Theory Overview of X17
Beyond the Standard Model

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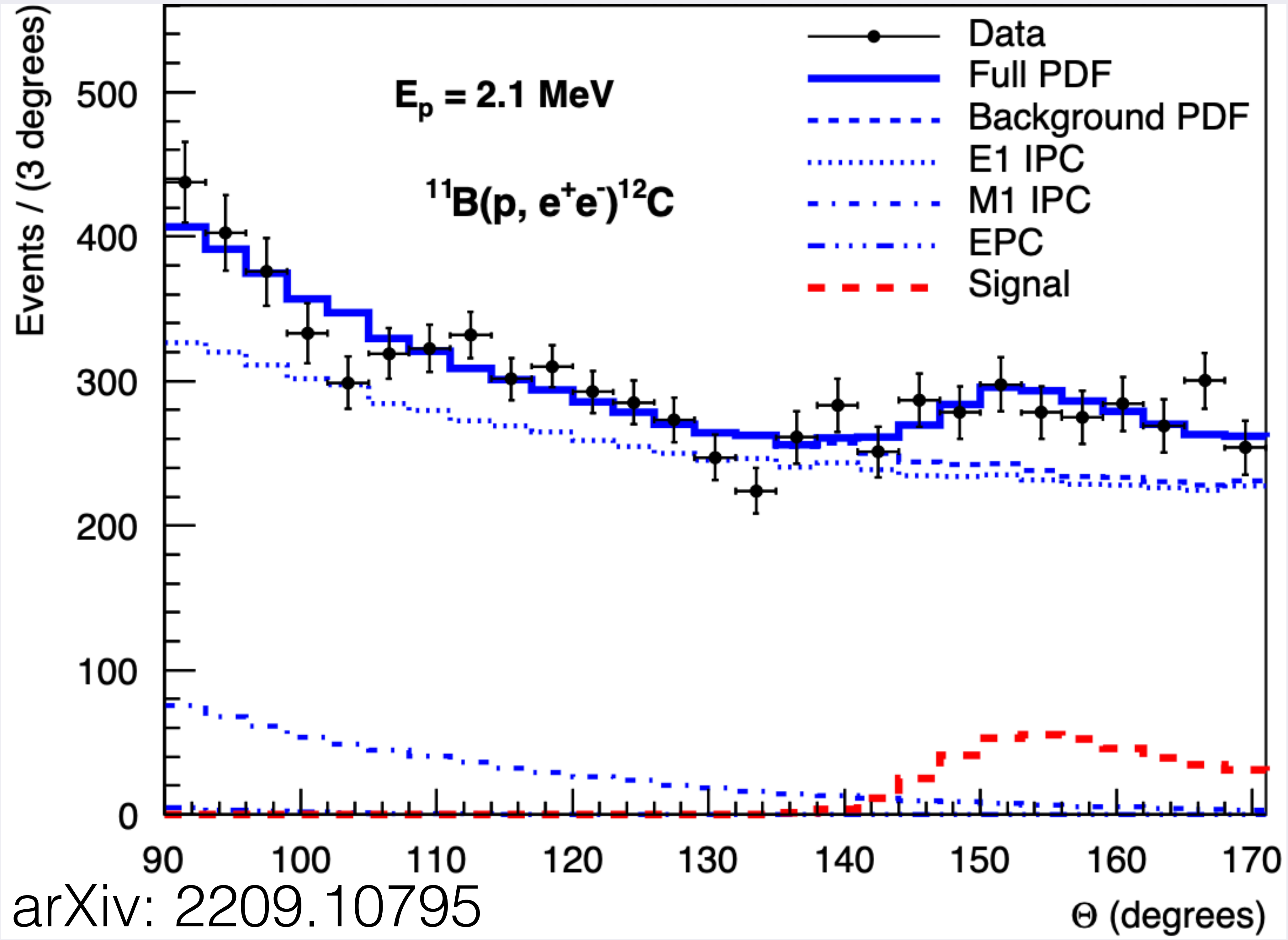
Workshop on Multi-front Exotic Phenomena in Particles and Astrophysics
21 October 2023

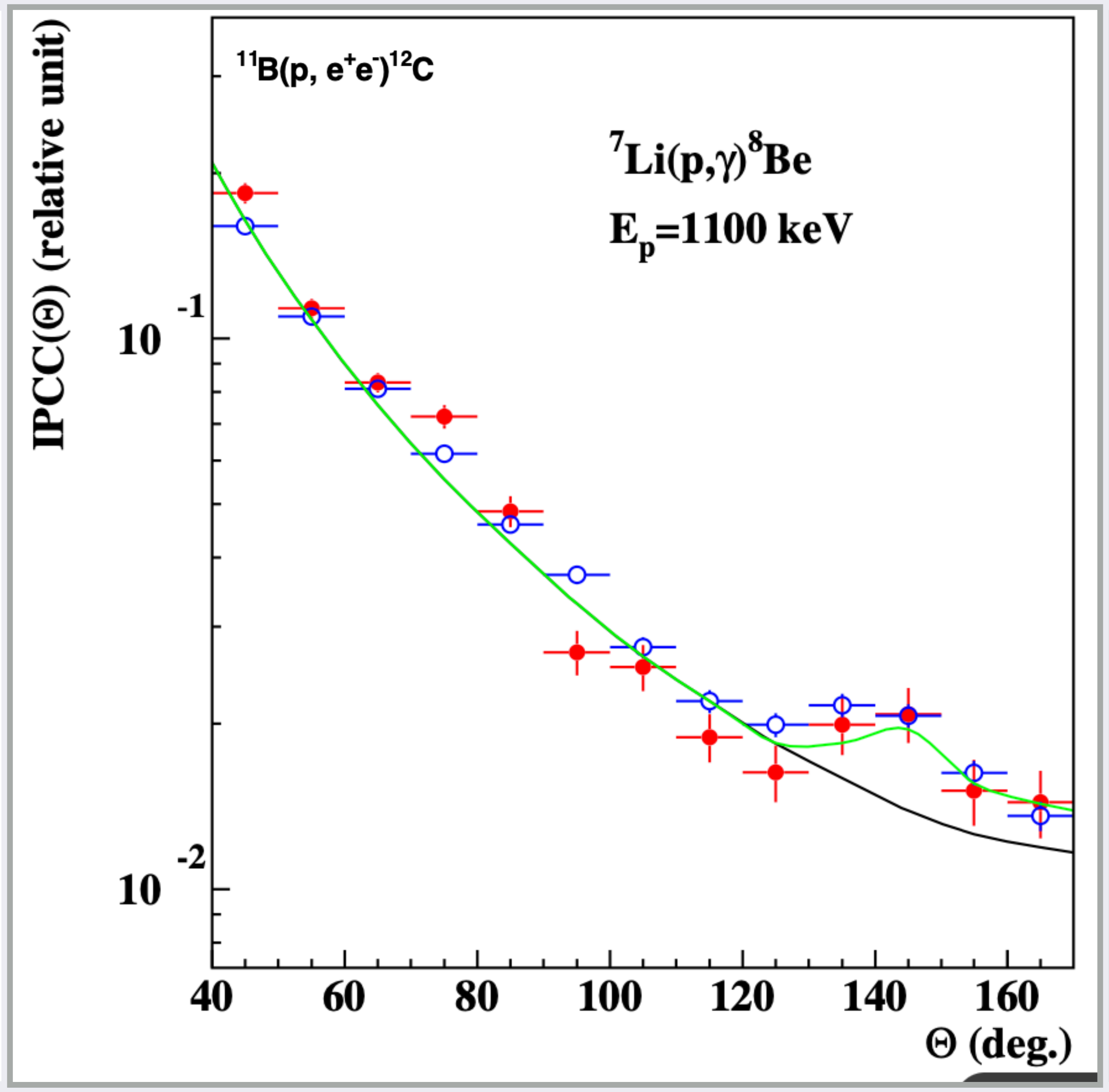
ATOMKI’s Results

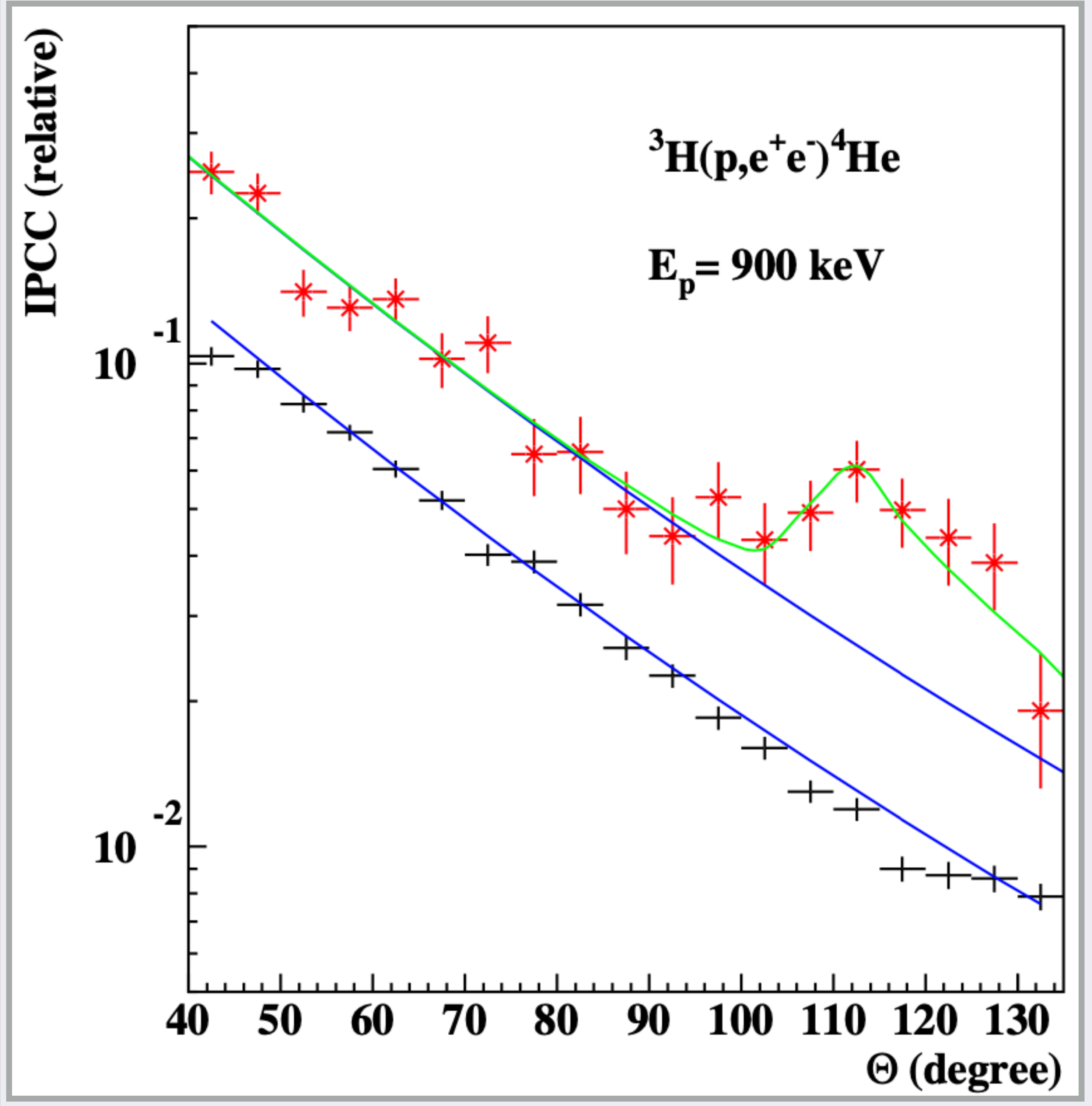
The ATOMKI collaboration has reported three, >7 sigma, anomalies in nuclear decays



arXiv: 2209.10795

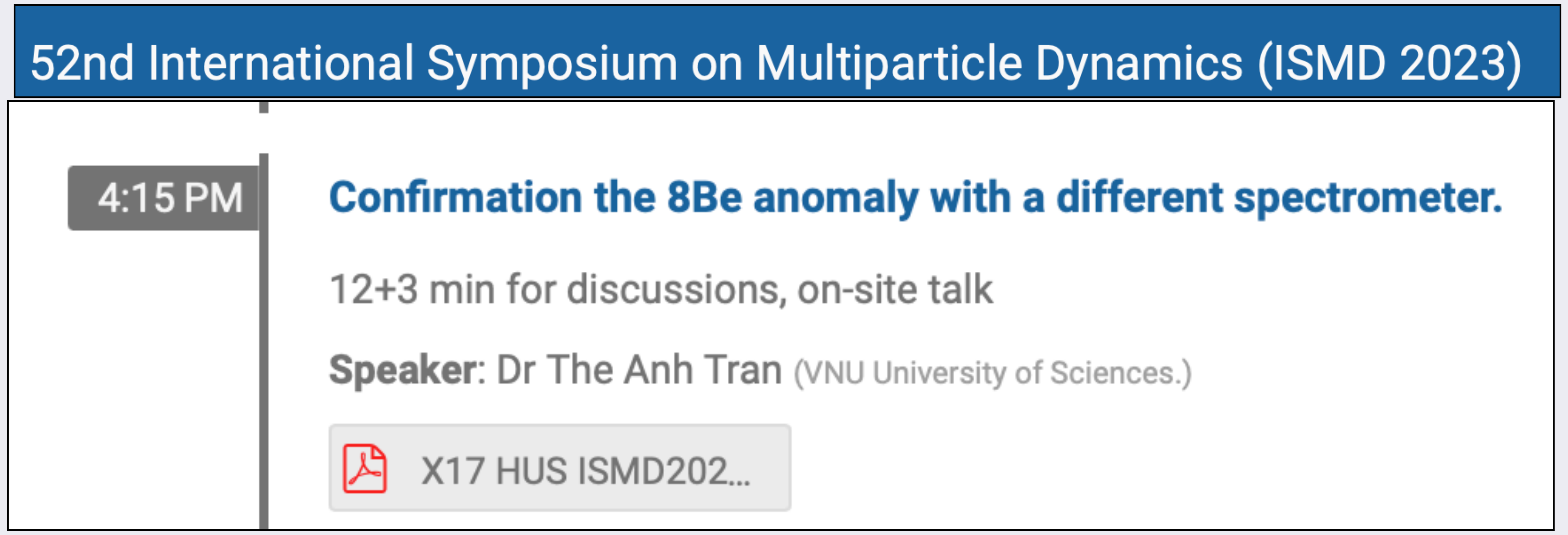
EPJ Web Conf. 232 (2020) 04005





Beyond ATOMKI

Reported results



52nd International Symposium on Multiparticle Dynamics (ISMD 2023)

4:15 PM

Confirmation the 8Be anomaly with a different spectrometer.

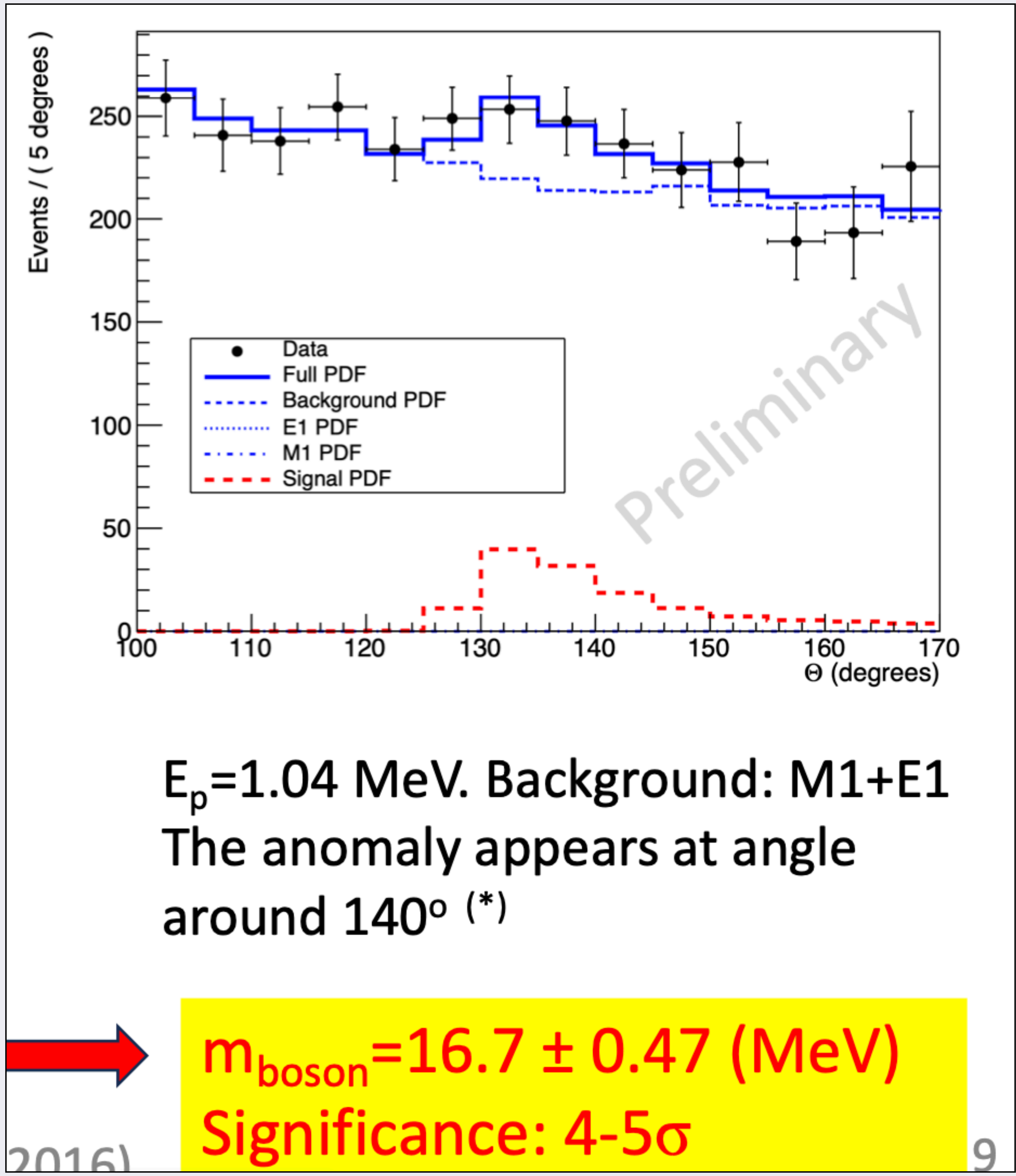
12+3 min for discussions, on-site talk

Speaker: Dr The Anh Tran (VNU University of Sciences.)

X17 HUS ISMD202...

Exciting prospect of confirmation

Still waiting for the official publication



E_p=1.04 MeV. Background: M1+E1

The anomaly appears at angle around 140° (*)

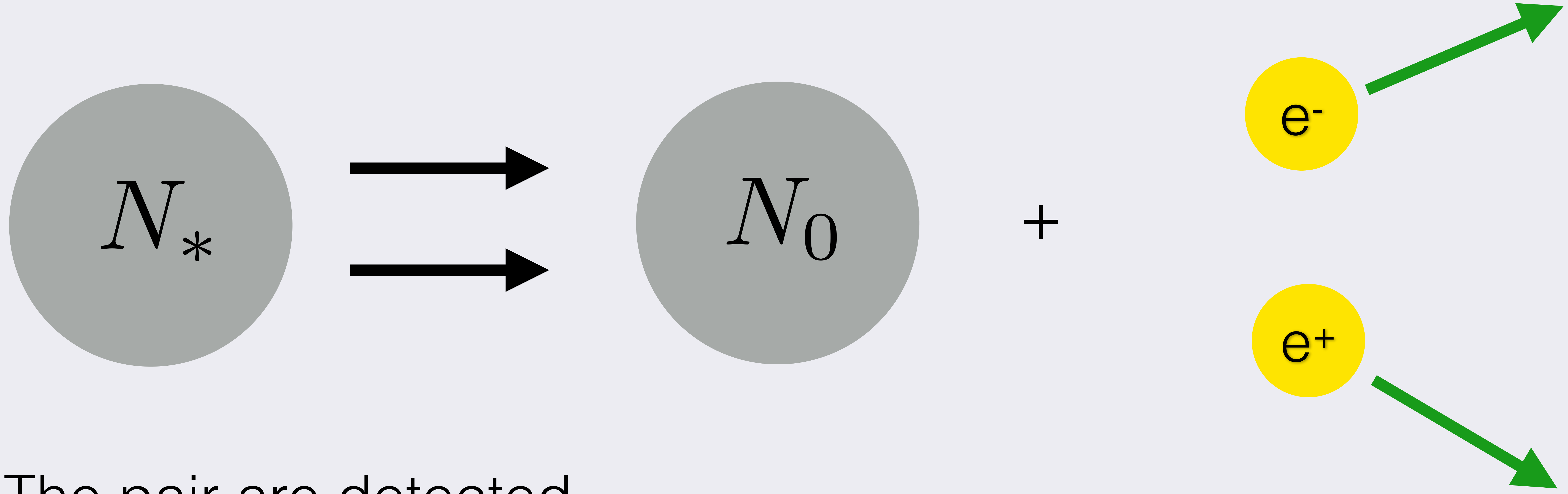
m_{boson}=16.7 ± 0.47 (MeV)

Significance: 4-5σ

Schematic Experimental Set-Up

Proton beam strikes target nucleus, producing an excited state

Excited state decays to ground state and produces electron-positron pair



The pair are detected

BSM Possibilities

The background produced through electromagnetic processes

Either pair creation during the initial collision (EPC)

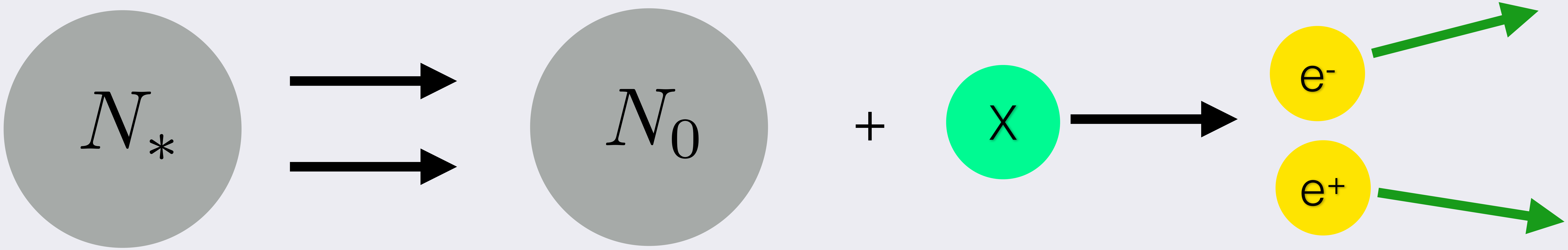
$$p + \mathrm{Target} \to N_* + \gamma^{(\star)} \to N_* + e^+e^-$$

Or pair creation during the decay (IPC)

$$N_* \to N_0 + \gamma^{(\star)} \to N_0 + e^+e^-$$

ATOMKI excesses are consistent with the production of a new boson, called X

Can all results come from one new particle?

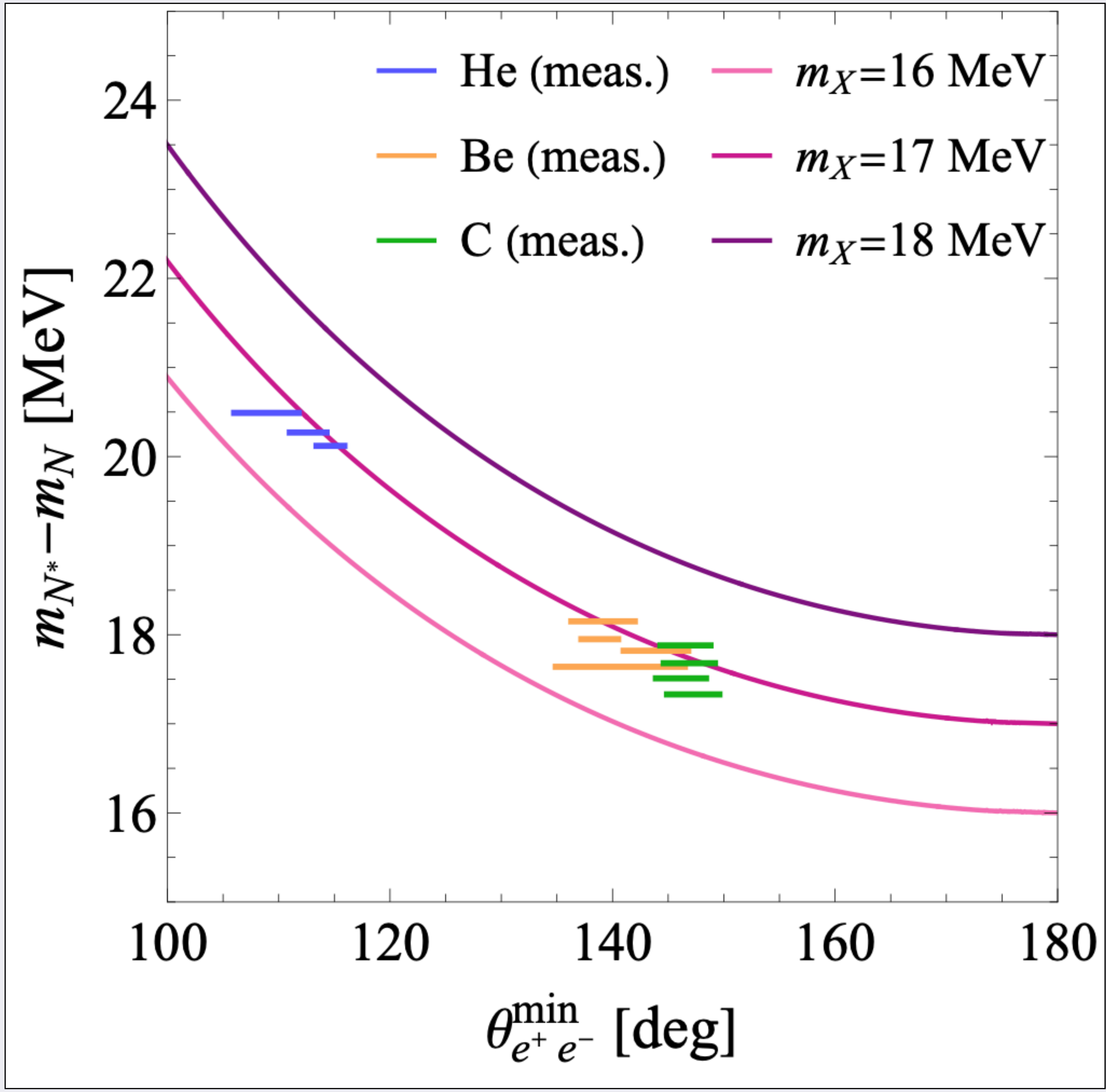


Kinematic Consistency

Denton and Gehrlein,
Phys.Rev.D 108 (2023) 1, 015009

Results across several experiments are consistent with a boson with mass a little less than 17 MeV

What about dynamical consistency?



Spin & Parity

The nuclear states are categorized by their spin and parity J^P

The same can be done for X boson possibilities

The ground states are all 0^+ states, so assuming parity is a good symmetry

$$J_* = L \oplus J_X \quad P_* = (-1)^L P_X$$

These simple observations already imply interesting results

If X is spin-0 its He width is likely to be larger than Be

Opposite for axial vector

The vector decays are both P-wave

The Be decay shows the X is not 0^+

X N_*	0^+	0^-	1^-	1^+
${}^4\mathrm{He}\ 0^-$	—	S	—	P
${}^4\mathrm{He}\ 0^+$	S	—	P	—
${}^{12}\mathrm{C}\ 1^-$	P	—	$S,\ D$	P
${}^8\mathrm{Be}\ 1^+$	—	P	P	$S,\ D$

Examining Dynamics

We examine each possible X boson, according to spin and parity

- At low energies the definite parity parts of X dominate decays
- E.g., if X is spin-0, only pseudoscalar part can explain beryllium result

$$1^+ \rightarrow 0^+ + 0^- \qquad\qquad 1^+ \not\rightarrow 0^+ + 0^+$$

More complete investigation of the particle dynamics using effective field theory

- Effective operators are composed of nuclear states each described by a point-like quantum field

Ground State N_0 Excited State N_*

Feng, Tait, CV, *Phys. Rev. D* 102 (2020) 3, 036016

Examining Dynamics

EFT operators encapsulate spin-parity and produce decay widths of excited states

To compare with other experiments we look at more elementary particles

Nuclear decays are matched to nucleon couplings to the X boson, assuming isospin

Determines decay rates up to **unknown** nuclear matrix elements

For vector X, decay widths can be compared to photon decays

Nuclear physics divides out

Analysis assumes X particle is produced from **resonance**

Feng, Tait, CV, *Phys. Rev. D* 102 (2020) 3, 036016

Vector X

Vector X decays are compared to known electromagnetic decays to eliminate unknown nuclear matrix elements

Define the X couplings with a factor of the QED coupling

$$J_X^\mu = e\varepsilon_p \overline{p}\gamma^\mu p + e\varepsilon_n \overline{n}\gamma^\mu n = \frac{1}{2}e(\varepsilon_p + \varepsilon_n)J_0^\mu + \frac{1}{2}e(\varepsilon_p - \varepsilon_n)J_1^\mu$$

The photon current is similar $J_\gamma^\mu = e\overline{p}\gamma^\mu p = \frac{1}{2}eJ_0^\mu + \frac{1}{2}eJ_1^\mu$

Factors of $\frac{1}{2}e\langle N_0|J_{0,1}^\mu|N_*\rangle$ are common to both X and photon decays

Feng, Tait, CV, *Phys. Rev. D* 102 (2020) 3, 036016

Vector X and Beryllium

Beryllium decay dominated by

$$\mathcal{M} = \langle N_0 X | \frac{1}{2}(\varepsilon_p + \varepsilon_n)\, e\, C_{V,\mathrm{Be}}\, \mathcal{O}_{5P}^{(1)} | N_* \rangle = \frac{1}{2}(\varepsilon_p + \varepsilon_n)\, e\, C_{V,\mathrm{Be}} \frac{1}{\Lambda} \varepsilon^{\mu\nu\alpha\beta}\, p_{*\mu}\, \epsilon_{*\nu}\, p_{X\alpha}\, \epsilon_{X\beta}$$

with

$$\mathcal{O}_{5P}^{(1)} = \frac{N_0^\dagger}{\Lambda} \varepsilon^{\mu\nu\alpha\beta}\, (\partial_\mu N_{*\nu})\, \partial_\alpha X_\beta \qquad C_{V,\mathrm{Be}}\, \frac{1}{\Lambda} \varepsilon^{\mu\nu\alpha\beta}\, p_{*\nu}\, \epsilon_{*\alpha}\, p_{X\beta} = \langle {}^8\mathrm{Be} | J_0^\mu | {}^8\mathrm{Be}(18.15) \rangle$$

Operator is “accidentally” gauge invariant when we replace X by the photon:

$$\mathcal{O}_{5P}^{\gamma} = \frac{N_0^\dagger}{2\Lambda} \varepsilon^{\mu\nu\alpha\beta}\, (\partial_\mu N_{*\nu})\, \partial_\alpha F_{\alpha\beta}$$

X and photon decays mediated by the same operator

Feng, Tait, CV, *Phys. Rev. D* 102 (2020) 3, 036016

Vector X and Beryllium

Simple ratio

$$\frac{\Gamma_X^{^8\mathrm{Be}}}{\Gamma_\gamma^{^8\mathrm{Be}}} = (\varepsilon_p + \varepsilon_n)^2 \, \frac{p_{X,\mathrm{Be}}^3}{p_{\gamma,\mathrm{Be}}^3}$$

Modified slightly by isospin mixing with nearby iso-spin 1 state

$$\frac{\Gamma_X^{^8\mathrm{Be}}}{\Gamma_\gamma^{^8\mathrm{Be}}} = \left|-0.09\,(\varepsilon_p + \varepsilon_n) + 1.09\,(\varepsilon_p - \varepsilon_n)\right|^2 \, \frac{p_{X,\mathrm{Be}}^3}{p_{\gamma,\mathrm{Be}}^3}$$

$$\approx 0.043\,\left|-0.09\,(\varepsilon_p + \varepsilon_n) + 1.09\,(\varepsilon_p - \varepsilon_n)\right|^2$$

Isospin breaking can also be included:

$$\frac{\Gamma_X^{^8\mathrm{Be}}}{\Gamma_\gamma^{^8\mathrm{Be}}} = \left|0.05\,(\varepsilon_p + \varepsilon_n) + 0.95\,(\varepsilon_p - \varepsilon_n)\right|^2 \, \frac{p_{X,\mathrm{Be}}^3}{p_{\gamma,\mathrm{Be}}^3}$$

$$\approx 0.043\,\left|0.05\,(\varepsilon_p + \varepsilon_n) + 0.95\,(\varepsilon_p - \varepsilon_n)\right|^2$$

Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo 1608.03591

Vector X constraints

The electromagnetic decay widths have been measured, can make definite statements about X couplings to SM fields and compare to other experiments

The coupling to the proton is limited by NA48/2 searches for $\pi \to X\gamma$

$$|\varepsilon_p| < 1.2 \times 10^{-3}$$

There is a much weaker bound on the neutron coupling from lead-neutron scattering

$$|\varepsilon_n| < 2 \times 10^{-2}$$

The beryllium results favor nucleon couplings of order 10^{-2}, implying “protophobic” couplings

Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo 1608.03591

X Analysis Summary in 2020

If X is a scalar, 0^+, it cannot explain the beryllium signal

$$1^+ \not\to 0^+ + 0^+$$

Found pseudo scalar not a good fit

Did not consider ALP dynamics,
see Alves *Phys.Rev.D* 103 (2021) 5, 055018

Axial vector a marginal fit

Vector a good fit of Be and He signals (only signals published)

Feng, Tait, CV, *Phys. Rev. D* 102 (2020) 3, 036016

Independent Analysis

A group of Nuclear theorists analyzed the Helium system
Viviani, Filandri, Girlanda, Gustavino, Kievsky, Marcucci, Schiavilla,
Phys.Rev.C 105 (2022) 1, 014001

Using different methods they conclude

“…the ^{8}Be and ^{4}He anomalies can be explained simultaneously by the exchange of a proto-phobic vector X17. For an axial X17 exchange, the coupling constants appear to be inconsistent with each other… A pseudoscalar X17 exchange also seems to be excluded… ”

Including Carbon

When we (Feng, Tait, CV) checked the consistency of Be and He signals, we also included a prediction for Carbon-12

Essentially $\Gamma_X \sim 10^{-5}\Gamma_{\mathrm{E0}}$

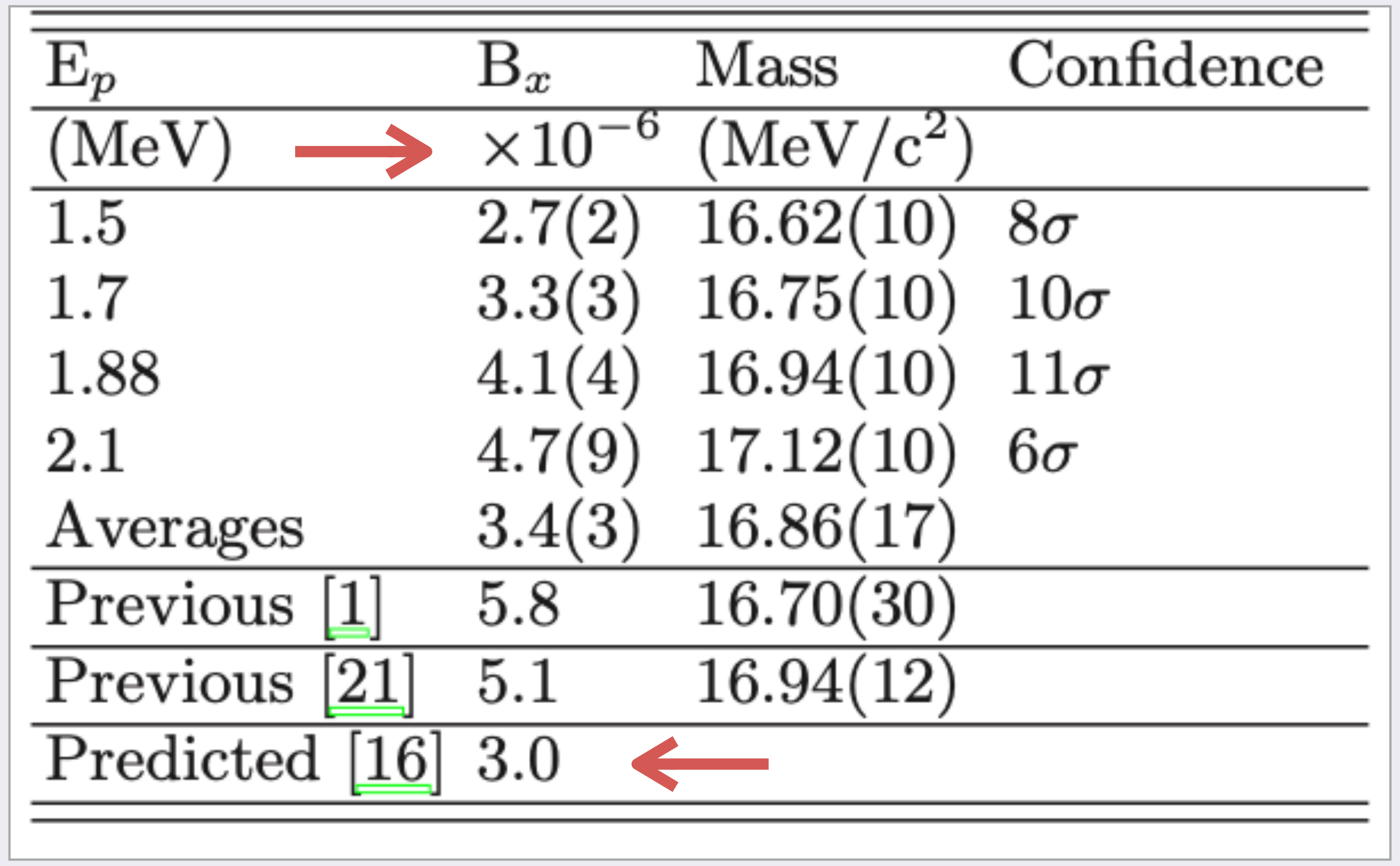
Width of Carbon resonance is much wider

A bump-like feature at several energies

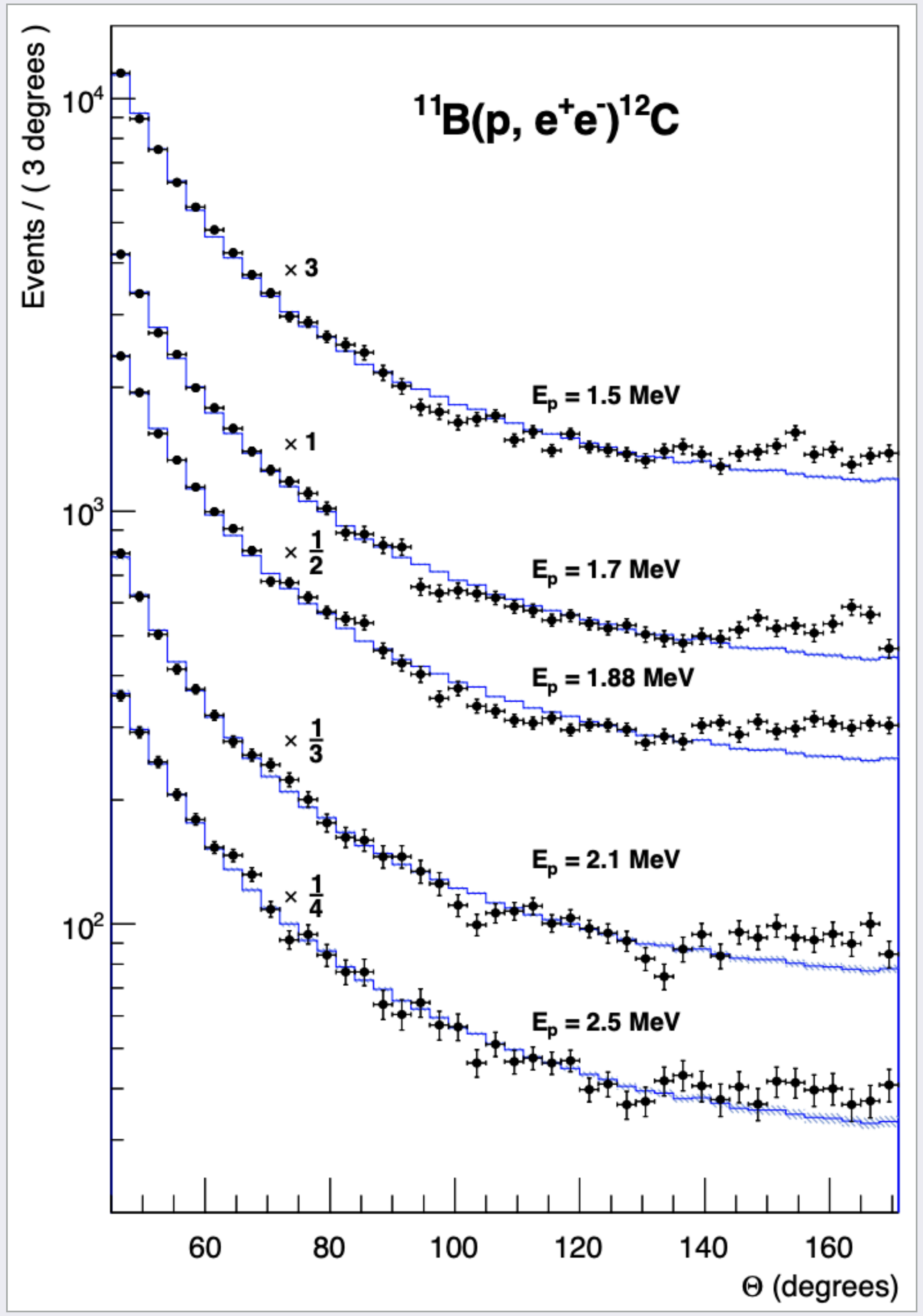
- Seems to agree with non-resonant component of production?

Branching differs by about a factor of 10

But prediction assumed resonant production



E_p	B_x	Mass	Confidence
(MeV) →	$\times 10^{-6}$	(MeV/c^2)	
1.5	2.7(2)	16.62(10)	8σ
1.7	3.3(3)	16.75(10)	10σ
1.88	4.1(4)	16.94(10)	11σ
2.1	4.7(9)	17.12(10)	6σ
Averages	3.4(3)	16.86(17)	
Previous [1]	5.8	16.70(30)	
Previous [21]	5.1	16.94(12)	
Predicted [16]	3.0 ←		

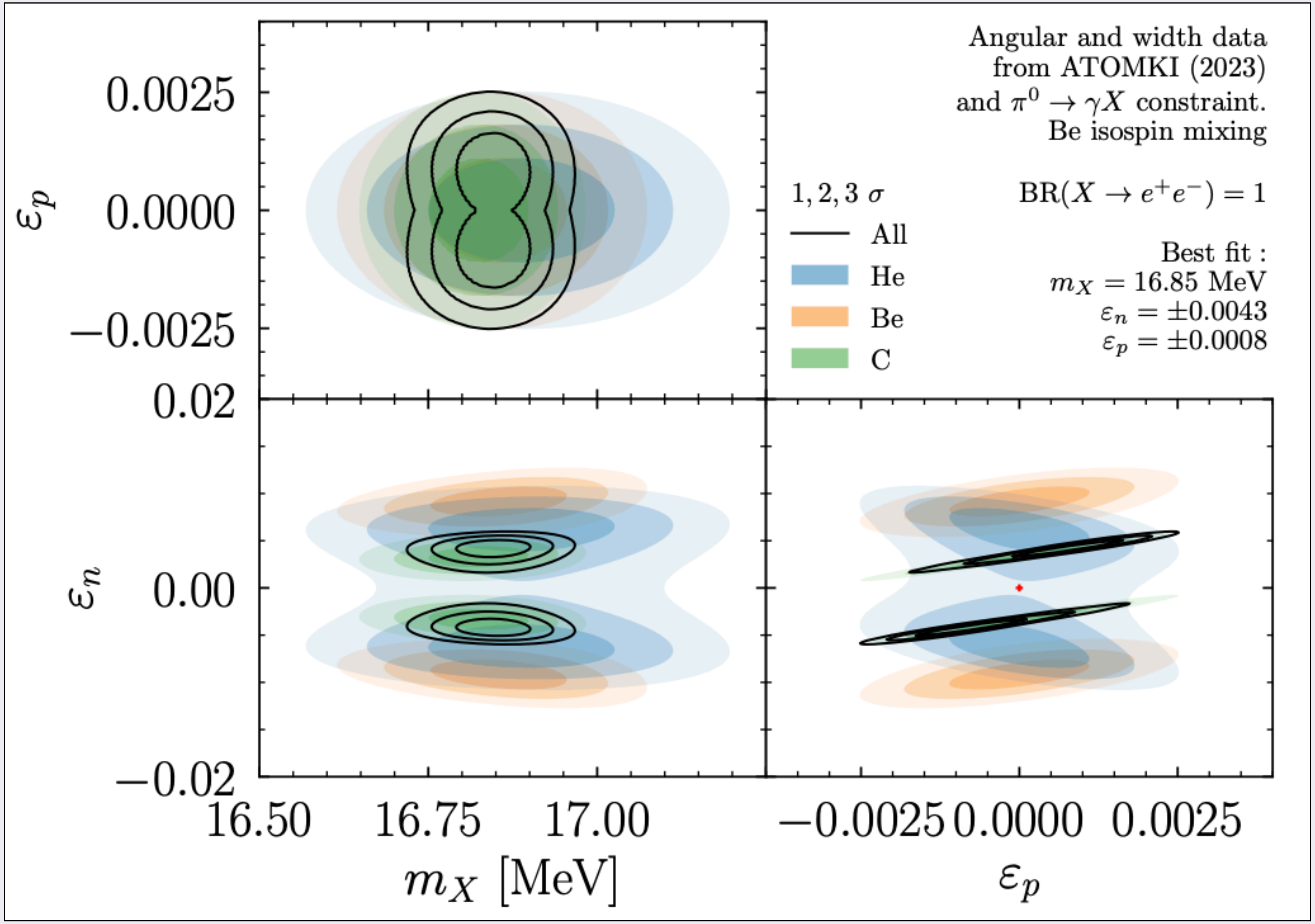


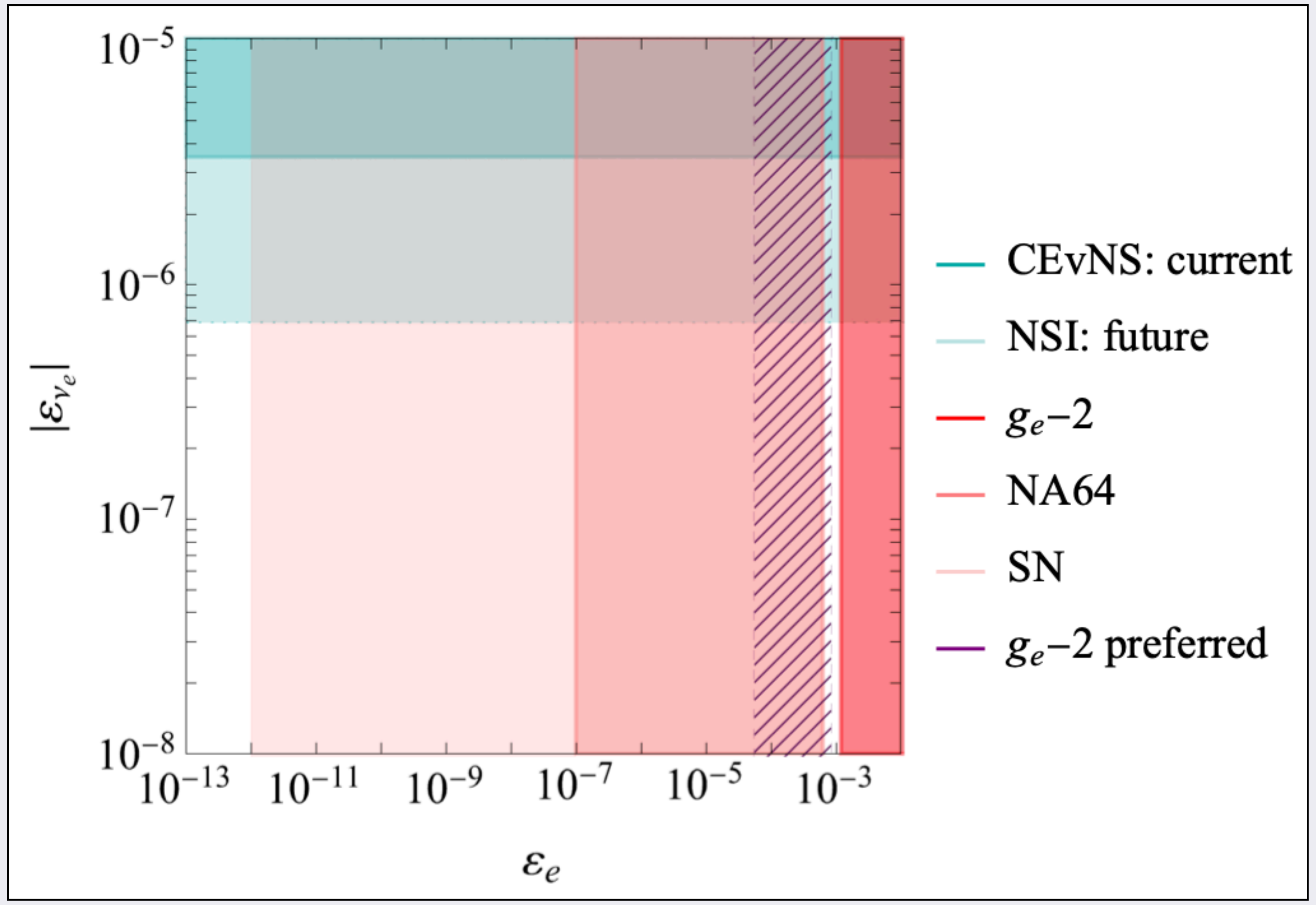
Updated Bounds

Denton and Gehrlein, *Phys.Rev.D* 108 (2023) 1, 015009

Considered vectors only

See some tension between Be and C





Updated View

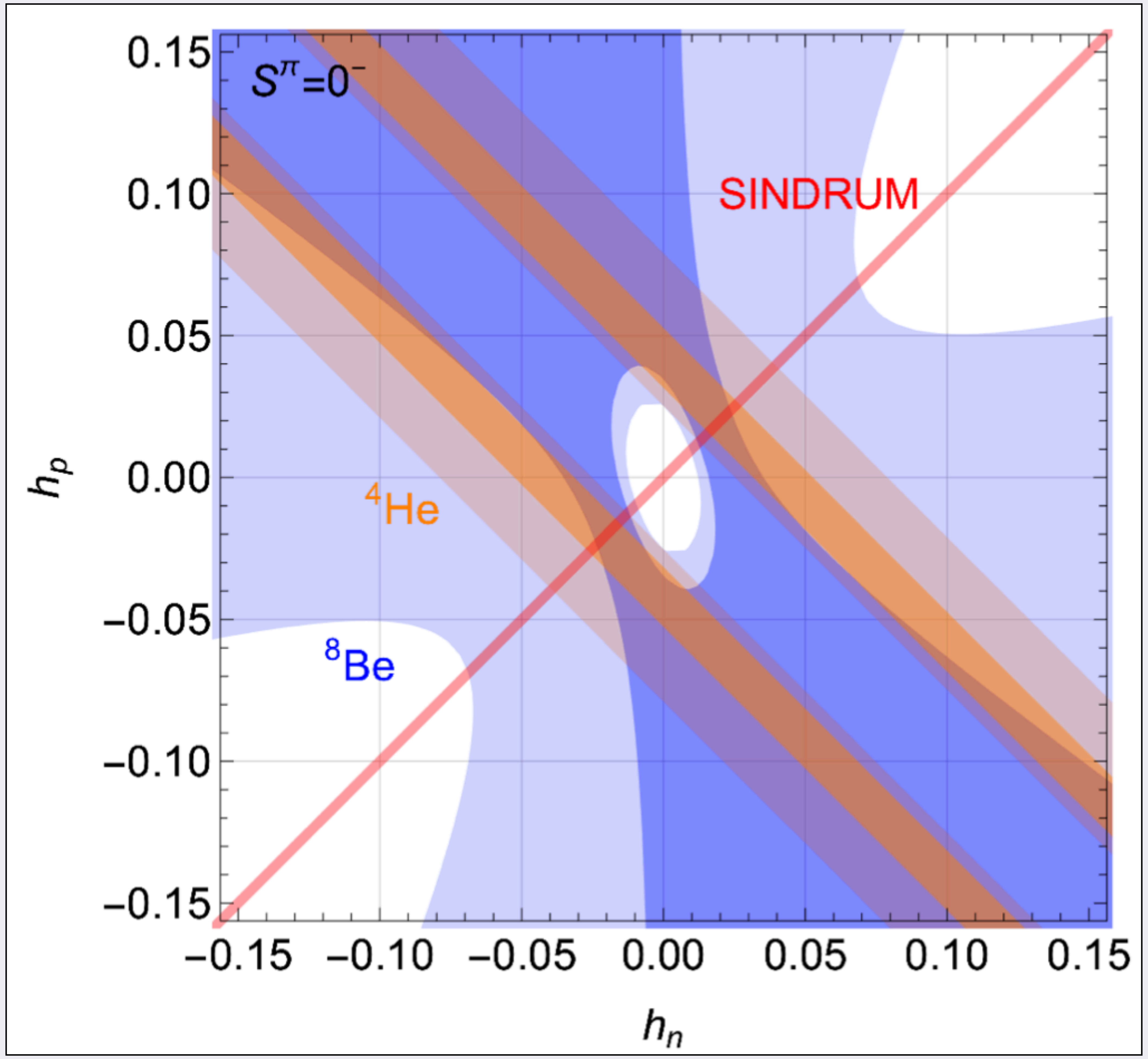
Barducci and Toni, *JHEP* 02 (2023) 154

Only axial-vector seems allowed

Considered scalars without definite parity, also seem ruled out

Colored regions are allowed

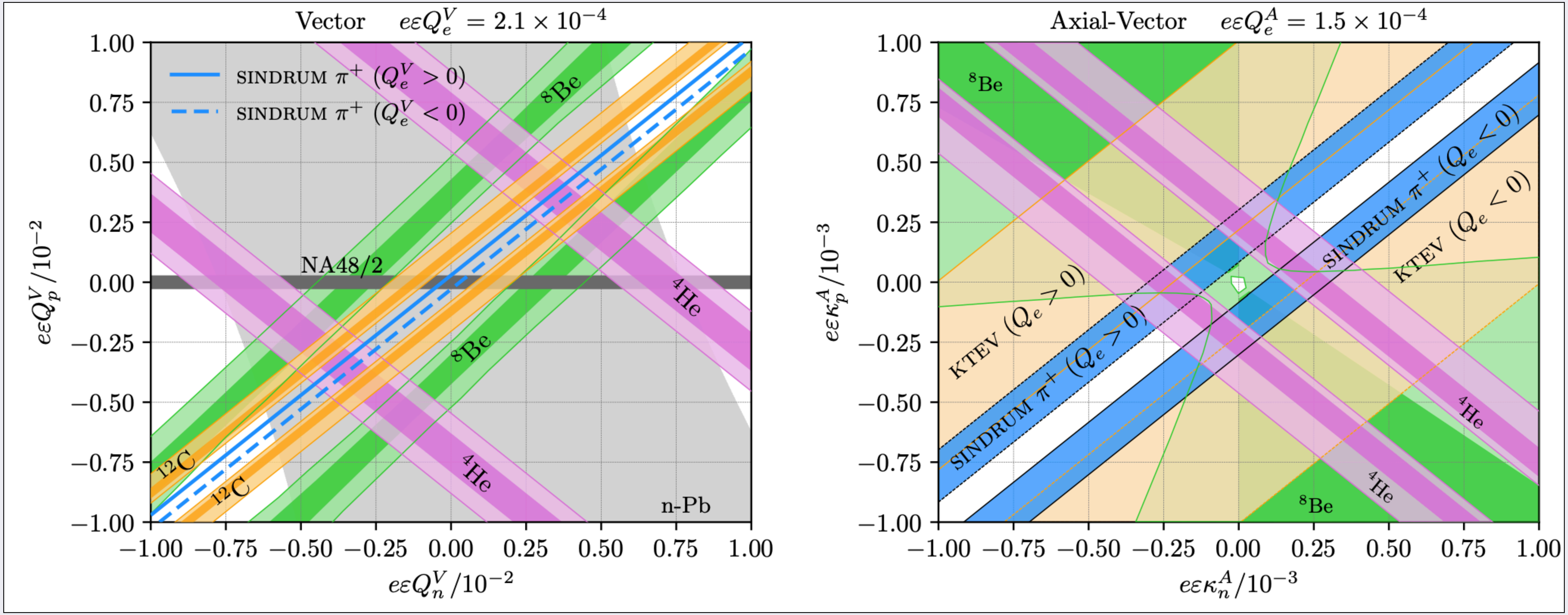
No region for Carbon-12 signal



Pion Constraints

From Hostert and Pospelov, *Phys.Rev.D* 108 (2023) 5, 055011

Filled in regions are **allowed** regions



Final Thoughts

Nuclear transitions are a natural place to look for MeV mass particles with small interactions to the SM

The ATOMKI group has reported new resonance structures in Beryllium, Helium, and Carbon that may originate beyond the SM

Significant uncertainties remain

Further experiments needed

Summary

BSM Scalar - Cannot explain ATOMKI signal in Beryllium

BSM Pseudoscalar - Cannot explain ATOMKI results in Carbon

BSM scalar combinations also excluded

BSM Vector - Excluded by charged Pion decays

BSM Axial-vector - remains most viable possibility

X N_*	0^+	0^-	1^-	1^+
$^4\mathrm{He}\ 0^-$	—	S	—	P
$^4\mathrm{He}\ 0^+$	S	—	P	—
$^{12}\mathrm{C}\ 1^-$	P	—	$S,\ D$	P
$^8\mathrm{Be}\ 1^+$	—	P	P	$S,\ D$