Experimental framework of the X17 anomaly

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ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED
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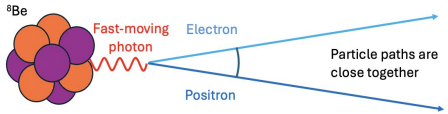
FRIB Theory Alliance

ATOMKI experiments

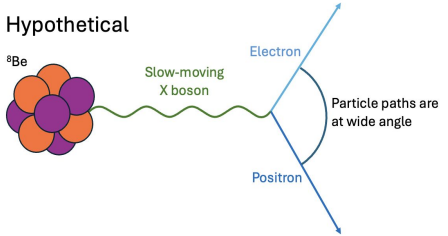
Attila Krasznahorkay

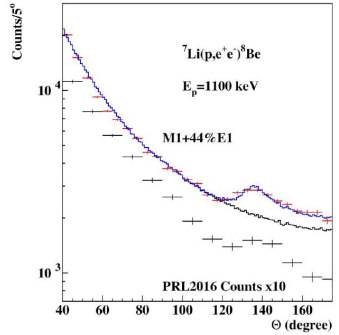
The ATOMKI group observed an excess of e^-e^+ pairs emitted at large relative angle in the $^3H(p,e^-e^+)^4He$, $^7Li(p,e^-e^+)^8Be$, $^{11}B(p,e^-e^+)^{12}C$ nuclear reactions. This excess can be explained with the creation (and decay into e^-e^+ pairs) of a new particle with mass ~17 MeV, called **X17 boson**.

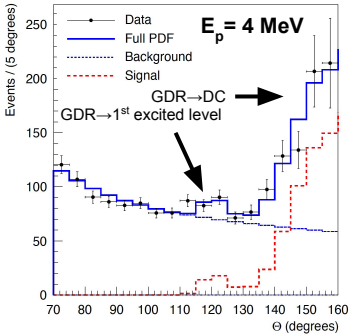
Expected ^{8}Be Transition



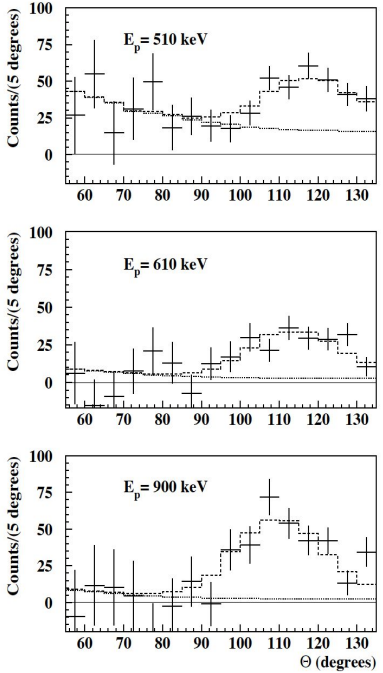
Hypothetical



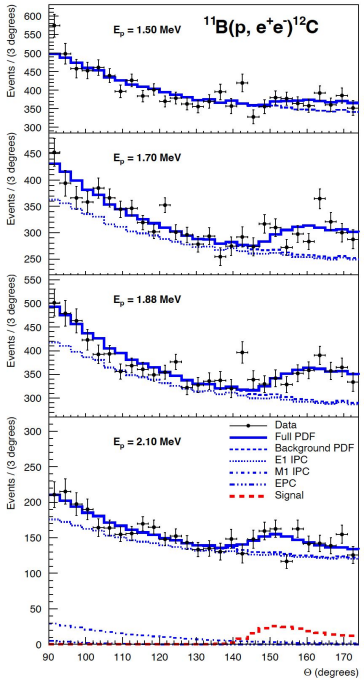




$^7Li(p,e^-e^+)^8Be$



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



$^{11}B(p,e^-e^+)^{12}C$

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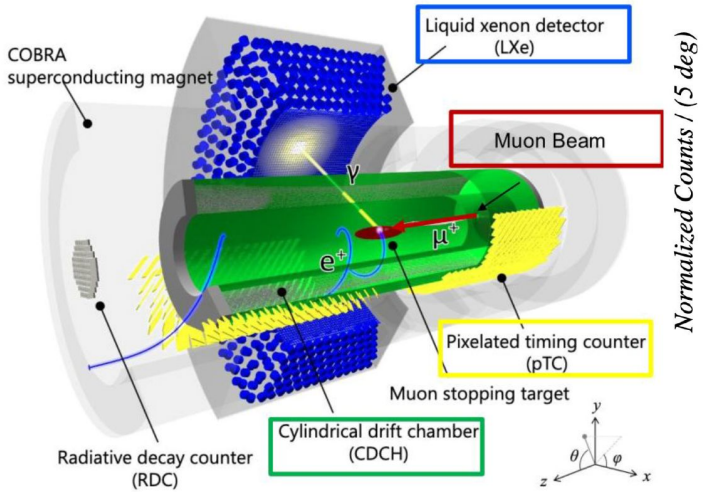
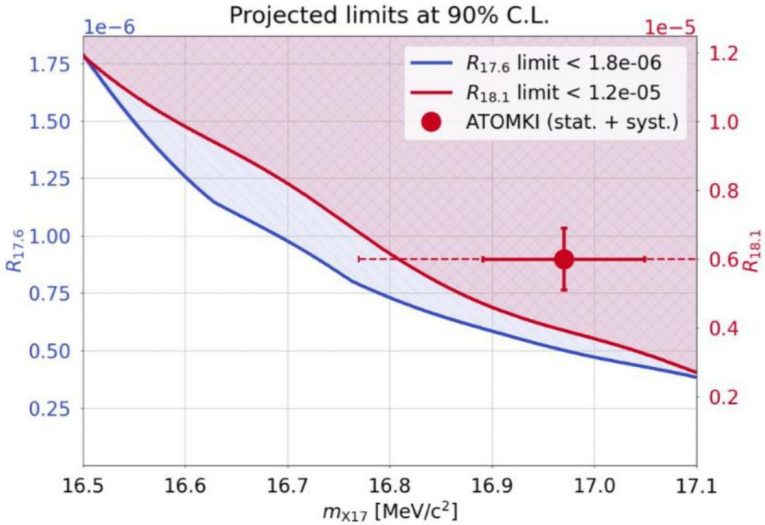
MEG II experiment

Hicham Benmansour

The $^{7}Li(p,e^{-}e^{+})^{8}Be$ at MEGII

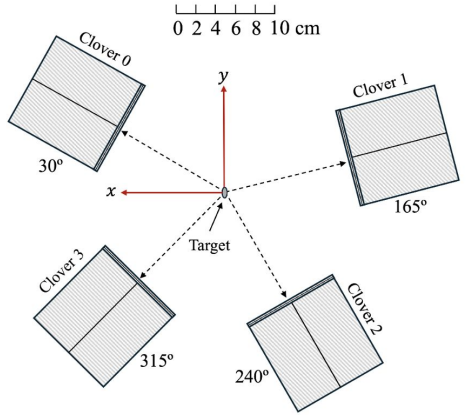




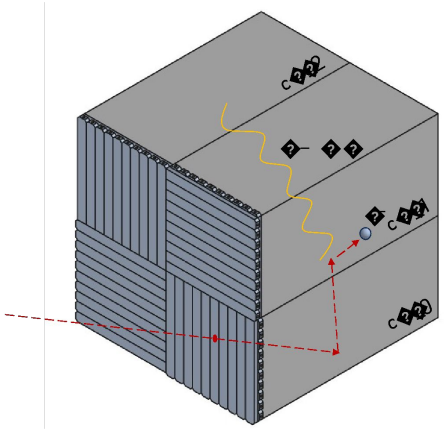
LNL experiment

Benito Gongora Servin

The $^{7}Li(p,e^{-}e^{+})^{8}Be$ at LNL



Similar to the ATOMKI setup, but all detector operate in vacuum → Improve angular resolution by reducing material budget.



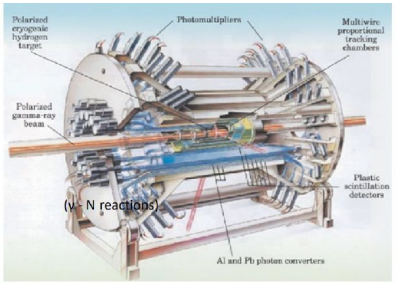
Montreal experiment

Luca Doria

The $^{7}Li(p,e^{-}e^{+})^{8}Be$ at Montreal

The Montreal X-17 Project

- Use parts of the DAPHNE experiment (Saclay/Mainz*)
- Tracking MWPC chamber & 16 scintillators (NE102A)
- Scints & MWPC from U. Mainz → now @ Montreal
- Phototubes and some ADC/TDC's borrowed from TRIUMF



Large solid angle coverage → 0.95 x 4π

*Many thanks to

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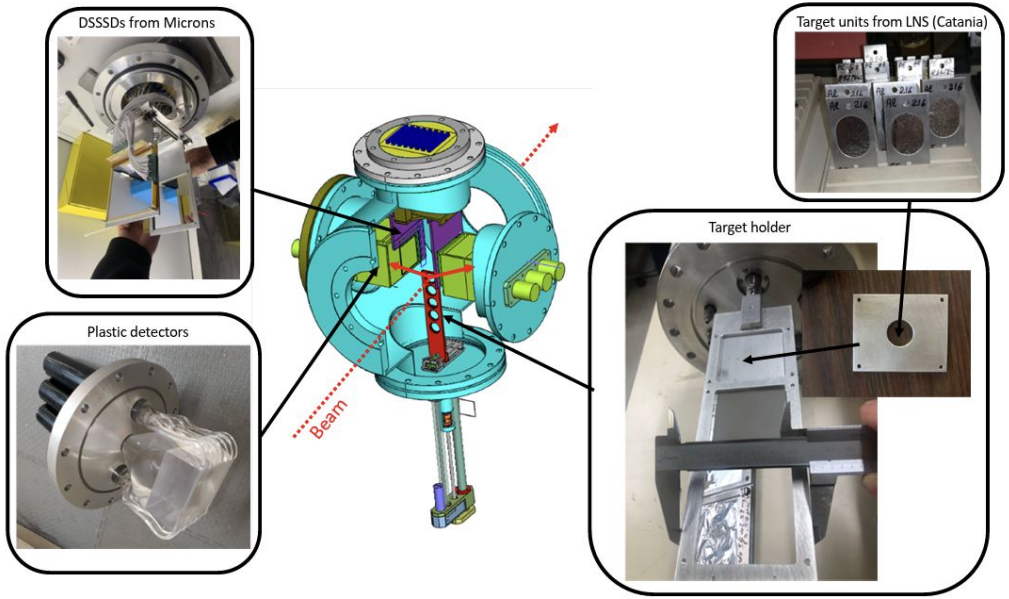
New Jedi experiment

Beyhan Bastin

The $^{7}Li(p,e^{-}e^{+})^{8}Be$ at GANIL



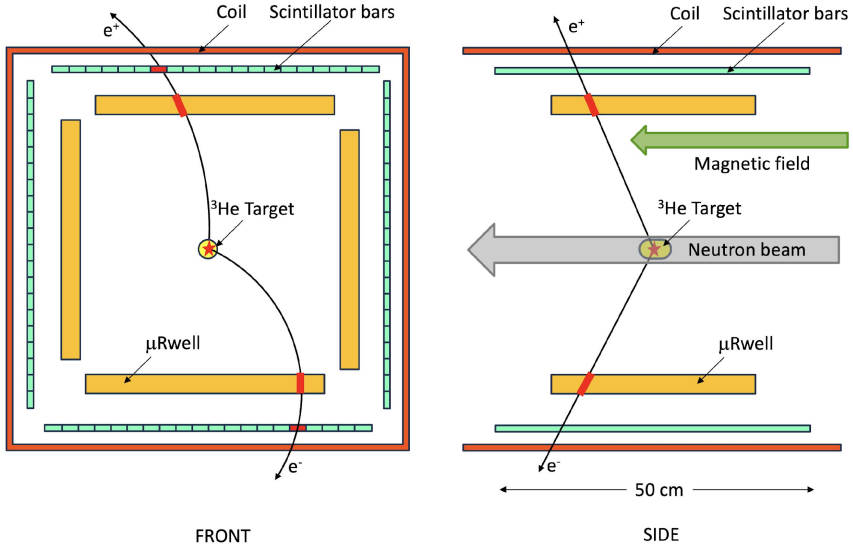
Carlo Gustavino

The ^{3}He(n,e$^-$e$^+$)^{4}He at n_TOF

-Pulsed neutron beam

Detector requirements:
-Low sensitivity to photons and neutrons
-Large acceptance
-ejectiles charge and kinematics

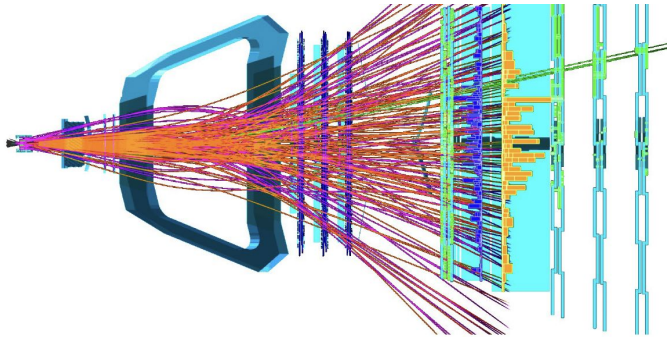
-4 μRwells with a large (3 cm) gap
→ 3D tracking
-4 planes 50x50 cm^2, of scintillator bars
→ Trigger and neutron energy with TOF technique
-Coil (B = 500 Gauss)
→ charge and momentum reconstruction of ejectiles



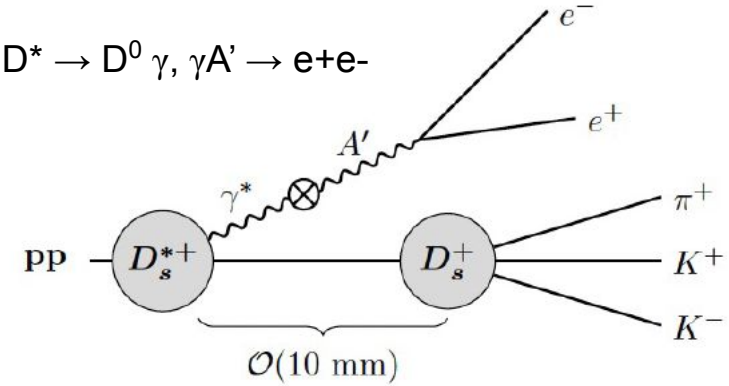
LHCb at CERN

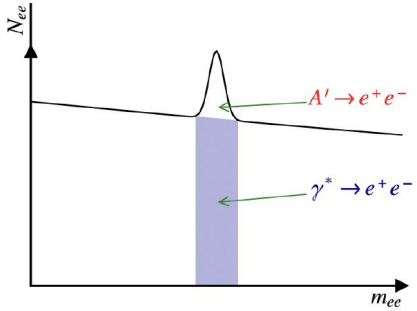
Martino Borsato

Huge background, the strategy is to exploit selected processes inside the shower, e.g.



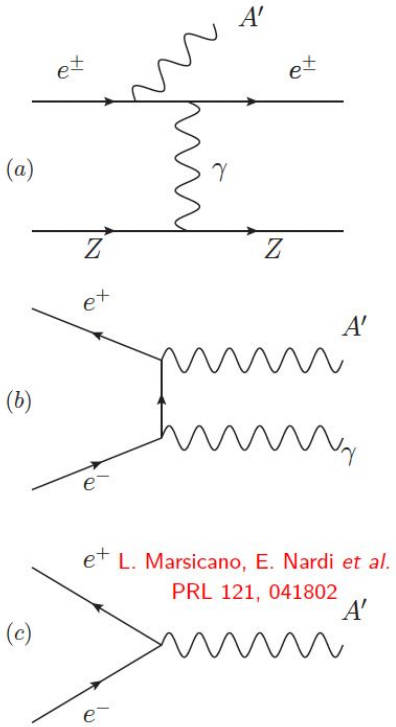
$D^* \rightarrow D^0 \gamma$, $\gamma A' \rightarrow e^+e^-$

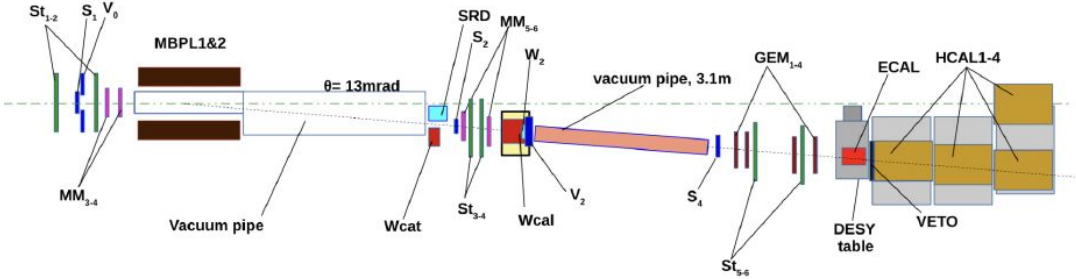


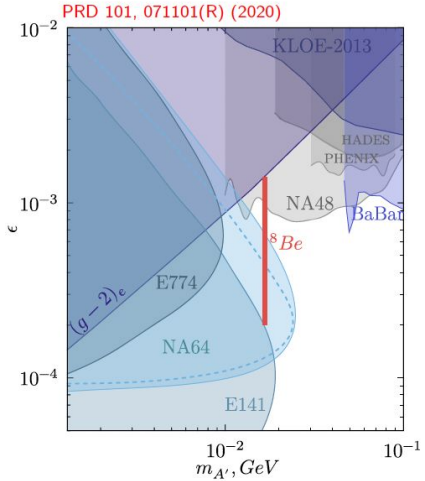


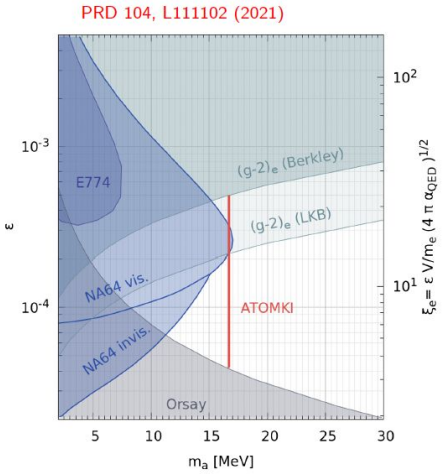
NA64 experiment

Luca Marsicano



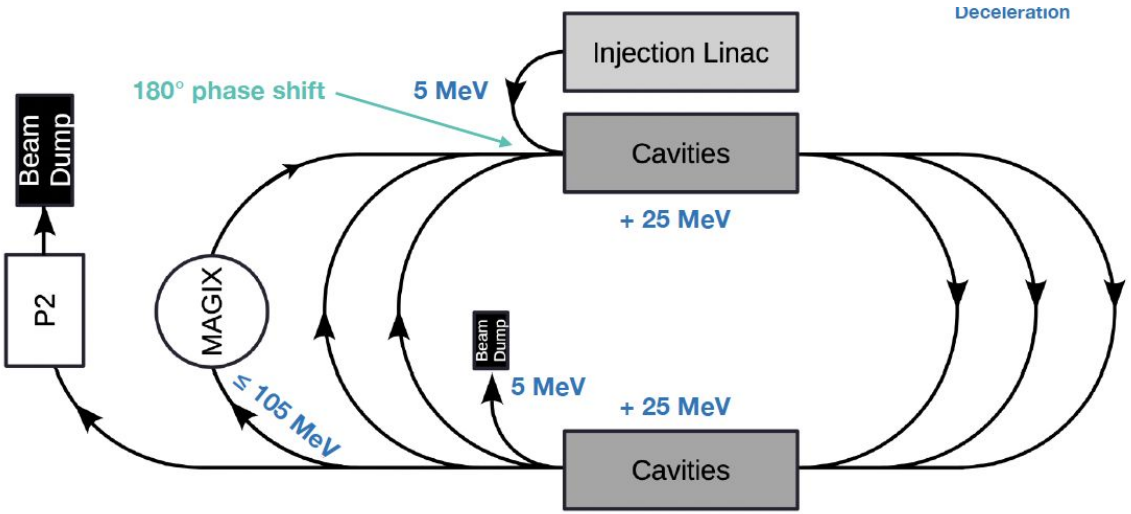


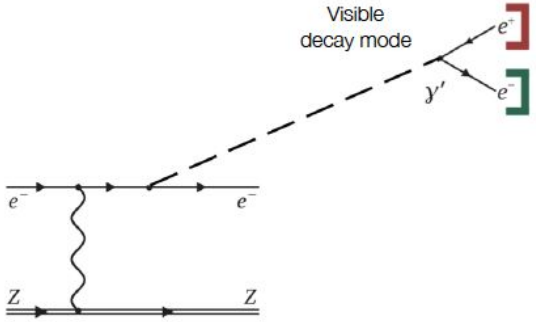


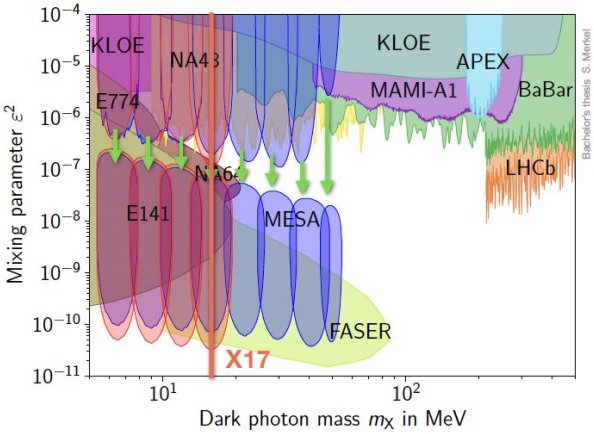


MAGIX experiment

Stefan Merkel

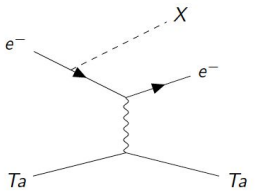


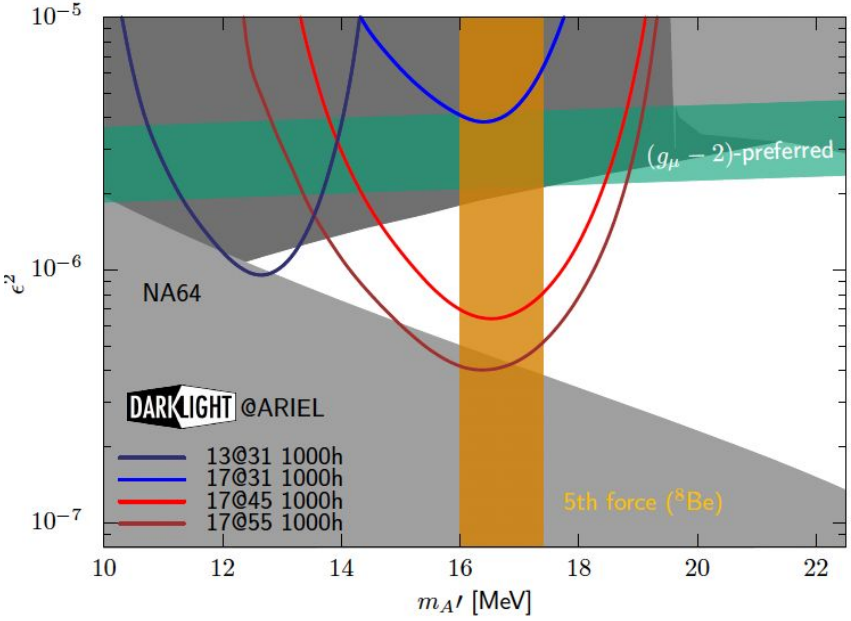


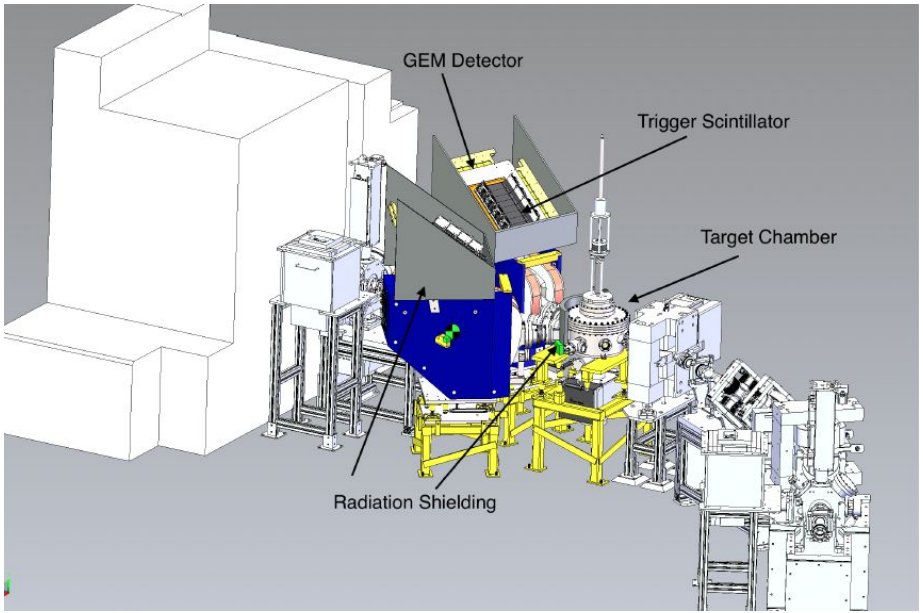


Darklight experiment

Ethan Cline



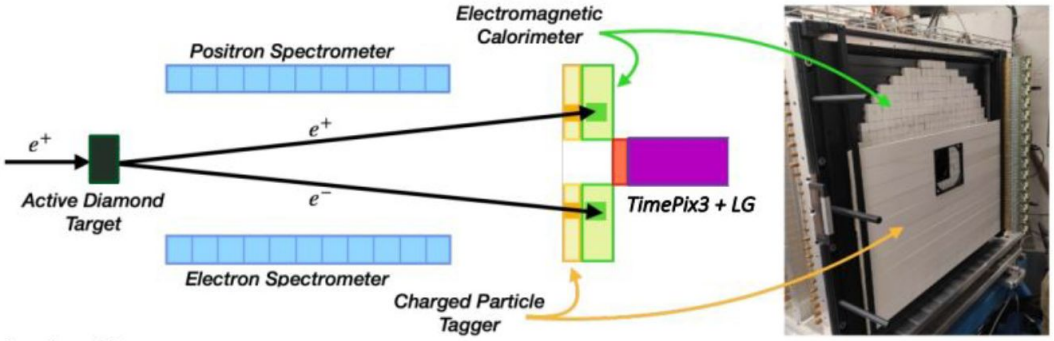


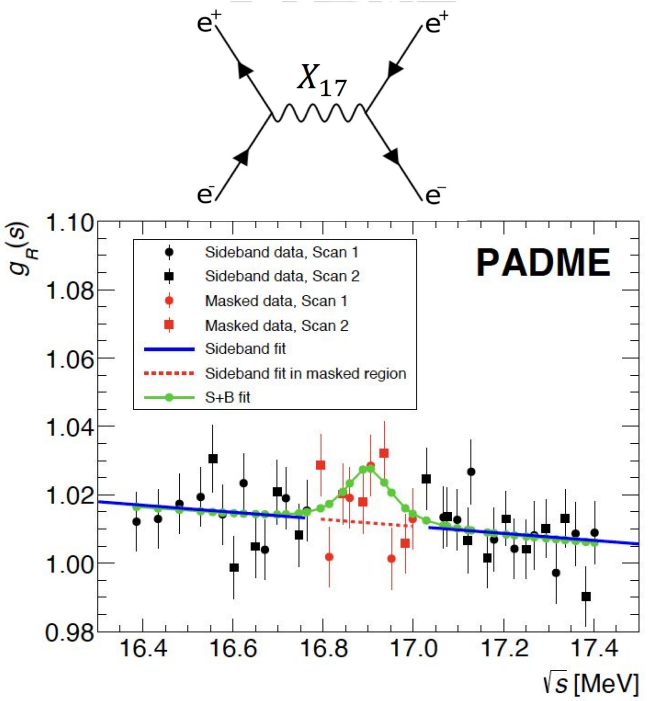


Mauro Raggi

Resonant X17 in e+e- annihilation at PADME

- *42 points in 263 MeV < E_{beam} < 292 MeV and δE_{beam} ~ 0.75*
- *6 points out-of-resonance, where the $X17$ production is forbidden:*
- *5 points with 205 MeV ≤ E_{beam} ≤ 212 MeV*
- *1 point with E_{beam} = 402 MeV*





Theoretical framework of the X17 anomaly

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ATOMKI search

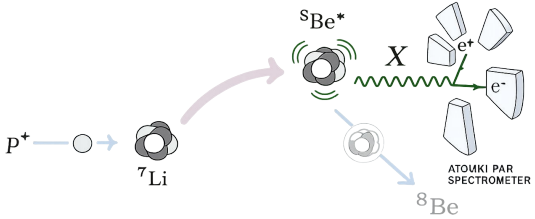
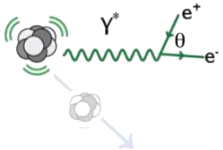
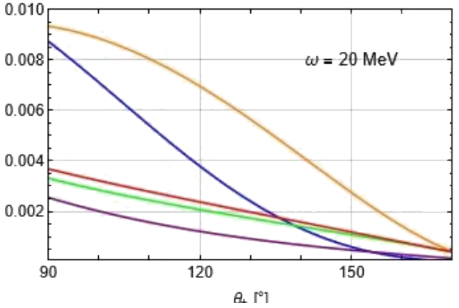


Figure taken from Feng, 2016



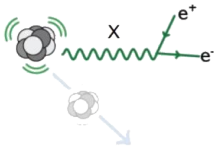


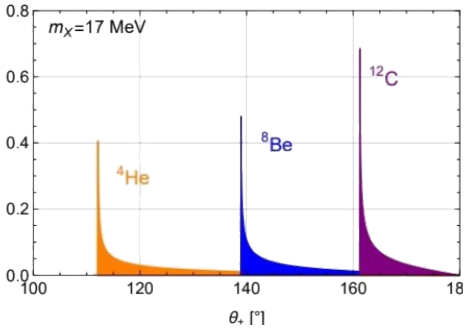
At wide angles, QED predicts a rapid decrease in the angular correlation of lepton pairs

$$\text{Signal Rate} = \sigma(N^* \to N + X) \times \text{BR}(X \to e^+e^-)$$

coupled to nuclear matter (quarks and gluons)

coupled to electrons/positrons





Bump-like distribution

Figures taken from Daniele Barducci & Claudio Toni, 2023

X17 decay kinematics

The ATOMKI anomalies show well-defined features, explained by the kinematics of the X17 hypothesis

• The e^+e^- opening angles of the anomalous peaks are around 140°, 115° and 155°–160° for the ^{8}Be, ^{4}He and ^{12}C anomalies.

• The excesses are resonant bumps located at the same e^+e^- invariant mass.

• The anomalous signal is observed only inside the kinematic region |y| < 0.5, where y is the energy asymmetry.

Changing the beam energy or the assumed X17 mass shifts the θee(y) curve, so the angular correlation is both a discovery handle and a mass discriminator.

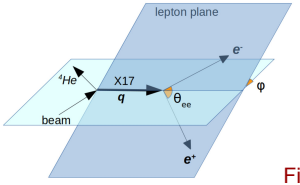


Fig. from Viviani et al., 2021

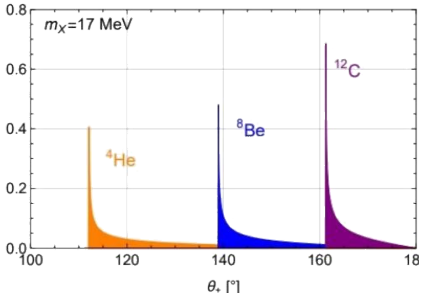
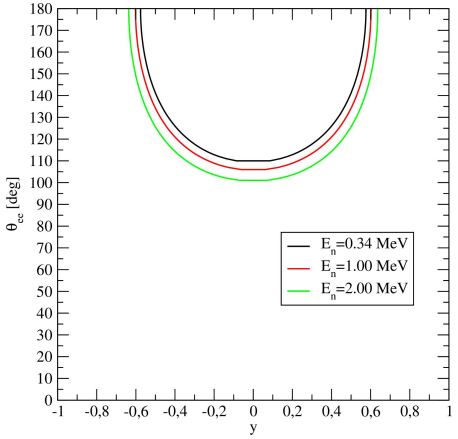


Fig. from Daniele Barducci & Claudio Toni, 2023



The anomaly triggered many theoretical speculations…

OVERVIEW

[Feng et al., 2016] "*Protophobic Fifth Force Interpretation of the Observed Anomaly in 8Be Nuclear Transitions*"

[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 MeV/c²: Nuclear transitions and light meson decays*"

[Wong, 2022] *"QED Meson Description of the X17 and Other Anomalous Particles"*

Essential ingredients for the theoretical analysis

Reliable nuclear-structure calculations ideally from ab initio methods	Model	Implications for SM ,BSM physics and hidden sector
Speakers	**Speakers**	**Speakers**
Petr Navratil • Laura Elisa Marcucci • Cornelis Mommers • Aldo Bonasera • Adrian Thompson • Johan Rathsman	Stefano Moretti • Yasar Hicyilmaz • Max Fieg • Claudio Toni & Daniele Barducci • Emrys Peets	Vincenzo Fiorentino • Sergi Gonzalez-Solis • Marco Graziani

Key theoretical implication

The same signal hypothesis must remain compatible with particle-physics constraints and with a controlled nuclear calculation.

X17 interaction with electrons

The boson must couple strongly enough to decay promptly to e^+e^-, but weakly enough to survive beam-dump and collider searches

Generic interaction

$$\mathcal{L} = e\varepsilon_e \bar{e}(x)\Gamma e(x)X(x)$$

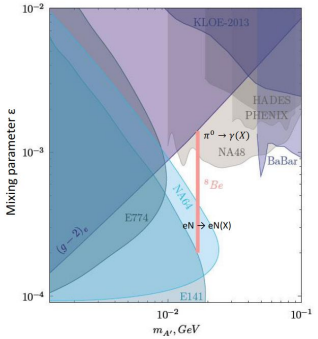
- $\Gamma = 1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \ldots$
- e = electric charge (e > 0)
- X(x) X17 field

Key points

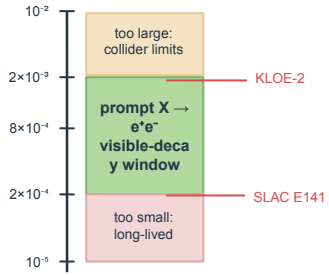
- Benchmark scenarios assume $X \to e^-e^+$ dominates the visible decay pattern [Feng *et al.*, 2016–2020]
- Width scales as $\Gamma_X \approx \varepsilon_e^2\, \alpha\, M_X$
- The X17 must decay in the apparatus: $|\varepsilon_e| > 10^{-5}$
- Interesting window: roughly 10^{-4} to 10^{-3}

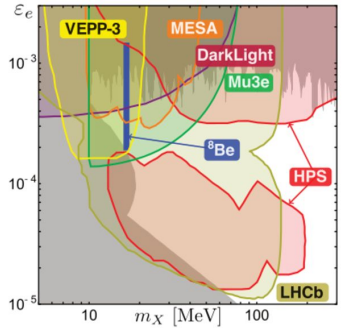
Search constraints

- SLAC E141: $|\varepsilon_e| > 2 \times 10^{-4}$ [Alexander *et al.*, 2017]
- NA64: $|\varepsilon_e| > 6.8 \times 10^{-4}$ [Banerjee *et al.*, 2020]
- KLOE-2: $|\varepsilon_e| < 2 \times 10^{-3}$ [Feng *et al.*,2016]



Viable ε_e band at $M_X \approx 17$ MeV





Coupling with quarks

Assuming definite parity for simplicity, there are four possible scenarios.

Scalar (S):

$$\mathcal{L}_q^S = e\,\frac{m_q}{\Lambda_S}\,\bar{q}(\varepsilon_0 + \varepsilon_z\tau_3)q\,X,$$
$$\mathcal{L}_N^S = \eta_0^S\,\bar{N}NX + \eta_z^S\,\bar{N}\tau_3 NX$$

$$\eta_0^S = \varepsilon_0\left(-\frac{4c_1 m_\pi^2}{\Lambda_S}\right), \quad \eta_z^S = \varepsilon_z\left(-\frac{2c_5 m_\pi^2}{\Lambda_S}\right)$$

Pseudoscalar (P):

$$\mathcal{L}_q^P = e\,\frac{m_q}{\Lambda_S}\,\bar{q}(\varepsilon_0 + \varepsilon_z\tau_3)i\gamma^5 q\,X,$$
$$\mathcal{L}_N^P = \eta_0^P\,\bar{N}i\gamma^5 NX + \eta_z^P\,\bar{N}i\gamma^5\tau_3 NX + 2\eta_z^P\,\frac{B_c}{m_\pi^2}\,\bar{N}i\gamma^5\tau_3 X$$

$$\eta_0^P = \varepsilon_0\,\frac{2m_\pi^2 m_N(d_{18}+2d_{19})}{\Lambda_S}, \quad \eta_z^P = \varepsilon_z\,\frac{f_\pi m_\pi^2}{\Lambda_S}$$

Vector (V):

$$\mathcal{L}_q^V = e\,\bar{q}(\varepsilon_0 + \varepsilon_z\tau_3)\gamma^\mu q\,X_\mu,$$
$$\mathcal{L}_N^V = \eta_0^V\,\bar{N}\gamma^\mu NX_\mu + \eta_z^V\,\bar{N}\gamma^\mu\tau_3 NX_\mu + \text{mag. mom.}$$

$$\eta_0^V = 3\varepsilon_0, \quad \eta_z^V = \varepsilon_z$$

Axial (A):

$$\mathcal{L}_q^A = e\sum_f \varepsilon_f\,\bar{f}\gamma^\mu\gamma^5 f X_\mu,$$
$$\mathcal{L}_N^A = \eta_0^A\,\bar{N}\gamma^\mu\gamma^5 NX_\mu + \eta_z^A\,\bar{N}\gamma^\mu\gamma^5\tau_3 NX_\mu$$

$$\eta_0^A = (3F - D)\varepsilon_0, \quad \eta_z^A = (F + D)\varepsilon_z$$

Viviani et al., 2021

Process $N^* \to N$	X boson spin parity $S\pi = 1^-$	$S\pi = 1^+$	$S\pi = 0^-$	$S\pi = 0^+$
^{8}Be(18.15) → ^{8}Be	1	0, 2	1	/
^{8}Be(17.64) → ^{8}Be	1	0, 2	1	/
^{4}He(21.01) → ^{4}He	/	1	0	/
^{4}He(20.21) → ^{4}He	1	/	/	0
^{12}C(17.23) → ^{12}C	0, 2	1	/	1

Daniele Barducci & Claudio Toni, 2023

- The scalar scenario is excluded by parity conservation in Beryllium transitions.
- The pseudoscalar scenario is excluded by parity conservation in Carbon transition.

Further constraints from Kaon decay

Hostert, Pospelov and Thompson, arXiv:2602.19479

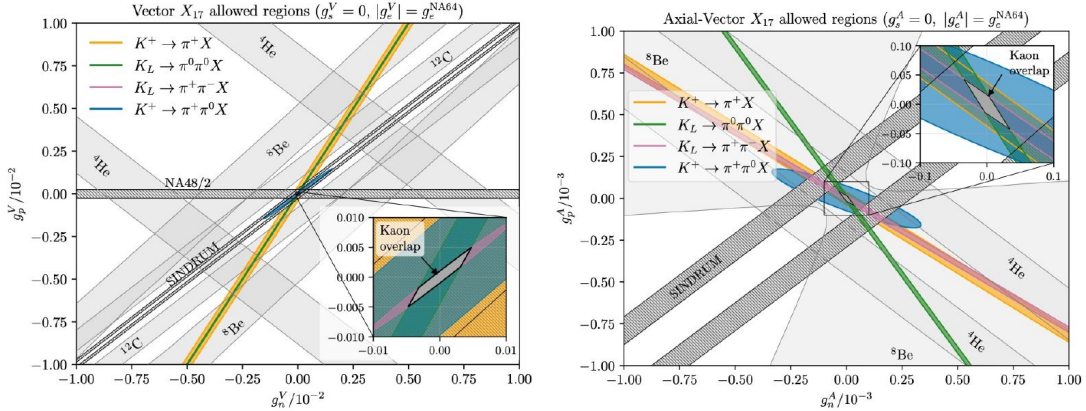


FIG. 5. The allowed regions in the 17 MeV spin-1 boson coupled to a vector (left) or axial-vector (right) current for $g_s^{V,A} = 0$, setting the electron coupling to saturate the lower bound from NA64 [25]. The 90% CL allowed regions for different kaon decay channels are shown in color, together with their overlap, which is highlighted by the inset axis. Constraints from pion decays are shown as dark grey bands. For SINDRUM, the two bands correspond to different sign choices for g_e^V (left) or g_e^V (right). The 2σ allowed regions for the ^{4}He, ^{8}Be, ^{12}C ATOMKI anomalies are shown as light shaded grey (from [56]). The preference regions for ^{12}C in the axial-vector case are beyond the axis boundaries [29].

Other constraints: Johan Rathsman (CEvNS) and Yasar Hicyilmaz (NSI/IceCube).

Coupling with quarks

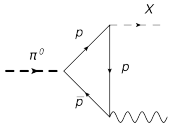
OVERVIEW

Protophobic vector boson

[Feng et al., 2016-2020][Barducci&Toni, 2023],[Hostert et al.]

Quantum numbers J^π = 1⁻

- NA48 constrains $\pi^0 \to \gamma X$ [Batley et al., 2015]
- Escape route: suppress the proton coupling
- $|2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}$



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

- Vector X17 gives δa_e > 0
- In principle compatible with the anomaly window

Other aspects

- The Carbon anomaly is in tension with a combined explanation of the Beryllium and Helium anomalies and the NA48 constraint
- Additionally, Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi + \to e + \nu X$

Piophobic axion

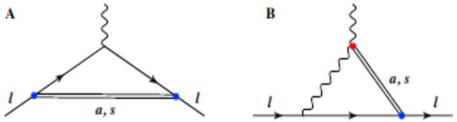
[Alves, 2020]

Quantum number J^π = 0⁻

- A generic 17 MeV QCD axion is usually excluded [Alves & Weiner, 2017]
- Viable only with strongly suppressed π^0 mixing
- $|\theta_{a-\pi}| < 10^{-4}$

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

- Tree-level pseudoscalar contribution gives δa_e < 0
- Barr-Zee-type loops can modify the conclusion



Other aspects

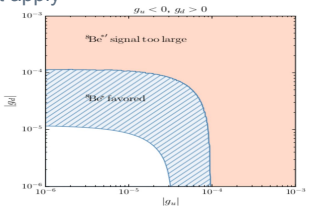
- Tension with parity conservation in Carbon transition

Light axial vector

[Kozaczuk, Morrissey & Stroberg, 2016] [Barducci &Toni,2023][Hostert et al.]

Quantum number J^π = 1⁺

- NA48 limit does not apply



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

- Axial X17 gives δa_e < 0
- That tends to worsen the electron g-2 tension

Other aspects

- An axial-vector X17 is dynamically consistent for Helium and Beryllium.
- Particle-hole shell model approximation for Carbon excited state [Mommers and Vanderhaeghen] indicates tension in the axial-vector scenario!
- Additionally, Hostert and Pospelov calculated the constraints coming from the SINDRUM search

Why a fully dynamical nuclear treatment is essential

OVERVIEW

Other possible explanations of the observed bumps may involve resonant nuclear effects or higher-order QED corrections

- In ^{3}H(p, e$^+$e$^-$)^{4}He, the dominant J^π = 1$^-$ scattering state generates only a smooth angular correlation [Viviani et al., 2021].
- Higher-order QED corrections increase with the opening angle θ_{ee} and may contribute to the ^{8}Be excess near $\theta_{ee} \approx 140°$.
- It is presently unclear whether the same QED mechanism can also explain the sharper ^{4}He peak, observed near $\theta_{ee} \approx 110°$.

Common picture

$$p + {}^3H \rightarrow ({}^4He)^* \rightarrow {}^4He + X \rightarrow {}^4He + e^+e^-$$

This two-step resonance-saturation picture is useful, but too restrictive once continuum dynamics is treated explicitly.

What the ab initio analyses show

Realistic nuclear structure and continuum dynamics → σ(θee)

(Viviani, 2021; Viviani, 2025)

The X17 hypothesis must be tested together with realistic nuclear structure and continuum dynamics, not on resonance quantum numbers alone.

Workshop nuclear inputs: ab initio calculations by Petr Navratil and Laura Elisa Marcucci, plus Aldo Bonasera's perspective on pair production in p+LiF.

FONDAZIONE BRUNO KESSLER · ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED · EURO-LABS · INFN Istituto Nazionale di Fisica Nucleare · FRIB Theory Alliance

The X17 particle, status and new ideas

Workshop sessions overview

The workshop combines experimental searches and theory sessions, moving from the anomaly overview and dedicated measurements to nuclear calculations, model building and dark-sector interpretations.

EXPERIMENTAL TRACK

I X17 anomaly overview

II Experimental searches I

III Experimental searches II

IV Experimental searches III

V CERN programmes

VIII Fudan experimental plan

XIV Experimental searches IV

THEORY TRACK

VI Ab initio nuclear theory

VII Nuclear structure and constraints

IX Constraints on the X17 boson

X Gauge extensions

XI Couplings and symmetry

XII Dark sector portals

XIII Cosmology and dark sector

Venue and support

ECT* / FBK, Trento - with FRIB Alliance Theory (EUSTIPEN) and EURO-LABS support.

SUPPORTING INSTITUTIONS

Experimental sessions overview

OVERVIEW

I X17 anomaly: experimental overview — MON

- Attila Krasznahorkay — Experiments to Detect the X17 Particle

II Experimental searches I — MON

- Stefan Merkel — Dark Photon Search with MAGIX at MESA
- Ethan Cline — DarkLight: a Model-Independent Search for the X17
- Michael Hasinoff — TBA (TRIUMF-614)

III Experimental searches II — TUE

- Fabio Bossi — Highlights of the LNF/X17 Workshop
- Hicham Benmansour — X17 Search with the MEG II Experiment

IV Experimental searches III — TUE

- Carlo Gustavino — Probing the X17 Boson with Proton and Neutron Beams
- Benito Gongora Servin — Anomalous Internal Pair Creation in Be at LNL-INFN
- Mauro Raggi — The PADME Experiment

V CERN experimental programmes — TUE

- Martino Borsato — Ongoing Search for X17 at LHCb
- Luca Marsicano — Searching for X17 with NA64 at CERN SPS

VIII Experimental plan at Fudan University — WED

- Wanbing He — Experimental Plan for the X17 Particle Search at Fudan University
- Jie Zhao — Experimental Plan for the X17 Particle Search at Fudan University

XIV Experimental searches IV — FRI

- Beyhan Bastin — Light Boson Searches with New JEDI: Results and Perspectives
- Mohammad Faiz Khan — TBA
- Luca Doria — The Montreal X17 Experiment: Status Report

Theoretical sessions overview

OVERVIEW

VI Ab initio nuclear theory — WED

- Petr Navratil — Ab Initio Calculations of p-Induced e^+e^- Processes
- Laura Elisa Marcucci — Ab-Initio Studies of A=3,4 Nuclear Processes and X17

VII Nuclear structure and constraints — WED

- Cornelis Mommers — Constraining the Axial-Vector X17 Interpretation with 12C Data
- Aldo Bonasera — Pair Production in p+LiF Reactions

IX Constraints on the X17 boson — WED

- Adrian Thompson — Kaon Decay Constraints on Vector Bosons Coupled to Non-Conserved Currents
- Johan Rathsman — Probing X17 with Coherent Elastic Neutrino Nucleus Scattering

X Gauge extensions — THU

- Stefano Moretti — The X17 in U(1)'-Extended 2HDMs
- Yasar Hicyilmaz — Constraining X17: Neutrino NSI and IceCube Data

XI Couplings and symmetry — THU

- Max Fieg — The X17 with Chiral Couplings
- Claudio Toni & Daniele Barducci — An Updated View on Parity-Conserving X17 Scenarios
- Emrys Peets — X17 as a Protophobic Vector: Viable Couplings and GP Search Methods

XII Dark sector portals — THU

- Vincenzo Fiorentino — Axion-Like Electrophilic Portal for Pion Dark Matter
- Sergi Gonzalez-Solis — Searching for Light Dark Particles with η and η' Mesons

XIII Cosmology and dark sectors — THU

- Marco Graziani — Light Dark Sector via Thermal Decays of Dark Matter