The X17 anomaly: status and prospect

Enrico Nardi

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Laboratori Nazionali di Frascati

LNF General Seminar, December 15, 2022

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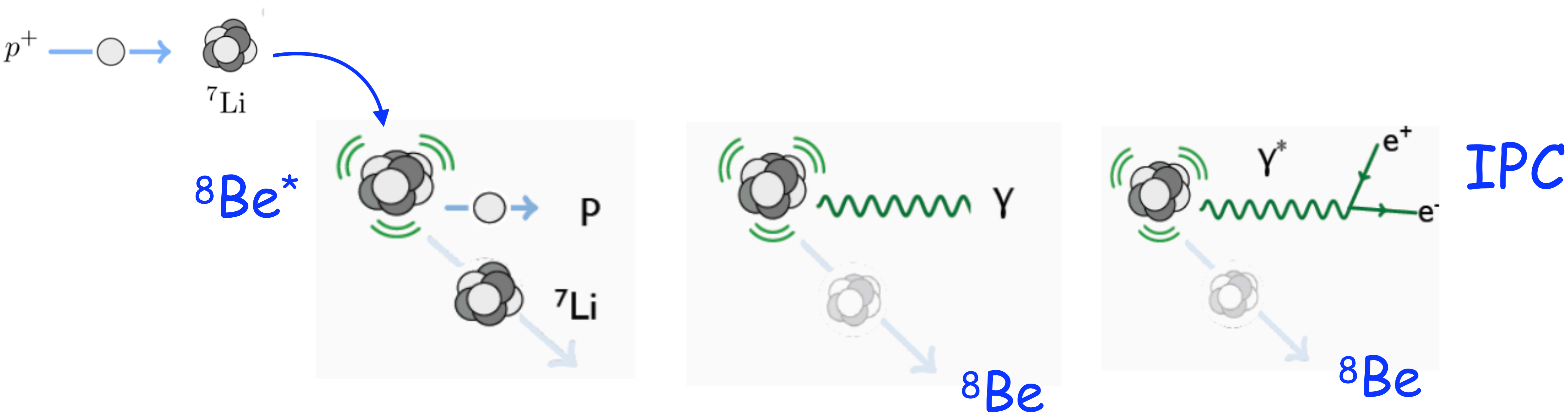
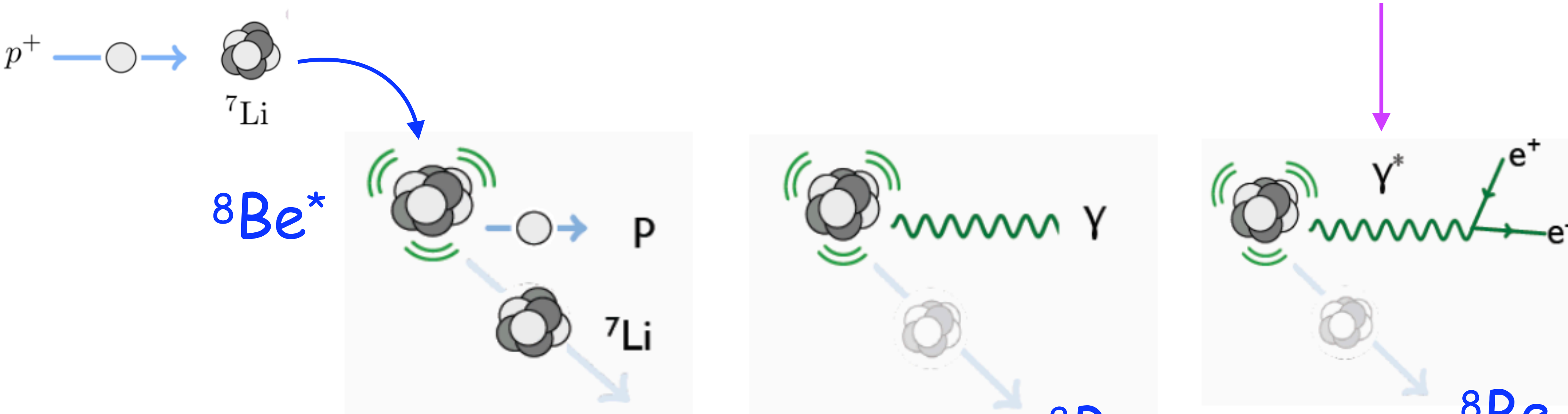


$^8Be^* \to p + {}^7Li$	(mostly)
$^8Be^* \to {}^8Be + \gamma$	($B_\gamma = 1.4 \times 10^{-5}$)
$^8Be^* \to {}^8Be + e^+e^-$	($B_{e\pm} = 4 \times 10^{-3}\, B_\gamma$)

$^{8}Be^{*}$(18.15MeV) de-excitation process:

X_{17} (M_X=17MeV)



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IPC

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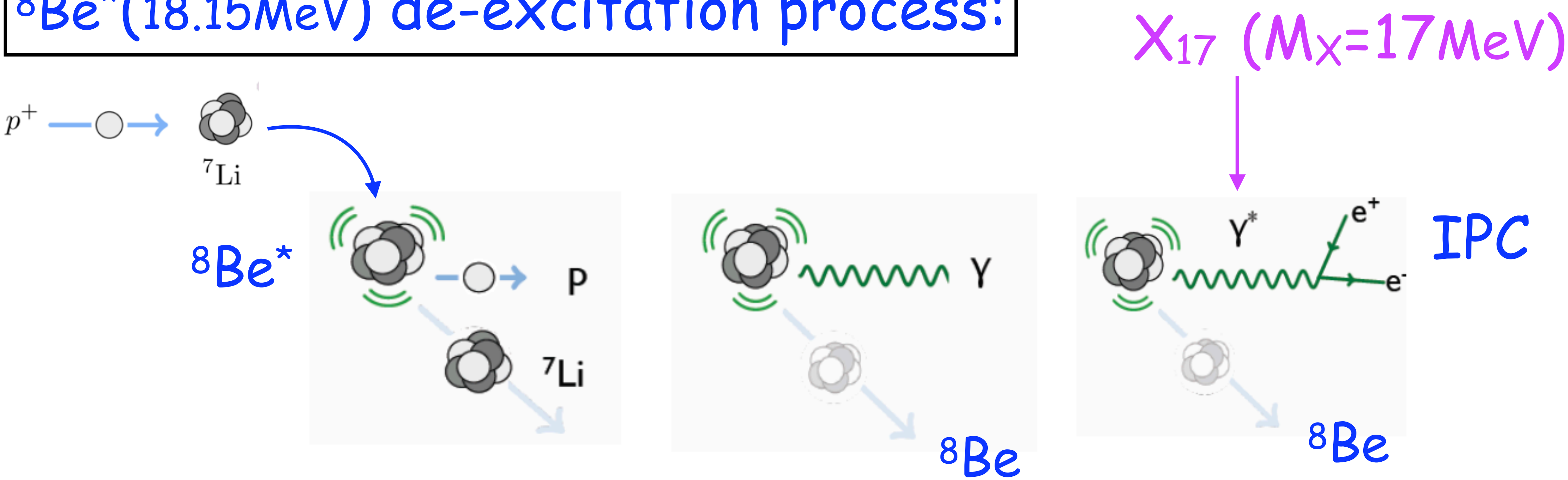

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Anomaly first observed in ^8Be Nuclear Transitions

=>

$^8Be^* \to {}^8Be + X_{17}$ ($\theta \sim 140^\circ$)

$\hookrightarrow e^+e^-$ ($B_X = 6 \times 10^{-6}\, B_\gamma$)

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- 2022: Confirmation of e^+e^- excess in $^{12}C^*$(17.2 MeV) -> g.s. at large angles [~ 155° - 160°] [A.J. Krasznahorkay, e-Print: 2209.10795 [nucl-ex], rev. v2 Nov. 2,2022]

The Atomki experimental apparatus

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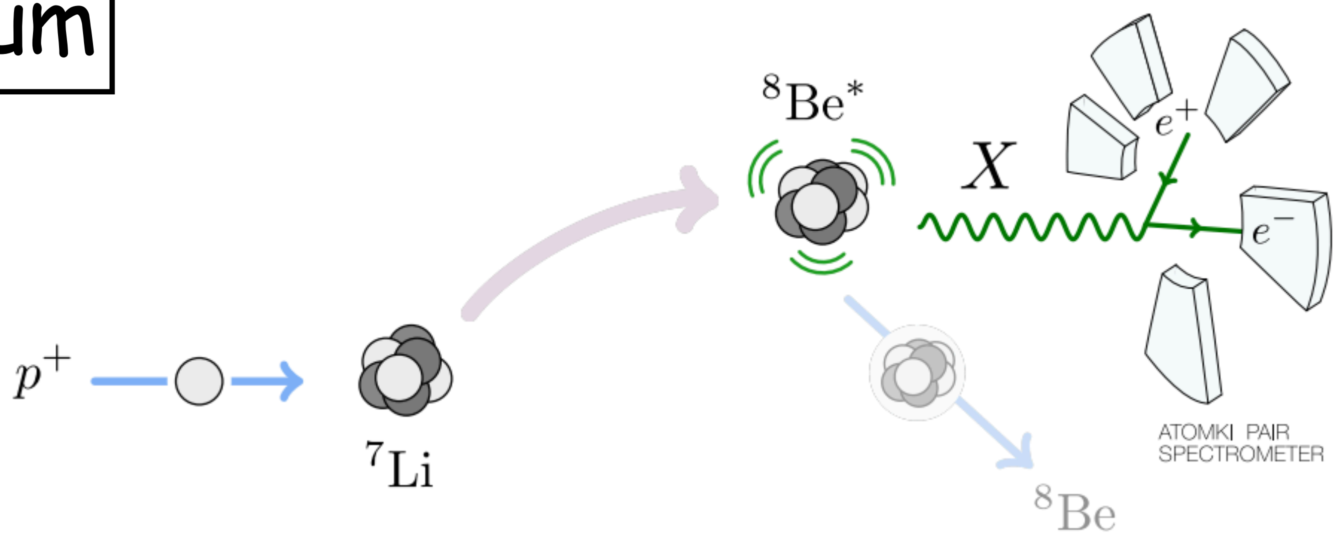
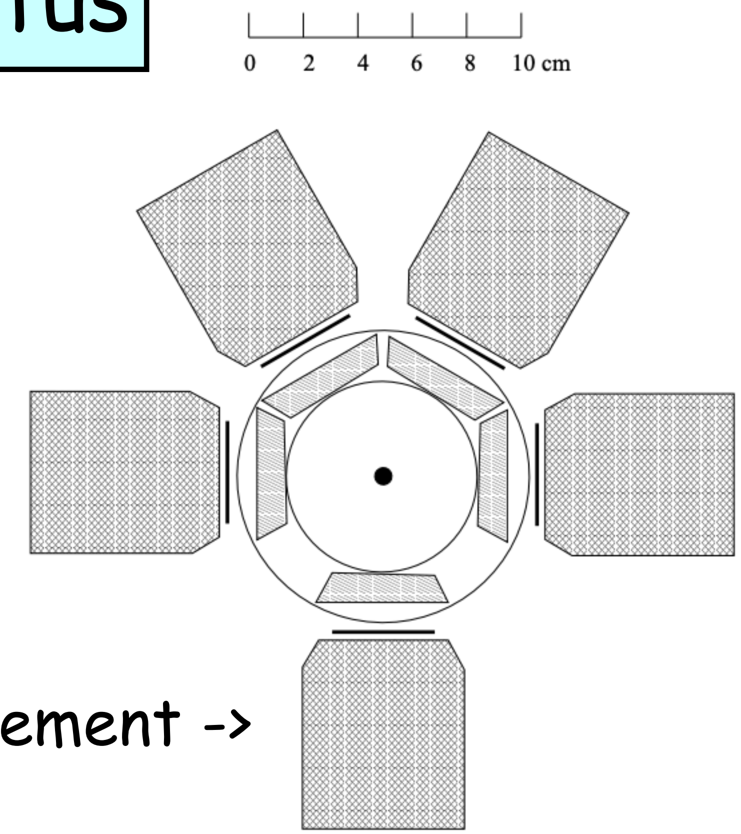
Berillium



Feng+, 1608.0359

Five telescopes arrangement ->



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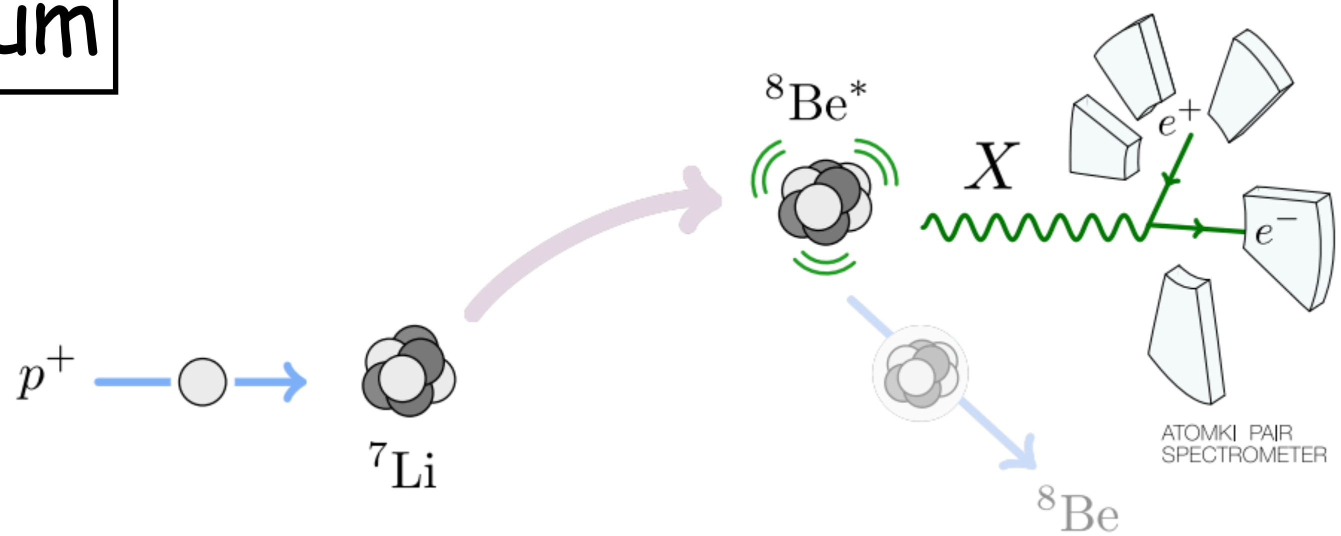

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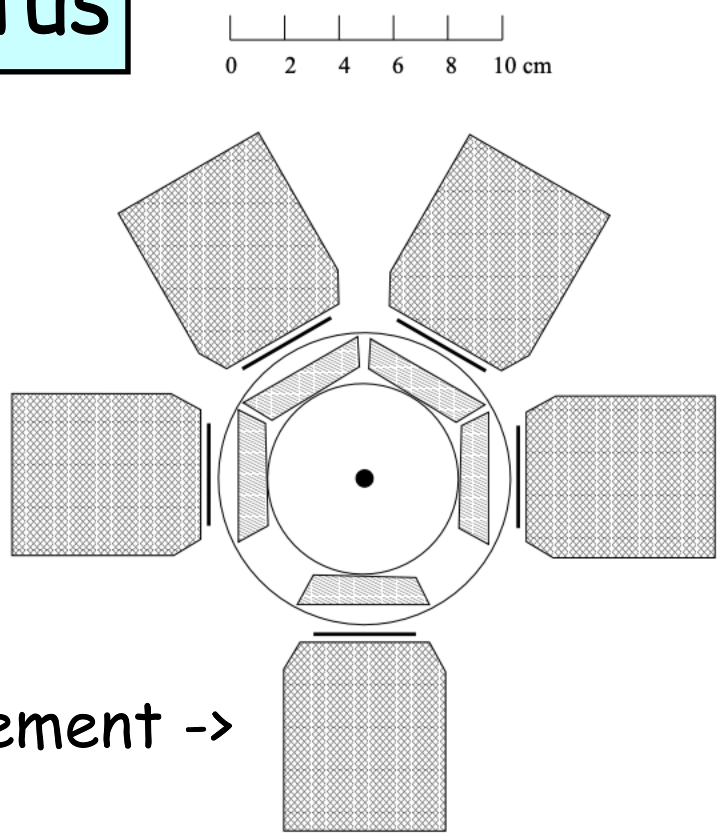

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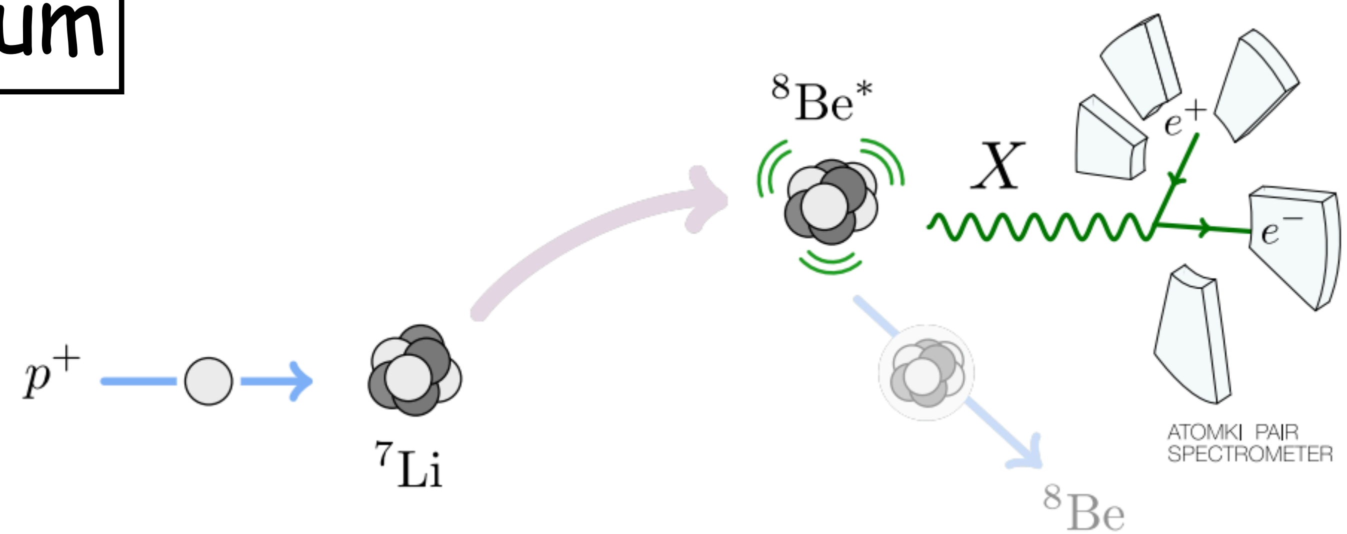

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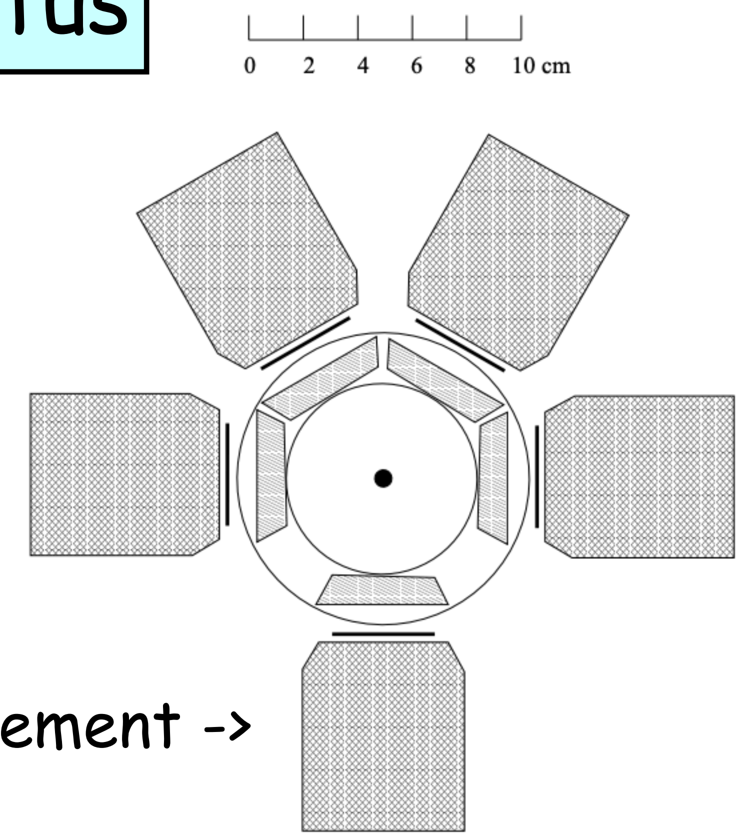

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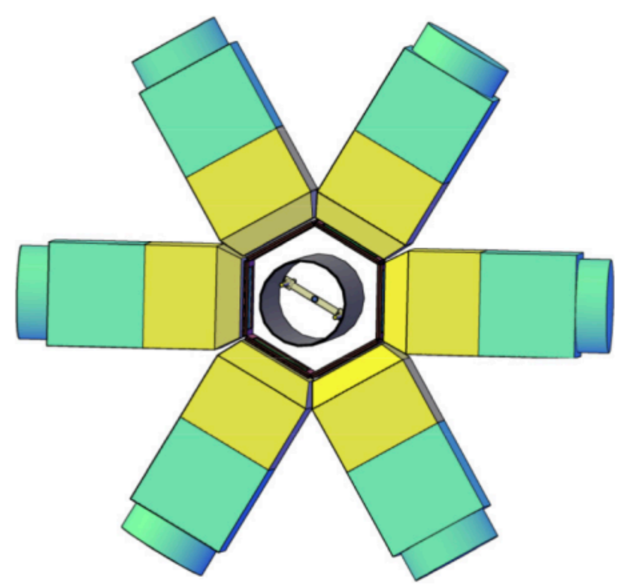
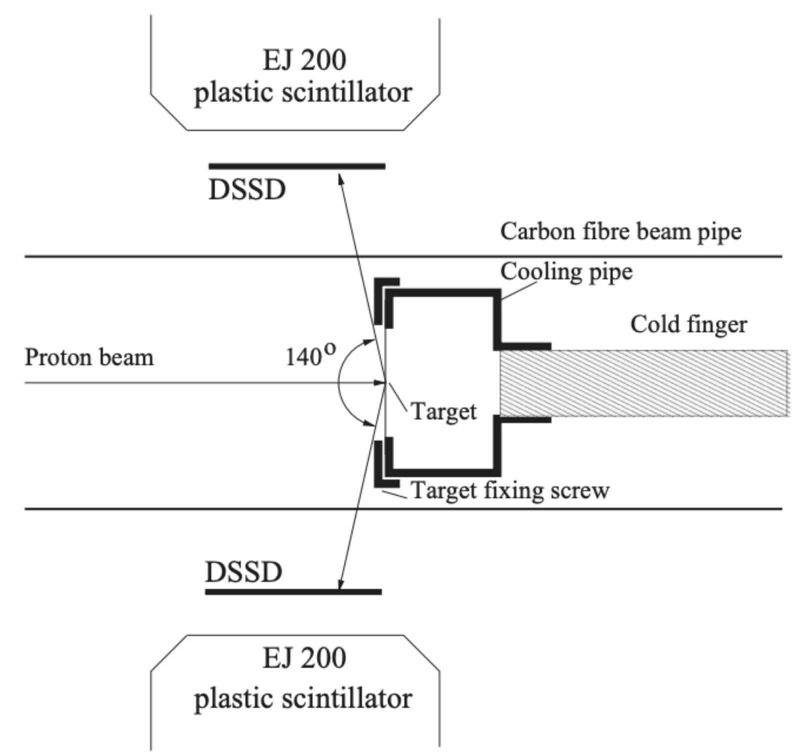


Six telescopes arrangement ->



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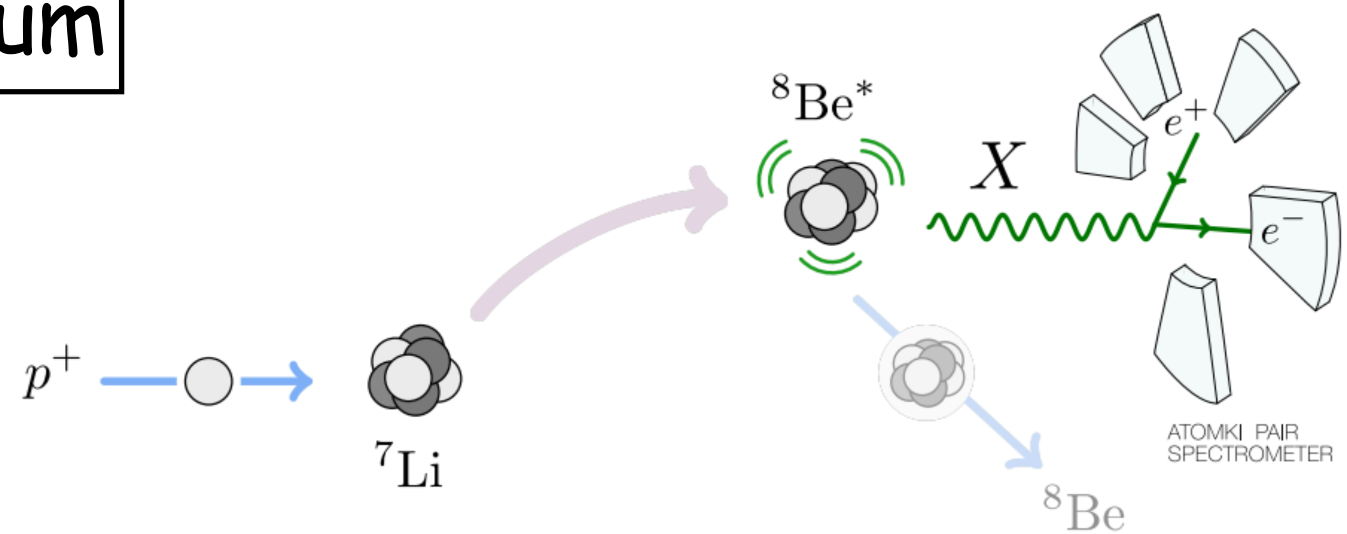

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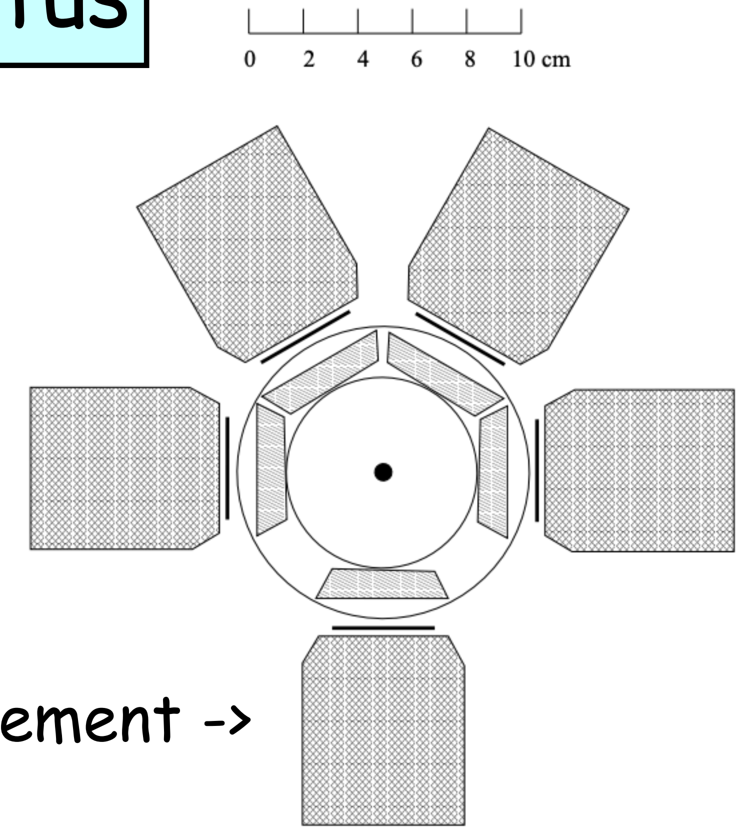

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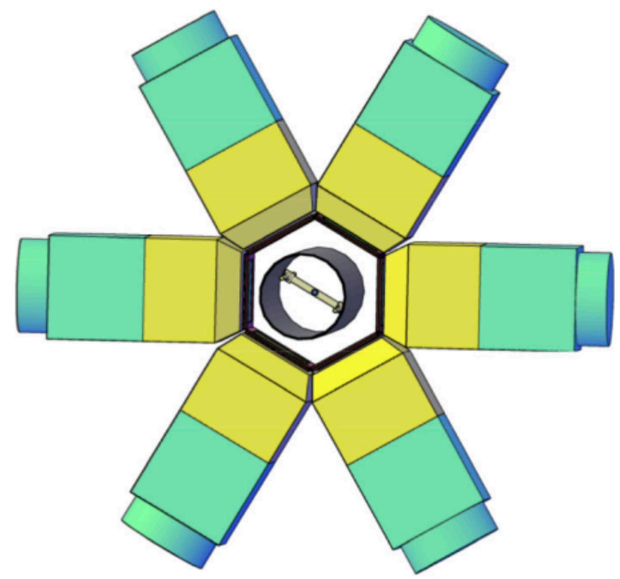

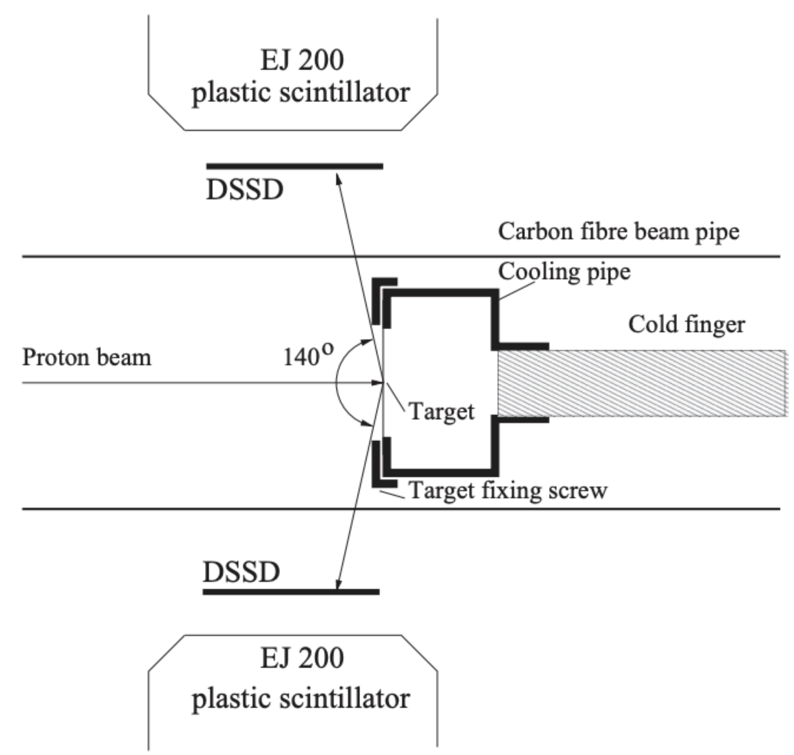

Atomki e^+e^- pairs measurements:

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

Berillium nuclear transitions

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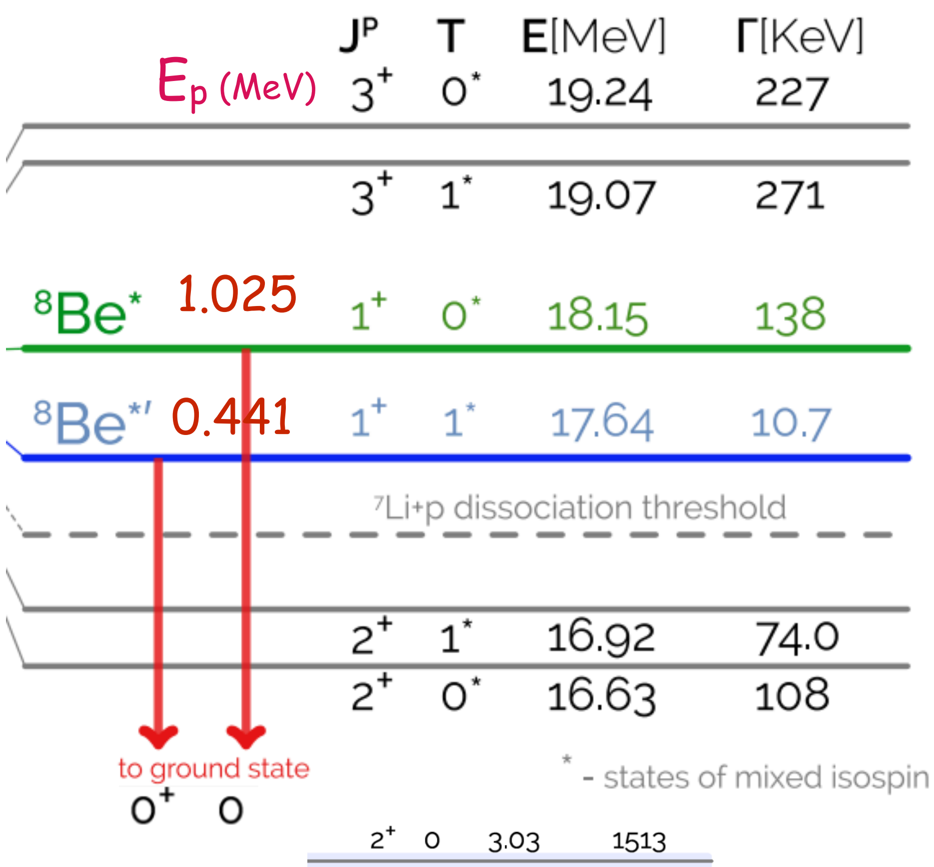
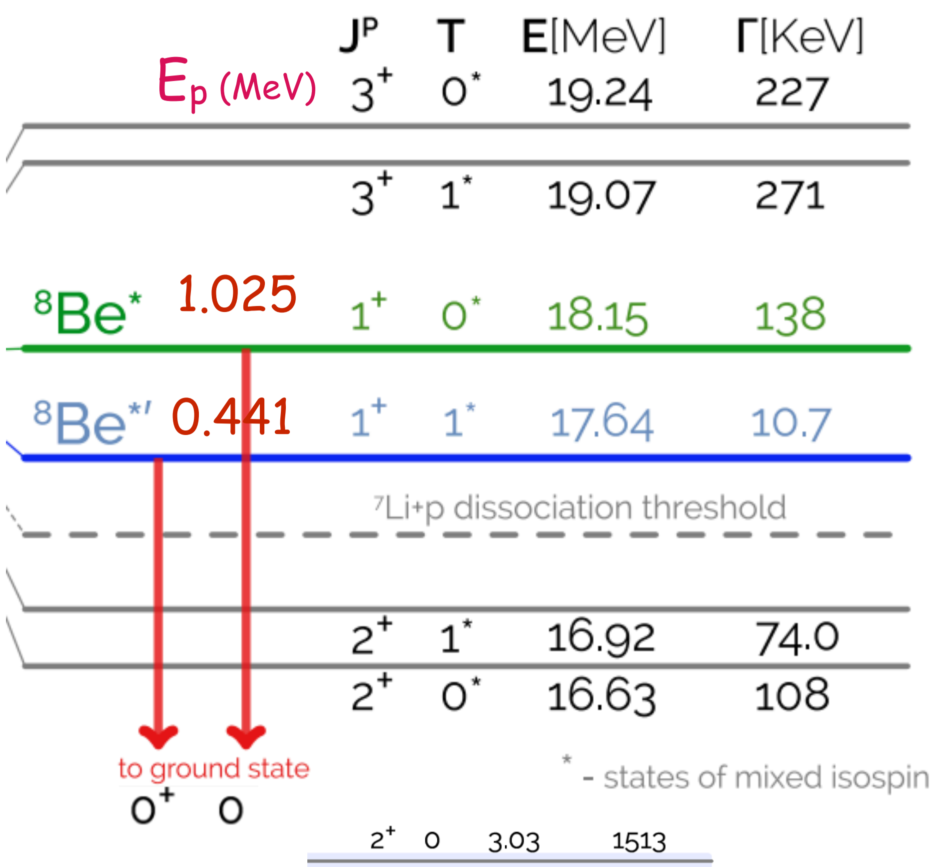
Resonant transition $p+{}^7Li \rightarrow {}^8Be^* \rightarrow \ldots$

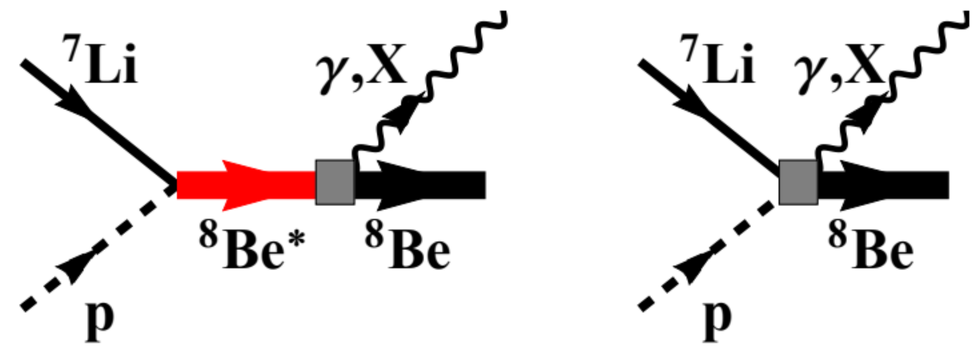


Berillium nuclear transitions

Resonant transition p+^{7}Li -> ^{8}Be* -> ...

Radiative p + ^{7}Li -> ^{8}Be + γ





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

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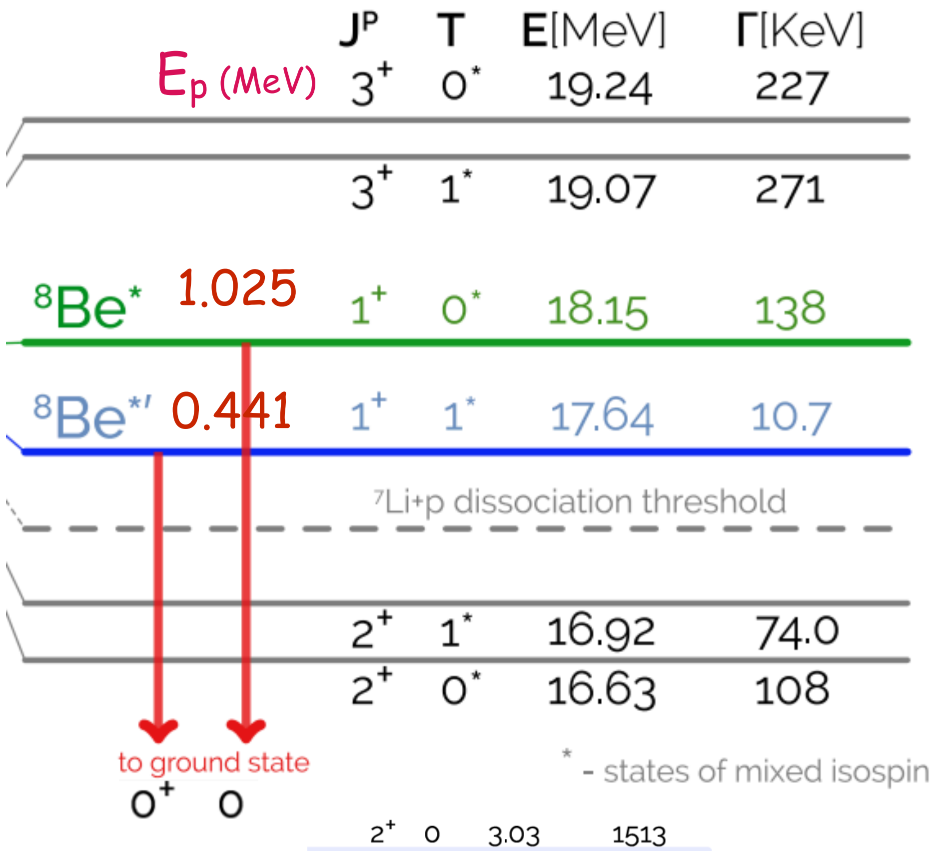

Resonant transition $p + {}^7Li \rightarrow {}^8Be^* \rightarrow \dots$

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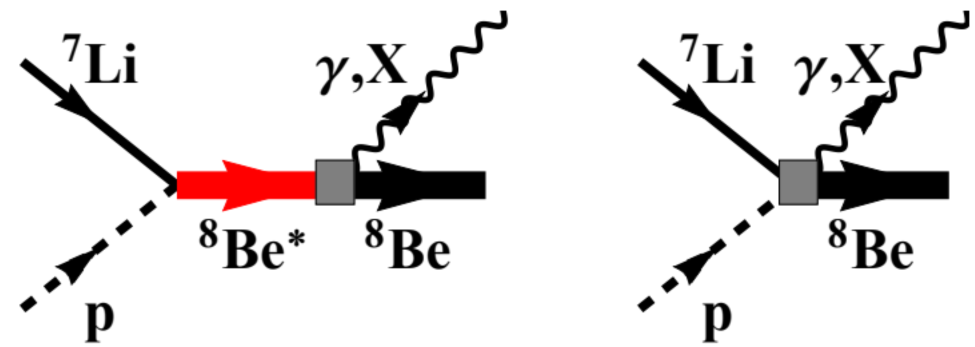

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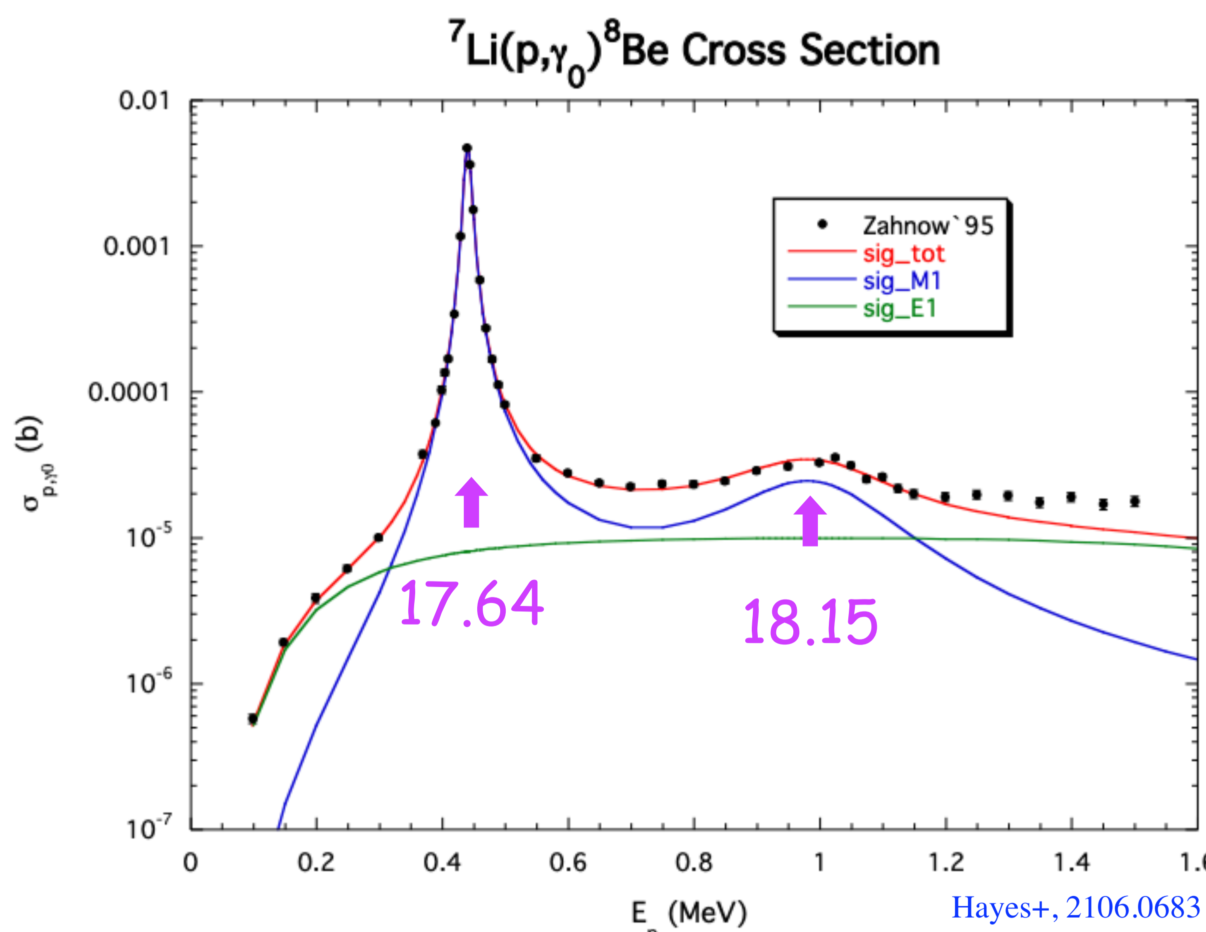

Atomki results for ^{8}Be [PRL 116, 042501 (2016)]

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^{8}Be*(18.15MeV) IsoS

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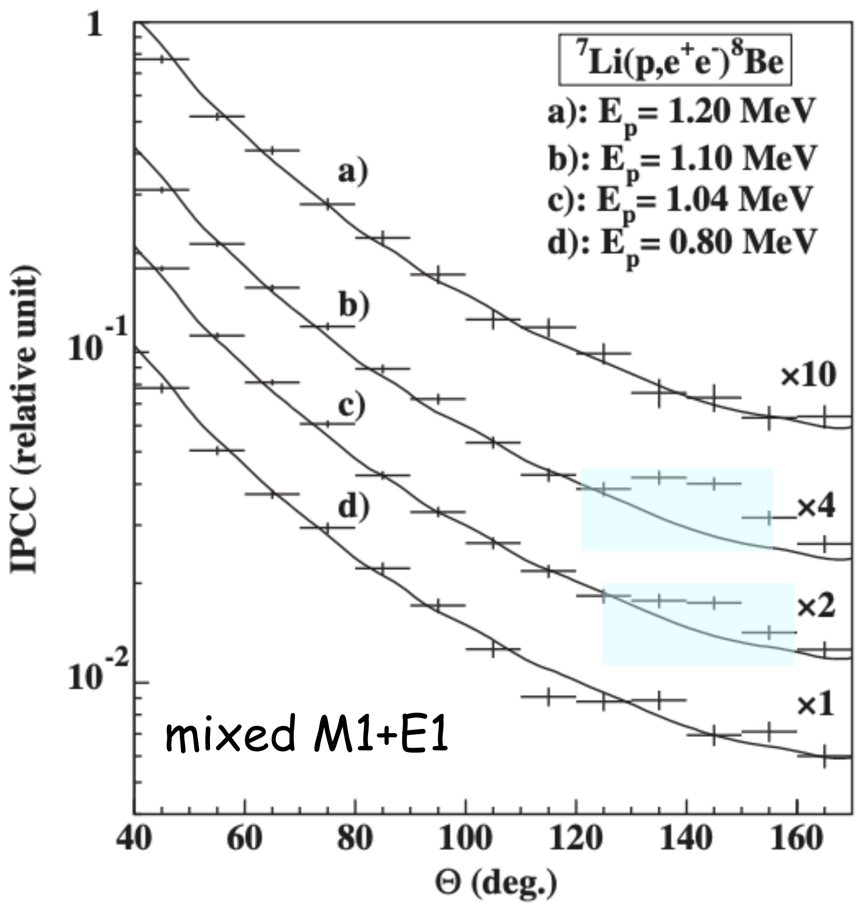
Angular correlation



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Energy gate: $E_\pm$ > 18 MeV

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

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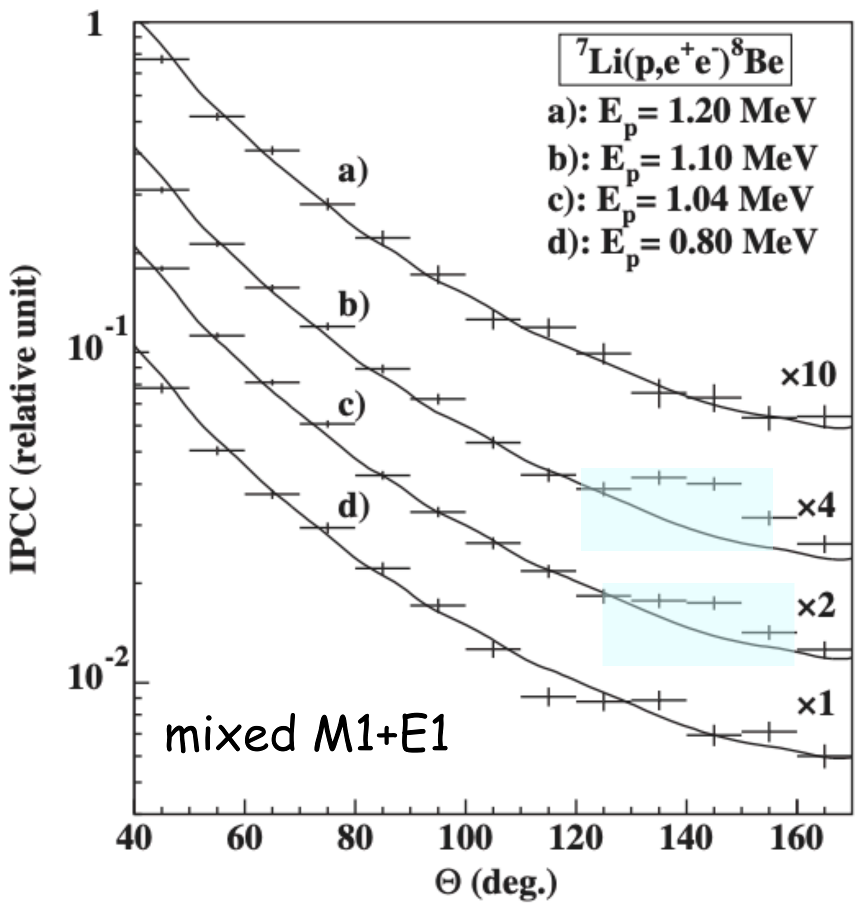

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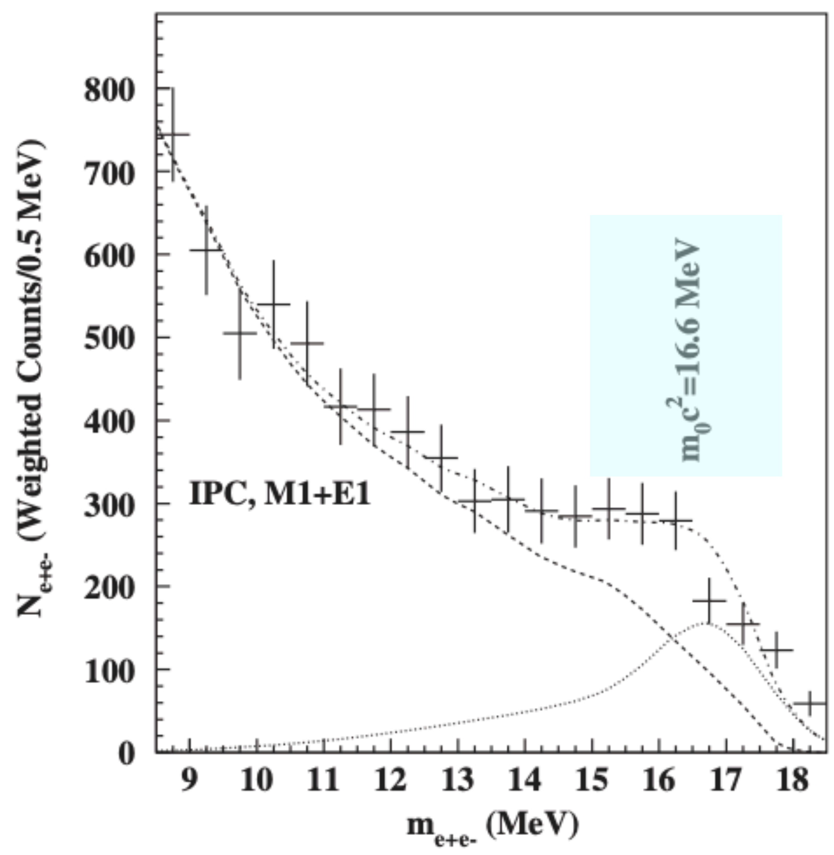

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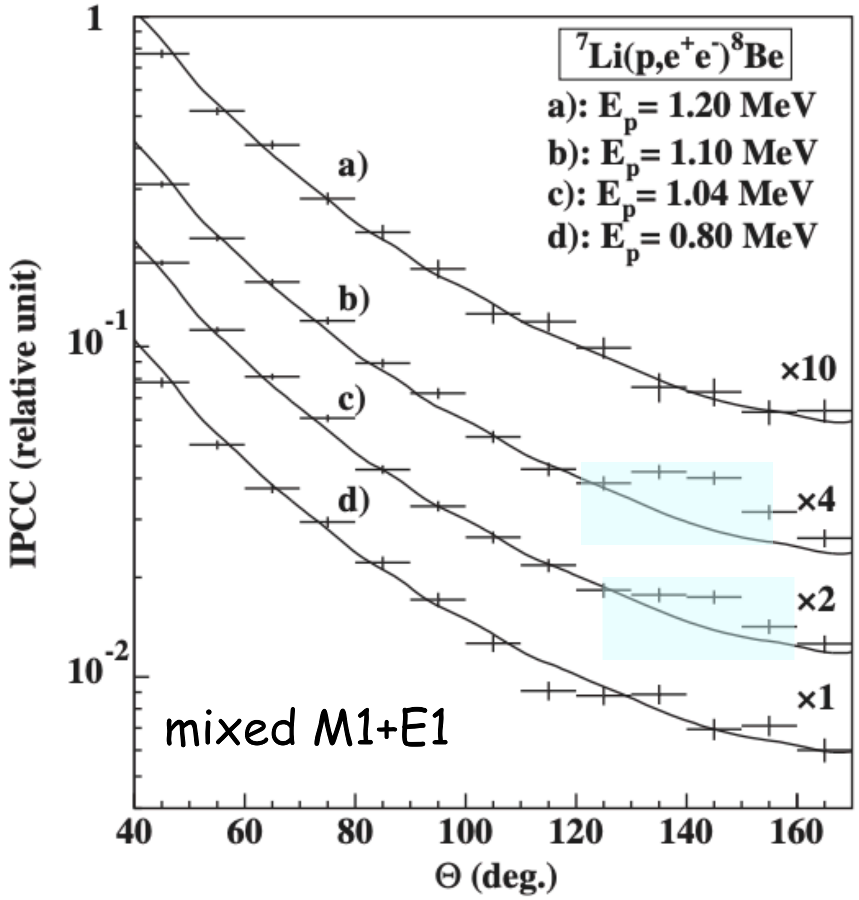

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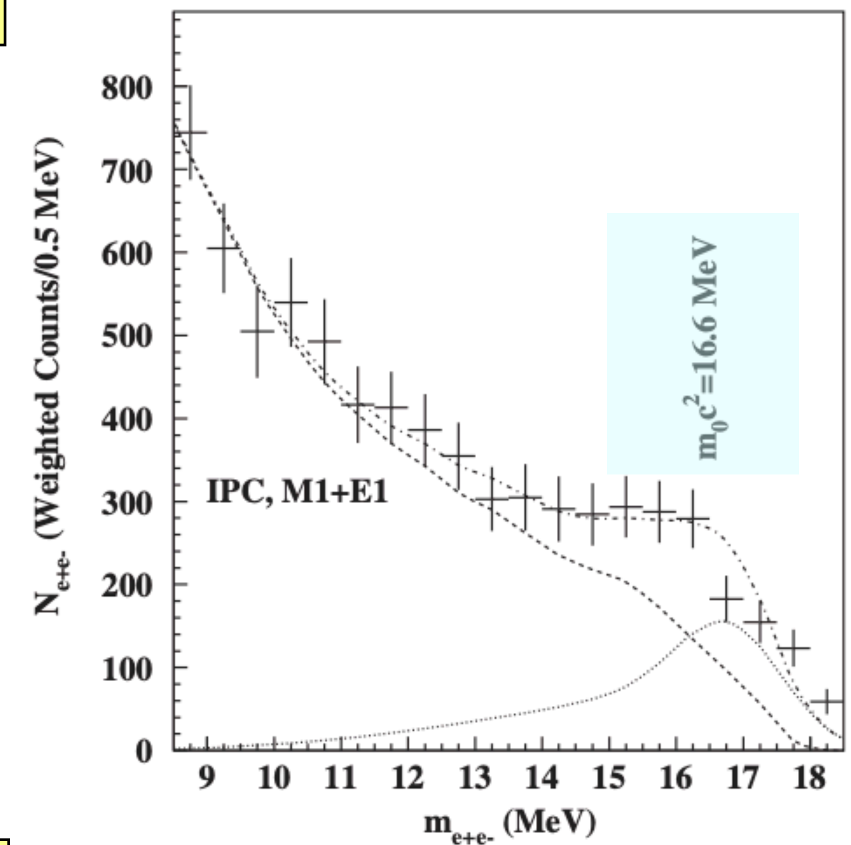

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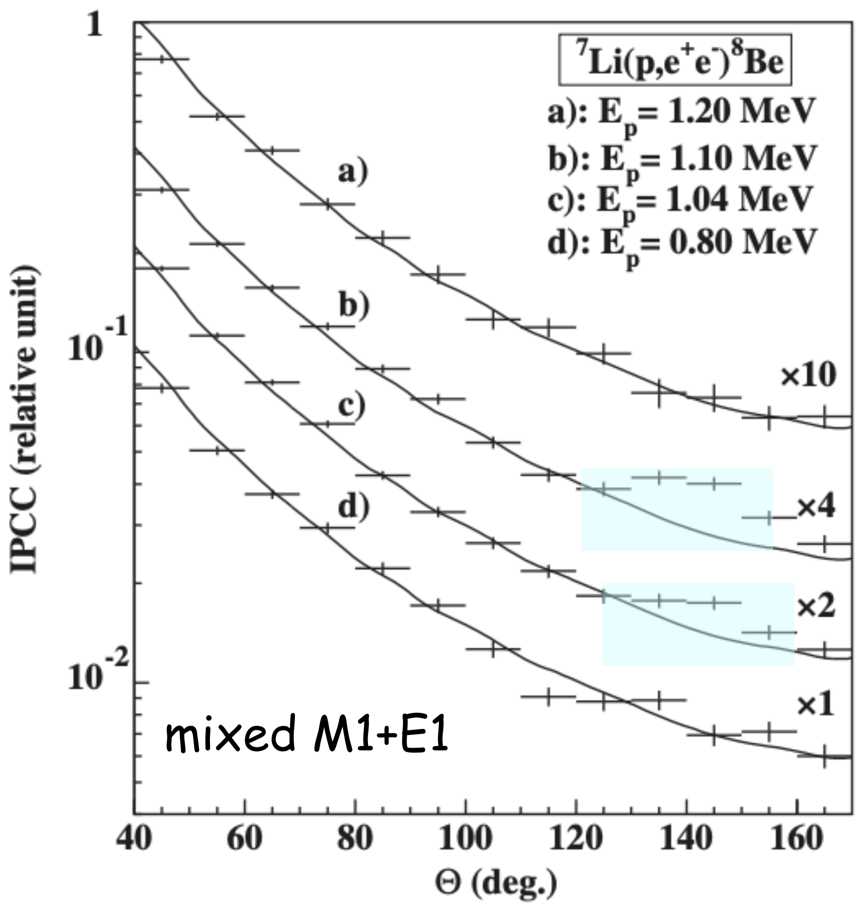

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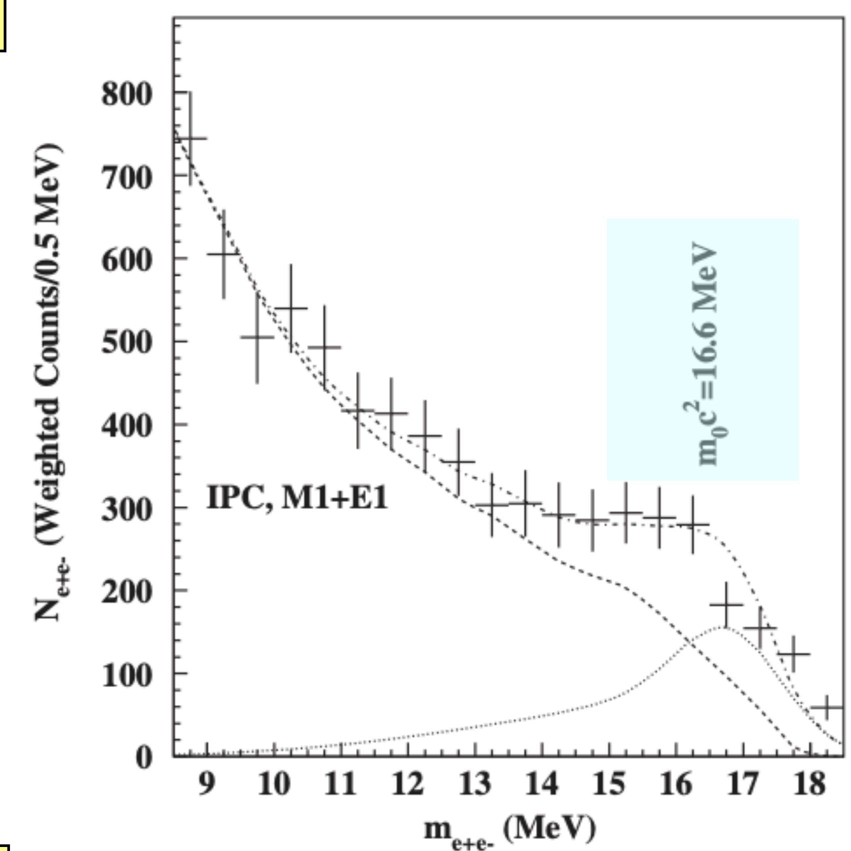
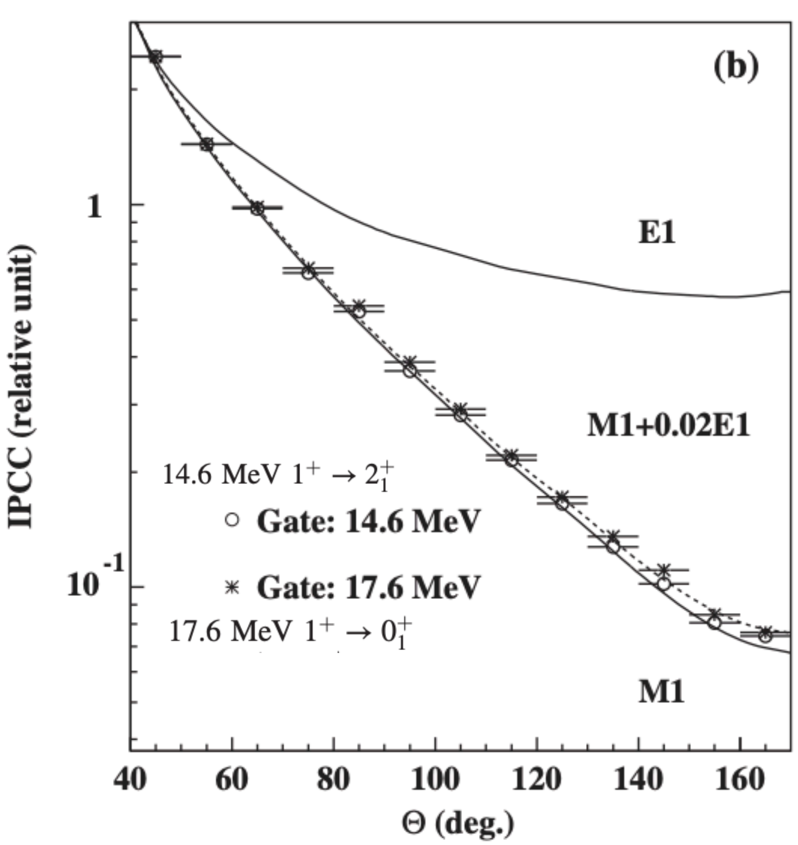


^{8}Be*(17.64MeV) IsoV



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,

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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.

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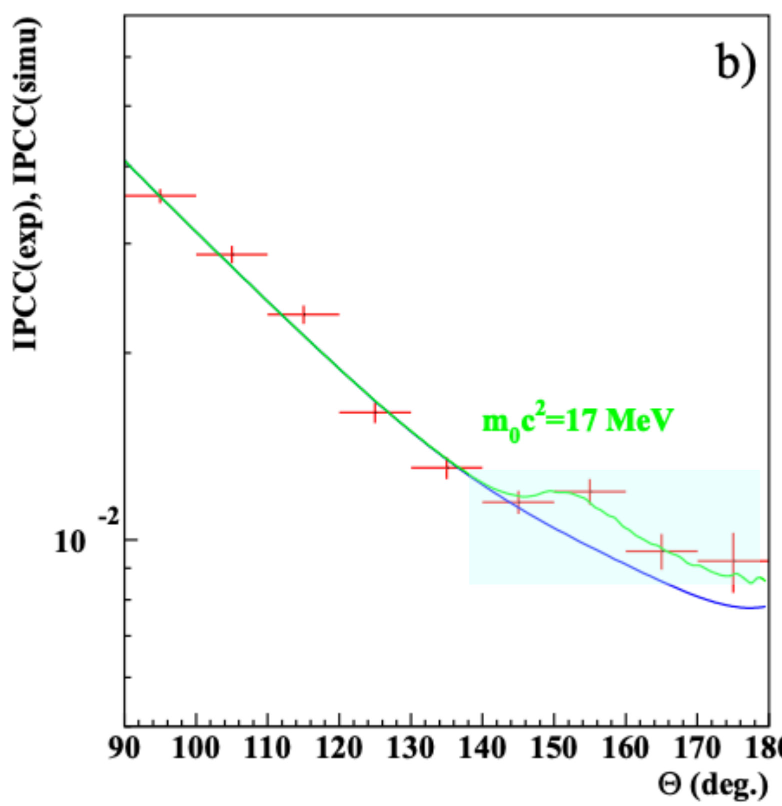
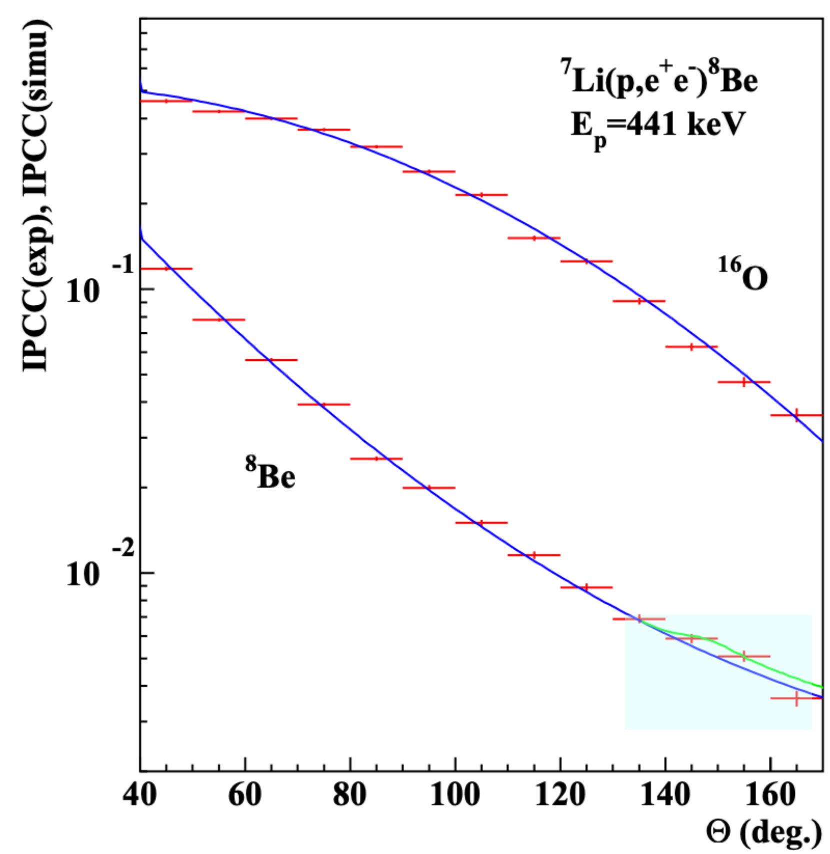
Bump location:
150° (17.64 MeV) vs.
140° (18.15 MeV)

Messina symposium (Oct 2016)



Bormio meeting (Jan 2017)



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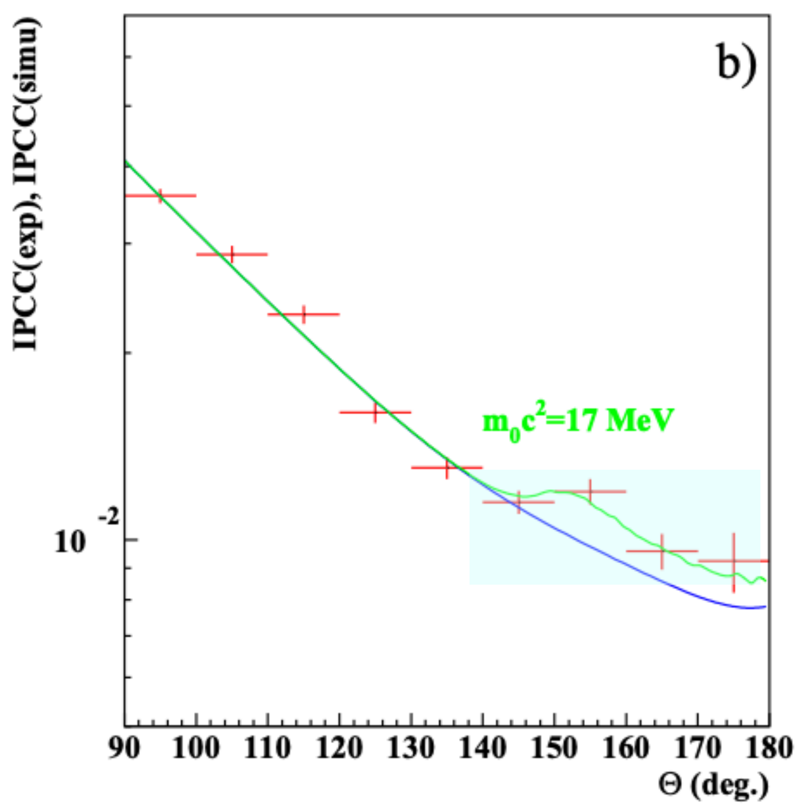

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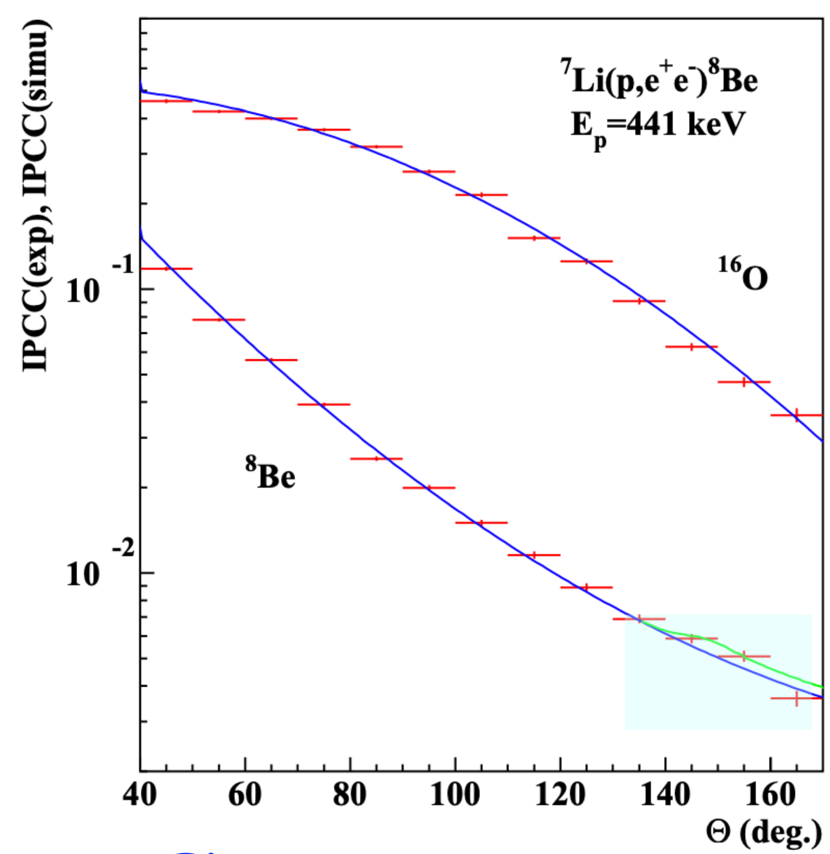


Axial vector boson

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 ?

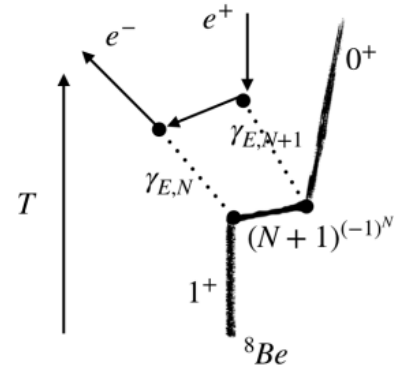
Zhang & Miller PLB, arXiv:1703.04588 [nucl-th]

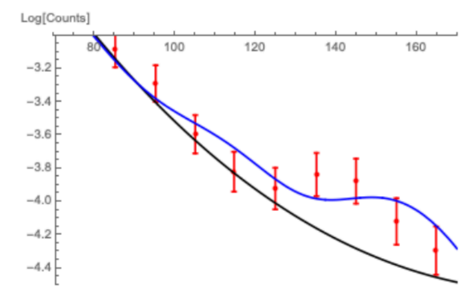
Interferences between different multipoles. Possibility of using the nuclear transition form factor to explain the anomaly

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.

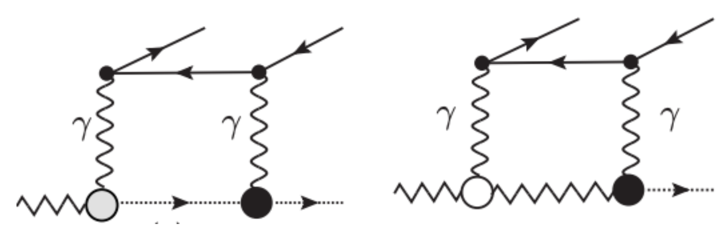
Zhang & Miller PLB, arXiv:2008.11288 [hep-ph]

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 a particle interpretation [Feng+, PRL 1604.07411 [hep-ph]; PRD 1608.03591 [hep-ph]]

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

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

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 $\pi^0 \to X\gamma$

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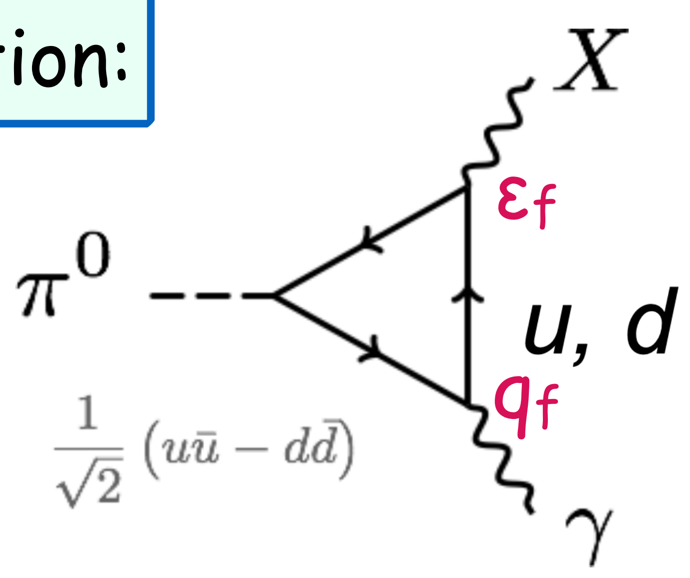

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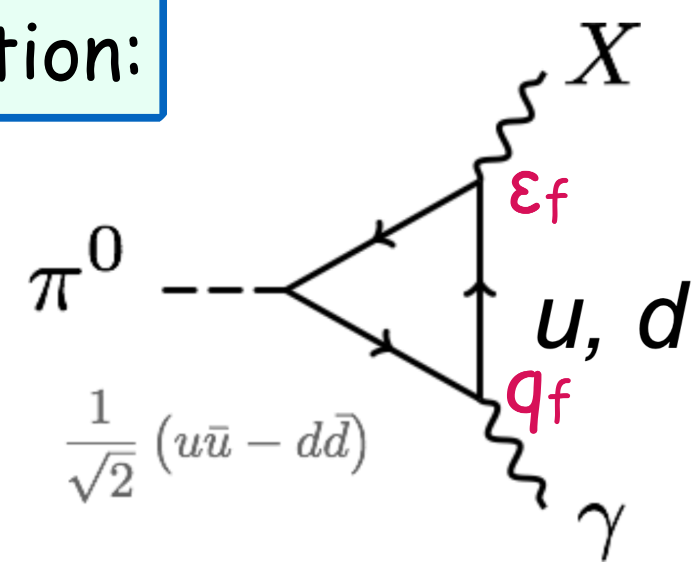
$B_X/B_\gamma \propto (\varepsilon_p+\varepsilon_n)^2 (p_X/p_\gamma)^3 \approx 6 \times 10^{-6}$ (Atomki)

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



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

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

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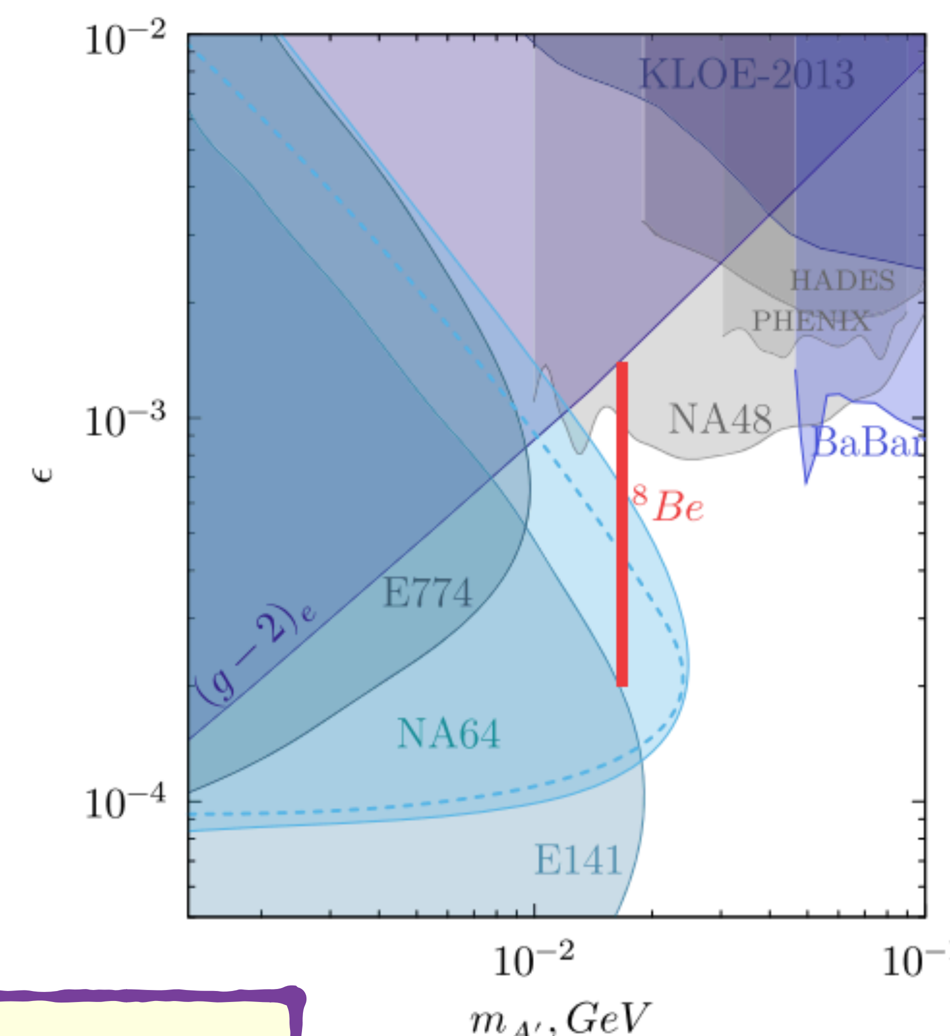
Current limits on X17

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

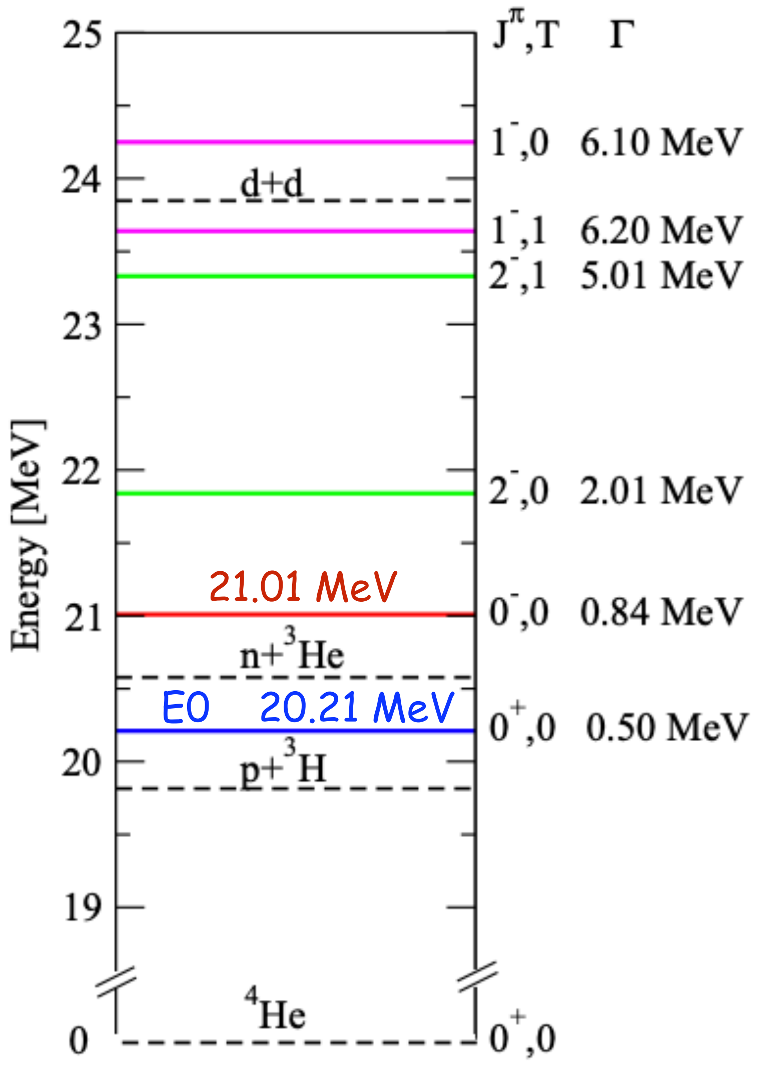
The X17 boson could be produced in the bremsstrahlung reaction $e^- Z \rightarrow e^- Z\, X$ by a high energy beam (150 GeV) of electrons incident on the active target in the NA64 experiment, and observed through its decay $X \rightarrow e^+e^-$



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

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

Helium 4 nuclear transitions



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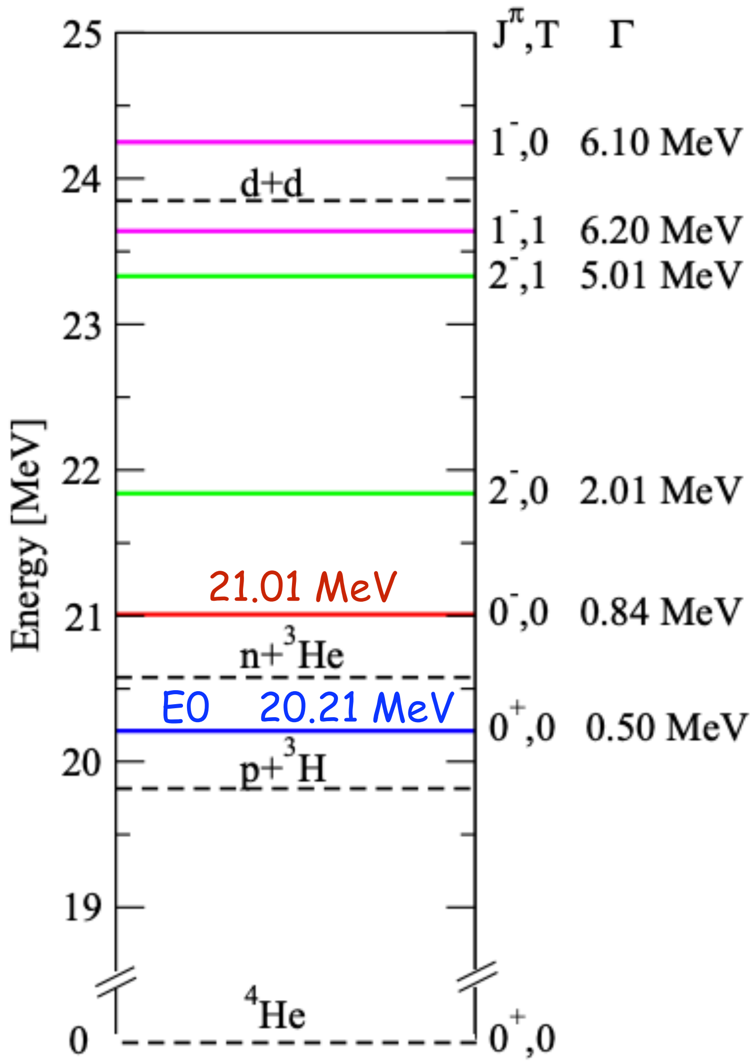
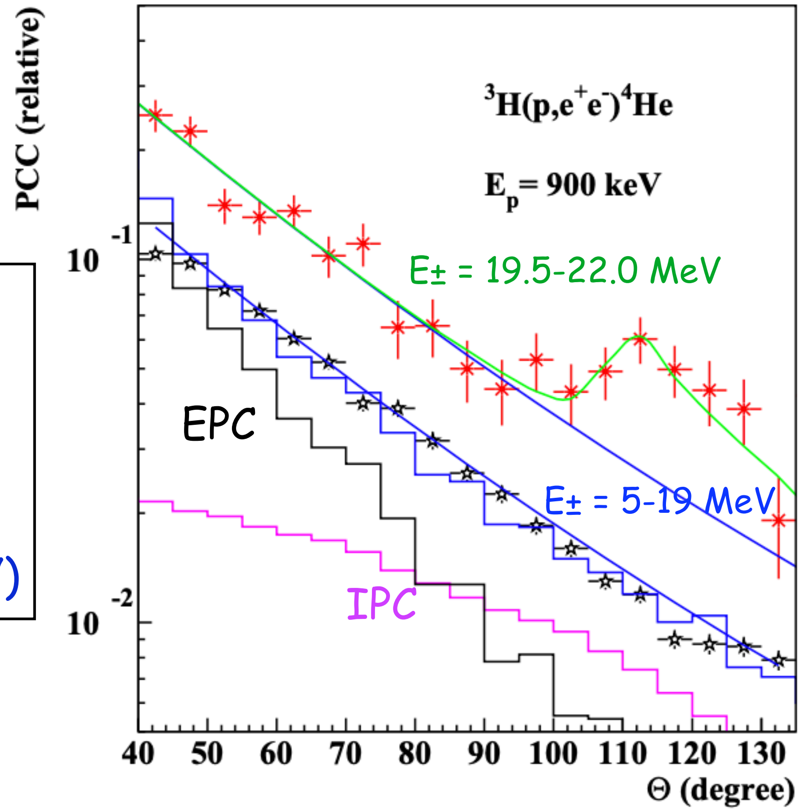
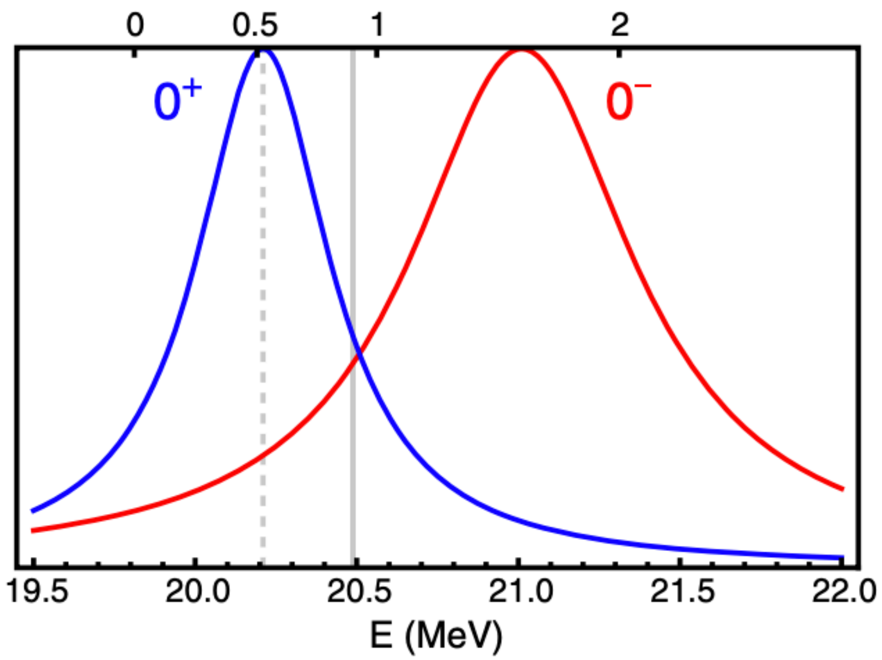


arXiv:1910.10459 [nucl-ex] E_p=900 keV
(below E(p,n) = 1.018 keV threshold)
excites the ^{4}He nucleus to E*=20.49 MeV
and populates the second ^{4}He excited state
0^-(21.01 MeV) overlapped with 0^+(20.21 MeV)





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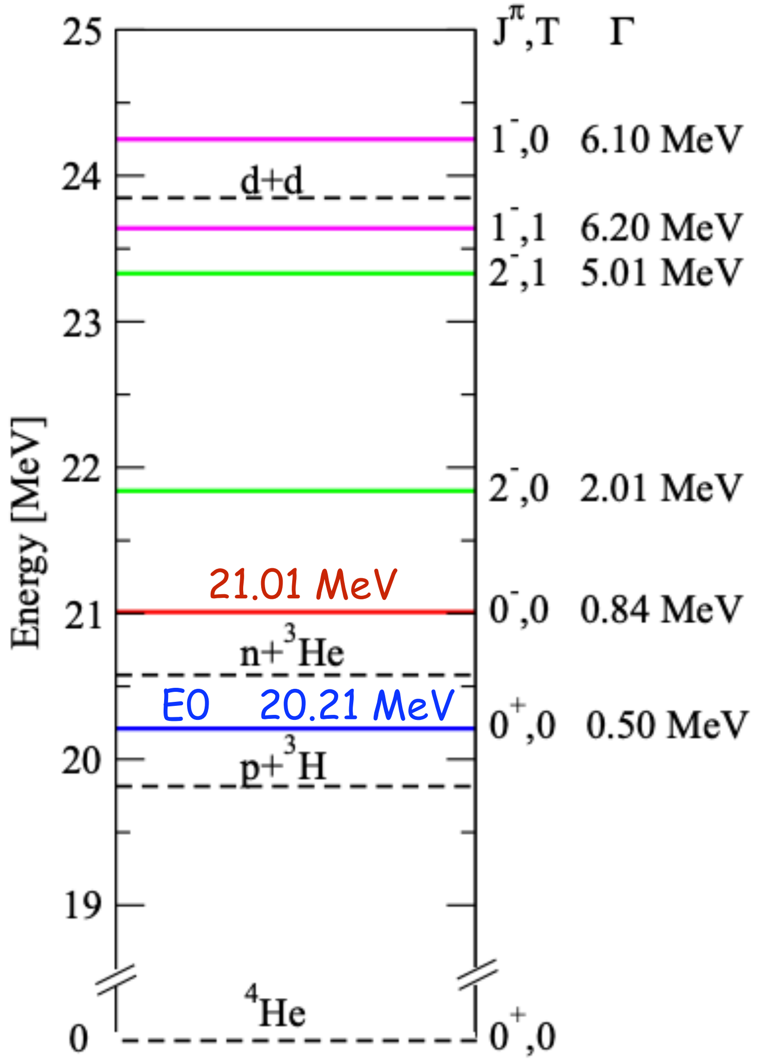

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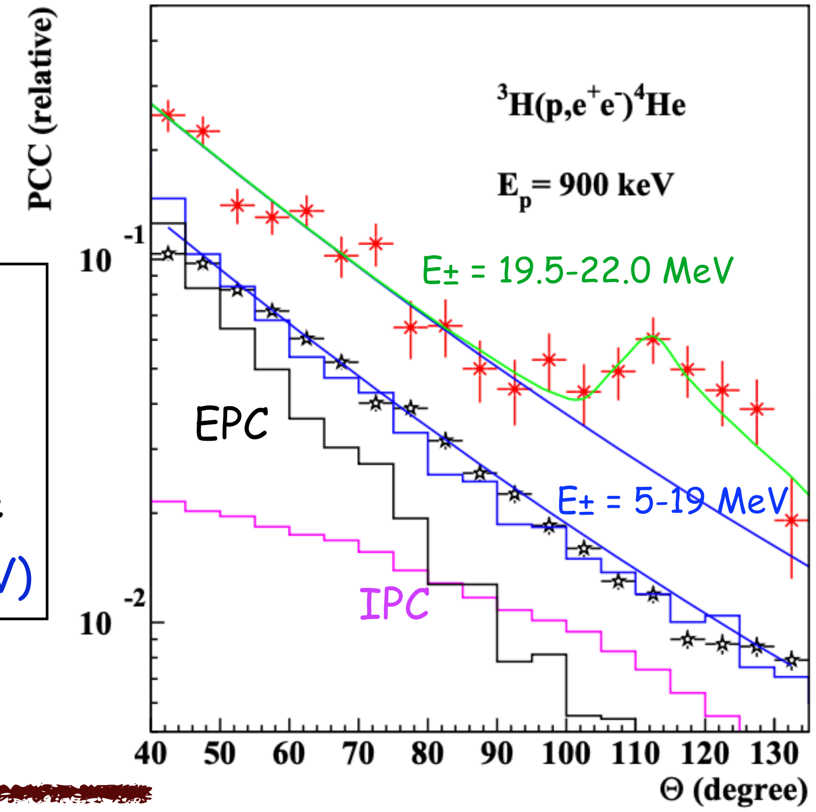

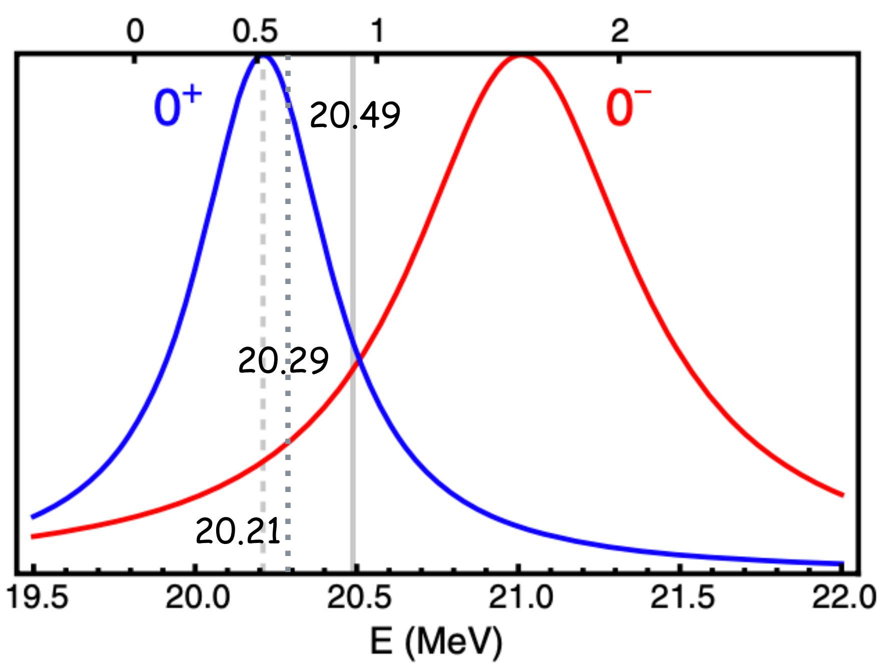

PRC (2021) [arXiv:2104.1075 [nucl-ex]]
E_p = 510, 610, 900 keV to induce direct
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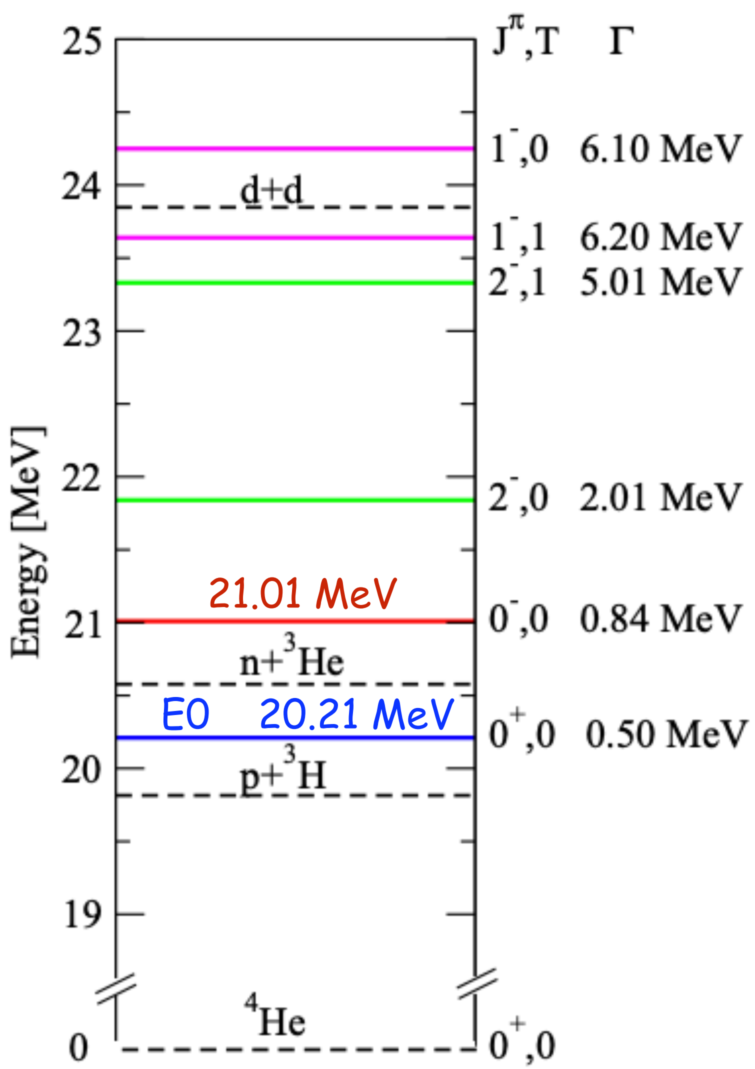

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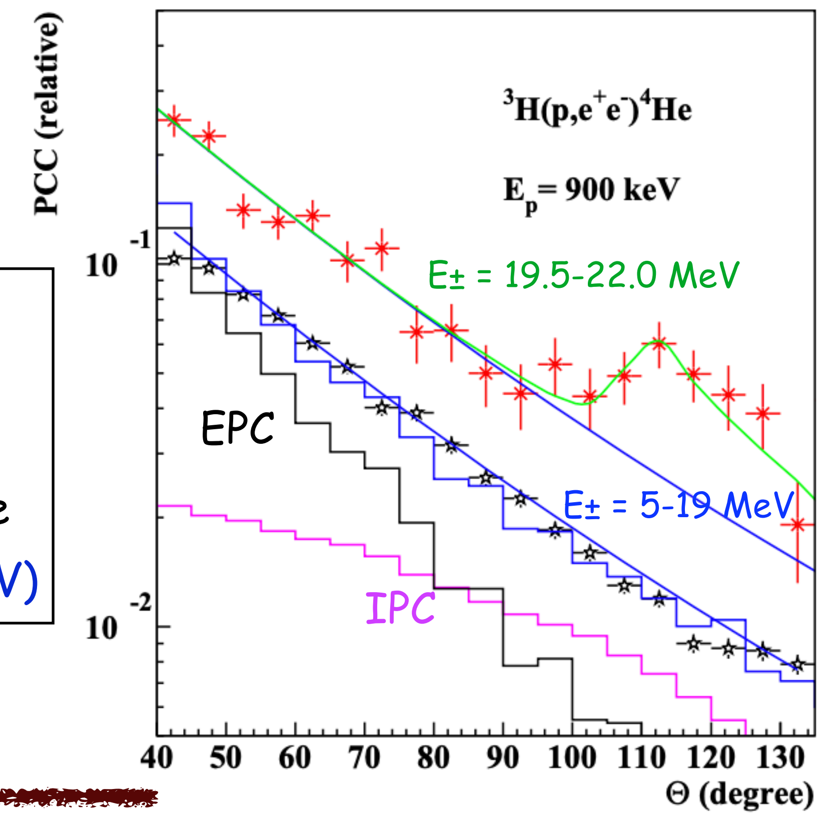

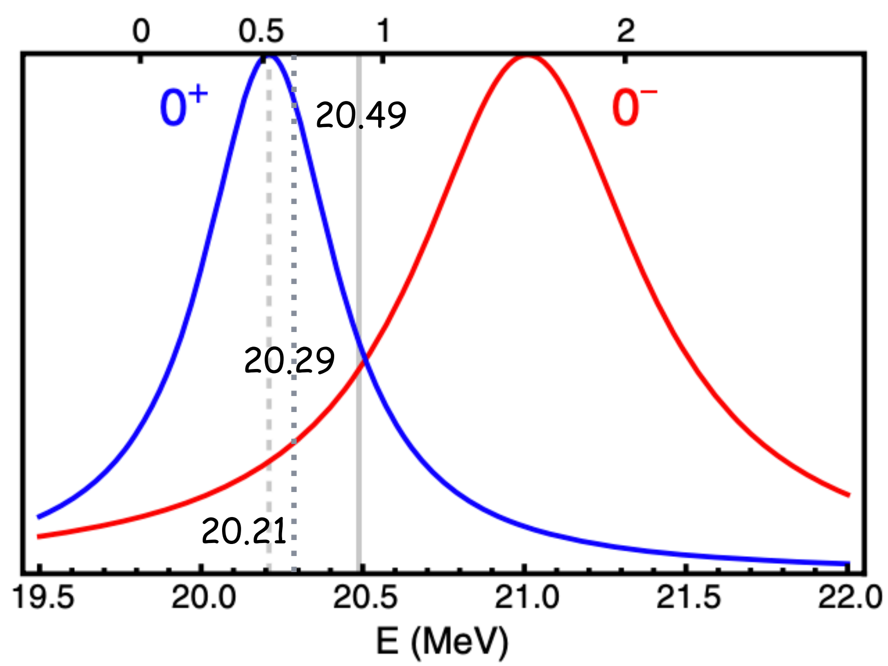

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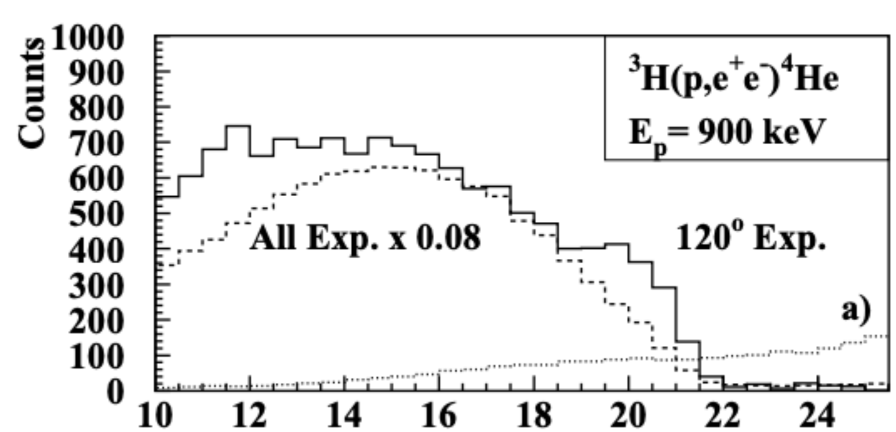

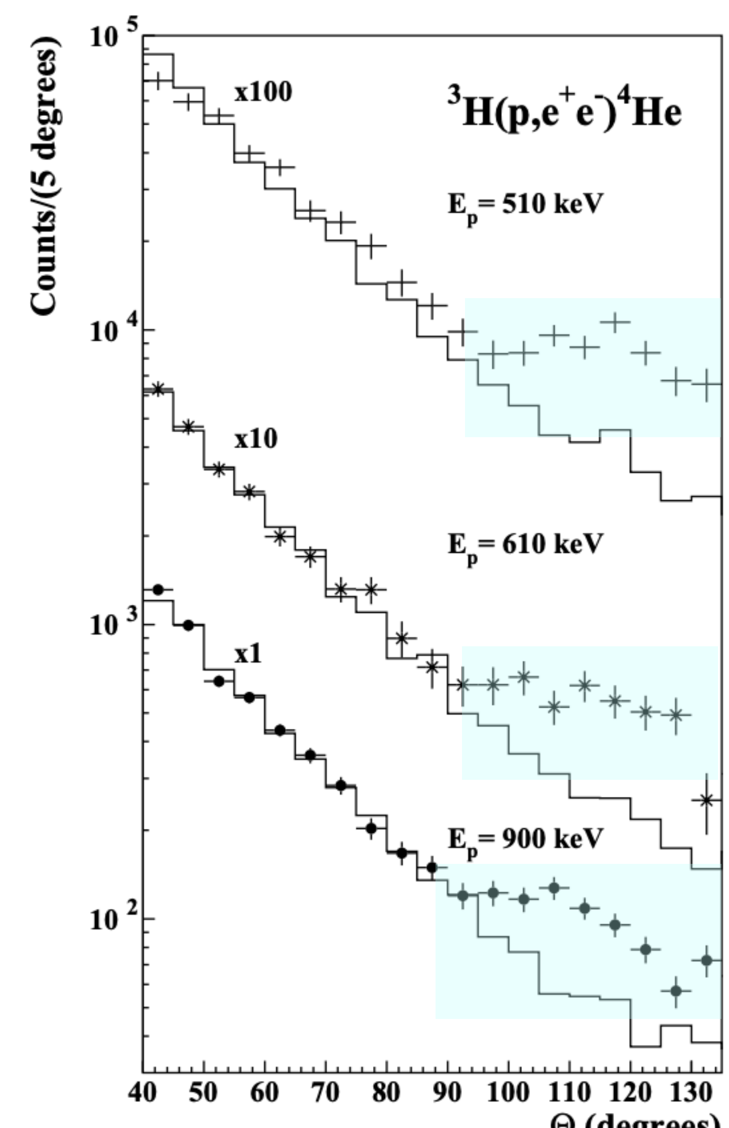

^{4}He anomaly: Standard Model explanations ?

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The X17 boson and the $^3H(p,e^+e^-)^4He$ and $^3He(n,e^+e^-)^4He$ 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
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<u>Main results:</u>

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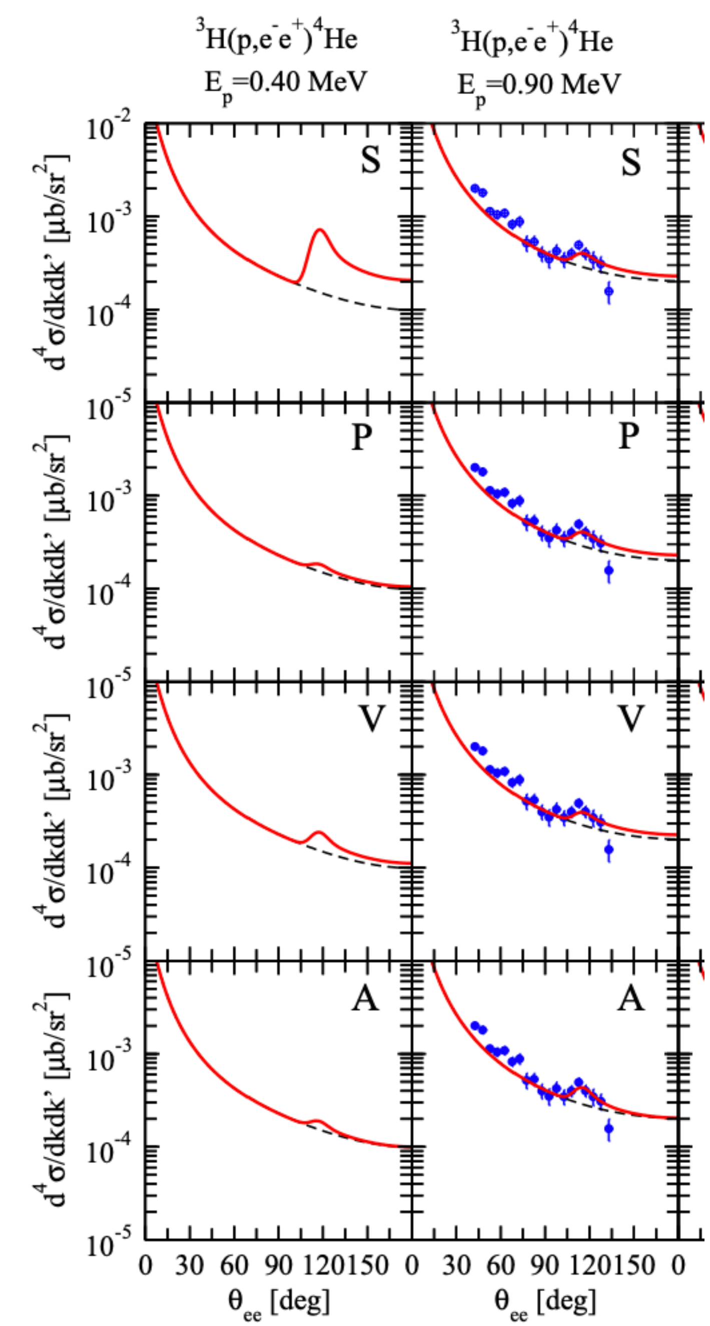
- Measurements at $\theta_{\nu_p} \neq 90^o$ can discriminate X=V,A,S,P



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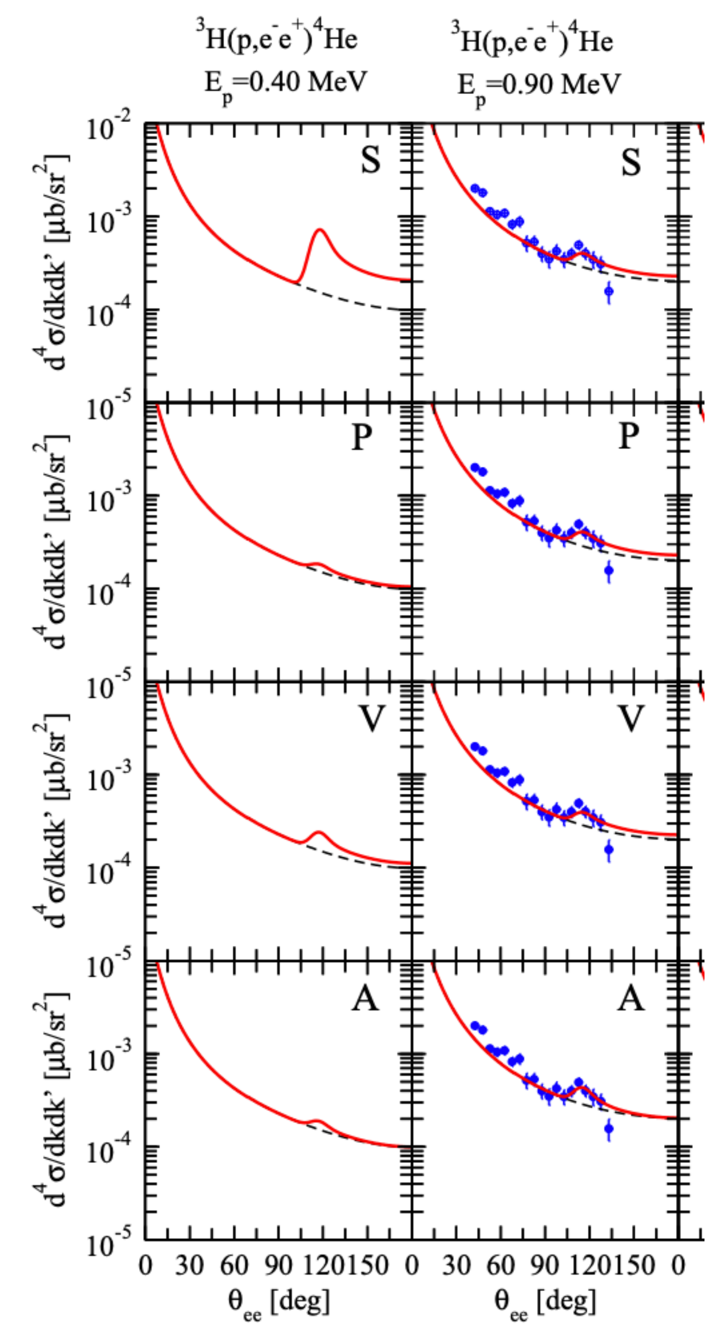

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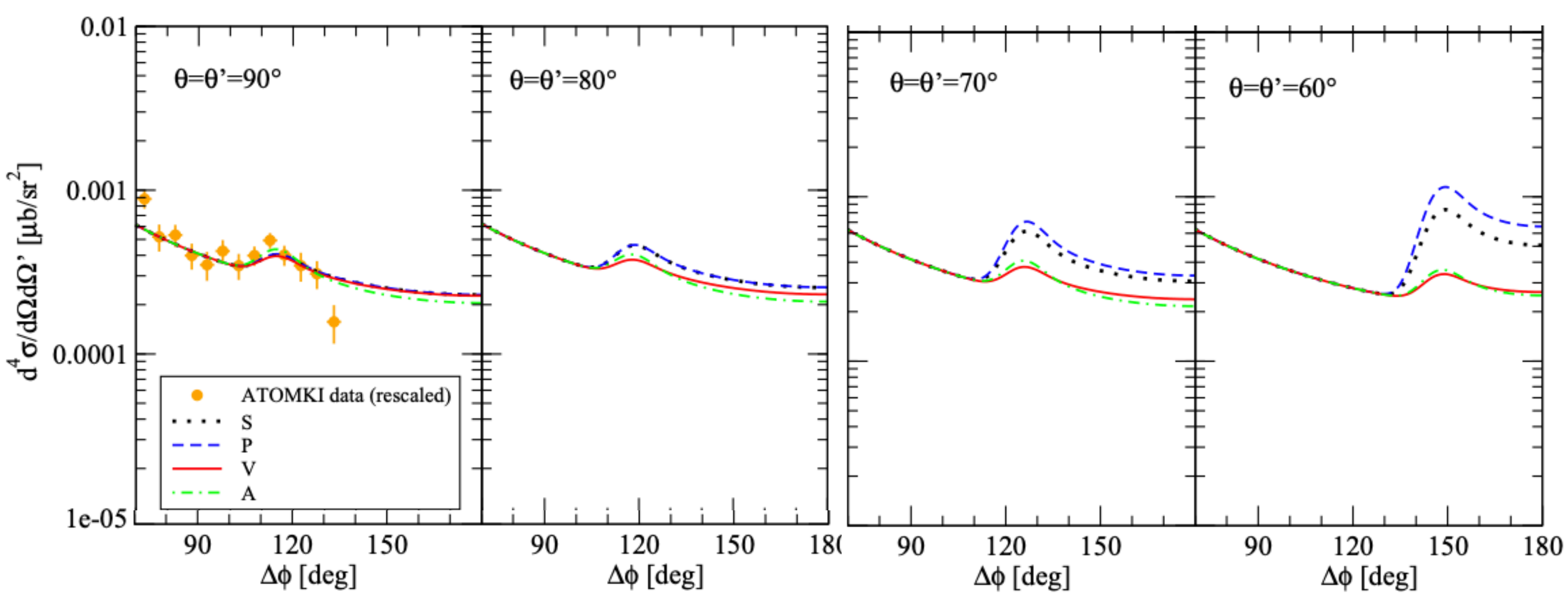

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The theor. values are: $\theta^{min}_{\pm}$ = 112° [^{4}He(20.49)]; 139°[^{8}Be(18.15)]; 161° [^{12}C(17.23)].

[Exact for spin 0, approximate for spin 1]

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N_*	$J_*^{P_*}$	T_*	Γ_{N_*} [keV]	$B(N_* \to N_0\gamma)$
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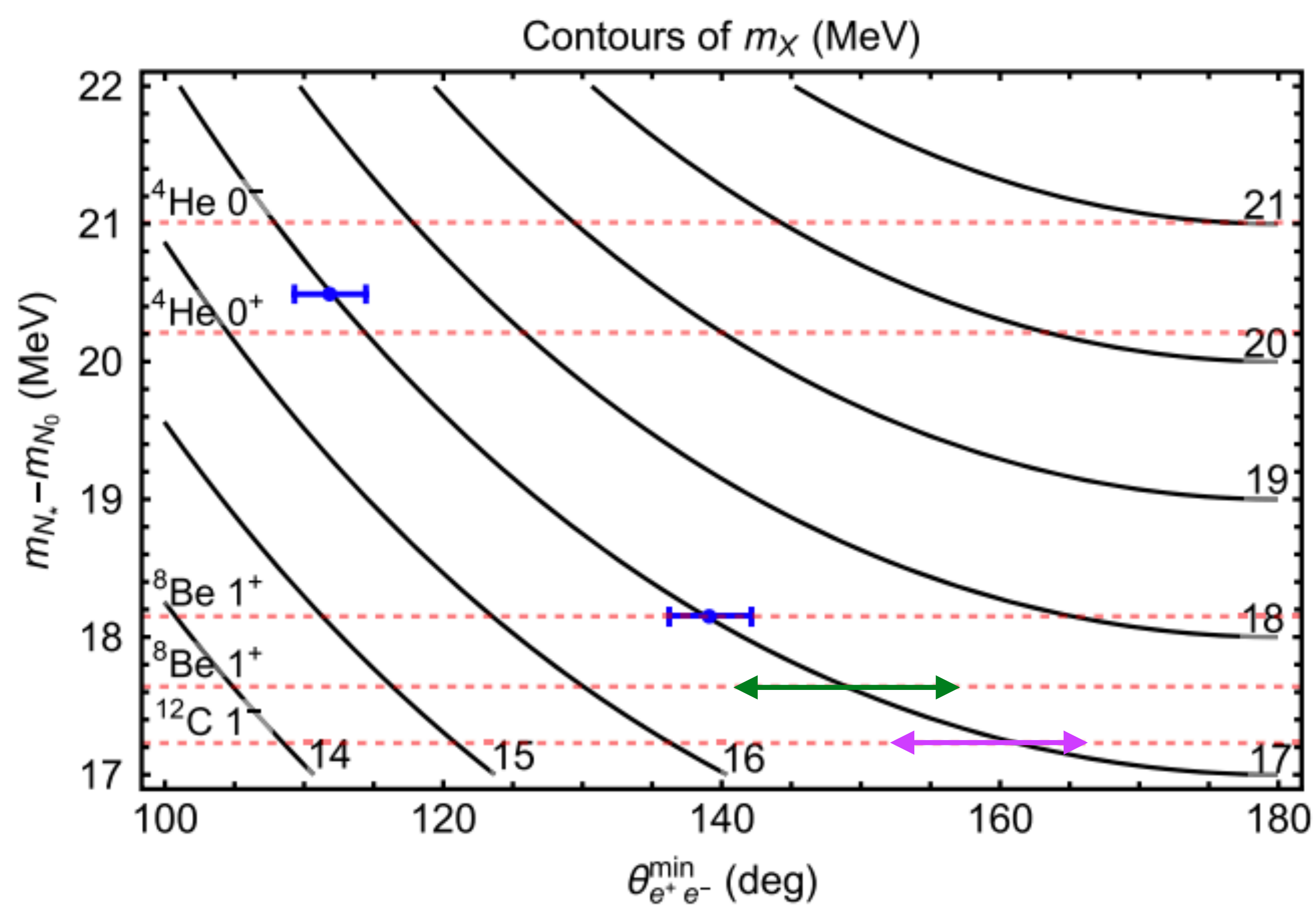

Preliminary results for ^{12}C

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

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

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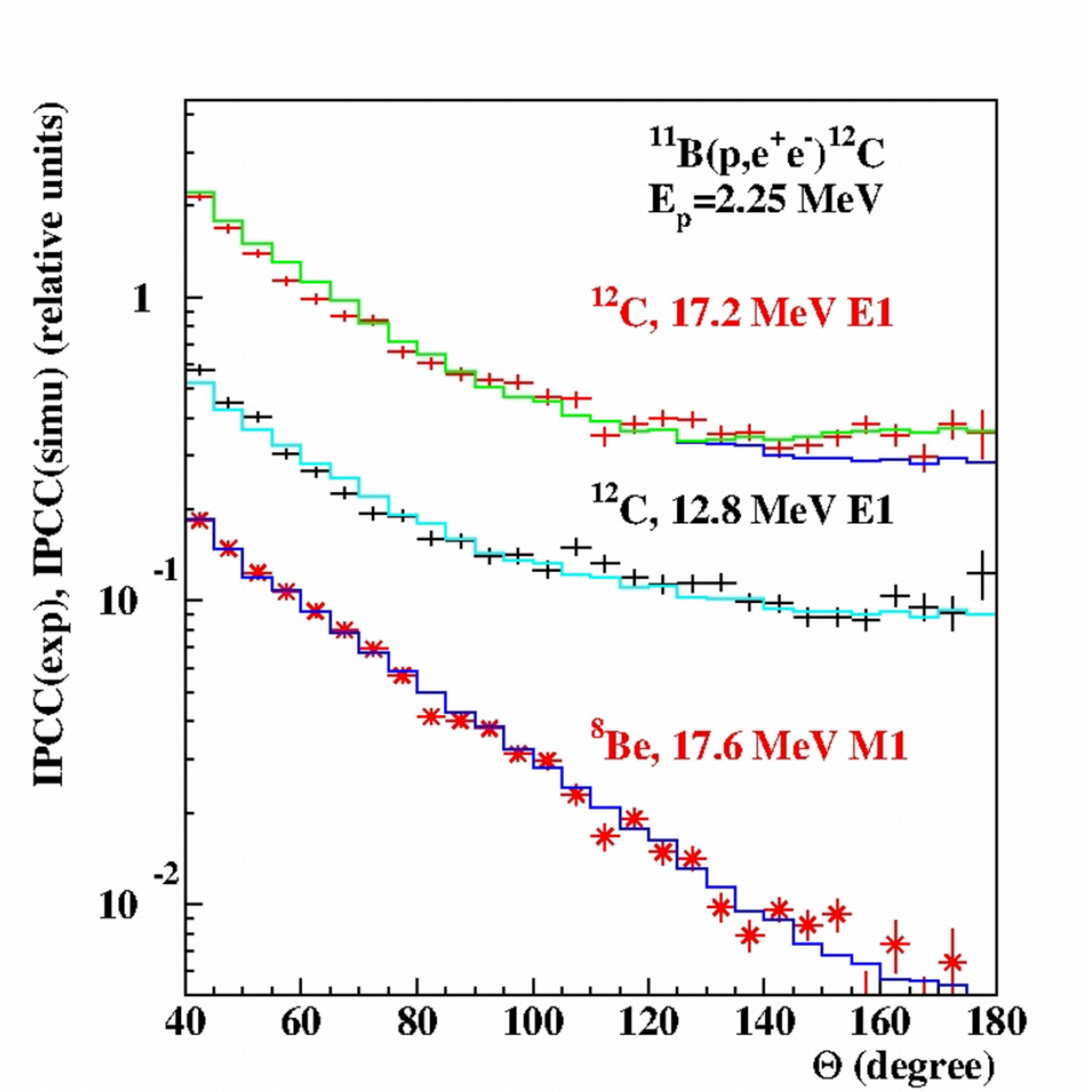
A. Krasznahorkay
"Shedding light on X17 Workshop
Rome, September 6-8, 2021



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

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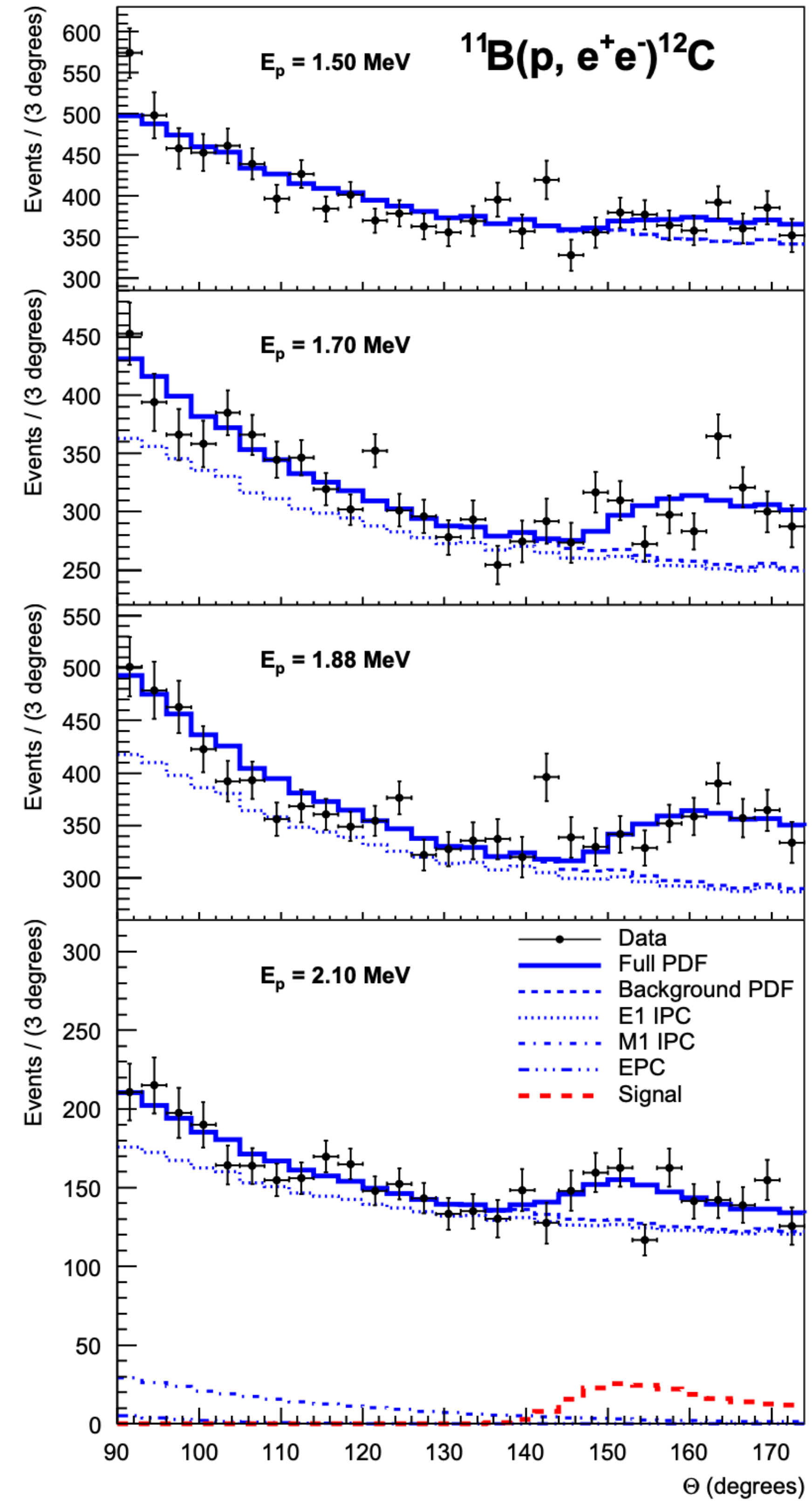
E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	



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

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Measured X_{17} 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 X_{17} couplings ?

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

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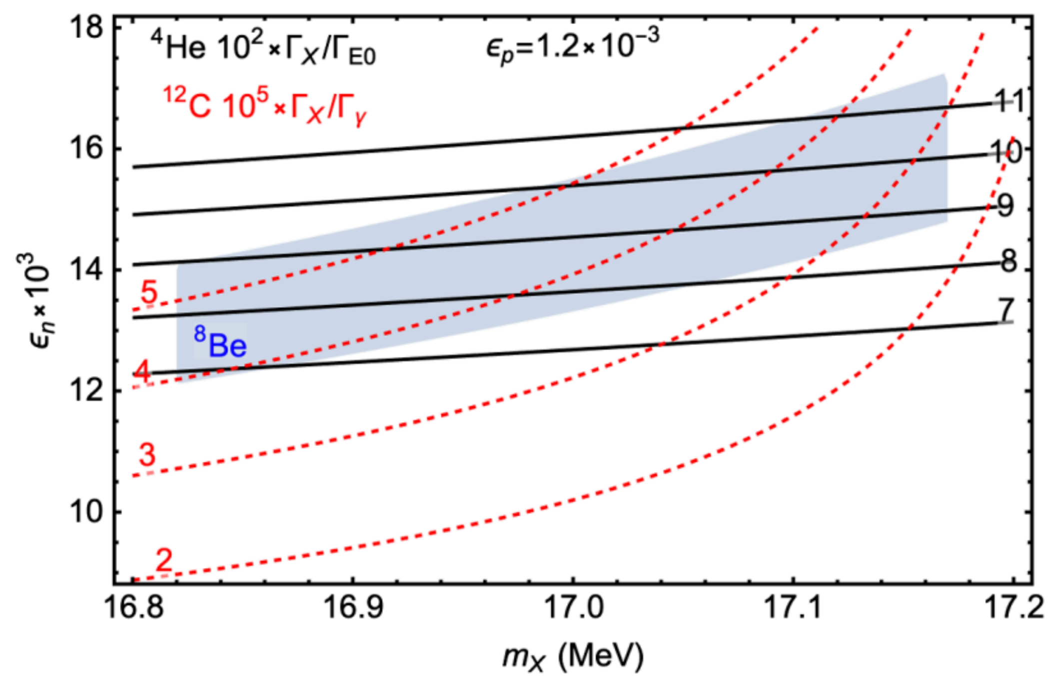
$$\frac{\Gamma_X^{\mathrm{Be}}}{\Gamma_\gamma^{\mathrm{Be}}} \equiv \frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + X)}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq 6 \times 10^{-6} \qquad {}^8\mathrm{Be}^*(18.15)$$

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

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



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

Allowed nuclear transitions and X_{17} 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:

$J^* = L \oplus J_X$

$P^* = (-1)^L P_X$

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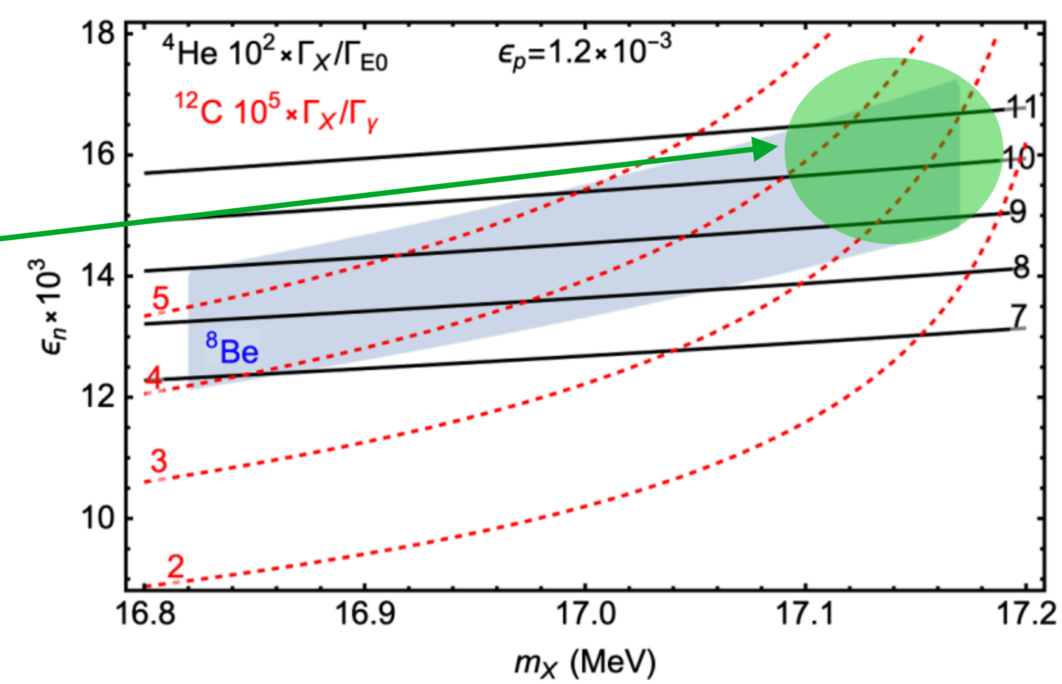
Are these branchings consistent with a single set of X_{17} couplings ?

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

Axial vector: might also explain ^{8}Be - ^{4}He - ^{12}C consistency

(See Barducci & Toni, arXiv:2212.06453)



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 strongly disfavoured ^{8}Be [Zhang+, (2017)]; ^{4}He [Viviani+, (2021)]
- ^{8}Be - ^{4}He - ^{12}C anomalies kinematically & dynamically consistent for V (and A)
  (see Barducci & Toni, arXiv:2212.06453)
- For ^{12}C the effect was predicted, and confirmed by experimental data

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Indeed PADME has the capability to provide a truly extraordinary evidence for the X17 !

Experimental perspective: Mostly 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 ?)

U. Montreal: Tandem Van de Graaff $E_p \in$ 0.4-1.0 MeV: ^{8}Be*(18.15MeV)

Data Taking should take place in early 2023 [arXiv:2211.11900 [physics.ins-det]]

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

^{4}He via ^{3}H(p,e$^+$e$^-$)^{4}He 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

^{3}He(n,e$^+$e$^-$)^{4}He. Measurements: 2023-24 (CERN LoI approved CERN-INTC-2021-041 / INTC-I-233)

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

IPN@ORSAY (?)

Validation/confutation from a particle physics experiment

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

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BTF@LNF: $E_+ \sim$ 150 - 500 MeV

$\sqrt{s} \sim$ 12.5 - 22.5 MeV

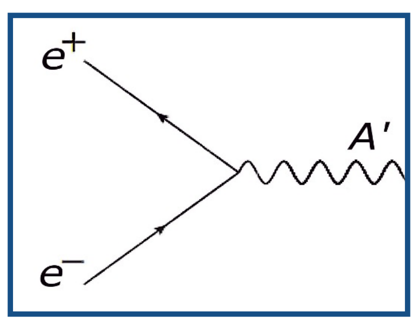
M_X=17 MeV E_+=285 MeV

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

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

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

"Huge" cross section !



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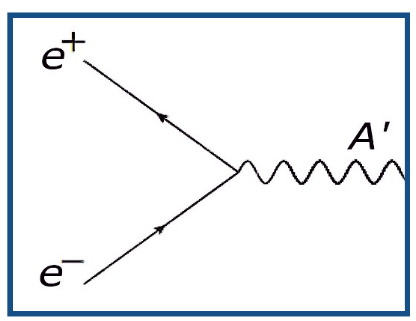
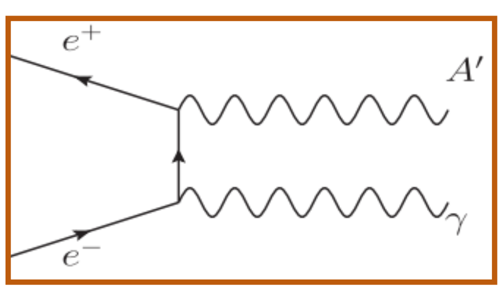
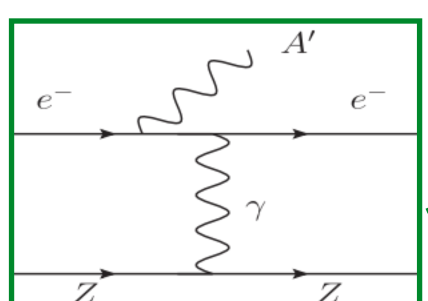
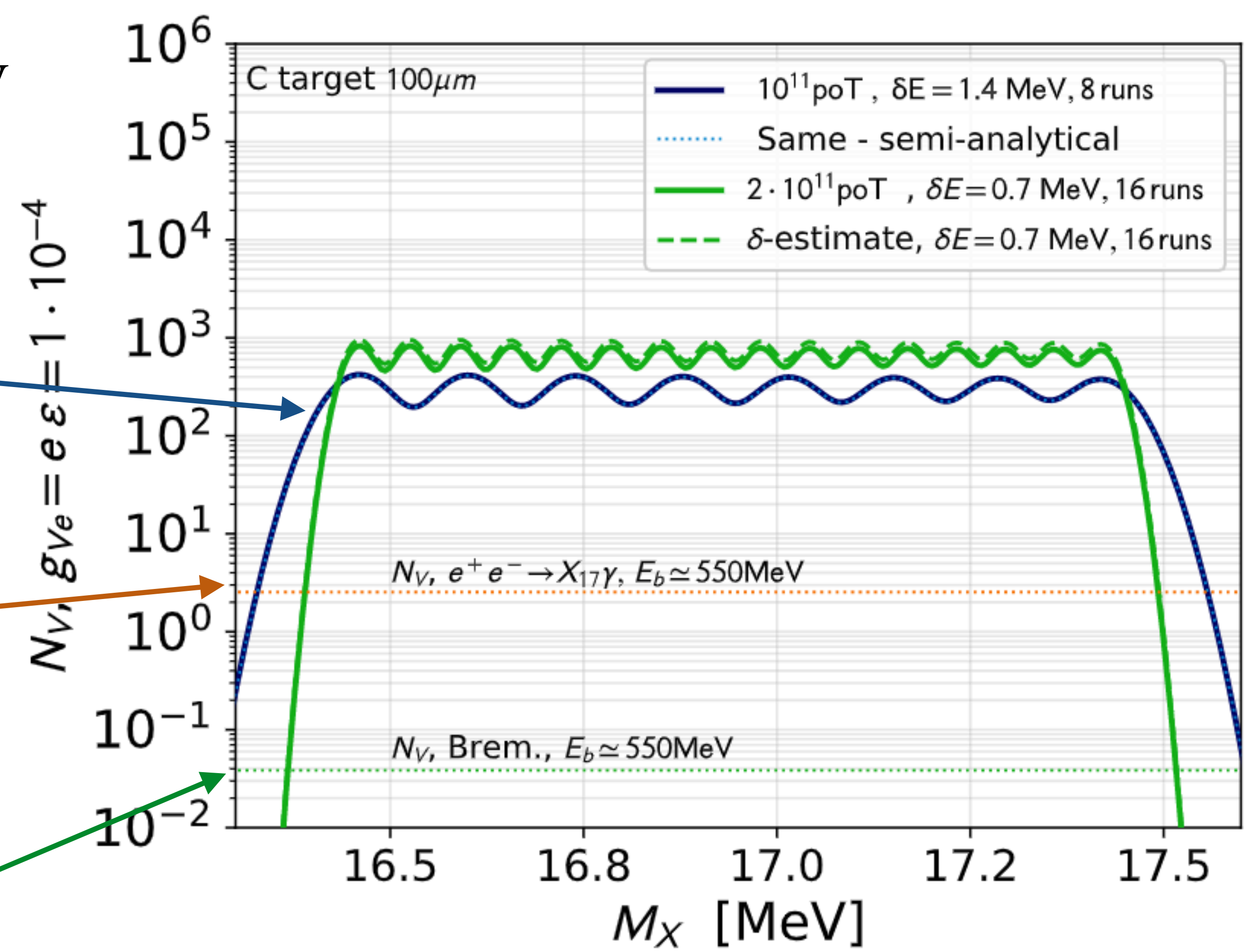


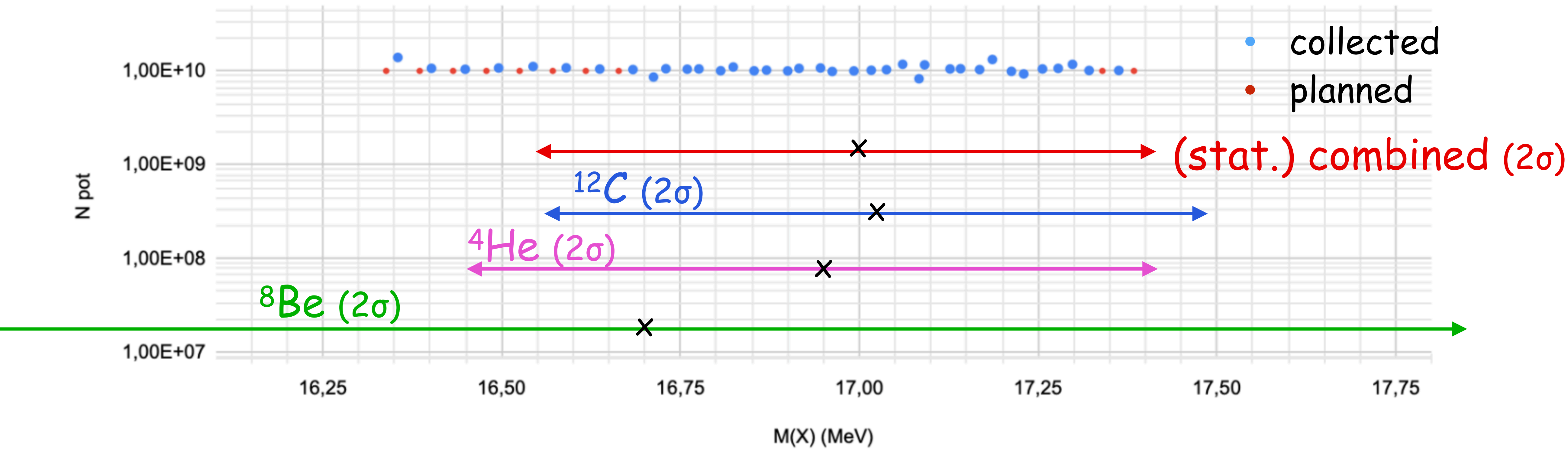


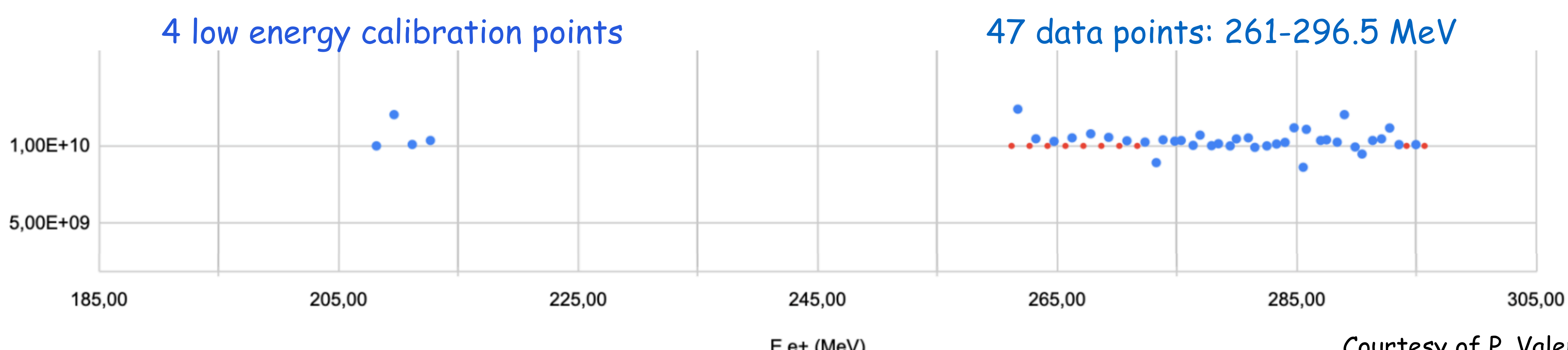




Resonant search for the X17 boson at PADME

Current status of data taking





Courtesy of P. Valente

Resonant X17 search at PADME: EXCLUSION

- 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, better than we expected
- 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)

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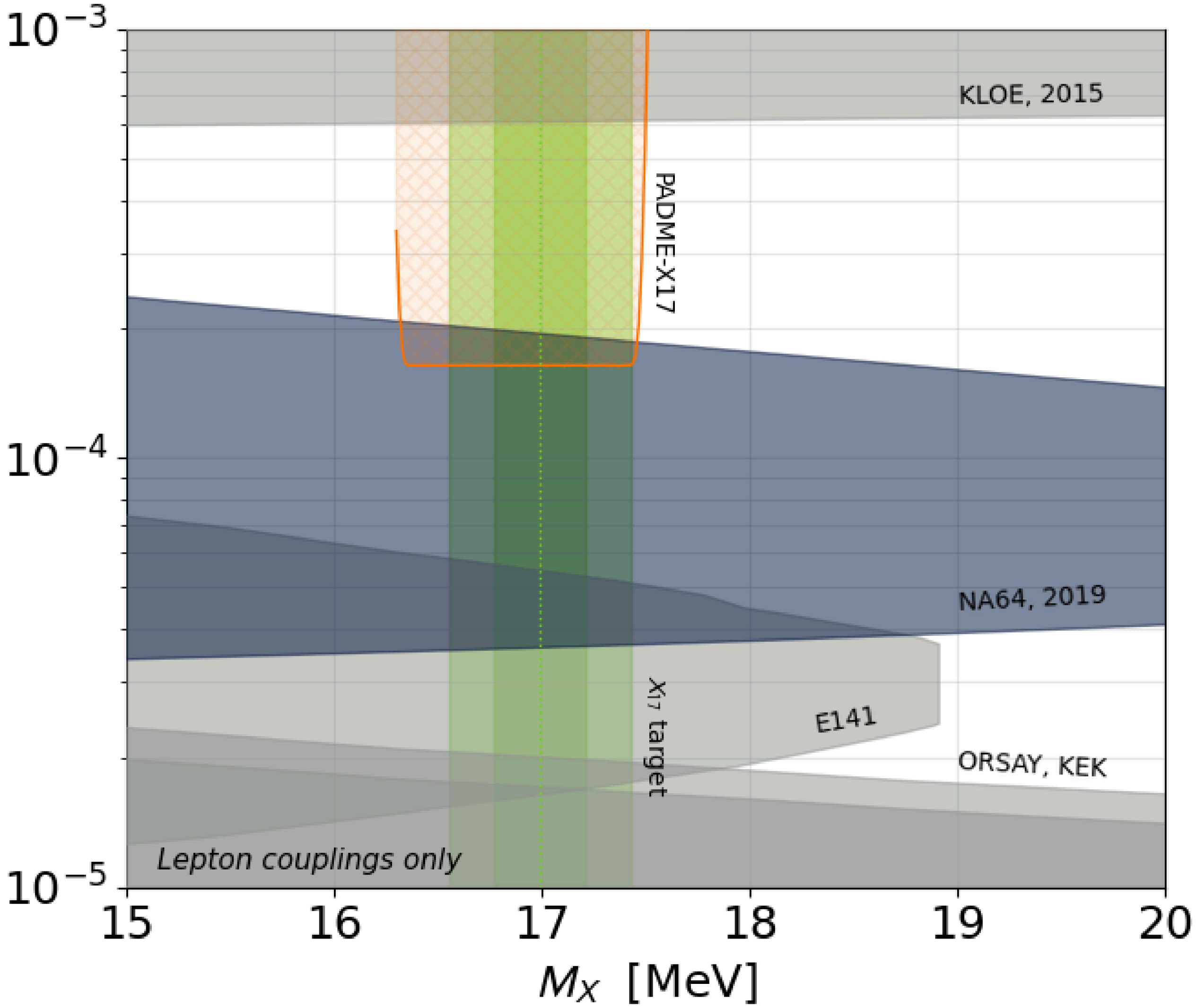

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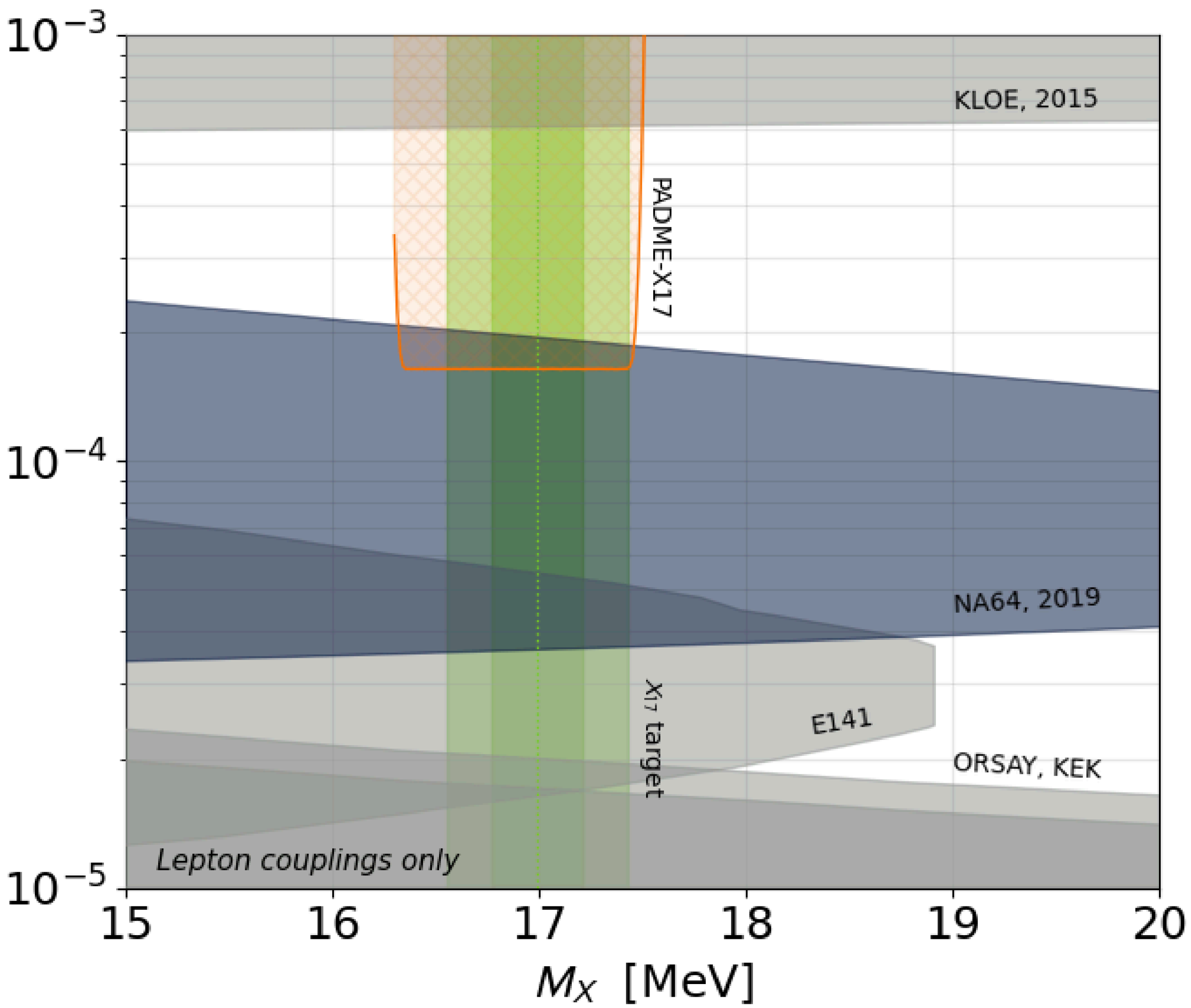
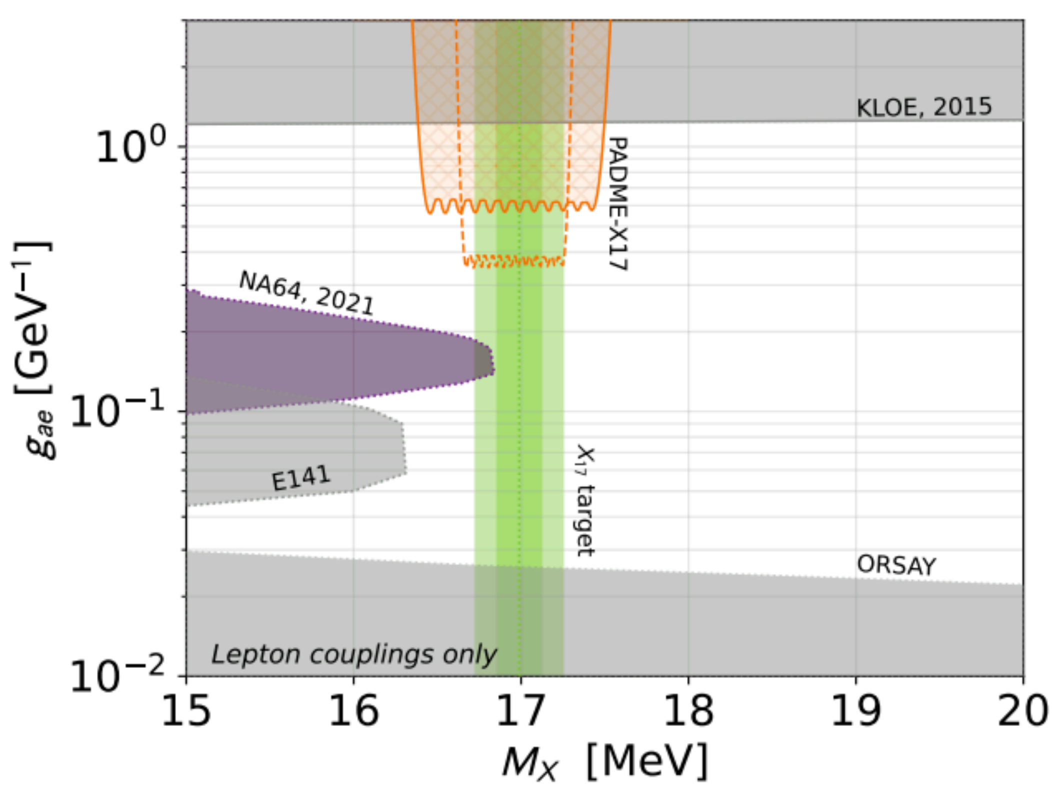


Pseudoscalar



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Resonant X17 search at PADME: VALIDATION

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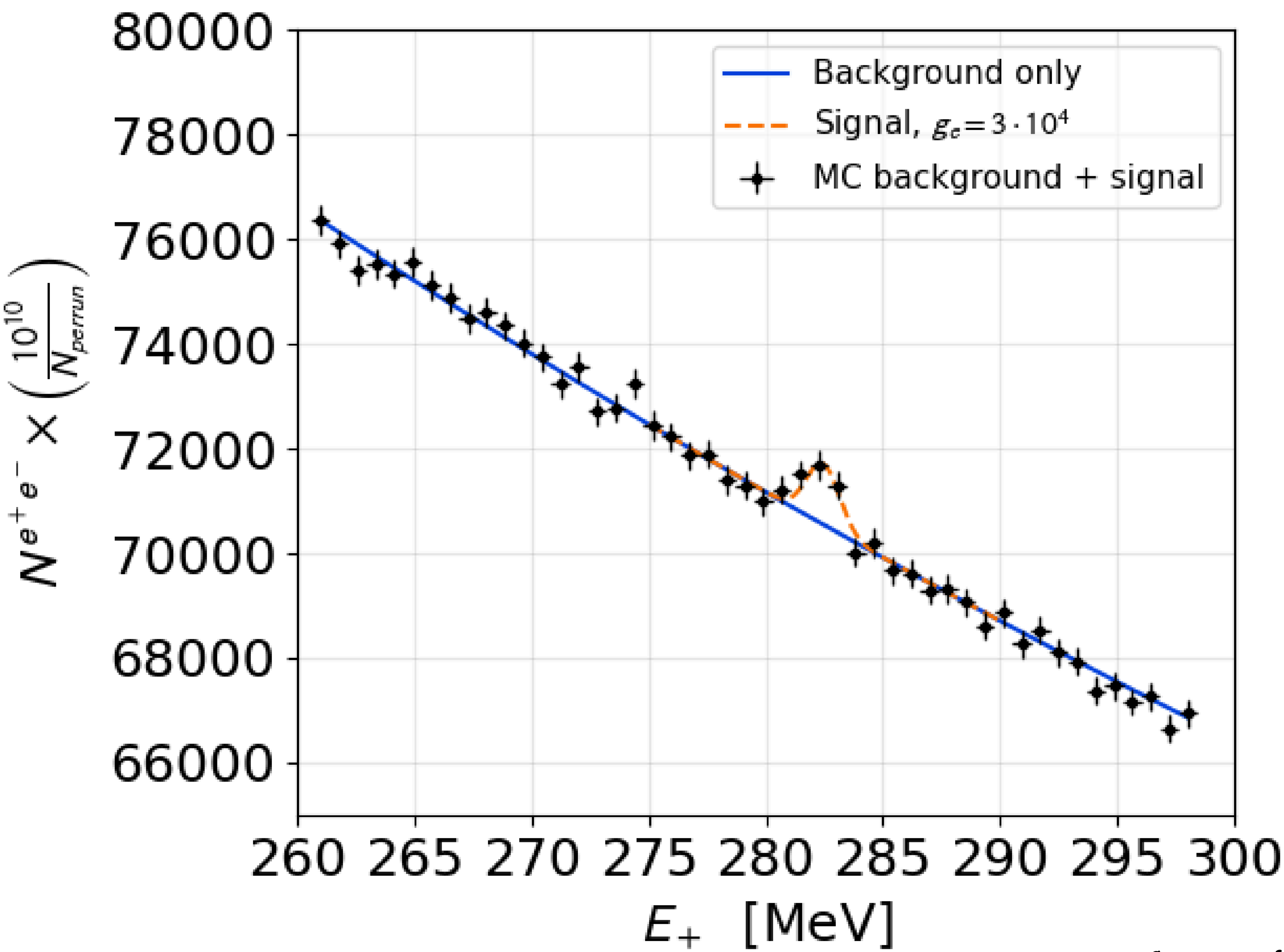

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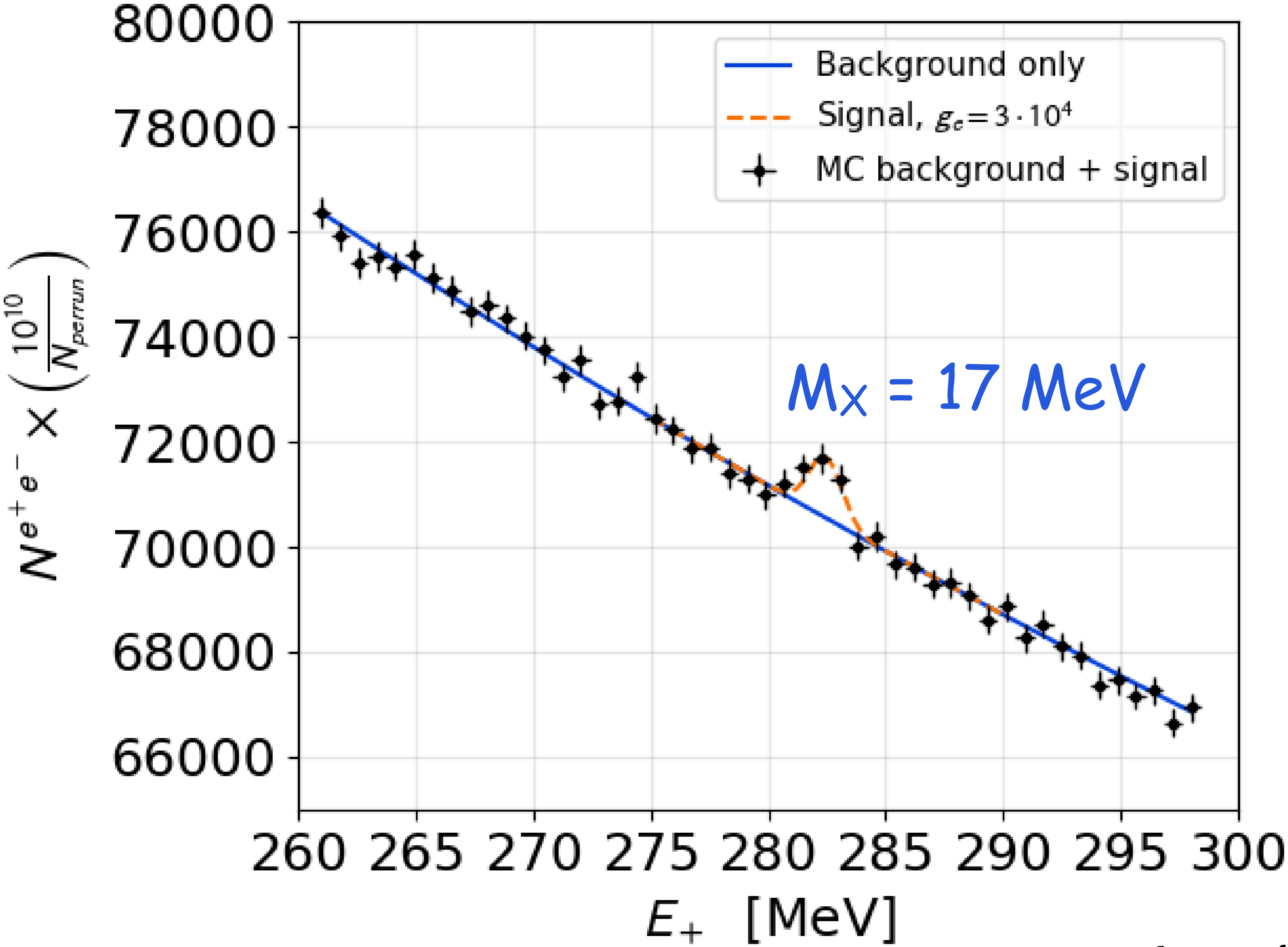

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- Three anomalies observed in nuclear transitions appear to be consistent with a particle physics interpretation (X_{17})
- Statistical evidence is very strong (~ 7σ for each nucleus)
- Explanations via higher order nuclear effects, interferences, higher multipoles contributions, are theoretically (strongly) disfavoured…
- Present data from a single experiment. Independent validation needed.
- Intense effort for new Nucl. Phys. experiments is ongoing. First results expected in late 2023.
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Acknowlegments

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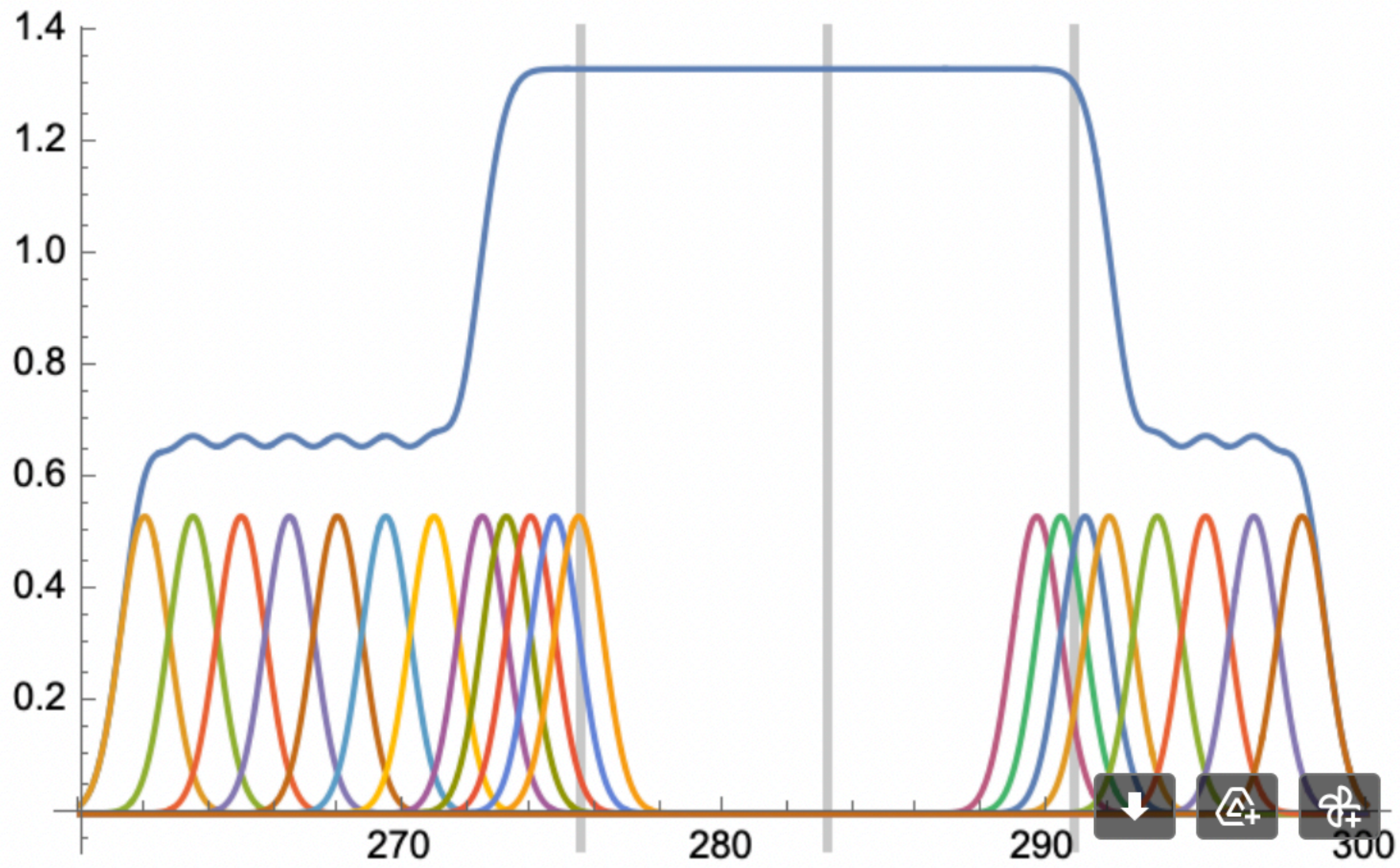
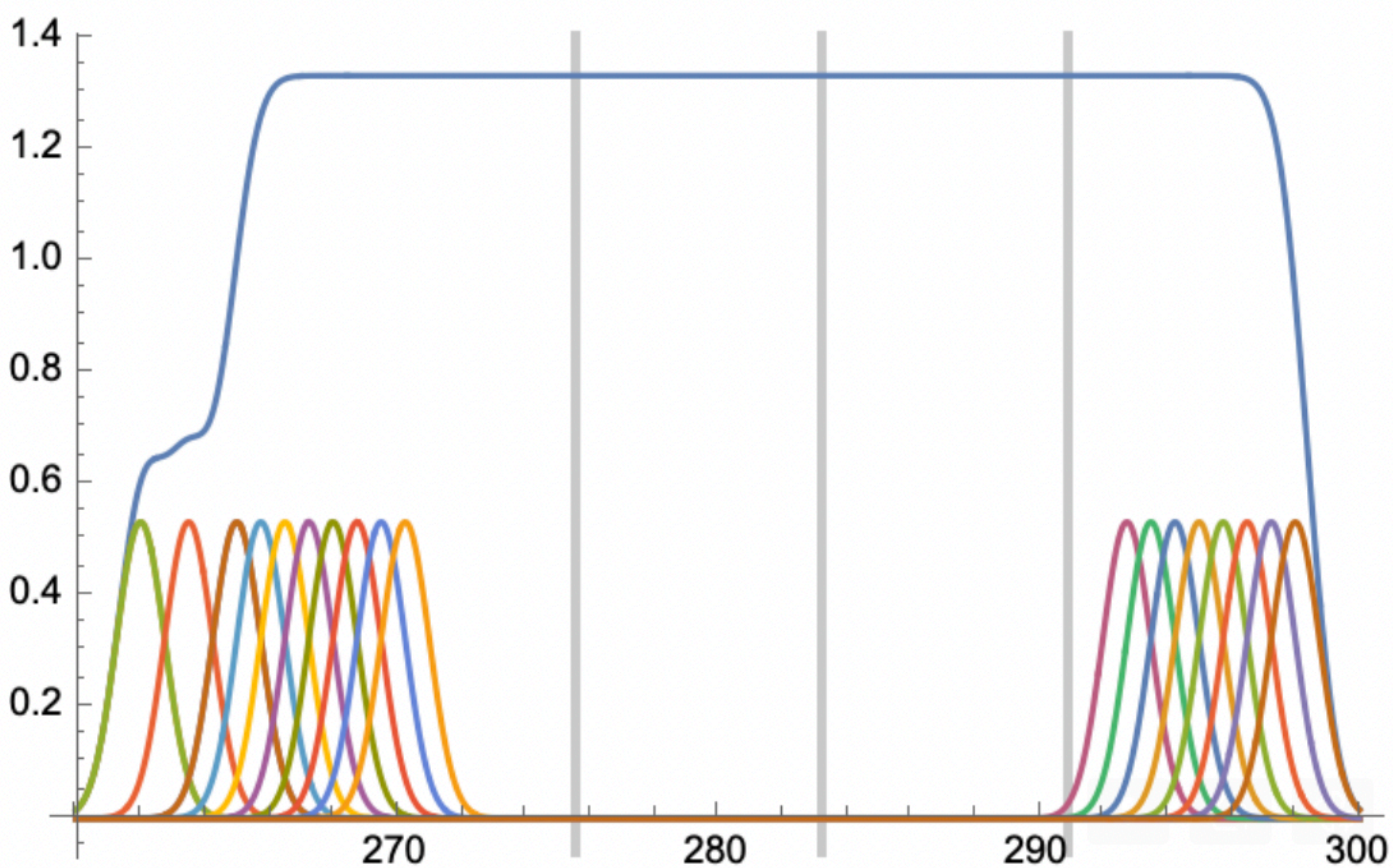
Paolo Valente, Mauro Raggi & the PADME team
Luca Foggetta & the BTF team



38 points
15 Dec. 2022



38+9 points
23 Dec. 2022

LKB 2020 result from ^{87}Rb recoil velocity

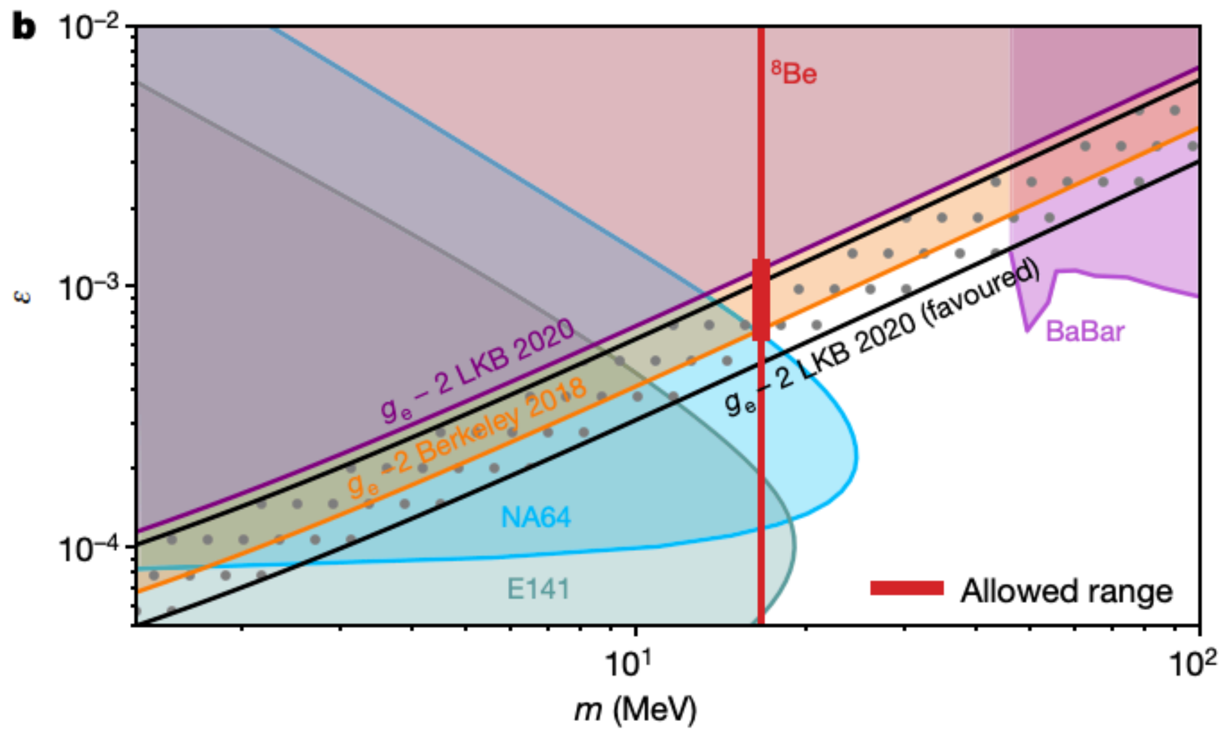
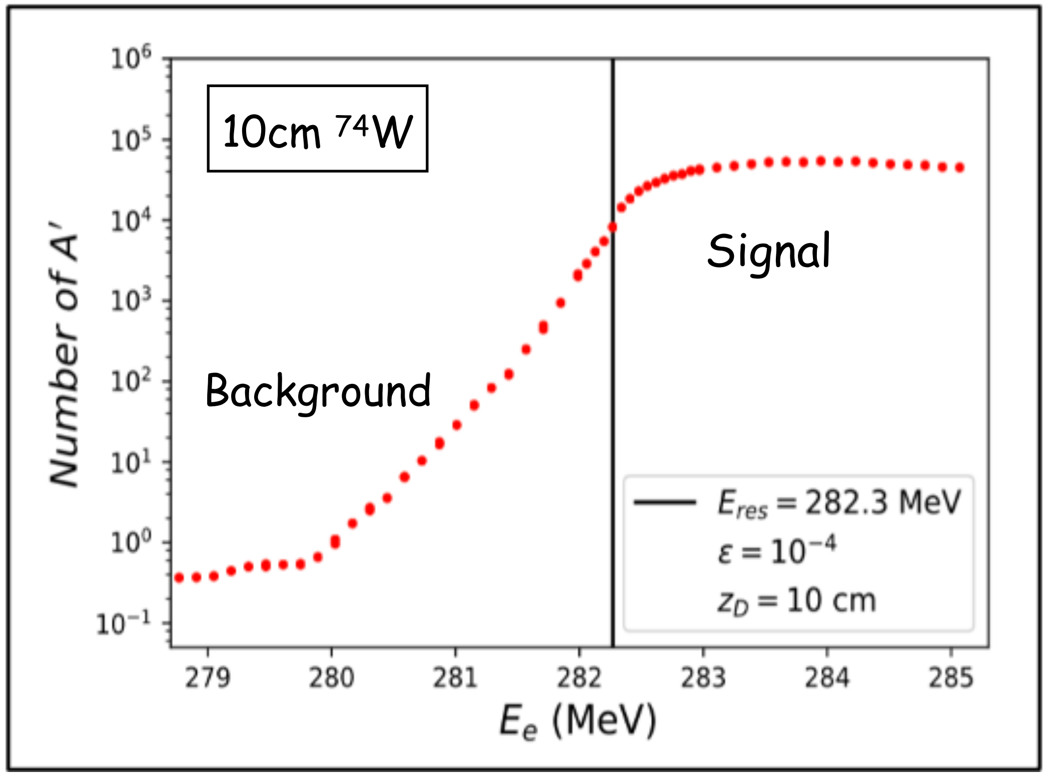


Fig. 4 | Impact on the test of the standard-model prediction of a_e and limits on hypothetical *X* boson. a, Summary of contributions to the relative uncertainty on δa_e. The horizontal green line corresponds to the δa_e value obtained by taking into account the muon magnetic moment discrepancy and using 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.

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

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



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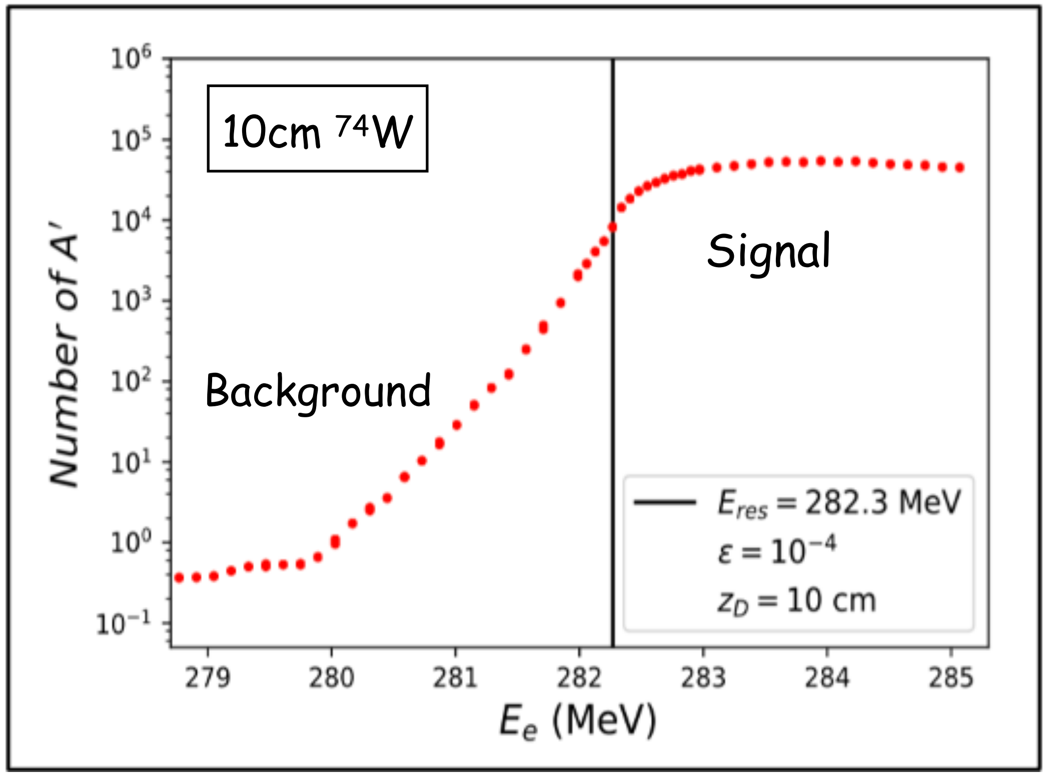

- Although not optimal for X —> e^+e^- detection/reconstruction (conceived for $e^+ e^-$ —> γ $X_{invis.}$) the existing PADME detector can be used (with minor upgrades)
- Beam tests at 280-290 MeV will be performed soon (weeks)
- Physics run most probably only after the summer 😠