Fundamental Physics at the MeV scale in Australia

https://arxiv.org/abs/2302.13281

Martin Sevior[1)], Lindsey Bignell[2,3)], Irene Bolognino[4,3)], Catalina Curceanu[5)] , Tibor Kibédi[2)], Alasdair McLean[4,3)], Adam Steinberg[1)], Andrew Stuchbery[2)], Martin White[4)]

(+Nic. Jackson, Connor Rush, Adrian Babic – Melbourne M.Sc. Students,
Michael Baker, Andrea Thamm (U. Mass.))

[1)] School of Physics, University of Melbourne

[2)]Department of Nuclear Physics and Accelerator Applications, Australian National University

[3)]ARC Centre of Excellence for Dark Matter Particle Physics

[4)]Adelaide University

[5)]INFN (Frascati)

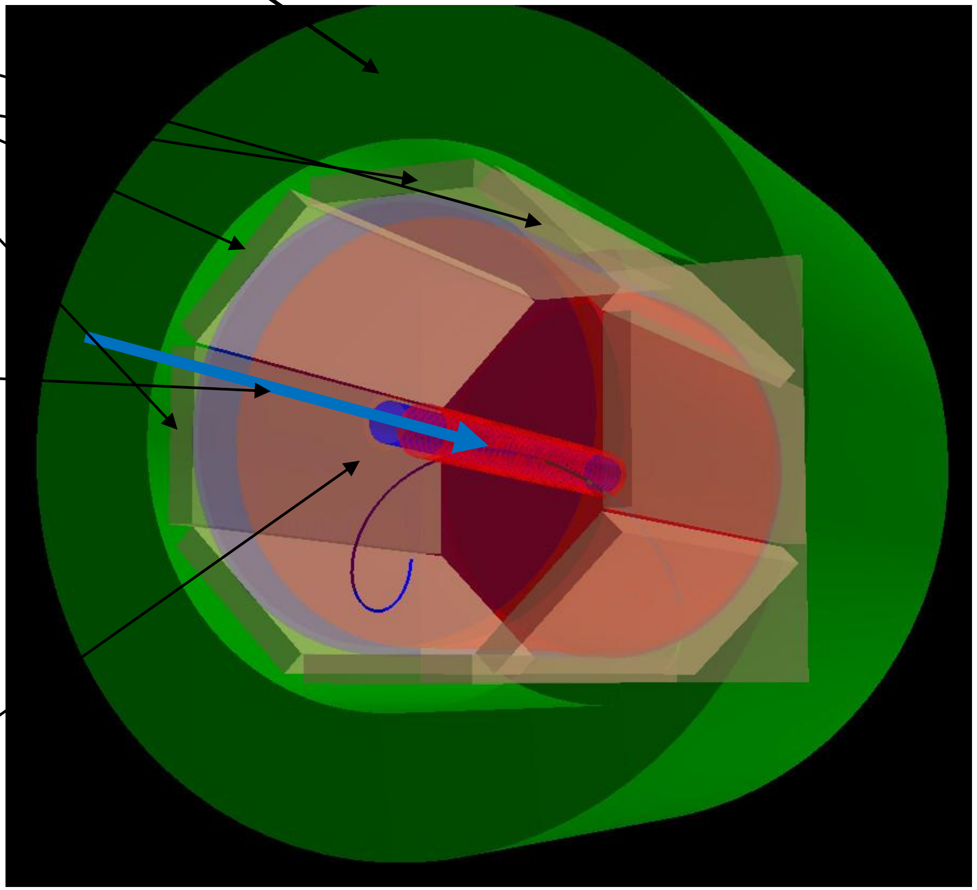
Beamline Instrument for MeV-scale particle and nuclear Physics (BLIMP)
Pelletron (Melbourne), 14 UD (ANU)

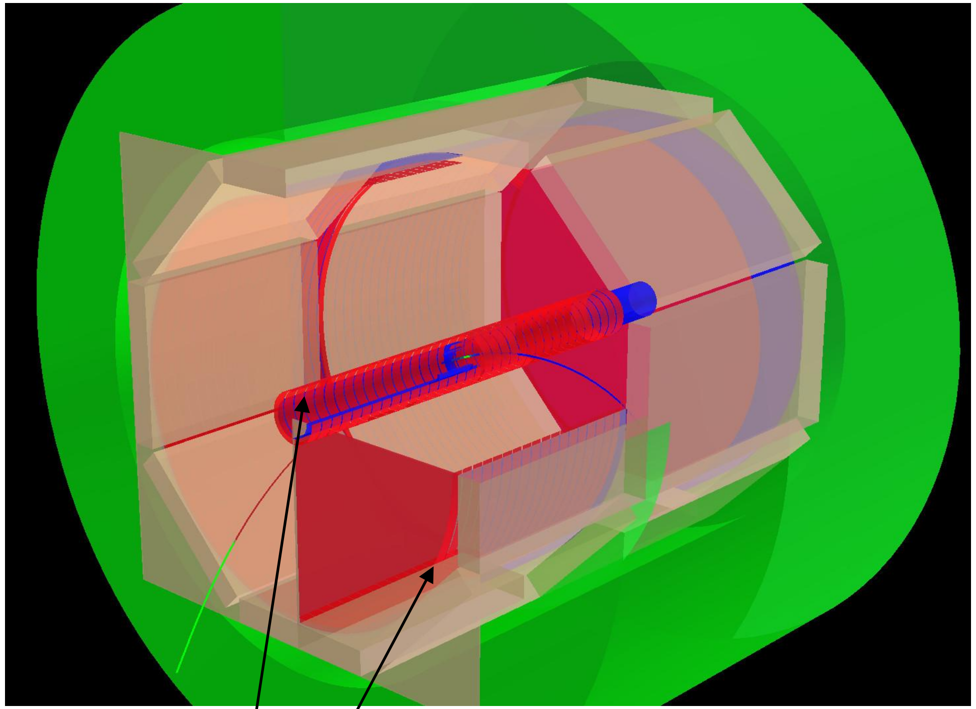
Iron Yoke (Electromagnet)

Trigger scintillators

Proton beam

Beam Pipe

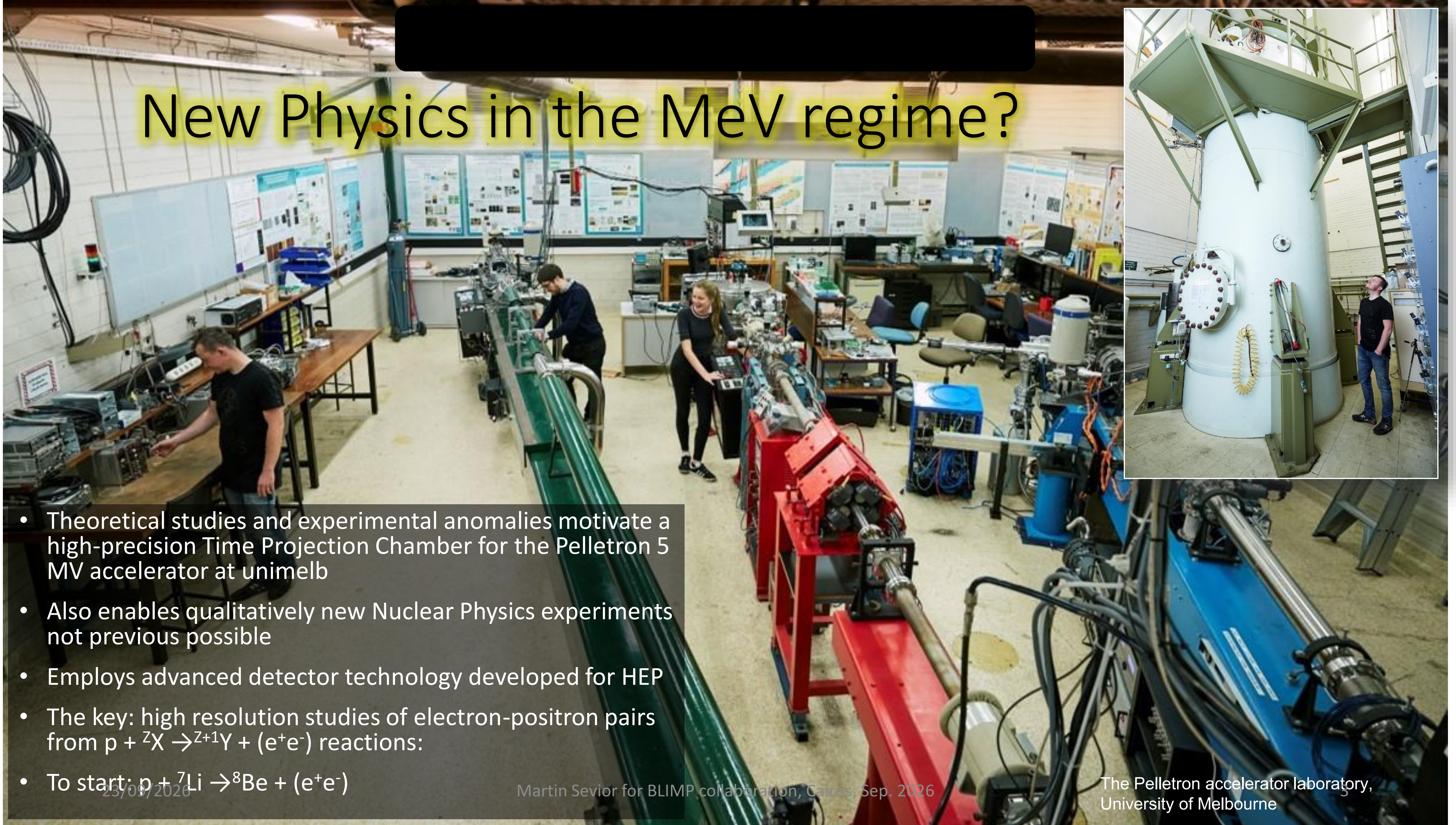




Electric Field Cage

[redacted]

New Physics in the MeV regime?

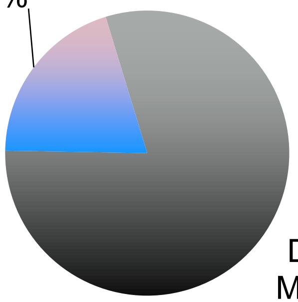


- Theoretical studies and experimental anomalies motivate a high-precision Time Projection Chamber for the Pelletron 5 MV accelerator at unimelb
- Also enables qualitatively new Nuclear Physics experiments not previous possible
- Employs advanced detector technology developed for HEP
- The key: high resolution studies of electron-positron pairs from p + $^{Z}X \rightarrow ^{Z+1}Y + (e^{+}e^{-})$ reactions:
- To start: p + $^{7}Li \rightarrow ^{8}Be + (e^{+}e^{-})$

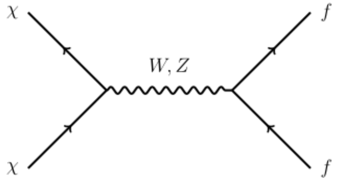
The Pelletron accelerator laboratory, University of Melbourne

Particle Physics Motivation – “Dark Sector”

Dark Matter => New Physics



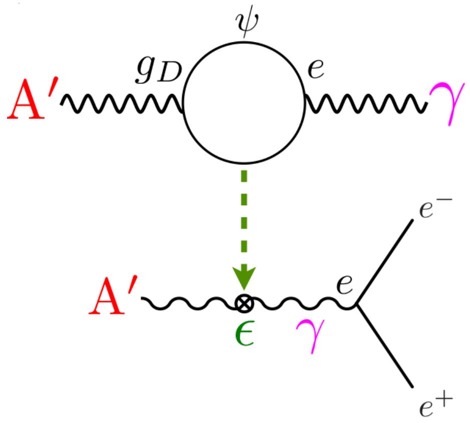
MeV-GeV thermal relic DM requires new, comparably light mediators to achieve required annihilation cross-section for Thermal freeze-out.



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

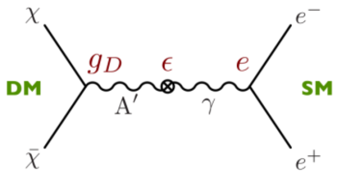
[Lee & Weinberg 77]

A “minimal” dark sector theory = χ + a new mediator A′

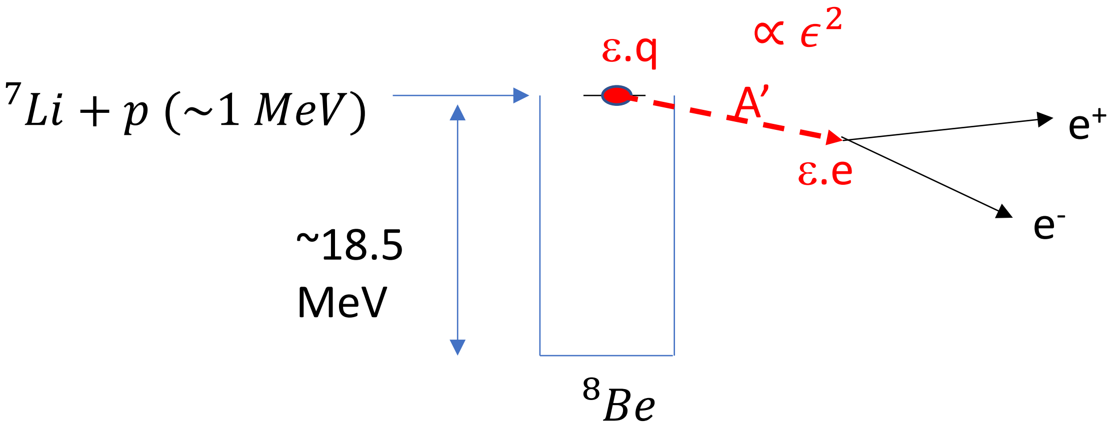


A dark photon, A′, can mix with the SM photon, generating an ϵe coupling to SM fermions:

$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$



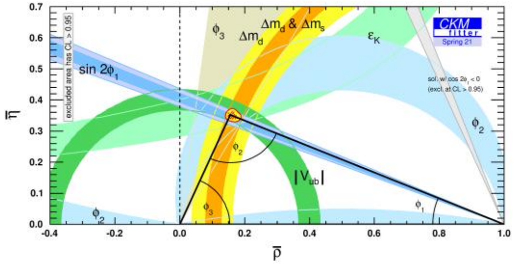
[(Tim Nelson, SLACMass, Feb 2020)]



Can produce ~2×10^{11} 5 - 22 MeV γ’s
=> Competitive search for Dark Photons

Axion Like Particles (ALPs)

QCD $\mathcal{L}$ has a CP-violating angle similar to the CKM matrix



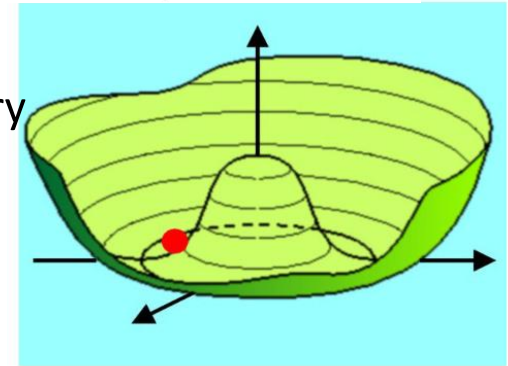
$$\mathcal{L} \subset \bar{\theta}\frac{\alpha_s}{8\pi} G_a^{\mu\nu}\tilde{G}_{a,\mu\nu}$$

$\bar{\theta}$ in the range: $0-\pi$

Neutron dipole moment=> $\bar{\theta} < 10^{-10}$

$\Rightarrow$ Strong CP problem!

Solved with the Peccei-Quinn $U(1)_{PQ}$ symmetry



Broken by the vev of a SM singlet scalar field:

$$\sigma(x) = \frac{1}{\sqrt{2}}\left(v_{PQ} + \rho(x)\right) e^{iA(x)/f}$$

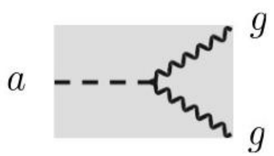
Scale of this field **>> 1 TeV** (given by f)

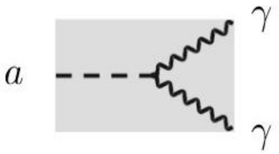
The field $\theta_A = A/f_A$ acts as a space-time dependent field to cancel $\bar{\theta}$

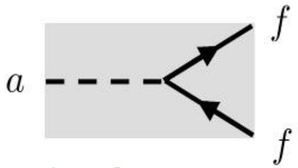
Gives rise to a pseudo Nambu-Goldstone boson: **axion**

The 0^- **axion** , feebly couples to gluons, photons and fermions

$$\text{SM } \mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A}{f_A}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} - \frac{\alpha}{8\pi}C_{A\gamma}\frac{A}{f_A}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{Af}}{f_A}\partial_\mu A\bar{\psi}_f\gamma^\mu\gamma_5\psi_f$$







[Powell 16, Ringwald 16,Peccei&Quinn77;Weinberg 78; Wiczek 78]

Axion Like Particles (ALPs) arise from additional global symmetries:

- Global lepton number symmetry: Majoron

[Chikashige et al. 78; Gelmini &Roncadelli 81]

- Global family symmetry: Familon

[Wiczek 82; Berezhiani & Kholpov 90]

- Quantum Gravity

[Bauer, Neubert, Renner, Schnubel, Thamm 22]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{G'_{ig}}{f_{a'_i}}a'_i G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{G'_{i\gamma}}{f_{a'_i}}a'_i F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{G'_{if}}{f_{a'_i}}\partial_\mu a'_i\bar{\psi}_f\gamma^\mu\gamma_5\psi_f$$

Then the particle corresponding to the excitation:

$$\frac{A(x)}{f_A} \equiv \frac{C'_{ig}}{f'_i}a'_i$$

Is the **axion**

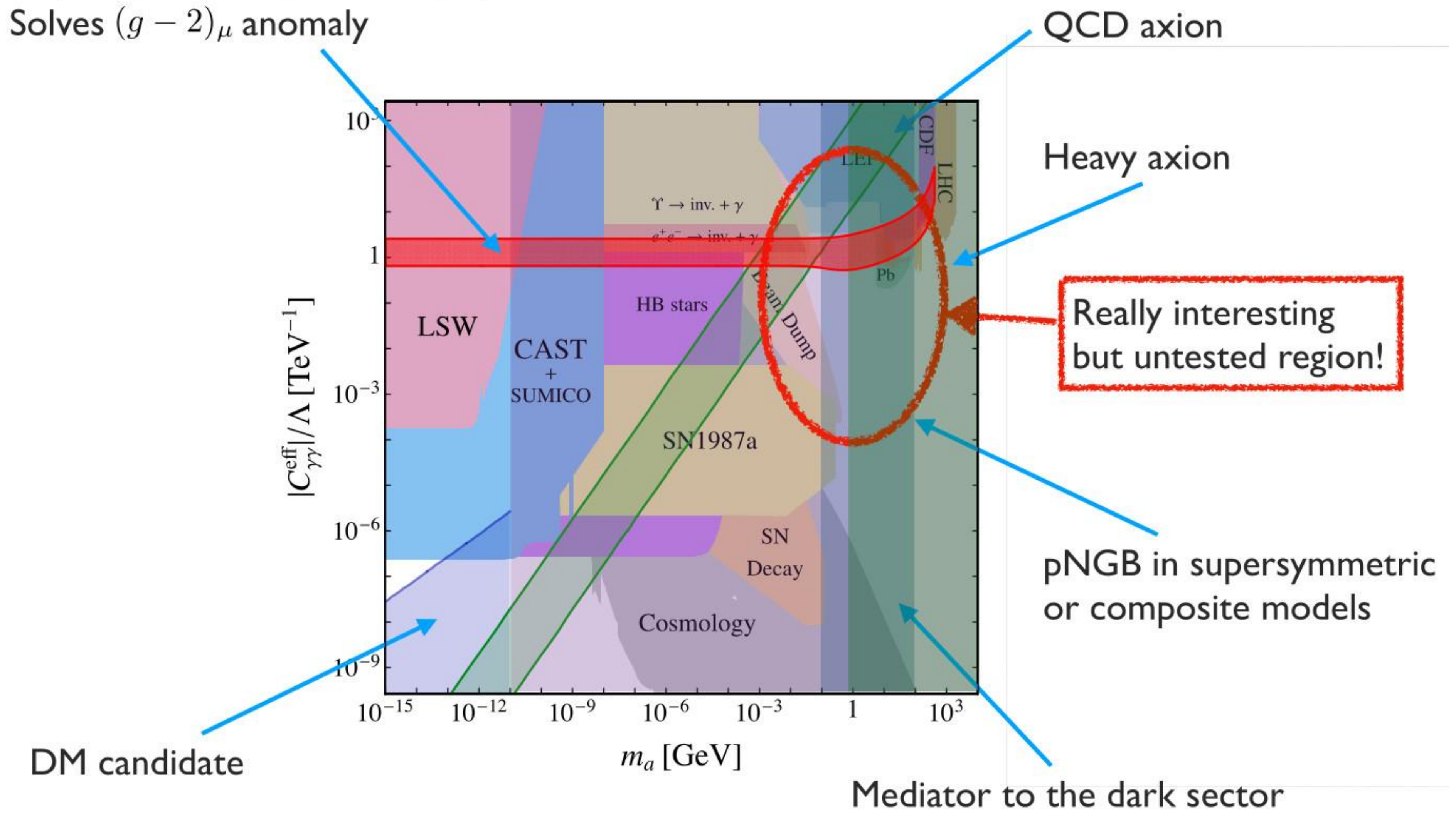
Excitations of the field orthogonal to this are called **Axion-Like-Particles (ALPs)**

In principle **ALPS** have different coupling to gluons ($\frac{G'_{ig}}{f_{a'_i}}$), photons ($\frac{G'_{i\gamma}}{f_{a'_i}}$) and fermions ($\frac{G'_{if}}{f_{a'_i}}$)

Nuclear decays can explore viable ALP parameter-space and hence are sensitive to multi-TeV Physics!

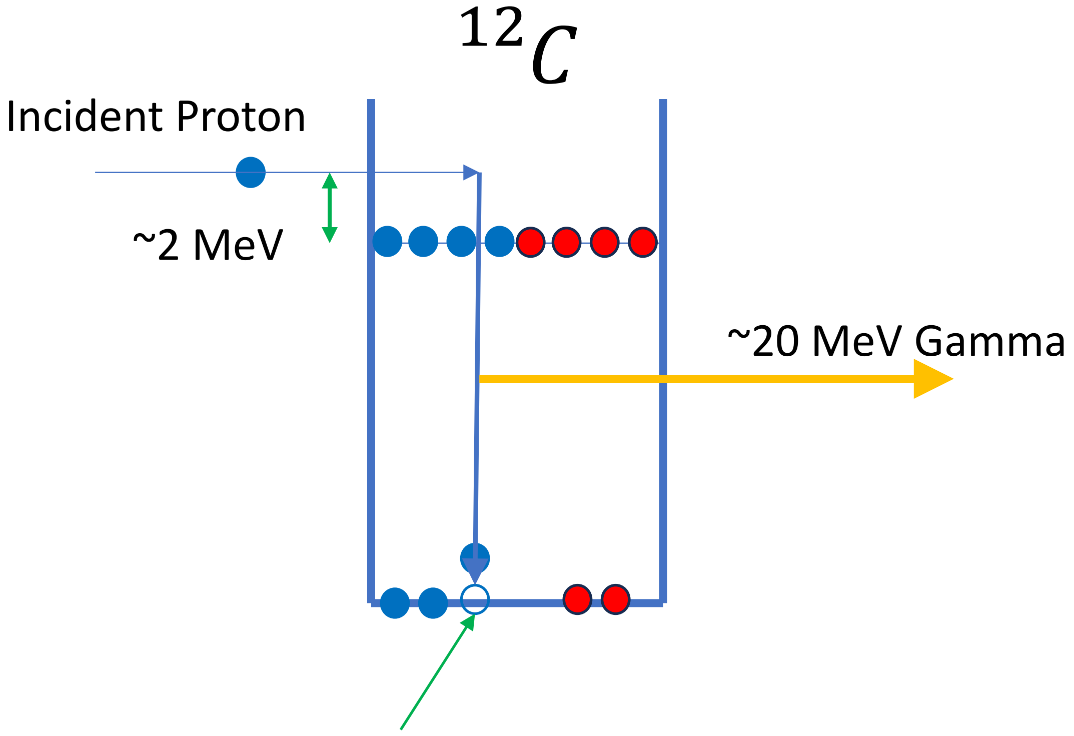
ALP mass to gamma-coupling parameter-space

Bauer, Neubert, Thamm JHEP 12 (2017) 044
Bauer, Neubert, Renner, Schnubel, Thamm PRL 124 (2020) 21



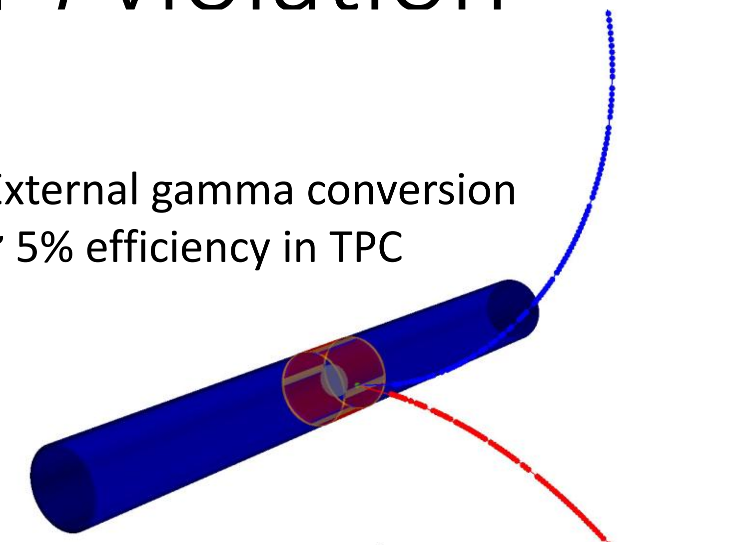
Pauli Exclusion Principle (PEP) violation

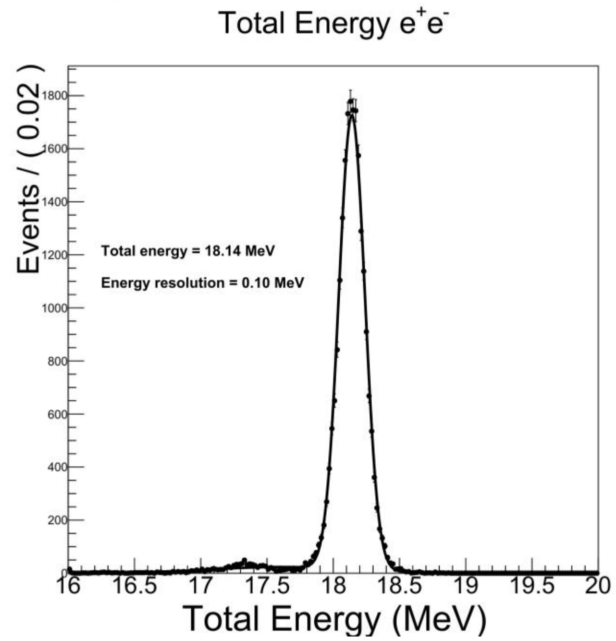
Requires “fresh” fermions. Possible in Quantum Gravity.
Tests Physics at the Planck scale.
[Phys. Rev. Lett. **129**, 131301](#) (2022)
[Acta Phys.Polon.Supp. 17 (2024) 1, 1-A6](#)



PEP excluded state

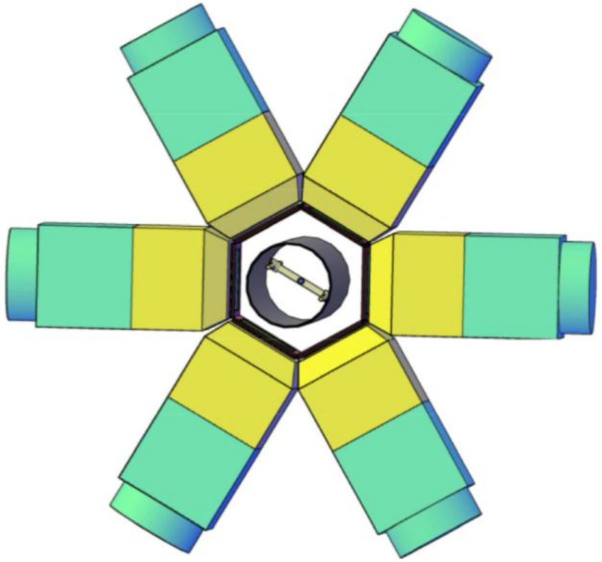
External gamma conversion
~ 5% efficiency in TPC

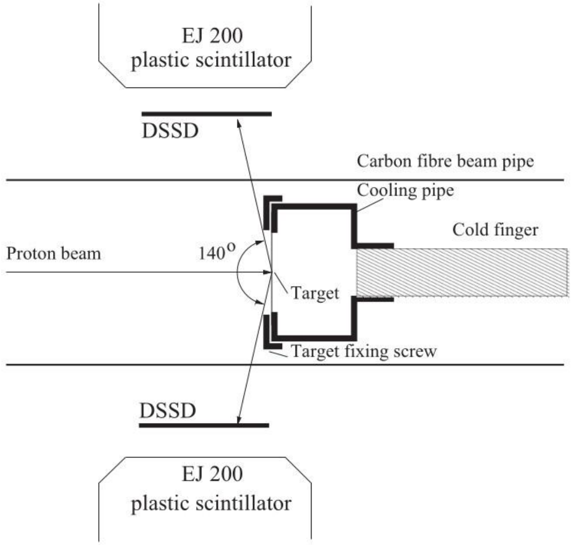




Particle Physics Motivation - Experiment

- Well motivated theories for the existence of feebly interacting fundamental boson at the MeV scale.
- ATOMKI group have found evidence for this at ~17 MeV invariant mass, the "X17"



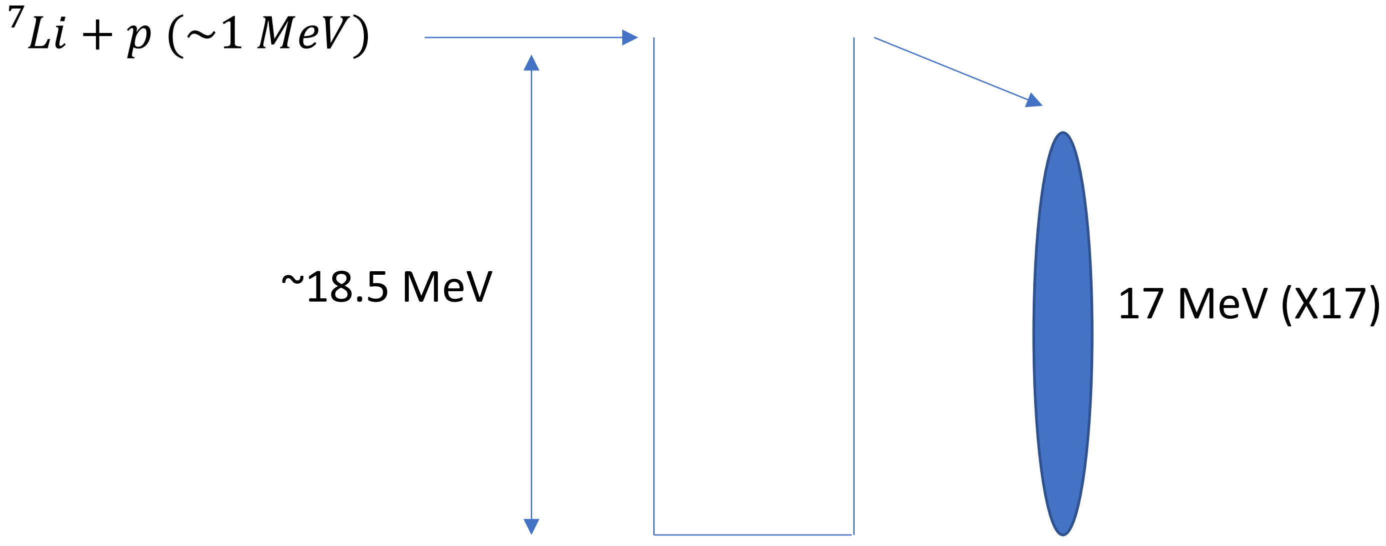


X17

- Initial anomaly: $p + 7Li \rightarrow {}^{8}Be + X17(\rightarrow e^{+}e^{-})$ (2016)
- Also: $p + {}^{3}H \rightarrow 4He + X17(\rightarrow e^{+}e^{-})$ (2021)
- Also: $p + 11B \rightarrow {}^{12}C + X17(\rightarrow e^{+}e^{-})$ (2022)

ATOMKI signature: Unexpected larger yield of $(e^{+}e^{-})$ events at large opening angles

Better Signature: Invariant mass of $e^{+}e^{-}$ = Mass of X17

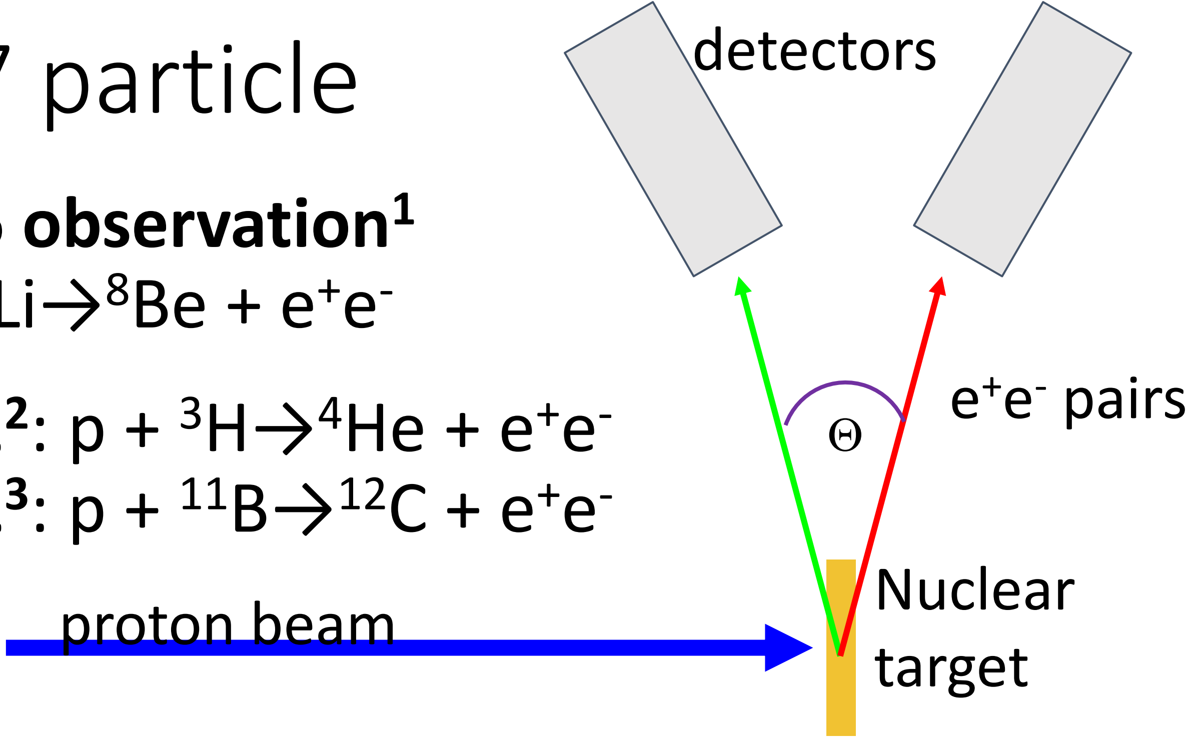


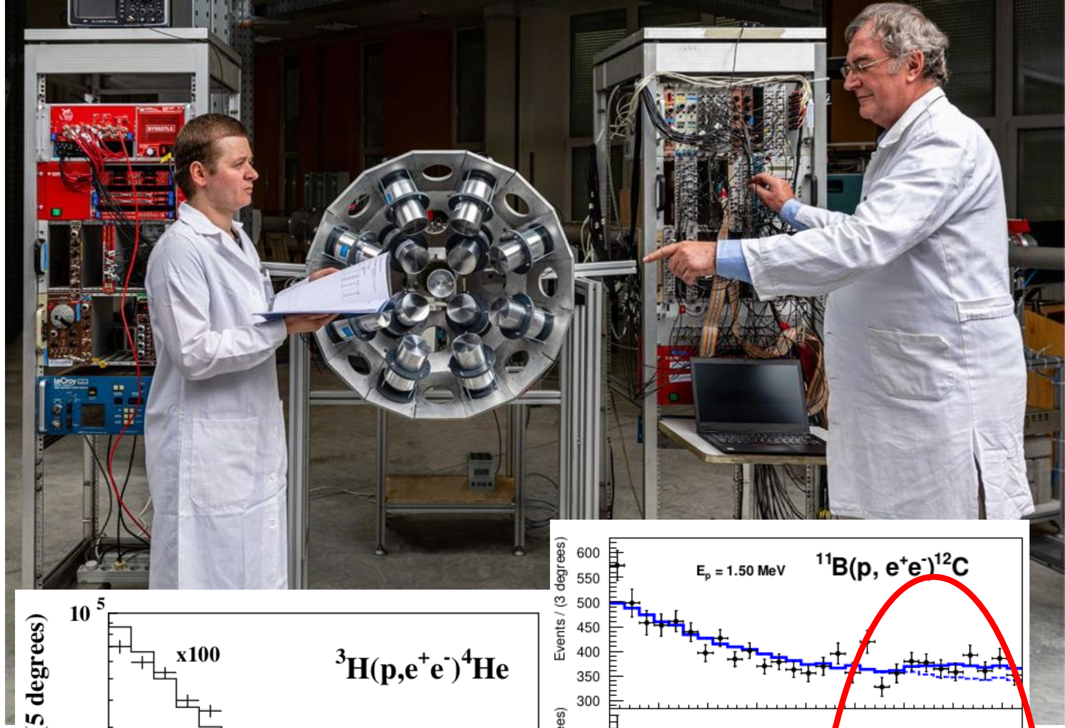
An opportunity to do fundamental Physics research on the Pelletron

X17 particle

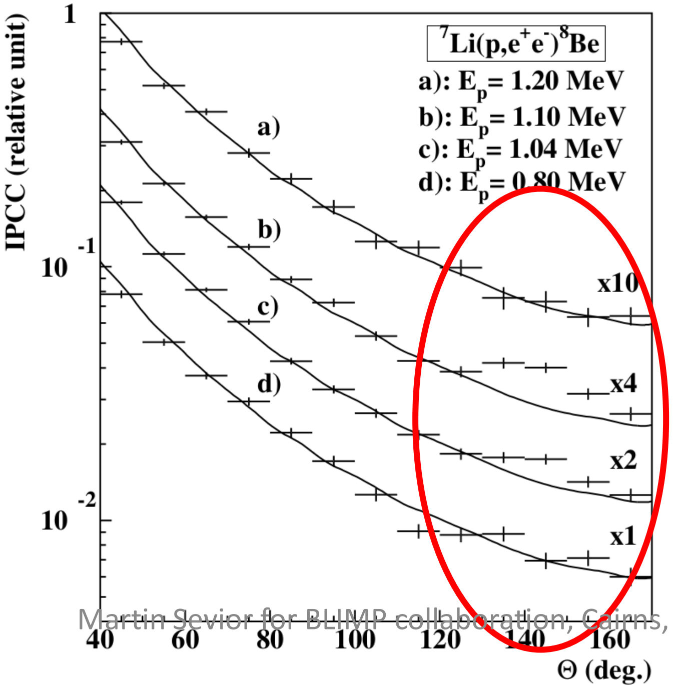
2016 observation[1]
p + ^{7}Li→^{8}Be + e^+e^-

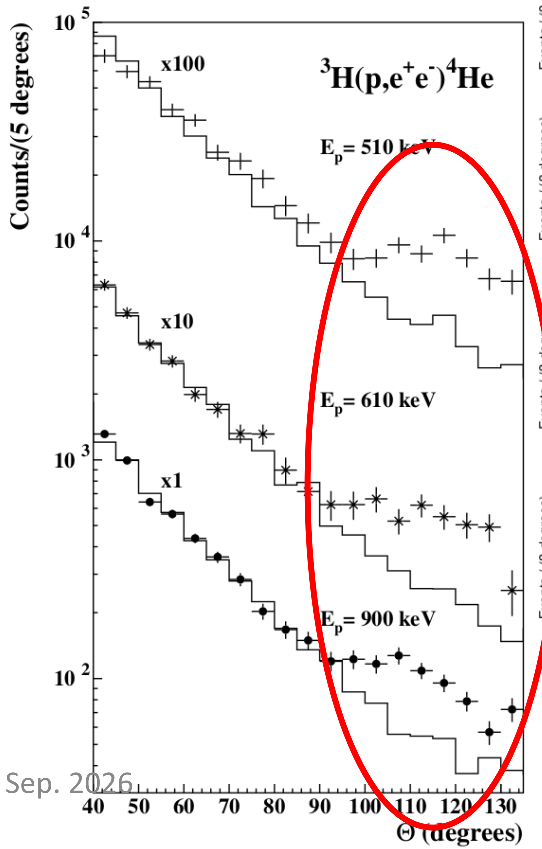
2021[2]: p + ^{3}H→^{4}He + e^+e^-
2022[3]: p + ^{11}B→^{12}C + e^+e^-

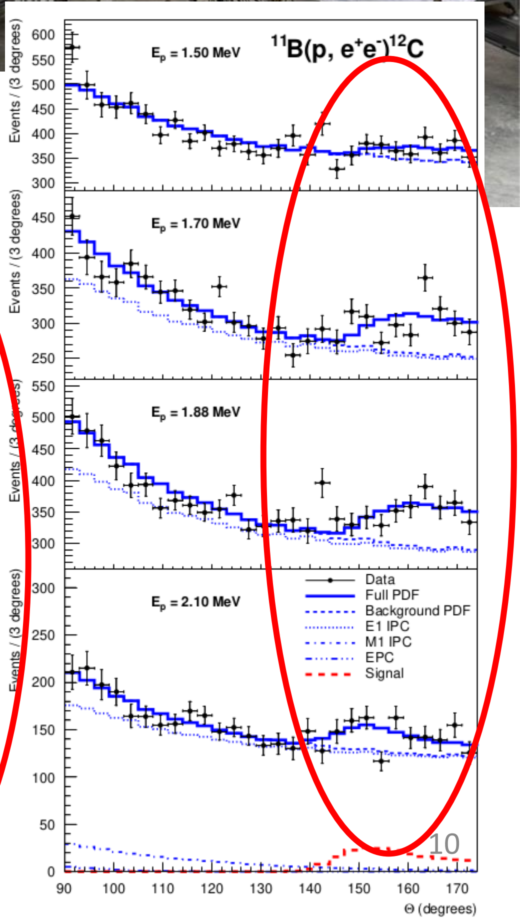




E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		







1: arxiv 1504.01527, (PRL **116**, 04215, (2016))
2: arxiv 2104.10075, (PRC **104**,044003, (2021))
3: arxiv 2209.10795, (PRC **106**, L061601 (2022))

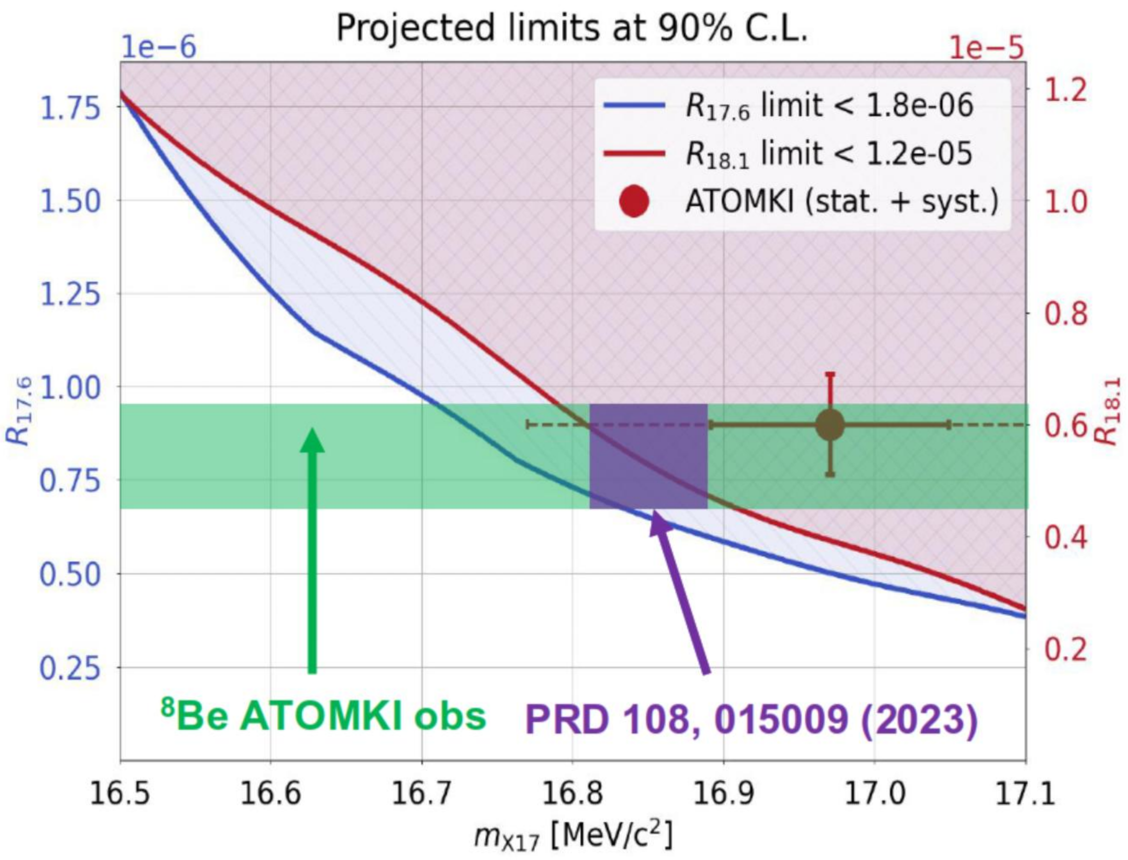
Recent Results -MEG-II

Search for the X17 particle in $^{7}Li(pe^{+}e^{-})^{8}Be$ **processes with the MEG II detector**
Eur.Phys.J.C 85 (2025) 7, 763 DOI: [10.1140/epjc/s10052-025-14345-0](https://doi.org/10.1140/epjc/s10052-025-14345-0)

Measurement on Li7 target to reproduce Be8 ATOMKI result, no signal found
ULs on BR(^{8}Be*→ ^{8}Be ee, anomaly)/BR(^{8}Be* → ^{8}Be γ) for 17.6, 18.1 MeV transitions

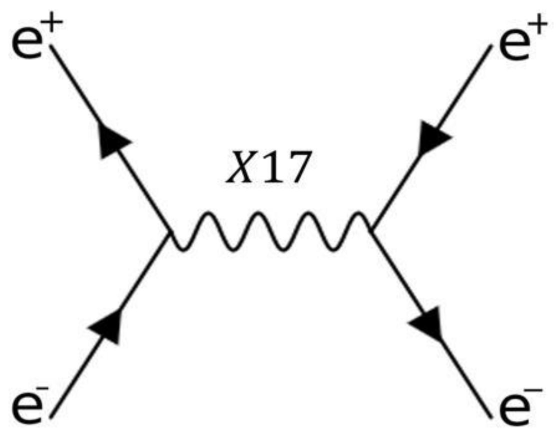
The MEG-II result remains compatible [Barducci, et al. ,HEP 04 (2025) 035] with the ATOMKI combination MX = 16.85(4) MeV

[Denton, Gehrlein PRD108, 015009 (2023)]

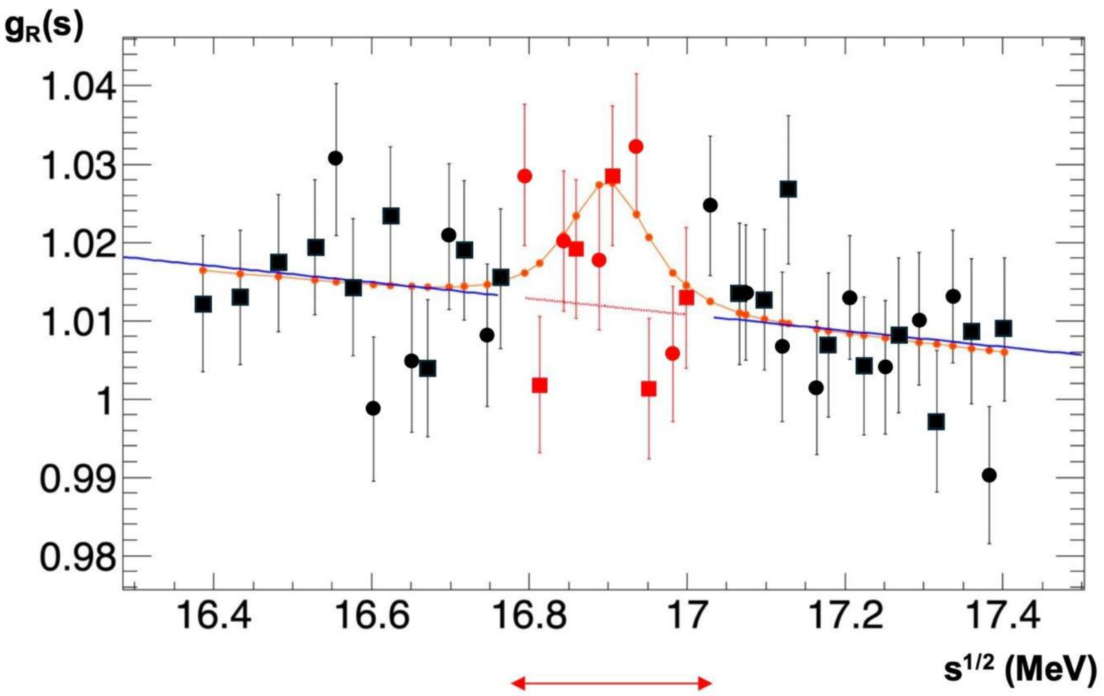


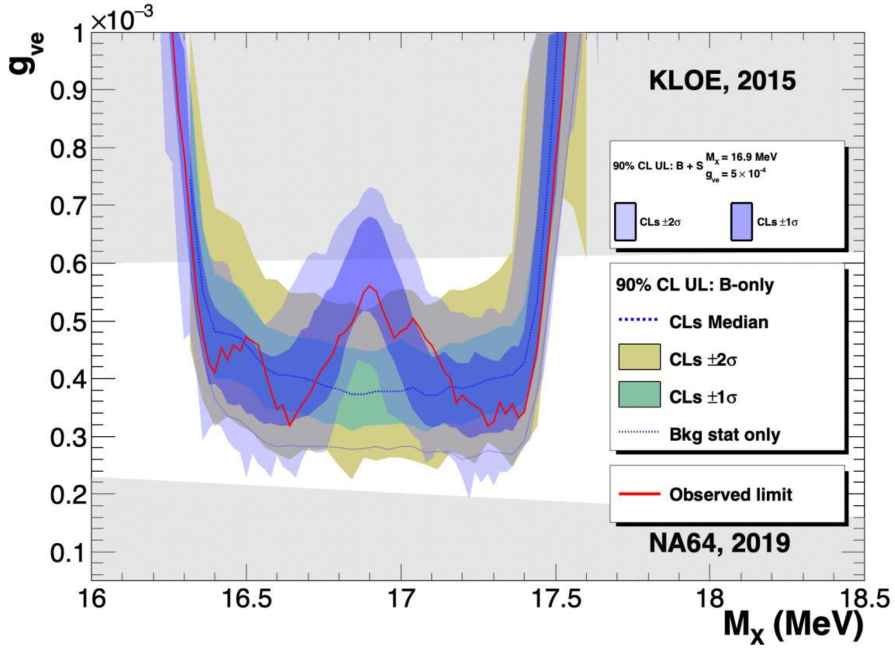
Recent Results - PADME

arxiv:2505.24979 *J. High Energ. Phys.* **2025**, 7 (2025)



PADME Search for a resonance on a thin target
At PADME, X17 produced through resonant annihilation in thin target: Scan around E(e+) ~ 283 MeV

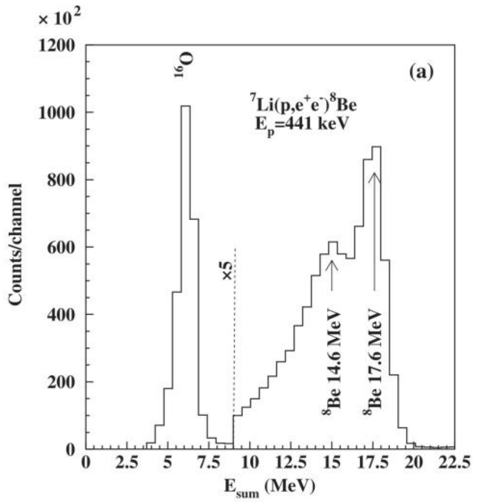




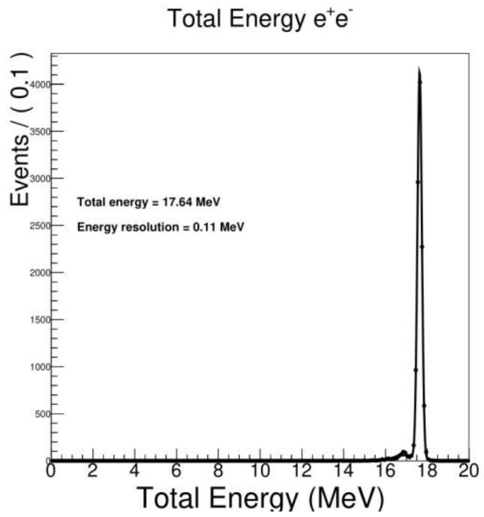
Excess with global significance of 2 σ

New Physics may exist at MeV- scale Observable via "$X \rightarrow e^+e^-$" using Melbourne Pelletron

We plan to build a Time Projection Chamber (TPC) and perform far higher precision experiments on the Pelletron

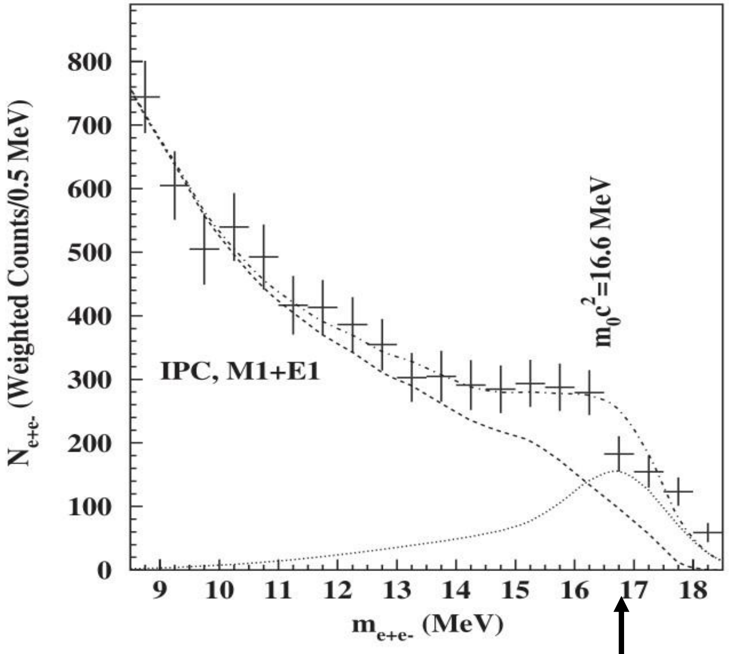


ATOMKI Energy Sum
resolution ~1.5 MeV



TPC Energy Sum
resolution 0.1 MeV

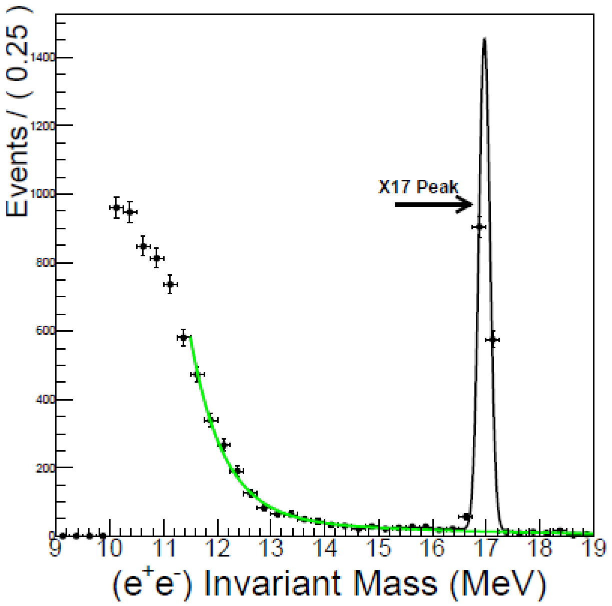
e^+e^- Invariant Mass



X17

ATOMKI X17 result
For p + ^{7}Li→^{8}Be + e$^+$e$^-$

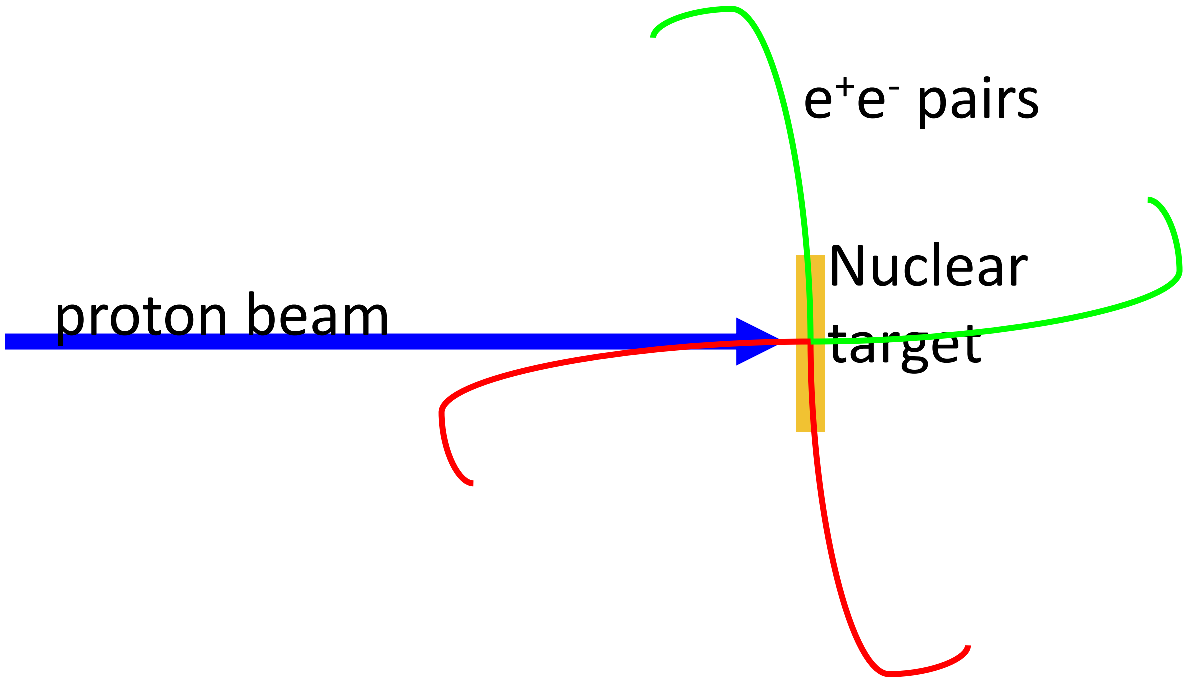
e^+e^- Invariant Mass

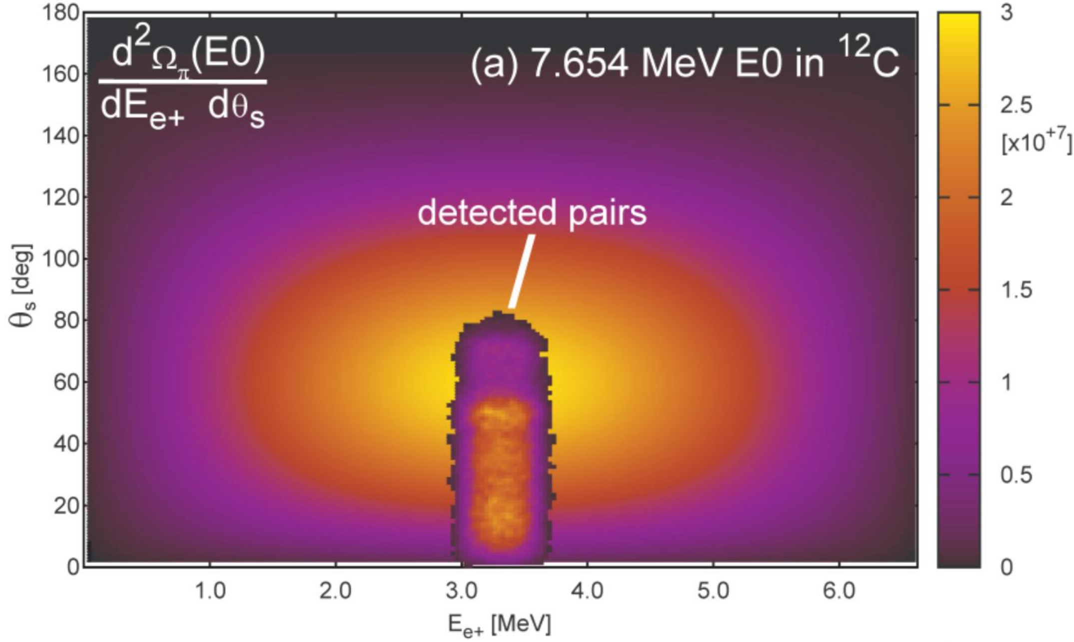


Our expectation from TPC
If the X17 exists

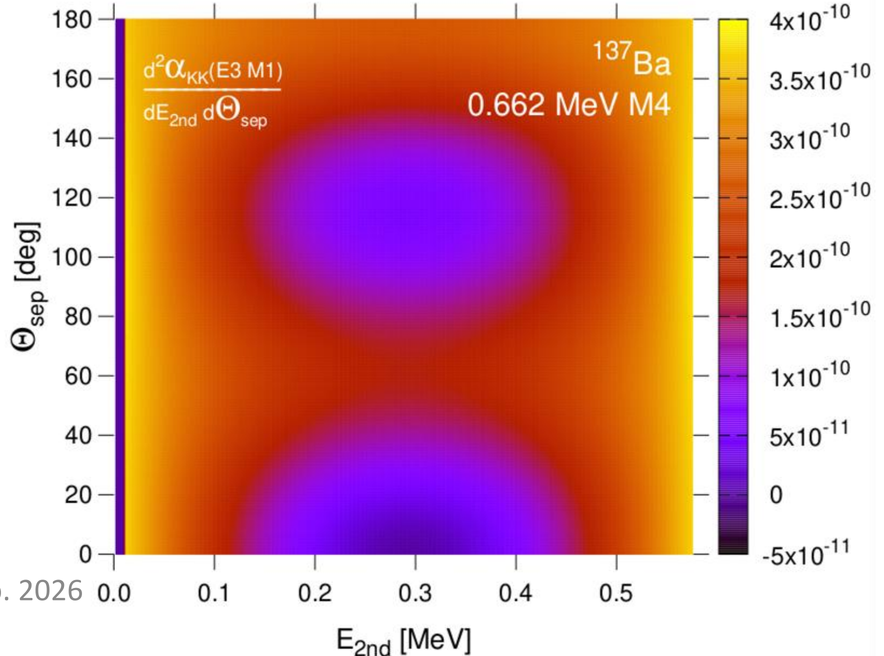
Applications in Nuclear Physics

World-first double-differential IPC cross-section measurements





Also, large acceptance enables investigation of multi-particle final states



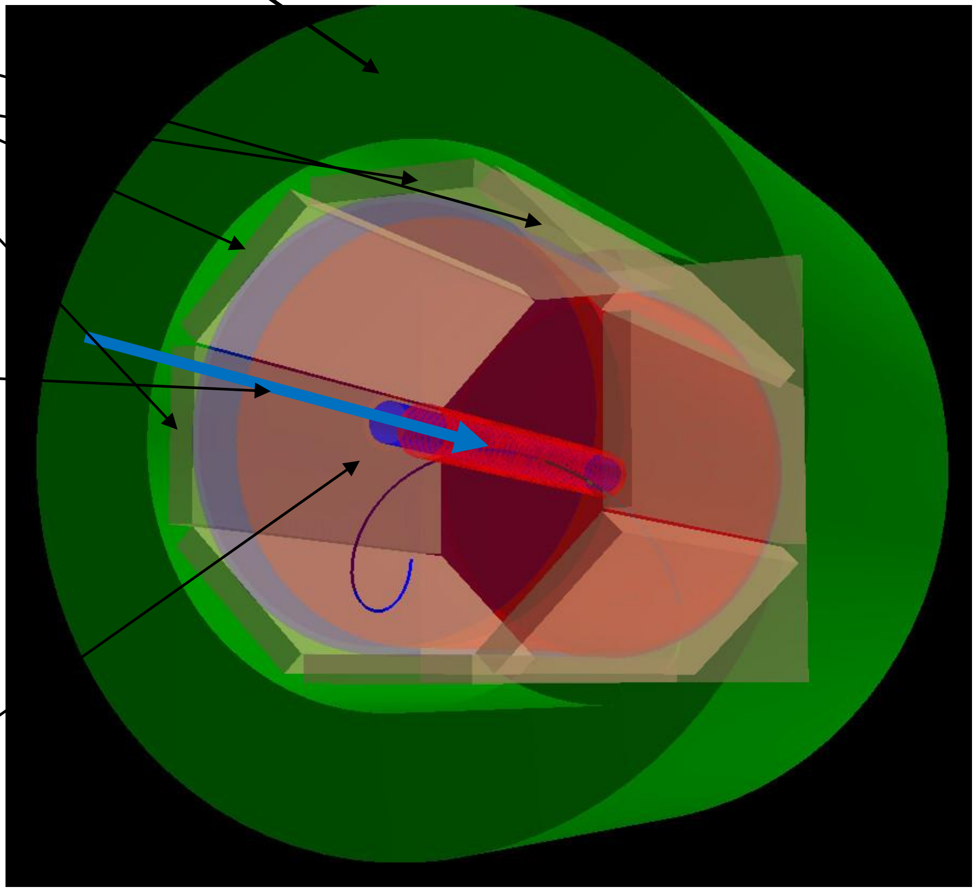
Unobserved 2-quantum nuclear processes[1]:

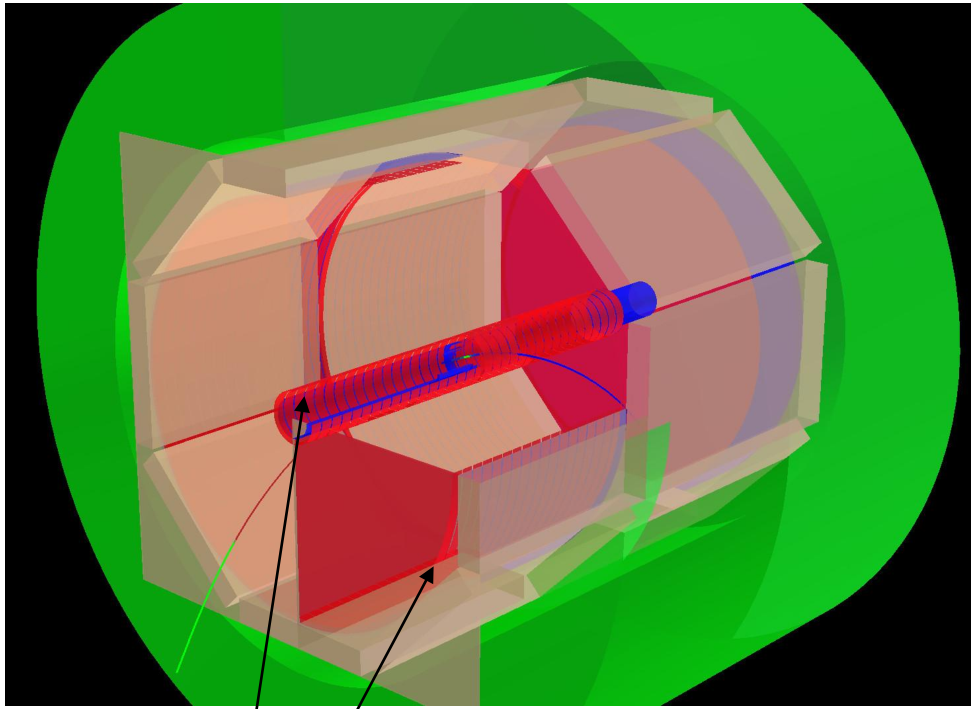
Double internal pair conversion (4th order EM process e.g. ^{137}Ba (K-K, K-L, L-L)

Both are qualitatively new Nuclear Physics investigations

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

BLIMP is a Time Projection Chamber





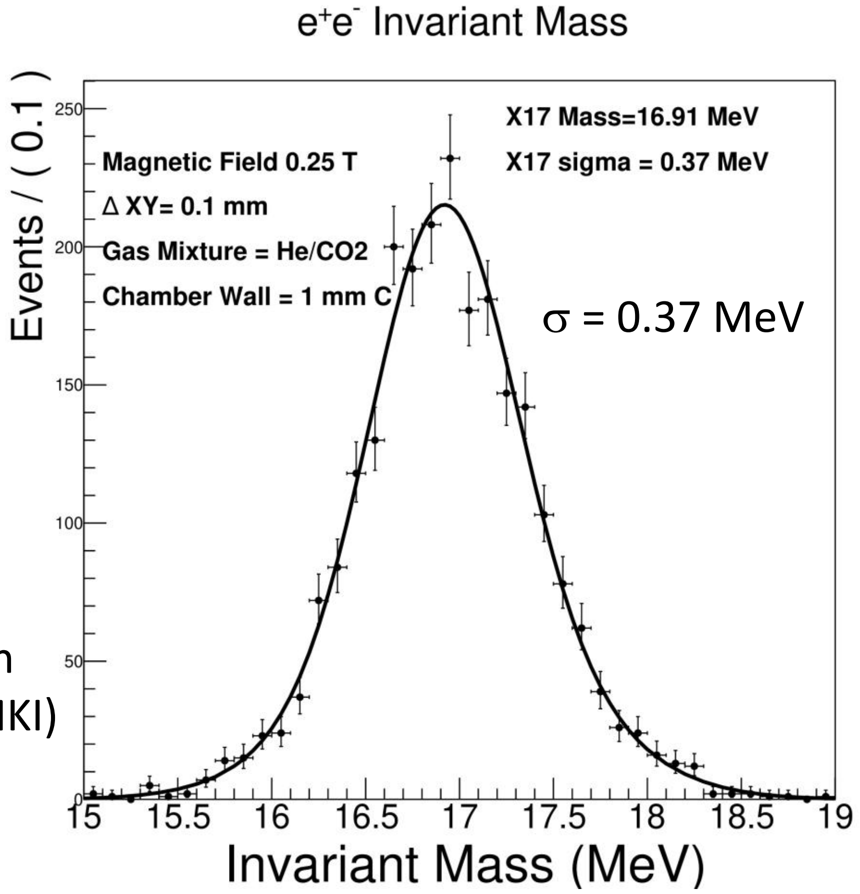
Design of BLIMP

- Conceptual design using EVE package in ROOT
- Simulate electric fields inside the TPC and micromegas with COMSOL
- Simulate Gas based detectors with HEP software GARFIELD
- Simulate passage of primary electrons through TPC with Geant4
- Record space-point hits with the expected resolution
- Employ Genfit2 to reconstruct Particle trajectories
- Employ RAVE to reconstruct interaction
- Employ ROOT EVE for event display and visually validate reconstruction
- Employ ROOT roofit to determine signal in the presence of background
- Development of TPC and MPGD expertise at Melbourne, Adelaide and ANU

Geant4 + Genfit2 + RAVE

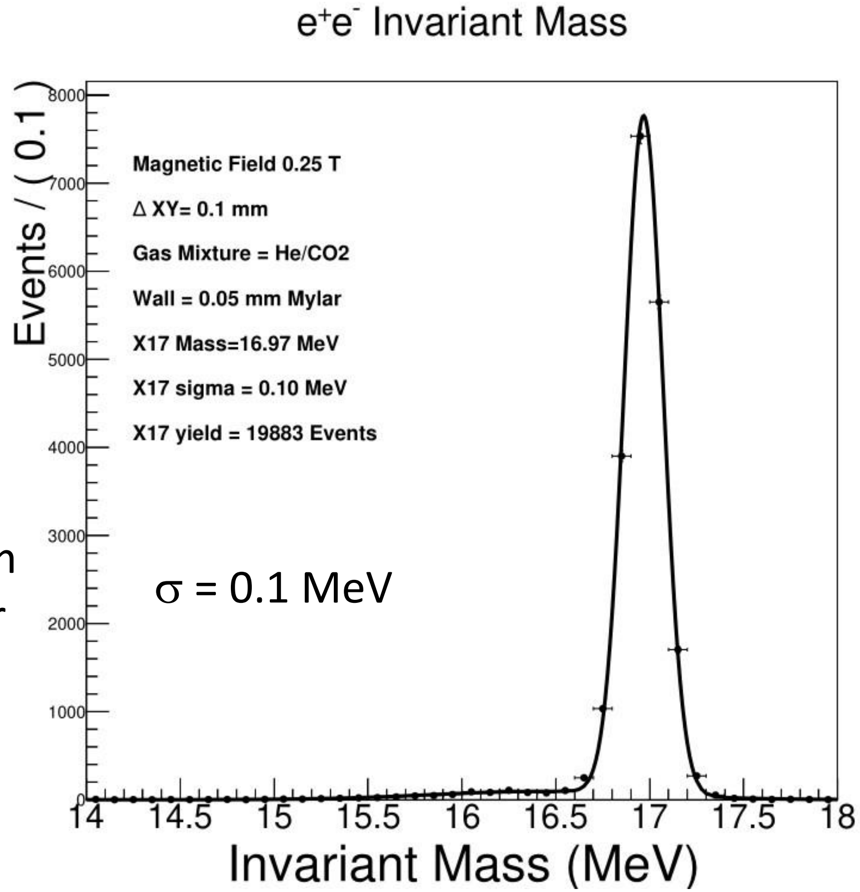
- Made numerous simulations.
- Assumed single-electron identification and 100 µm resolution in x-y, 1 mm in z
- Gas 90:10 He / CO_2 + thin Target chamber => very good invariant mass resolution

1 mm
Carbon
(ATOMKI)



Thin-walled Target
Chamber is key

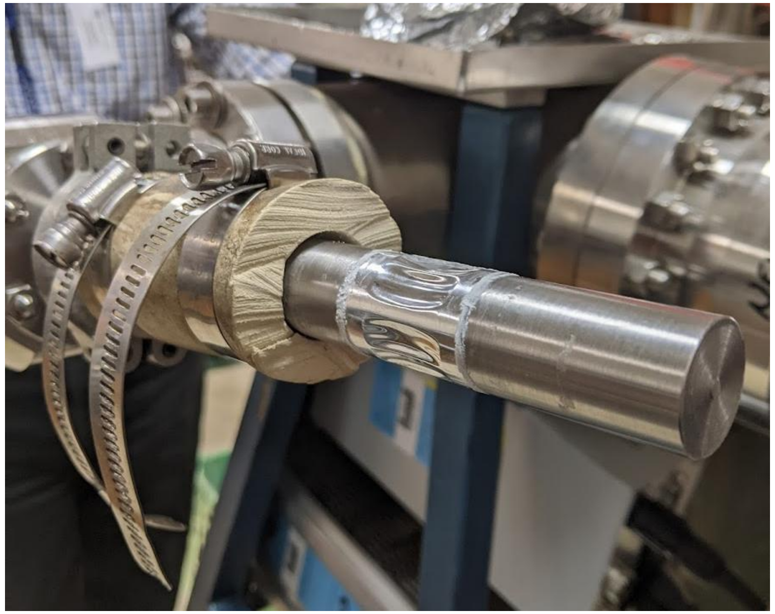
50 µm
Mylar

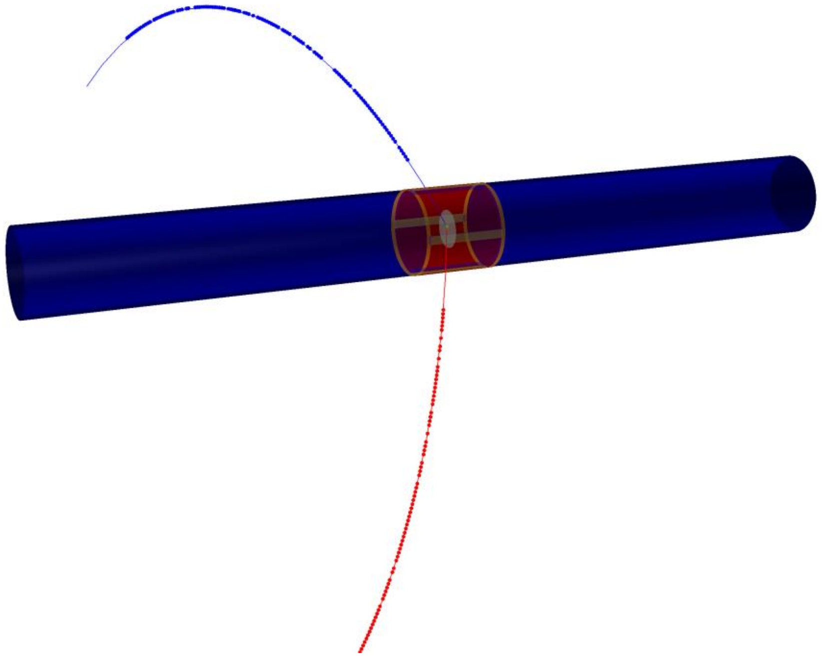


Prototype BLIMP Target Chamber

Best Invariant Mass Resolution requires very thin vacuum wall

Shear strength of Mylar foil (15 kg/mm^2) implies 50 micron thick foil has a factor of 20 safety under vacuum



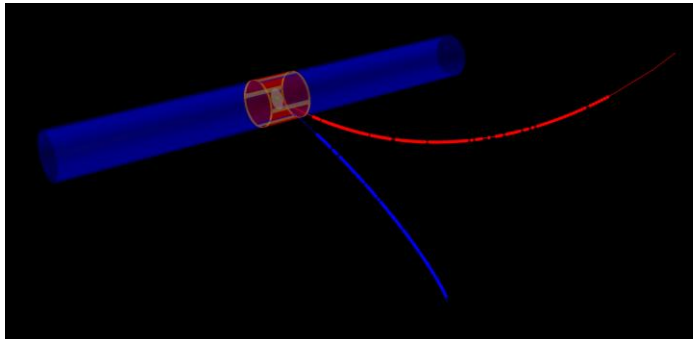


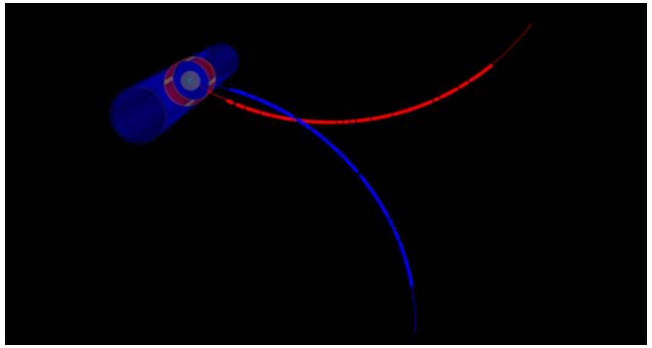
Internal Conversion Background (IPC)

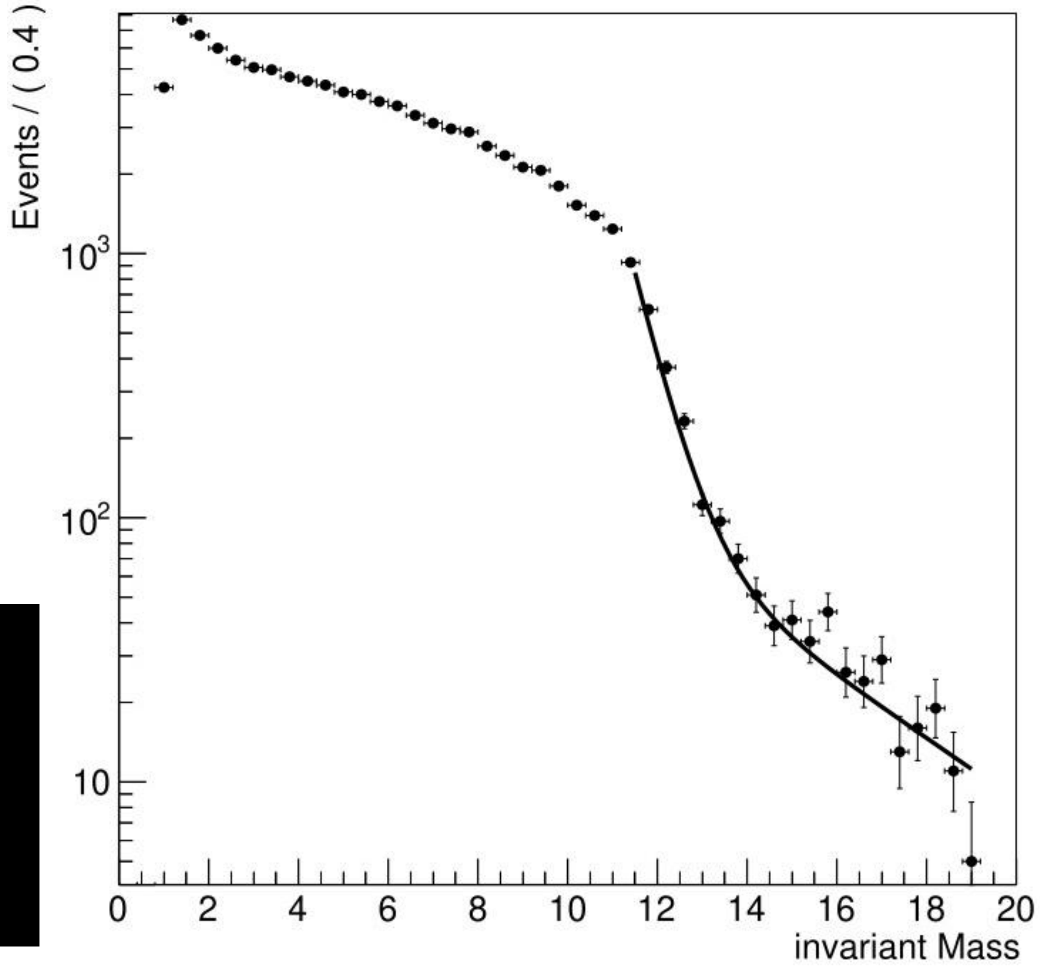
Irreducible background comes from Nuclear Internal Conversion

$$^8_4Be^* \rightarrow {}^8_4Be + \gamma^* \rightarrow e^+e^-$$

- Peaks at low invariant mass
- Simulated with Born-approximation
- Full GEANT4 Simulation + genfit2 + RAVE reconstruction with realistic TPC hits (~130)

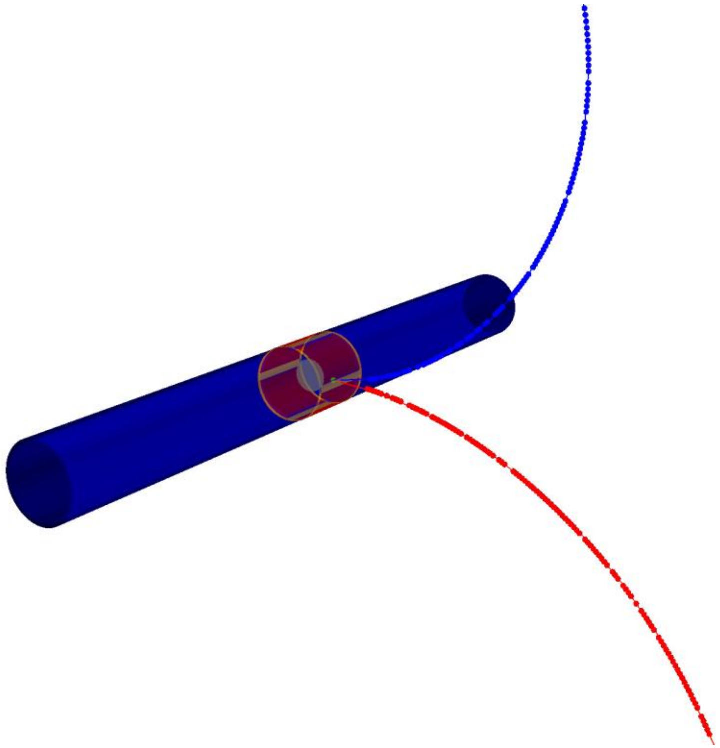




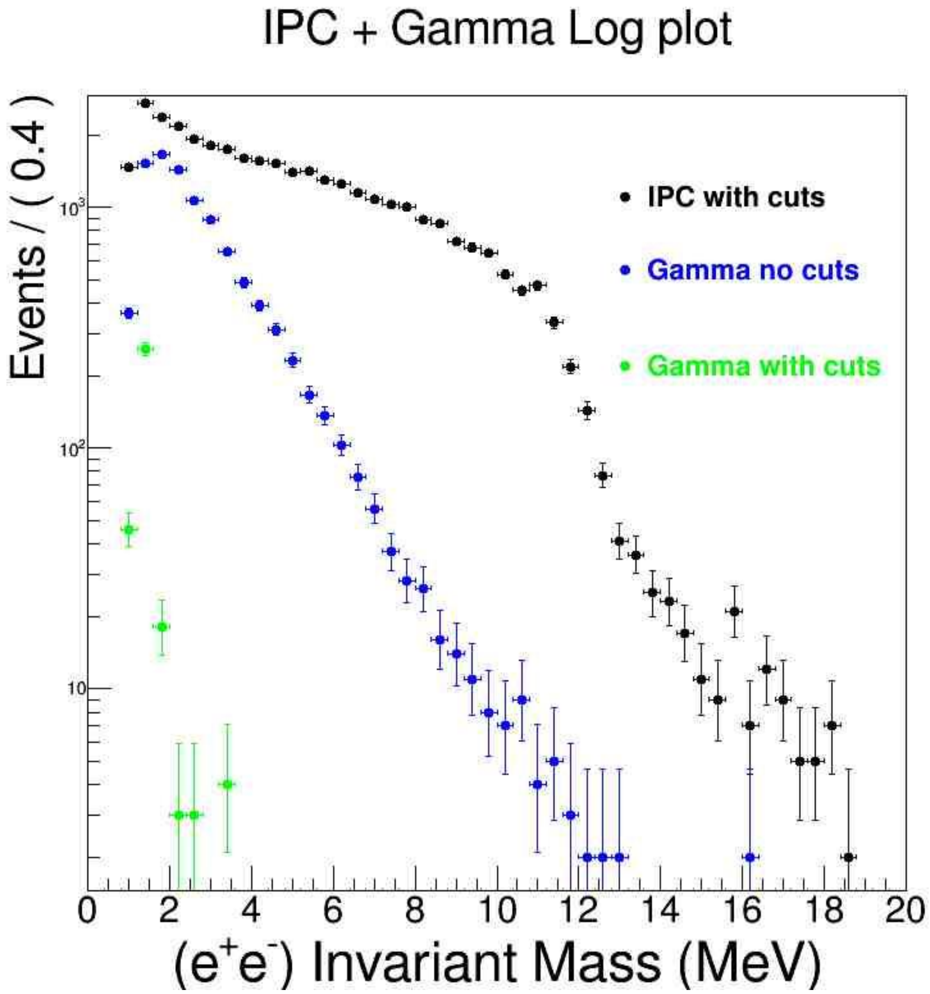


Black line is an ansatz fit

External Gamma conversion

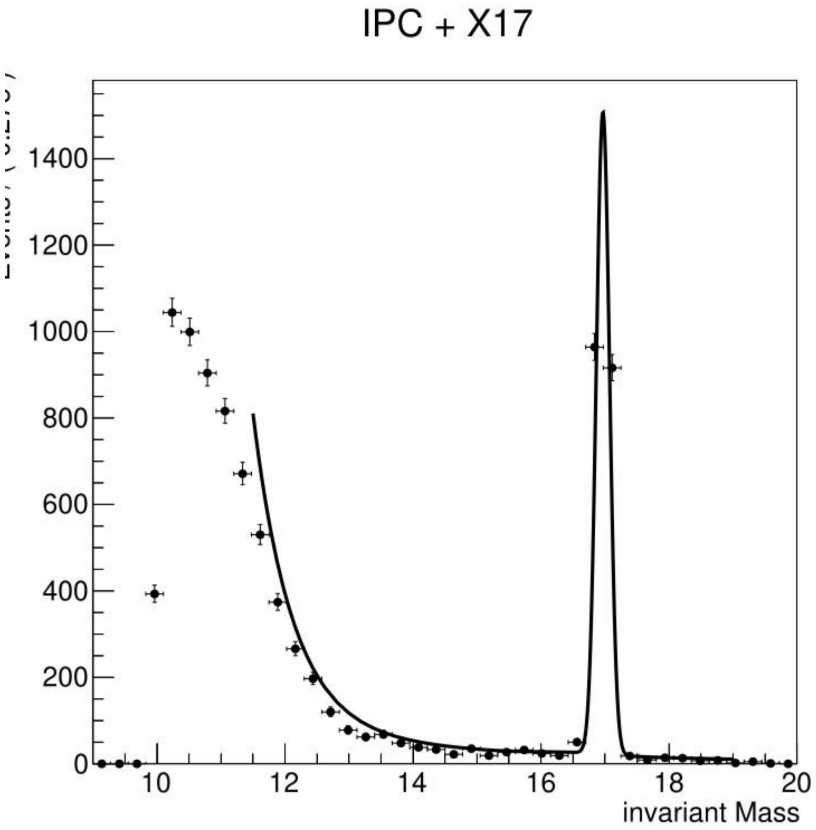


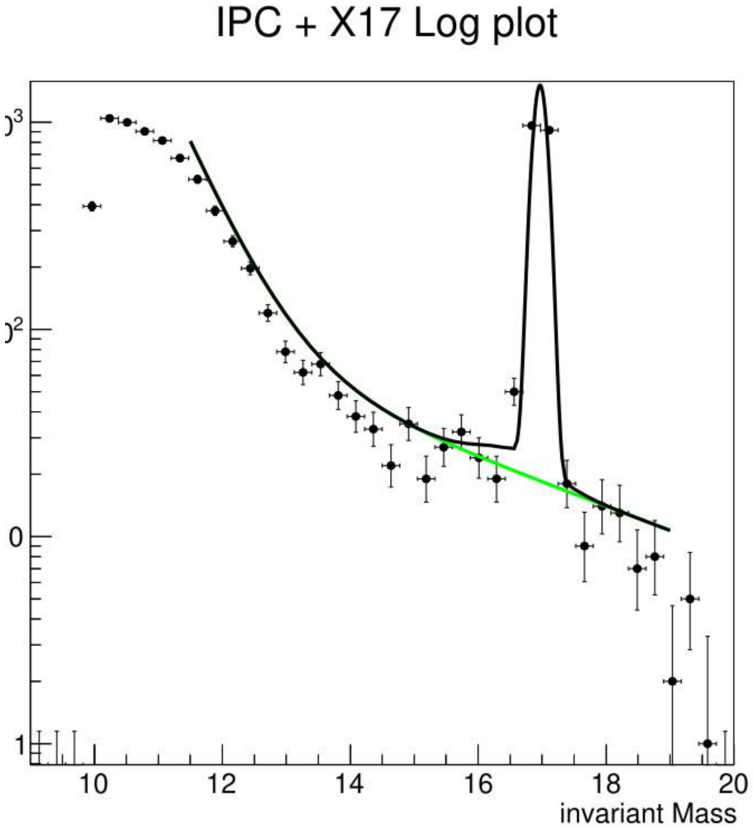
- Large flux of 18 MeV γ's from $p + {}^{7}Li \rightarrow {}^{8}Be + \gamma$
- These can externally convert via $\gamma \rightarrow e^{+}e^{-}$ in material
- Simulated 10^{8} of these
- Low mass near the target limits conversions to 0.01%
- Vertex constraint removes > 99%
- Background is negligible compared to IPC



X17 + IPC background

- Full simulation and reconstruction of IPC+X17 with 50 µm Mylar vacuum wall
- 4 Day run on Pelletron. 1µA proton beam, 10^{19} /cm^{2} ^{7}Li target
- Quantify sensitivity as a function of BR relative to $p + {}^{7}Li \rightarrow {}^{8}Be + \gamma$
- ATOMKI found X17 with BR ~6×10^{-6} (p, γ) at 6 σ



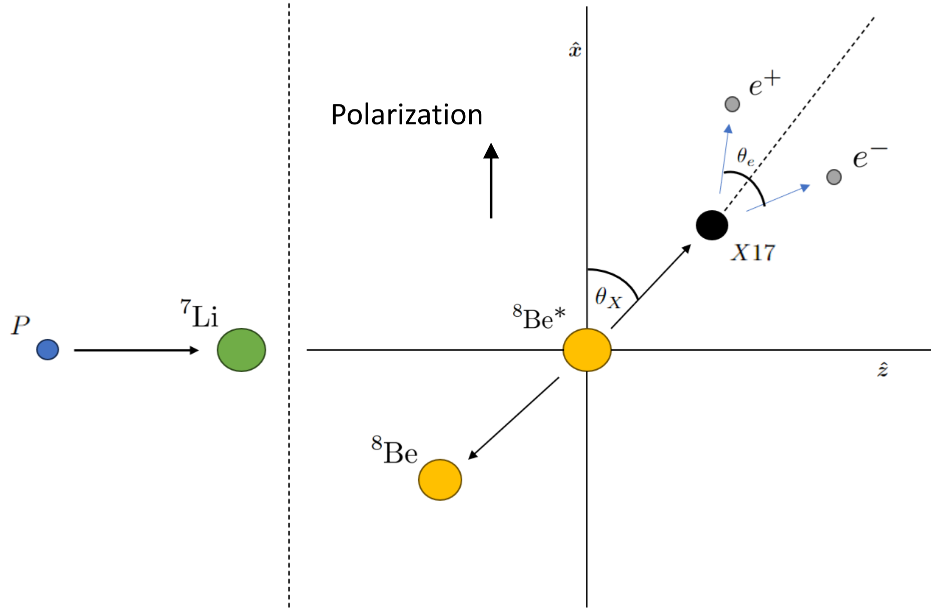


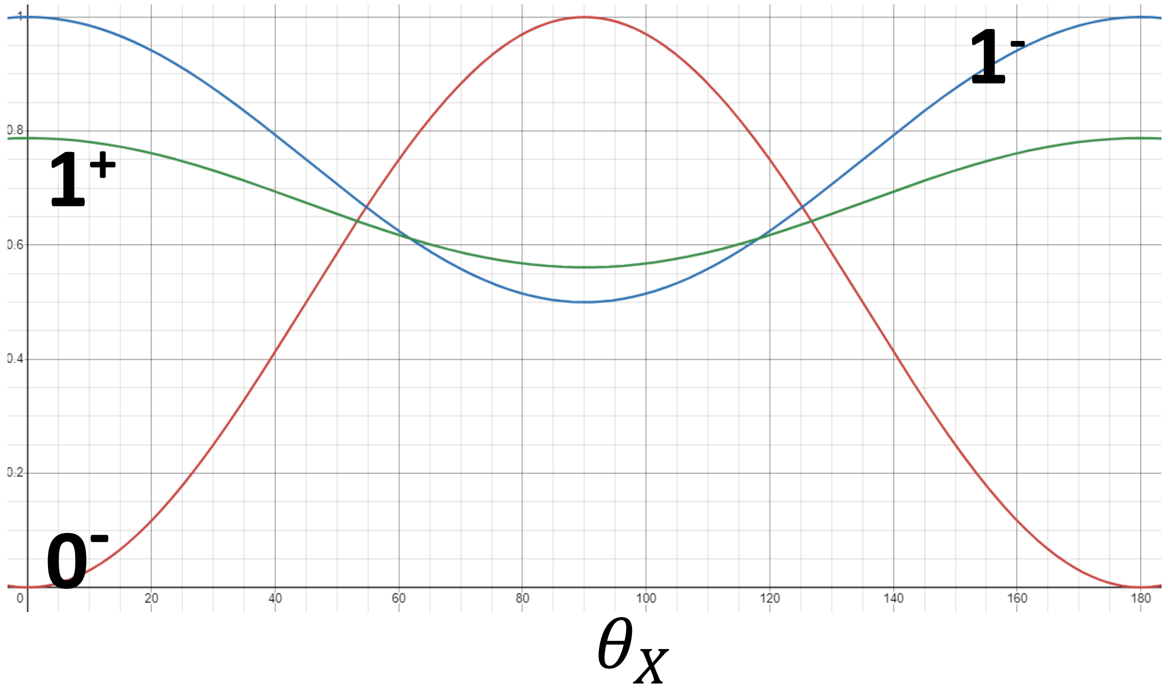
X17 BR= 6×10^{-6} (p, γ)
1908 +- 45 events
42 σ significance

Spin and Parity of X17

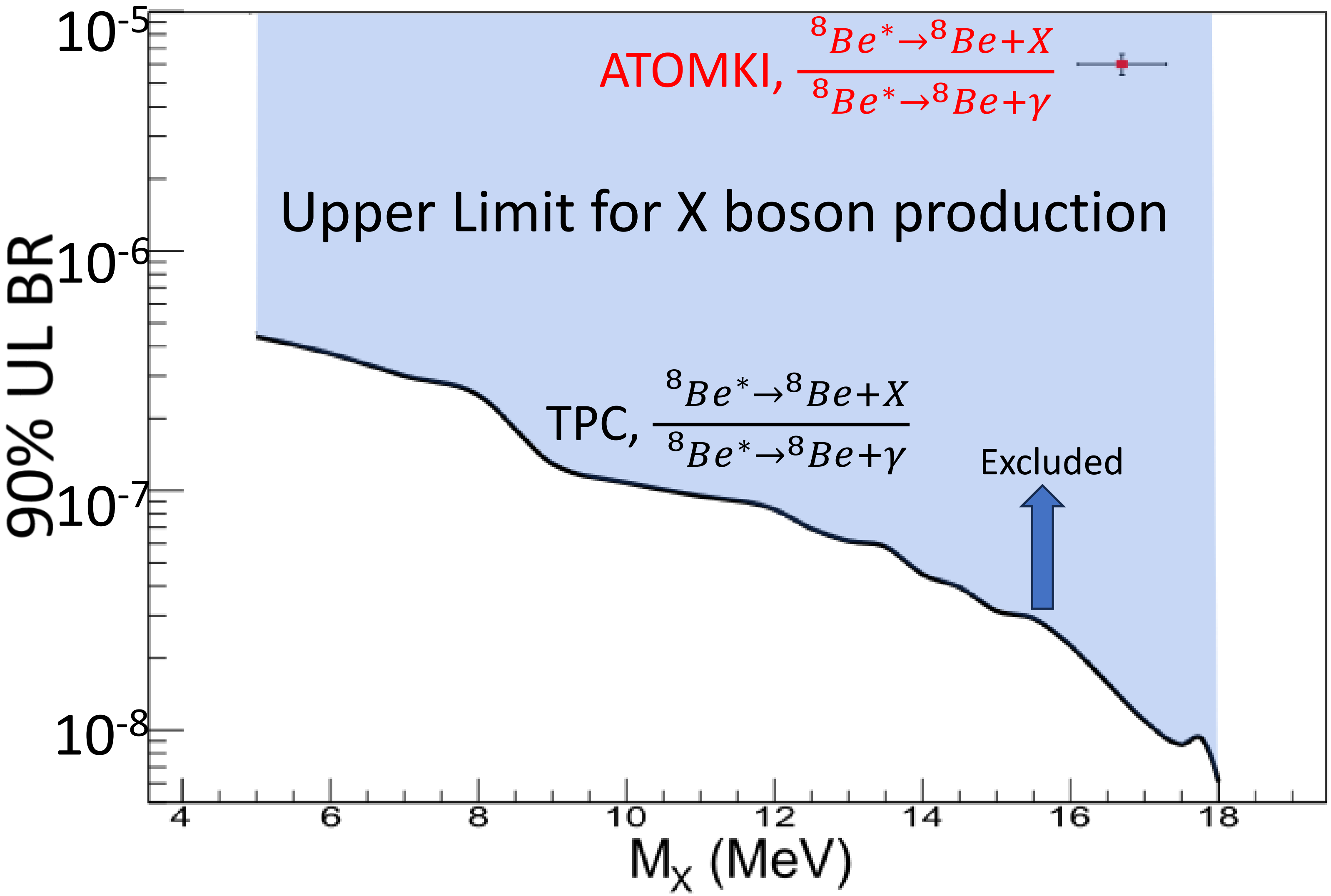
Should we find the X17, we can also determine its spin and parity via an angular analysis

J^P (X17)	Angular Distribution
0^-	$sin^2(\theta_X)$
1^-	$1 + cos^2(\theta_X)$
1^+	$8\ \alpha^2 + 4\sqrt{2}\alpha\beta(3\cos^2(\theta_X) - 1) + \beta^2(7 - 3\cos(2\theta_X))$





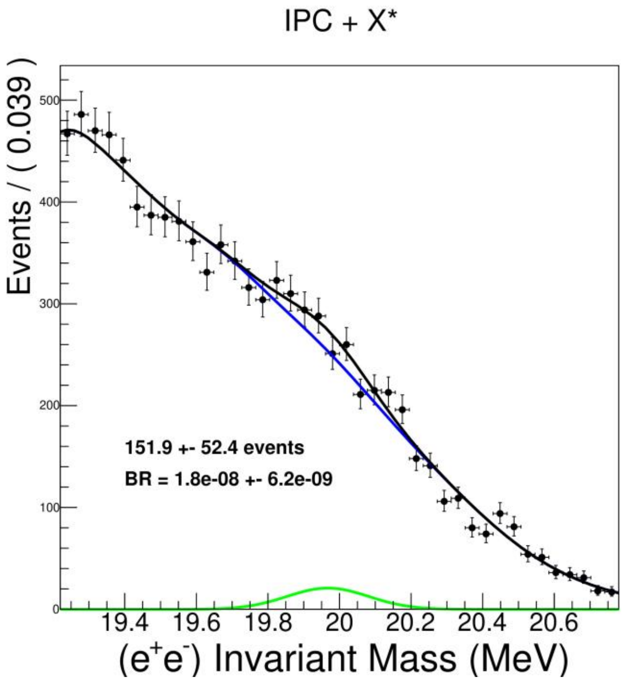
X17 Upper limit from BLIMP

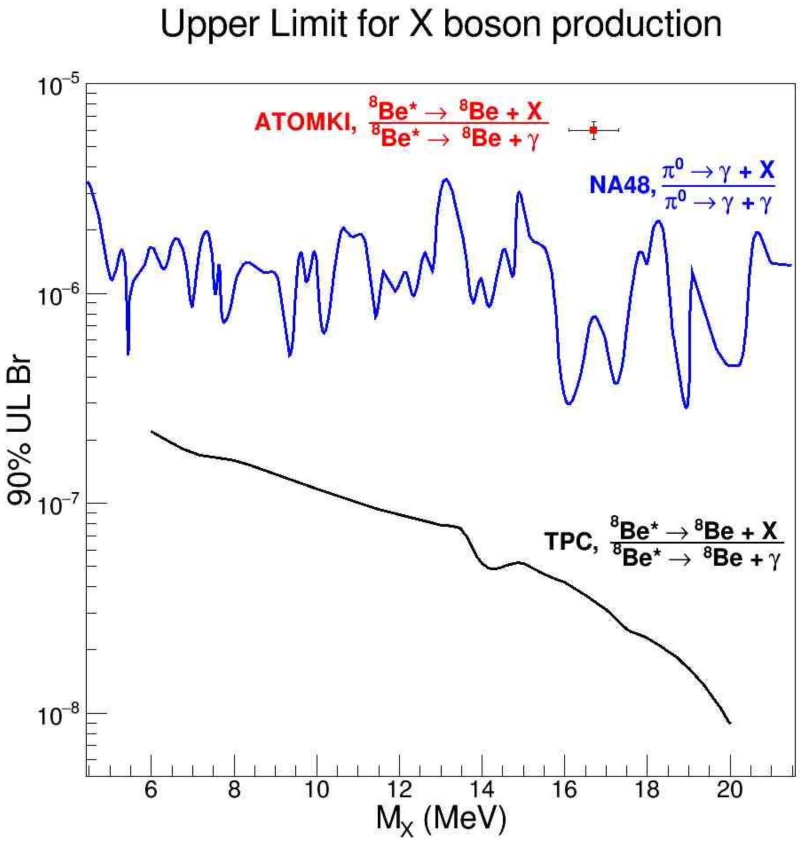


Exclude X17 by over 2 orders of magnitude!

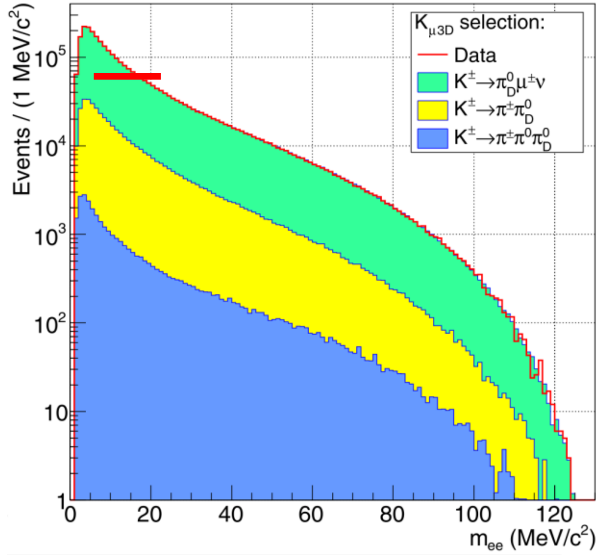
No X17 signal => Can run at 4.5 MeV, Beam $2\mu A$, Target $2\times10^{20}\ Li\ cm^{-2}$, 30 - day run =>$2\times10^{11}\ \gamma$'s (NA48 had $1.4\times10^{9}\ \pi^{0}$ data sample) Bump-hunt in Invariant-mass spectrum

World-best exclusion for prompt, weakly coupled bosons in 5 - 22 MeV range





90% Upper limits on BR($\frac{^8Be^*\to Be+X(e^+e^-)}{^8Be^*\to Be+\gamma}$)



NA48 - Huge background at 5- 22 MeV

IPC Background peaks at 1.1 MeV

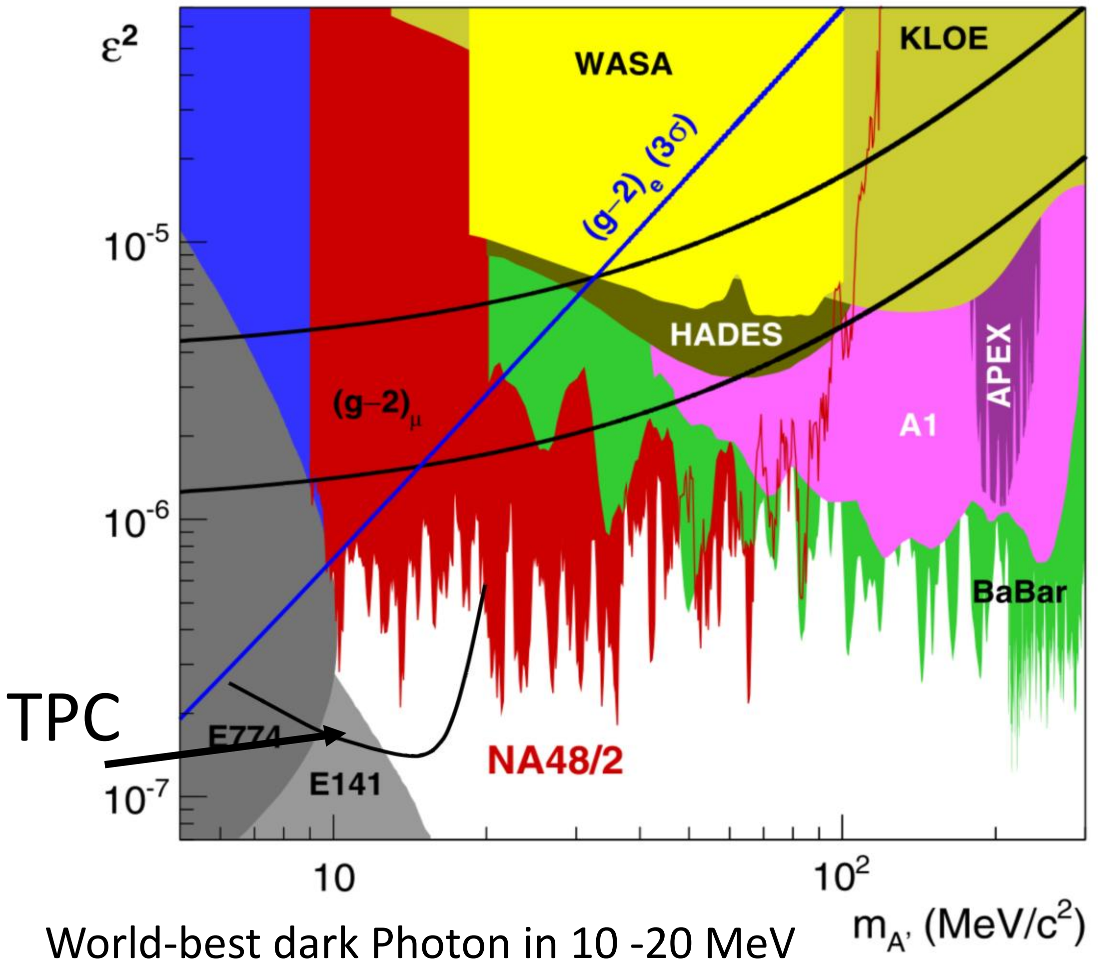
Choose reaction for optimized X mass range

Reaction	Q-value	Mass Range for search
$p+{}^{7}\mathrm{Li}\to{}^{8}\mathrm{Be}+(e^+e^-)$	17.2	15 - 20 MeV
$p+{}^{3}\mathrm{H}\to{}^{4}\mathrm{He}+(e^+e^-)$	19.8	17 - 22 MeV
$p+{}^{27}\mathrm{Al}\to{}^{28}\mathrm{Si}+(e^+e^-)$	11.6	9 - 15 MeV
$p+{}^{25}\mathrm{Mg}\to{}^{26}\mathrm{Al}+(e^+e^-)$	5.2	5 - 10 MeV
$p+{}^{12}\mathrm{C}\to{}^{13}\mathrm{N}+(e^+e^-)$	1.9	3 - 5.5 MeV

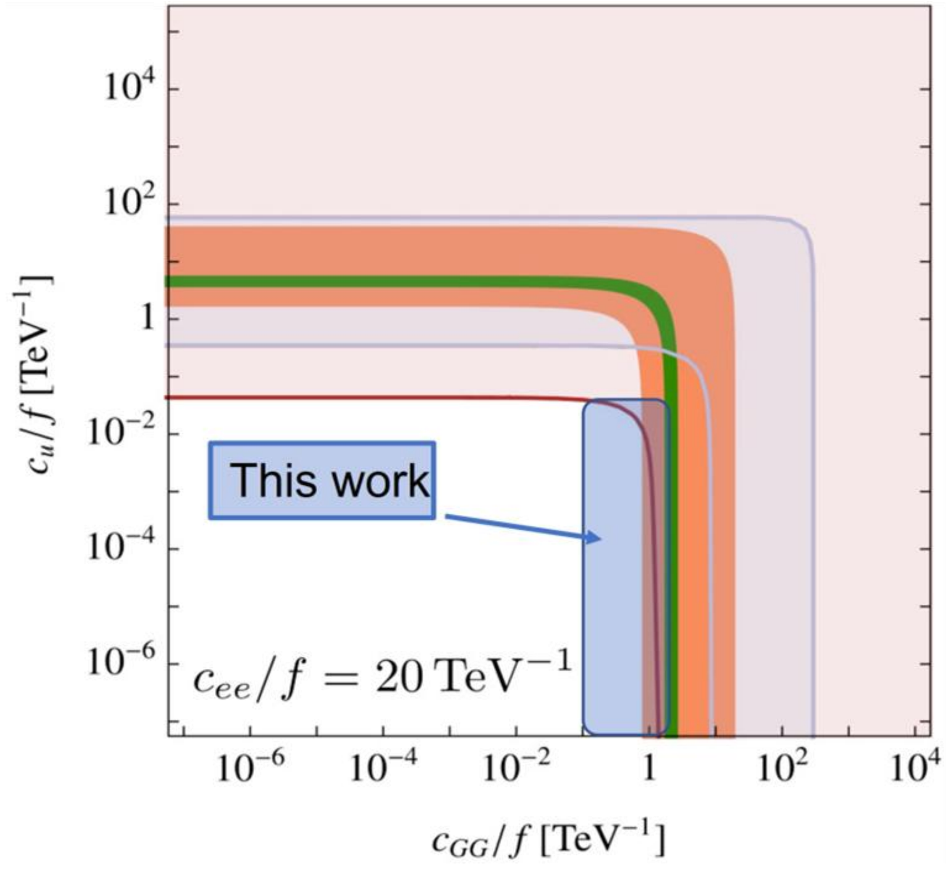
Dark Photon and ALP limits from BR($\frac{{}^8Be^* \to Be + X(e^+e^-)}{{}^8Be^* \to Be + \gamma}$)

Feng et al. (PRL 117, 071803 (2016))

$$\frac{{}^8Be^* \to Be + X(e^+e^-)}{{}^8Be^* \to Be + \ \gamma} = \varepsilon^2 \frac{P_X^3}{P_\gamma^3}$$



World-best dark Photon in 10 -20 MeV

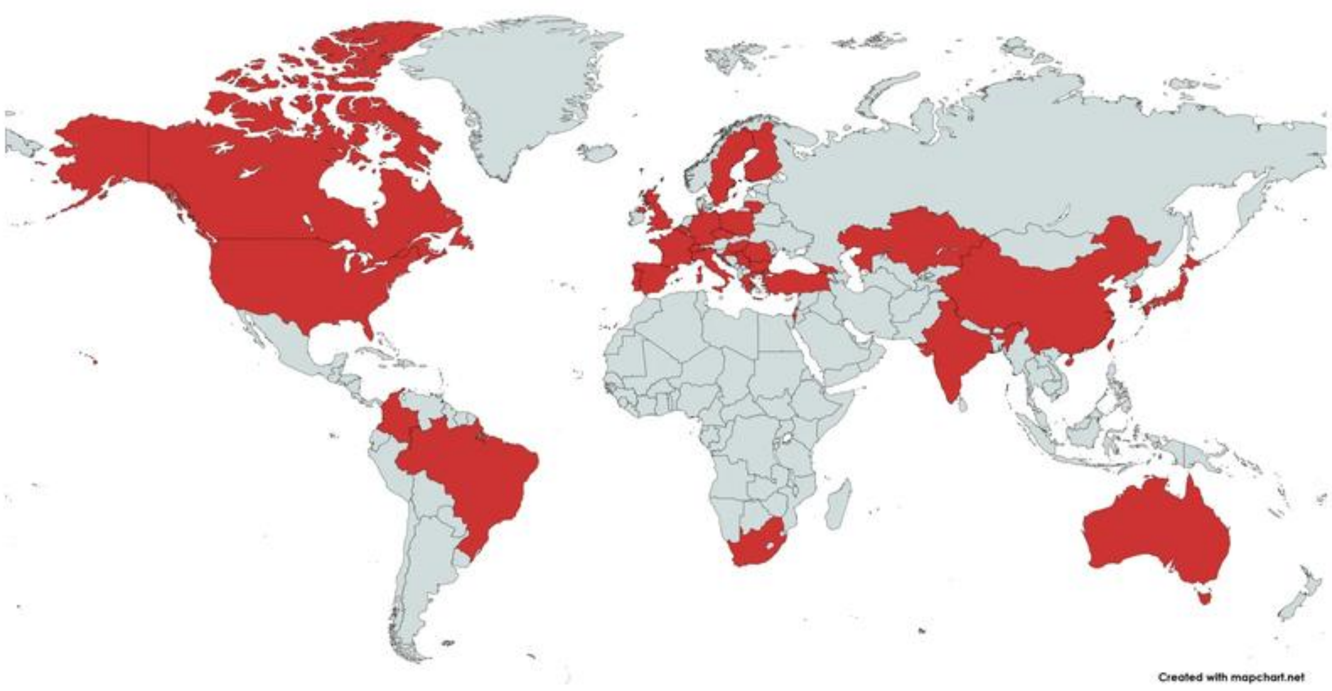


World-best ALP limit in this range
(Probing Multi-TeV scale on the Pelletron)

Instrumentation Experience

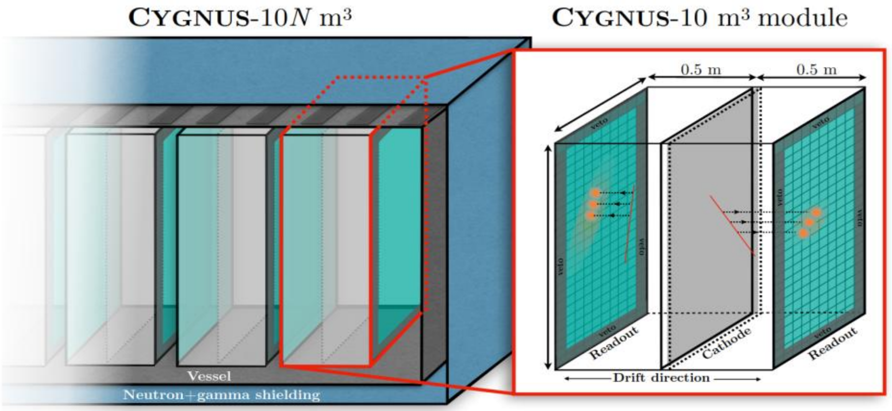
- MicroPattern Gas Detector and TPC detector development at ANU, Adelaide and Melbourne
- All three are members of DRD1 Collaboration (based in CERN)

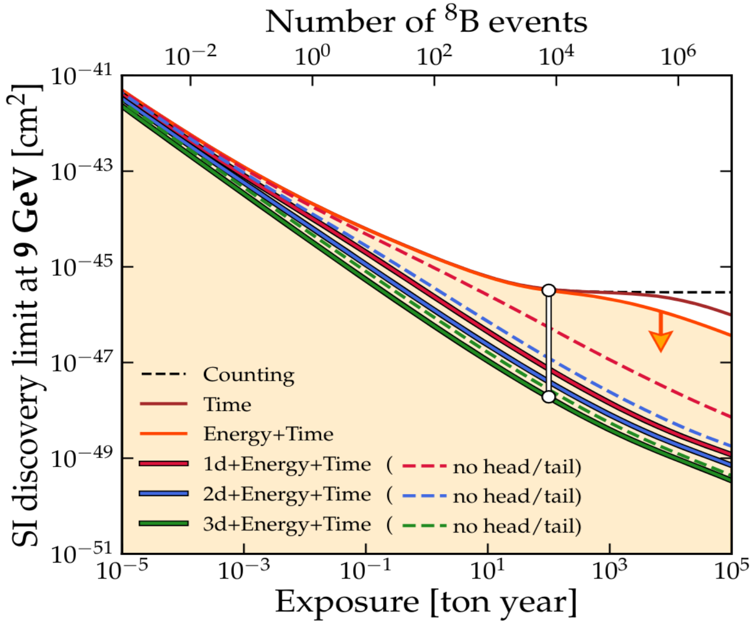
Development of Gaseous Detectors Technologies



Adelaide and ANU in Cygnus

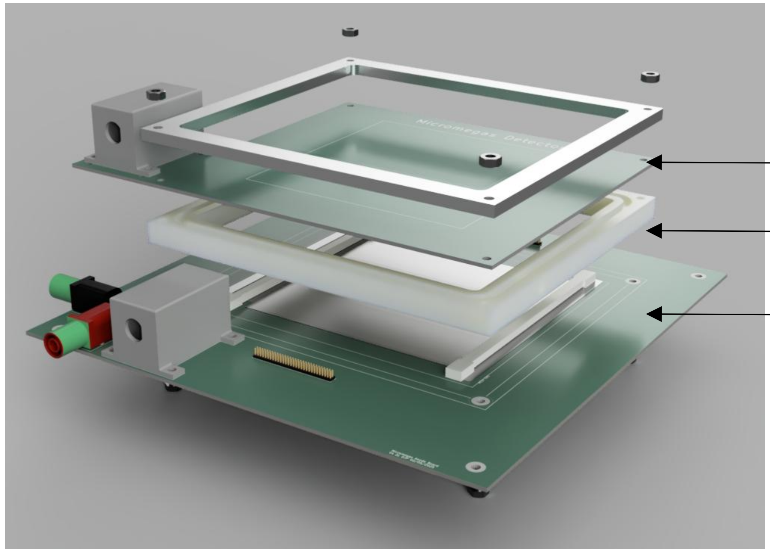
DM Discovery in the Neutrino "Fog"





Melbourne (N. Jackson, C. Rush, A. Babic M.Sc.)

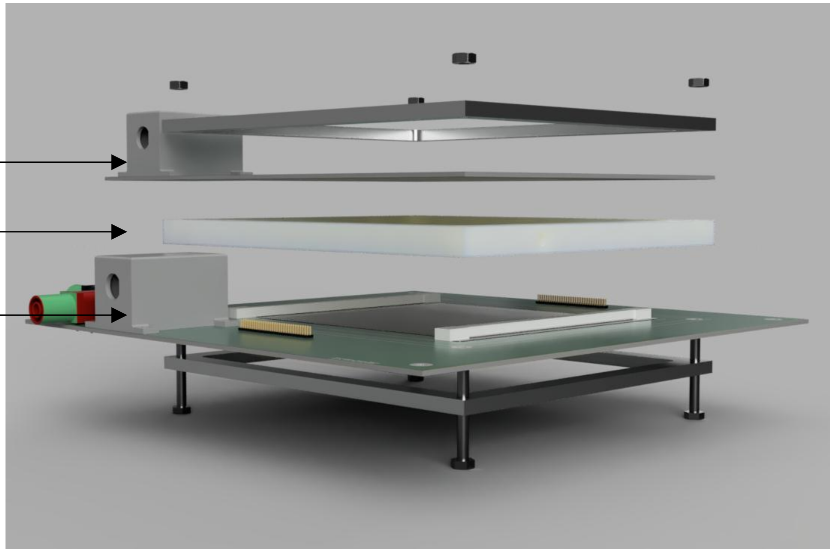
- Local Micromegas Design

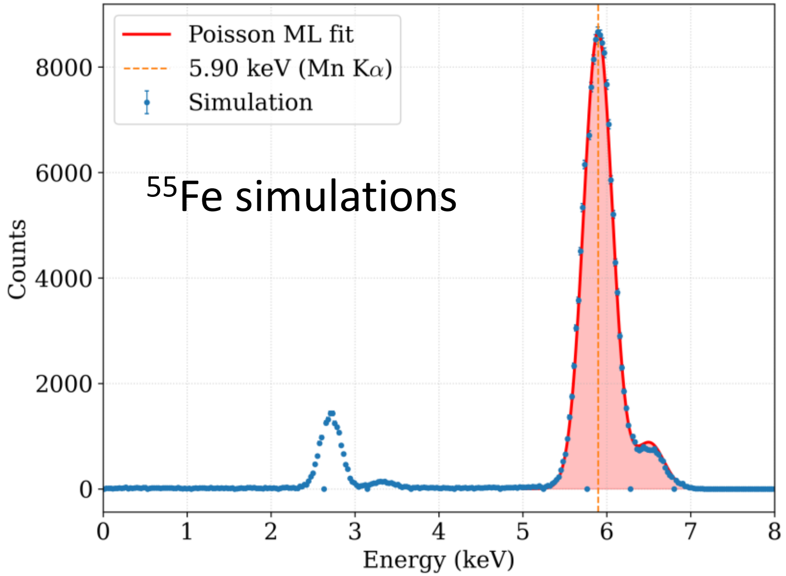


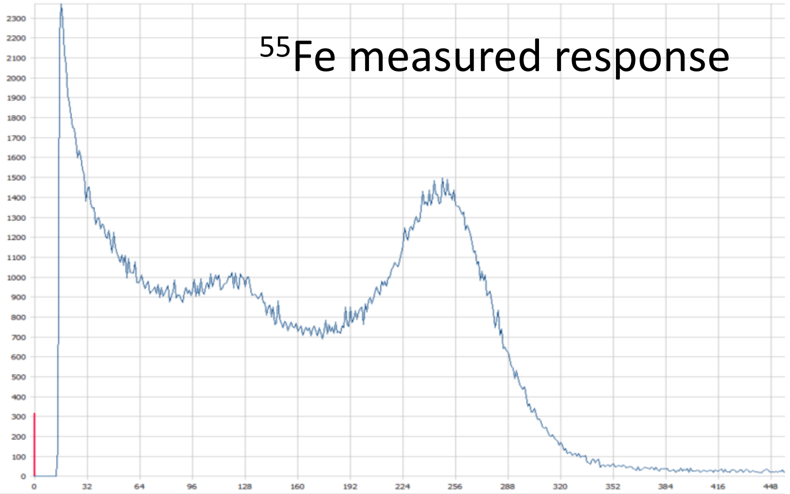
Cathode

Gas Spacer

Anode

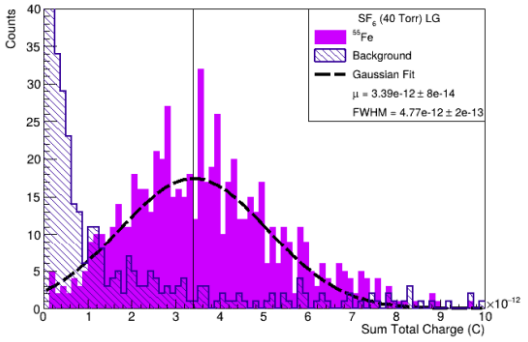


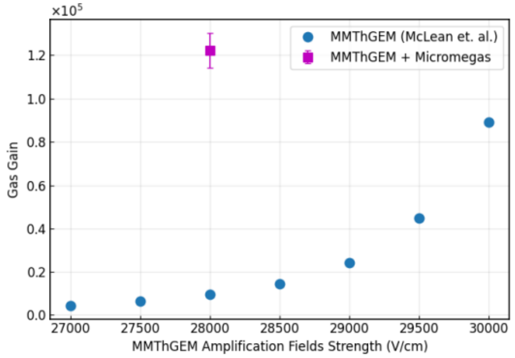


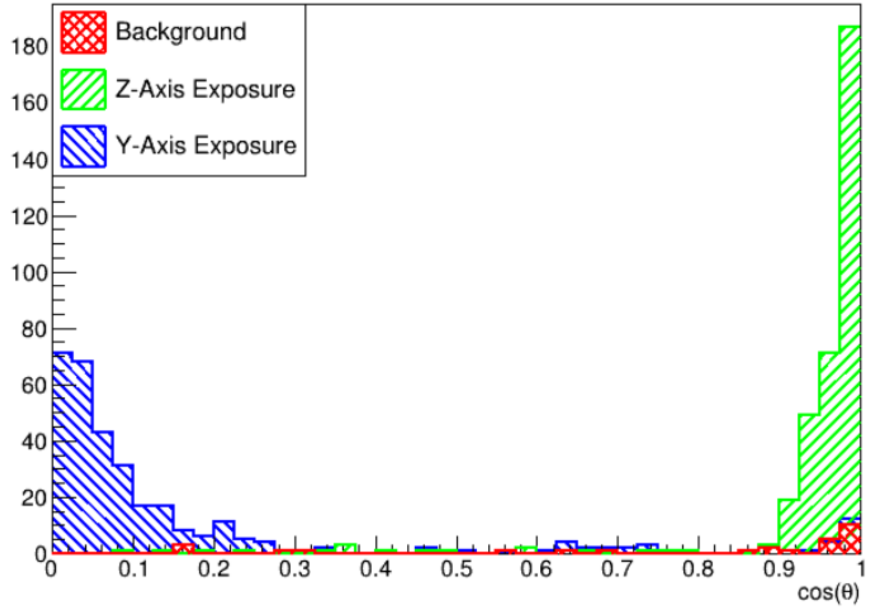


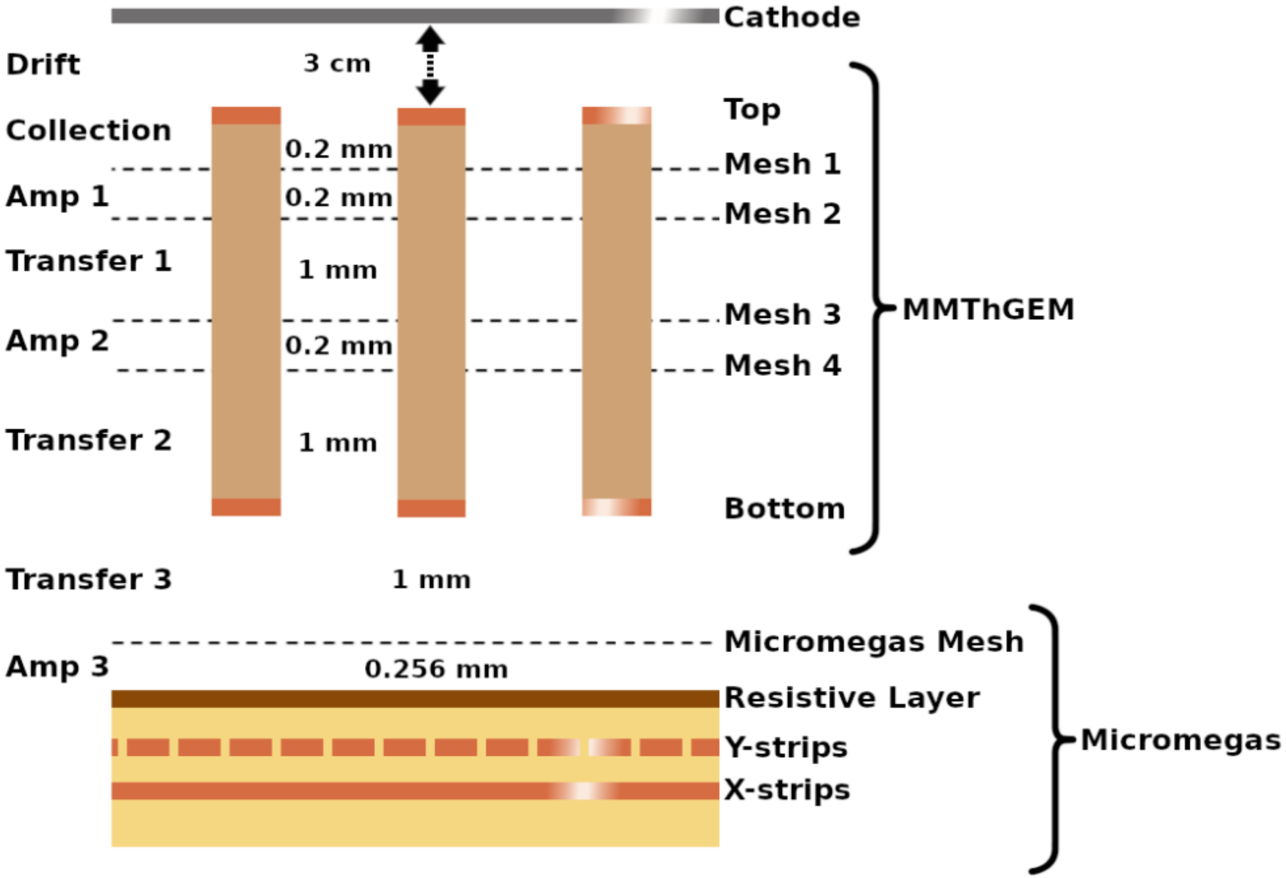
Adelaide

- Multi-stage Gas Gain for negative Ion detection (Directional DM)
- Capability for single-electron sensitivity







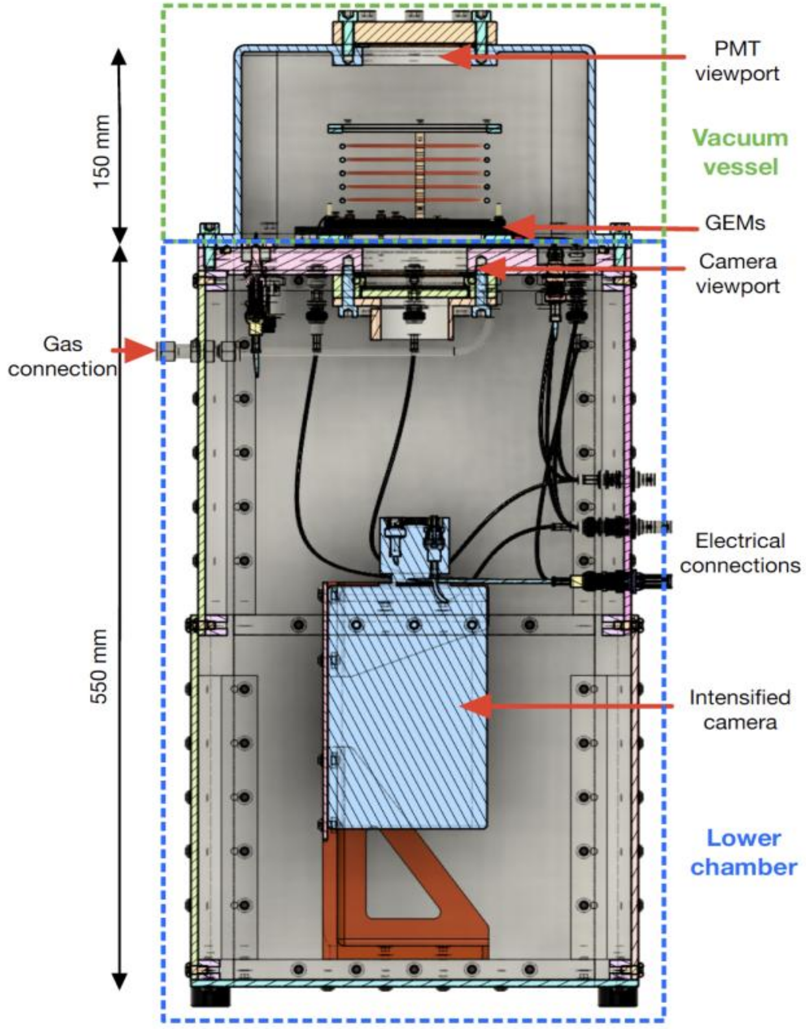


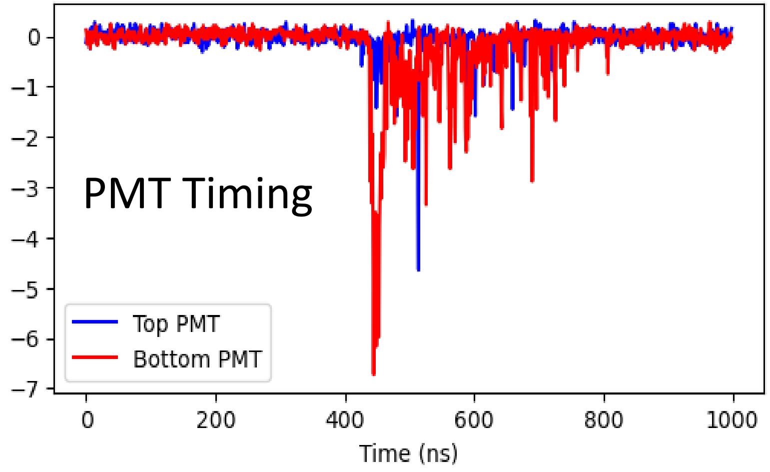
A.G. McLean *et al* 2026 *JINST* **21** P07047

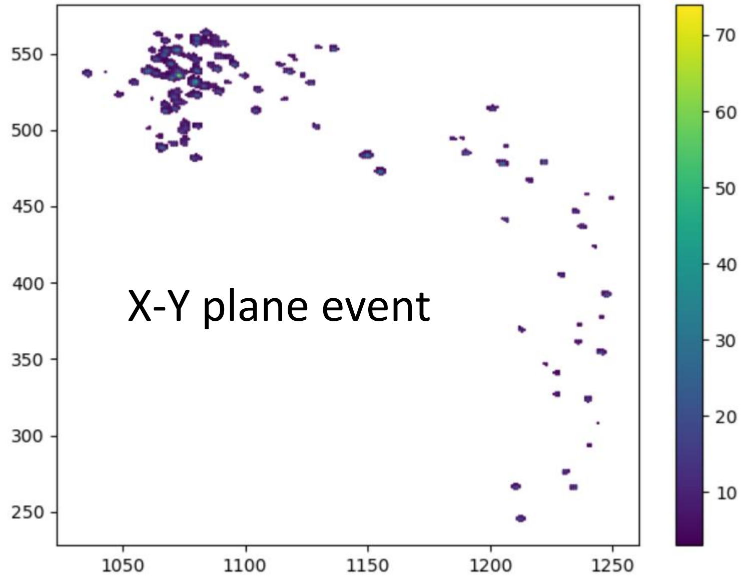
ANU

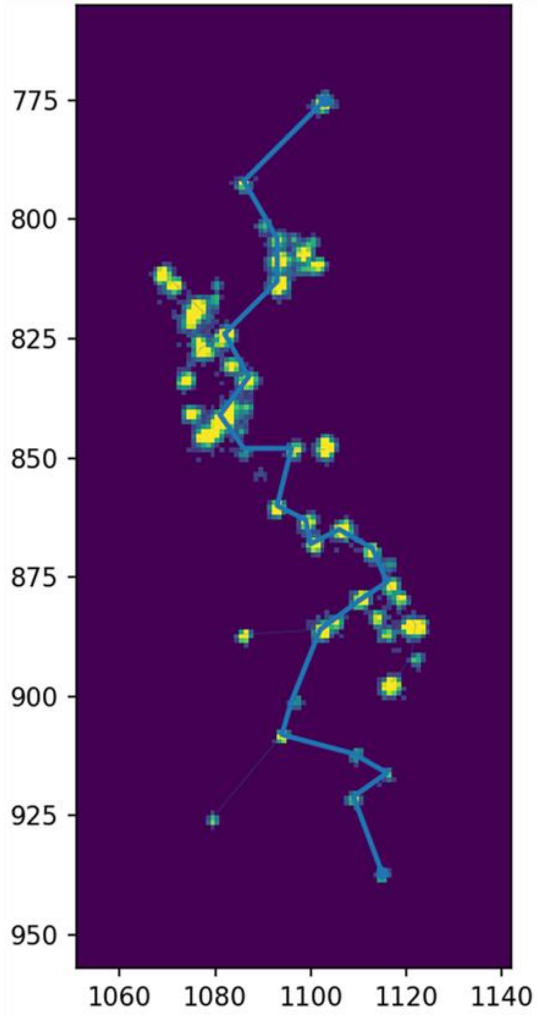
^{241}Am Source

- Optical Readout of TPC









X-Z plane Event

Conclusions

- BLIMP can exclude the X17 with > 2 orders of magnitude in an identical nuclear system
- Unique facility – world-leading probe of dark photon/ALP physics, PEP violations. Others?
- Significant first measurements for fundamental Nuclear Physics
- Significant Instrumentation effort to support BLIMP

- ARC LIEF 2027 bid in place….

- New collaborators welcome!

- More details in our arxiv paper: https://arxiv.org/abs/2302.13281

Backup

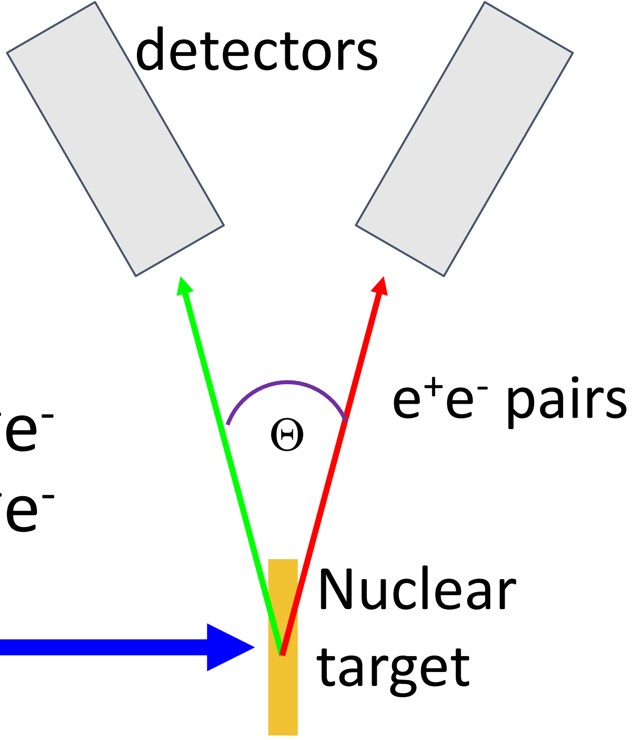
X17 particle

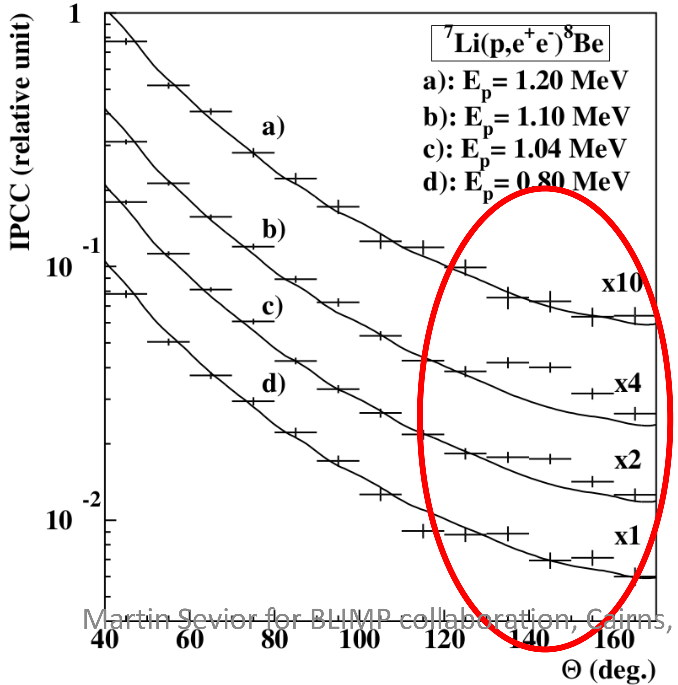
2016 observation[1]

p + ^{7}Li→^{8}Be + $e^{+}e^{-}$

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

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





1: arxiv 1504.01527 (PRL **116**, 04215, (2016))

X17 particle

2016 observation[1]
p + ^{7}Li→^{8}Be + e$^+$e$^-$

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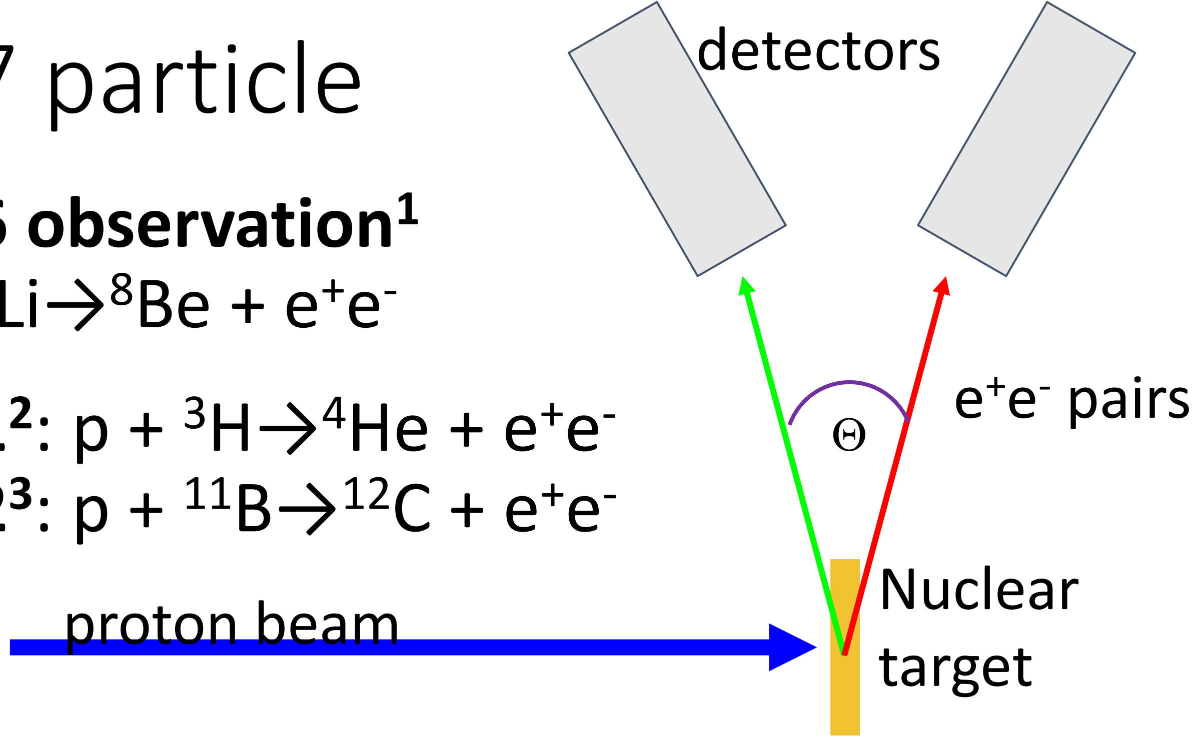
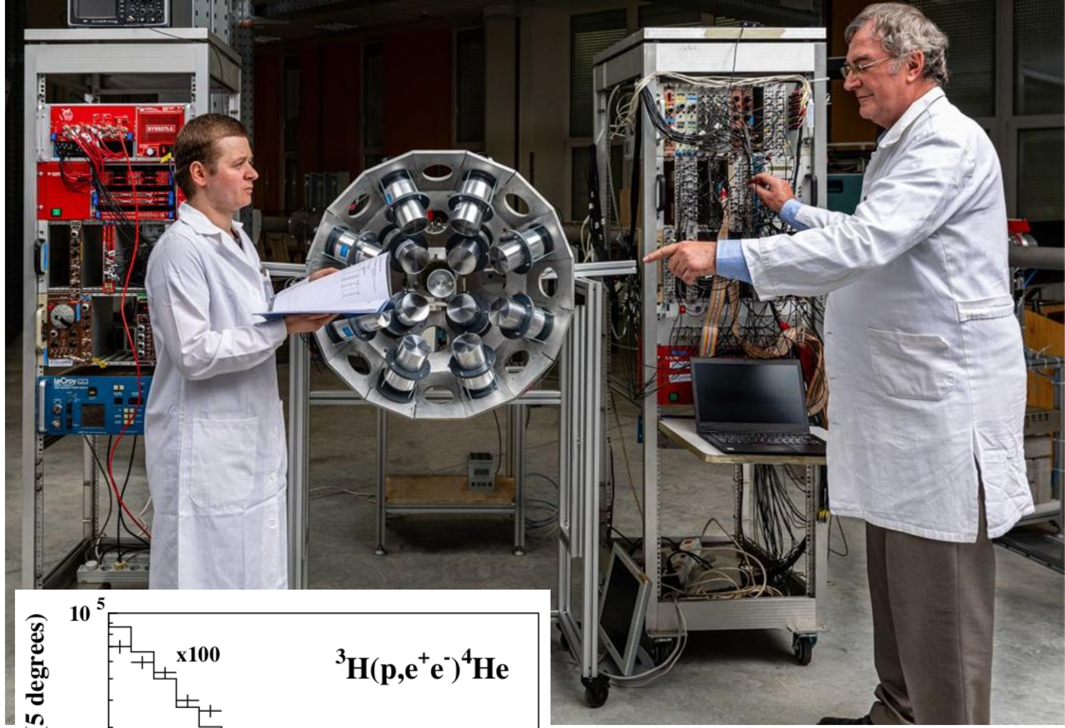
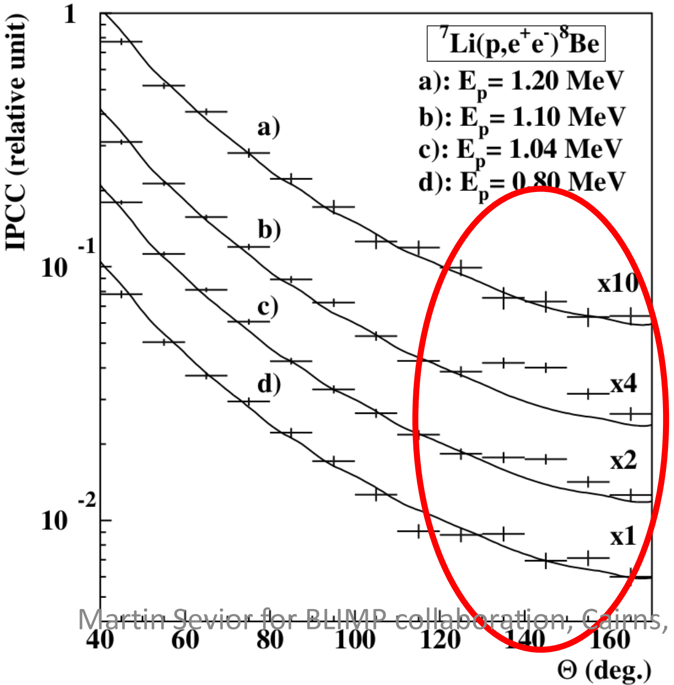
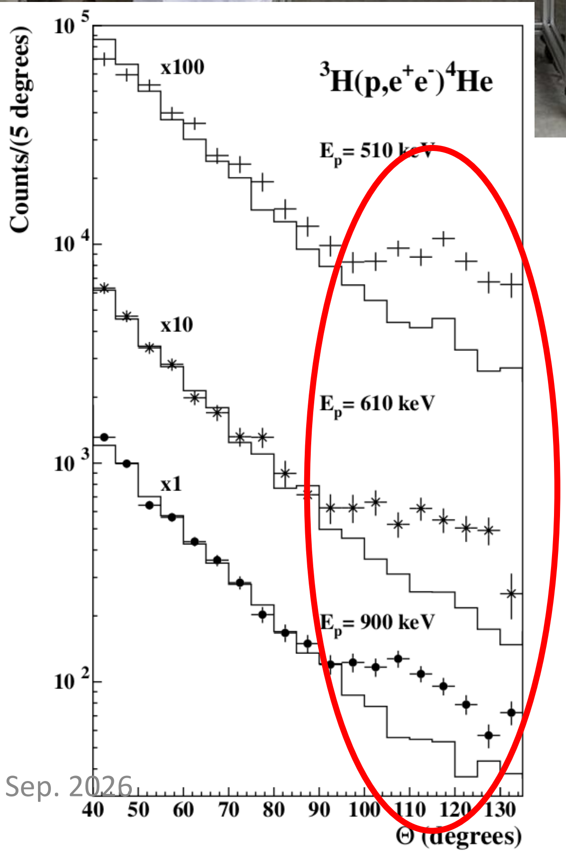


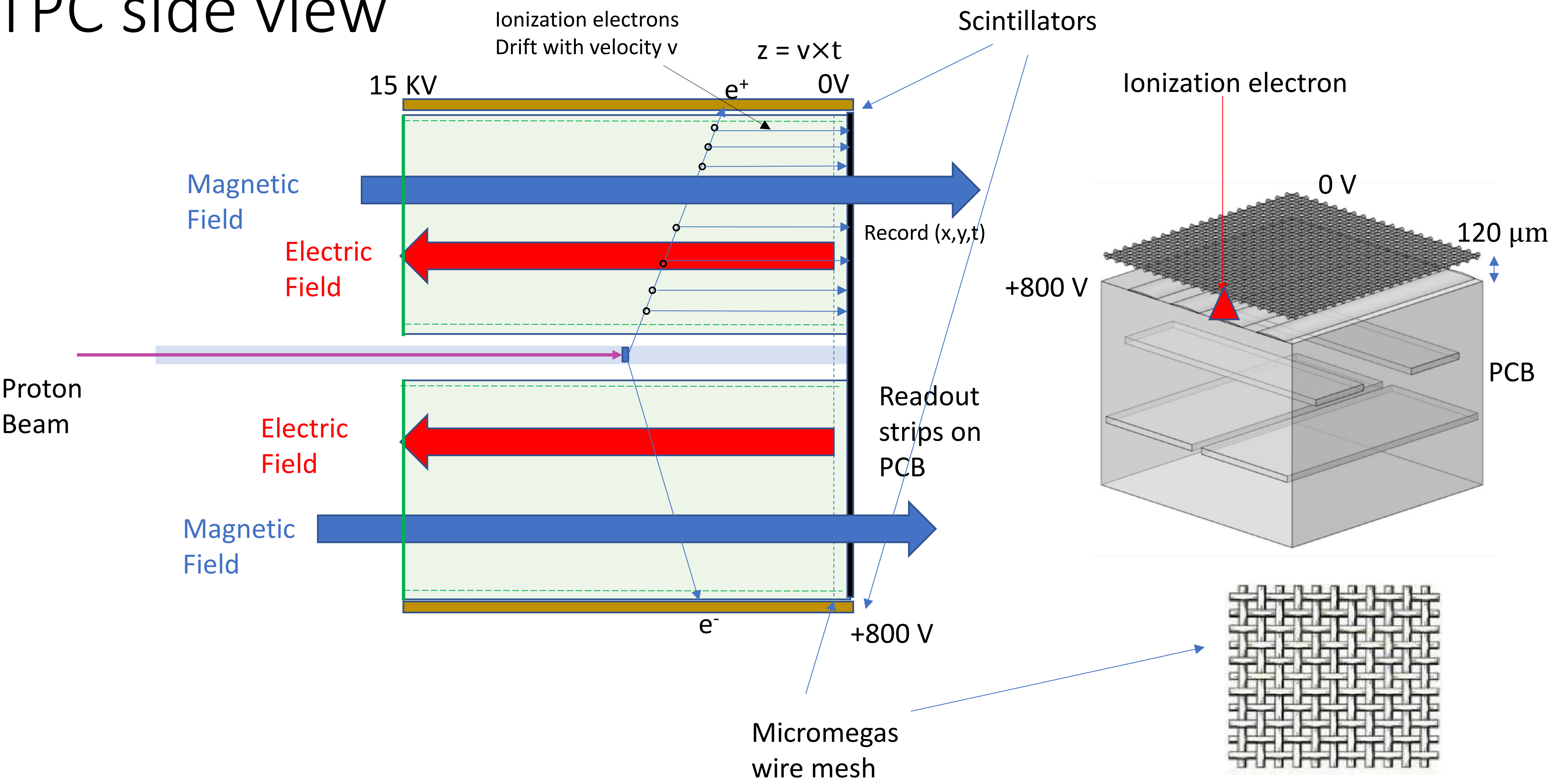




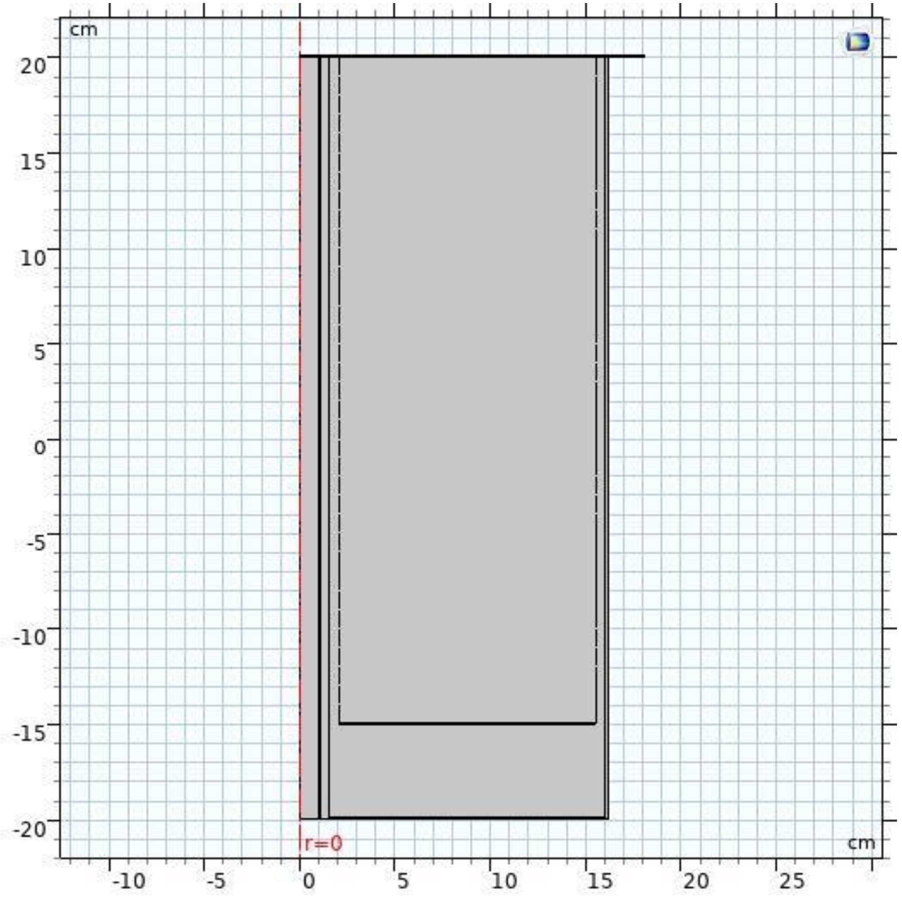


1: arxiv 1504.01527 (PRL **116**, 04215, (2016))
2: arxiv 2104.10075 (PRC **104**,044003, (2021))

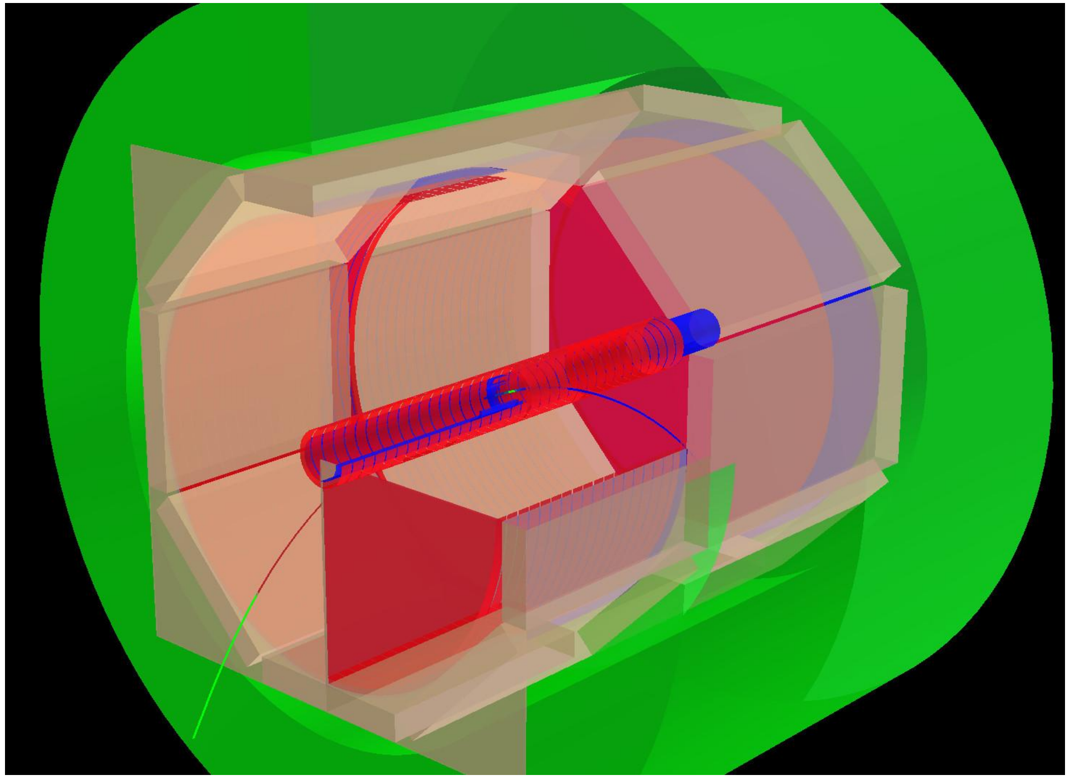
TPC side view



COMSOL electric field simulation of Field Cage

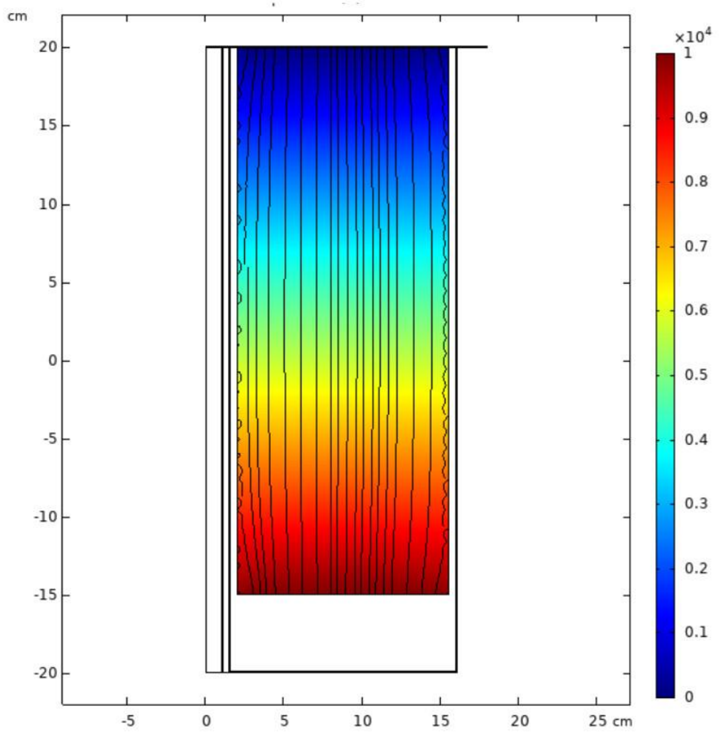


2D geometry with axial symmetry
Employed in COMSOL

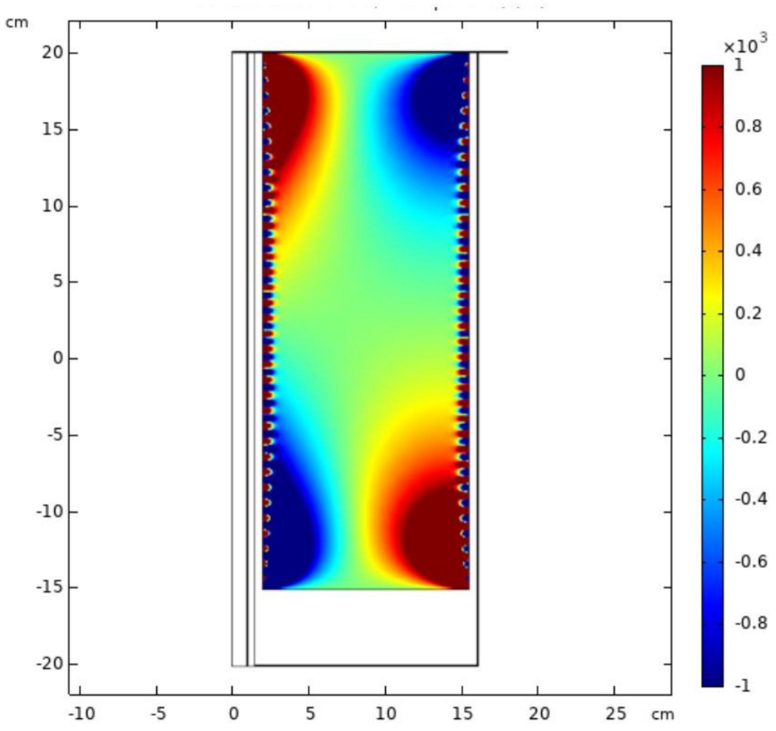


3D geometry

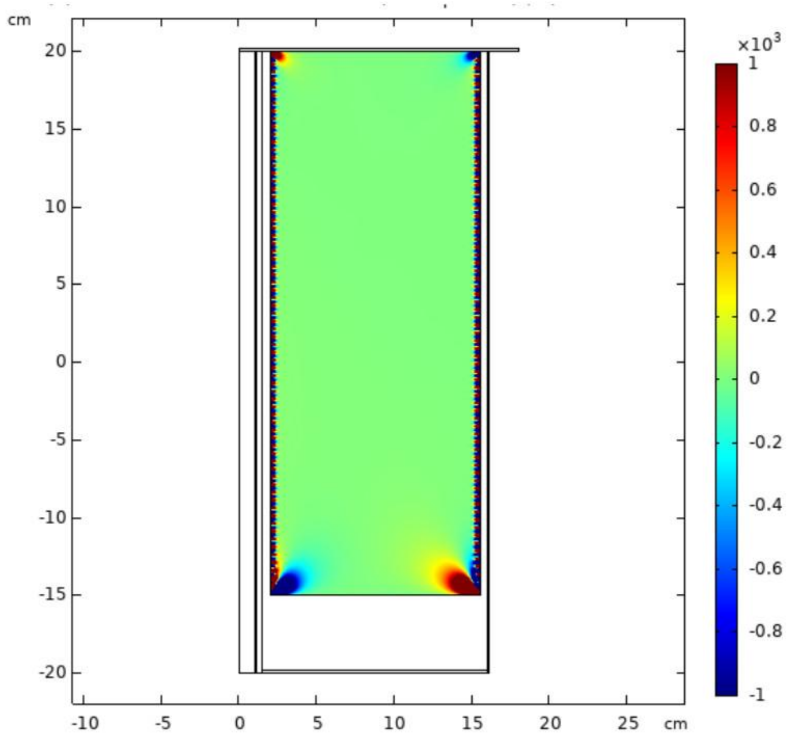
COMSOL electric field simulation of Field Cage



Default Electric field
Z Component



Default Electric field
radial Component



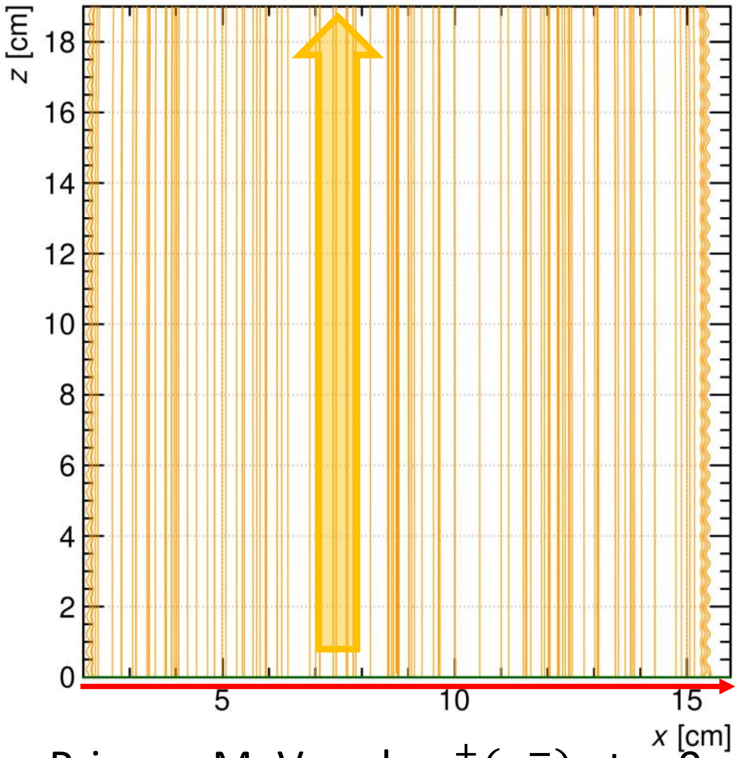
Optimized Electric field
radial Component

Default: 9 mm rings placed 1 mm apart

Optimized: 4.5 mm rings placed 0.5 mm apart
Initial upstream ring 1 mm downstream of
cathode disk

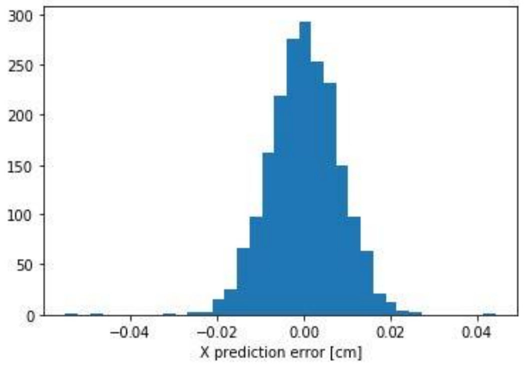
Garfield Simulation of electron release and drift

Ionization electrons drift to detector at z=19 cm



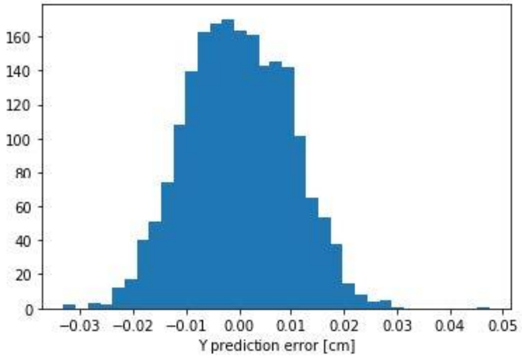
Primary MeV-scale $e^+(e^-)$ at z=0

Around 100 electrons per track released via ionization.

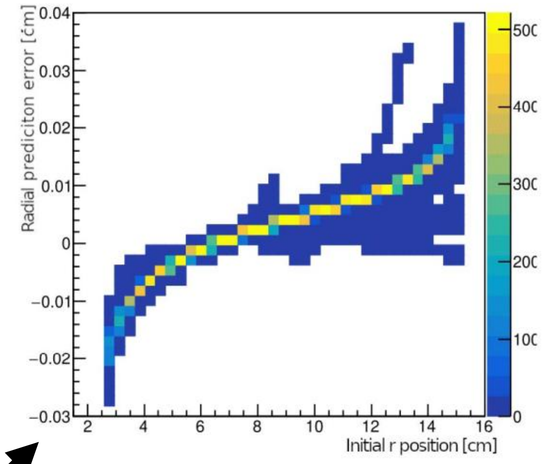


Uncorrected Resolution

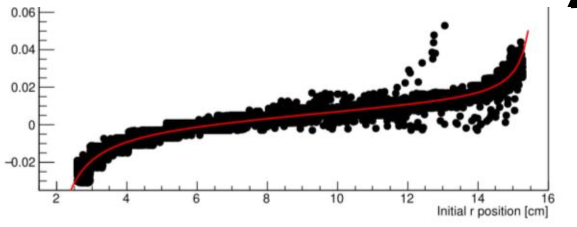
100 μm resolution

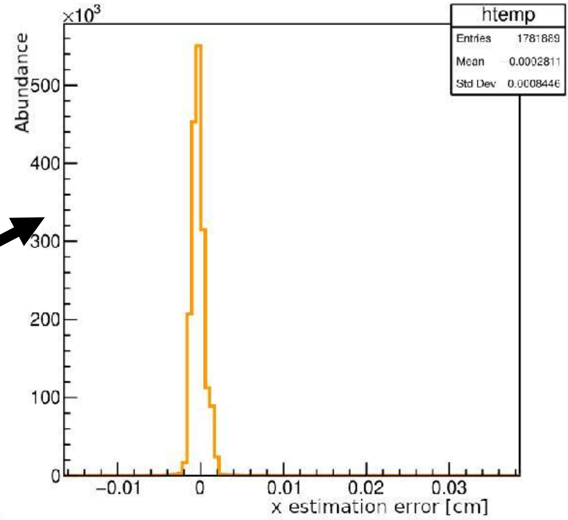


Correlation in Radial position

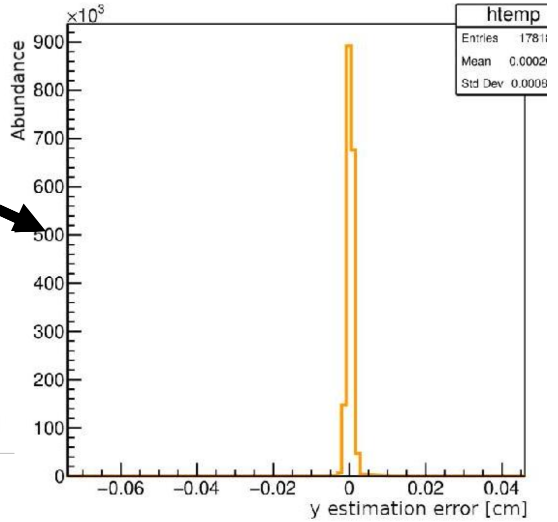


Corrected





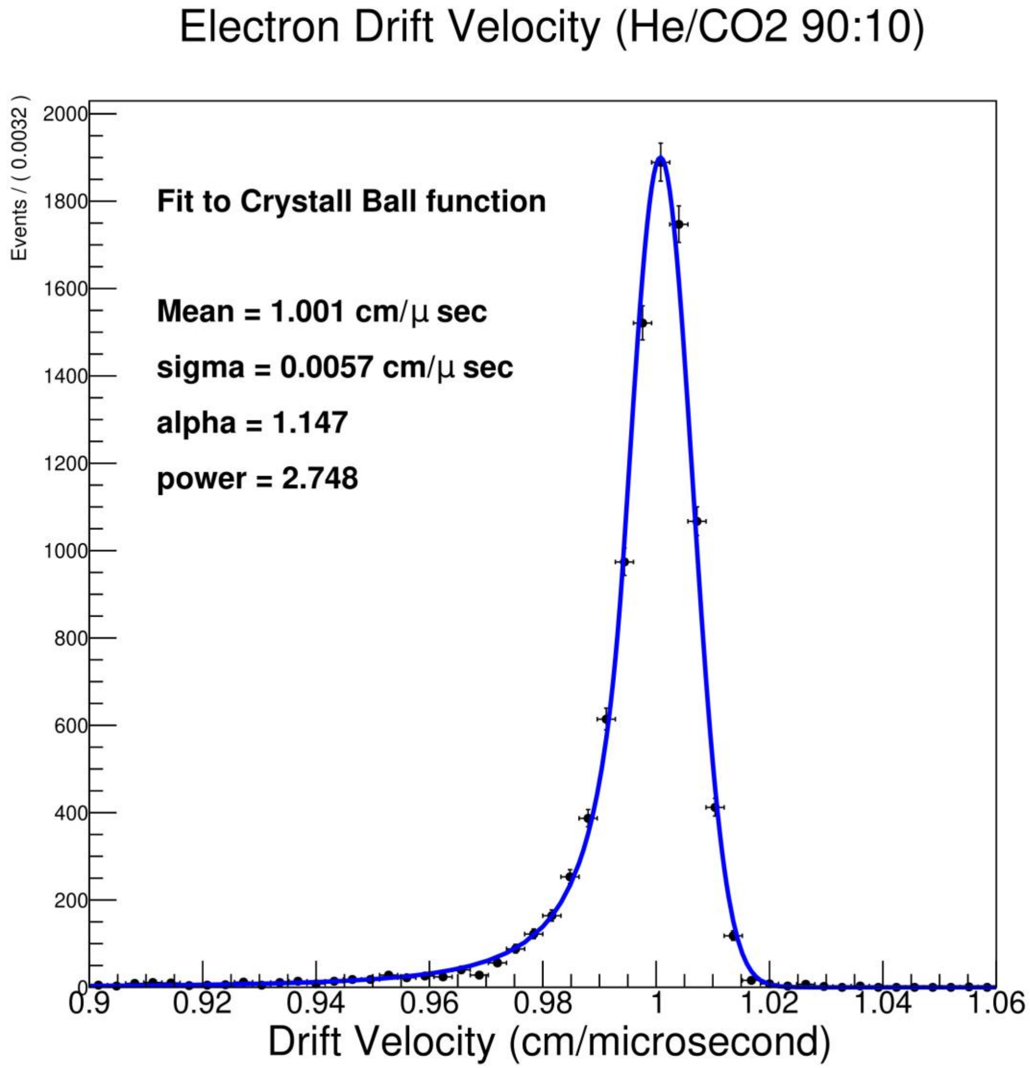
Corrected Resolution



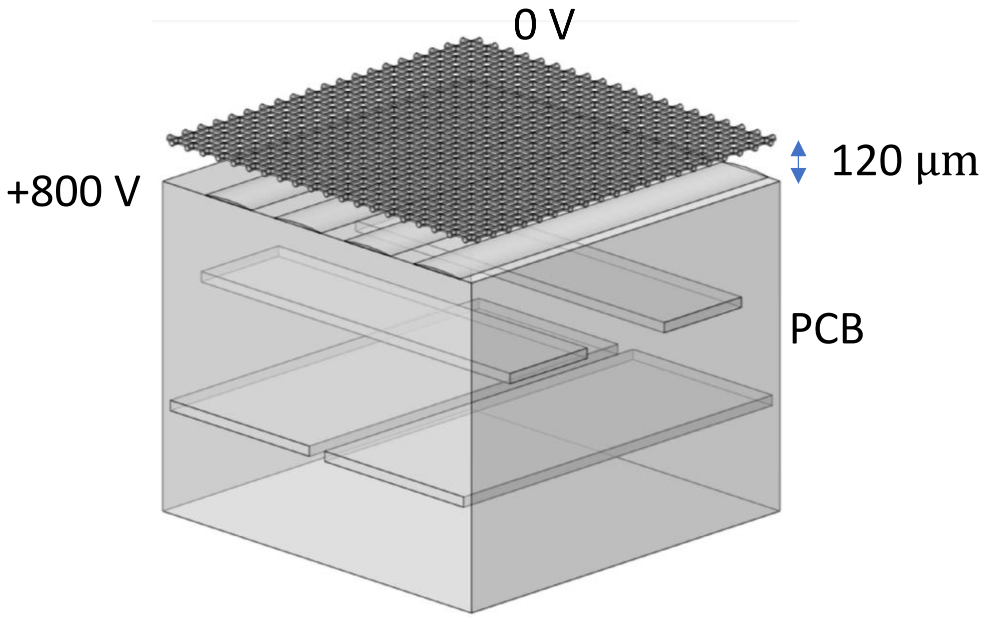
10 μm resolution

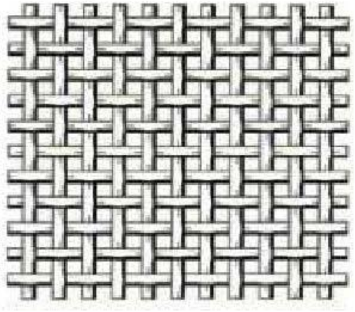
Garfield simulation of drift velocity

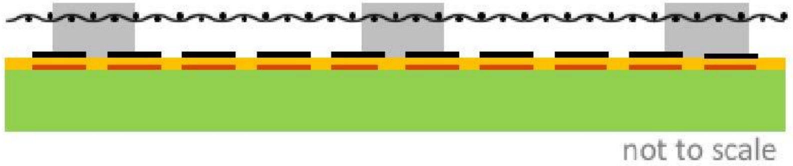
Dispersion of drift velocity is ~ 0.6%
Gives rise to a z-resolution of ~ 1mm

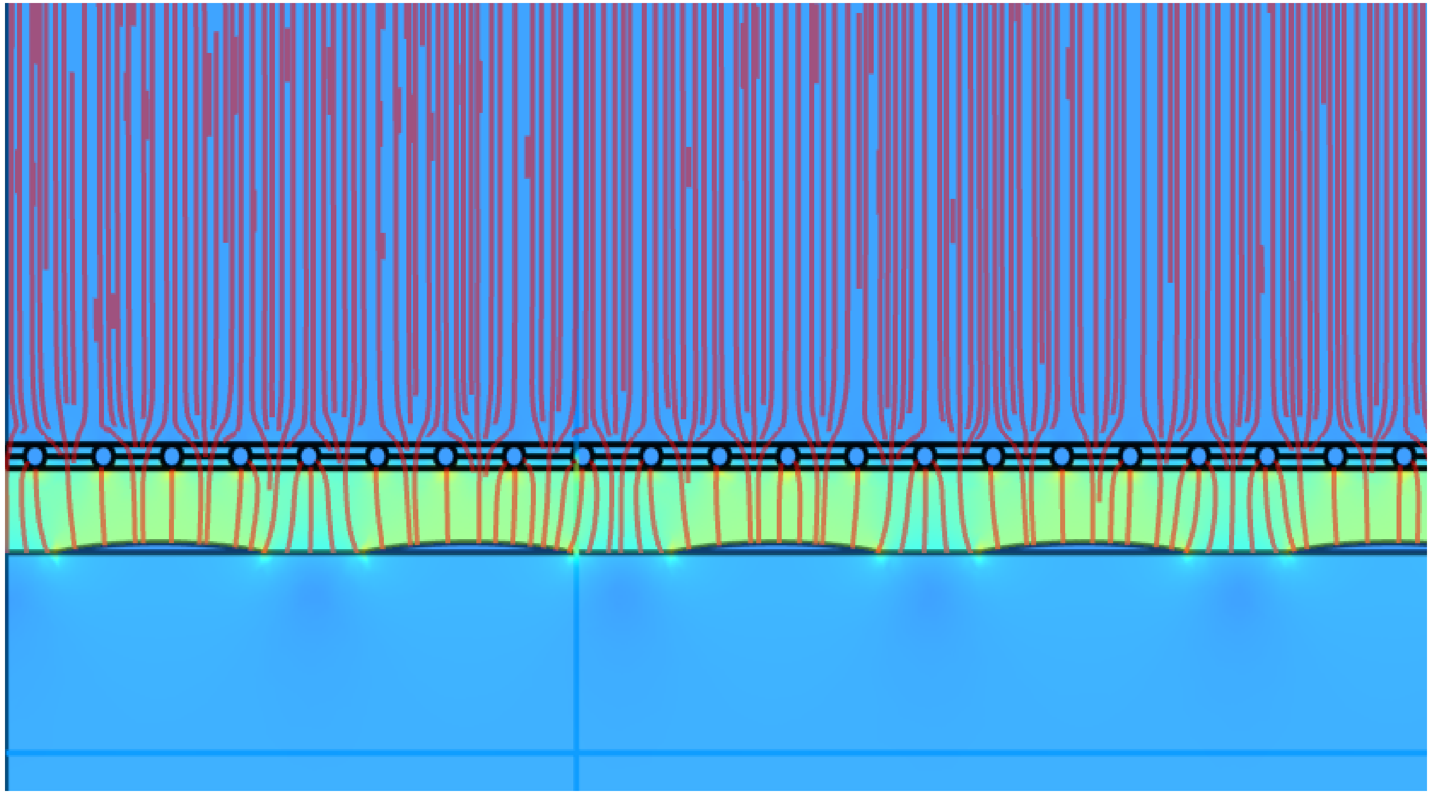


COMSOL + Garfield simulation of micromegas



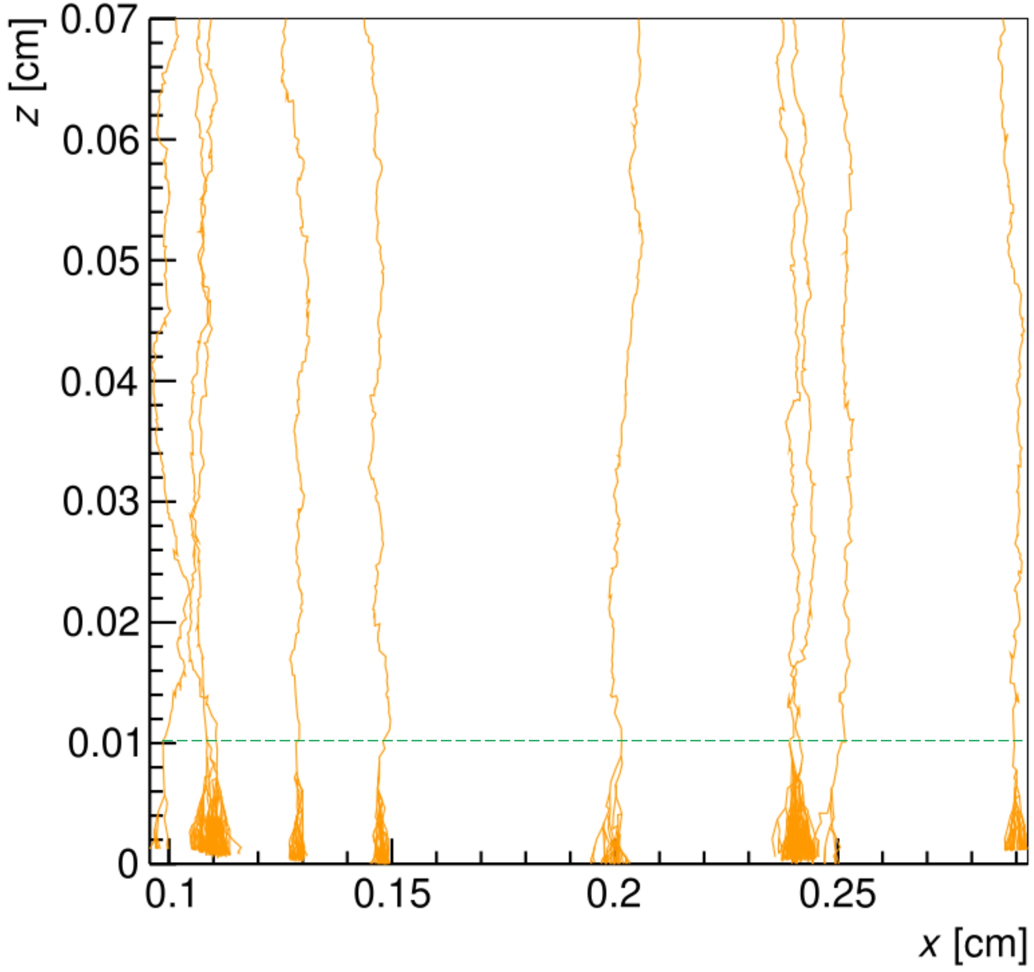




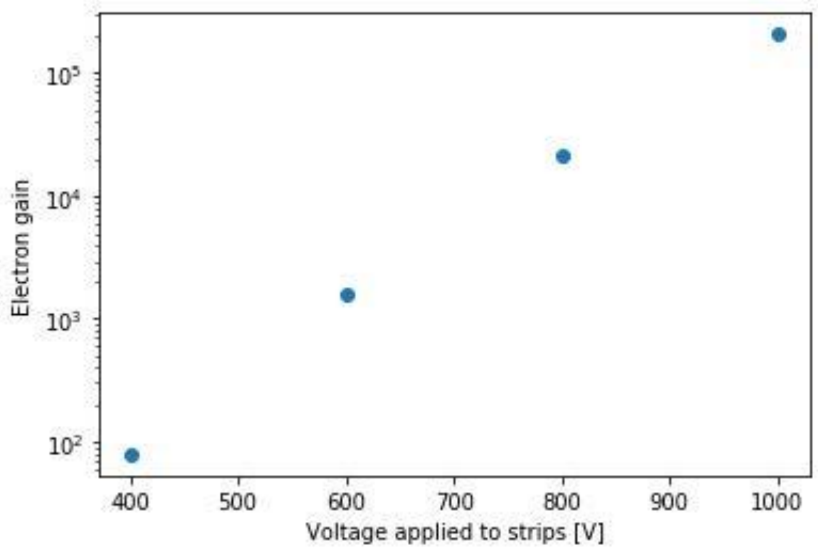


Electrons are directed through the mesh and enter the amplification region

Garfield simulation of Micromegas amplification

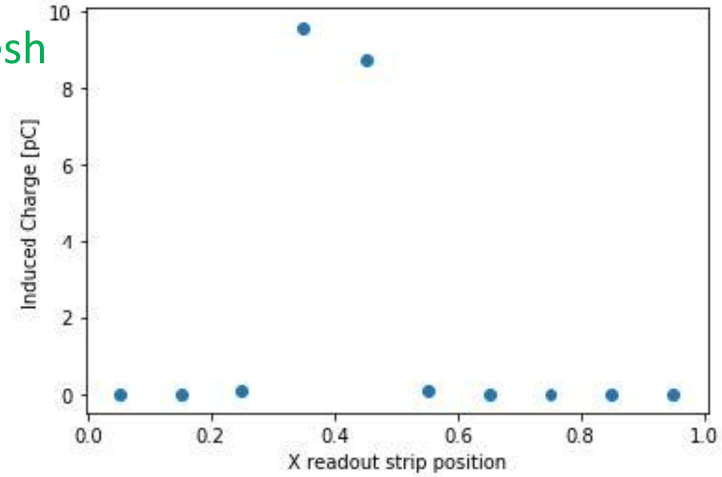


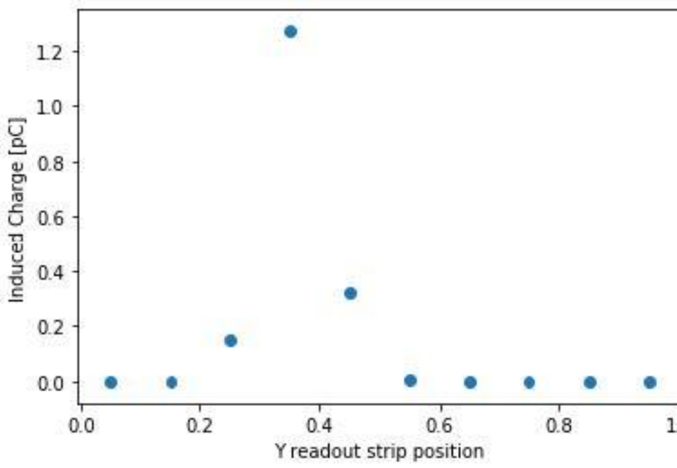
Electron avalanche providing gas gain



800 V over ~ 100 microns provides ~ 10^4 gas gain

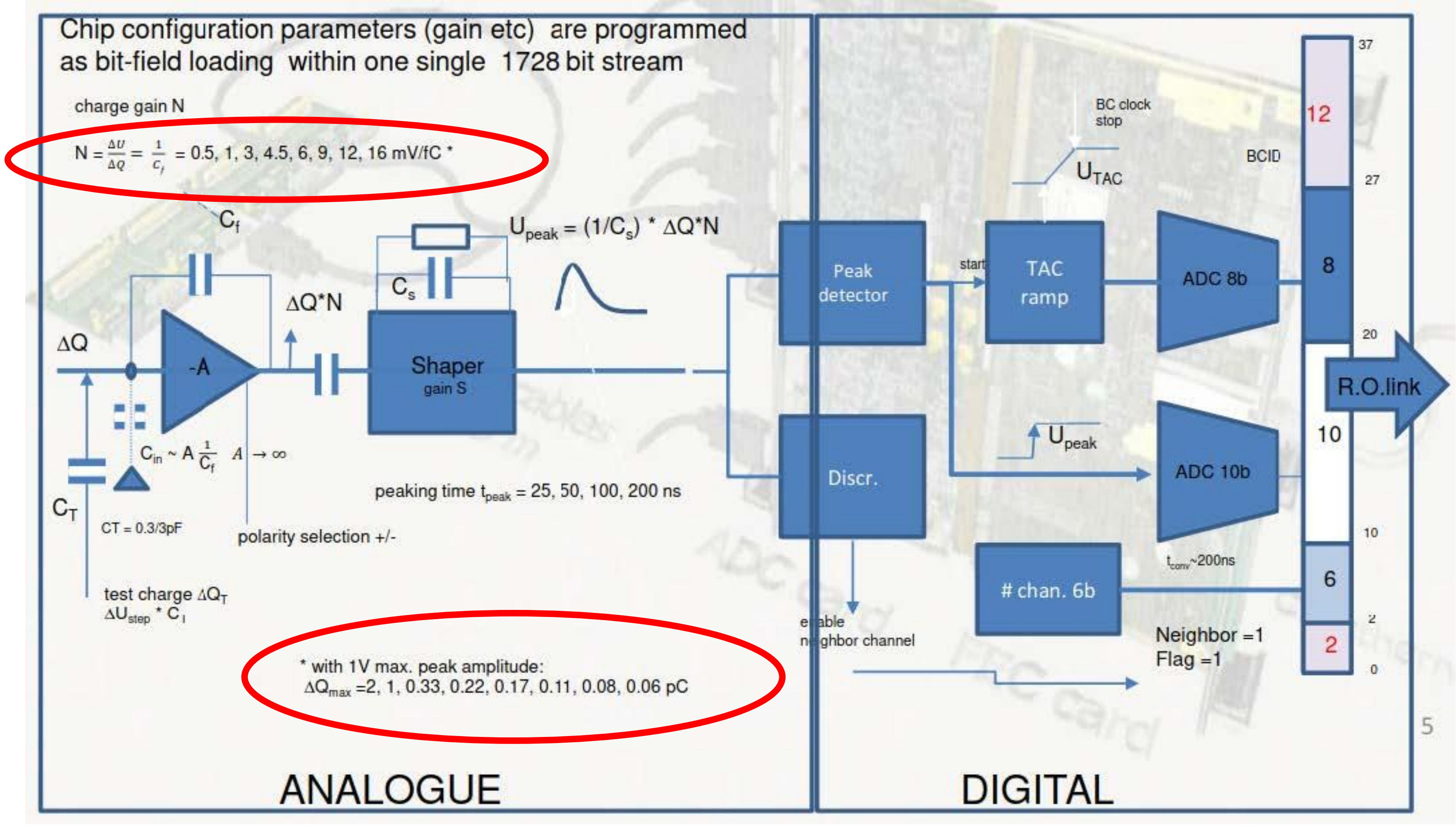
Induces pulses of around 5 pC on readout strips





LHC VMM ASICs + Scalable Readout System

- Readout strips with VMM ASICs

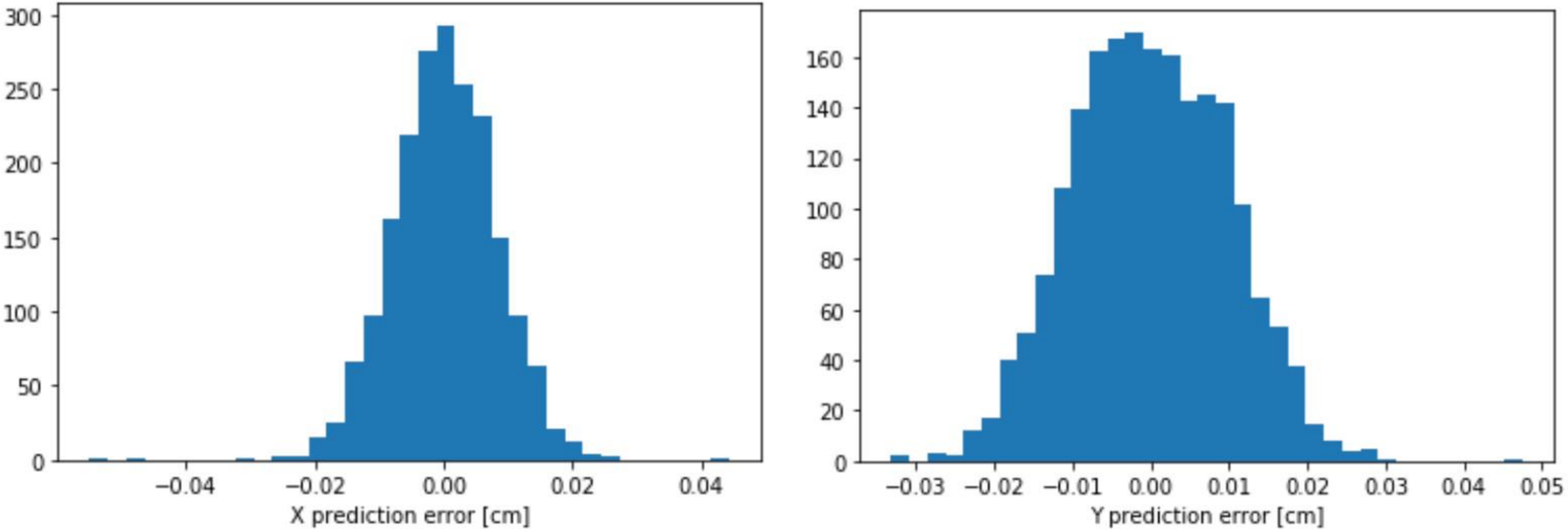


~fC pulses from strips in the range for VMM

Programmable gain
Test charge input

Records channel number, analogue charge, Time with 1 ns resolution and 64 μ-sec dynamic range

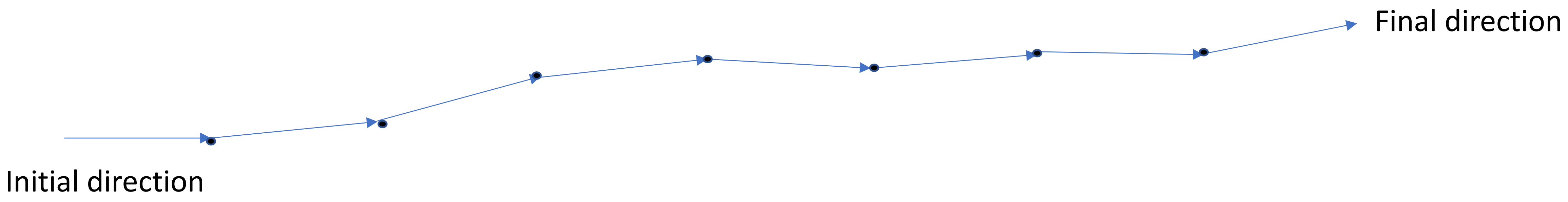
Projected x-y resolution ~ 100 microns



Design will work to provide 100 micron spatial resolution in (x,y)

Geant 4 Simulations

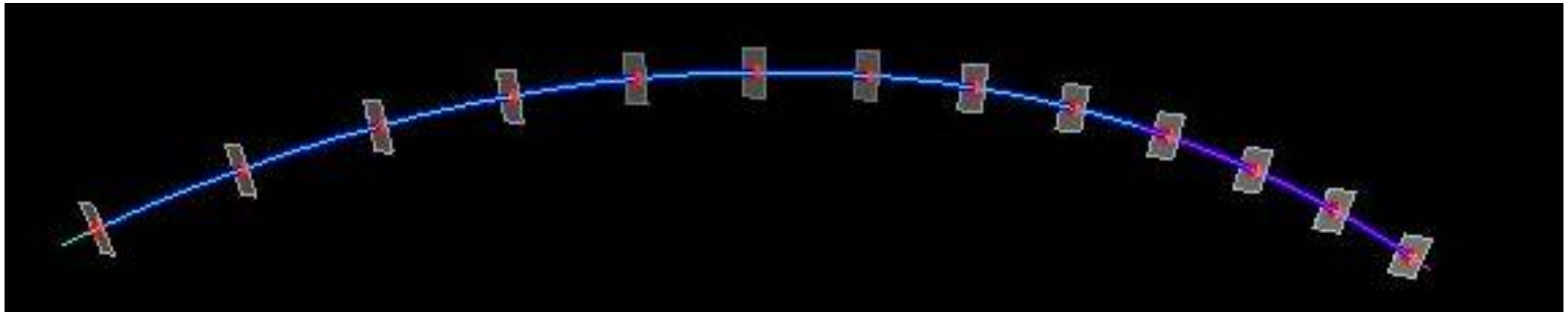
- As charged particles propagate through matter interact causing:
  - “Multiple” small angle scattering causing direction change
  - Energy loss as they transfer energy to the medium
  - Ionization liberating electrons
- Have set up a Geant 4 simulation of the TPC



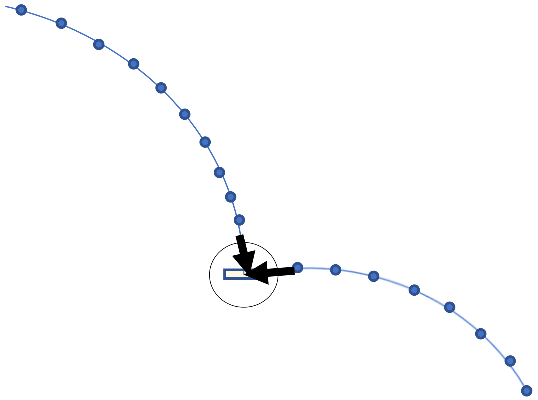
Accurate determination of the Invariant mass of the e+ e- pair requires a precise measurement of the magnitude and direction of the charged particles
Accurate simulation of multiple scattering required.
Minimize the effect.
Low Density, Low Z material

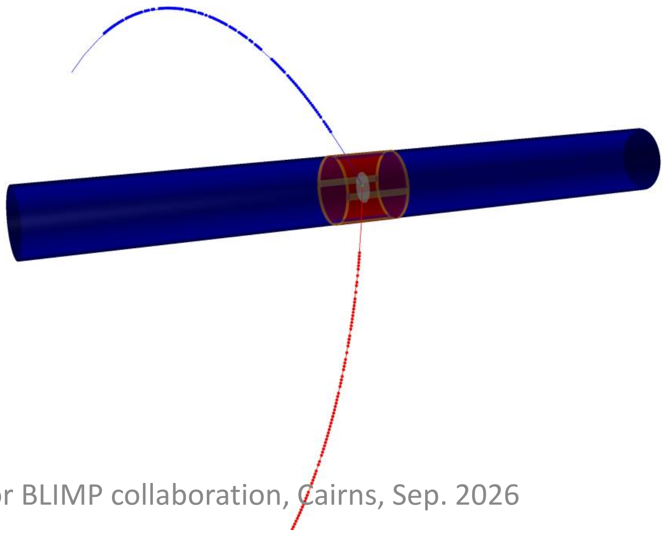
Genfit2 + RAVE

- Developed reconstruction software using “genfit2” HEP software library to reconstruct tracks



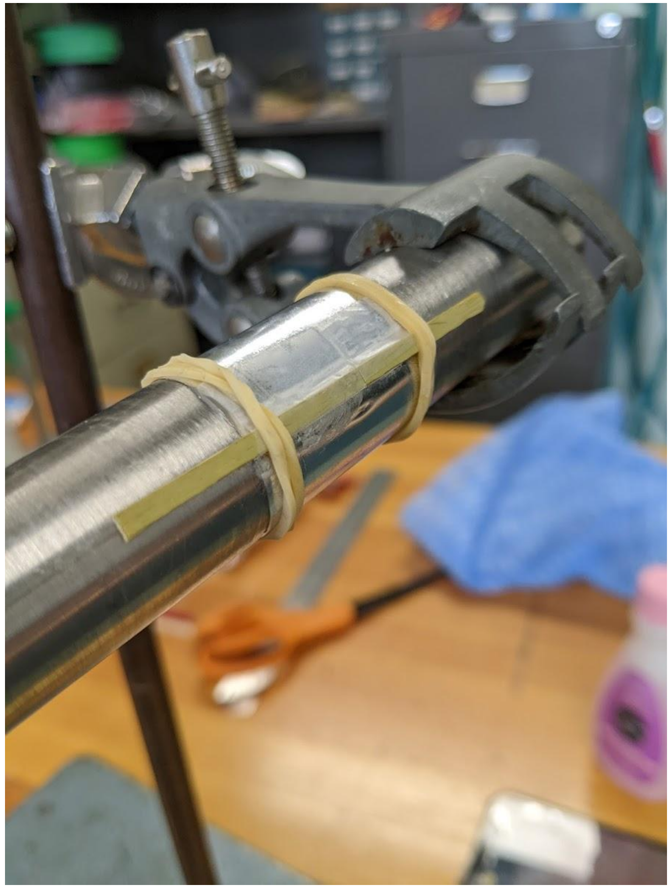
- Developed vertex reconstruction software using “RAVE” HEP software library to project tracks to a common vertex

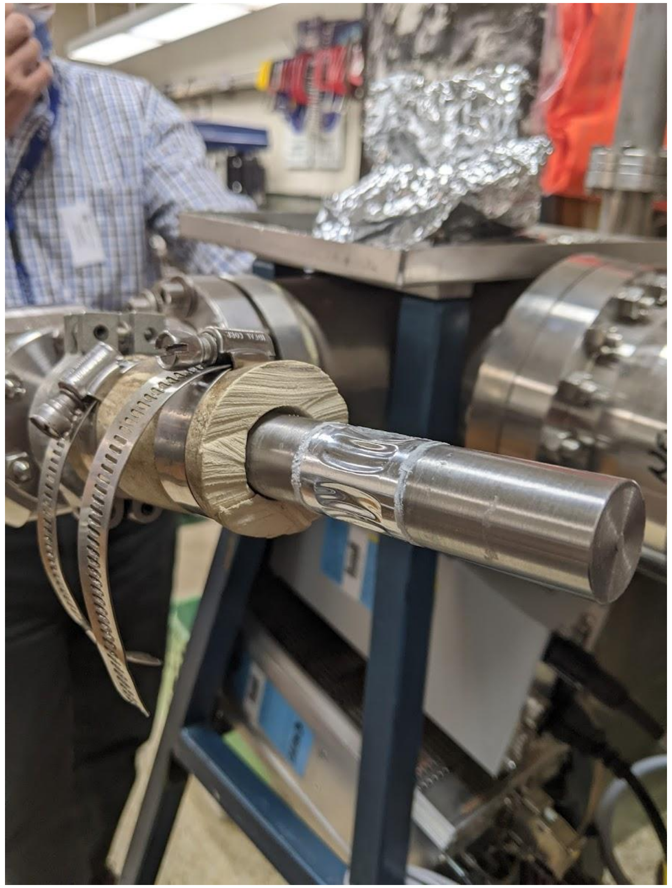




Target Chamber

- Prototype Target Chamber

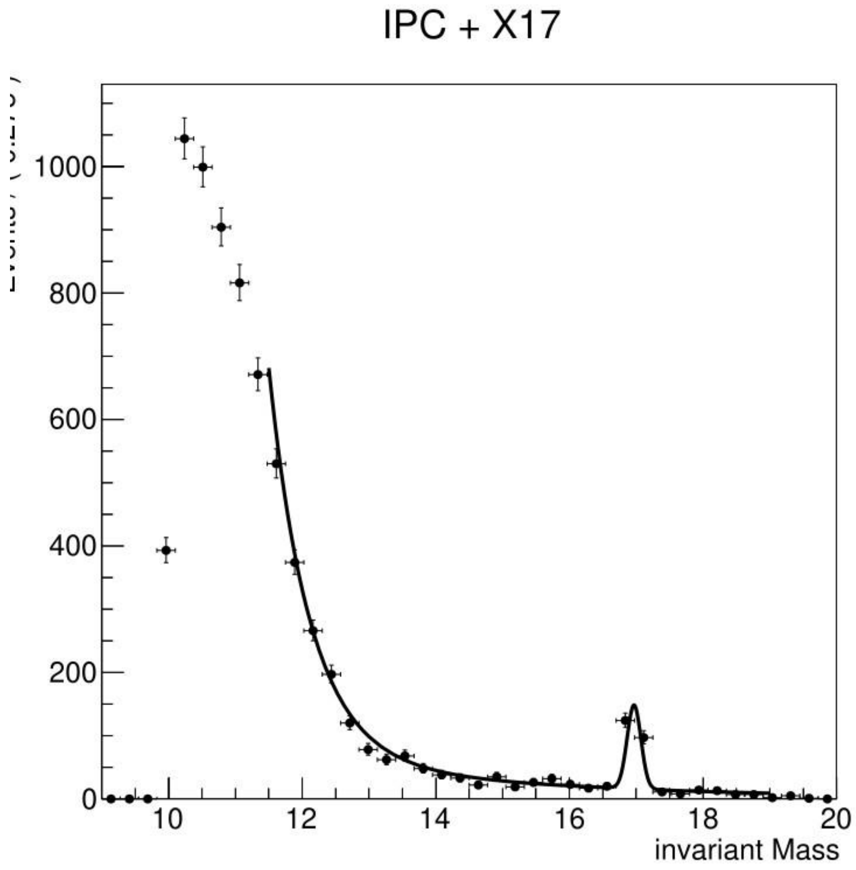


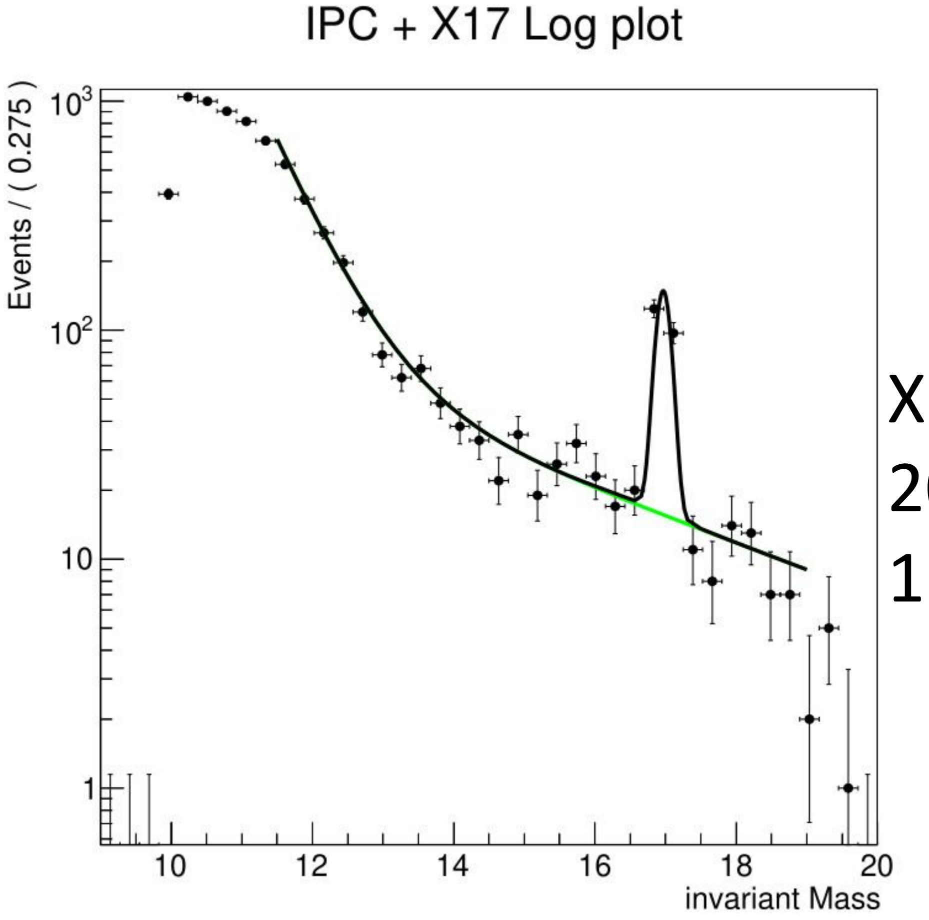


Mylar foil on stainless steel pipe, nicely holds vacuum.
Reached 1.1×10^{-5} Torr (limited by outgassing in the connector)

X17 + IPC background (2)

4 day run



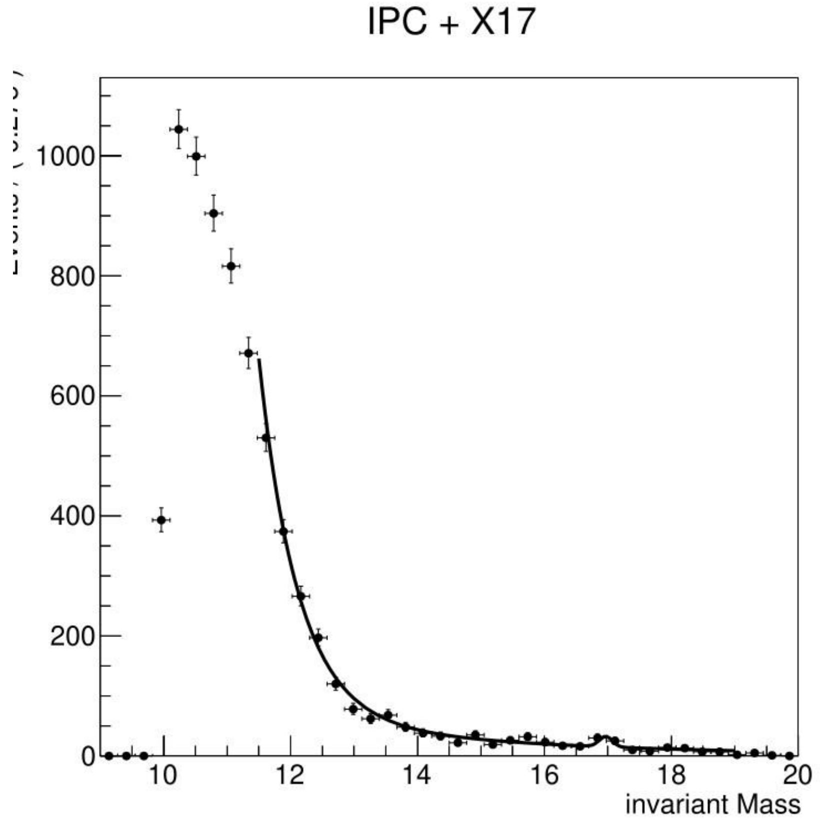


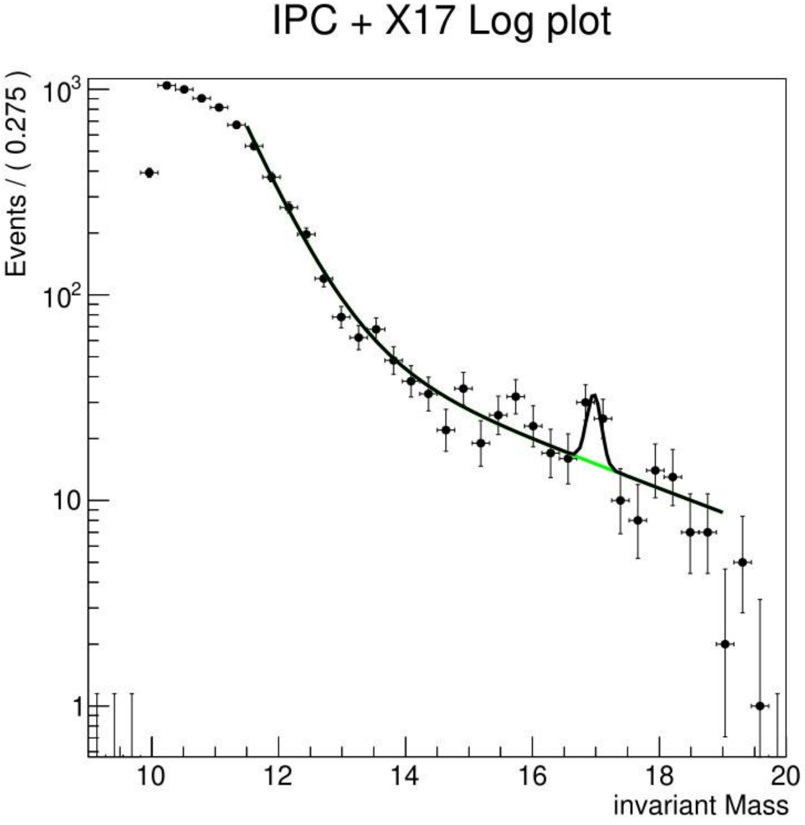
X17 BR= $6 \times 10^{-7}(p, \gamma)$
201 +- 16 events
12 σ significance

X17 + IPC background (3)

Plenty of head-room statistically!
Can increase beam current to 2 μA
Target Thickness to $2 \times 10^{19}\ atoms/cm^2$
Run time to 40 days
Gives a factor of 40 increase in statistics!

4 day run





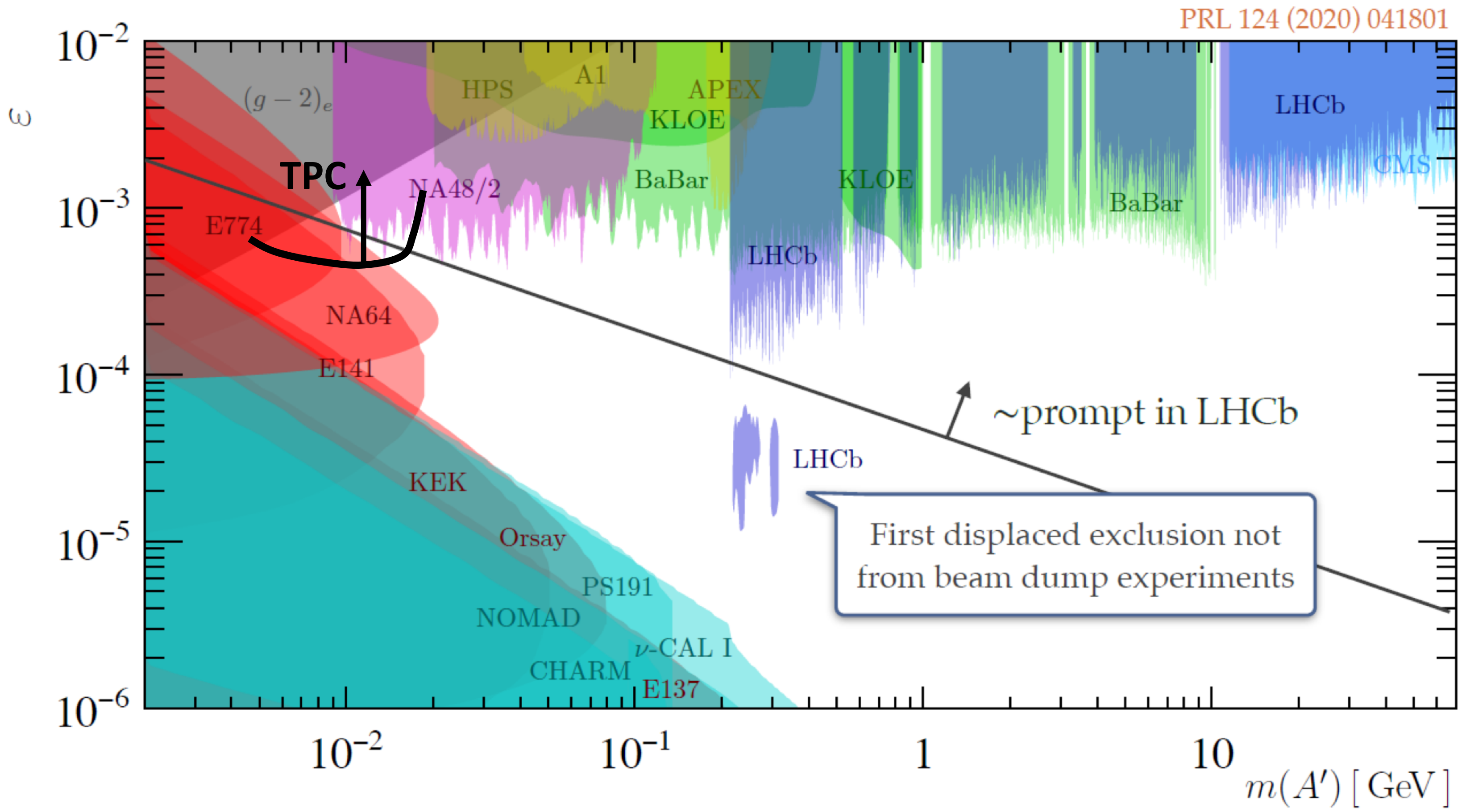
X17 BR= $6 \times 10^{-8}(p,\gamma)$
27 +- 8 events
3.3 σ significance

Data rates

- Comes from Thick-target bump hunt search + exclusion
- Run at 4.5 MeV, Beam $2\mu A$, Target $2 \times 10^{20}\ Li\ cm^{-2}$
- Cross Section for $p + {}^{7}Li \rightarrow {}^{8}Be + \gamma$ = 30 μb
- N(γ)/sec = $3 \times 10^{-29} \times 2 \times 10^{20} \times 1.25 \times 10^{13} = 7.5 \times 10^{4}\ s^{-1}$
- Approx 0.01% gamma's convert = 7.5 events/sec
- IPC rate = $3.5 \times 10^{-3} \times 7.5 \times 10^{4} \times 0.5 = 131$events/sec
- 12 Kbytes/event $1.2 \times 10^{4} \times 140 =$ 1.7 megabytes/sec
- 145 GB/day
- 4.5 TB for 30-day run

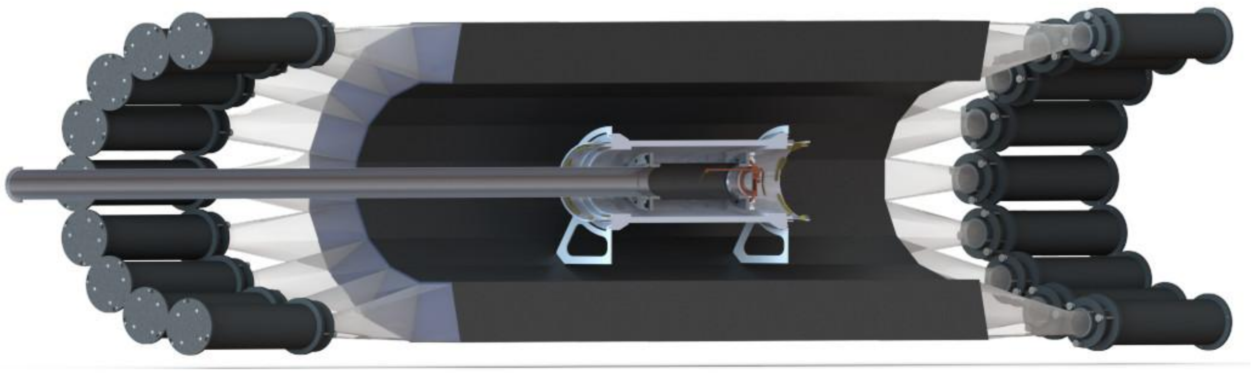
Well within the capacities of the unimelb Spartan HPC

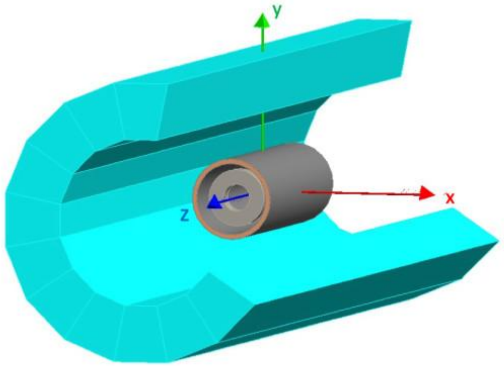
Comparison to LHCb for generic dark photon

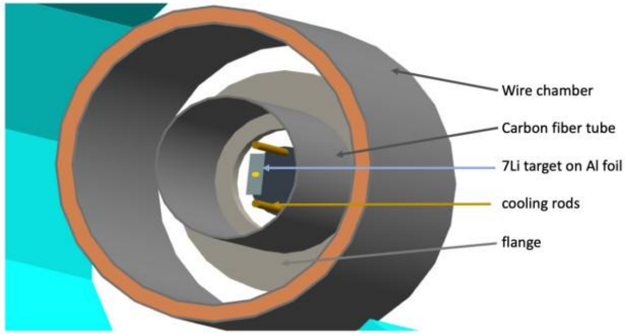


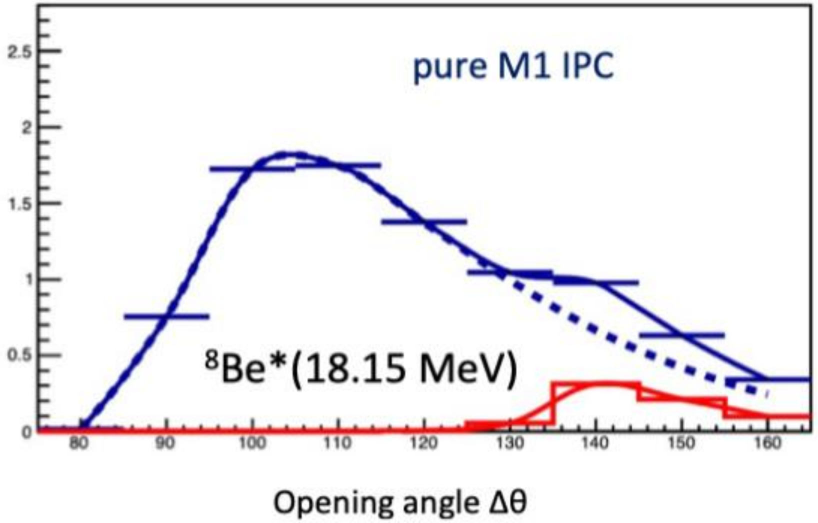
Search for the X17 at University of Montreal

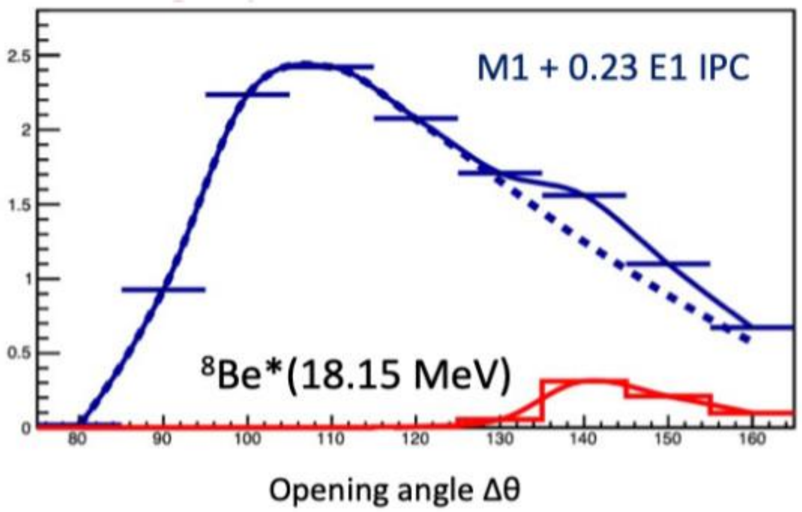
Openning angle measurement of e^+e^- pairs from $p +^7 Li \rightarrow^8 Be + (e^+e^-)$











arXiv:2211.11900v1