The X17 anomaly

M. Viviani

INFN, Sezione di Pisa &
Department of Physics, University of Pisa
Pisa (Italy)

INFN-Pisa

Zoom seminar
July 7, 2021
Pisa, Italy

Outline

Collaborators

- A. Kievsky, & L.E. Marcucci - *INFN-Pisa & Pisa University, Pisa (Italy)*
- L. Girlanda *University of Salento & INFN-Lecce, Lecce (Italy)*
- E. Filandri *PhD student, Trento University, Trento (Italy)*
- R. Schiavilla *Jefferson Lab. & ODU, Norfolk (VA, USA)*

Outline

The X17 boson "anomaly"

The ATOMKI experiments

- [Krasznahorkay *et al.*, PRL **116**, 042501 (2016)]: "Observation of Anomalous Internal Pair Creation in ^{8}Be: 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.*, `arXiv:2104.10075` (20 April 2021)]: "A new anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle"

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

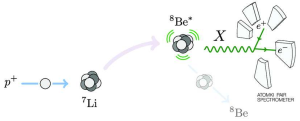


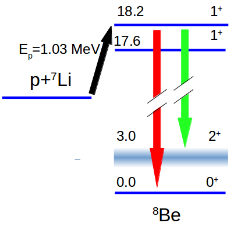
image from [Feng *et al.*, 2016]

Previous "anomalies" found in IPC

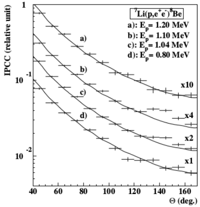
- [de Boer *et al.*, Phy. Lett. **B388**, 235 (1996); J. Phys. G 27 L29 (2001)]: IKF Frankfurt: 9 MeV Boson?
- [Vitéz *et al.*, Acta Physica Polonica B **39**, 483 (2008)]
- [de Boer & Fields, Int. J. mod. Phys. E **20**, 1787 (2011)]

The ^{8}Be experiment

[Krasznahorkay *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: $^7\mathrm{Li} + p \to (^8\mathrm{Be})^*$

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

The ^{4}He 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 $^3\mathrm{H}(p, e^- e^+)^4\mathrm{He}$, proton beam of 0.90 MeV

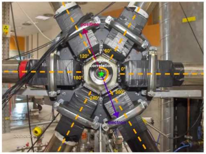
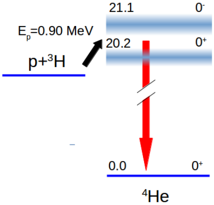
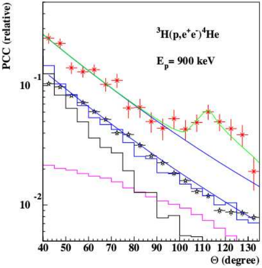


Figure 3. The Atomki nuclear spectrometer. This is an upgraded detector



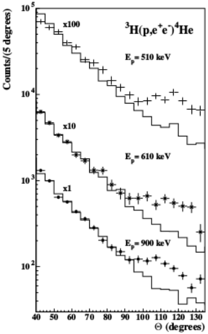
Angular distribution of the $e^- e^+$ pair (IPC+EPC)



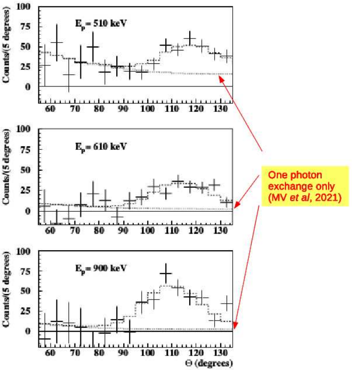
The ^{4}He experiment (2021)

- [Krasznahorkay *et al.*, `arXiv:2104.10075`]
- Reaction $^3\mathrm{H}(p, e^- e^+)^4\mathrm{He}$, 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

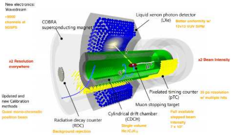


These announcements triggered new expt. activities . . .

Courtesy by C. Gustavino (INFN-Rome)

Experiment	
LHCb	Charm meson decay $D^*(2007)^0 \to D^0 A'$ $A' \to e^- e^+$
Mu3e	Muon decay channel $\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$ ($A' \to e^- e^+$)
VEPP-3	$e^- e^+ \to A' \gamma$
KLOE-2	$e^- e^+ \to \gamma (X \to e^- e^+)$
MESA	e- beam on gaseous target, to produce A'
Darklight	e- scattering of H gas target, to produce A'
HPS	e- beam on W to study $A' \to e^- e^+$ and $A' \to \mu^- \mu^+$
PADME	e+ beam on diamond target $e^- e^+ \to X\gamma$
NA64	$eZ \to eZ + X17$
NSL	^{8}Be ($A' \to$ e-e+)
^{8}BeP	^{8}Be ($A' \to$ e-e+)
New JEDI	^{8}Be/^{3}He/d... ($A' \to$ e-e+)
Montréal	^{8}Be ($A' \to$ e-e+)
NSCL	^{8}Be ($A' \to$ e-e+)
IUAP CTU	^{8}Be and ^{4}He ($A' \to$ e-e+)
n_TOF	^{4}He and ^{8}Be ($A' \to$ e-e+) (proton and neutron beams)
MEG2	^{8}Be
NUCLEX	^{8}Be

MEG



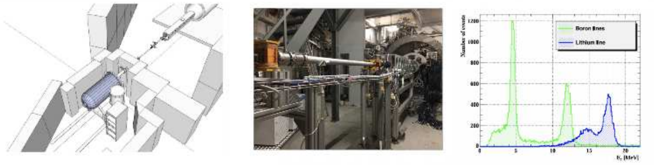
Experiments involving people of INFN (INFN-Pisa)

- LNL: $^7\text{Li}(p, e^+e^-)^8\text{Be}$ NUCLEX
- PSI: $^7\text{Li}(p, e^+e^-)^8\text{Be}$ MEGII (Papa, Baldini, Cei, Chiappini, Donato, Francesconi, Galli, Grassi, Signorelli, . . .)
- n_ToF at CERN: $^3\text{He}(n, e^+e^-)^4\text{He}$ (Carosi, Marcucci, Kievsky, MV)
- Belle II (Bettarini, Casarosa, Forti, Paoloni, Rizzo, Zani, . . .)

^{8}Be experiment at PSI

Courtesy by A. Papa (INFN-Pisa)

MEGII CW accelerator and Fifth force target

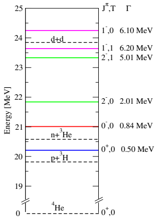


Schedule

- Proton beam used to test the apparatus (built to study $\mu \to e$ 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

and theoretical speculations. . .

- [Kozaczuk, Morrissey, & Stroberg, 2016] “Light axial vector bosons, nuclear transitions, and the ^{8}Be anomaly”
- [Delle Rose, Khalil, & Moretti, 2017] “Explanation of the 17 MeV Atomki anomaly in a U(1)’ -extended two Higgs doublet model”
- [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 MeV/c^2: Nuclear transitions and light meson decays”
- . . .



Most of the speculations based on “resonance saturation”

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

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

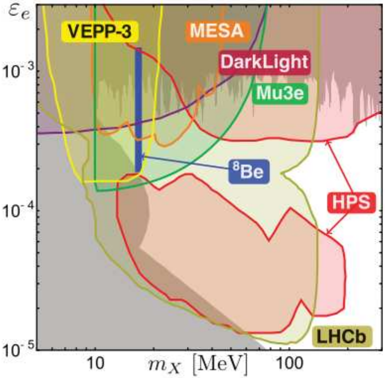
X17 interaction with electrons

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

$$\mathcal{L} = e\varepsilon_e \overline{e}(x)\Gamma e(x)X(x) + e\varepsilon_u \overline{u}(x)\Gamma u(x)X(x) + \cdots$$

X17 decay

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

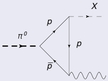


Proposed models

"Protophobic" vector boson
[Feng *et al.*, 2016–2020]
Fifth force

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

NA48 limit for $\pi^0 \to \gamma X$
[Batley *et al.*, 2015]
A way out: the particle X does not couple with protons
$|2\varepsilon_u + \varepsilon_d| < 8\ 10^{-4}$



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

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

"Piophobic" axion [Alves, 2020]

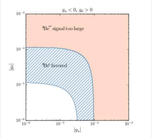
Quantum number $J^\pi = 0^-$

QCD axion with mass $\sim$ 17 MeV excluded generally
[Alves & Weiner, 2017]
A way out: no mixing with π^0
$\mathcal{L} = \theta_{a-\pi} X(x) \pi^0(x)$,
$|\theta_{a-\pi}| < 10^{-4}$

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 $\to \delta a_\mu \approx 0$ [Borsanyi *et al.*, 2021]

Outline

1 Introduction

2 Theoretical study of the $A = 4$ reactions

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

4 Incorporating the X17

5 Conclusions

Theoretical study of the $A = 4$ 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 χEFT & 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, ...)

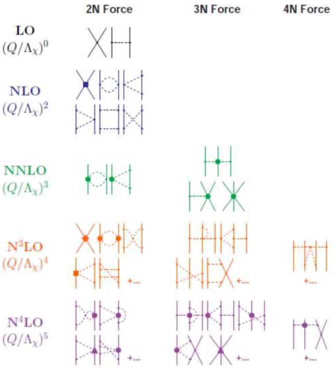
Modern nuclear interactions (continued)

- 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, Kreb, & 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]

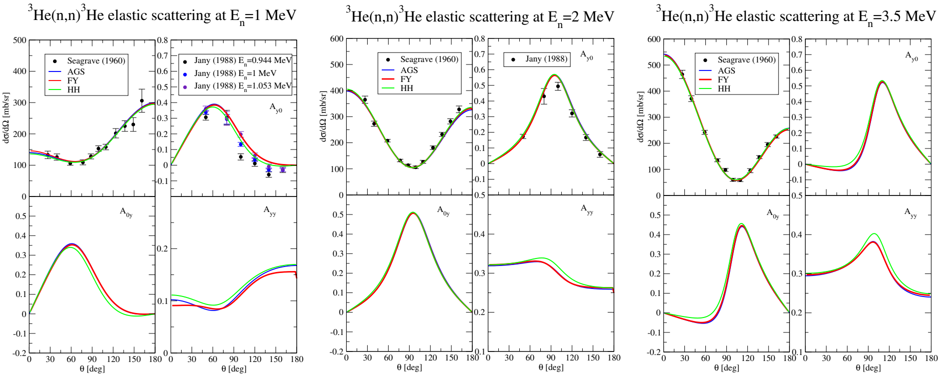
LEC's fitted to the NN database or πN database. Cutoff $\Lambda = 450 - 600$ MeV

3N interaction

- N2LO [Epelbaum *et al*, 2002] two LECS c_D and c_E: fitted to reproduce $B(^3\mathrm{H})$ and some other observable
- 3N force at N3LO & N4LO [Krebs *et al.*, 2012-2013]
- $+\Delta$ 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}He(n, n)^{3}He elastic scattering



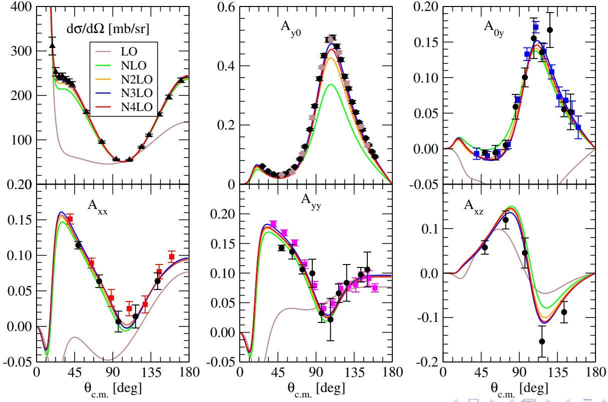
AGS= Deltuva & Fonseca – FY= Lazauskas & Carbonell – HH= present work

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

NN potentials up to N4LO [Entem, Machleidt, & Nosyk, 2017]
Theoretical error estimated using the method proposed by [Epelbaum, Kreb, & Meissner, 2014]
$\Delta X_i = \max[Q|X_i - X_{i-1}|, Q^2|X_{i-1} - X_{i-2}|, \ldots]$
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 $B(^3\mathrm{H})$ and tritium GTME by [Marcucci *et al.*, 2018]



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

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

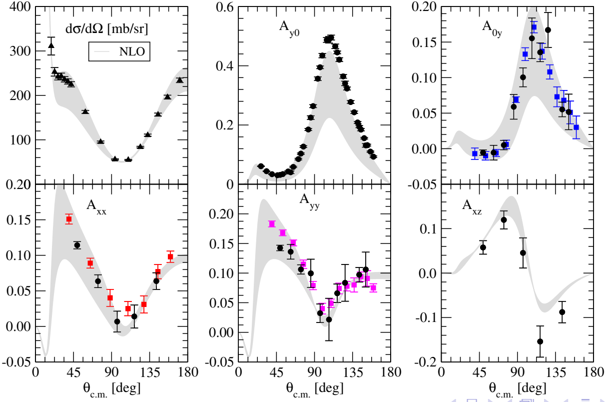
Theoretical error estimated using the method proposed by [Epelbaum, Kreb, & Meissner, 2014]

$\Delta X_i = \max[Q|X_i - X_{i-1}|, Q^2|X_{i-1} - X_{i-2}|, \ldots]$

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 $B({}^3\mathrm{H})$ and tritium GTME by [Marcucci *et al.*, 2018]



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

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

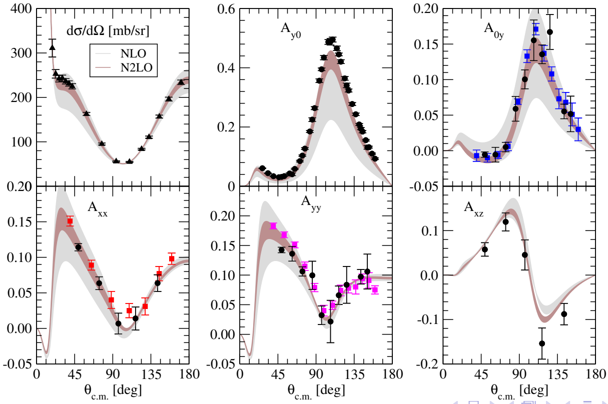
Theoretical error estimated using the method proposed by [Epelbaum, Kreb, & Meissner, 2014]

$\Delta X_i = \max[Q|X_i - X_{i-1}|, Q^2|X_{i-1} - X_{i-2}|, \ldots]$

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 $B({}^3\mathrm{H})$ and tritium GTME by [Marcucci *et al.*, 2018]



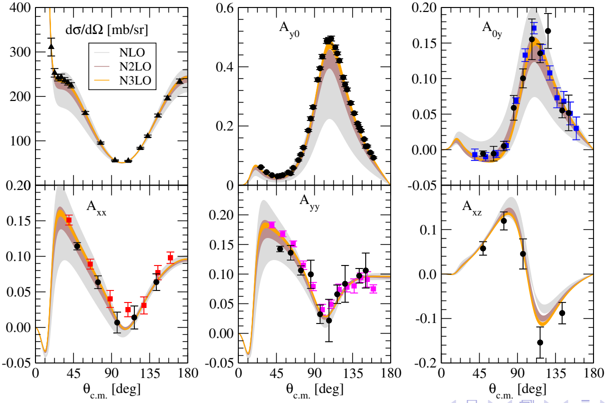
$p + {}^3\mathrm{He}$ elastic scattering

NN potentials up to N4LO [Entem, Machleidt, & Nosyk, 2017]
Theoretical error estimated using the method proposed by [Epelbaum, Kreb, & Meissner, 2014]

$\Delta X_i = \max[Q|X_i - X_{i-1}|, Q^2|X_{i-1} - X_{i-2}|, \ldots]$
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 $B({}^3\mathrm{H})$ and tritium GTME by [Marcucci *et al.*, 2018]



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

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

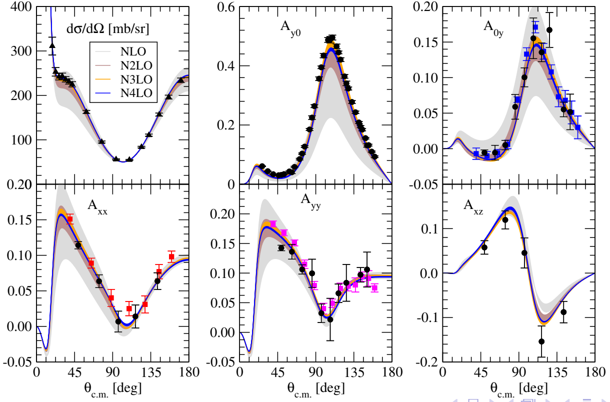
Theoretical error estimated using the method proposed by [Epelbaum, Kreb, & Meissner, 2014]

$\Delta X_i = max[Q|X_i - X_{i-1}|, Q^2|X_{i-1} - X_{i-2}|, \ldots]$

with $Q = m_\pi/\Lambda$

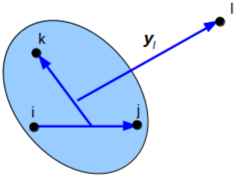
Order	V_{NN}	W_{3N}
0	LO	—
1	NLO	—
2	N2LO	N2LO
3	N3LO	N2LO* (N3LO c_i from table IX of EMN17)
4	N4LO	N2LO** (N4LO c_i from table IX of EMN17)

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



Calculation of transition amplitudes

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



Initial/final wave functions

Ψ_4: ^{4}He bound state wave function $J^\pi = 0^+$

Ψ_{1+3}: scattering wave function – decomposed in components of definite LSJ

$$\Psi_{1+3} = \sum_{LMSS_zJJ_z} (\frac{1}{2}m_3\frac{1}{2}m_1|SS_z)(LMSS_z|JJ_z)4\pi i^L Y^*_{LM}(\hat{p})e^{i\sigma_L}\Psi^{LSJ}_{1+3}$$

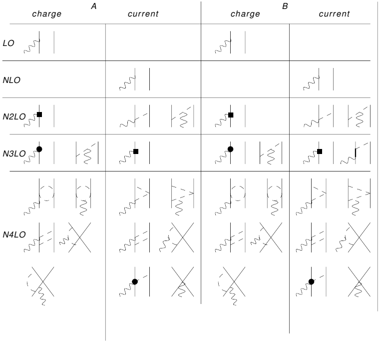
p relative momentum

EM charge & currents transition operators

EM current from χEFT

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



Reduced matrix elements (RMEs)

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

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

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

Selection rules

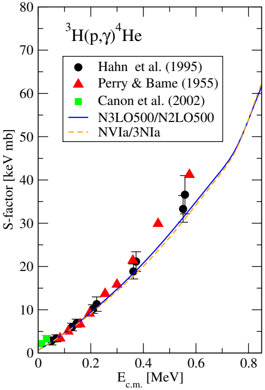
Parity of $\Psi_4 = +$, parity of $\Psi_{1+3}^{LSJJ_z} = (-)^L$

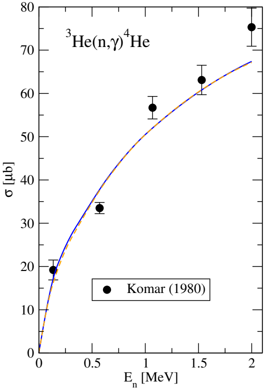
state	$^{2S+1}L_J$	charge multipoles	current multipoles
0^+	$^1S_0$	C_0^{000}	–
0^-	$^3P_0$	–	–
1^+	$^3S_1, {}^3D_1,$	–	M_1^{LS1}
1^-	$^1P_1, {}^3P_1,$	C_1^{LS1}	E_1^{LS1}
2^+	$^1D_2, {}^3D_2,$	C_2^{LS2}	E_2^{LS2}
2^-	$^3P_2, {}^3F_2,$	–	M_2^{LS2}

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

Interest

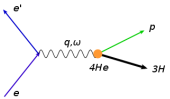
- BBN, production of $^4\mathrm{He}$
- Dominated by the E_1 transition $1^- \to 0^+$
- No sensivity to interactions/MEC
- Real γ's conversion in $e^- e^+$ from interaction with the apparatus
- $\to$ external pair convertion (EPC)





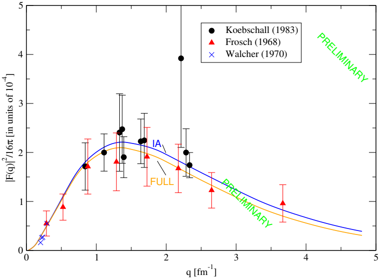
The ^{4}He transition form factor

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

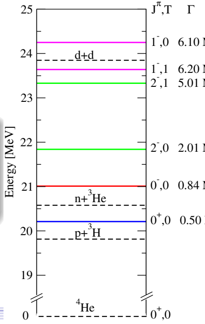


- Sensitive to the excitation of the 1st excited 0^+ state of ^{4}He
- $\mathcal{S}_{\mathcal{M}}(q,\omega) \sim |C_0|^2$

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

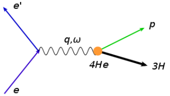


[Hiyama *et al.*, (2004)] calculation treating the first excited state as a bound state



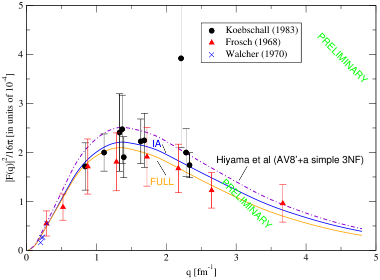
The ^{4}He transition form factor

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

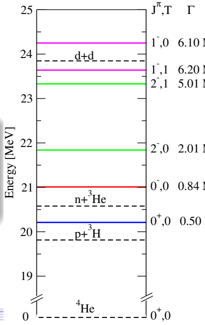


- Sensitive to the excitation of the 1st excited 0^+ state of ^{4}He
- $\mathcal{S}_{\mathcal{M}}(q,\omega) \sim |C_0|^2$

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



Outline

1 Introduction

2 Theoretical study of the $A = 4$ reactions

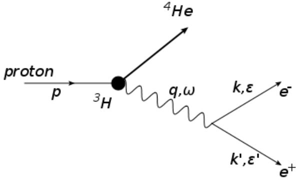
3 The $^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$ and $^3\mathrm{He}(n, e^+e^-)^4\mathrm{He}$ processes

4 Incorporating the X17

5 Conclusions

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

"Standard" EM process



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

$E_0 = E_p + B_4 - B_3 \approx 20$ MeV, $\boldsymbol{q} = \boldsymbol{k} + \boldsymbol{k}'$, $\omega = \epsilon + \epsilon'$, $Q^2 = \omega^2 - q^2 > 0$ "time-like"
$\cos\theta_{ee} = \hat{k}\cdot\hat{k}'$, $i = L, T, TT, TT', LT, LT'$

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

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

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

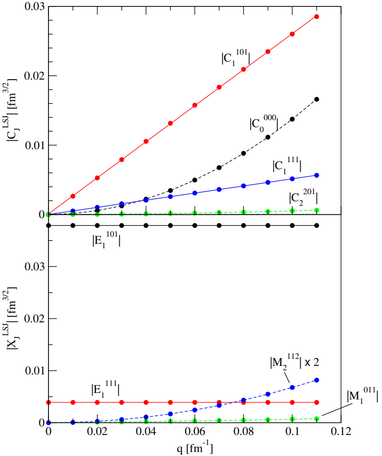
RME's: q dependence

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

Behaviour at $q \to 0$

- $q = |\boldsymbol{k} + \boldsymbol{k}'| \to 0$: lepton pair emitted back-to-back
- $Q^2 = \omega^2 \approx E_0^2$ finite
- $v_L = \frac{Q^4}{q^4}(\epsilon\epsilon' + \boldsymbol{k}\cdot\boldsymbol{k}' - m_e^2) \to 1/q^2$
- A carefull calculation of the RMEs is needed: RMEs$\sim q^n$, $n > 0$

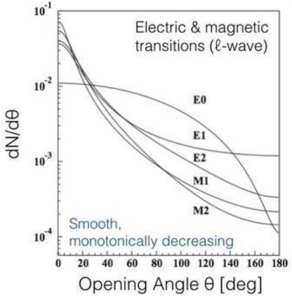
- $\sum_{j=1}^{A} \frac{1+\tau_z(j)}{2} = 2$
- $e^{i\boldsymbol{q}\cdot\boldsymbol{r}_j} = 1 + i\boldsymbol{q}\cdot\boldsymbol{r}_j + \frac{1}{2}(i\boldsymbol{q}\cdot\boldsymbol{r}_j)^2 + \cdots$
- $J^\pi = 0^+$: first contributing order q^2
- $J^\pi = 1^-$: first contribution order q
- $J^\pi = 2^+$: first contribution order q^2

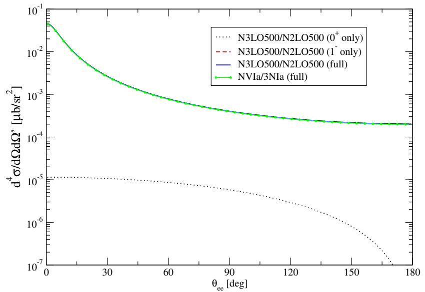


$^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$ cross section in the one-photon-exchange approximation

Calculation using
N3LO500/N2LO500 + χEFT current by
[Pastore *et al.*, 2009]
NVIa/3Na* + χEFT 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"

Outline

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, . . .)
- $E \sim 1$ MeV: nuclear physics experiments

EFT approach

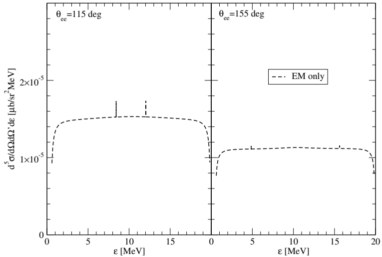
1. Start with a generic interaction Lagrangian with electrons, u and d quarks, . . .
2. Generate the interaction at hadronic level using χEFT
3. Accurately compute the matrix elements of the generated operators

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

- $\epsilon =$ 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

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



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

$$\frac{1}{|D_X|^2} \to \frac{\pi}{|\alpha_i|} \frac{1}{\Gamma_X M_X} \delta(\epsilon - \epsilon_i)\ .$$

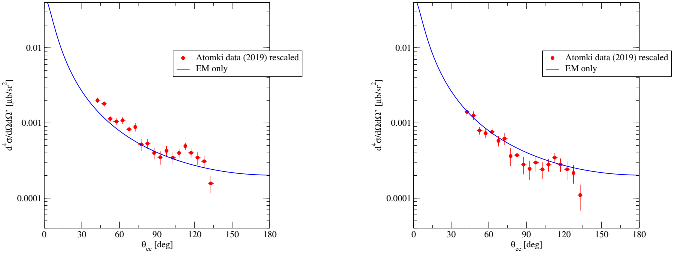
$$\frac{d^4\sigma}{d\hat{\mathbf{k}}\, d\hat{\mathbf{k}}'} = \int_{m_e}^{E_{max}} \sigma_{EM}(\epsilon) + \sum_i \left[2\varepsilon_e \Im\Big(R_X(\epsilon_i)\Big) \frac{\pi}{|\alpha_i|} + \varepsilon_e^2 R_{XX}(\epsilon) \frac{\pi}{|\alpha_i| M_X \Gamma_X} \right.$$

No sensitivity to ε_e and the interference term!!!

Fit of the 2019 data

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

Problem!

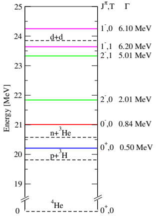


Here there is also the problem of the EPC pairs!

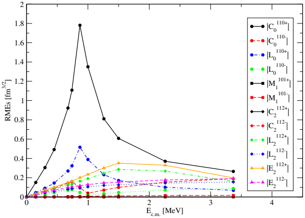
Energy dependence RME's

S=scalar, P=pseudoscalar, V=vector, A=axial X17

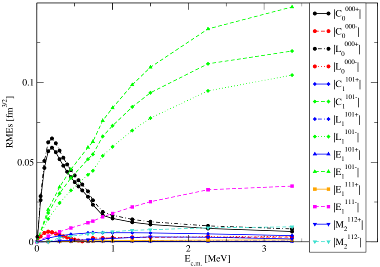
Levels of ^{4}He



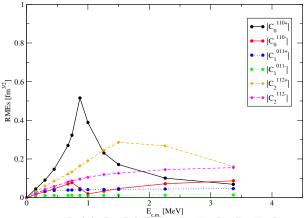
A RME's



S,V RME's



P RME's

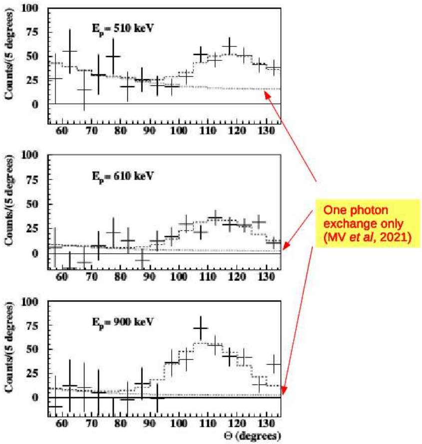


Fit of the 2021 data

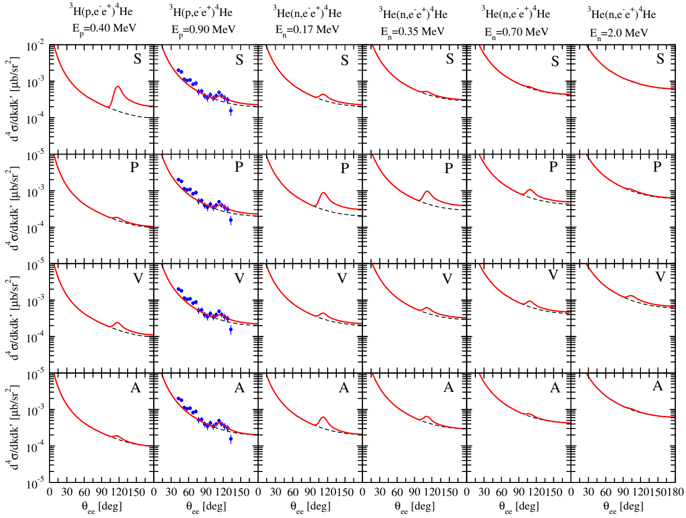
- For the 2021, the background has been somehow subtracted
- but the procedure it is still difficult to be applied
- Furthermore: finite angular/energy resolution of the target, geometry of the detector, efficiencies, etc.

For the moment

- let us study he 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

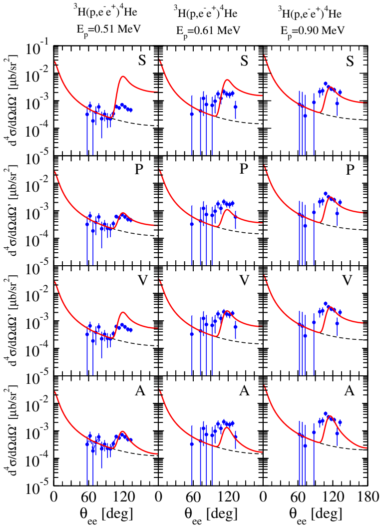


pair emission in the perpendicular plane – peak fitted at 0.90 MeV



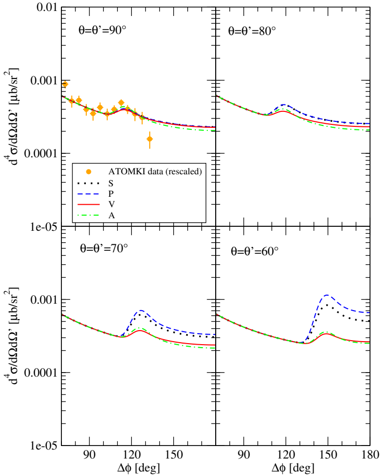
Comparison with the 2021 ATOMKI data

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



Out of the perpendicular plane study

θ (θ') angle of the e^- (e^+) momentum with respect to the incident beam
peak fitted at 0.90 MeV



Extracted coupling constants

$$\varepsilon_0 = \frac{\varepsilon_u + \varepsilon_d}{2} \qquad \varepsilon_z = \frac{\varepsilon_u - \varepsilon_d}{2} \qquad \left[2\varepsilon_u + \varepsilon_d = 0 \Rightarrow 3\varepsilon_0 + \varepsilon_z = 0\right]$$

	N3LO500/N2LO500		NVIa/3NIa	
Case	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}	$-\mathbf{3}\,\varepsilon_0$	2.66×10^{-3}	$-\mathbf{3}\,\varepsilon_0$
A	2.58×10^{-3}	**0**	2.89×10^{-3}	**0**

First rough estimates – very uncertain due to the aforementioned difficulties

Vector case

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

Pseudoscalar case

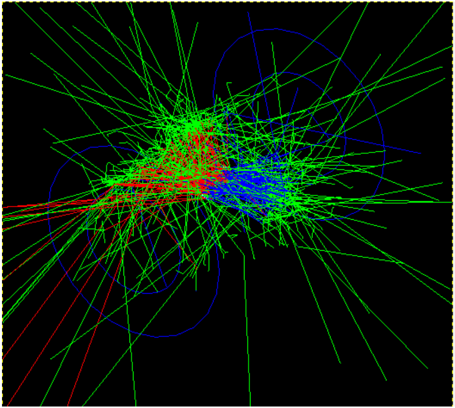
- $|\varepsilon_{u,d}| \sim 1$ Alves, 2020], Delle Rose *et al.*, 2019]
- too small!

Axial case

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

Geant studies for the n_ToF experiment

Courtesy of A. Mazzone (CNR, Bari)



$^3\mathrm{He}(n, e^- e^+)^4\mathrm{He}$ at CERN (n_ToF)

LoI approved - technical design in progress

4π detector/reconstruction of the tracks/particle identification

[C. Gustavino *et al.*, 2021]

Outline

Conclusions and perspectives

Analysis of the $^4\mathrm{He}$ ATOMKI “anomaly”

- Accurate description of the nuclear dynamics using state-of-the-art techniques
- Test using $F_{\mathcal{M}}(q)$ and $p + {}^3\mathrm{H}$, $n + {}^3\mathrm{He}$ 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 $^3\mathrm{He}(n, e^- e^+)^4\mathrm{He}$ process
  - technical design in progress
  - GEANT analysis currently in progress
- Study of possible “standard” explanation
  - Two-photon exchange contribution [Aleksejevs *et al.*, 2021] for $^8\mathrm{Be}$
  - Repeat this study for $^4\mathrm{He}$ using our wave functions
- If the anomaly is confirmed, full χEFT treatment of the X17-nucleon interaction

Thank you for your attention!