

The X17 puzzle

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Outline

- 1 Introduction
- 2 Theoretical study of $A = 4$ reactions
- 3 The ${}^3\text{H}(p, e^+ e^-){}^4\text{He}$ and ${}^3\text{He}(n, e^+ e^-){}^4\text{He}$ processes
- 4 Incorporating the X17
- 5 A new experimental search of X17
- 6 Conclusions

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The X17 boson “anomaly”

The ATOMKI experiments

- [Krasznahorkay *et al.*, PRL **116**, 042501 (2016)]: “Observation of Anomalous Internal Pair Creation in ^8Be : A Possible Indication of a Light, Neutral Boson”
- [Krasznahorkay *et al.*, arXiv:1910.10459 (23 October 2019)]: “New evidence supporting the existence of the hypothetic X17 particle”
- [Krasznahorkay *et al.*, PRC **104**, 044003 (2021)]: “A new anomaly observed in ^4He supports the existence of the hypothetical X17 particle”

Reaction	m_X [MeV]	Δm_X (stat) [MeV]	Δm_X (syst) [MeV]	τ [sec]	Evidence
$^7\text{Li}(p, e^+e^-)^8\text{Be}$	16.70	0.35	0.50	10^{-14}	$> 5\sigma$
$^3\text{H}(p, e^+e^-)^4\text{He}$ (2019)	16.84	0.16	0.20		$> 7.2\sigma$
$^3\text{H}(p, e^+e^-)^4\text{He}$ (2021)	16.94	0.12	0.21		$> 8.9\sigma$

Measurements of the e^+e^- angular correlation in the internal pair conversion (IPC) nuclear transition

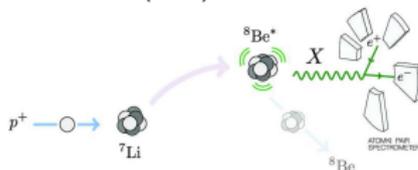


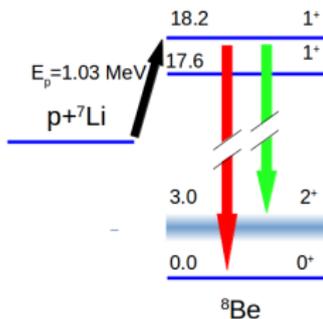
image from [Feng *et al.*, 2016]

Previous “anomalies” found in IPC

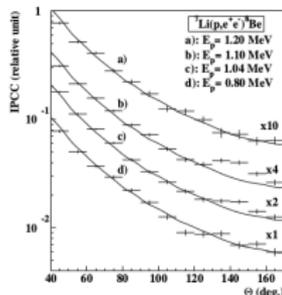
- [de Boer *et al.*, Phys. Lett. **B388**, 235 (1996); J. Phys. G **27** L29 (2001)]: IKF Frankfurt: 9 MeV Boson?
- [Vitéz *et al.*, Acta Physica Polonica B **39**, 483 (2008)]
- [de Boer & Fields, Int. J. mod. Phys. E **20**, 1787 (2011)]

The ^8Be experiment

[Krasznahorka *et al.*, PRL **116**, 042501 (2016)]



Angular distribution of the e^-e^+ pair



- [Tanedo, www.particlebites.com/?p=3970 (Aug. 25, 2016)] “The Delirium over Beryllium” for a nice introduction to the experiment and the possible explanations
- [Zhang & Miller, 2017] “Can nuclear physics explain the anomaly observed in the internal pair production in the Beryllium-8 nucleus?”

Process: $^7\text{Li} + p \rightarrow (^8\text{Be})^*$

- Radiative capture: $(^8\text{Be})^* \rightarrow ^8\text{Be} + \gamma$
- IPC (standard): $(^8\text{Be})^* \rightarrow ^8\text{Be} + \gamma^* \rightarrow ^8\text{Be} + e^+e^-$
- IPC (exotic): $(^8\text{Be})^* \rightarrow ^8\text{Be} + X \rightarrow ^8\text{Be} + e^+e^-$
- Background: real γ converting to e^+e^- from interaction with the apparatus = external pair conversion (EPC)

The ^4He experiment (2019)

- [Krasznahorkay *et al.*, arXiv:1910.10459v1], [Firak *et al.*, EPJ Web Conf. **232**, 04005 (2020)]
- [Frankenthal, <https://www.particlebites.com/?p=6696> (Jan. 4, 2020)] “The Delirium over Helium” for an update of the precedent *particlebites.com* report
- cerncourier.com/a/rekindled-atomki-anomaly-merits-closer-scrutiny/
- Reaction $^3\text{H}(p, e^- e^+) ^4\text{He}$, proton beam of 0.90 MeV

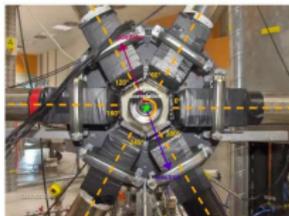
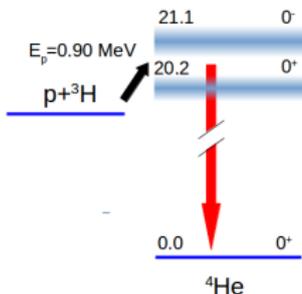
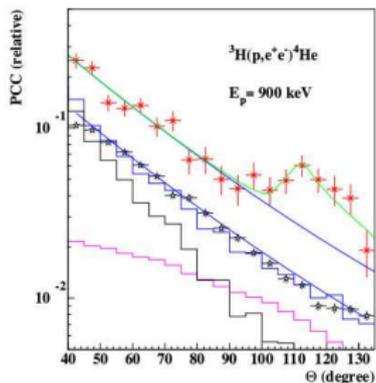


Figure 3. The Atomki nuclear spectrometer. This is an upgraded detector



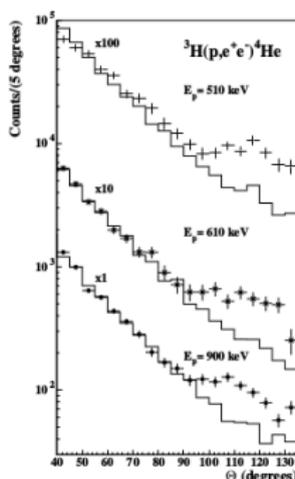
Angular distribution of the $e^- e^+$ pair
(IPC+EPC)



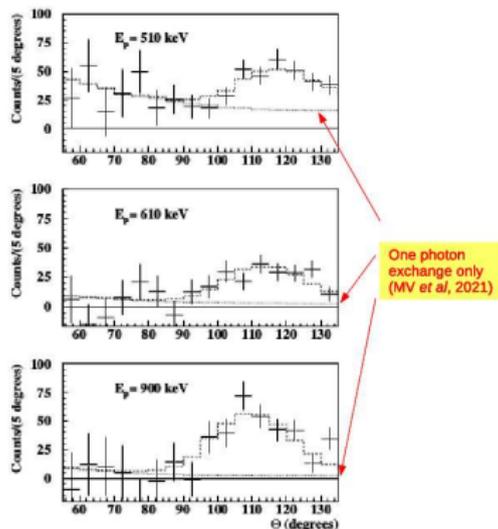
The ^4He experiment (2021)

- [Krasznahorkay *et al.*, PRC **104**, 044003 (2021)]
- Reaction $^3\text{H}(p, e^- e^+)^4\text{He}$, now 3 energies of the proton beam: 0.51, 0.61, and 0.90 MeV

Measured angular distribution of the $e^- e^+$ pairs

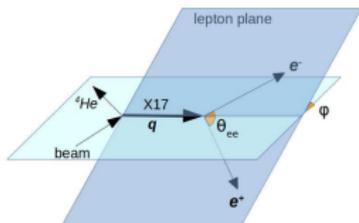


GEANT analysis: Subtraction of the background of pairs created EPC processes



X17 kinematics (1)

Process: $n + {}^3\text{He} \rightarrow {}^4\text{He} + X_{17}$ followed by $X_{17} \rightarrow e^- + e^+$



- ϵ = electron energy
- ϵ' = positron energy

In the Lab.

- $T_n + m_n + M_3 = E_X + M_4 + T_4$

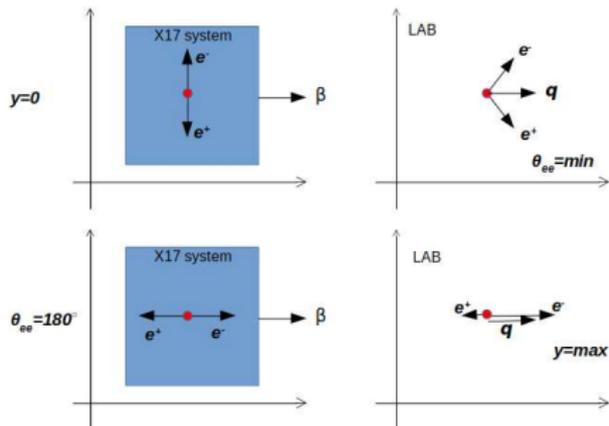
- disregarding T_4 :

$$E_X = \sqrt{M_X^2 + q^2} = T_n - B_3 + B_4 \approx 20 \text{ MeV}$$

- $E_X = 20 \text{ MeV}: \beta_X \approx 0.53$

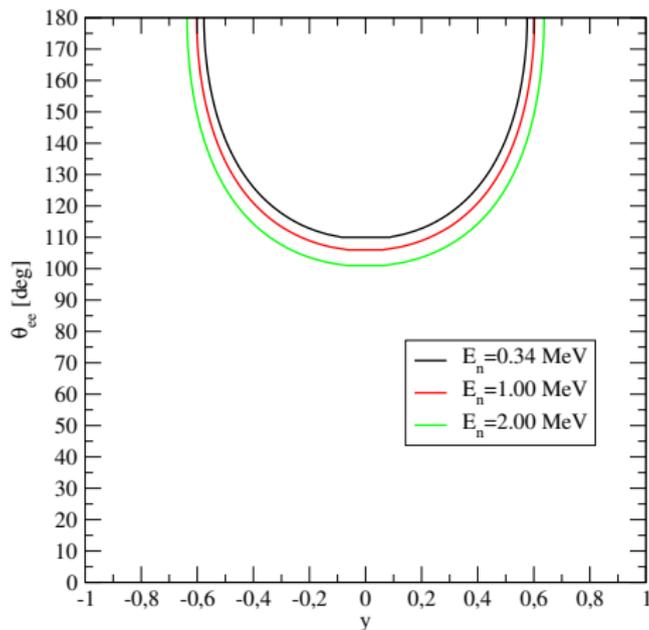
- tight relation between y and θ_{ee}

$$y = \frac{\epsilon - \epsilon'}{\epsilon + \epsilon'}$$



X17 kinematics (2)

Process: $n + {}^3\text{He} \rightarrow {}^4\text{He} + X_{17}$ followed by $X_{17} \rightarrow e^- + e^+$

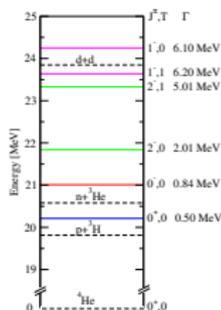


$$y = \frac{\epsilon - \epsilon'}{\epsilon + \epsilon'}$$

Also sensitive to the X17 mass M_X

and theoretical speculations...

- [Kozaczuk, Morrissey, & Stroberg, 2016] “Light axial vector bosons, nuclear transitions, and the ^8Be anomaly”
- [Delle Rose, Khalil, & Moretti, 2019] “New Physics Suggested by Atomki Anomaly”
- [Feng, Tait, & Verhaaren, 2020] “Dynamical Evidence For a Fifth Force Explanation of the ATOMKI Nuclear Anomalies”
- [Fayet, 2020] “The U boson, interpolating between a generalized dark photon or dark Z , an axial boson and an axionlike particle”
- [Alves, 2020] “Signals of the QCD axion with mass of $17 \text{ MeV}/c^2$: Nuclear transitions and light meson decays”
- “Shedding light on X17”, workshop held at Centro Fermi, Rome, Sep 6–8, 2021



Most of the speculations based on “resonance saturation”

Assumed mechanism $p + ^3\text{H} \rightarrow (^4\text{He})^* \rightarrow ^4\text{He} + X$,
followed by the decay $X \rightarrow e^+ e^-$

Motivation of this work:

- solve accurately the $A = 4$ nuclear dynamics
- include the contribution of all relevant waves
- treat the X17 interaction within the χPT framework

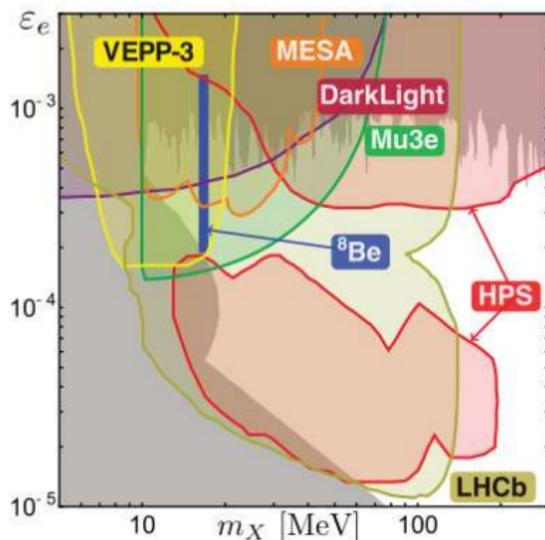
X17 interaction with electrons

- $\Gamma = 1, \gamma^5, \gamma^\mu, \gamma^\mu \gamma^5, \dots$
- e = electric charge ($e > 0$)
- $X(x)$ X17 field

$$\mathcal{L} = e\epsilon_e \bar{e}(x)\Gamma e(x)X(x) + e\epsilon_u \bar{u}(x)\Gamma u(x)X(x) + \dots$$

X17 decay

- $X \rightarrow e^- e^+, \nu \bar{\nu}, \dots$
- Decay channel in $e^- e^+$ dominant [Feng *et al.*, 2016–2020]
- $\Gamma_X \approx \epsilon_e^2 \alpha M_X$
- The X17 must decay in the apparatus
 $\rightarrow |\epsilon_e| > 10^{-5}$
- Beam dump experiments:
 - SLAC E141 $|\epsilon_e| > 2 \cdot 10^{-4}$
[Alexander *et al.*, 2017]
 - NA64 $|\epsilon_e| > 6.8 \cdot 10^{-4}$ [Banerjee *et al.*, 2020]
- Direct search in $e^- e^+$ experiments:
KLOE2 $|\epsilon_e| < 2 \cdot 10^{-3}$ [Feng *et al.*; 2016]



Proposed models

“Protophobic” vector boson
[Feng *et al.*, 2016–2020]

Fifth force

Quantum numbers $J^\pi = 1^-$

NA48 limit for $\pi^0 \rightarrow \gamma X$
[Batley *et al.*, 2015]

A way out: the particle X
does not couple with protons

$$|2\varepsilon_U + \varepsilon_D| < 8 \cdot 10^{-4}$$



Relation with $a_e = (g-2)_e/2$

- New estimate of α
[Morel *et al.*, 2020]
- $\rightarrow \delta a_e = (4.8 \pm 3.0) \times 10^{-13} (+1.6\sigma)$
- Contribution of a vector boson X17: $\delta a_e > 0$
- Consistent with the ^8Be anomaly!

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“Piophobic” axion [Alves,
2020]

Quantum number $J^\pi = 0^-$

QCD axion with mass ~ 17
MeV excluded generally
[Alves & Weiner, 2017]

A way out: no mixing with π^0

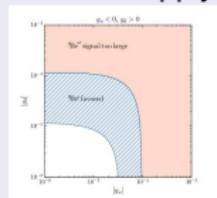
$$\mathcal{L} = \theta_{a-\pi} X(x) \pi^0(x),$$
$$|\theta_{a-\pi}| < 10^{-4}$$

The X17 puzzle

Light axial vector [Kozaczuk,
Morrissey, & Stroberg, 2016]

Quantum number $J^\pi = 1^+$

In this case the NA48 limit
does not apply



Relation with $a_e = (g-2)_e/2$

- Contribution of an axial boson X17: $\delta a_e < 0$
- It would make the problem worse!
- New LQCD calculation
 $\rightarrow \delta a_\mu \approx 0$ [Borsanyi
et al., 2021]

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Theoretical study of $A = 4$ reactions

Numerical techniques for $A = 4$ for scattering

- Faddeev-Yakubovsky methods [Lazauskas & Carbonell, 2004], [Deltuva & Fonseca, 2007]
- Expansion on a basis: NCSM [Quaglioni, Navratil & Roth, 2010], Gaussians [Aoyama *et al.*, 2011], R-matrix [Descouvemont & Baye], HH [Kievsky, Marcucci, MV, *et al.*, 2008], ...

Modern nuclear interactions

- Based on χ EFT & χ -perturbation theory [Weinberg, 1966], [Callan *et al.*, 1969], [Gasser & Leutwyler, 1984]
- Expansion parameter Q/Λ_χ , $Q \sim m_\pi$, $\Lambda_\chi \approx 1$ GeV [Weinberg, 1990-1992], [Ordoñez, Ray, & Van Kolck, 1996], [Epelbaum, Hammer, & Meissner, 2009] for a review
- NN interaction:
 - Lowest order (LO) $(Q/\Lambda_\chi)^0$: one-pion-exchange potential + contact interactions
 - next-to-leading (NLO): 1 loop+dimensional regularization, etc
 - The various contributions can be visualized through TOPT diagrams
 - Cutoff $\Lambda = 400 - 600$ MeV for the non-perturbative regularization: the results should not depend on it
 - Example: N3LO500 \rightarrow interaction at N3LO with $\Lambda = 500$ MeV
 - Still under progress (Efimov & universality, counting rule, ...)

Modern nuclear interactions (continued)

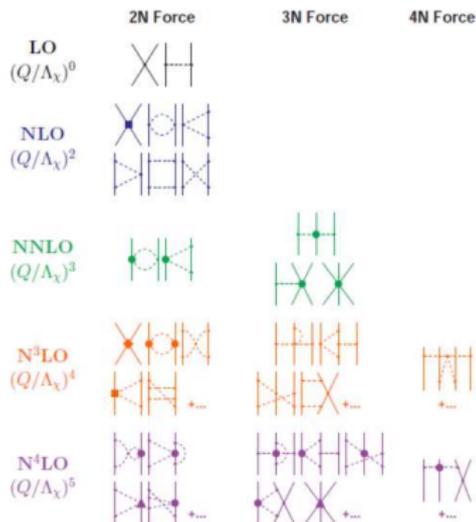
- 3N interaction: developed at N4LO, but for the moment practical calculations are possible only at N2LO
- contact terms at N4LO [Girlanda, Kievsky, Marcucci, MV]

Various methods exist for estimating the “theoretical uncertainties” due to the truncation of the expansion

[Epelbaum, Krebs, & Meissner, 2014], Bayesian method [Melendez *et al.*, 2019]

Interactions

See, for example [Epelbaum, 2010], [Machleidt & Entem, 2011]



NN interaction

- Jülich (up to N4LO) [Epelbaum, Krebs, & Meissner, 2014], [Reinert, Krebs, & Epelbaum, 2017]
- Idaho (up to N4LO) [Entem, Machleidt, & Nosyk, 2017]
- N3LO + Δ dof's (Norfolk VIa, . . .) [Piarulli *et al.*, 2018]

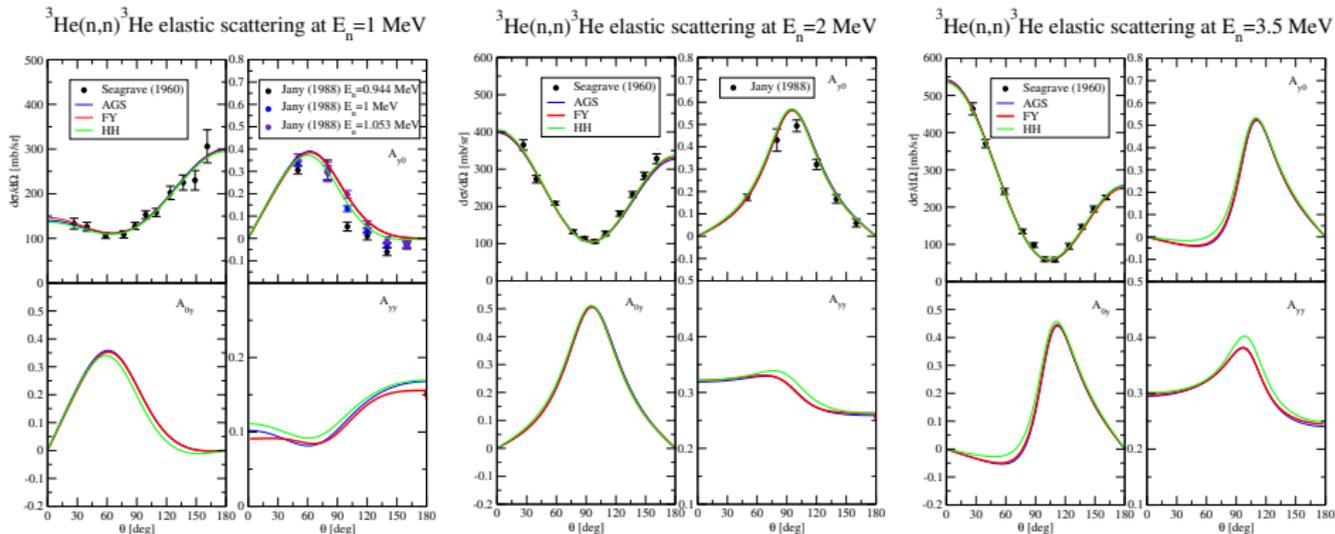
LEC's fitted to the NN database or πN database. Cutoff $\Lambda = 450 - 600$ MeV

3N interaction

- N2LO [Epelbaum *et al.*, 2002] two LECS c_D and c_E : fitted to reproduce $B(^3\text{H})$ and some other observable
- 3N force at N3LO & N4LO [Krebs *et al.*, 2012-2013]
- + Δ dof's [Baroni *et al.*, 2018], [Krebs *et al.*, 2018]
- +13 new LEC's at N4LO [Girlanda *et al.*, 2019-. . .]

Benchmark test of 4N scattering calculations

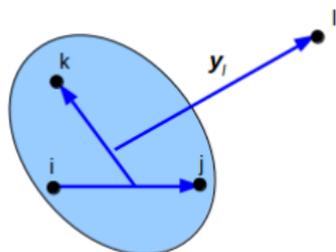
N3LO500 potential – ${}^3\text{He}(n, n){}^3\text{He}$ elastic scattering



AGS= Deltuva & Fonseca – FY= Lazauskas & Carbonell – HH= present work

Calculation of transition amplitudes

We need 1) initial/final wave functions 2) transition operators (currents & charges)



Initial/final wave functions

Ψ_4 : ${}^4\text{He}$ bound state wave function $J^\pi = 0^+$
 Ψ_{1+3} : scattering wave function – decomposed in components of definite LSJ

$$\Psi_{1+3} = \sum_{LMSS_zJJ_z} \left(\frac{1}{2} m_3 \frac{1}{2} m_1 |SS_z\rangle (LMSS_z|JJ_z) 4\pi i^L Y_{LM}^*(\hat{p}) e^{i\sigma L} \Psi_{1+3}^{LSJ} \right)$$

\mathbf{p} relative momentum

EM charge & currents transition operators

EM current from χ EFT

[Park *et al*, 1993], [Kolling *et al*, 2009], [Pastore *et al*, 2009]
Including the Δ d.o.f. [Schiavilla *et al.*, 2018]

A= Diagrams in standard χ EFT

B= Diagrams with the inclusion of the Δ d.o.f. up to N2LO

	charge	A	current	charge	B	current
LO						
NLO						
N2LO						
N3LO						
N4LO						

Reduced matrix elements (RMEs)

Multipole expansion of the transition operators (γ emission)
 expansion of $e^{i\mathbf{q}\cdot\mathbf{r}}$ + Wigner-Eckart theorem
 simplified by the fact that ${}^4\text{He}$ is a $\mathbf{J}^\pi = 0^+$ state

$$\langle \Psi_4 | \rho^\dagger(\mathbf{q}) | \Psi_{1+3}^{LSJJ_z} \rangle \sim C_J^{LSJ}, \quad J \geq 0$$

$$\langle \Psi_4 | \hat{\epsilon}_{\mathbf{q},\lambda}^* \cdot \mathbf{J}^\dagger(\mathbf{q}) | \Psi_{1+3}^{LSJJ_z} \rangle \sim (E_J^{LSJ} + \lambda M_J^{LSJ}), \quad J \geq 1$$

Selection rules

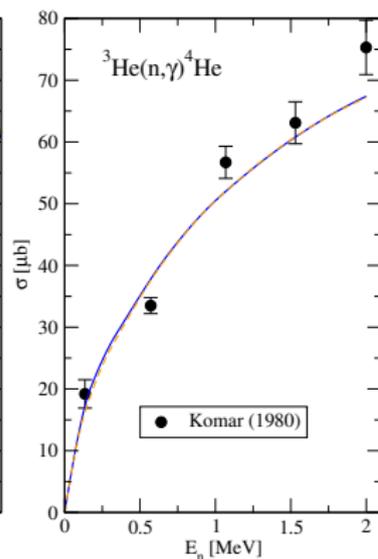
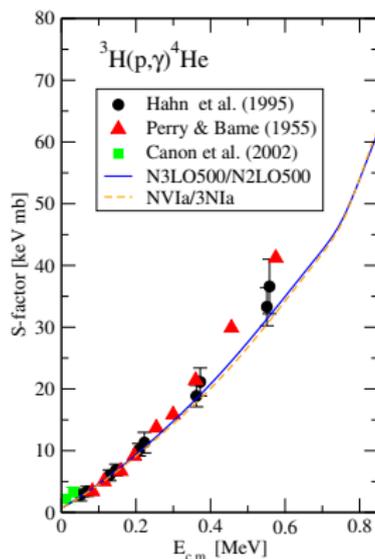
Parity of $\Psi_4 = +$, parity of $\Psi_{1+3}^{LSJJ_z} = (-)^L$

state	$2S+1 L_J$	charge multipoles	current multipoles
0^+	1S_0	C_0^{000}	—
0^-	3P_0	—	—
1^+	${}^3S_1, {}^3D_1,$	—	M_1^{LS1}
1^-	${}^1P_1, {}^3P_1,$	C_1^{LS1}	E_1^{LS1}
2^+	${}^1D_2, {}^3D_2,$	C_2^{LS2}	E_2^{LS2}
2^-	${}^3P_2, {}^3F_2,$	—	M_2^{LS2}

${}^3\text{H}(p, \gamma){}^4\text{He}$ and ${}^3\text{He}(n, \gamma){}^4\text{He}$ EM captures

Interest

- BBN, production of ${}^4\text{He}$
- Dominated by the E_1 transition $1^- \rightarrow 0^+$
- No sensitivity to interactions/MEC
- Real γ 's conversion in $e^- e^+$ from interaction with the apparatus
- \rightarrow external pair conversion (EPC)



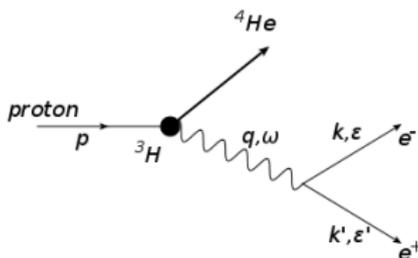
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The ${}^3\text{H}(p, e^+ e^-){}^4\text{He}$ and ${}^3\text{He}(n, e^+ e^-){}^4\text{He}$ processes

“Standard” EM process

$$\frac{d^6\sigma}{d\epsilon d\hat{k} d\epsilon' d\hat{k}'} = \frac{\alpha^2}{8\pi^3} \frac{kk'}{Q^4 v} \delta\left(E_0 - \epsilon - \epsilon' - \frac{(\mathbf{p} - \mathbf{q})^2}{2M_4}\right) \times \sum_i v_i R_i(q, \omega)$$



$$E_0 = E_p + B_4 - B_3 \approx 20 \text{ MeV}, \quad \mathbf{q} = \mathbf{k} + \mathbf{k}', \quad \omega = \epsilon + \epsilon', \quad Q^2 = \omega^2 - q^2 > 0 \text{ “time-like”}$$

$$\cos\theta_{ee} = \hat{\mathbf{k}} \cdot \hat{\mathbf{k}'}, \quad i = L, T, TT, TT', LT, LT'$$

$$v_L = \frac{Q^4}{q^4} (\epsilon\epsilon' + \mathbf{k} \cdot \mathbf{k}' - m_e^2) \quad R_L(q, \omega) = \sum_{m_1, m_3} |\langle \Psi_4 | \rho(\mathbf{q})^\dagger | \Psi_{m_1, m_3}^{(pt)} \rangle|^2 \sim \sum_{LSJ} |C_J^{LSJ}|^2$$

After integrating the δ over ϵ' and numerically over ϵ ($p_r = \epsilon'(k' - p \cos\theta' + k \cos\theta_{ee})/k'$)

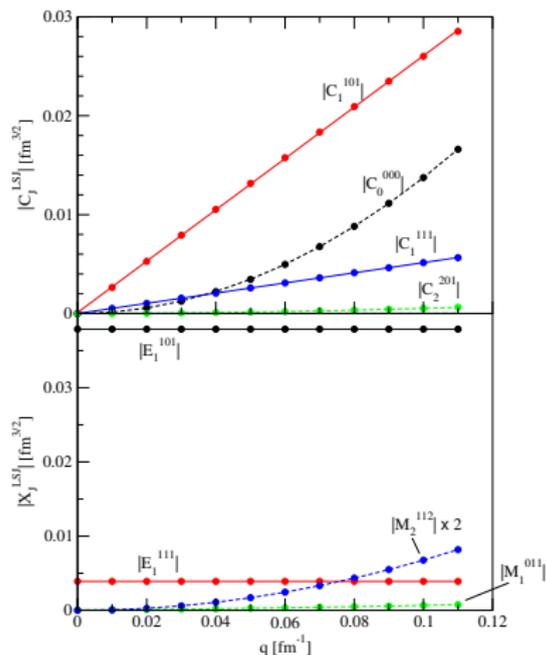
$$\frac{d^4\sigma}{d\hat{k} d\hat{k}'} = \frac{\alpha^2}{8\pi^3} \int_{m_e}^{\epsilon_{\max}} d\epsilon \left[\frac{kk'}{Q^4 v} \frac{1}{1 + p_r/M_4} \sum_i v_i R_i \right]_{\epsilon' \approx E_0 - \epsilon}$$

RME's: q dependence

$$C_J^{LSJ} \sim \langle \Psi_4 | \sum_{j=1}^A \frac{1 + \tau_z(j)}{2} e^{i\mathbf{q} \cdot \mathbf{r}_j} | \Psi_{1+3}^{LSJ} \rangle$$

Behaviour at $q \rightarrow 0$

- $q = |\mathbf{k} + \mathbf{k}'| \rightarrow 0$: lepton pair emitted back-to-back
- $Q^2 = \omega^2 \approx E_0^2$ finite
- $\nu_L = \frac{Q^4}{q^4} (\epsilon\epsilon' + \mathbf{k} \cdot \mathbf{k}' - m_e^2) \rightarrow 1/q^2$
- A careful calculation of the RMEs is needed: $\text{RMEs} \sim q^n, n > 0$
- $\sum_{j=1}^A \frac{1 + \tau_z(j)}{2} = 2$
- $e^{i\mathbf{q} \cdot \mathbf{r}_j} = 1 + i\mathbf{q} \cdot \mathbf{r}_j + \frac{1}{2}(i\mathbf{q} \cdot \mathbf{r}_j)^2 + \dots$
- $J^\pi = 0^+$: first contributing order q^2
- $J^\pi = 1^-$: first contribution order q
- $J^\pi = 2^+$: first contribution order q^2



${}^3\text{H}(p, e^+e^-){}^4\text{He}$ cross section in the one-photon-exchange approximation

Calculation using
N3LO500/N2LO500 + χ EFT current by

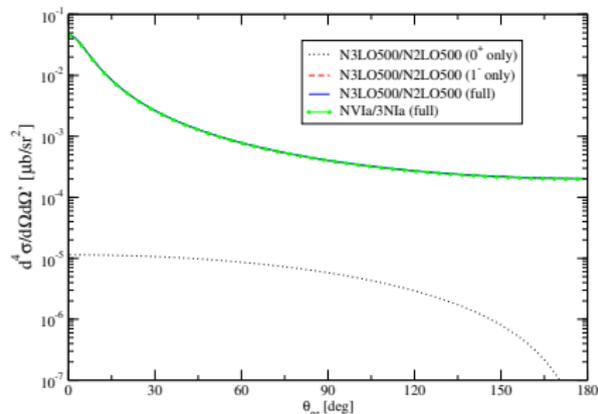
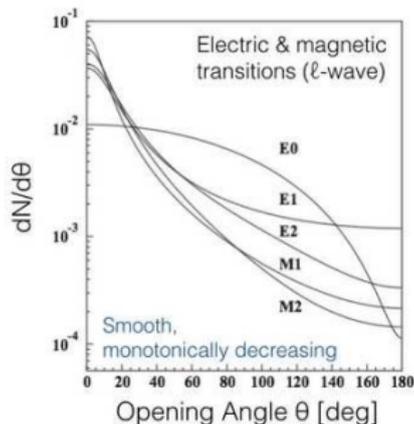
[Pastore *et al.*, 2009]

NV1a/3Na* + χ EFT current by [Schiavilla *et al.*,
2018]

Multipole angular distribution as reported in

[Tanedo,

www.particlebites.com/?p=3970]



Due to the simple q dependence of the RME's, no possible to explain any large angle "bump"

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Incorporating the X17

Scales ...

- $E \sim 1$ TeV BSM mechanism (axion, SSM, ...)
- $E \sim 1$ GeV: interaction with SM particles
- $E \sim 100$ MeV: interaction with hadrons (N, π, \dots)
- $E \sim 1$ MeV: nuclear physics experiments

- Propagator of a massive particle $1/D_X = 1/(Q^2 - M_X^2)$, where $Q^2 = (k + k')^2$
- $M_X \rightarrow M_X - i\frac{\Gamma_X}{2}$
- Γ_X from the process $X \rightarrow e^+e^-$
 - $\Gamma_X = \epsilon_e^2 \alpha M_X \sim 1$ eV
- $D_X = Q^2 - M_X^2 + i M_X \Gamma_X$, as $\Gamma_X \ll M_X$

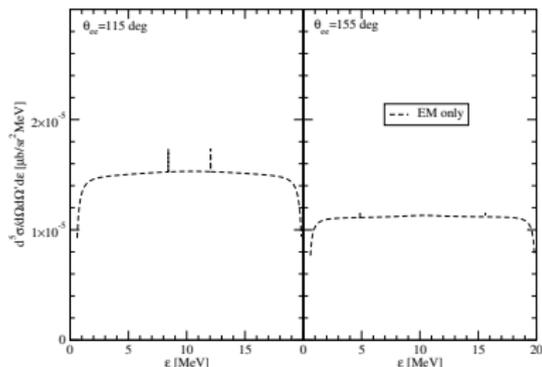
EFT approach

- 1 Start with a generic interaction Lagrangian with electrons, u and d quarks, ...
- 2 Generate the interaction at hadronic level using χ EFT
- 3 Accurately compute the matrix elements of the generated operators

- ϵ = electron energy
- Condition $Q^2 - M_X^2 = 0$ verified for $\epsilon = \epsilon_i, i = 1, 2$
- For $\epsilon \approx \epsilon_i, Q^2 - M_X^2 = \alpha_i(\epsilon - \epsilon_i)$

X17-induced cross section

$$\frac{d^5\sigma}{d\epsilon d\hat{\mathbf{k}} d\hat{\mathbf{k}}'} = \sigma_{EM}(\epsilon) + \epsilon_e \left[\frac{R_X(\epsilon)}{D_X} + \text{c.c.} \right] + \epsilon_e^2 \frac{R_{XX}(\epsilon)}{|D_X|^2} = \sigma_{EM}(\epsilon) + \frac{\epsilon_e [R_X(\epsilon) D_X^* + \text{c.c.}] + \epsilon_e^2 R_{XX}(\epsilon)}{|D_X|^2}$$



$$\Gamma_X \sim \epsilon_e^2 \alpha M_X$$

$$\frac{1}{|D_X|^2} \rightarrow \frac{\pi}{|\alpha_j|} \frac{1}{\Gamma_X M_X} \delta(\epsilon - \epsilon_j)$$

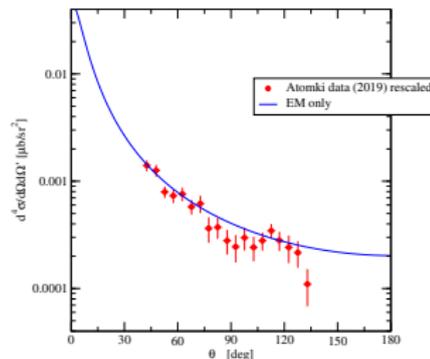
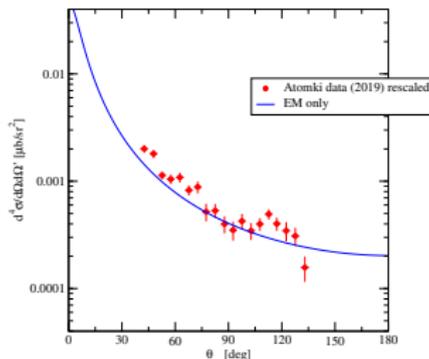
$$\frac{d^4\sigma}{d\hat{\mathbf{k}} d\hat{\mathbf{k}}'} = \int_{m_e}^{E_{max}} \sigma_{EM}(\epsilon) + \sum_i \left[2\epsilon_e \Im \left(R_X(\epsilon_i) \right) \frac{\pi}{|\alpha_j|} + \epsilon_e^2 R_{XX}(\epsilon) \frac{\pi}{|\alpha_j| M_X \Gamma_X} \right]$$

No sensitivity to ϵ_e and the interference term!!!

Fit of the 2019 data

- In the perpendicular plane, the X17 signal appears for $\theta_{ee} > 110^\circ$
- only a counting rate is furnished – no information on the flux/target/efficiencies
- Procedure:
 - rescale the ATOMKI rate by a factor so to reproduce the cross section for $\theta_{ee} < 110^\circ$
 - For these angles the cross section is EM only - no unknown parameter
 - Fix $M_X, \varepsilon_u, \varepsilon_d$ to reproduce the “bump”

Problem!



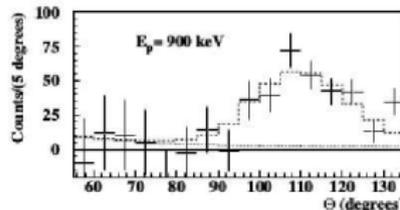
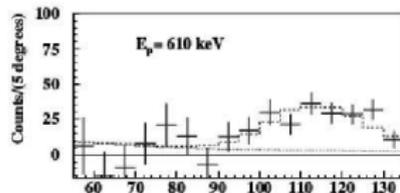
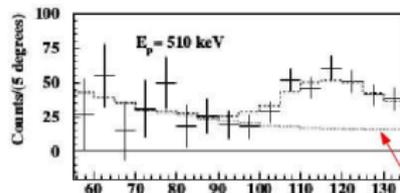
Here there is also the problem of the EPC pairs!

Fit of the 2021 data

- 2021 data: the background has been somehow subtracted
- but the procedure it is still difficult to be applied
- Furthermore: finite angular/energy resolution of the target, geometry of the detector, efficiencies, etc.

For the moment

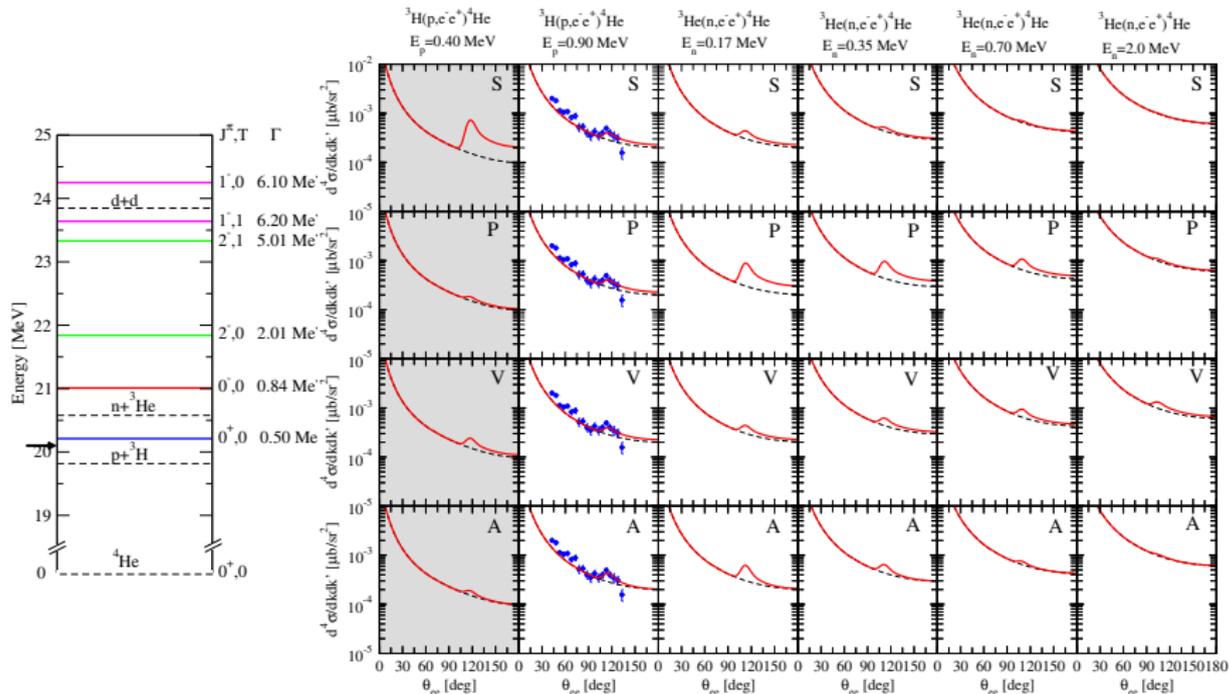
- let us study the dependence of the cross section on
 - beam energy
 - the e^+e^- emission angles
- see if it is possible to extract information on the hypothetical X17



One photon exchange only (MV et al, 2021)

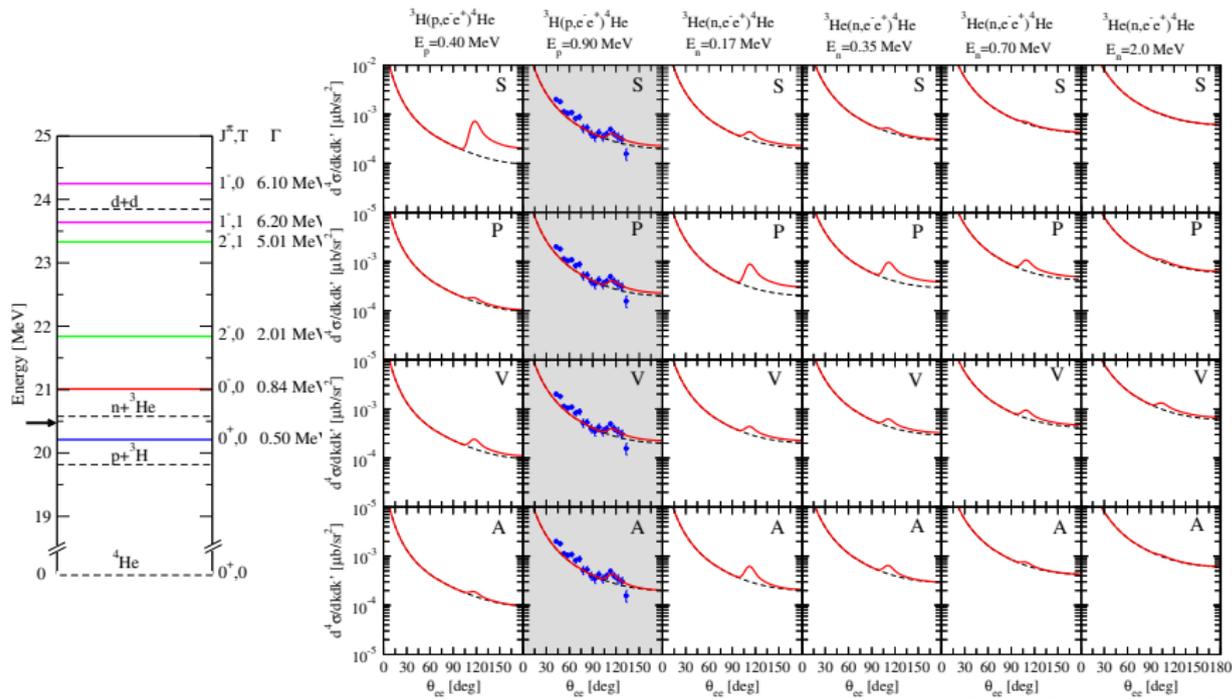
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



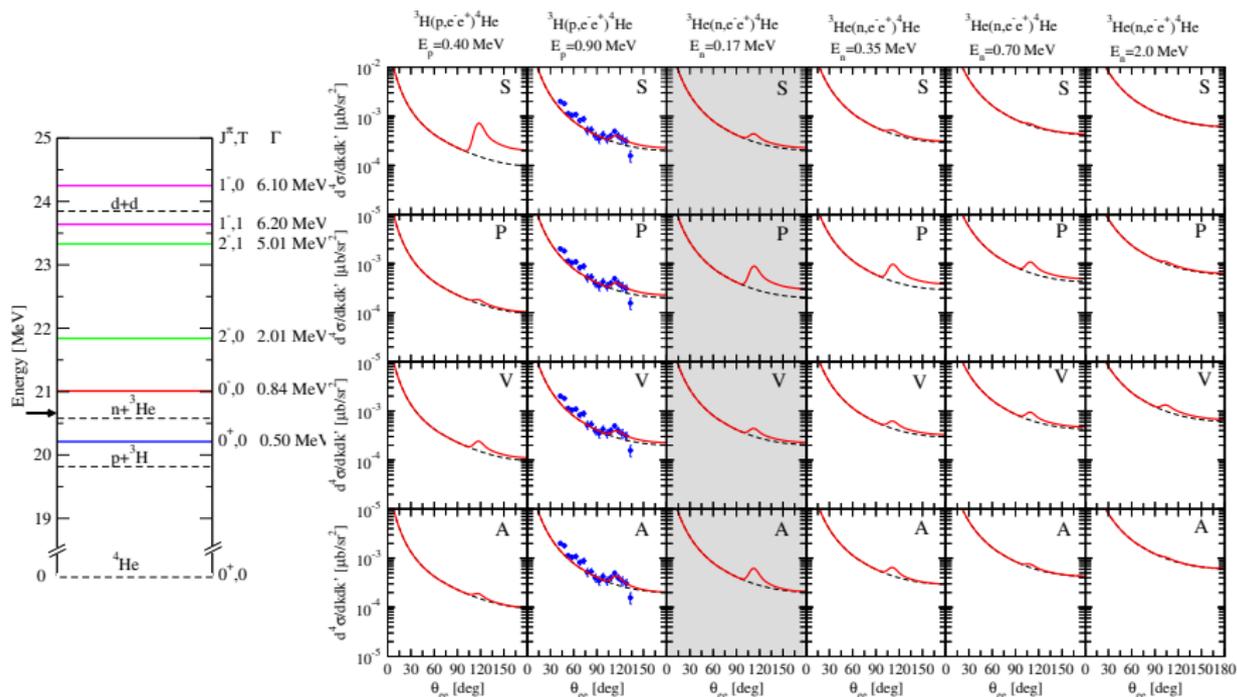
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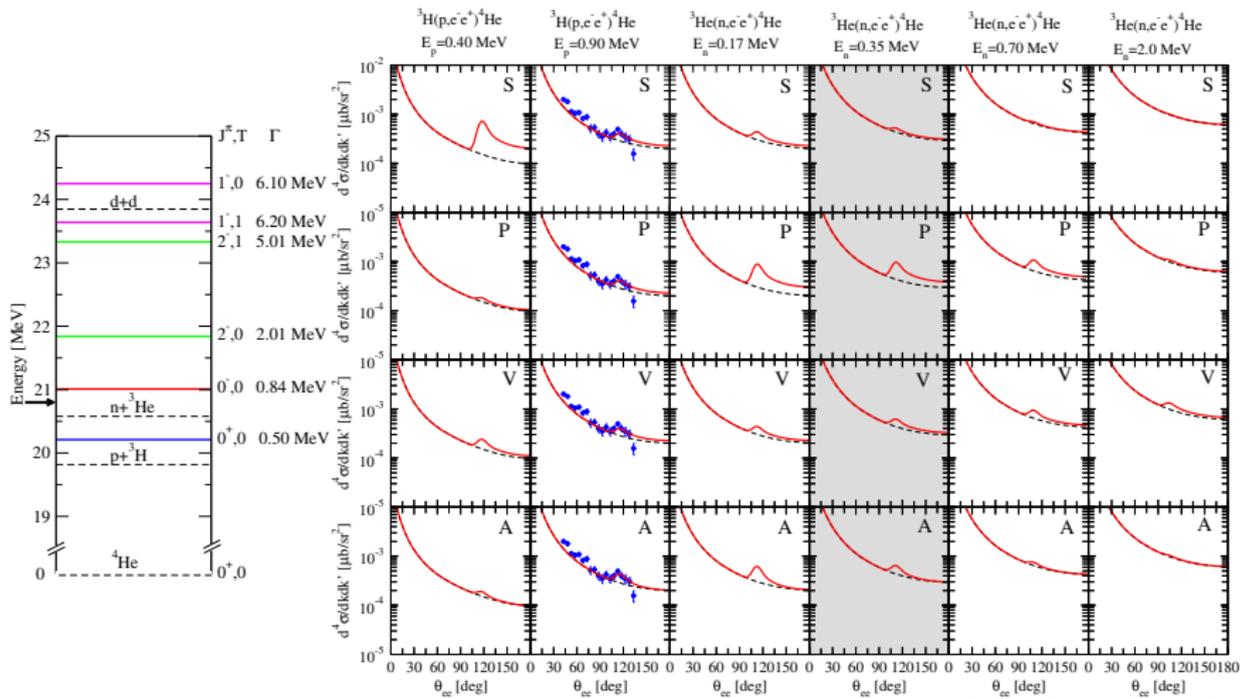
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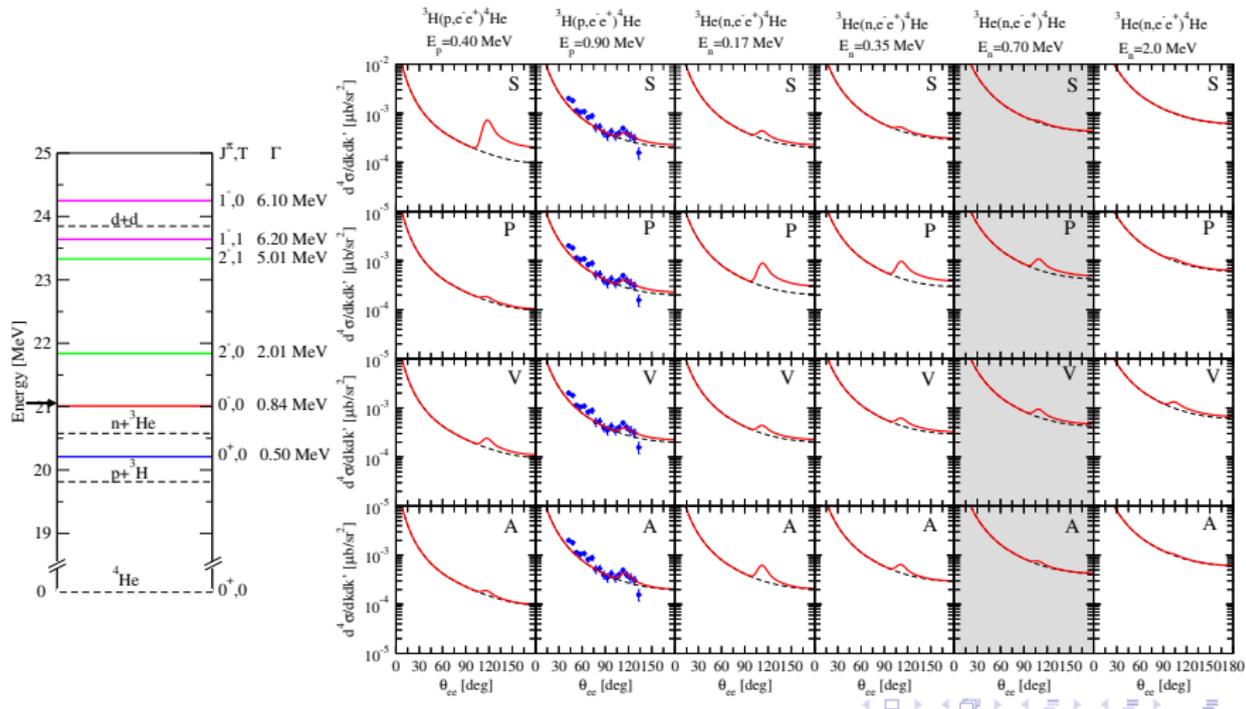
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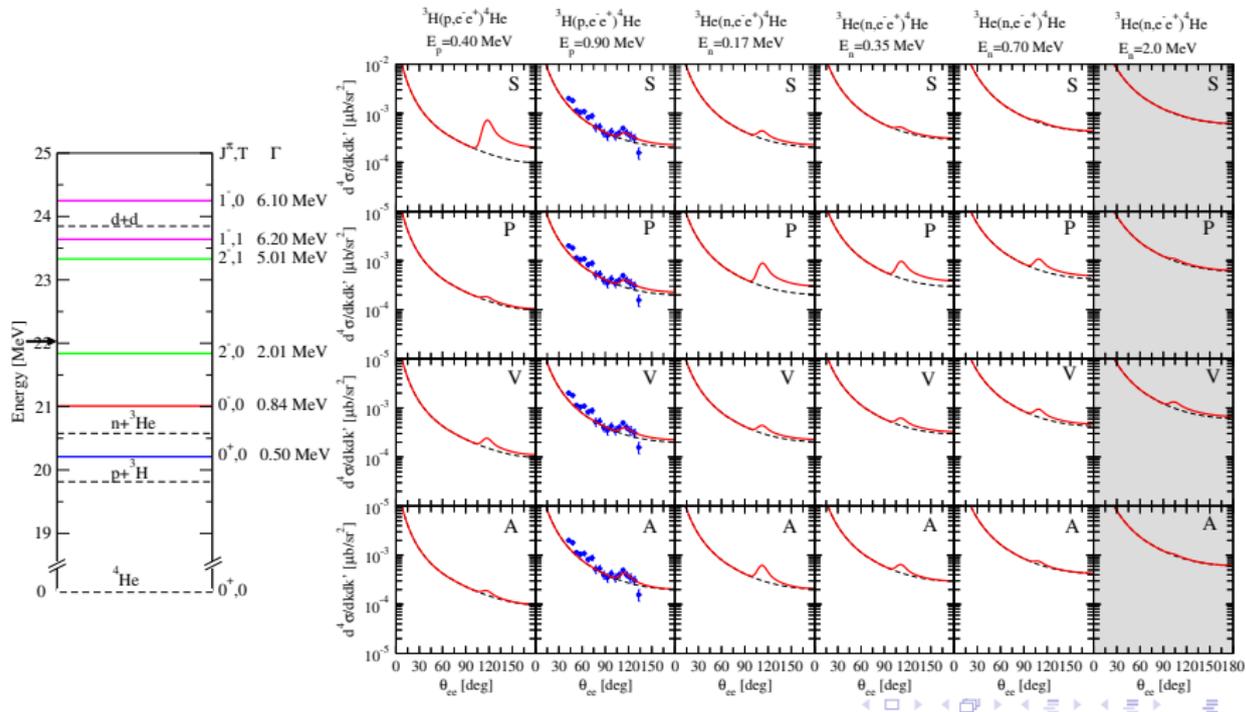
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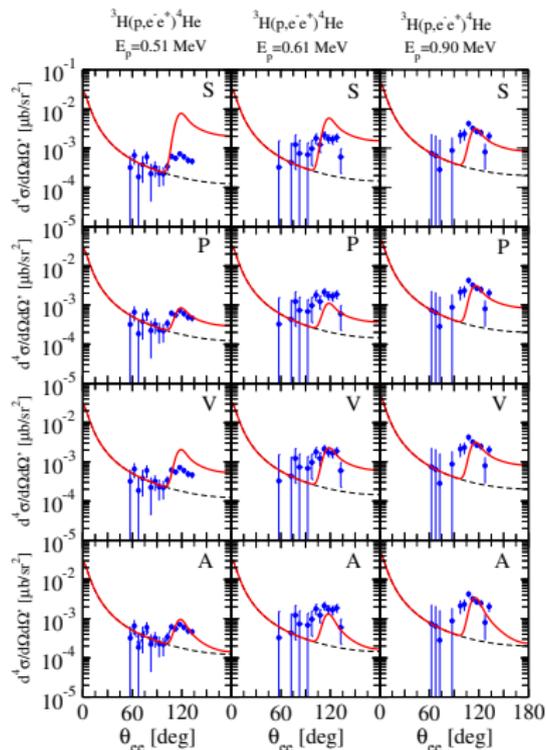
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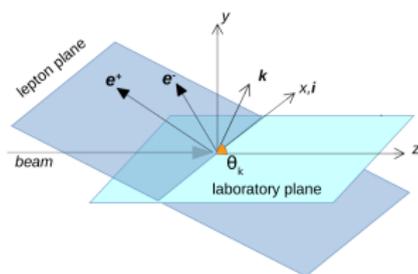


Comparison with the 2021 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



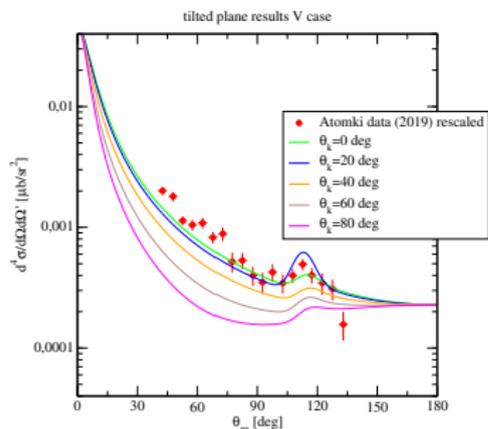
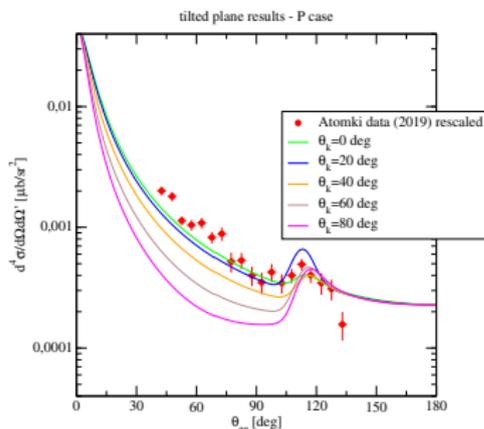
Out of the perpendicular plane study



Study of the cross section for leptons emitted
in a “tilted” plane

θ_k = angle of the perpendicular to the lepton
plane

$$E_p = 0.90 \text{ MeV}$$



Extracted coupling constants

$$\epsilon_0 = \frac{\epsilon_u + \epsilon_d}{2} \quad \epsilon_z = \frac{\epsilon_u - \epsilon_d}{2} \quad \left[2\epsilon_u + \epsilon_d = 0 \Rightarrow 3\epsilon_0 + \epsilon_z = 0 \right]$$

Case	N3LO500/N2LO500		NV1a/3NIa	
	ϵ_0	ϵ_z	ϵ_0	ϵ_z
S	0.86×10^0	0	0.75×10^0	0
P	0	5.06×10^0	0	4.82×10^0
P	2.55×10^1	0	2.72×10^1	0
V	2.56×10^{-3}	$-3\epsilon_0$	2.66×10^{-3}	$-3\epsilon_0$
A	2.58×10^{-3}	0	2.89×10^{-3}	0

First rough estimates – very uncertain due to the aforementioned difficulties

Vector case

- $|\epsilon_{u,d}| \sim 10^{-3}$ **Feng et al., 2016-2020**
- Consistent!

Pseudoscalar case

- $|\epsilon_{u,d}| \sim 1$ **Alves, 2020**, **Delle Rose et al., 2019**
- too small!

Axial case

- $|\epsilon_{u,d}| \sim 10^{-4}$ **[Kozaczuk, Morrissey, & Stroberg, 2016]**
- too small!

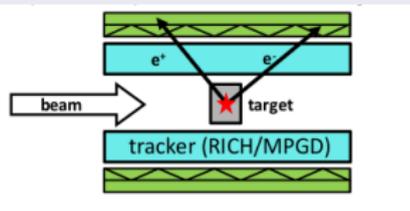
Outline

- 1 Introduction
- 2 Theoretical study of $A = 4$ reactions
- 3 The ${}^3\text{H}(p, e^+ e^-){}^4\text{He}$ and ${}^3\text{He}(n, e^+ e^-){}^4\text{He}$ processes
- 4 Incorporating the X17
- 5 A new experimental search of X17**
- 6 Conclusions

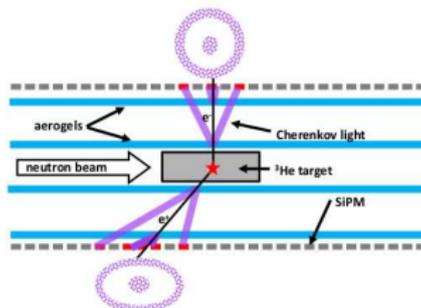
^4He experiment at CERN

$^3\text{He}(n, e^+ e^-)^4\text{He}$ using the neutron beam of the n_ToF experiment

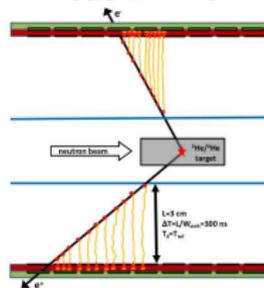
- neutron energy tagged by means of the time-of-flight
- background:
 - $^3\text{He}(n, n)^3\text{He}$
 - $^3\text{He}(n, p)^3\text{H}$: the most dangerous problem $\sigma_{(n,p)} \gg \sigma_{\text{IPC}}$
 - $^3\text{He}(n, \gamma)^4\text{He}$ followed by EPC
- Energy of the leptons is of several MeV:
 $\beta \sim 1$
- Energy of the protons \sim a few MeV:
 $\beta \ll 1$
- Tracker + calorimeter



Tracker solution
road 1: Cherenkov

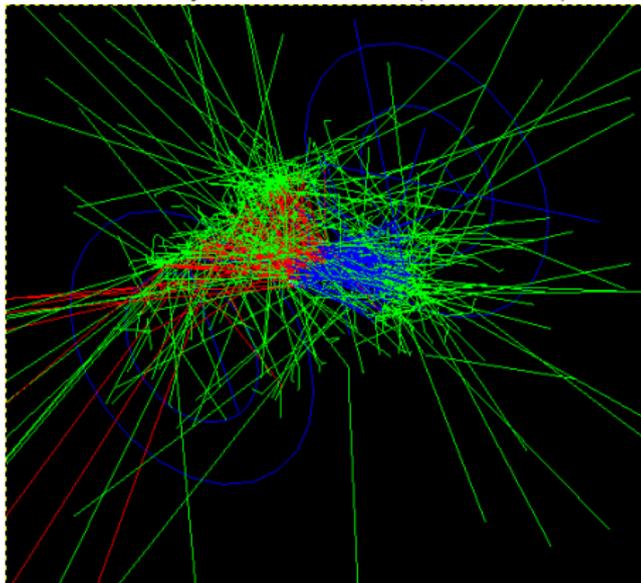


road 2: TPC



Geant studies for the n_ToF experiment

Courtesy of A. Mazzone (CNR, Bari)



${}^3\text{He}(n, e^- e^+){}^4\text{He}$ at CERN (n_ToF)
LoI approved - technical design in progress
 4π detector/reconstruction of the tracks/particle identification
[C. Gustavino *et al.*, 2021]

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Conclusions and perspectives

Analysis of the ^4He ATOMKI “anomaly”

- Accurate description of the nuclear dynamics using state-of-the-art techniques
- Test using $F_{\mathcal{M}}(q)$ and $p + ^3\text{H}$, $n + ^3\text{He}$ EM captures data: OK!
- Contribution of the 1^- wave very significant at all energies
- Inclusion of the possible emission of an X17, vs. the energy beam and the emission angles

Perspectives

- Collaboration with the ATOMKI group
 - we sent them generated X17 events for different mass and couplings
 - GEANT analysis of their experiment currently in progress
- Collaboration with the n_ToF group
- analysis of the $^3\text{He}(n, e^- e^+)^4\text{He}$ process
 - technical design in progress
 - GEANT analysis currently in progress
- Study of possible “standard” explanation
 - Two-photon exchange contribution [Aleksejevs *et al.*, 2021] for ^8Be
 - Repeat this study for ^4He using our wave functions
- If the anomaly is confirmed, full χEFT treatment of the X17-nucleon interaction

Theoretical group

- A. Kievsky, & L.E. Marcucci - *INFN-Pisa & UniPI*
- L. Girlanda *UniSalento & INFN-Lecce*
- E. Filandri *UniTN,*
- R. Schiavilla *Jefferson Lab., USA*

n_ToF Working group

- ❖ G. Gervino (UNITO)
 - ❖ P. Mastinu (INFN LNL)
 - ❖ C. Gustavino (INFN ROMA)
 - ❖ A. Mengoni (ENEA)
 - ❖ C. Massimi (UNIBOLOGNA)
 - ❖ N. Colonna (INFN BARI)
 - ❖ S. Fiore (ENEA ROMA)
 - ❖ A. Mazzone (CNR BARI)
 - ❖ M.C. Petrone (IFIN-HH BUCHAREST)
 - ❖ L. E. Marcucci (UNIPISA)
 - ❖ M. Viviani (INFN PISA)
 - ❖ A. Kievsky (INFN PISA)
 - ❖ L. Girlanda (UNISALENTO)
 - ❖ E. Cisbani (ISS)
 - ❖ F. Renga (INFN ROMA)
- Diagram illustrating the structure of the n_ToF Working group:
- The group is divided into three sub-groups:
 - n_TOF**: Includes G. Gervino, P. Mastinu, C. Gustavino, A. Mengoni, C. Massimi, N. Colonna, S. Fiore, A. Mazzone, and M.C. Petrone.
 - Theoretical group**: Includes L. E. Marcucci, M. Viviani, A. Kievsky, and L. Girlanda.
 - Detector R&D**: Includes E. Cisbani and F. Renga.

Working group (in evolution)

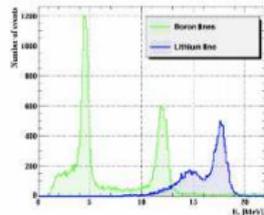
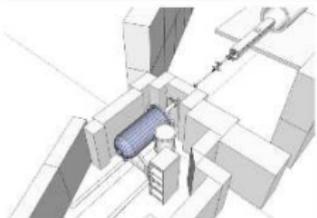
Thank you for your attention!

BACKUP SLIDES

^8Be experiment at PSI

Courtesy by A. Papa (INFN-Pisa)

MEGII CW accelerator and Fifth force target



Schedule

- Proton beam used to test the apparatus (built to study $\mu \rightarrow e$ process)
- The X-boson data taking period is scheduled for the beginning of next year (2022)
- A first test – very successful test – of gamma conversion has been done few days with the magnetic field off
- Several intermediate tests in 2021 are also scheduled during the maintenance main accelerator shut-down periods

$p + {}^3\text{He}$ elastic scattering

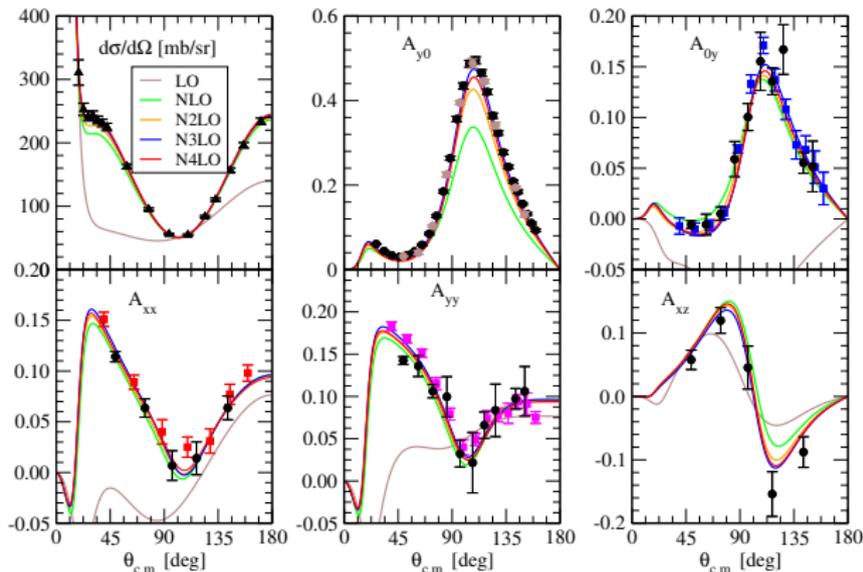
NN potentials up to N4LO [Entem, Machleidt, & Nosyk, 2017]

Theoretical error estimated using the method proposed by [Epelbaum, Krebs, & Meissner, 2014]

$\Delta X_i = \max[Q|X_i - X_{i-1}|, Q^2|X_{i-1} - X_{i-2}|, \dots]$
with $Q = m_\pi/\Lambda$

Order	V_{NN}	W_{3N}
0	LO	—
1	NLO	—
2	N2LO	N2LO
3	N3LO	N2LO* (N3LO c_i from table IX of EMN17)
4	N4LO	N2LO** (N4LO c_i from table IX of EMN17)

c_D, c_E fitted to $B({}^3\text{H})$ and tritium GTME by [Marcucci *et al.*, 2018]



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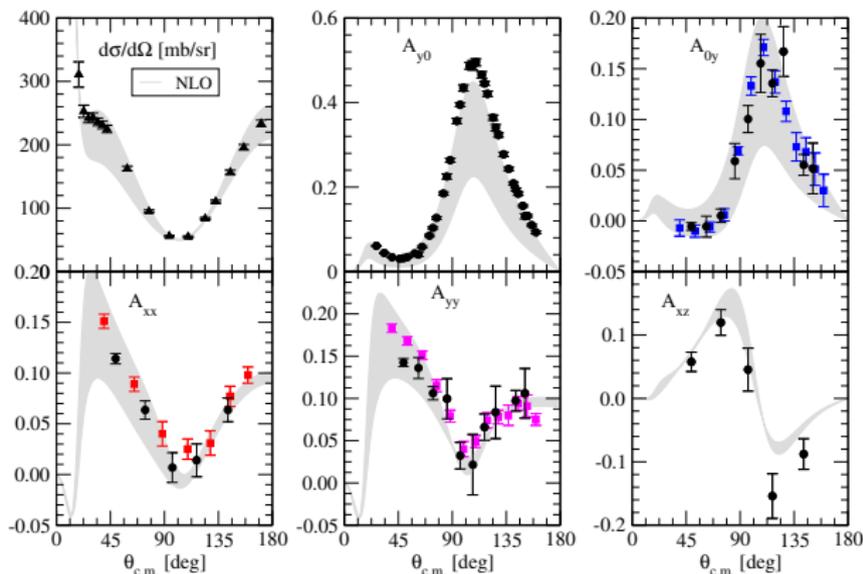
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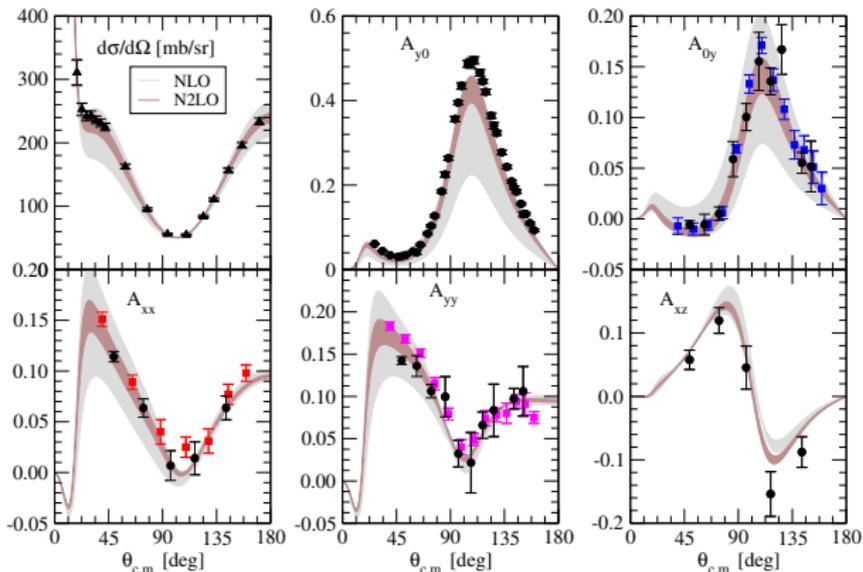
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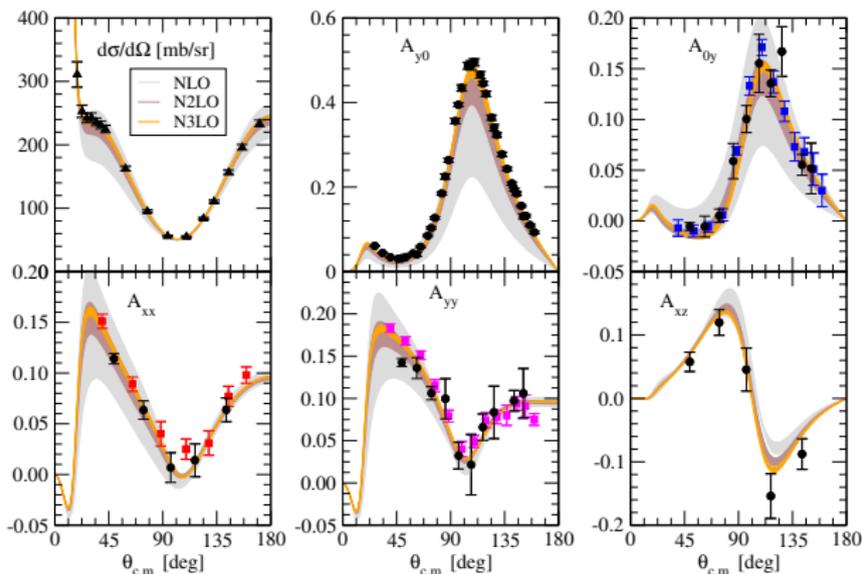
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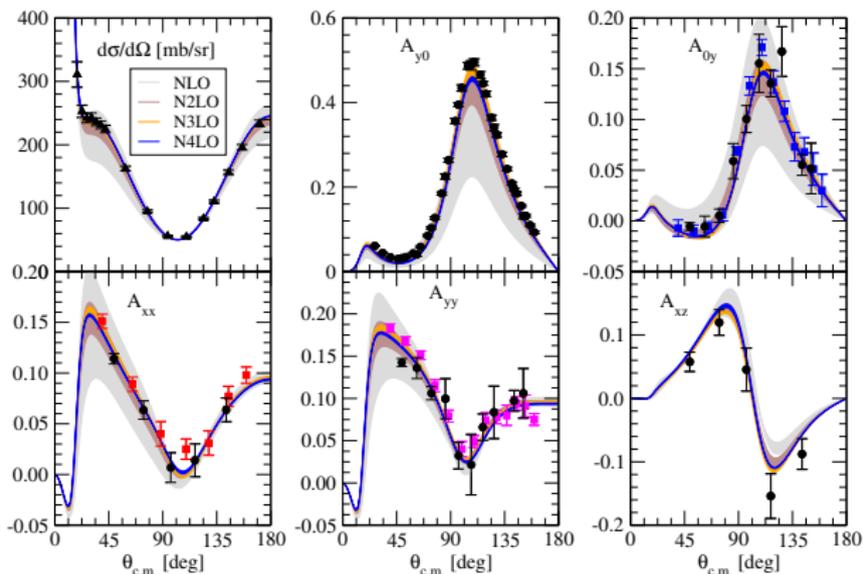
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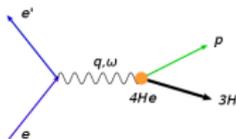
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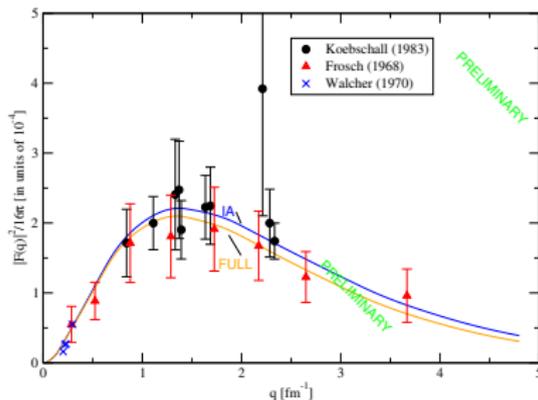
The ^4He transition form factor

$$S_{\mathcal{M}}(q, \omega) = \sum_n |\langle n | \rho(\mathbf{q}) | 0 \rangle|^2 \delta(\omega - E_n + E_0) \quad F_{\mathcal{M}}(q) = \int d\omega S_{\mathcal{M}}(q, \omega)$$



- Sensitive to the excitation of the 1st excited 0^+ state of ^4He
- $S_{\mathcal{M}}(q, \omega) \sim |C_0|^2$

Calculations performed with N3LO500/N2LO500 interaction
Integrated up to $E = 0.87$ MeV



[Hiyama *et al.*, (2004)]
calculation treating the first
excited state as a bound
state

