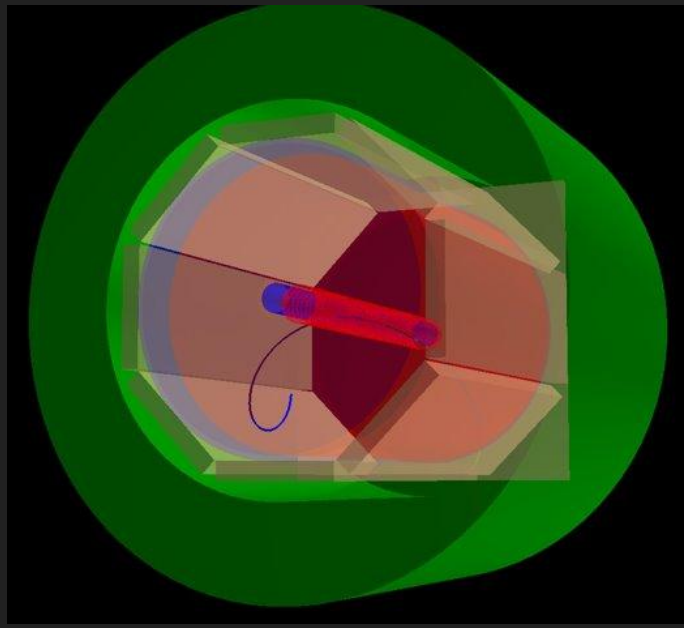
A Proposed Australian Facility for Particle and Nuclear Physics at the MeV-scale



1 Australian National University

2 ARC Centre of Excellence for Dark Matter Particle Physics

Lindsey Bignell[1,2], Jackson Dowie[1], David Jamieson[3], Tibor Kibedi[1], Martin Sevior[3], Andrew Stuchbery[1,2], Andrea Thamm[3]

3 The University of Melbourne

Have we found dark matter yet?

It depends…

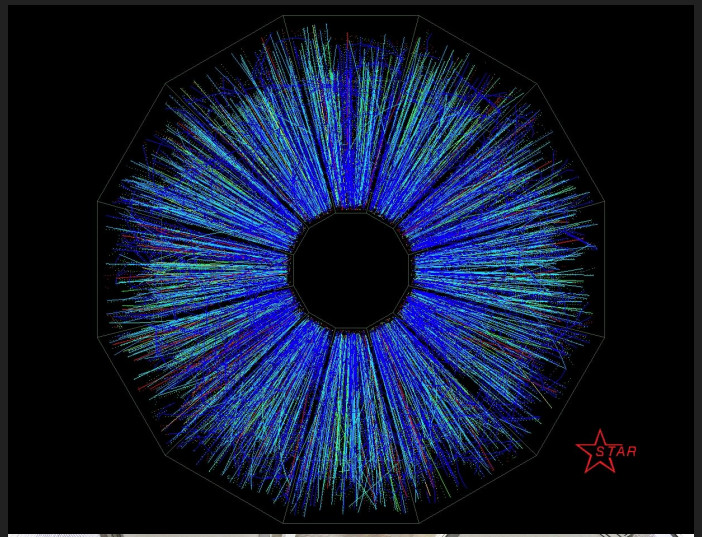
Direct searches → *no*[*]

Indirect hints: g-2? GCE? AMS? → hard to say

Accelerator-based:

→ *collider searches, beam dump, etc → no*

X17 → maybe?



Could an 'X17 Particle' Hint at a Fifth Force in the Universe?

Physicists Claim They've Found Even More Evidence of a New Force of Nature

PHYSICS 20 November 2019 By MIKE MCRAE

A 'no-brainer Nobel Prize': Hungarian scientists may have found a fifth force of nature

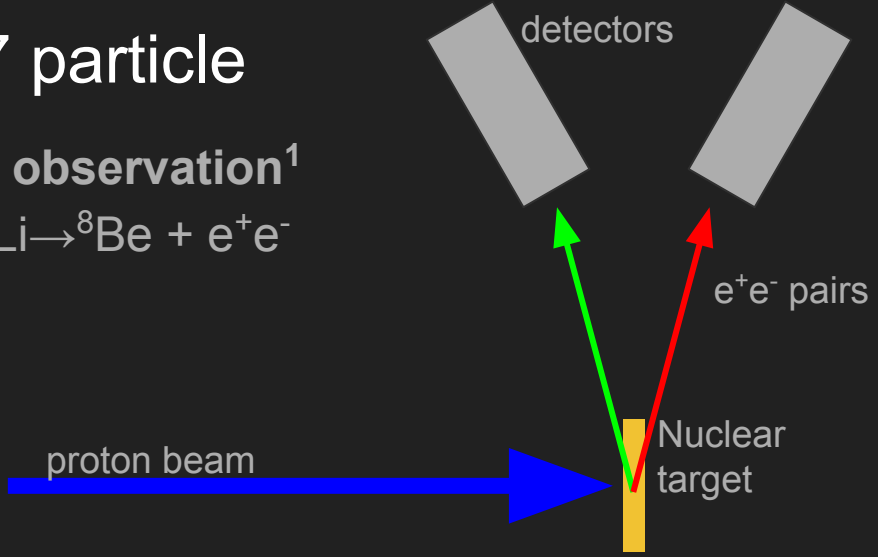
By Ryan Prior, CNN
Updated 2:44 PM EST, Sat November 23, 2019

[*]± DAMA

X17 particle

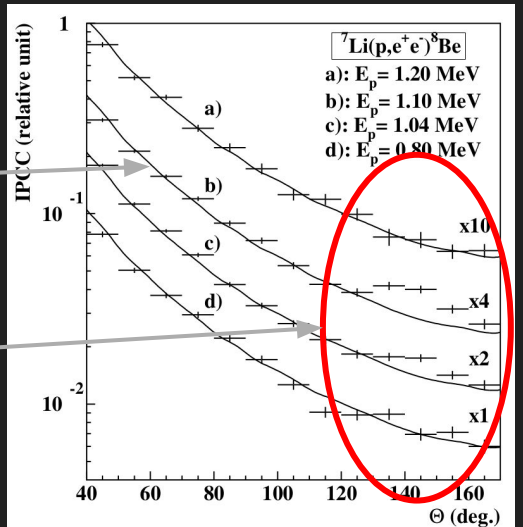
2015 observation[1]

$p + {}^{7}Li \rightarrow {}^{8}Be + e^{+}e^{-}$



Internal pair conversion

New particle?



1: arxiv 1504.01527,

X17 particle

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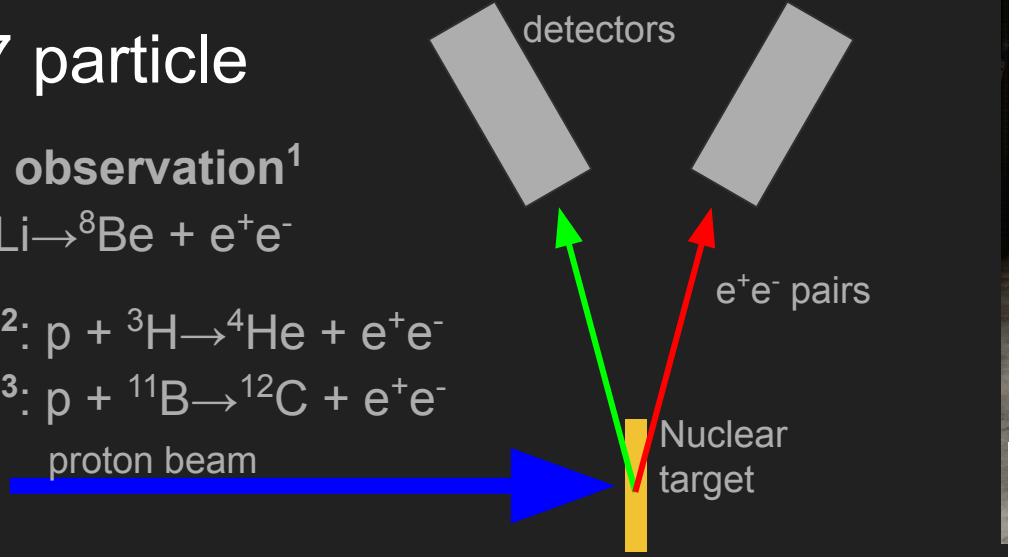
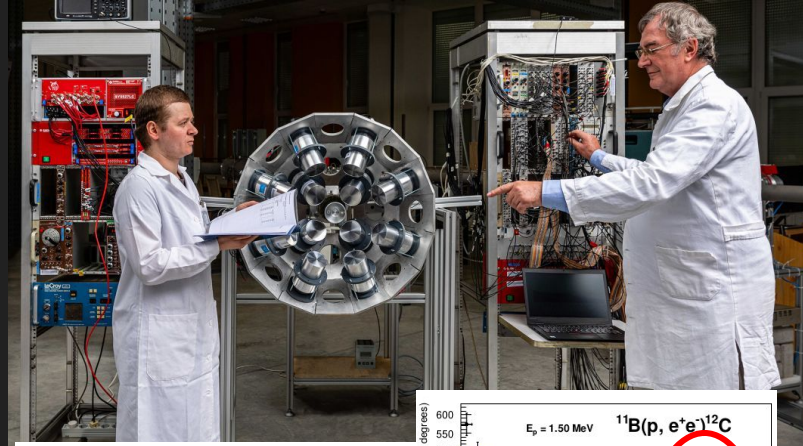
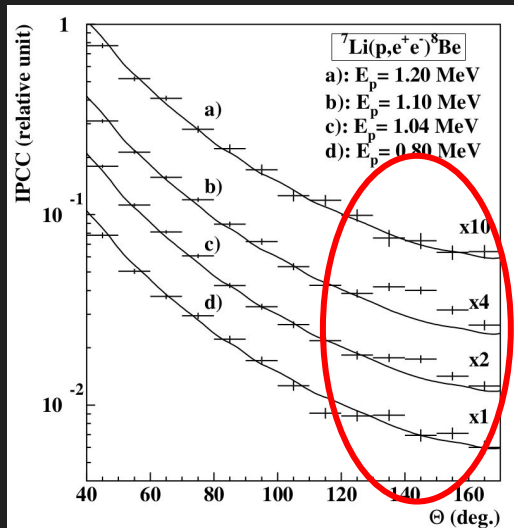
$p + {}^{7}Li \rightarrow {}^{8}Be + e^{+}e^{-}$

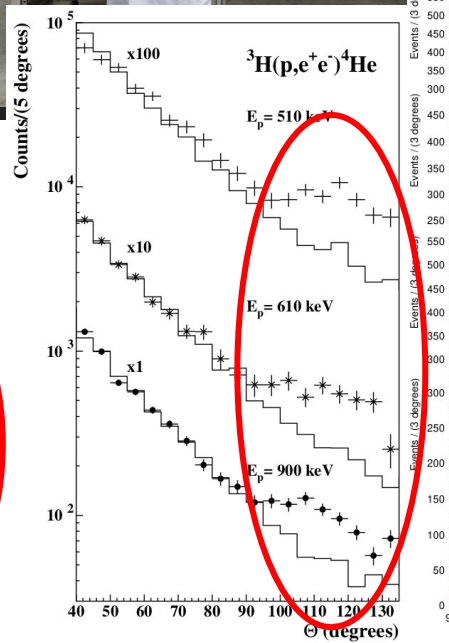
2021[2]: $p + {}^{3}H \rightarrow {}^{4}He + e^{+}e^{-}$

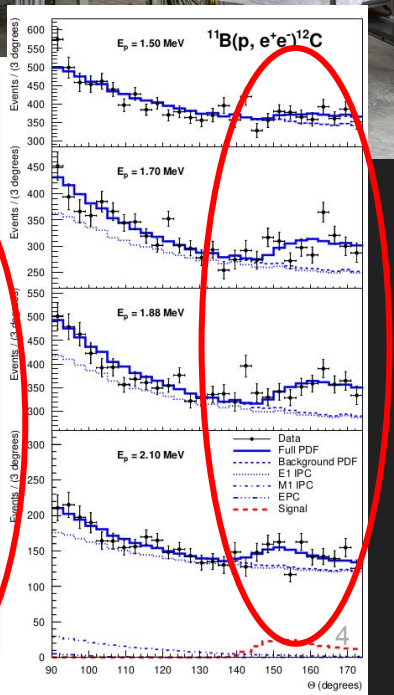
2022[3]: $p + {}^{11}B \rightarrow {}^{12}C + e^{+}e^{-}$











1: arxiv 1504.01527,
2: arxiv 2104.10075,
3: arxiv 2209.10795

X17 particle

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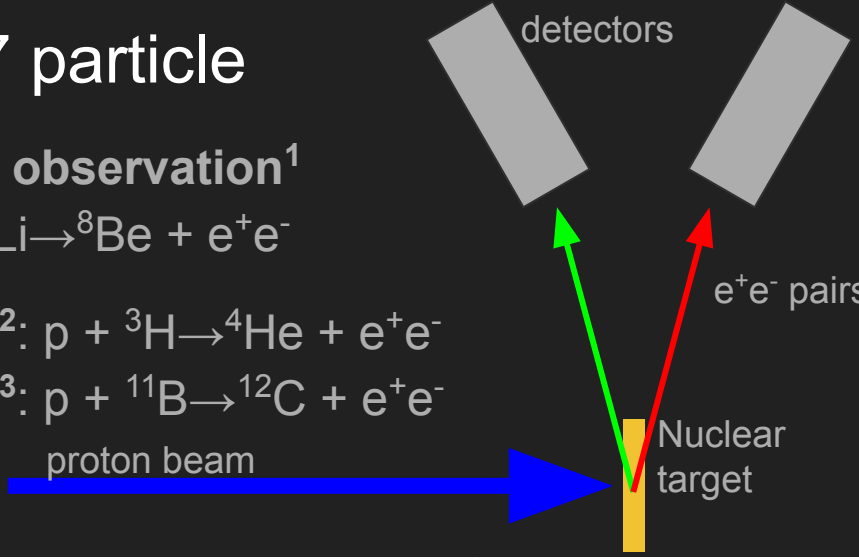
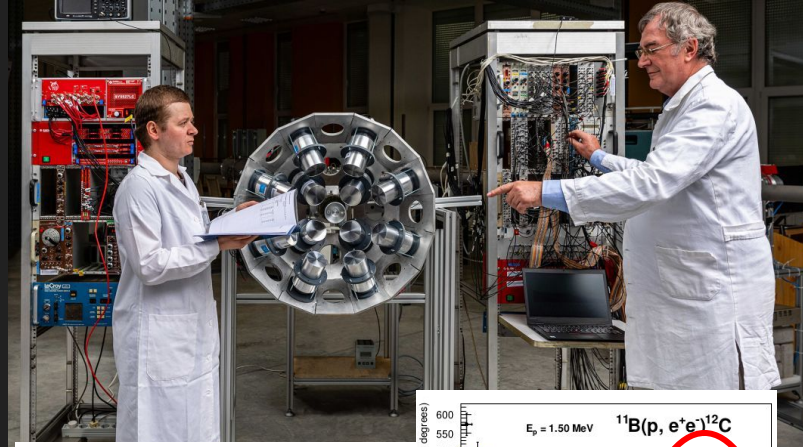
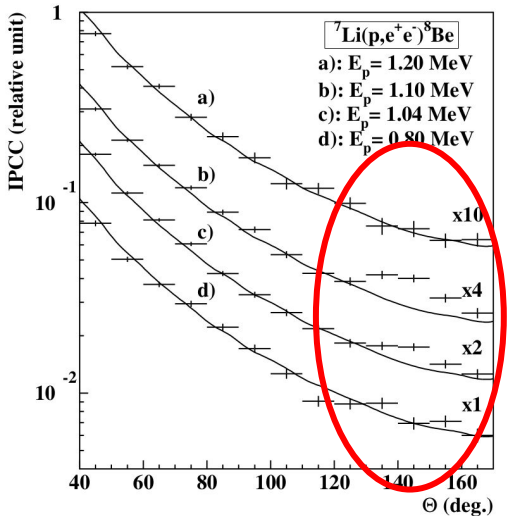
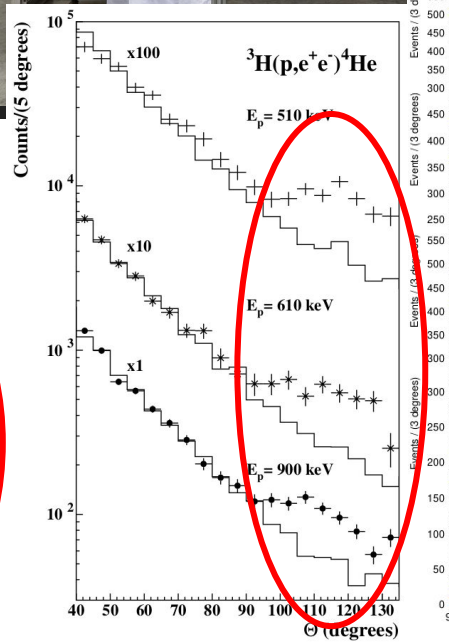
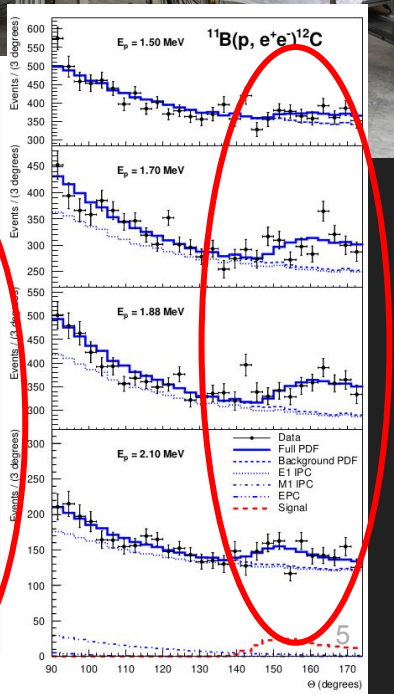




E_p (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		



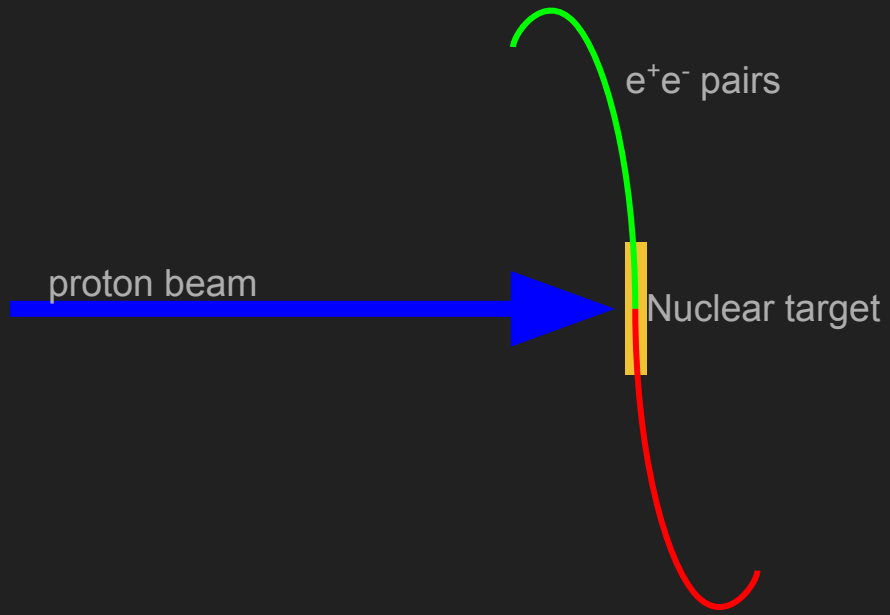




1: arxiv 1504.01527,
2: arxiv 2104.10075,
3: arxiv 2209.10795

Experimental Concept: new particle searches

$X \rightarrow e^+e^-$

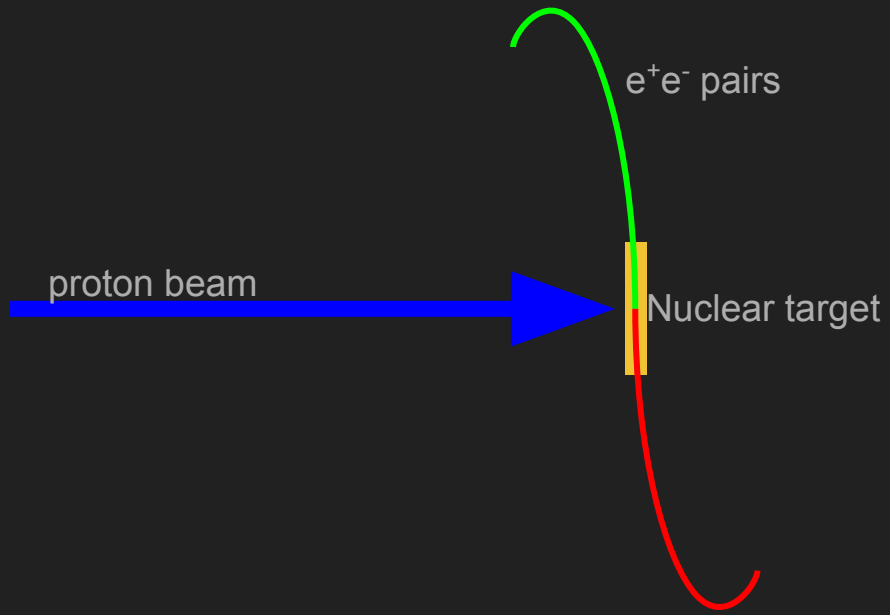


B-field → tracking
→4 momentum
→ invariant mass

Reactions of the form: $p + {}^{Z}X \rightarrow {}^{Z+1}Y + (e^+e^-)$

Experimental Concept: new particle searches

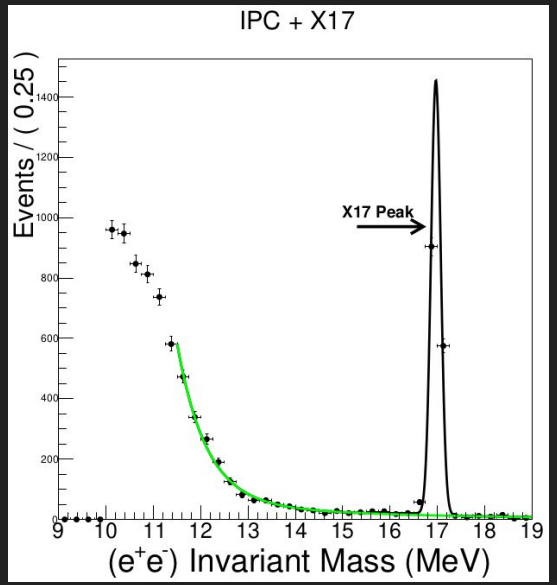
$X \rightarrow e^+e^-$



B-field → tracking

→4 momentum

→ invariant mass

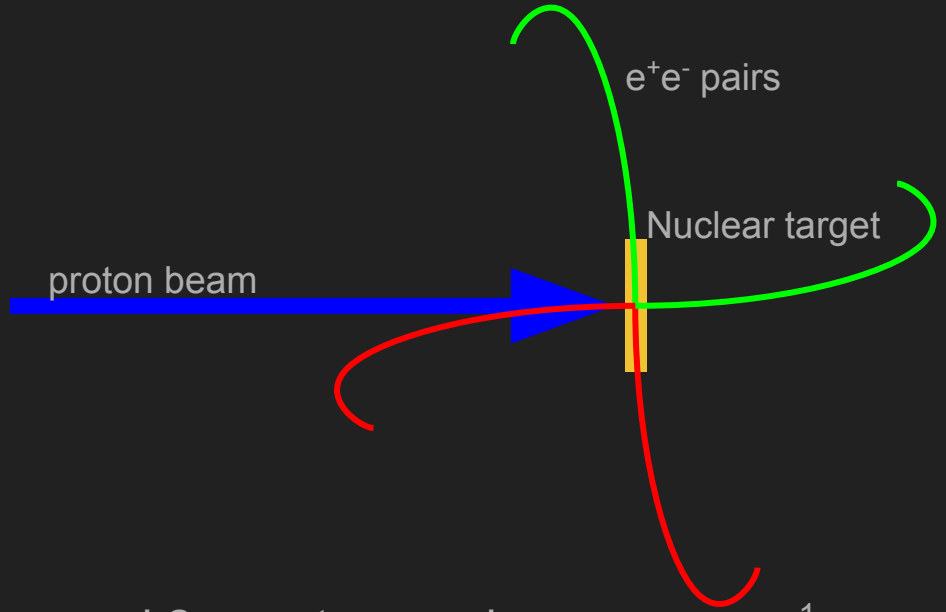


Reactions of the form: $p + {}^{Z}X \rightarrow {}^{Z+1}Y + (e^+e^-)$

X17, dark photon, ALPs, others?

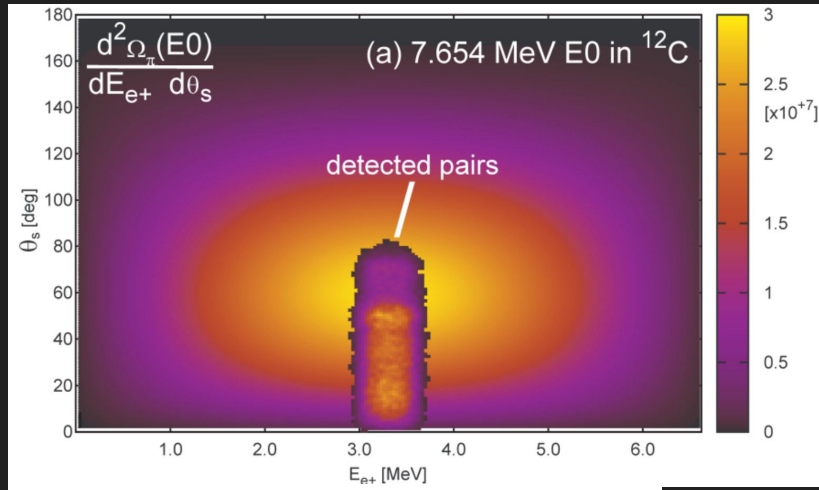
Experimental Concept: Nuclear Physics

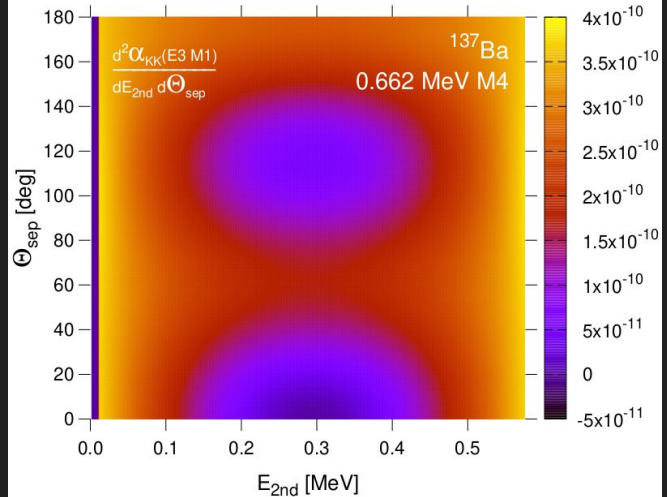
First double-differential IPC cross-sections



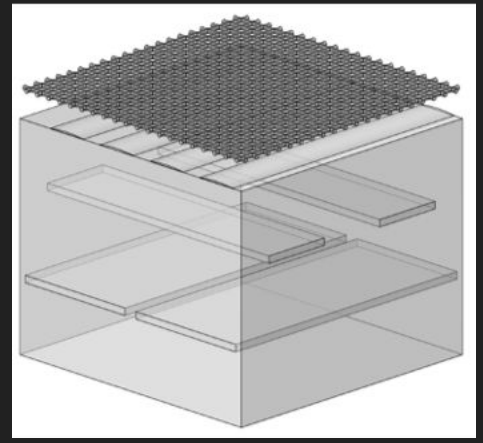
Unobserved 2-quantum nuclear processes[1]: double internal conversion, double internal pair conversion

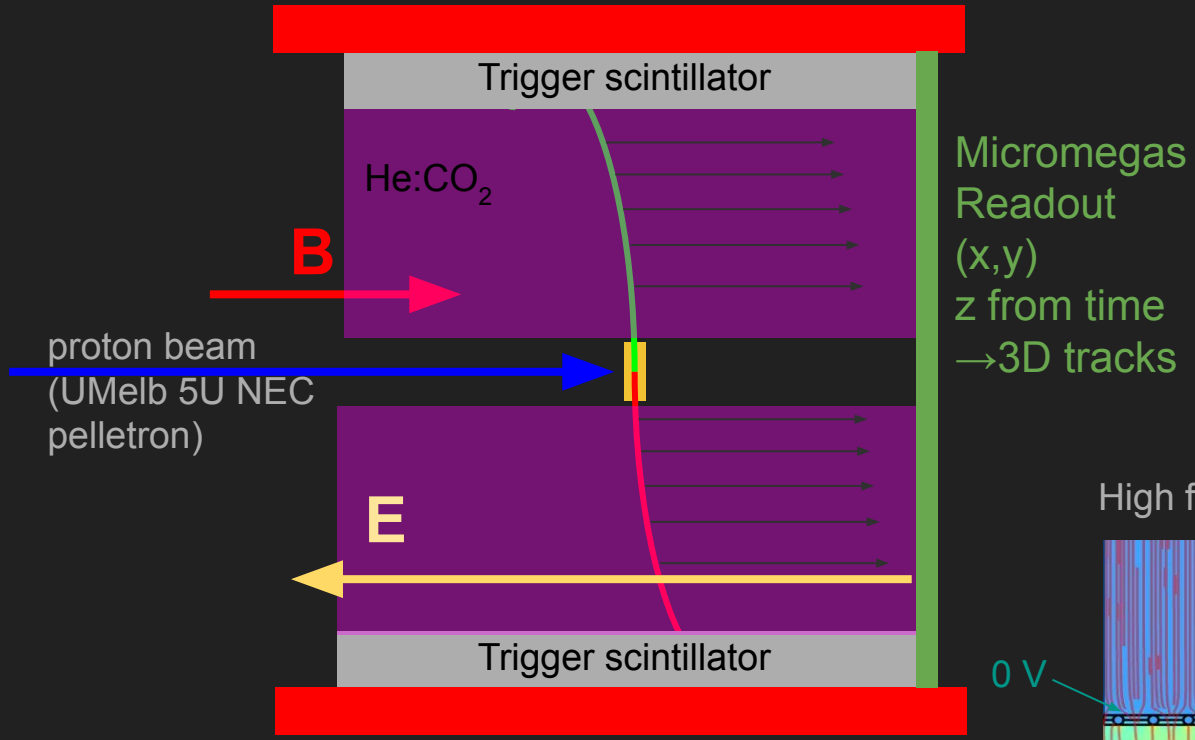
[1]Waltz et al. *Nature* **526**:406 (2015)



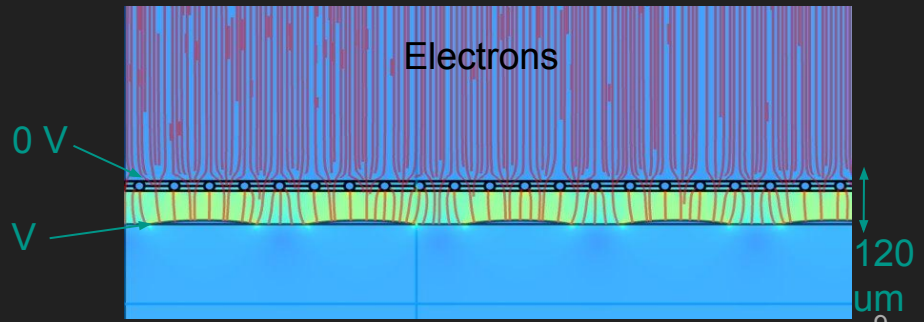


Experimental Design

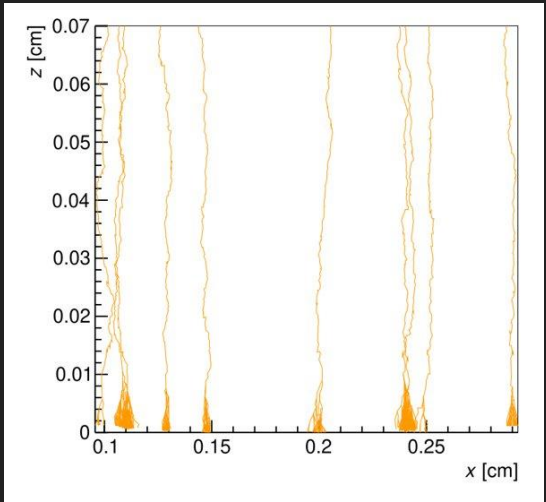


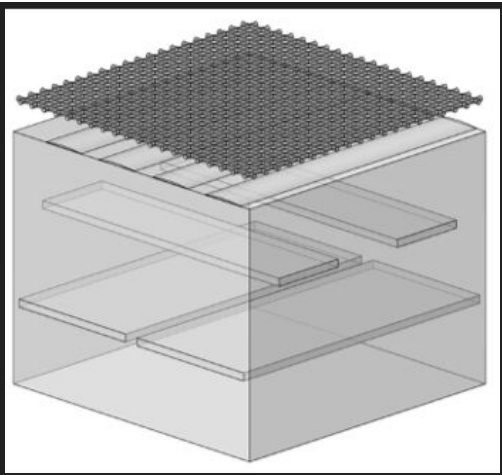


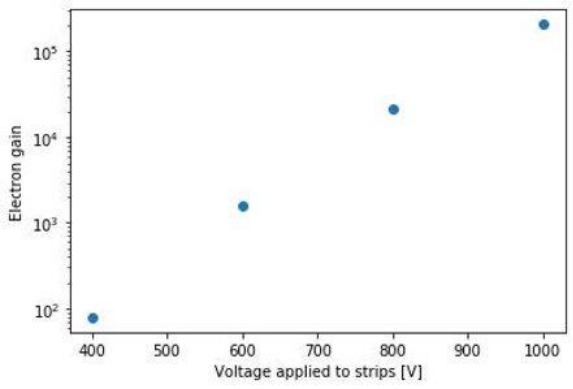
High field in micromegas → avalanche gain



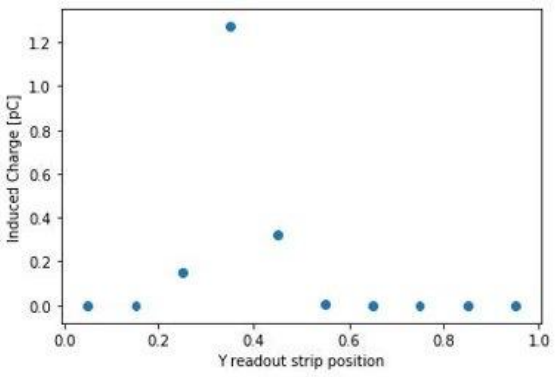
Micromegas Simulation (Garfield)

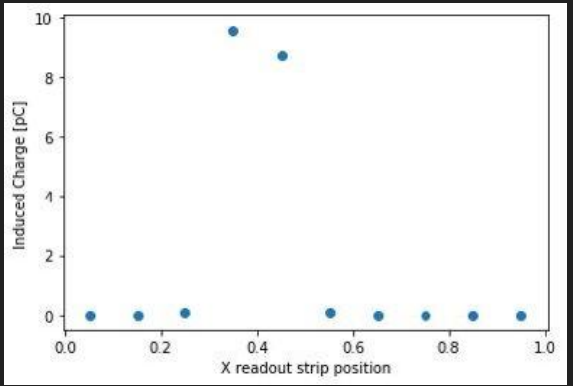






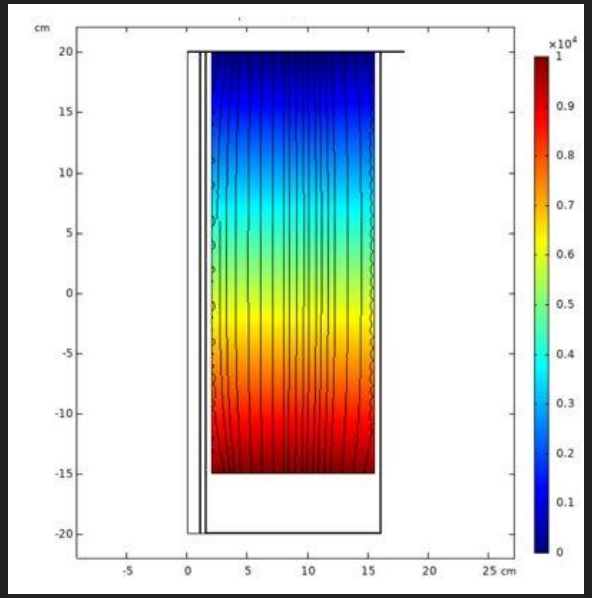
800 V gives ~10^4 gain



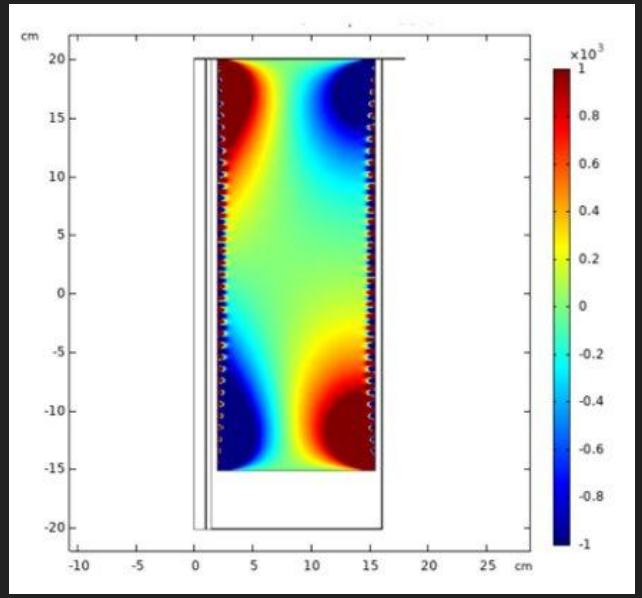


~pC pulses on the strips – within the linear range of ASIC readout (VMM)

E-field Simulations (COMSOL)

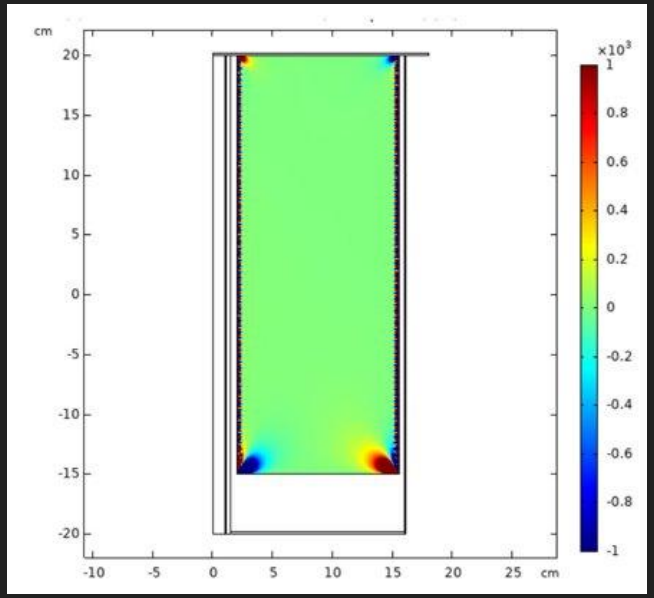


Z component



Radial component

9 mm rings, 1 mm separation



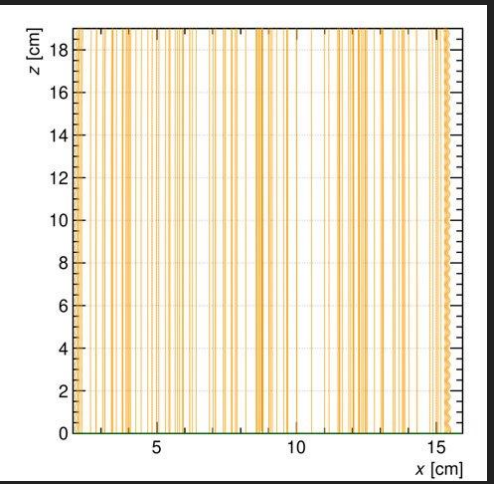
Radial component

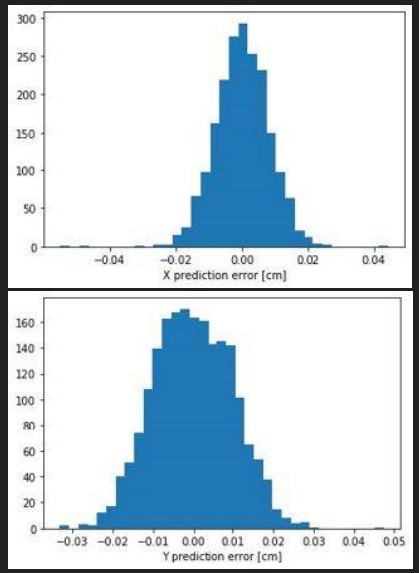
Optimized: 4.5 mm rings placed 0.5 mm apart

Initial upstream ring 1 mm downstream of cathode disk

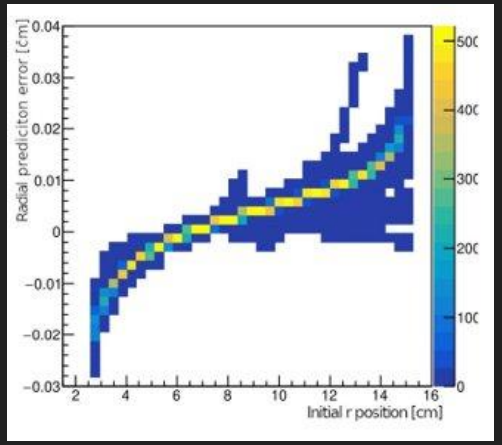
Electron Drift Simulations (Garfield)

What x/y resolution can we expect, given diffusion and the E-field?

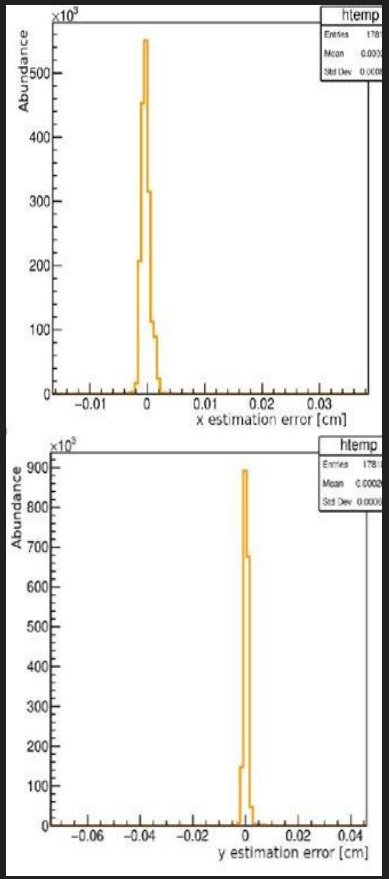




100 um resolution
(uncorrected)

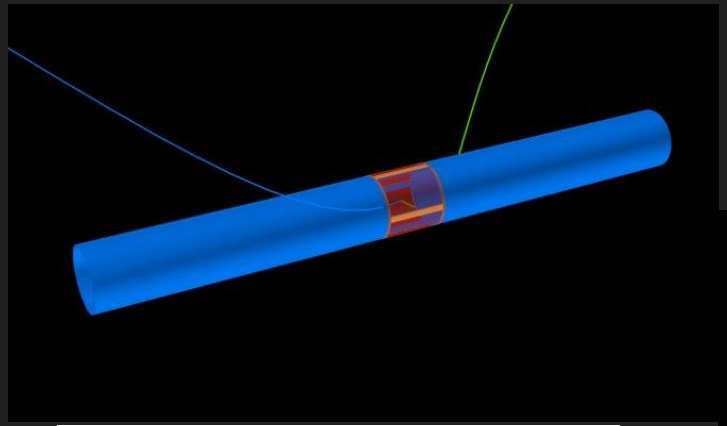


Error depends on
radial position



10 um resolution
(corrected)

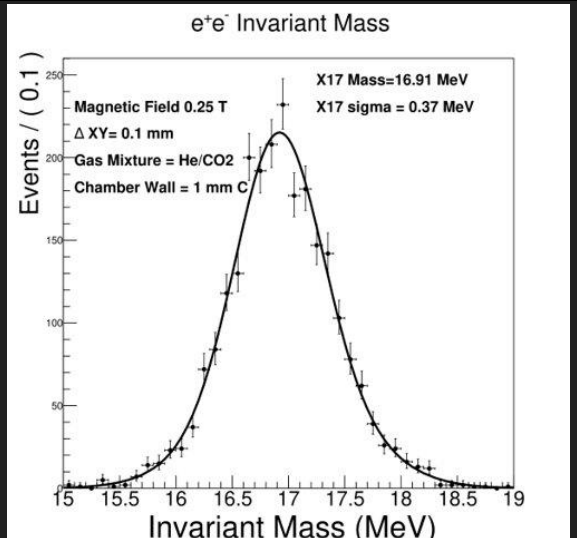
Track Reconstruction Simulation



Geant4: simulate tracks in the TPC

Genfit2: fit tracks

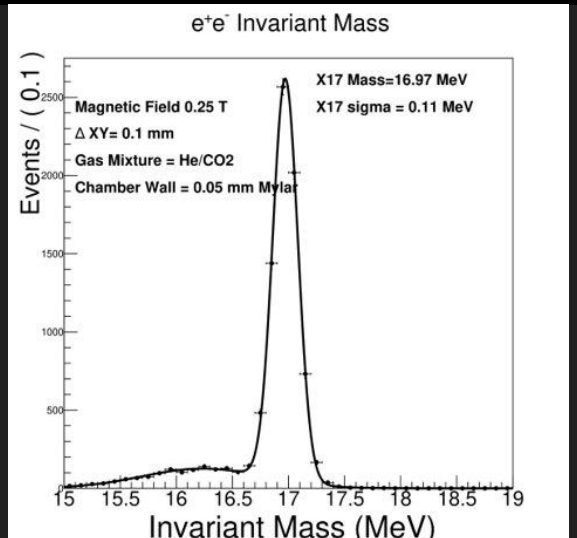
RAVE: vertex projection



Chamber wall thickness is key

←1 mm C

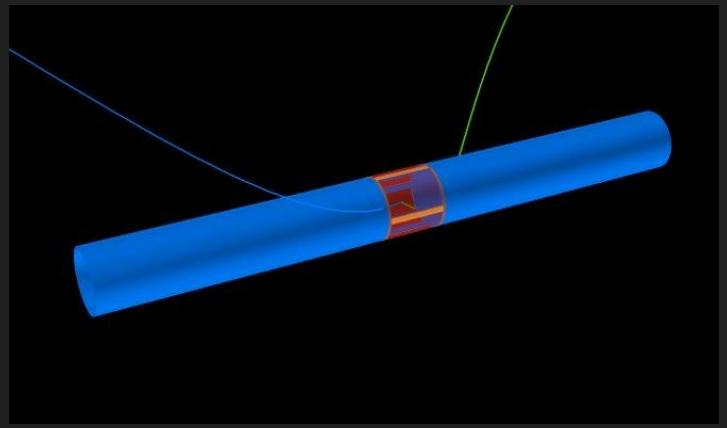
50 um mylar→



Chamber Wall

Mylar shear strength = 15 kg/mm^2

→50 um mylar with 300 mm^2 is factor of 20 from breaking



Vacuum tests →1.1 x 10^{-5} Torr (limited by connector outgassing)

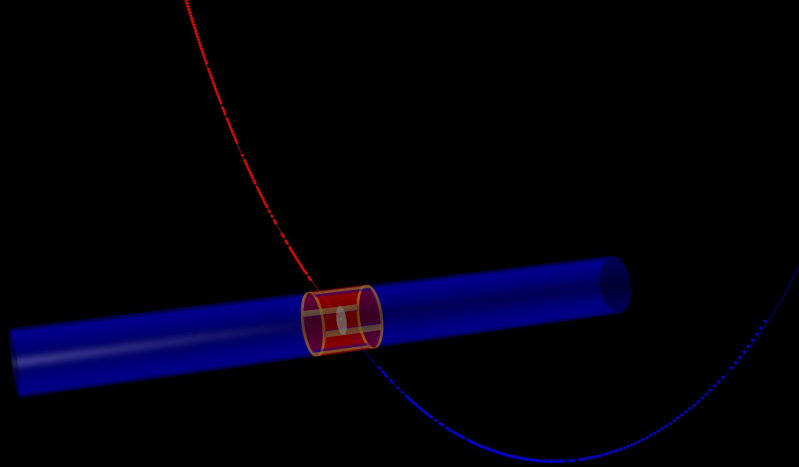
Particle search backgrounds

Non-e^+e^- pair events → event topology

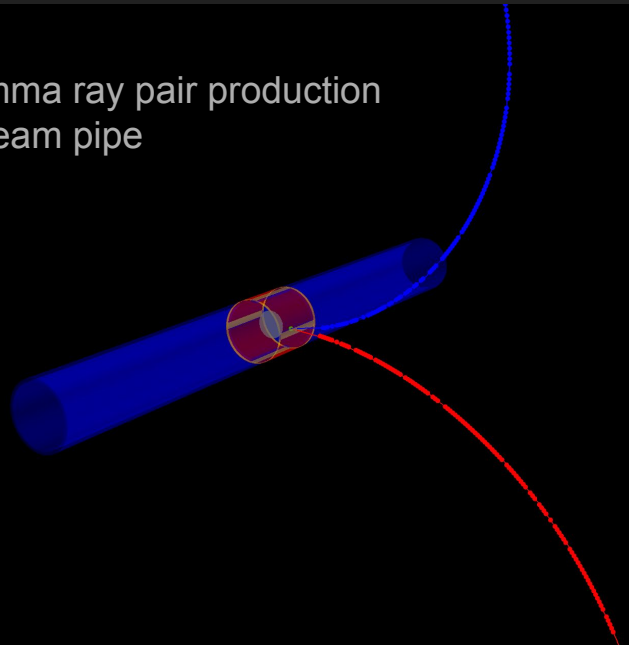
Gamma pair production → vertex fitting

Internal pair conversion → unavoidable

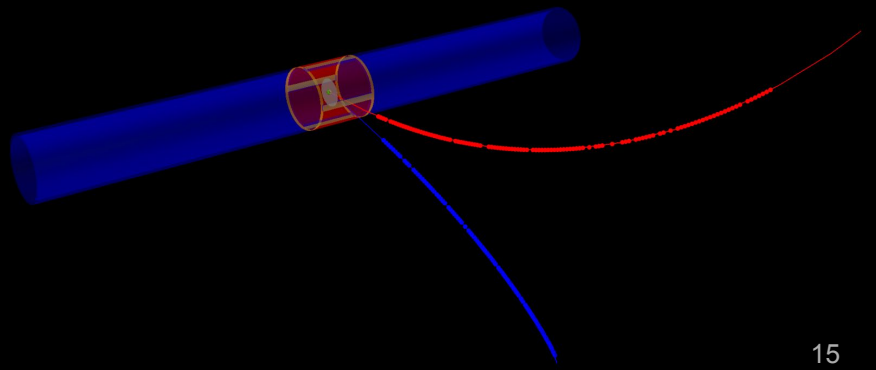
X17



Gamma ray pair production
in beam pipe



Internal pair conversion

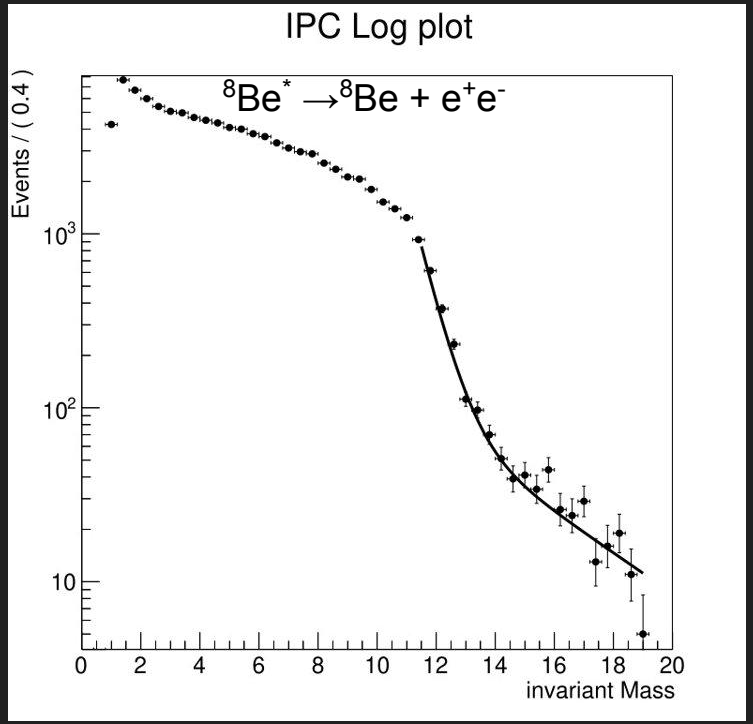


X17 sensitivity – Internal Pair Conversion Background

Irreducible EM decay background from: $p + {}^{Z}X \rightarrow {}^{Z+1}Y + (e^{+}e^{-})$

Simulated trivial (Born approximation) double differential IPC production

Peaks at low invariant mass. Low background near 17 MeV.



Black curve: ansatz fit to background.

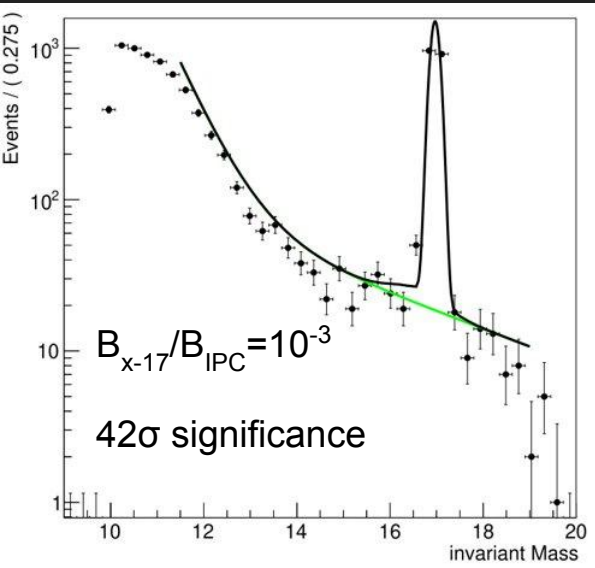
X17 sensitivity

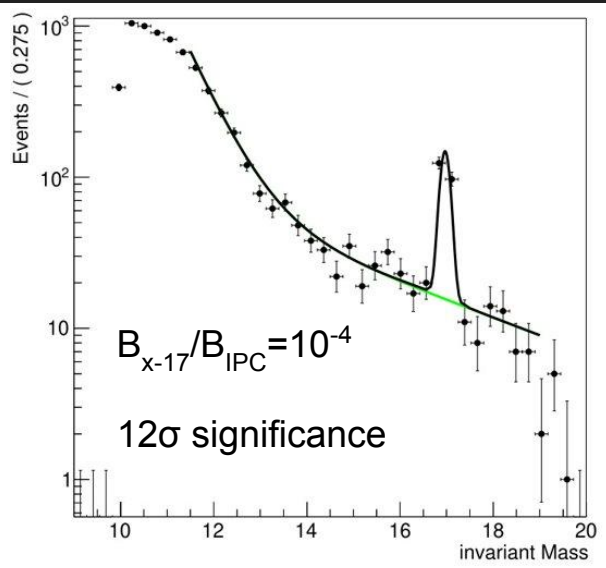
Simulation of TPC with X-17 + IPC background

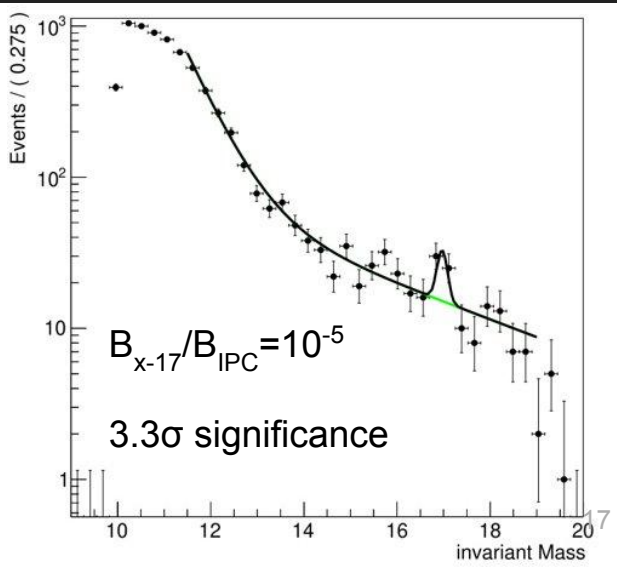
4 day Pelletron measurement, 1 μA beam current, 10^{19} cm^{-2} ^{7}Li target

Approx ATOMKI X-17 branching ratio

17 MeV boson production with smaller branching



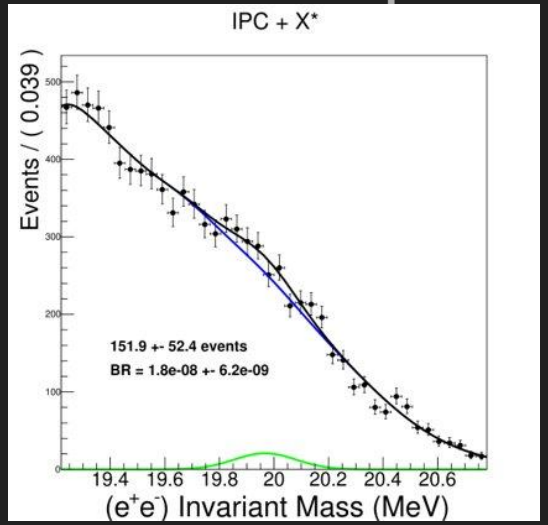




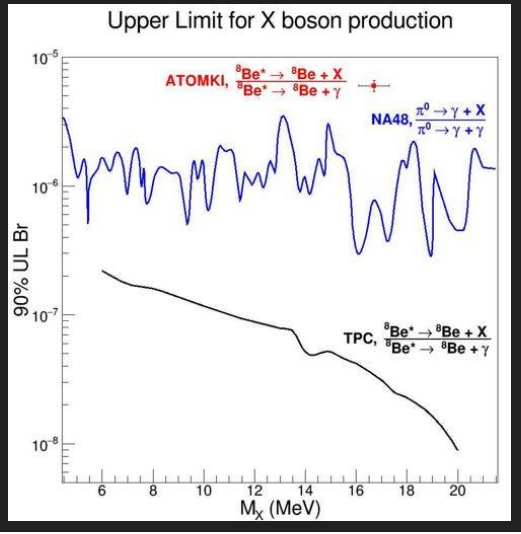
X Boson Sensitivity

30 day Pelletron run at 4.5 MeV for p + ^{7}Li →^{8}Be + X($e^{+}e^{-}$) searches

20 MeV example



90% confidence level limits



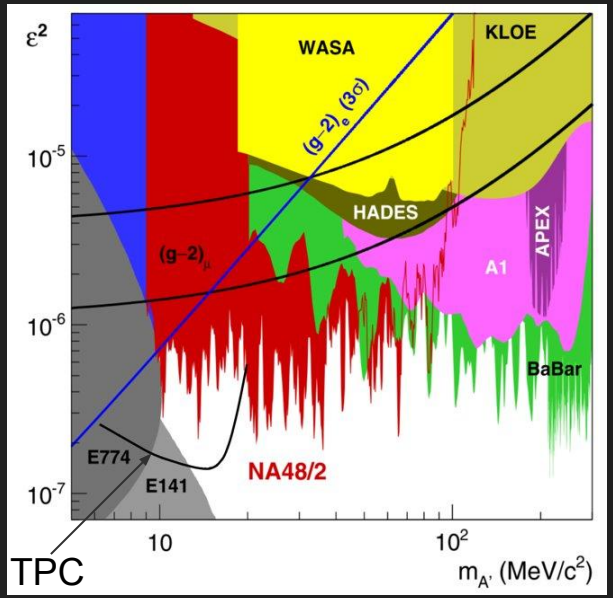
Note BR limits will vary with nucleus, and proton beam energy, so we can tune the search range

Reaction	Q-value	Mass Range for search
$p+^{7}\mathrm{Li}\rightarrow^{8}\mathrm{Be}+(e^{+}e^{-})$	16.7	15 - 20 MeV
$p+^{3}\mathrm{H}\rightarrow^{4}\mathrm{He}+(e^{+}e^{-})$	19.3	17 - 22 MeV
$p+^{27}\mathrm{Al}\rightarrow^{28}\mathrm{Si}+(e^{+}e^{-})$	11.1	9 - 15 MeV
$p+^{25}\mathrm{Mg}\rightarrow^{26}\mathrm{Al}+(e^{+}e^{-})$	5.7	5 - 10 MeV
$p+^{12}\mathrm{C}\rightarrow^{13}\mathrm{N}+(e^{+}e^{-})$	1.4	3 - 5.5 MeV

Dark Photon and ALP Sensitivity

30 day Pelletron run at 4.5 MeV for p + ^{7}Li $\rightarrow$ ^{8}Be + X(e^+e^-) searches (90% CL limits)

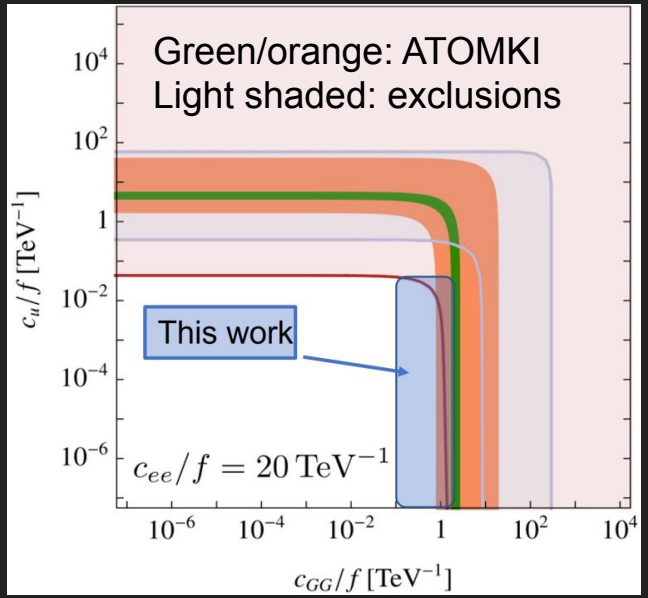
Dark Photon



World-best exclusion from 10-20 MeV

(Feng et al PRL **117**:071803, 2016)

Axion-Like Particle

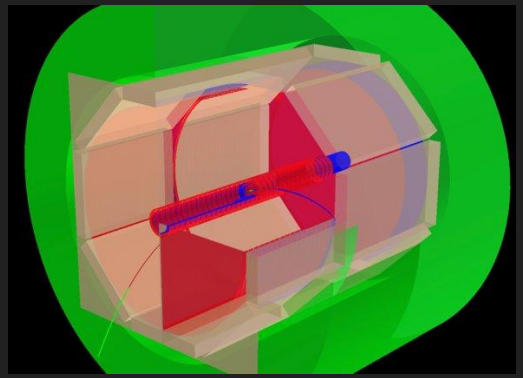


World-best ALP exclusion

(Bauer et al JHEP **2022**:56, 2022)

Summary

- Proposed TPC facility can exclude the X17 with > 2 orders of magnitude in sensitivity, in an identical nuclear system
- Unique facility – world-leading probe of dark photon/ALP physics. Others?
- Significant first measurements for fundamental Nuclear Physics



Australian National University

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE