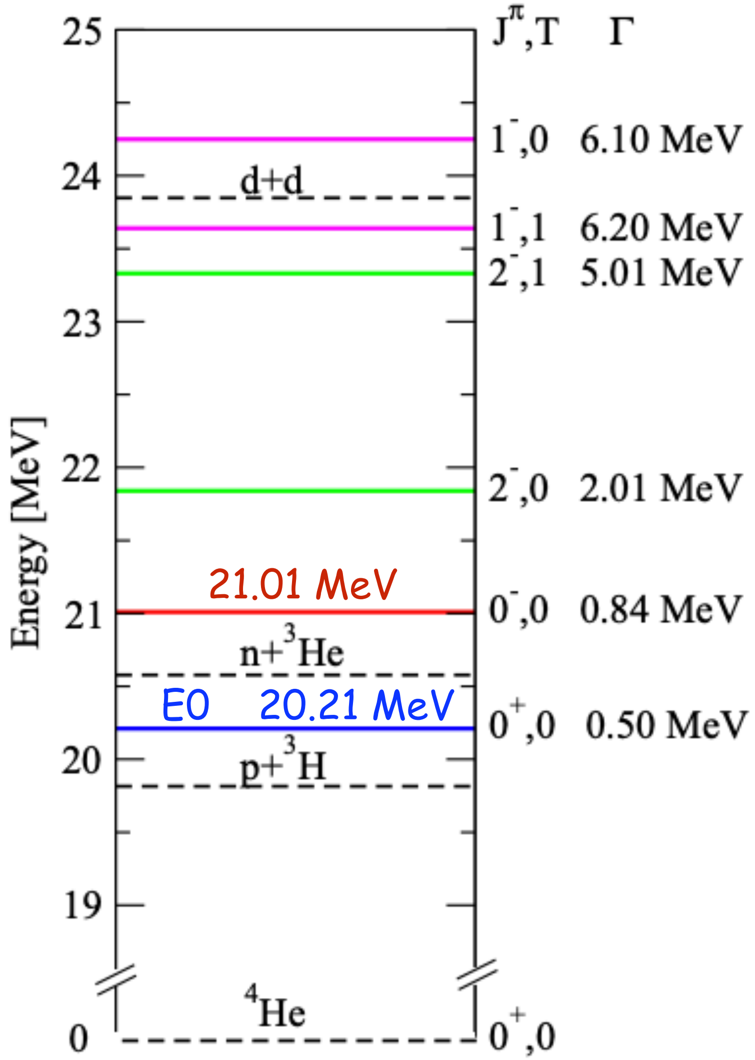

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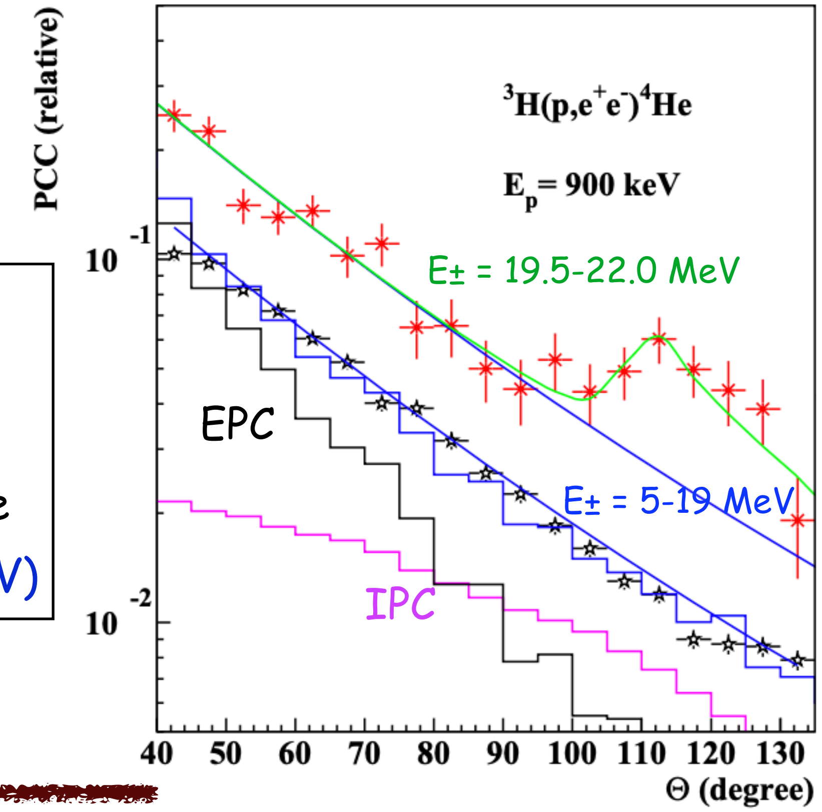

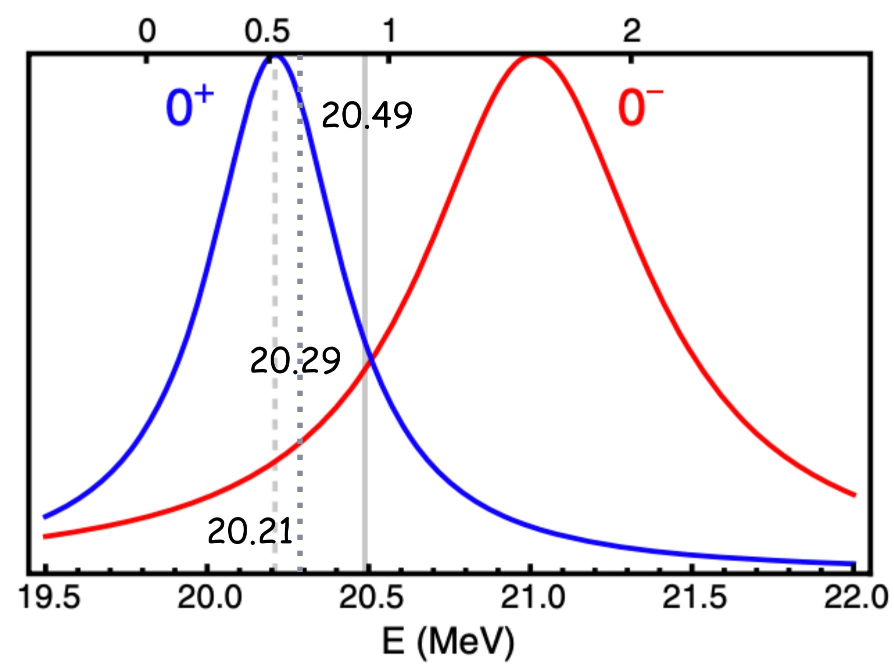

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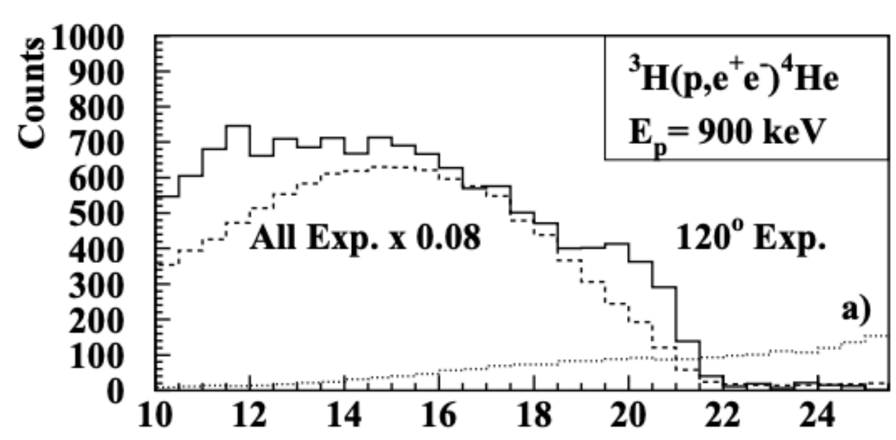

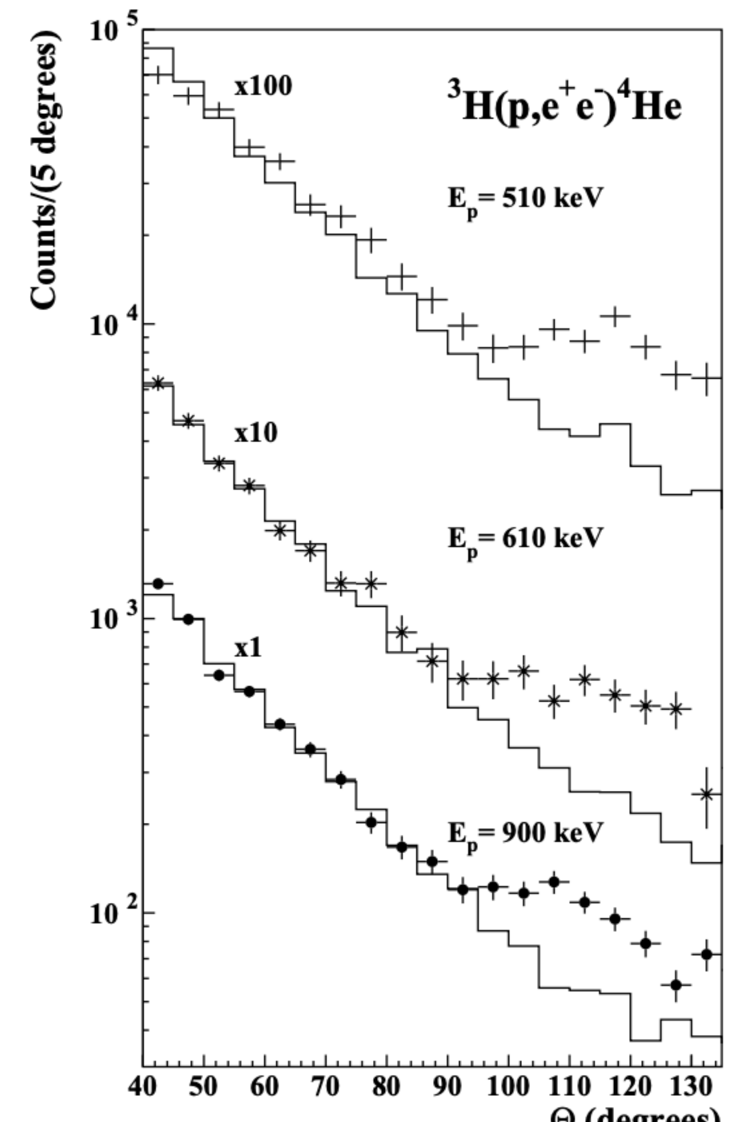

^{4}He anomaly: Standard Model explanations ?

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- Study of how the exchange of X_{17}(V,A,S,P) would impact such a process
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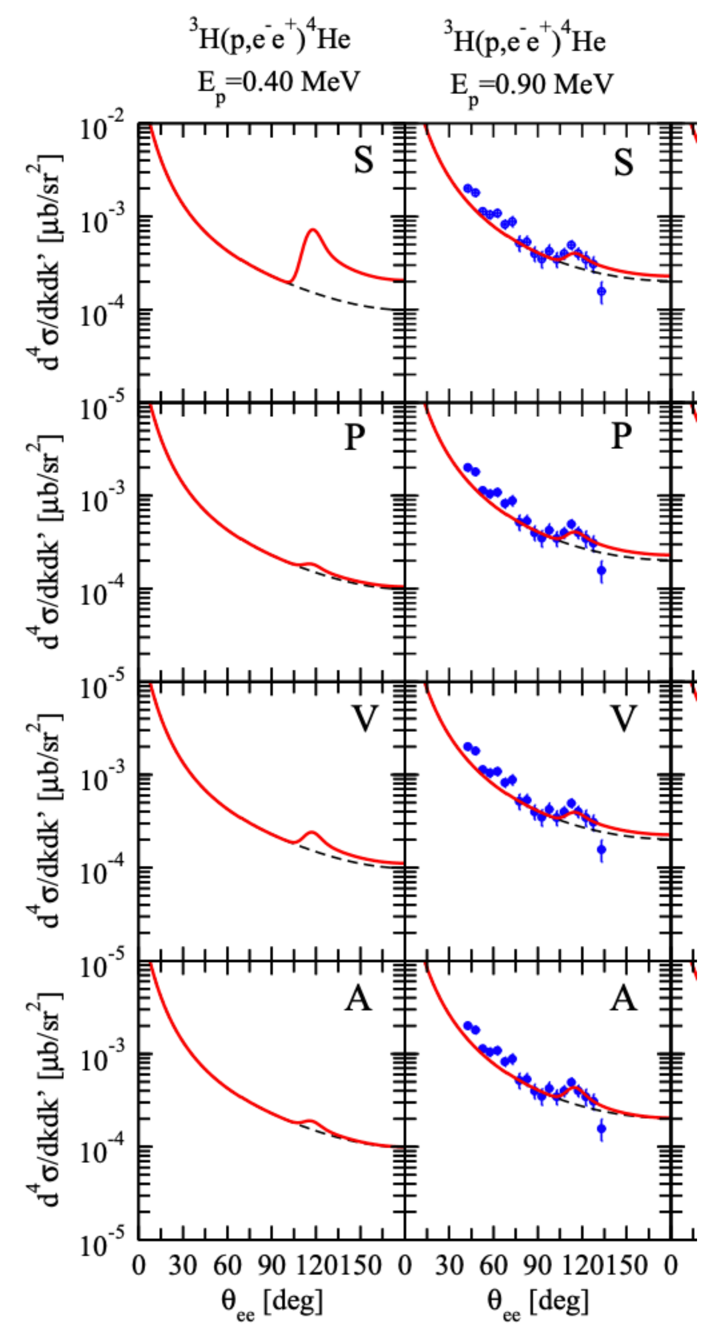

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θ_{v_p} = 90^o

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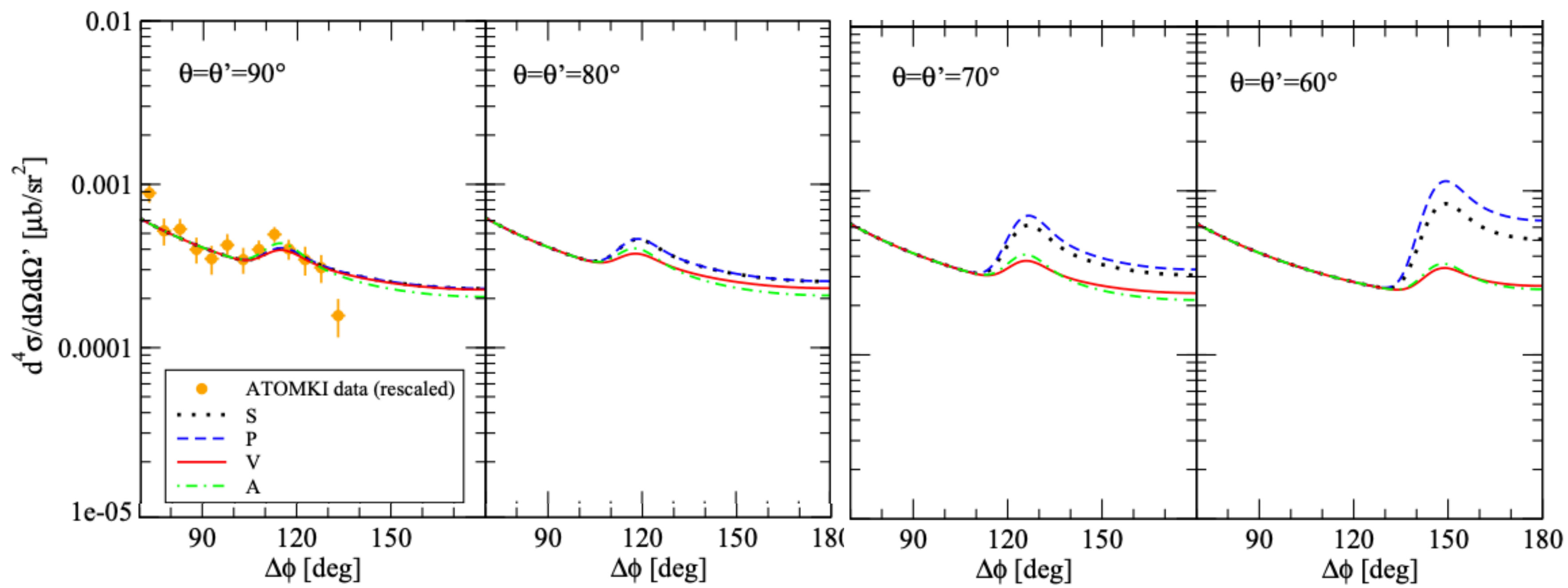

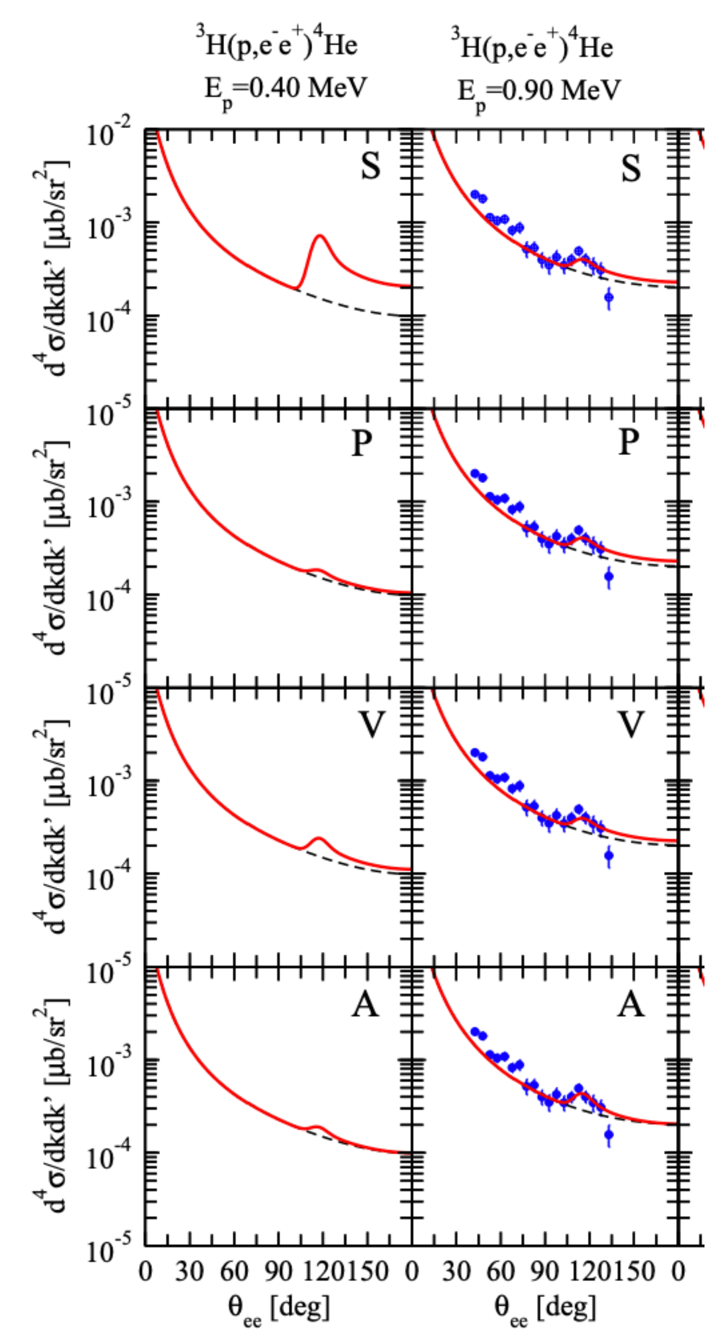

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The theor. values are: $\theta^{min}_{\pm}$ = 112° [^{4}He(20.49)]; 139°[^{8}Be(18.15)]; 161° [^{12}C(17.23)].

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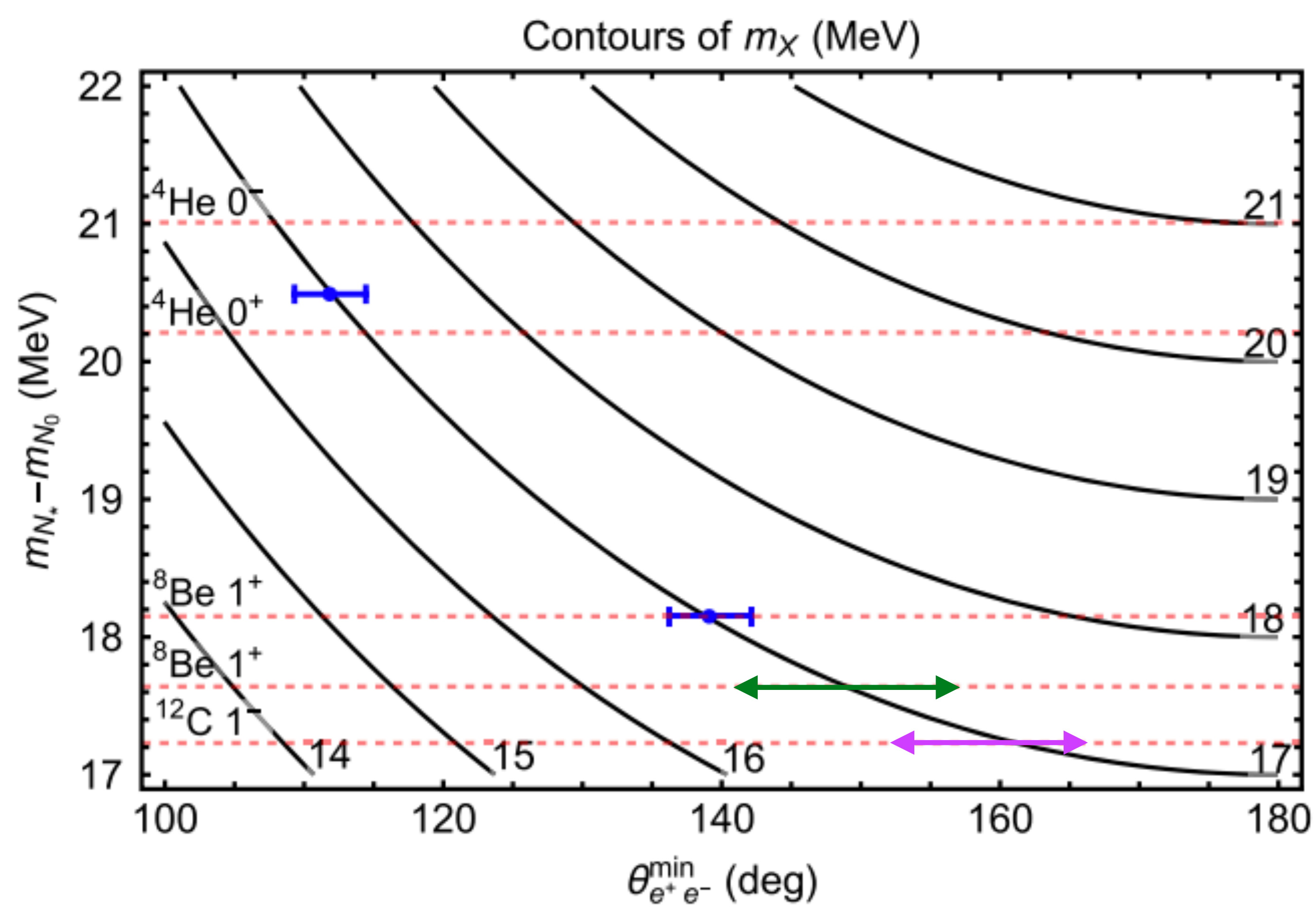

Preliminary results for ^{12}C

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

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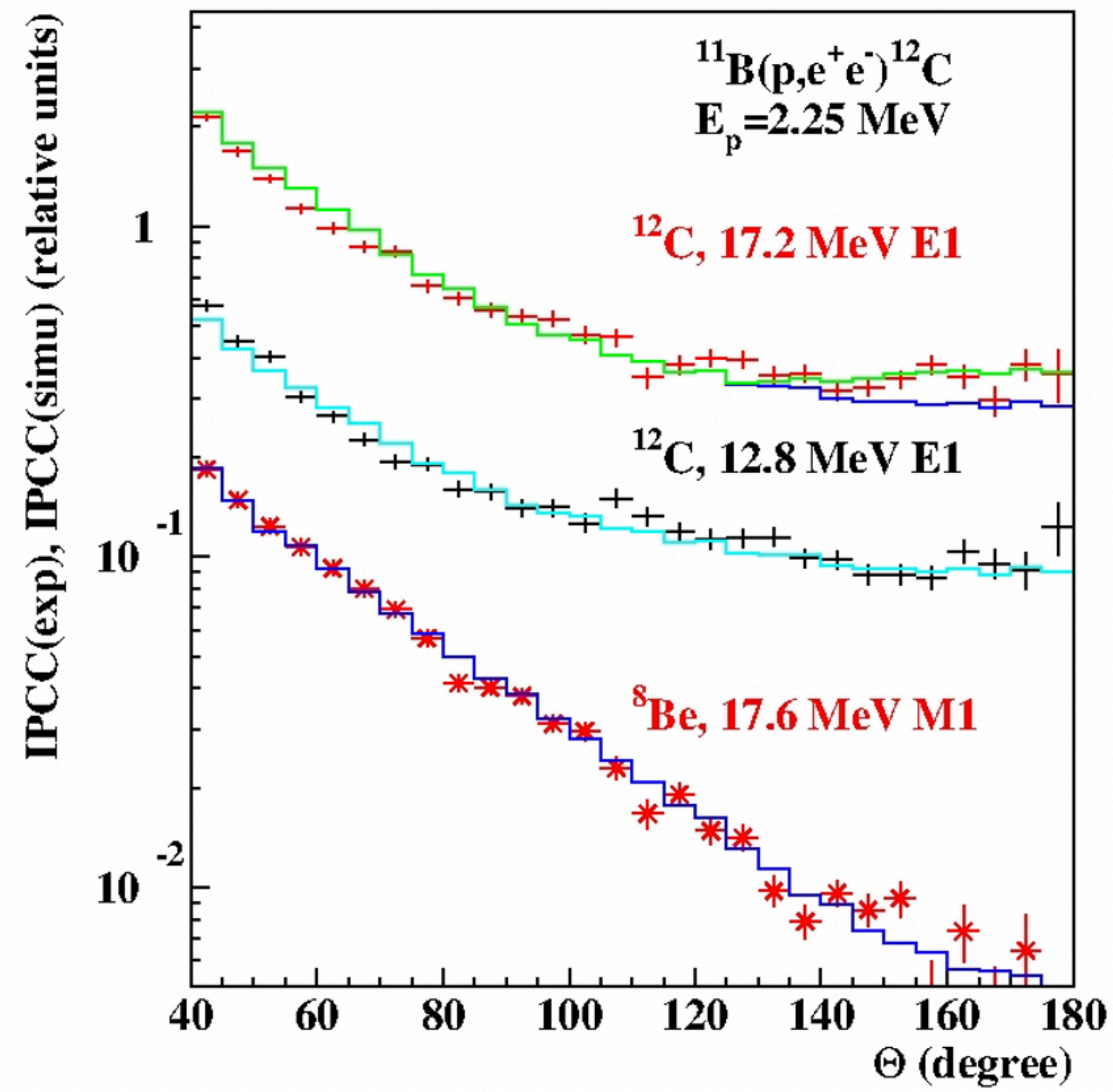
A. Krasznahorkay
"Shedding light on X17 Workshop
Rome, September 6-8, 2021



September 2022: Results for ^{12}C arXiv:2209.10795 [nucl-ex]

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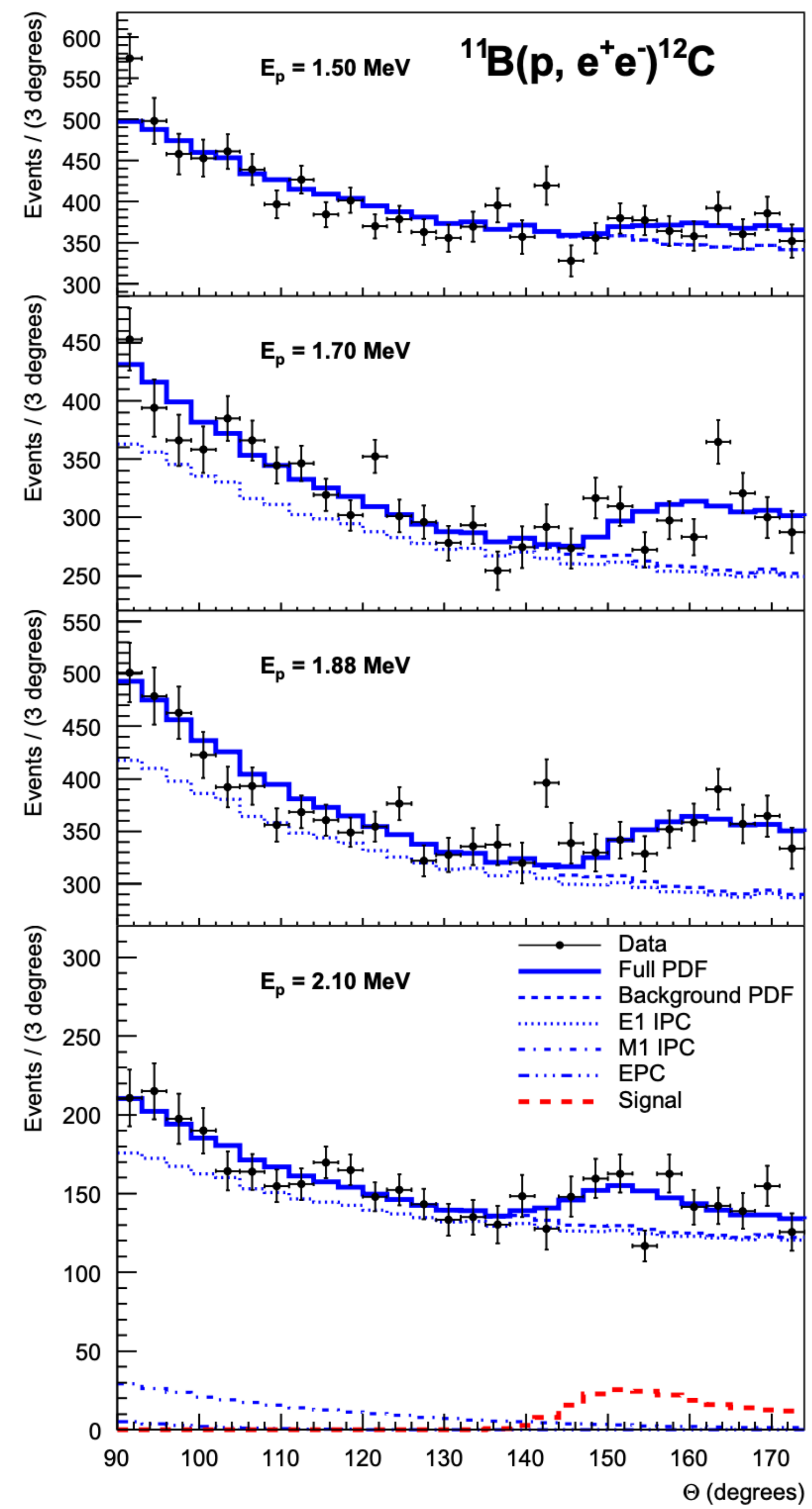
E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	



$M_X = 17.3 \pm 0.11 \pm 0.20$ MeV and B_X are consistent with the same X_{17} particle suggested by the ^8Be and ^4He anomalies

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

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Allowed nuclear transitions and X_{17} mediators

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Measured X_{17} production rates

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Are these branchings consistent with a single set of X_{17} couplings ?

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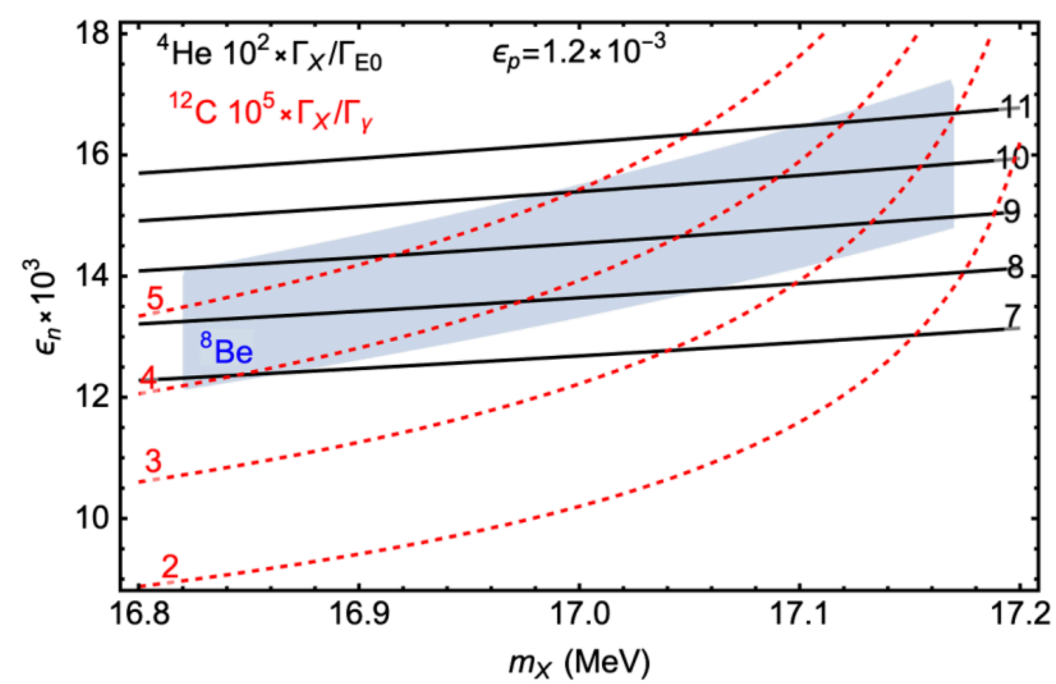

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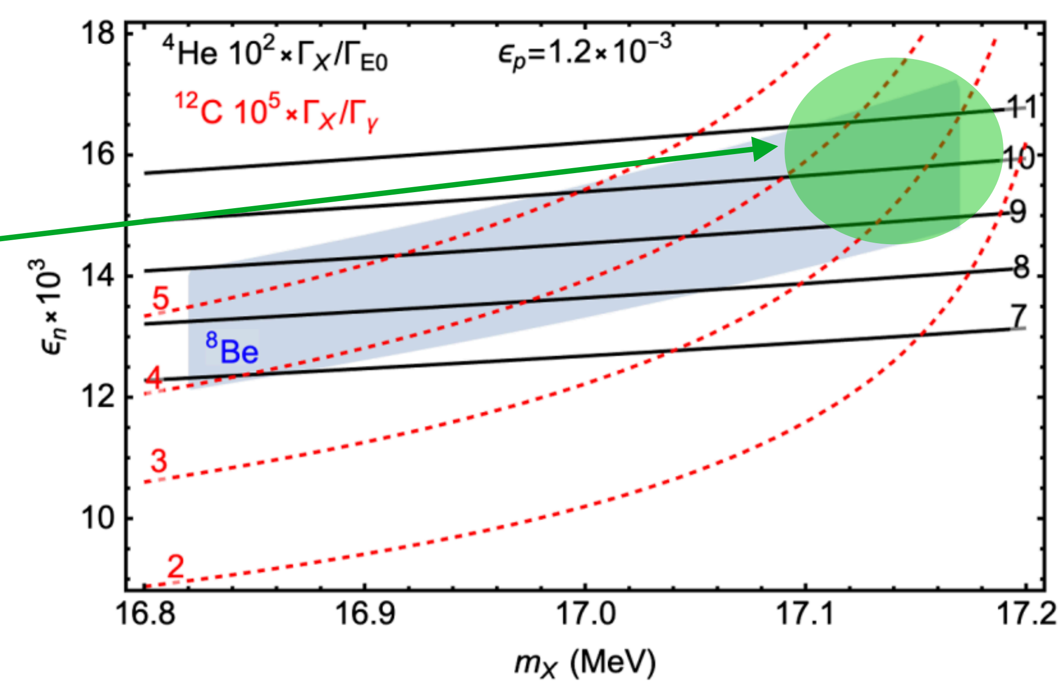
Protophobic Vector: ^{8}Be - ^{4}He - ^{12}C dynamical consistency region

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



Summarising:

- All the three 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 - ^{12}C anomalies kinematically & dynamically consistent for V (and A)
- For ^{12}C the effect was predicted, and confirmed by experimental data

Experimental perspective: Nuclear Physics

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)

Performed in Jan/Feb 2022 (possibly problems with ^{7}Li target ?)

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 ?)

IPN@ORSAY (?)

Validation/confutation from a particle physics experiment

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 (CERN-EPFL-Korea Theory Institute, early 2017)

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<u>BTF@LNF:</u> $E_+ \sim$ 250 - 500 MeV

$\sqrt{s} \sim$ 15.8 - 22.4 MeV

M_X=17 MeV E_+=289 MeV

Since $X_{17} \to e^+ e^-$,

then $e^+ e^- \to X_{17}$

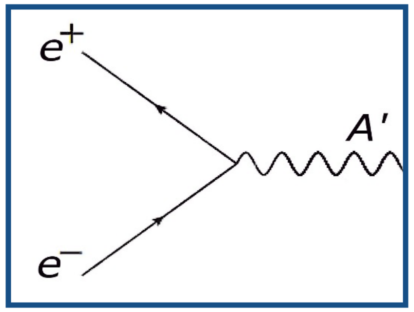
via positron-electron **resonant** annihilation (CERN-EPFL-Korea Theory Institute, early 2017)

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

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

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

"Huge" cross section !



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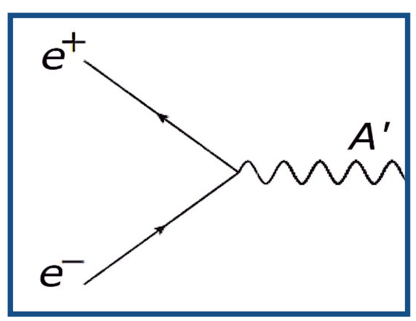
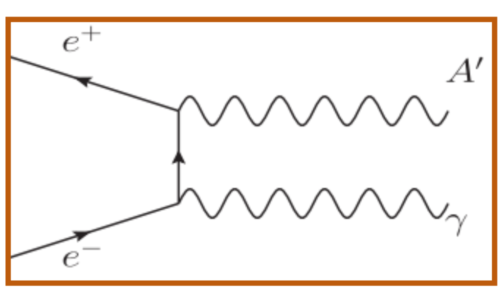
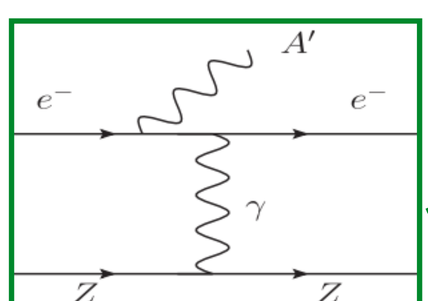
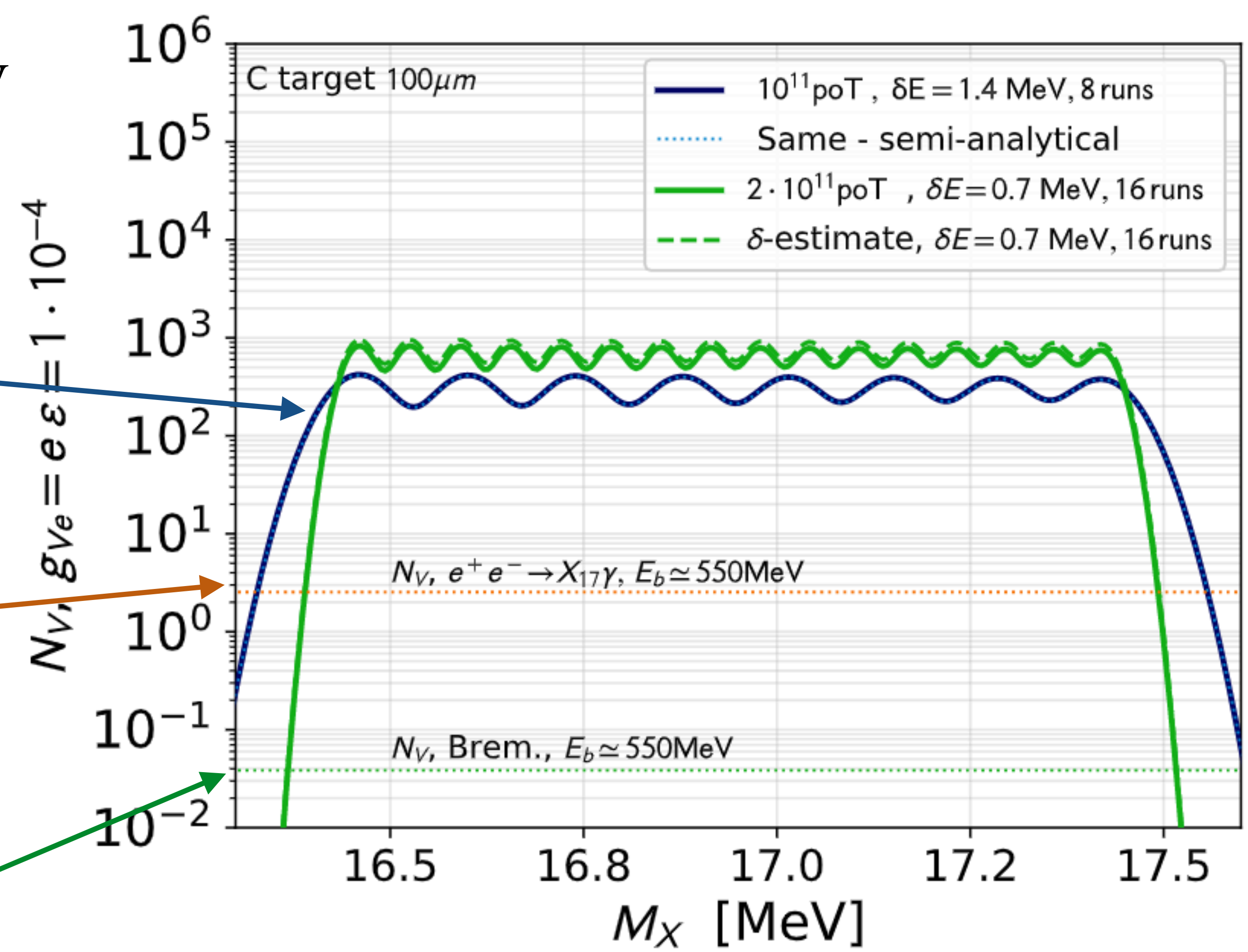




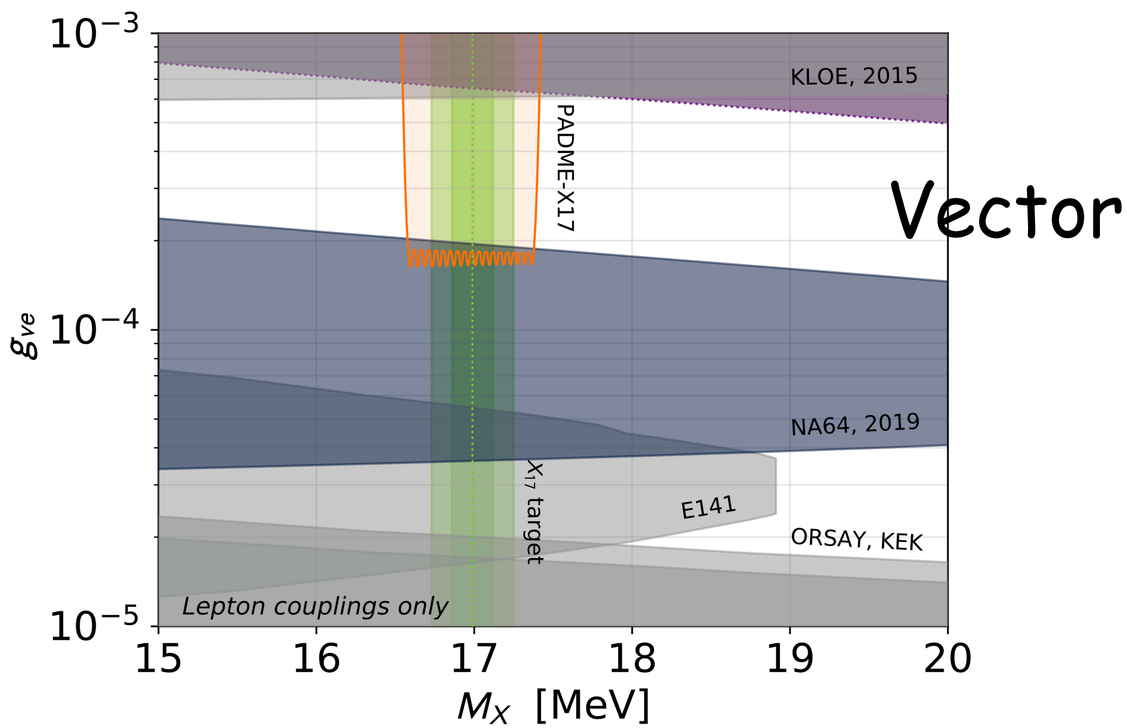


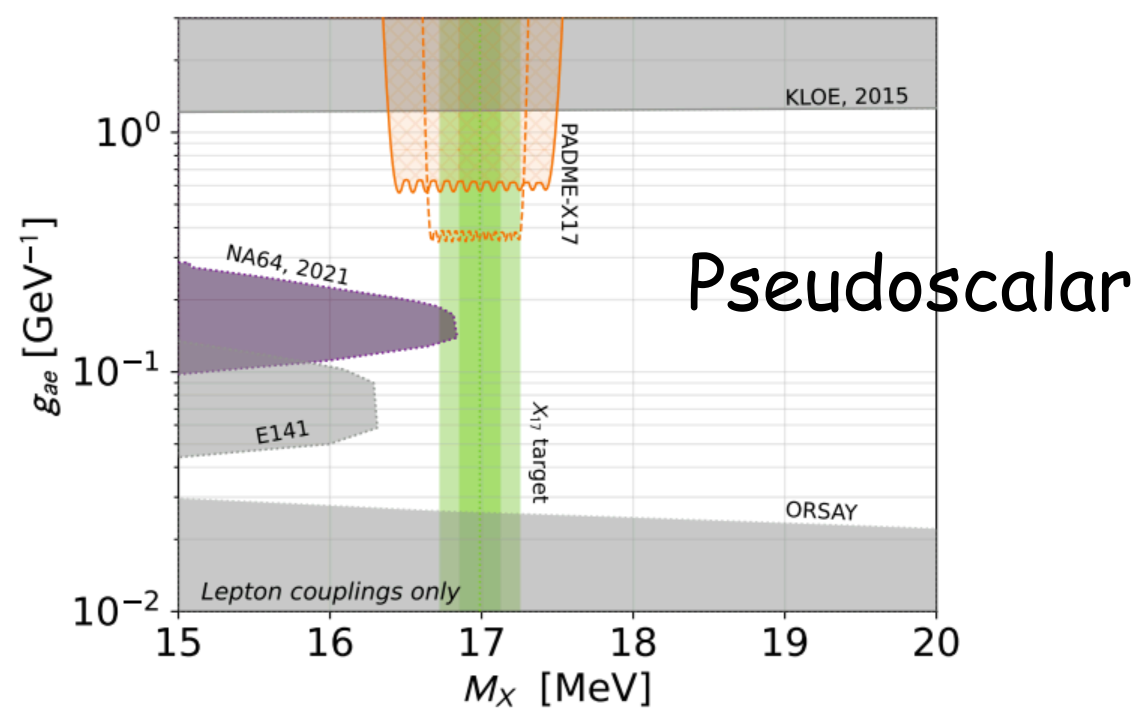


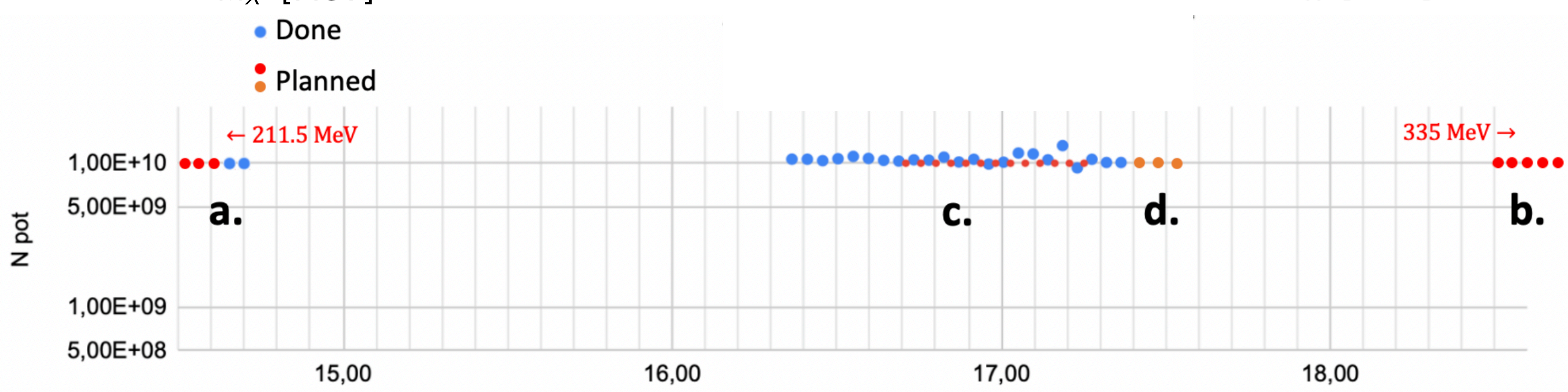
Resonant search for the X17 boson at PADME

- E. Nardi, C. Carvajal, A. Ghoshal, D. Meloni, M. Raggi PRD97 095004 (2018)
- L. Darme, M. Mancini, E. Nardi, M. Raggi arXiv:2209.09261 [hep-ph]

- Our exp. colleagues are presently collecting data $E_{beam} \sim 290$MeV
- Control of beam parameters is excellent, background understood
- Our projections indicate that the spin-1 X_{17} can be fully tested
- Spin-0 pseudoscalar only partially (but a 0^- particle is ^{12}C disfavoured)





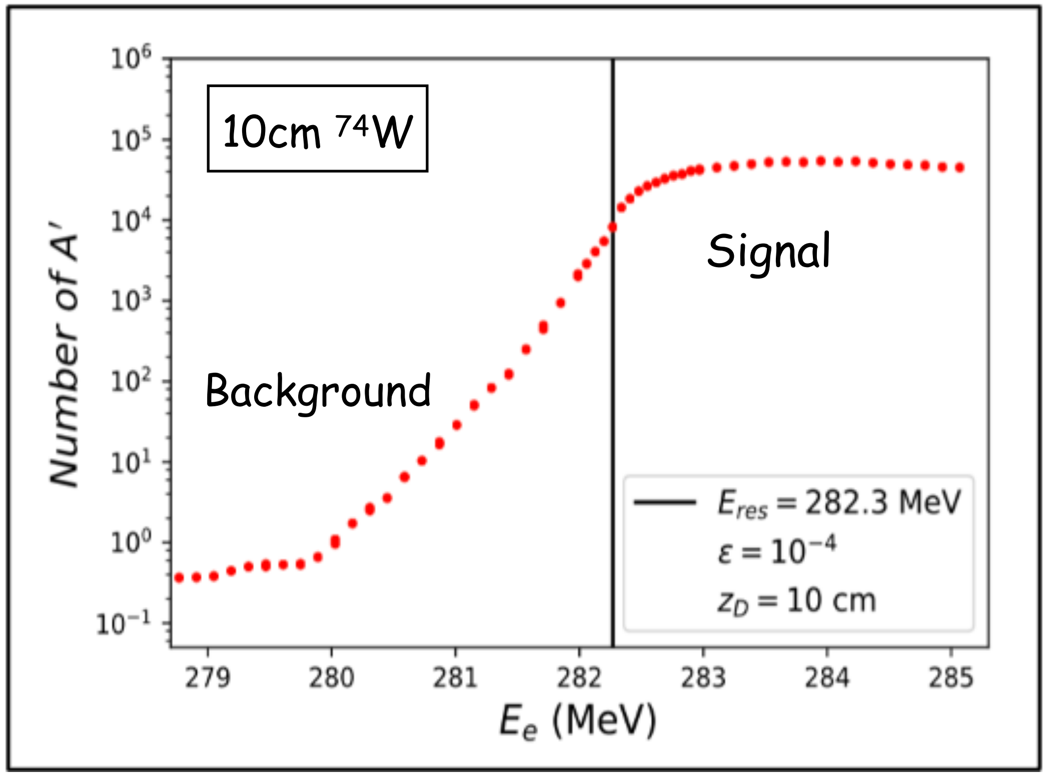


Conclusions

- Three anomalies observed in nuclear transitions appear to be consistent with a particle physics interpretation (X_{17})
- Statistical evidence is very strong (> 7σ)
- Explanations via higher order nuclear physics effects, interferences, higher multipoles contributions, are theoretically (strongly) disfavoured…
- Present data are from a single experiment. Independent verifications are needed.
- Intense effort for new Nucl. Phys. experiments is ongoing First results expected probably in late 2023.
- Being of a completely different nature, a particle physics experiment can be decisive to validate the X_{17} hypothesis.

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 😠

LKB 2020 result from ^{87}Rb recoil velocity

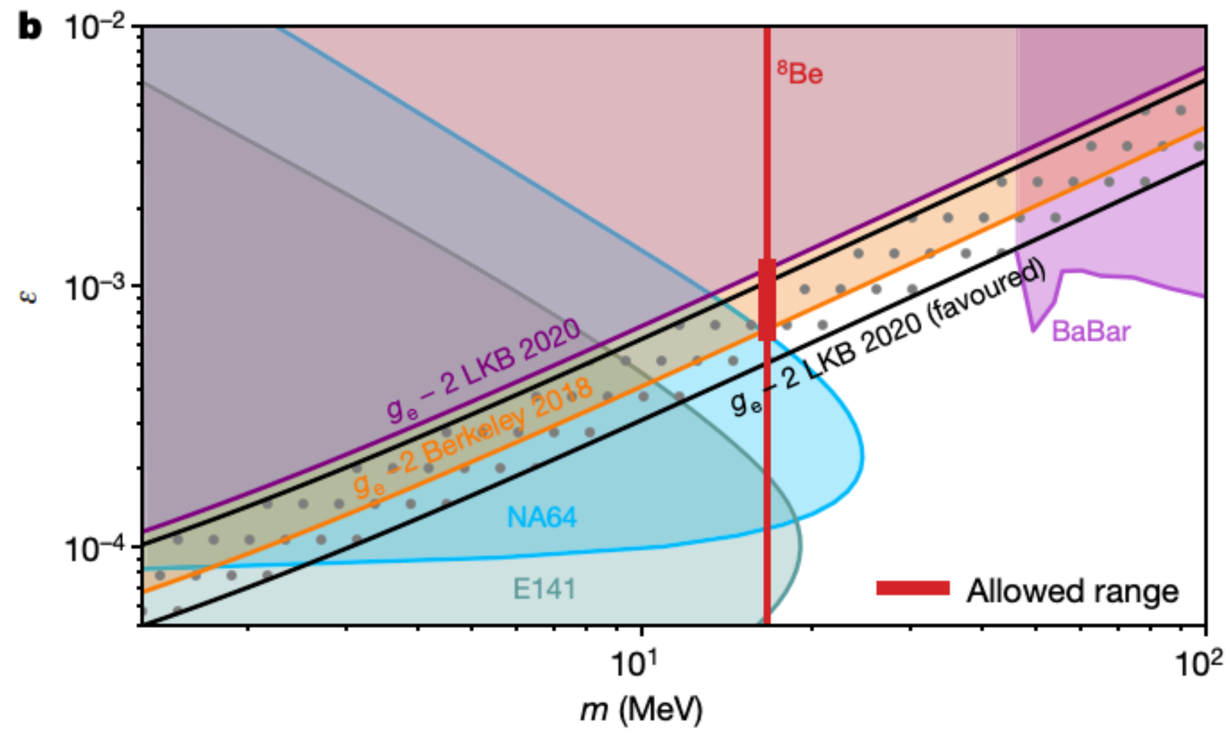


Fig. 4 | Impact on the test of the standard-model prediction of a_e and limits on hypothetical *X* boson. a, Summary of contributions to the relative uncertainty on δa_e. The horizontal green line corresponds to the δa_e value obtained by taking into account the muon magnetic moment discrepancy and using a naive scaling model. Previous data from ref. [9] (Harvard 2008), ref. [18] (LKB 2011), ref. [3] (Berkeley 2018), ref. [13] (Atomic Mass Evaluation, AME 2016), ref. [14] (Max-Planck-Institut für Kernphysik, MPIK 2014) and ref. [2] (RIKEN 2019). Also shown are the 10th-order and hadronic contributions in the calculation of the electron moment anomaly.
b, Exclusion area in (ε, m_X) space for the *X* boson. The grey, blue and light purple regions are ruled out by the E141[31], NA64[32] and BaBar[35] experiments, respectively. A test based on the magnetic moment of the electron rules out the orange region when using the Berkeley measurement[3] and the purple region when using the present result. Disregarding the Berkeley measurement, the remaining allowed range at 16.7 MeV is depicted by the thick red line. The zone favoured by $\delta a_e > 0$, as deduced from this work, is shown by grey dots.