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DARKLIGHT @ ARIEL, Anomalies, and Other X17 Searches

Ross Corliss

Stony Brook University

DarkLight Collaboration Meeting @TRIUMF, July 10-12, 2024

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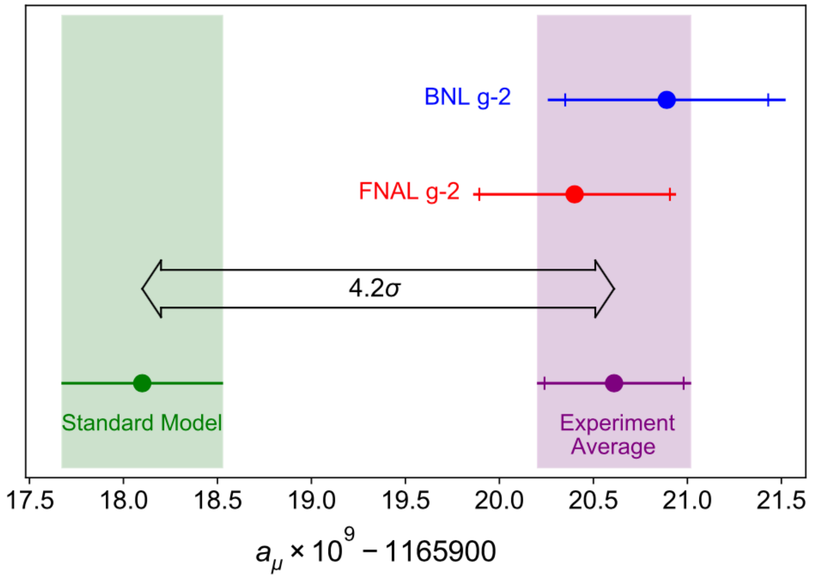
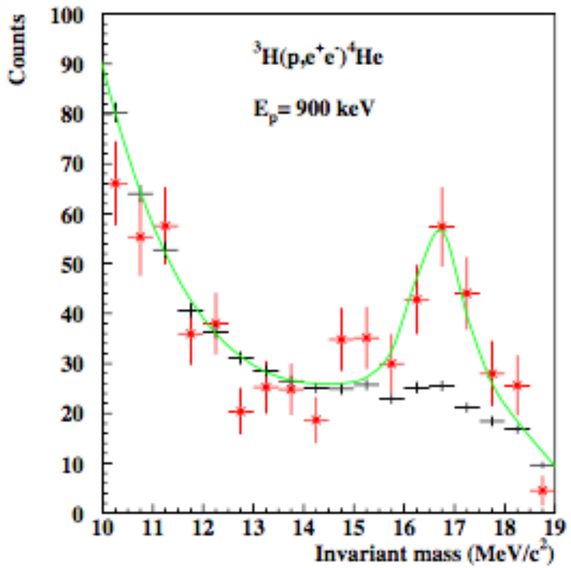
Physics Refresher

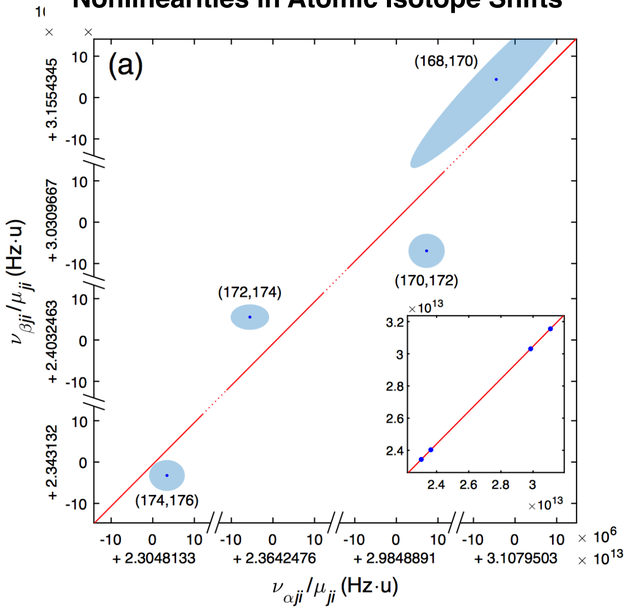
Muon g-2 Discrepancy



X17 in 4He and 8Be



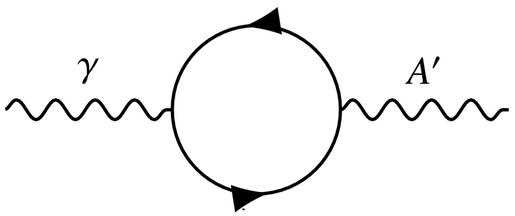
Nonlinearities in Atomic Isotope Shifts



- Anomalies could be resolved with a new interaction:
- Simple model: Kinetic Mixing with SM photon

  ➡ effective coupling to SM charge
- Full search-space allows flavor-dependent coupling:
- Parameterized by coupling (ϵ_f) and mass

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$



$$X^\mu \left(\Sigma_f e \epsilon_f \bar{f} \gamma_\mu f \right)$$

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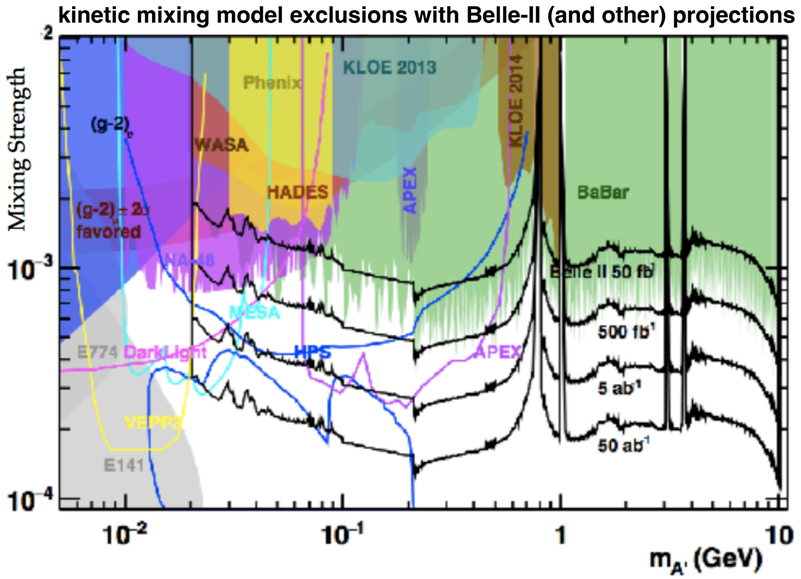
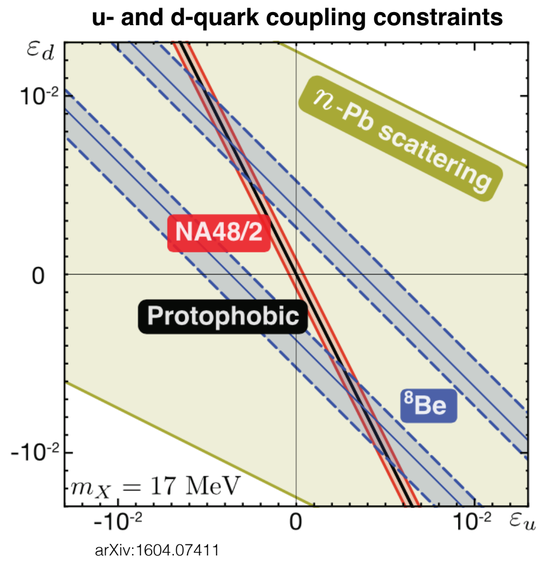
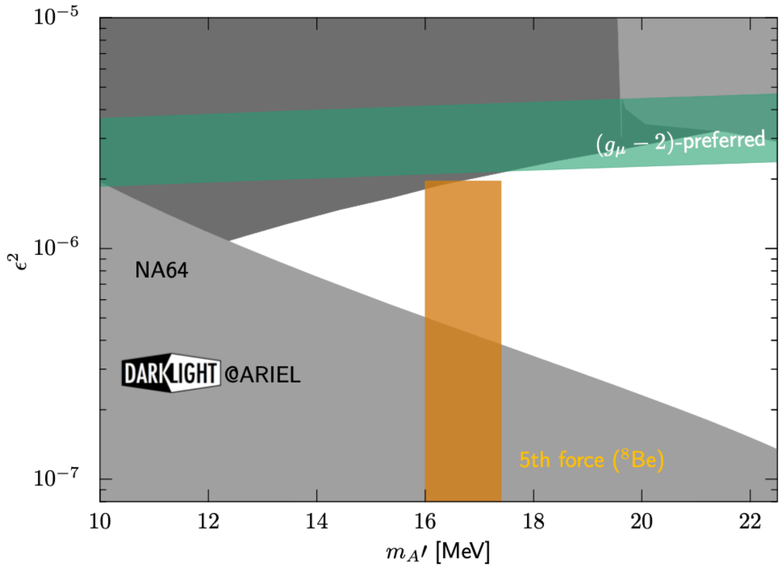
Direct Searches and Protophobia







- Kinetic mixing disfavored by existing searches via hadronic production of A'
- Flavor-dependent couplings allows 'protophobic' solution
- ***Purely leptonic production*** key aspect of expanded search for this new particle
- X17 region can be reached with **low beam energy**

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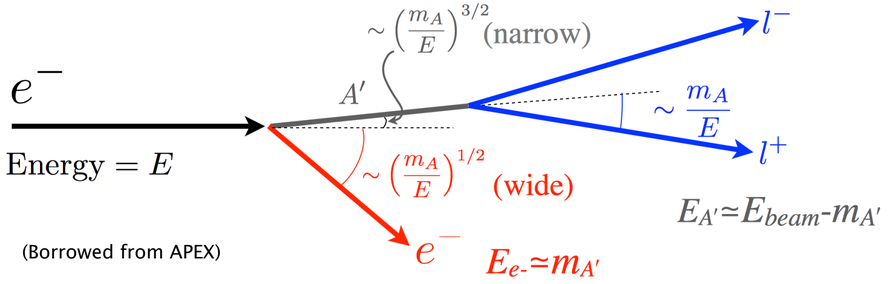
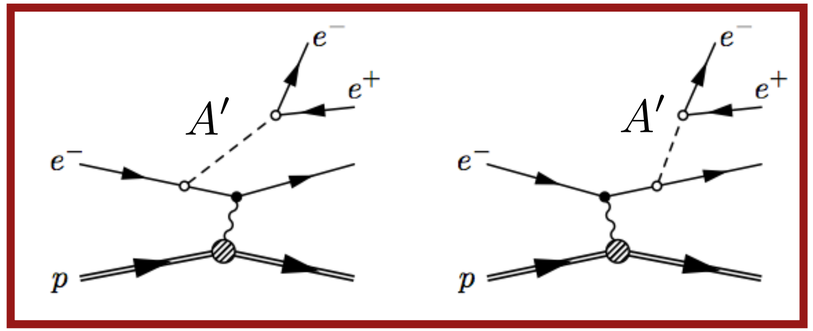
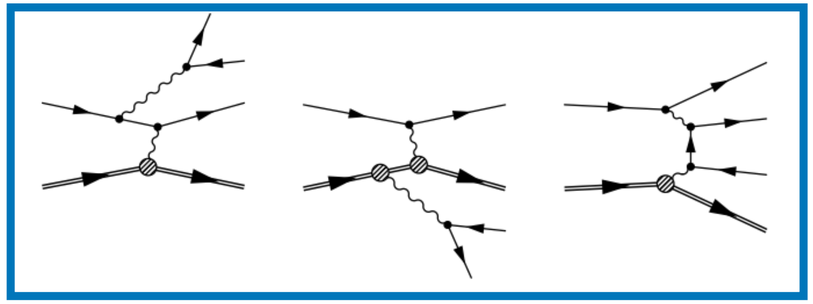
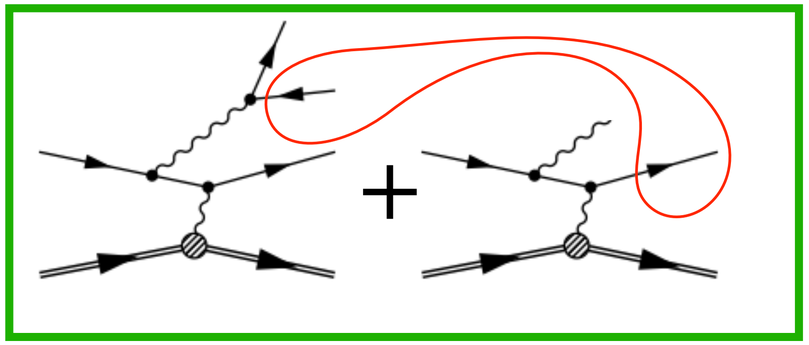
You Are Here



(Borrowed from APEX)







- Radiative production: S∝L

$$e^- + \mathrm{Ta} \rightarrow e^- + \mathrm{Ta} + A'$$

$$A' \rightarrow e^+ + e^-$$

- Irreducible QED background: $B_i \propto L$
  (replace A' with virtual photon. no mass peak)
- Combinatoric background: $B_c \propto L^2$

  (positron from QED background, electron from elastic scatter)

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Anomalies

- ATOMKI X17 ^{8}Be GDR (arxiv:2308.06473) and ^{12}C (arxiv:2209.10795), 4He, 8Be resonance
  - and in ^{8}Be @ VNU with ATOMKI assistance (arxiv:2401.11676)
  - and in C, Cu @ JINR in reanalysis (arxiv:2311.18632)
- FNAL g-2 combined result (arxiv:2308.06230)
- KTeV π^0 -> e^+e^- enhancement (arxiv:2212.06453v3)

- Neutron lifetime (PT Du et al 2020 J. Phys.: Conf. Ser. 1506 012004)

- Isotope Shifts (King Plots) (arxiv:2111.01429)
  (But recent studies match ab-initio calcs) (arxiv:2403.07792)
- Cosmic ^{7}Li underabundance (arxiv:1510.08858)
  ($1<M_X<20$MeV, but wants $\tau \gtrsim 100$s)

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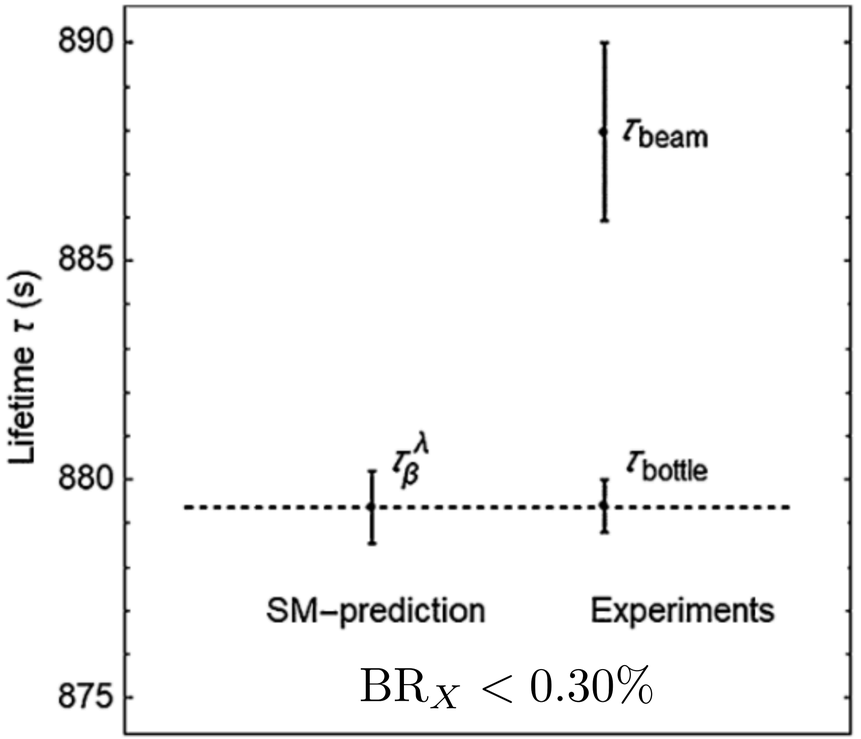
Neutron Lifetime

- Bottle lifetime: 879.4s±0.6 (look at survival ratio)
- Beam lifetime: 888.0s±2 (count decay protons)
- Can reconcile if neutron can decay to something other than a proton with BR~1%:

$$\tau_{\mathrm{beam}}^{-1} = \tau_{\beta}^{-1} \qquad \tau_{\mathrm{bottle}}^{-1} = \tau_{\beta}^{-1} + \tau_{X}^{-1}$$

- In principle mediated by light virtual boson (into some dark final state)
- *But* Dubbers et al. calculation of SM (e- decay only) prediction matches the *bottle* value.



https://doi.org/10.1016/j.physletb.2019.02.013

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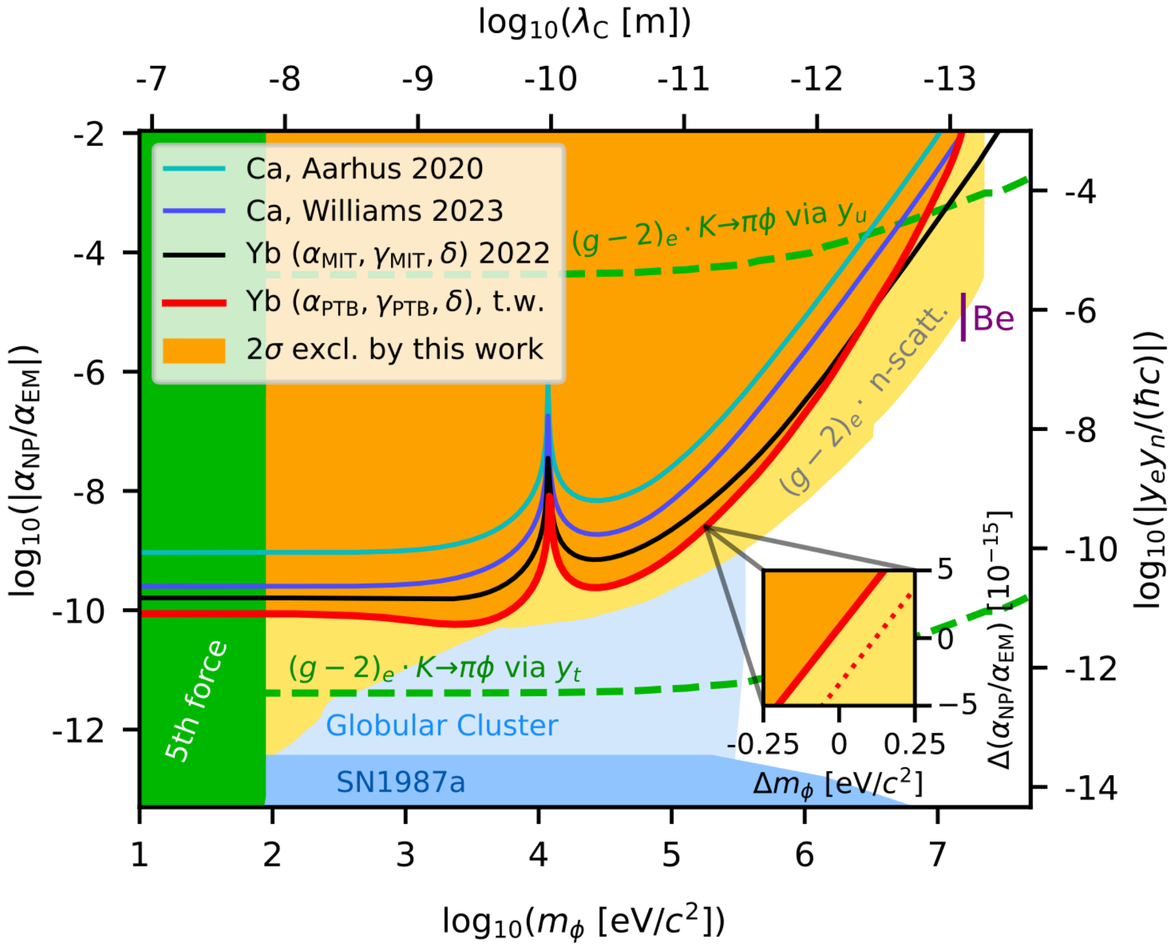
Isotope Shifts

- Compare atomic transition frequencies between different isotopes
- control effects due to mass and nucleus size by measuring super ratios of frequencies
- BSM electron-nucleus interactions would appear as frequency shifts beyond these effects
- 2021: Significant apparent nonlinearities might be BSM effect
- Recently: Recent Yb measurements fit well to SM nuclear deformation model. Cannot exclude all of X17 allowed region.
- *But if remaining nonlinearities are all due to new physics, mass and coupling would lie between solid and dotted red*



arxiv:2403.07792

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See backup slides for more on King Plots

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X17

- ATOMKI group sees anomaly in ^{8}Be, ^{4}He, ^{12}C
- Persists in original 5-fold and new 6-fold geometry
  - most detector angles are the same, but the *resonance angle* moves with species
- *Very* incompatible with simple kinetic mixing model
  - would have been seen in pion decay etc.

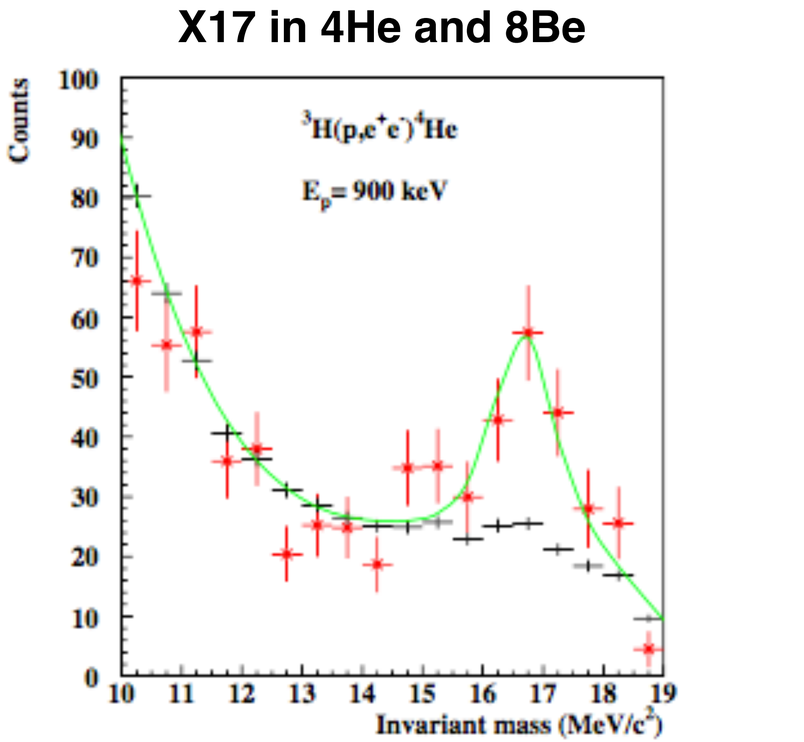

FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in ^{4}He.*

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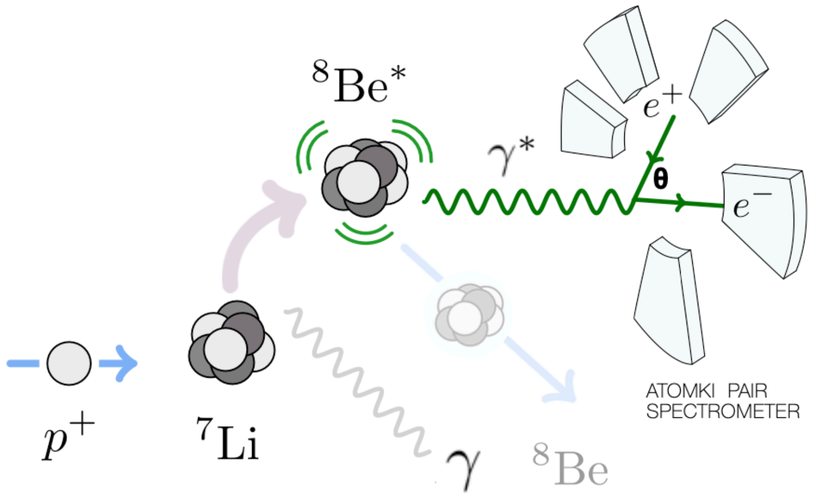
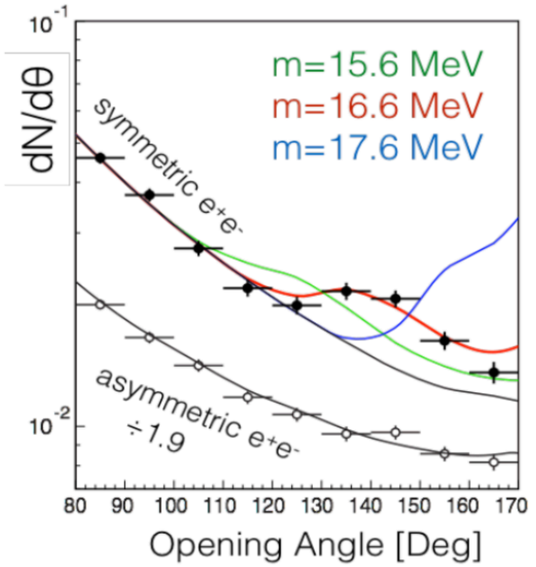
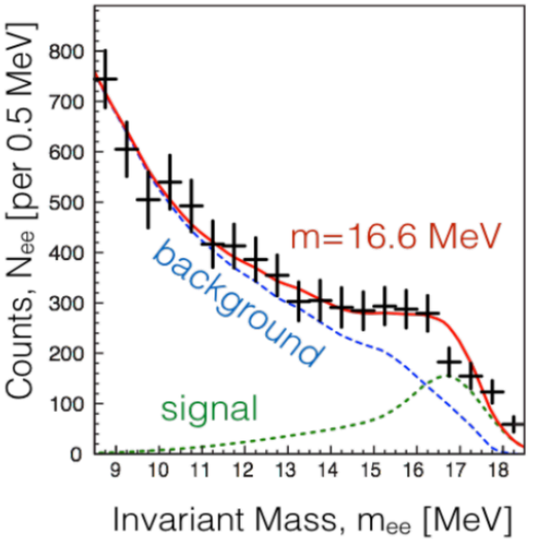
X17

- Very rarely, p+Li produces very excited ^{8}Be state
- Rarely, ^{8}Be will de-excite through photon/ internal pair creation (IPC)
- Detect e+e- pairs, construct spectra, verify against nuclear model
- ...and find an anomaly consistent with massive particle







arxiv:1707.09749

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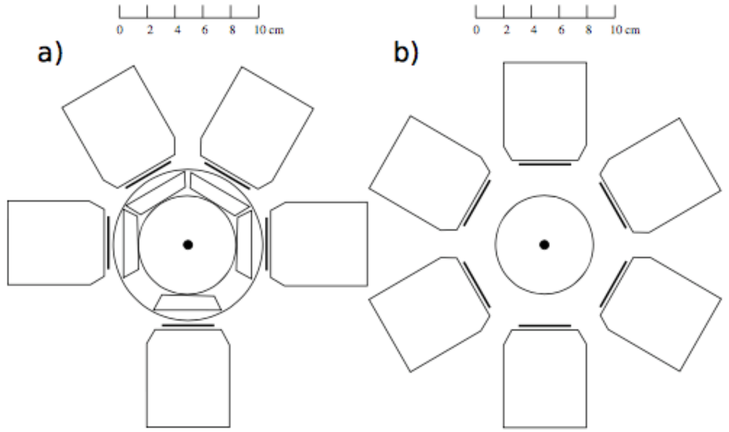
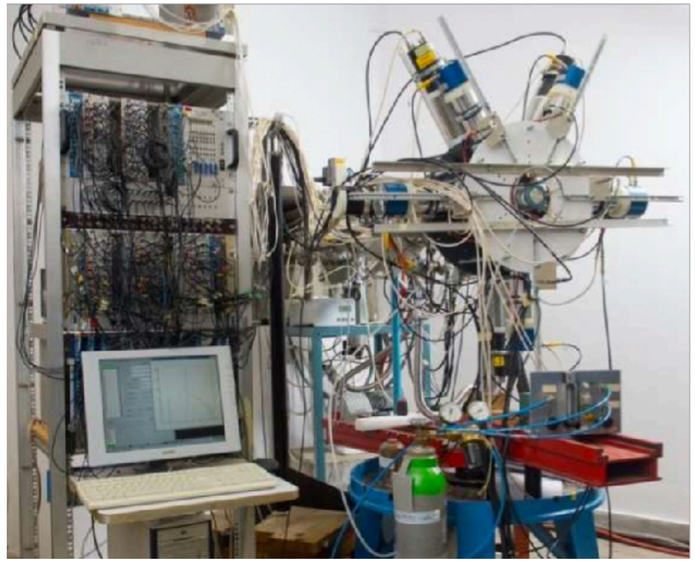
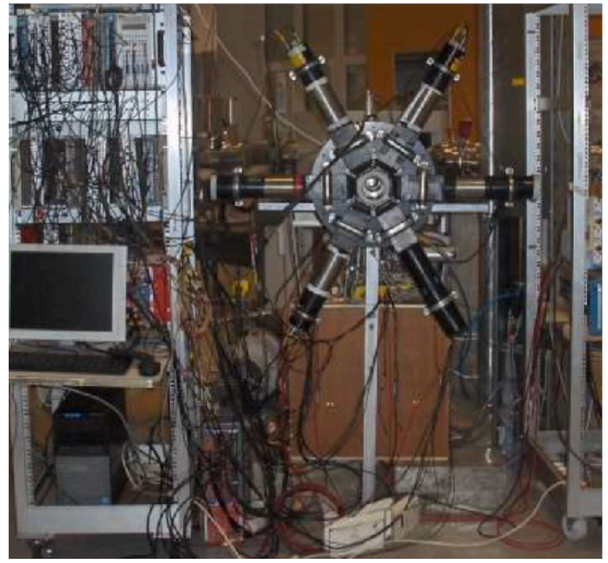
X17

- Seen in 5- and 6-fold detectors
- Seen in 3 different nuclei
- Could be nuclear effects, maybe intermediate state, interference, anomalous form factor... but no clear explanation yet.



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		





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X17 Through SM Effects?

- **NLO corrections and careful interference handling?** maybe, but explanation does not yet fit all observations (arxiv:2102.01127)
- **EFT framework?** requires unrealistic form factors for 8Be (https://doi.org/10.1016/j.physletb.2017.08.013)
- **nuclear decay chain with γγ→e+e-?** Can match rates and kinematics, but reaction 'not favoured in established nuclear models', and doesn't explain isospin structure (https://doi.org/10.1016/j.nuclphysa.2021.122143)
- **exotic tetraquark?** Can fit resonance, but predicts second resonance that should have been observed (arxiv:2006.01018)
- **...other exotic SM?**

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X17

- Angular momentum conservation in the different decays constrains the X17 J^P
- ATOMKI measurements each consistent with axial vector
  - and consistent with each other in terms of implied couplings.

	scalar 0^+	pseudo-scalar 0^-	axial vector 1^+	vector 1^-
8Be $1^+ \rightarrow 0^+$	✗	✓	✓	✓
4He $0^- \rightarrow 0^+$	✗	✓	✓	✗
12C $1^- \rightarrow 0^+$	✓	✗	✓	✓

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adapted from Daniel Firak (SBU)

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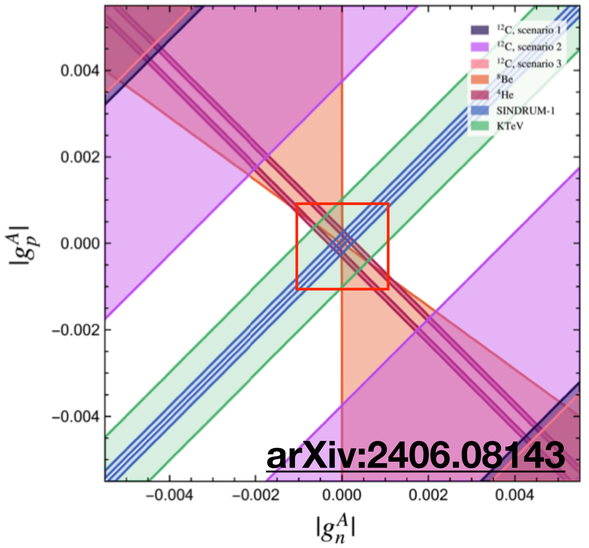
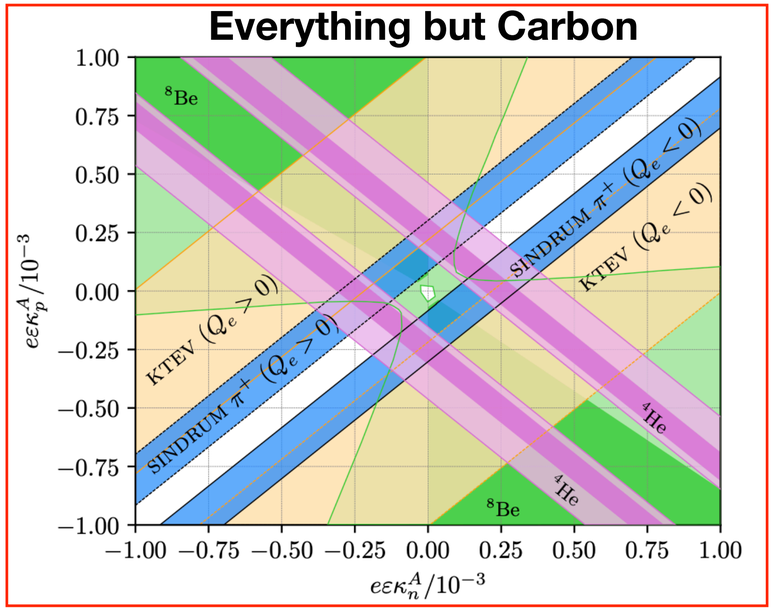
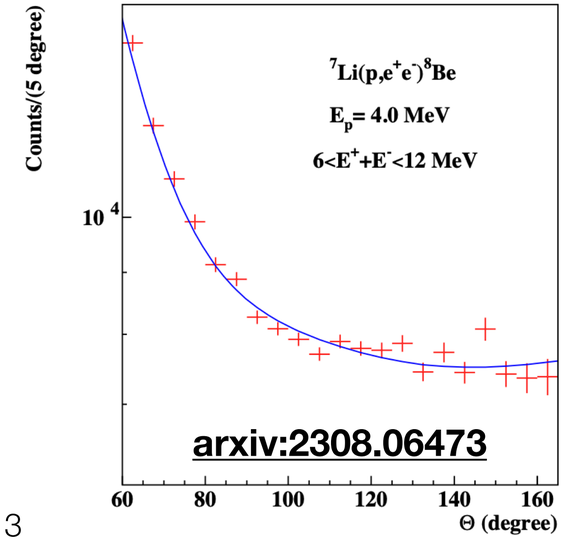
Further X17 News

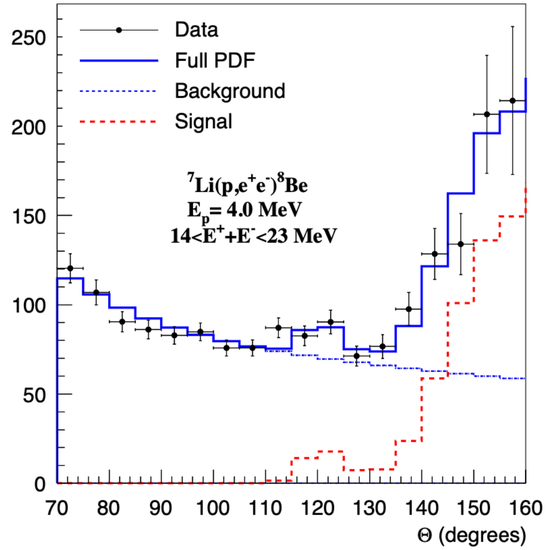
- Axial-vector particle with mass ~17MeV tension growing between measurements (Be,He, SINDRUM, KTeV constrain it heavily, C does not fit) (arXiv:2406.08143)

- Miller and Zhang (arxiv:2008.11288): axial-vector X17 should be produced in direct proton capture: ^{7}Li(p,e^{+}e^{-})^{8}Be off-resonance
- ATOMKI group sees it (with caveats): (arxiv:2205.07744)
- X17 should be visible in GDR (arxiv:2305.09066)
- ATOMKI group sees it (arxiv:2308.06473)









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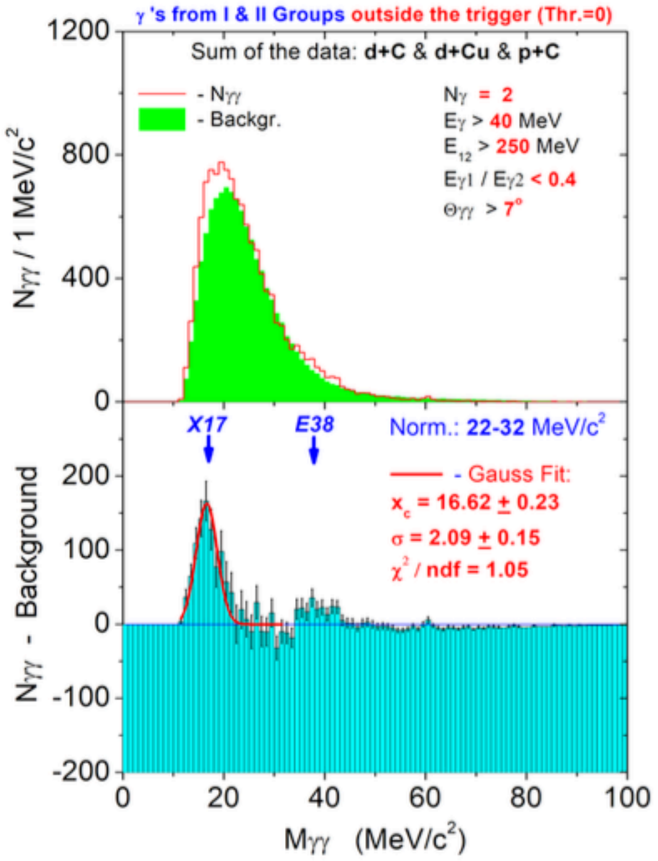
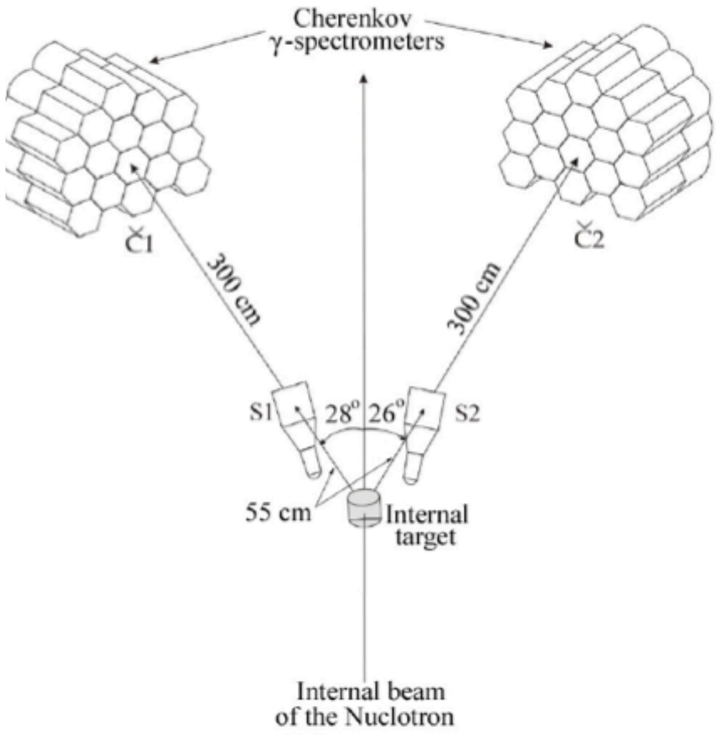
X17 at JINR

- *not* ATOMKI.
- re-analysis of data from Phys.Rev.C80:034001,2009
- p+C→γγ+X @ 5.5GeV/c (and d,p on C,Cu, 2.7-3.8 GeV/*c*/*n*)
- Designed for eta mesons spread across arms, but can look at γγ within a single arm.
- Combinatoric background from mixed events
- Signal shows up at low edge, but not 'last bin'.





arxiv:2311.18632

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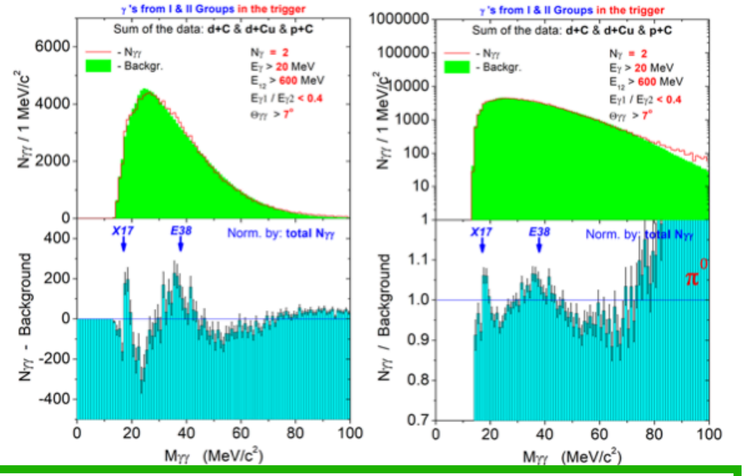
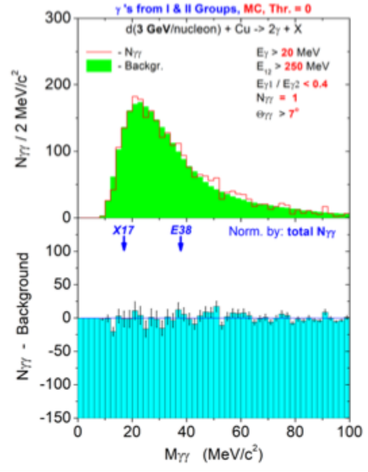
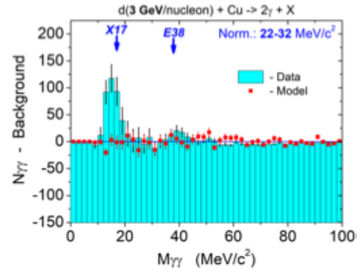
X17 at JINR

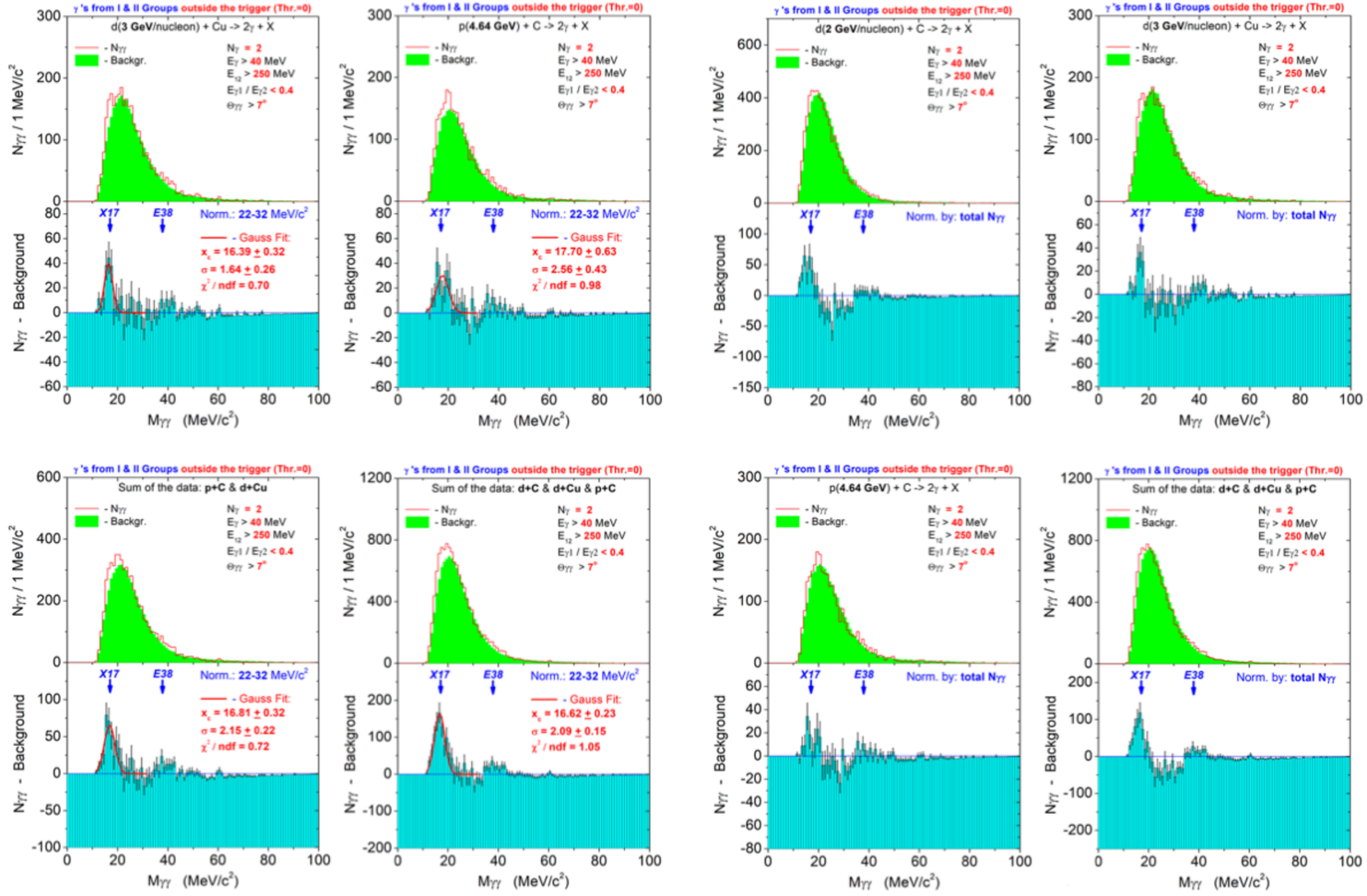
- A variety of datasets, cuts, and background normalizations...





Monte Carlo and ratio to data





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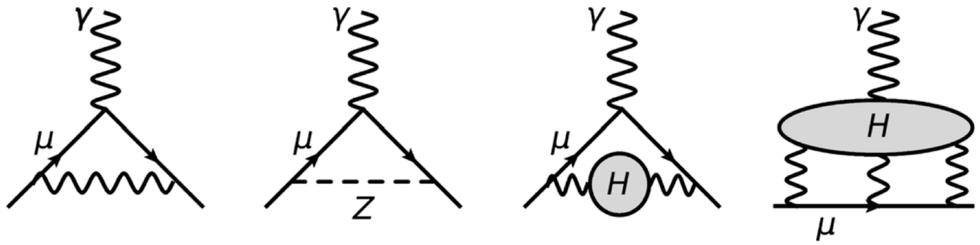
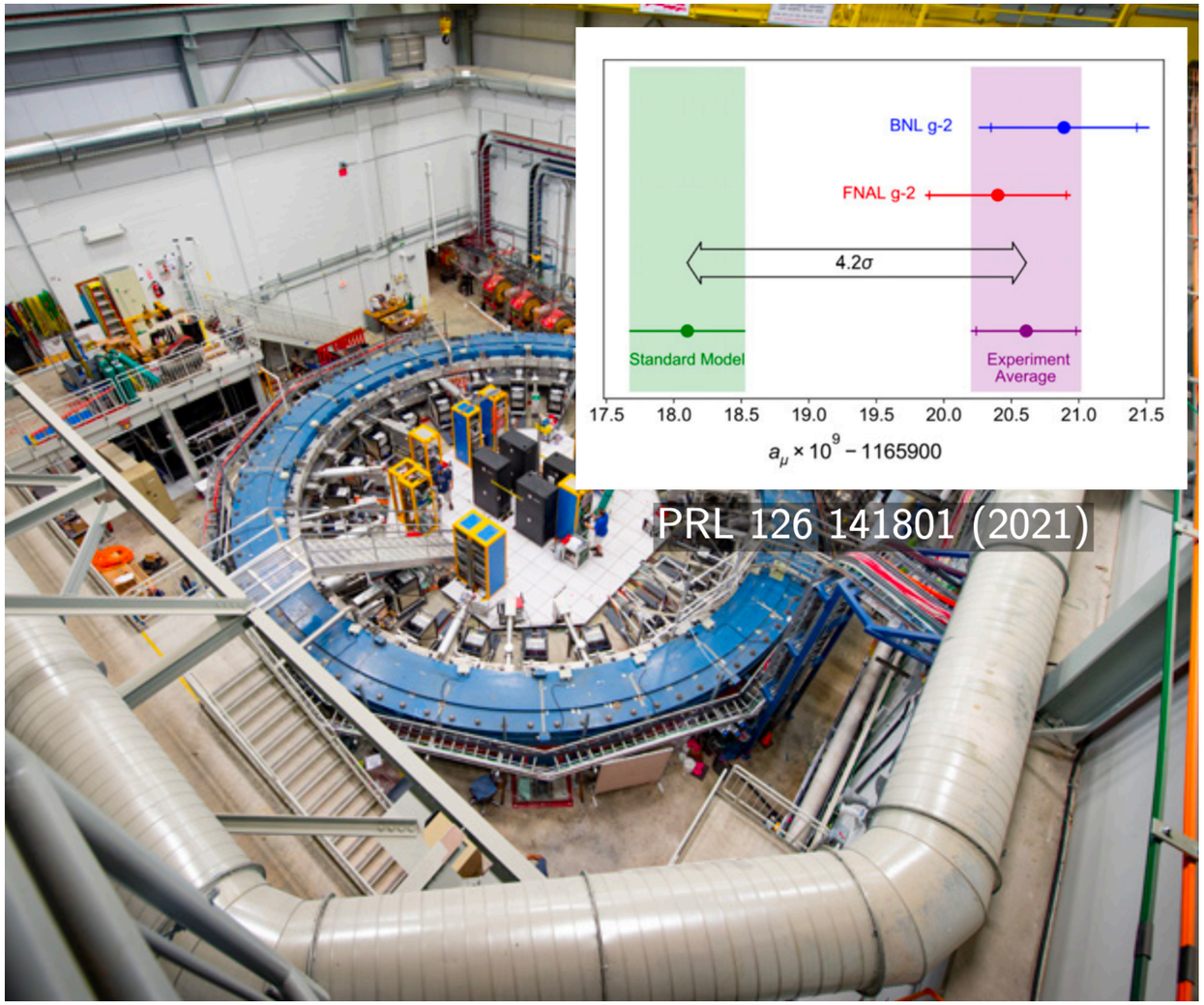
Fermilab g-2



- NLO effects in ***μμγ*** vertex yield 'anomalous' magnetic moment
- Measured anomalous moment is *anomalously* large.
- BSM physics would also appear here too (and generally have a larger effect than for electron)



PRL 126 141801 (2021)

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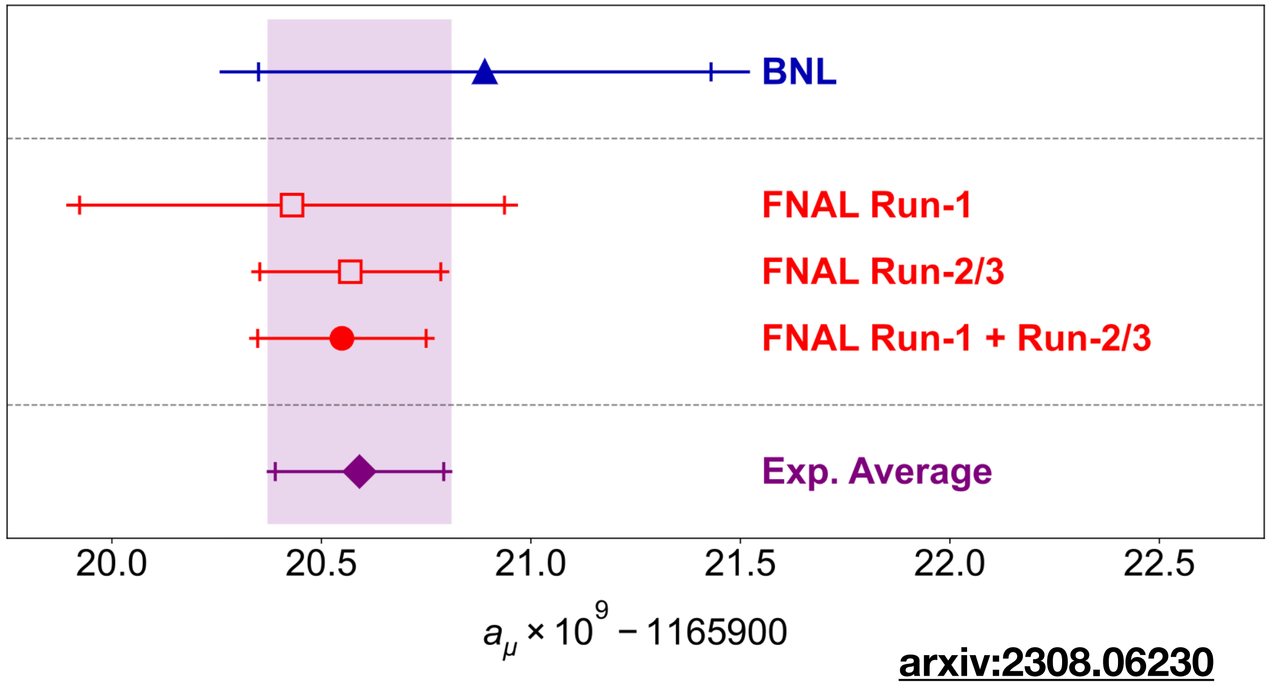
Combined Result

- New result using 2019+2020 data halves systematic uncertainties
  - and three more years of data should get another factor of 2
- Good agreement with previous measurements, 5σ tension with 2020 theory.
- But theory no longer in the main result-plot...



arxiv:2308.06230

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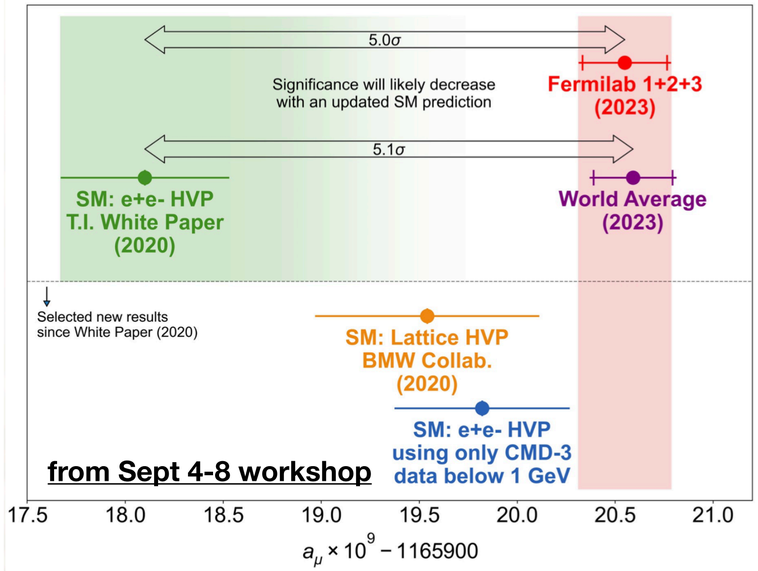
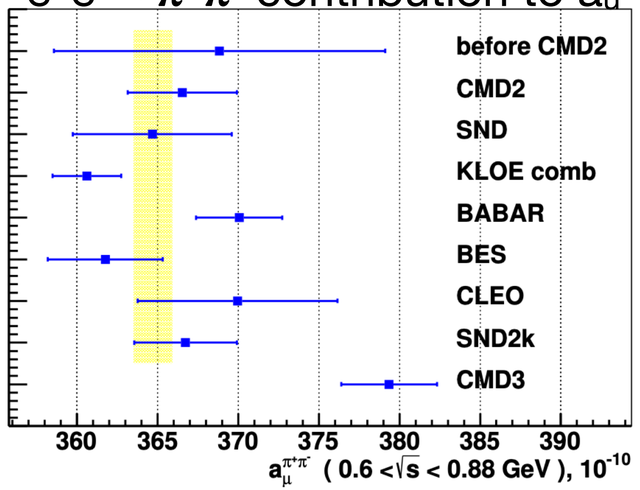
g-2 Theory

- 2021: Tension between predictions from Lattice and dispersive theory
  - BMW '21 ~1.5σ away, but with caveats, and was not used in PDG average.
- 2023: series of new, precise dispersive datasets agree with existing data
  - except CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$ (arxiv:2302.08834), in strong disagreement with all previous measurements.



$e^+e^- \to \pi^+\pi^-$ contribution to a_μ



arxiv:2302.08834

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g-2 Future

- Fermilab measurement expects to get another factor of 2 from remaining data
- J-PARC g-2 (E34) is expected to begin data taking in 2028, different systematics.
- Muon g-2 Theory Initiative is looking closely at lattice and dispersive results, and other theory issues
  - But no workshops since our last collaboration meeting.
- Tension between measurement and theory may go down, pushing preferred band down farther.

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A Survey of Searches

- Resonance in Nuclear Decays:
  - COPE - under construction
  - MEGII - **8Be ran in 2023, blinded**
  - Montreal/Project X17 - 8Be run in 2023+, blinded
  - Melbourne TPC - some prototypes, no recent news
  - New JEDI - some commissioning, no recent news
  - *et al*.

- General-Purpose Accelerator:
  - Belle II - **stats available. analyzing**
  - FASER - first prelim results now, closes from below
  - LHCb - stats in 2026 or so, no recent news

- Dark-Photon Specific:
  - LDMX - operates 2025+, closes from *below*. data hungry
  - MAGIX - begins 2025+
  - Mu3e - begins 2025+
  - NA64 - can modify to target X17
  - PADME - **ran in 2022. blinded. analyzing**
  - PRad - begins in 2025
  - *et al*.

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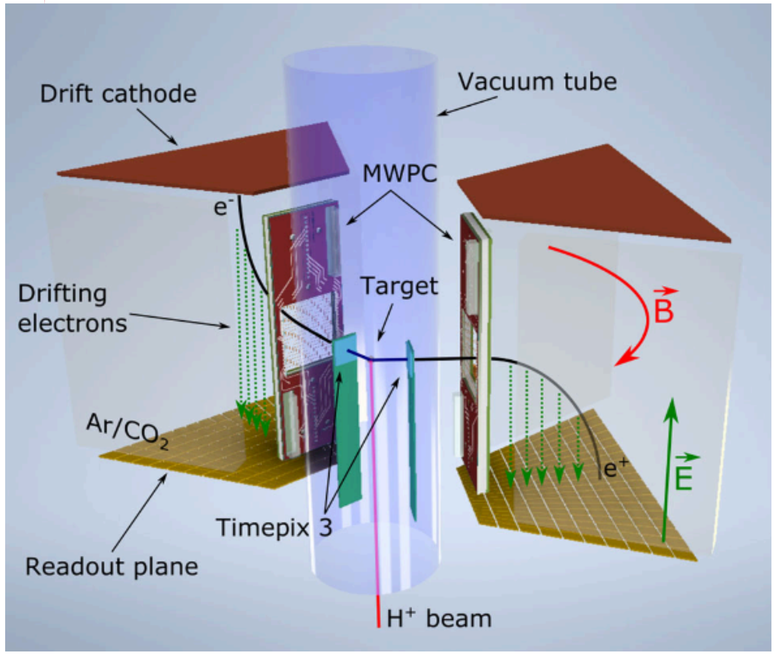
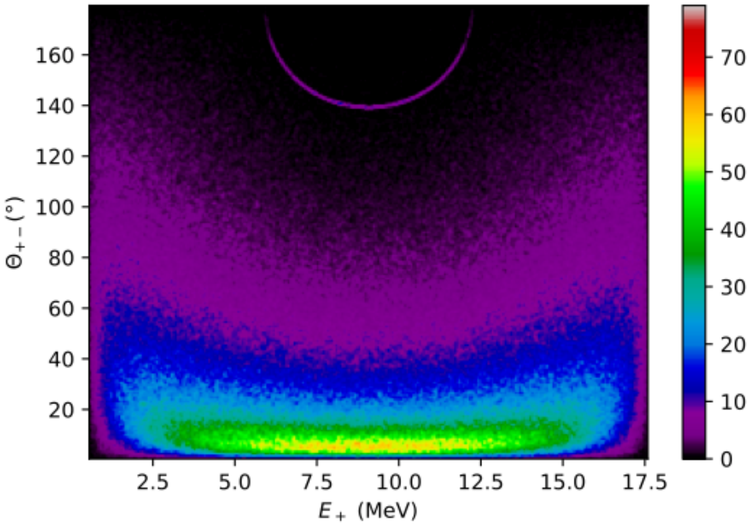
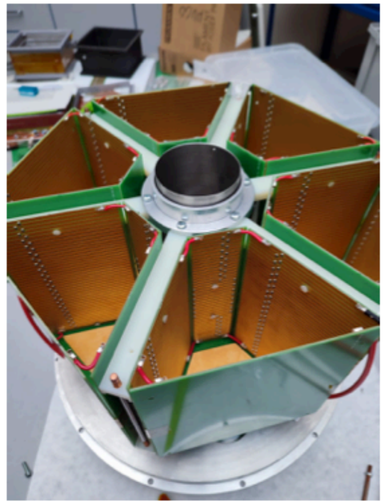
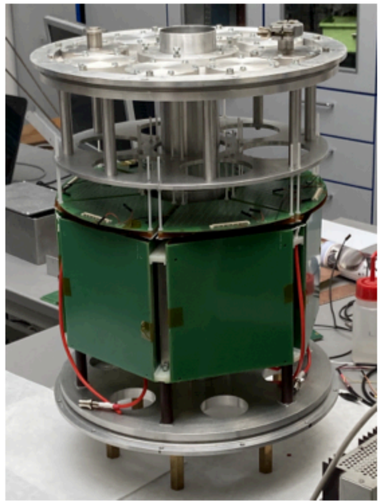
COPE*



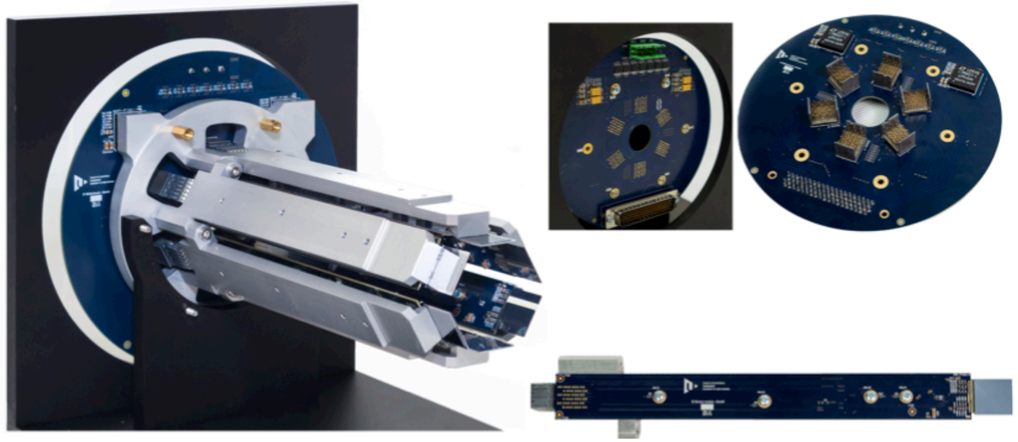


TPC units assembled - but no readout yet





200um Timepix3 hexagon



- COmpact Positron Electron spectrometer @ CTU Prague
- Proton beam on 7Li to produce 8Be and 4He
- Thinned Timepix3 ASICs in vacuum, MWPC+TPC in toroidal field
- No projected reach, but simulated ATOMKI peak is stark
- Under construction. TPX3 ready for beam testing, other components in earlier stages of assembly

***name unclear. They called it COPE in 2021, but not in recent presentations**

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ISMD 2023 update

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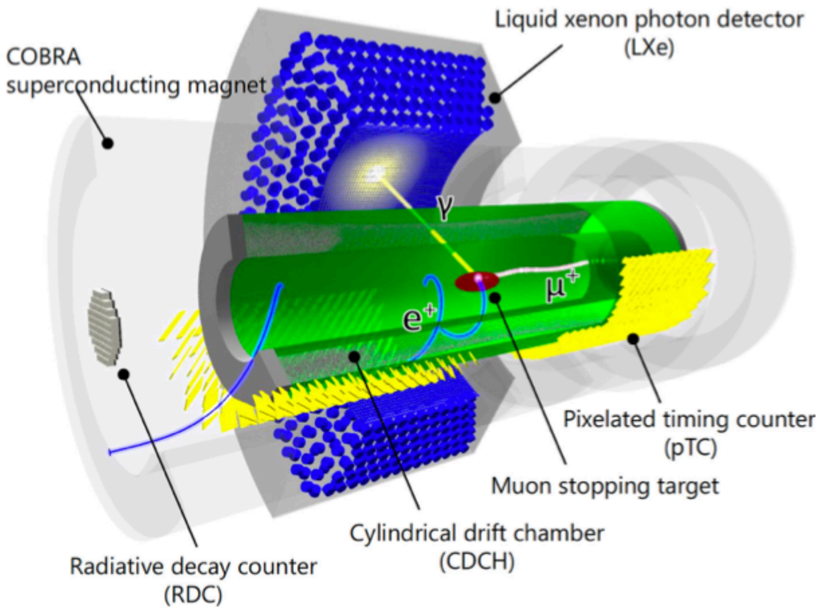
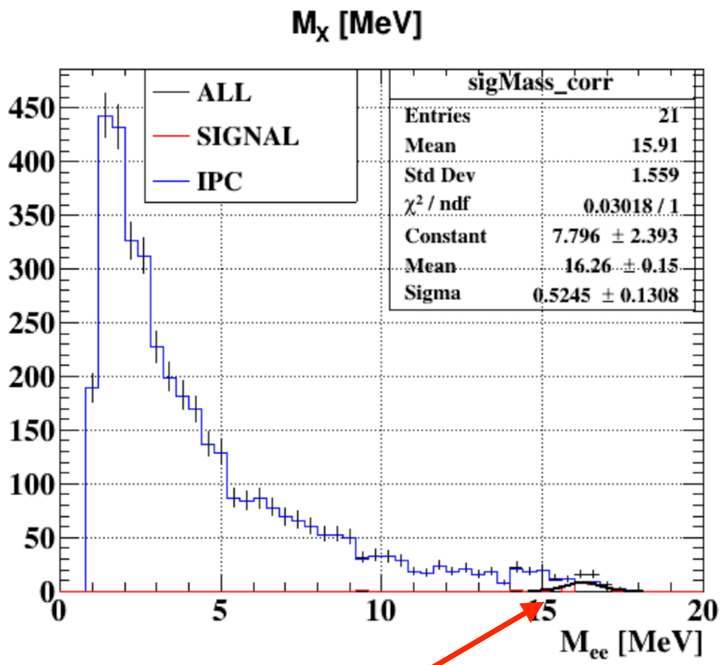
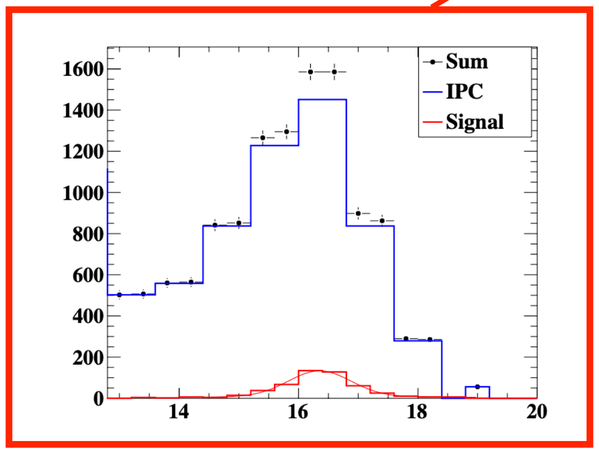
MEGII





- Built for $\mu^+ \rightarrow e^+ \gamma$ BR measurement
- drift chamber suitable for e+e- tracking, 0.5MeV mass res. with field turned down. Target region may still need redesign?
- proton beam produces 8Be states off Li target (used for calibration of LXe)
- **Ran while PSI shutdown:** 90M events accumulated as of May 2023
- Analysis in early stages

5σ in 40hrs, if IPC shape well controlled.



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Oct 2023 update

Manuel Meucci, 2022

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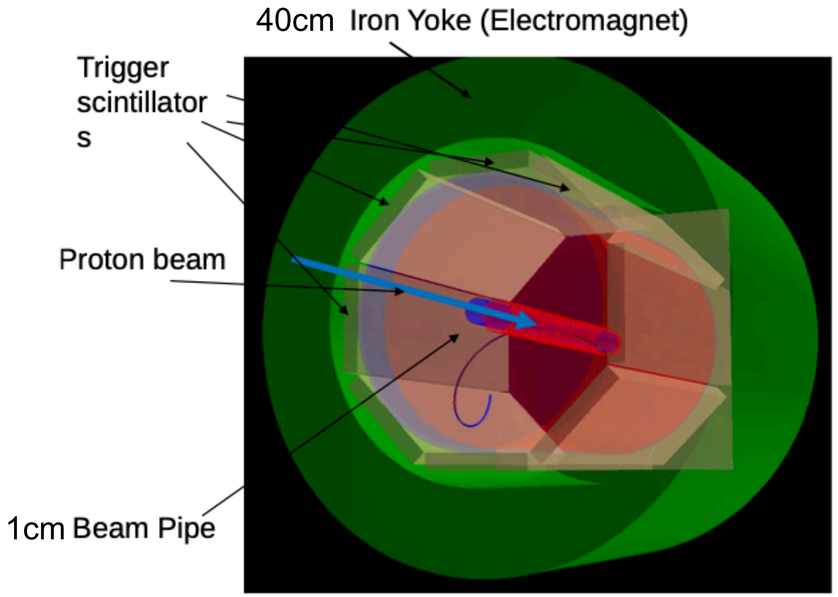
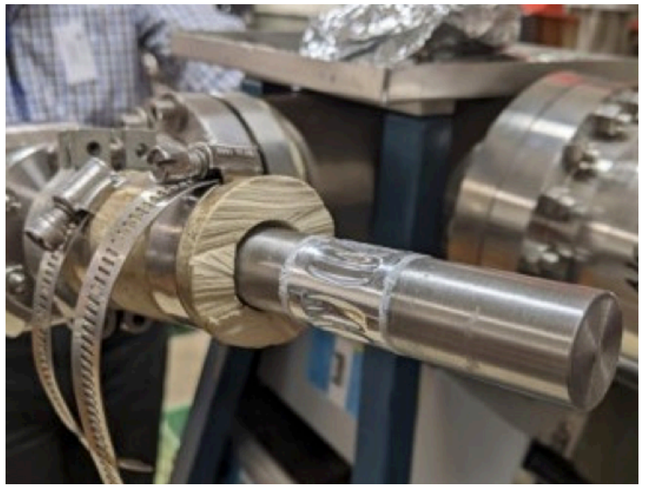
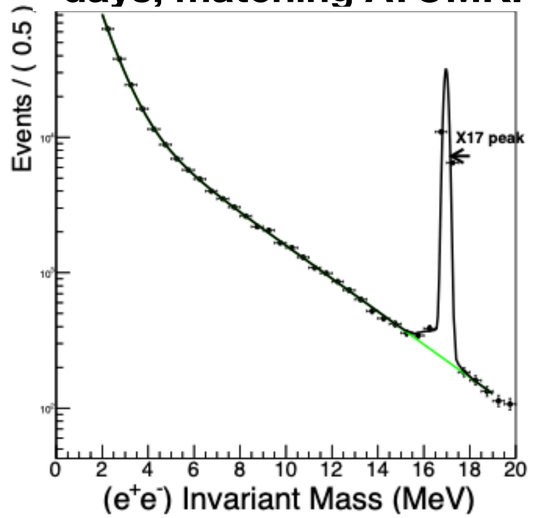
Melbourne TPC



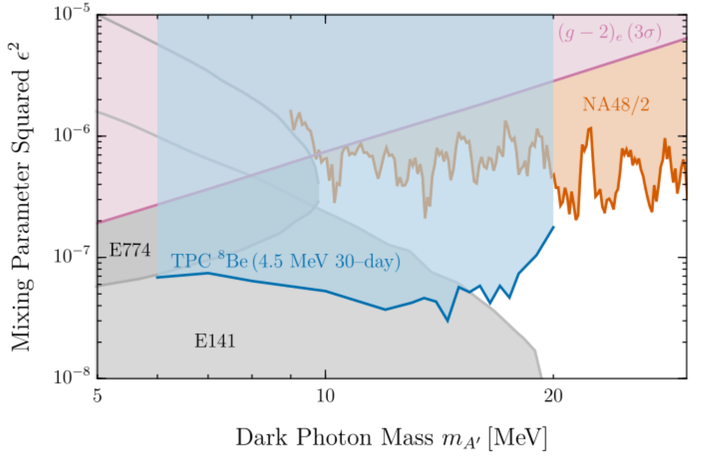
Prototype Chamber



Simulated Yield with 30 days, matching ATOMKI



- Purpose-built TPC for e+e- tracking, scintillating outer radius for trigger
- proton beam + target in vacuum, 50um mylar-window beampipe
- 8Be states off Li target, many other targets envisioned.
- Simulated including multiple scattering --> σ_M~100keV
- Proposed, some prototypes. No timeline yet.



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August presentation **arxiv:2302.13281**

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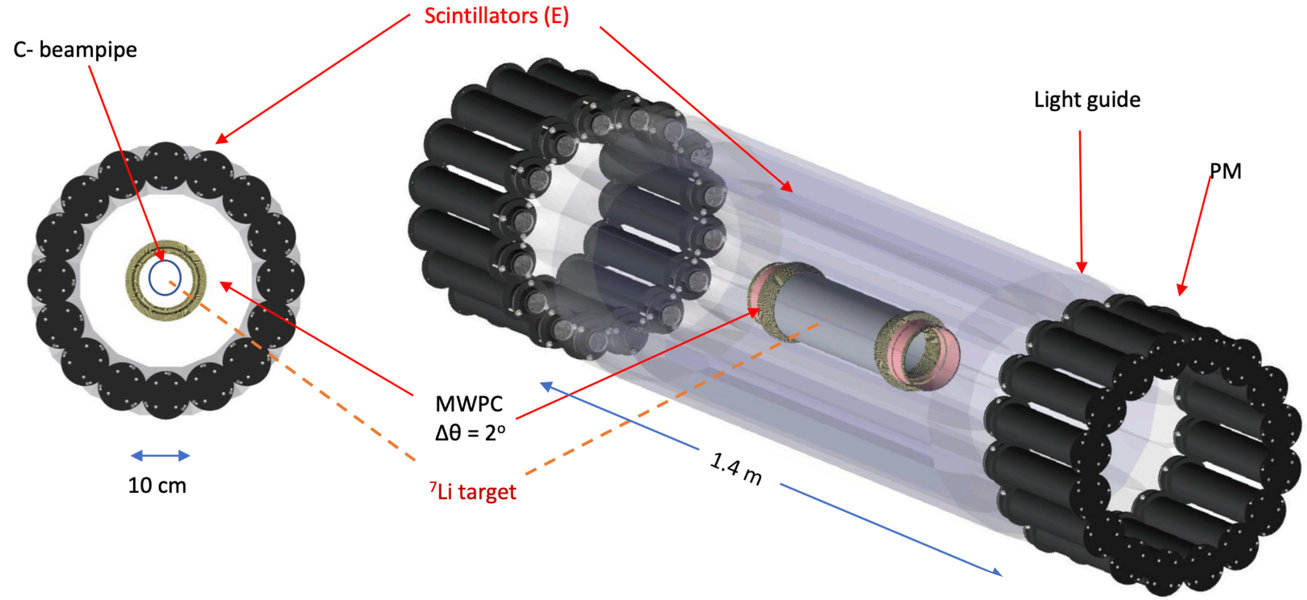
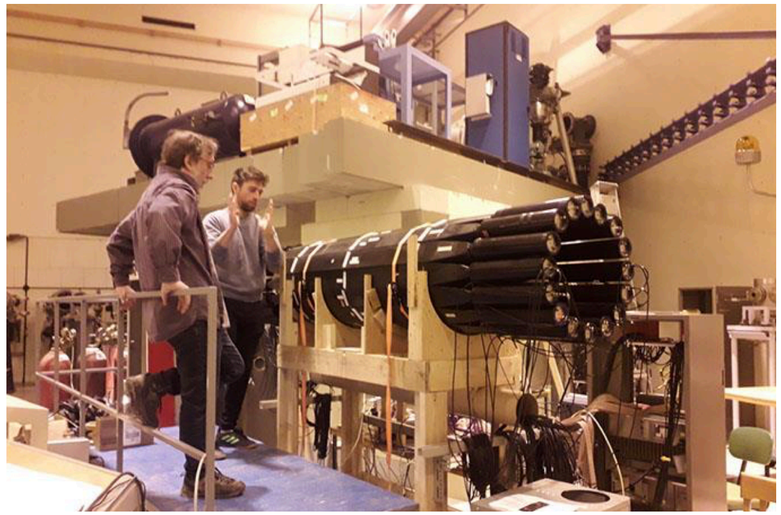
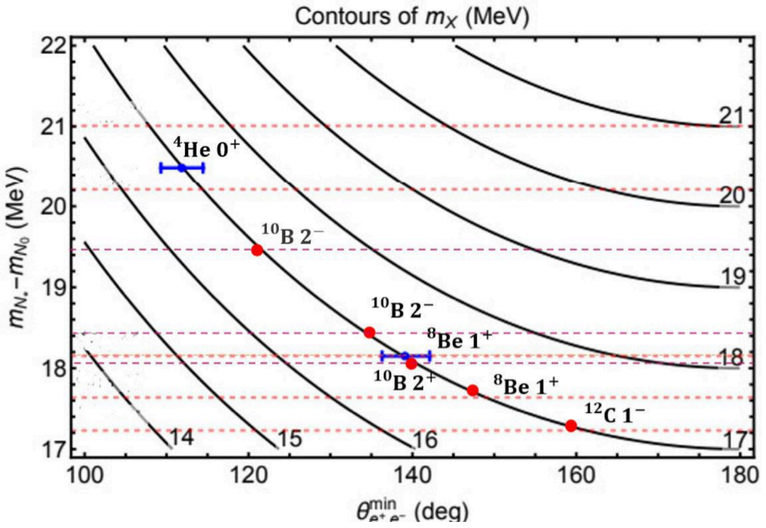
Montreal/Project X17







- High-acceptance, high resolution (~2º) verification of ATOMKI using DAPHNE parts, MWPCs, Scints
- Commissioning. Expected to take ^{8}Be data in 2023, but no news
- ^{3}He capture on ^{7}Li opens ^{10}B search as well (2024)
- GDR also accessible

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(July presentation)

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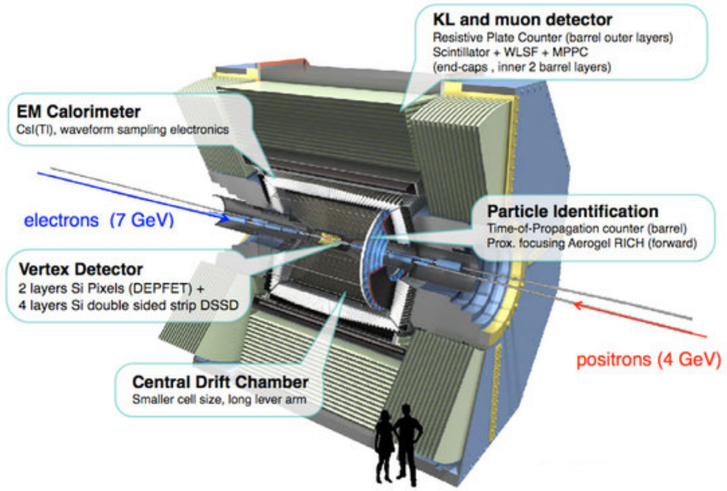
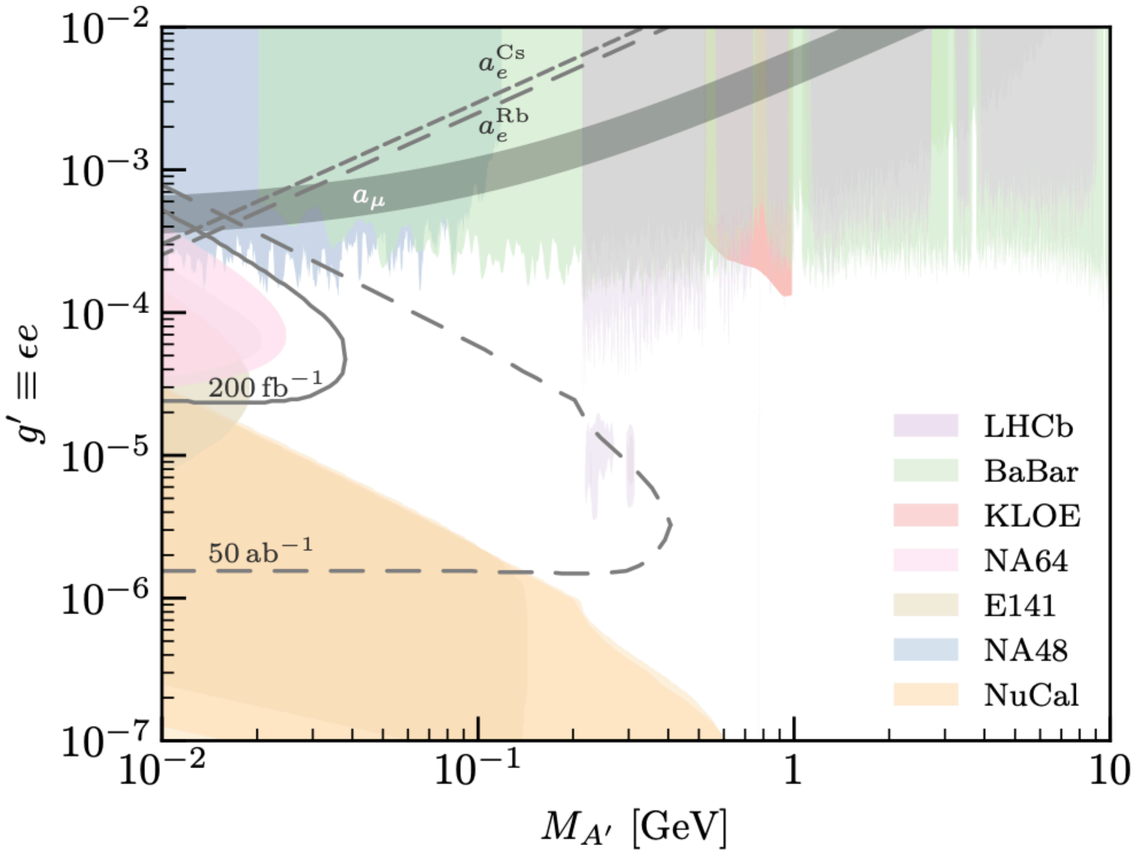
Belle-II





- Direct measurements don't reach down far enough even with full dataset. arxiv.:2012.04190
- X17-specific search (right) uses displaced vertices in J/Ψ decay
- ~200fb^{-1} collected as of 2023, 50ab^{-1}, expected by ~2025
- Analysis underway. **Claim that existing stats enough to exhaust protophobic X17 region** ($2\epsilon_u + \epsilon_d < 0.1\epsilon_u$).

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arxiv.:2203.03280

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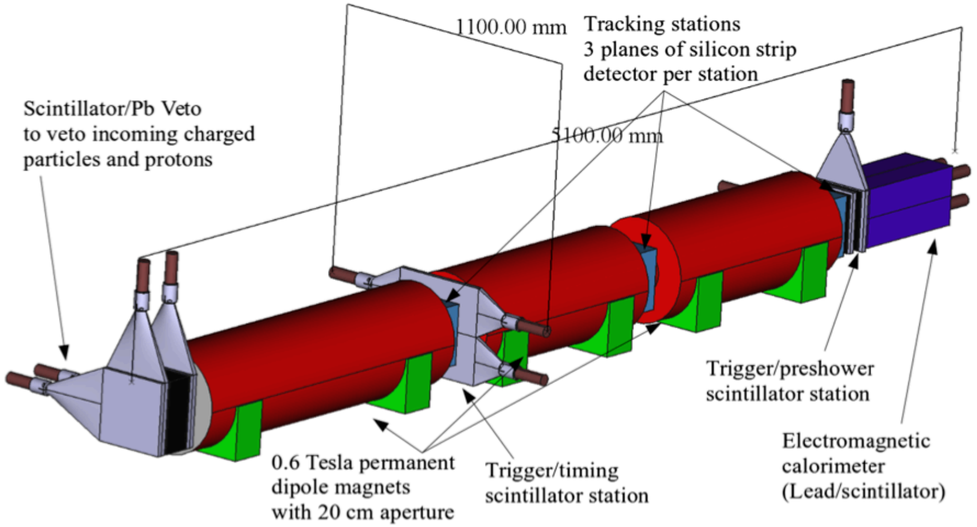
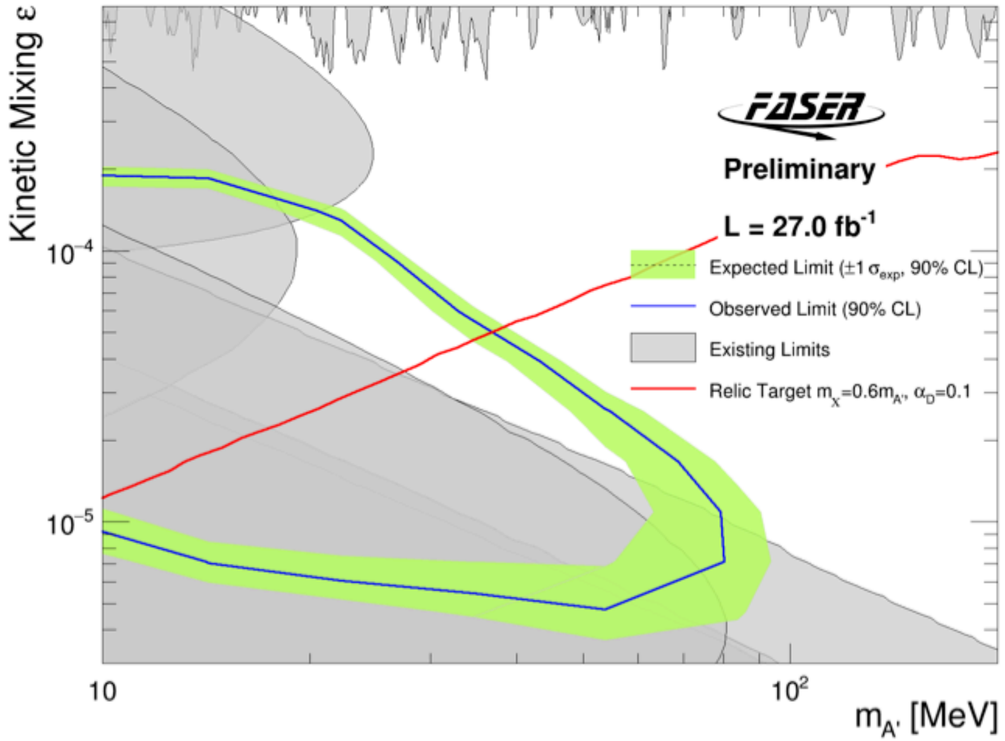
FASER





- ForwArd Search ExpeRiment, 480m downstream of ATLAS at LHC
- ECAL + Tracking stations with long dipole magnets
- Look for boosted A' decay to e^+e^- inside FASER volume.
- Beats NA64 only from below
- Prelim 27fb^{-1} from 2022 run closes/double-covers low-coupling

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arXiv:2305.08665

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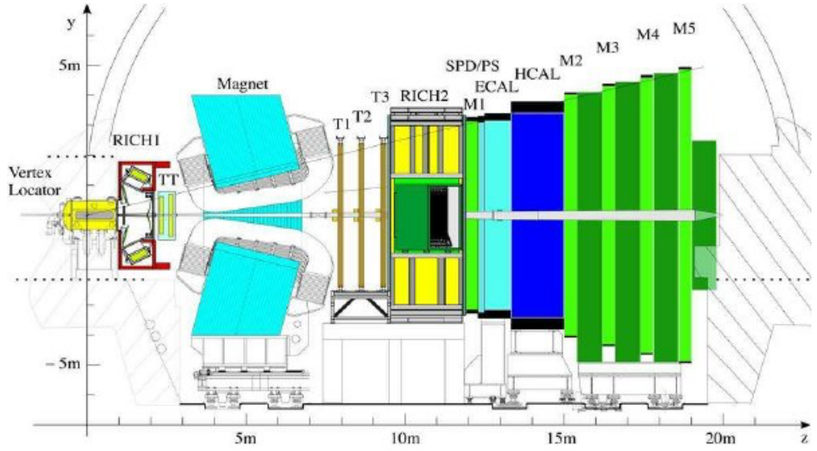
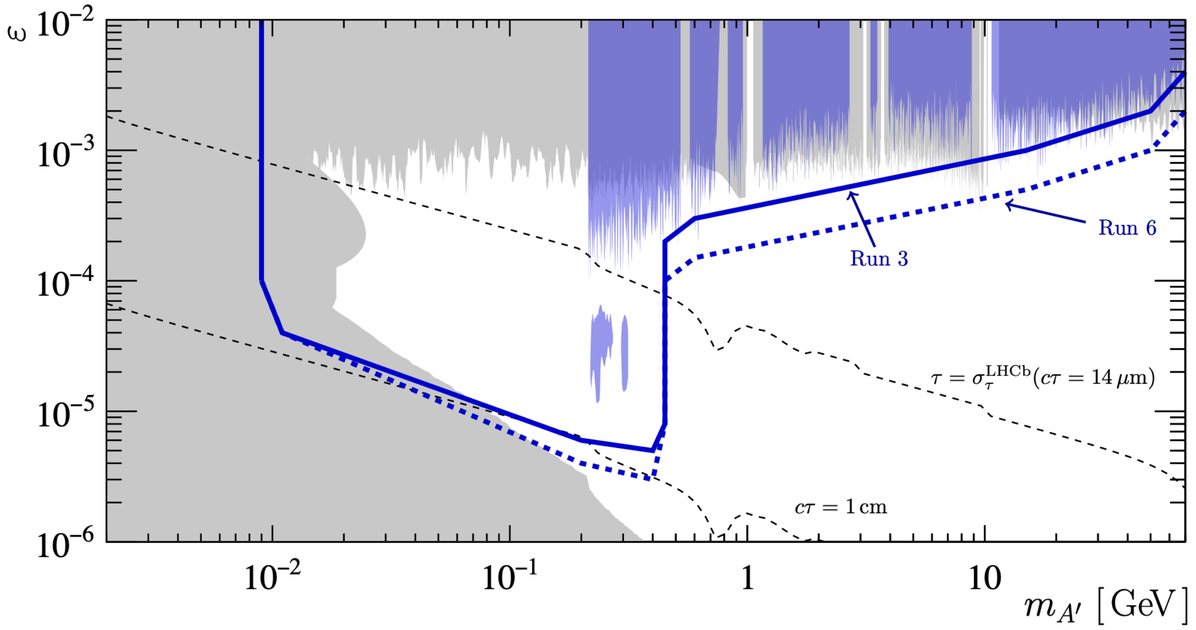
LHCb



- Upgrade for current run allows softer final states to be recorded
- 'recent advances' in trigger enable e+e- final states
- Can exhaust parameter space even with protophobic with sufficient data, (solid blue line, 2022-2026)
- No news yet (about dark matter) in 2024...



arXiv:2203.07048

(P. Ilten paper (arXiv:1801.04847) allows to recast simple dark photon measurements in more complex models)

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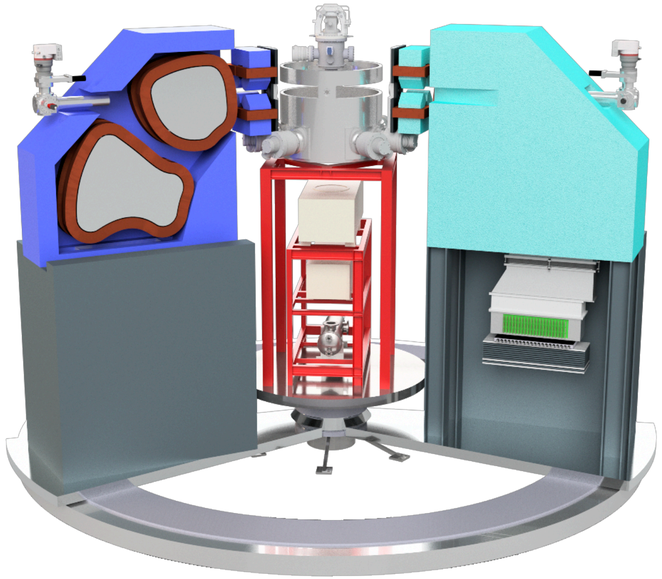
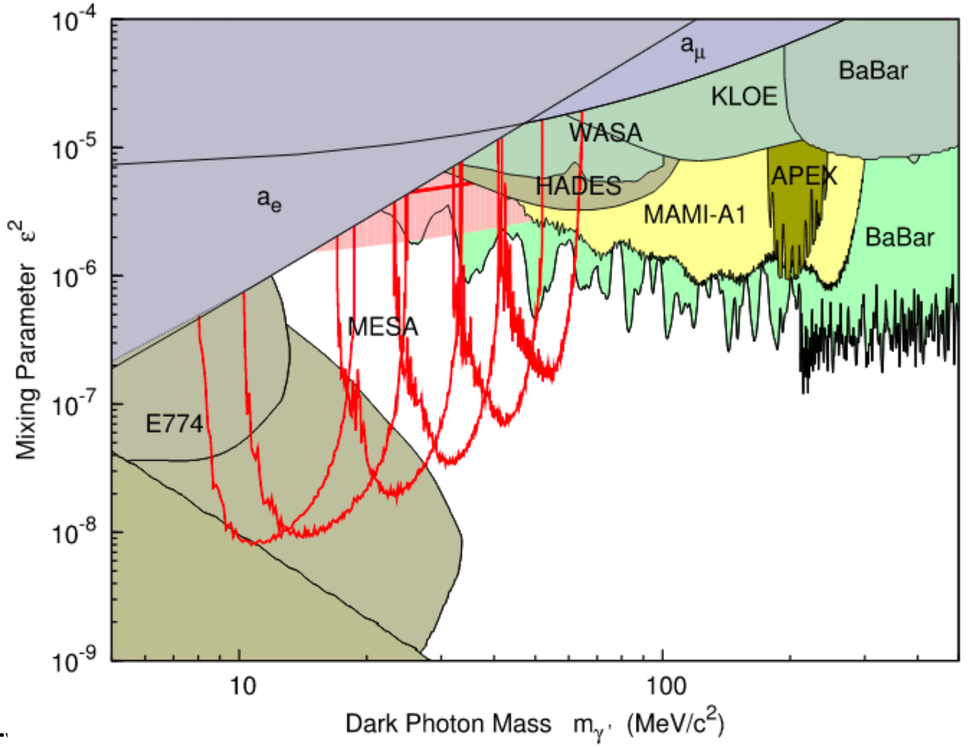
MAGIX





- Twin spectrometer, gas target @ MESA, 0.1MeV resolution
- Projects to reach X17 anomaly region w/ ~6mo at design luminosit,
- Direct e-X and also γD → e+e-pn bump-hunt
- MESA still under construction
- MAGIX start-up "shortly after" beam available

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arxiv:2307.02181 arxiv:2402.01027

https://magix.uni-mainz.de/physics.php

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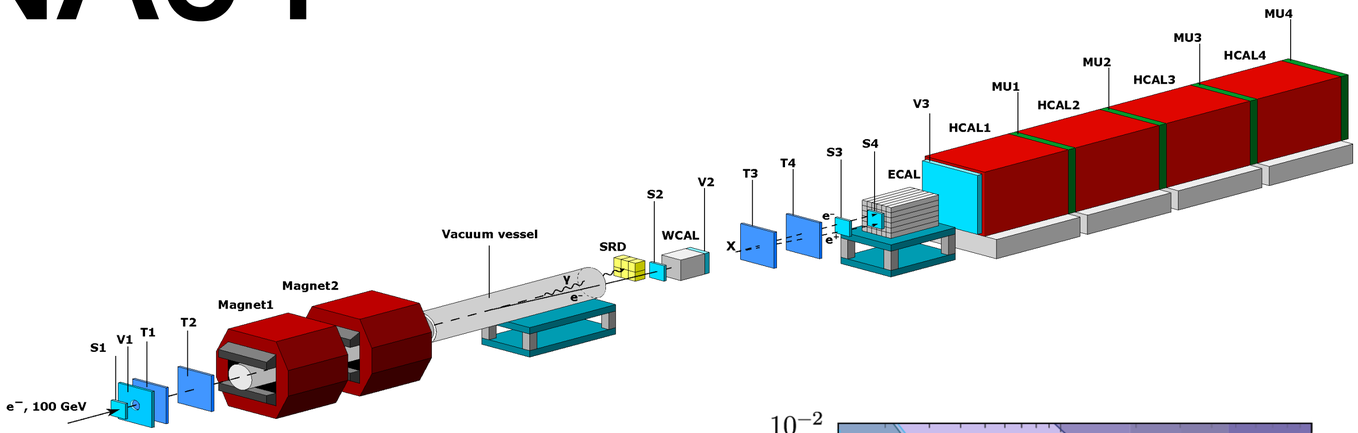
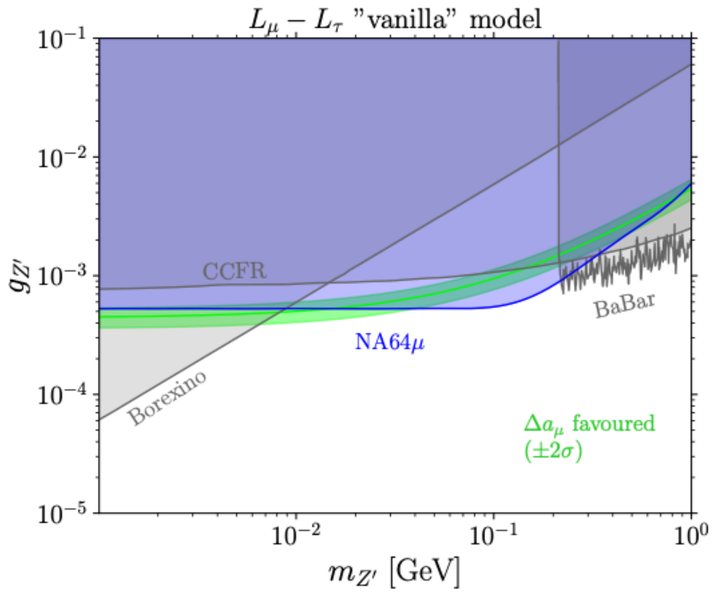
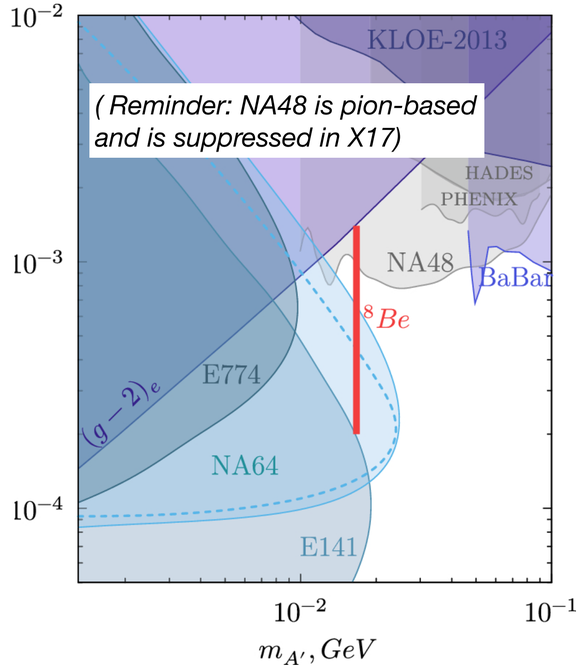
NA64

- e and mu fixed target experiment (SPS)
- 2020 combined analysis covers much of original ^{8}Be
- Upgrade of WCAL and magnet makes remaining X17 accessible(arxiv:2009.02756)
- Z' search with invisible final states reports no signal in the MeV-GeV range (arxiv:2401.01708)
- Can install upgraded visible setup to exhaust X17, if PADME results encourage.





arxiv:2401.01708



PhysRevD.101.071101

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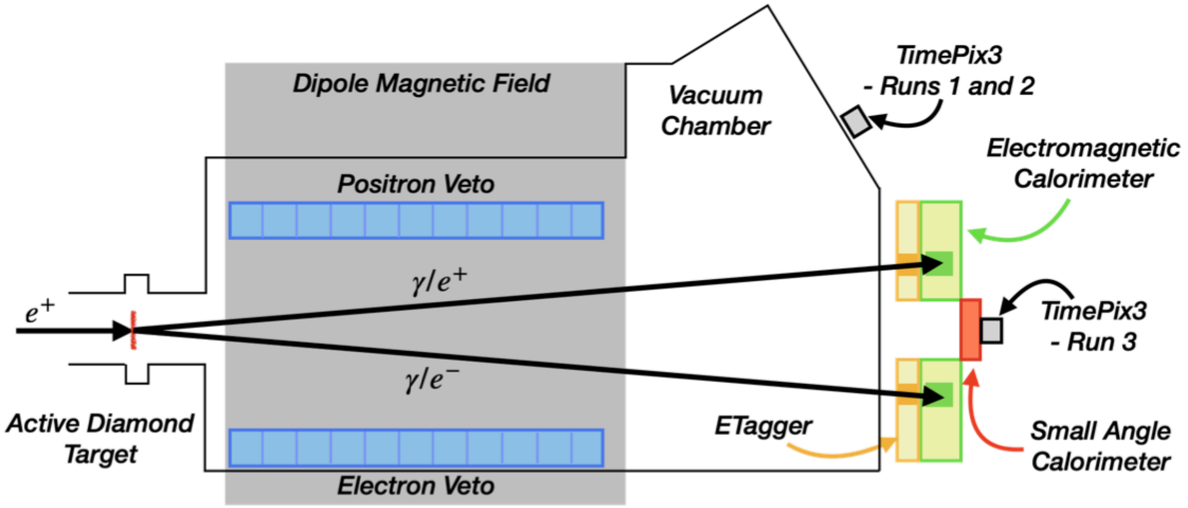
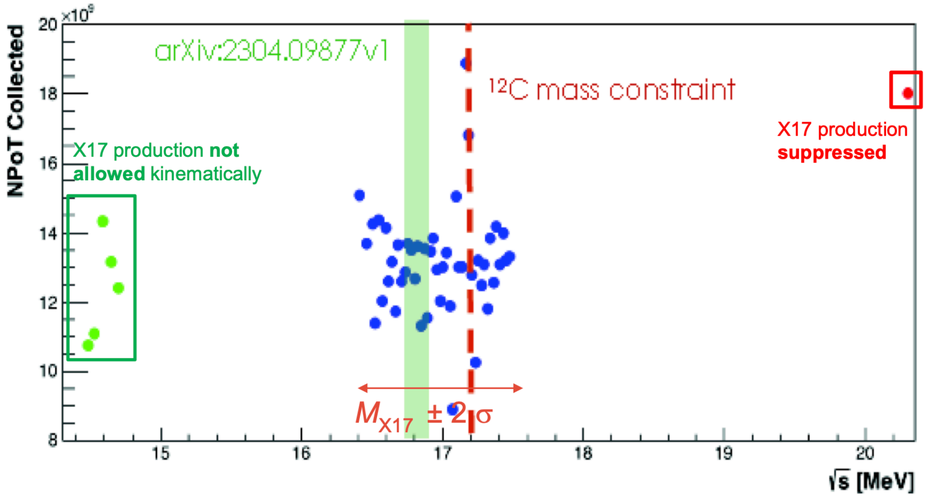
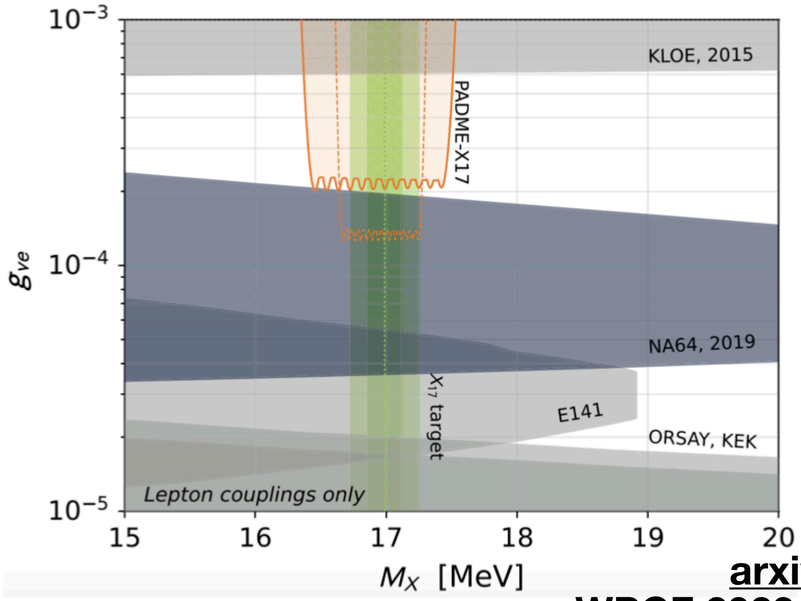
PADME





- Built for $e^+e^- \rightarrow \gamma A'$, modified for resonant X17 production in Run 3
- Data campaign completed in 2022:
  47 points 16.35 MeV - 17.5 MeV 10^{10} PoT each
- With projected sensitivity, fully covers remaining X17 region (narrow comb)



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arxiv:2305.08684
WPCF 2023 presentation

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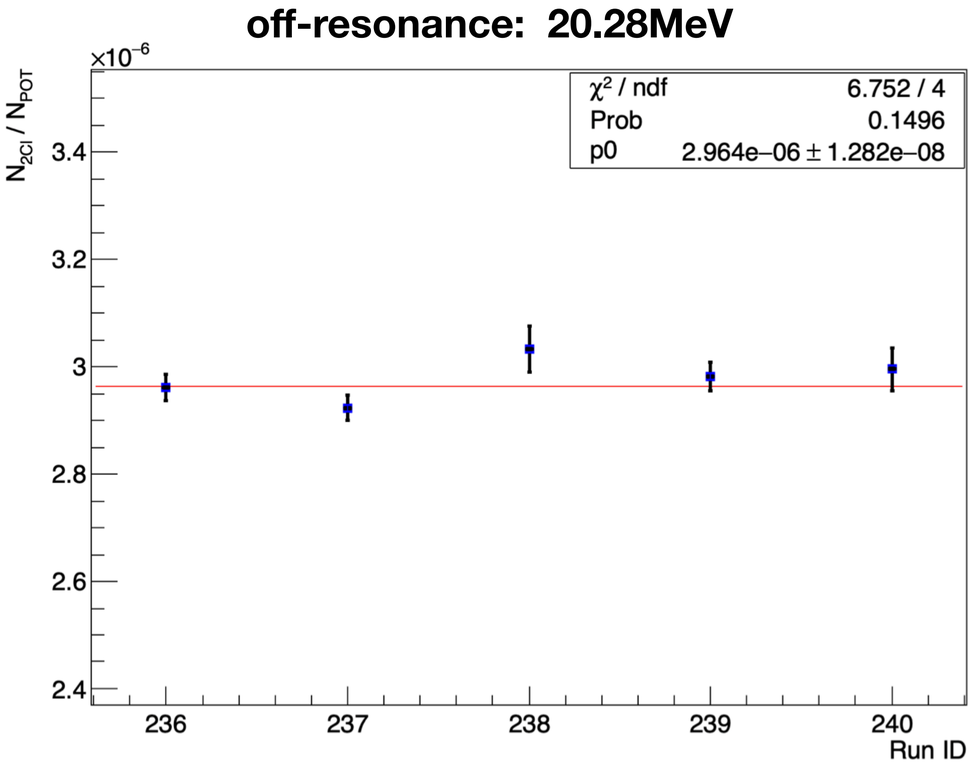
PADME

- Main analysis looks at number of two-cluster events per PoT (counting, not shape)
- X17 coupling predicts ~1% excess
- (May 2024) beam characterization using off-resonance data agrees with projections:
  - Luminosity precision of 2% absolute (<1% relative)
  - Measured beam position, momentum, energy spread, correspond to: σ_M ~40keV, σ_ε ~1%



arxiv:2405.07203

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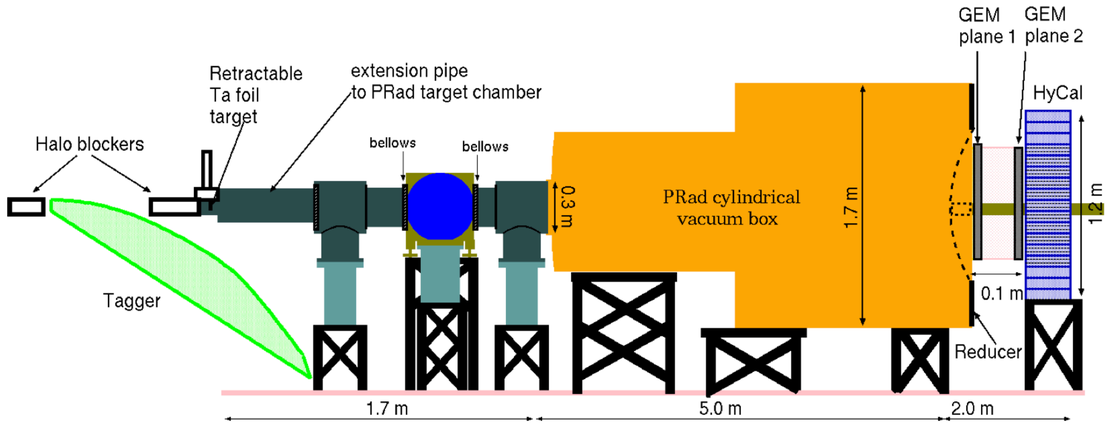
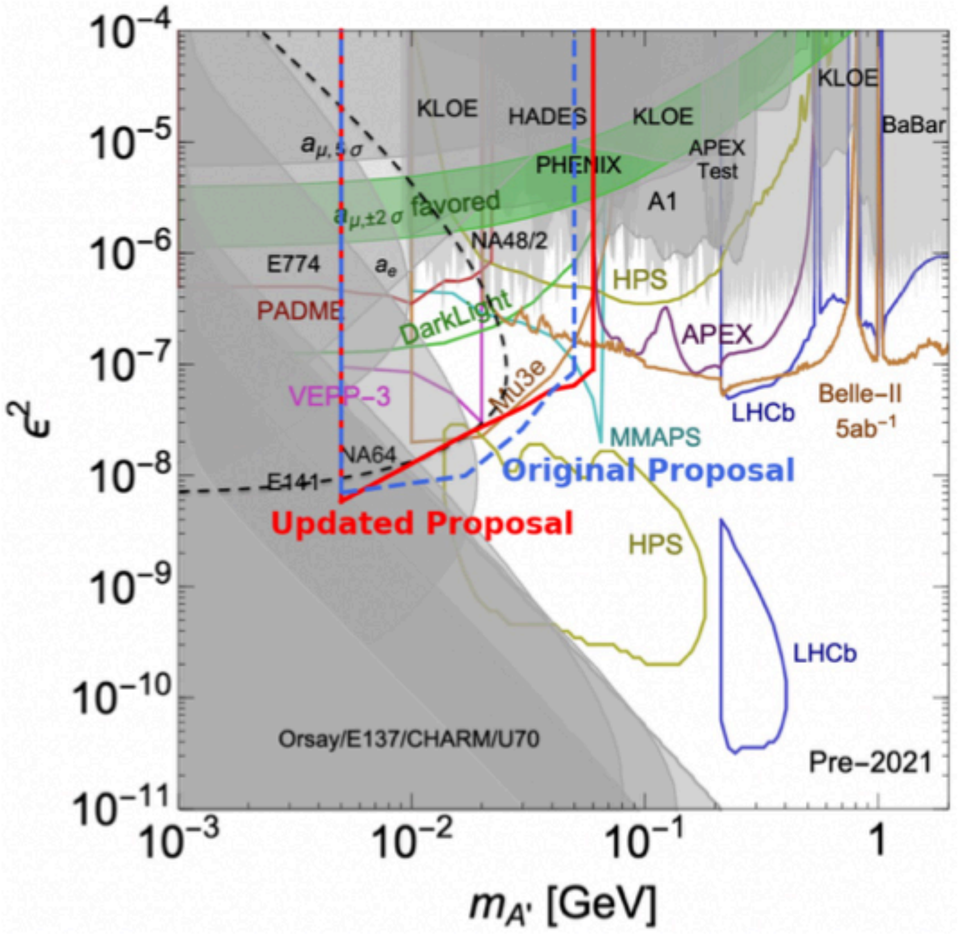
PRad



- Detect full $e^-e^-e^+$ in fixed target e- (JLab)
- Add γ-tagger, 1um Ta targets, GEM tracker planes
- Projection of ~~2.3σ~~ 5.1σ coverage (red)
- Approved for **60** days, PAC50 (2022)
- All components under construction now
- Expecting to run in Fall, 2025



CLAS collab. meeting 2024

arxiv.:2301.08768

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Summary

- Anomalies persist, and a conclusive explanation does not yet exist.
- X17 signals continue to appear, not all from ATOMKI group
- Many experiments are underway, some aiming to reach this region in the near future.
- In some cases, these will provide complementary coverage with DL@ARIEL
-
- "*This [area] is exciting and timely. The measurement/search is needed, and it will receive significant attention if completed before their competitors.*"

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Community Report: **https://doi.org/10.1140/epjc/s10052-023-11271-x**

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New In This Edition

- Isotope shifts now don't need new physics, but are not sensitive enough to exclude.
- 17MeV signals at VNU, JINR
- Additional analysis of ATOMKI results increases tension
- Belle reports data on tape
- COPE* making a lot of progress
- PADME releases more details of off-resonance analysis
- PRad schedule more concrete

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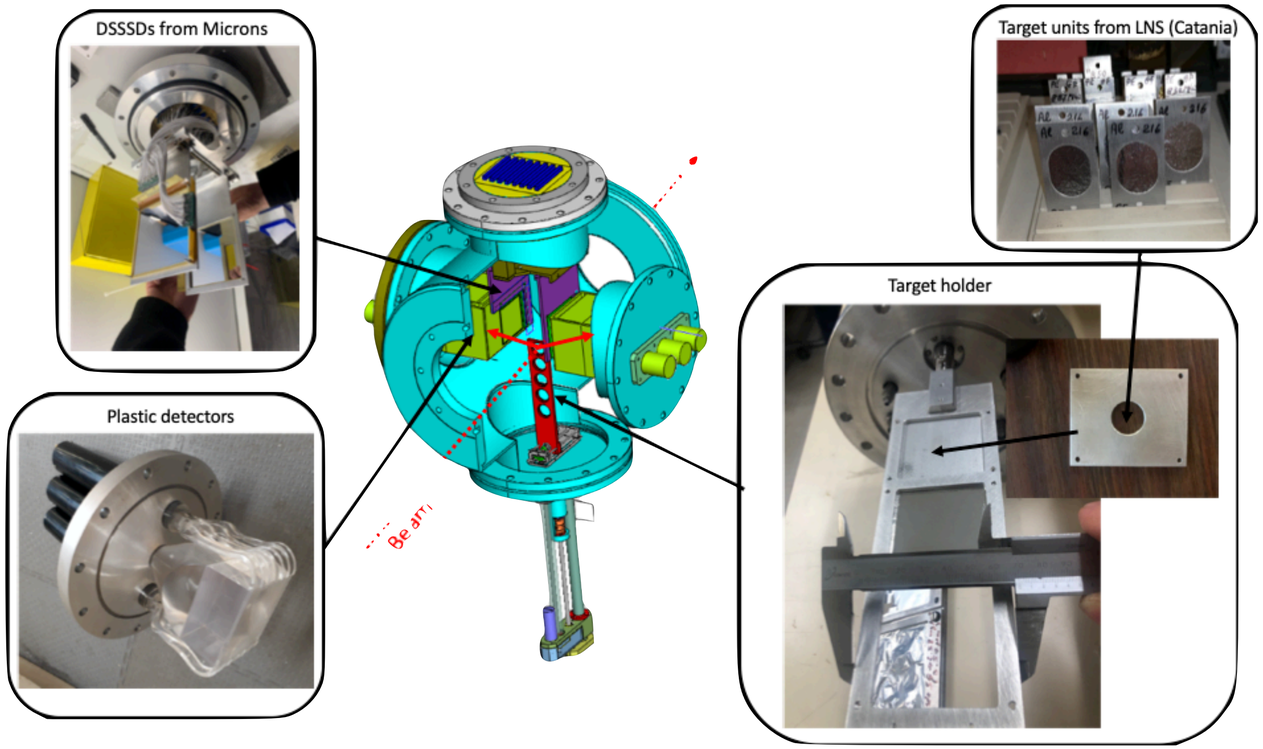
New JEDI

- LiF target on C backing to study $^{8}Be^{*}$
- Double-sided Si Strip Detectors: energy loss and angles for e+e-
- Plastic Scintillator: energy and veto of external events.
- Geometry chosen to focus on X17-like events



- Commissioning in 2020 at Rež tandetron, 470 and 1070keV proton beam.
- Multiple targets to disentangle fluorine contributions to signal
- Proposing MeV-scale program at SPIRAL2 (France)

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EPJ Web of Conferences 275, 01012 (Feb, 2023)

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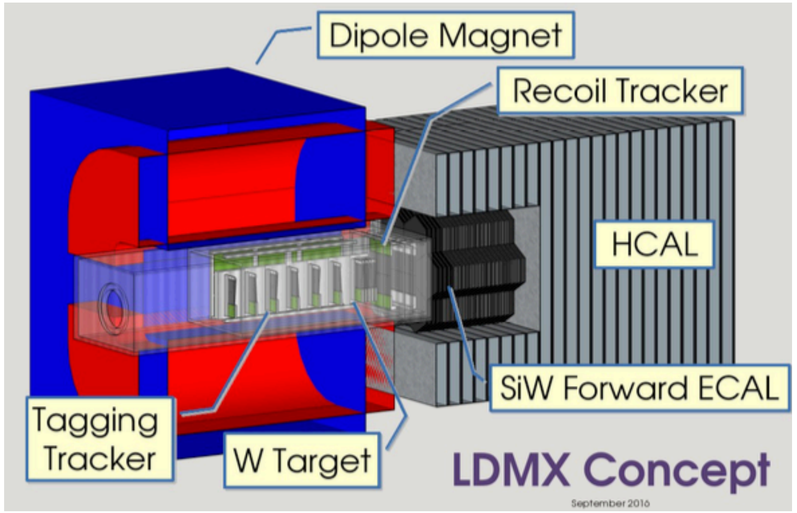
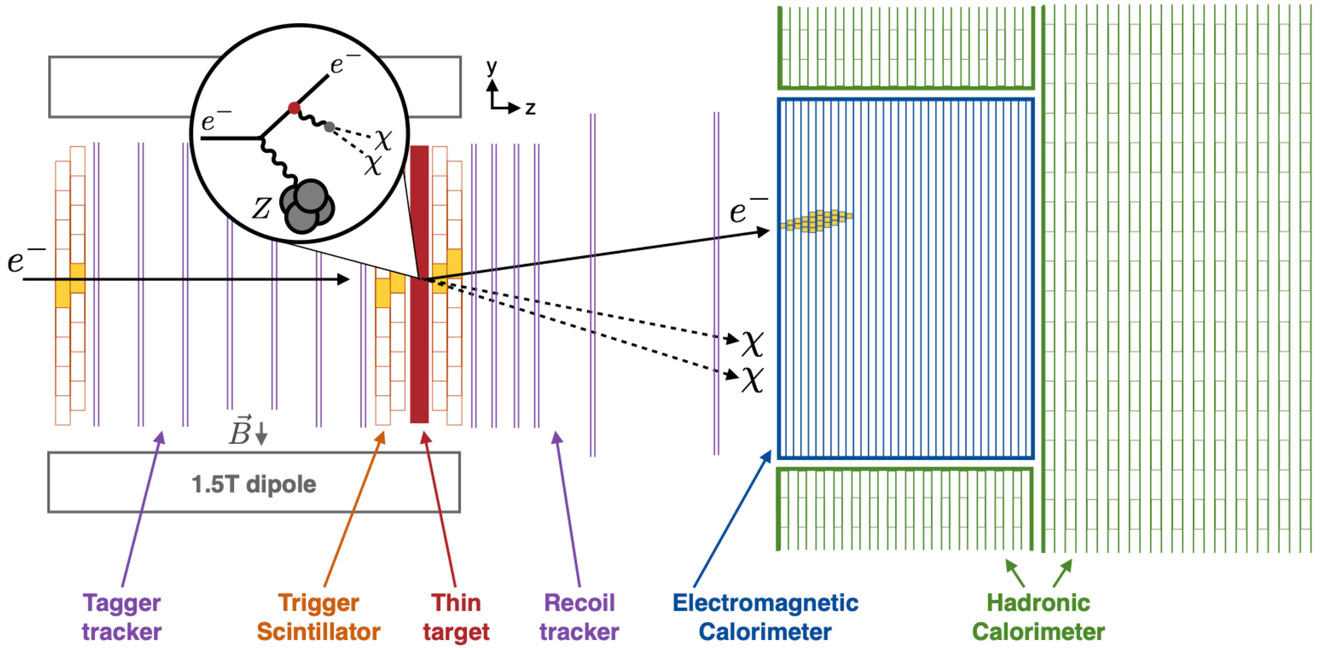
LDMX





- LCLS-II (SLAC) produces low-current, parasitic multi-GeV e^- beam
- Reconstruct e^- and recoil nucleus to detect invisible final states

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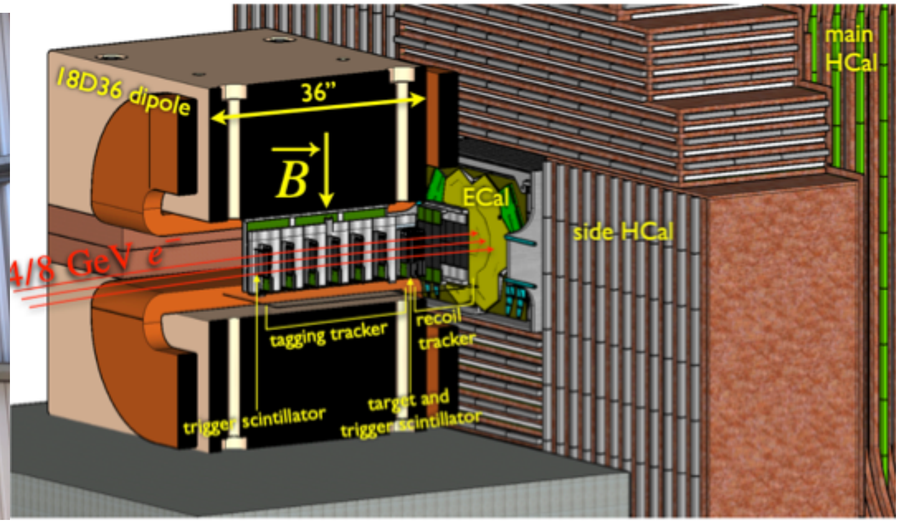
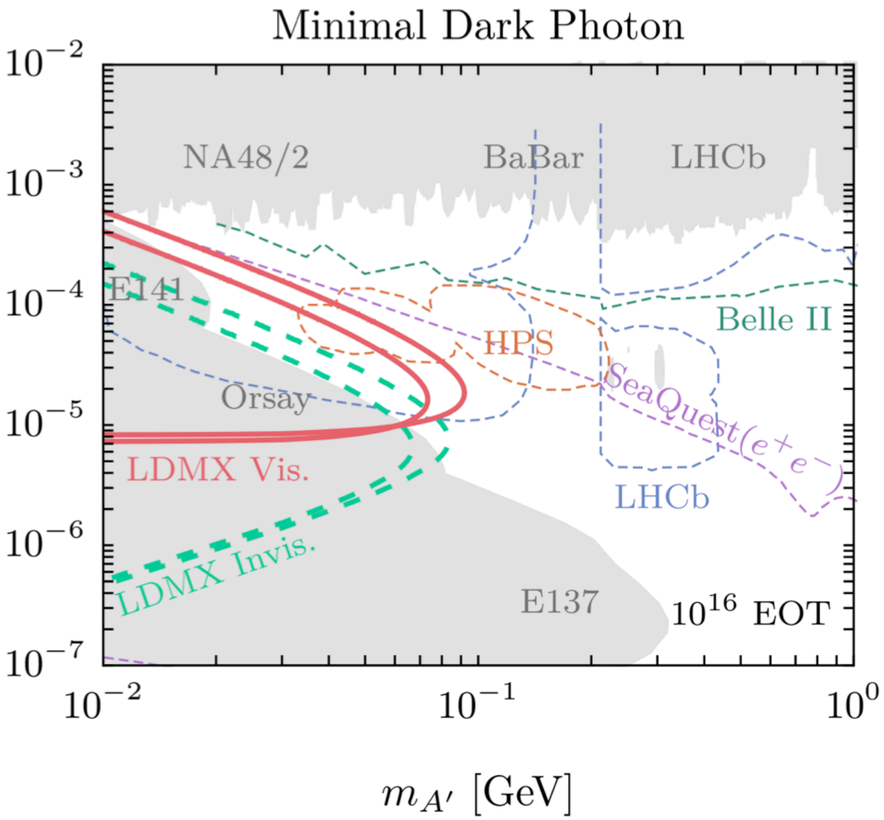
LDMX





- They have the magnet at SLAC -- needs refurbishing
- Mainly built for search via invisibles.
- Can do displaced vertices, but doesn't exhaust X17 -- even in high integrated luminosity assumption
- Starts in "2-3 years after establishing funding profile", several year run to reach full 10^{16} e.o.t. shown in plot

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arxiv:2203.08192

June 2023 status

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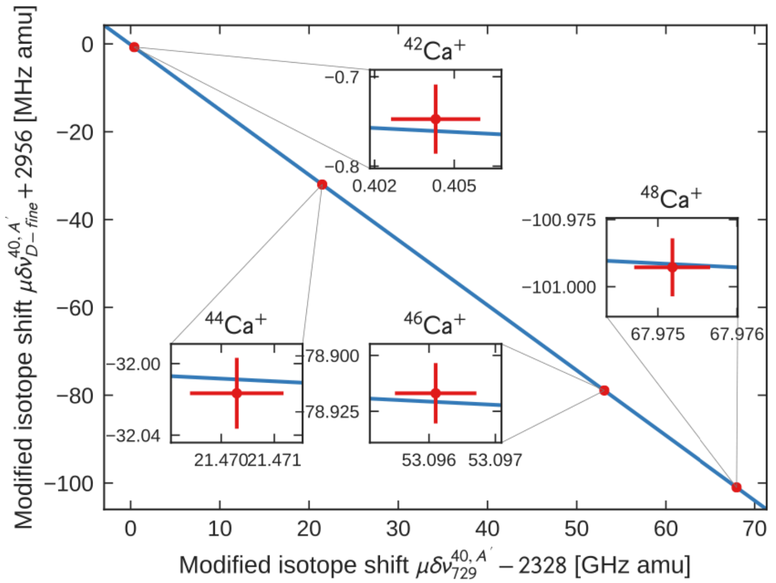
King Plots Explained

- Frequency difference between the same transition in two different isotopes (A, A') has two terms: Mass shift (nucleus recoil) and Field shift (nucleus size)
- 'Modified mass shift', $\mu\delta\nu_i^{AA'}$, divides out the mass dependence
- If we have two shifts (i,j) for the same isotope, we can factor out the nucleus size
- Field shift ratio and mass shift constants extracted from slope and intercept ... *if it's linear*
- nonlinearity=additional interaction with nucleus.

$$\delta\nu^{A,A'} = k_{\mathrm{MS}}\left(\frac{1}{m_A} - \frac{1}{m_{A'}}\right) + F\delta\left\langle r^2\right\rangle^{A,A'}$$

$$\mu\delta\nu_i^{AA'} = K_i + F_i\,\mu\,\delta\left\langle r_c^2\right\rangle^{AA'}$$

$$\mu\delta\nu_i^{AA'} = K_i - \frac{F_i}{F_j}K_j + \frac{F_i}{F_j}\,\mu\,\delta\nu_j^{AA'}$$



from Steffen Meyer's thesis ('17)

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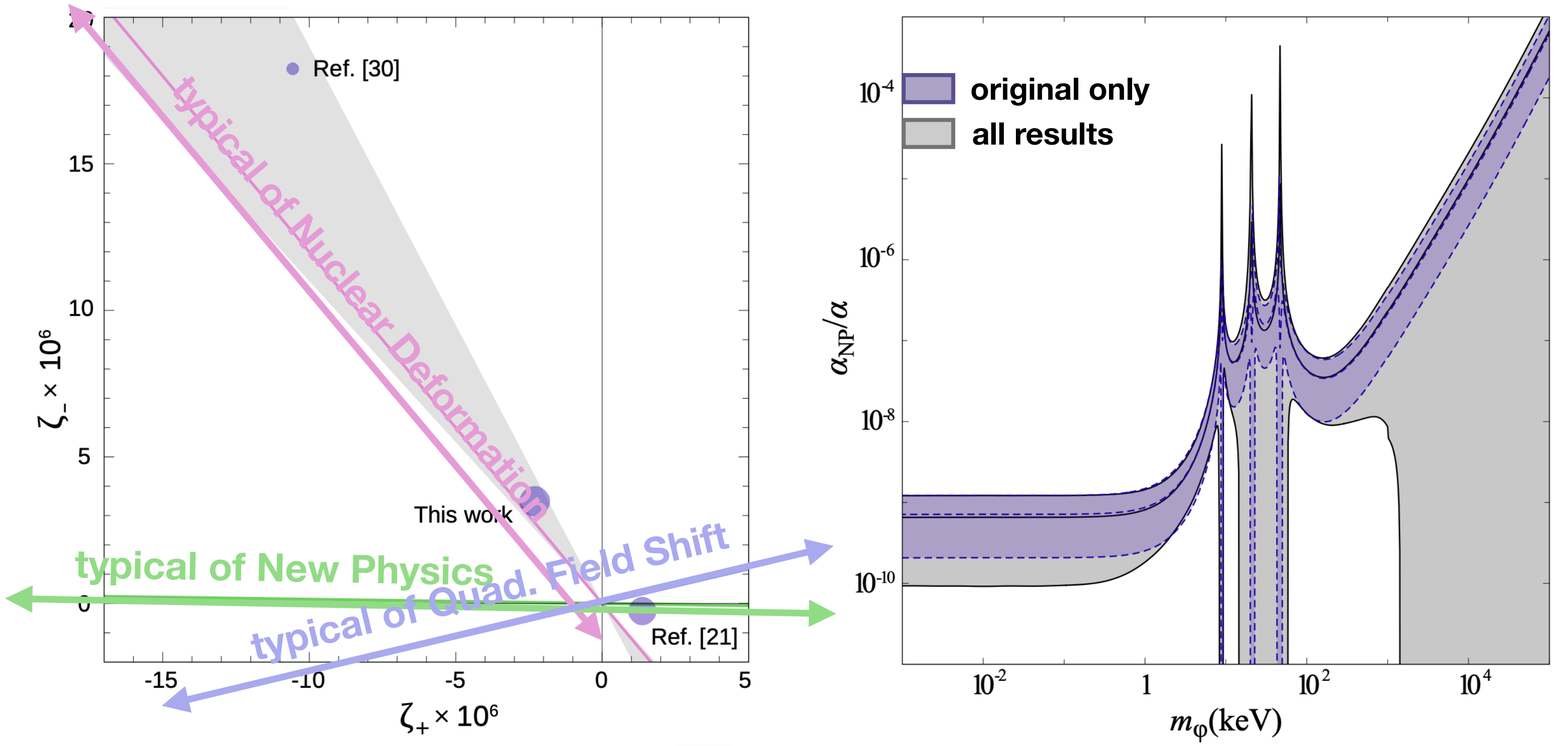
Nonlinear King Plots

- Yb isotope deviations from linearity, plotted as $\zeta_{\pm}$

$$\zeta_{\pm} \equiv d_{168} - d_{170} \pm (d_{172} - d_{174})$$

- (d_{168} is vertical deviation from straight-line fit for frequencies of isotope pair (168,170) with the same transition pair)
- Still prefers new physics, but newer results reduce overall significance at M_A>1MeV



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arxiv:2111.01429

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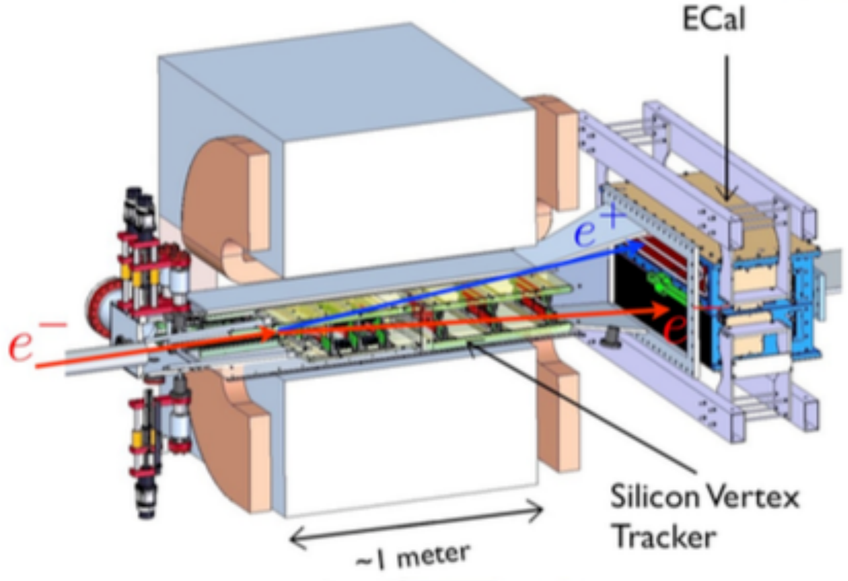
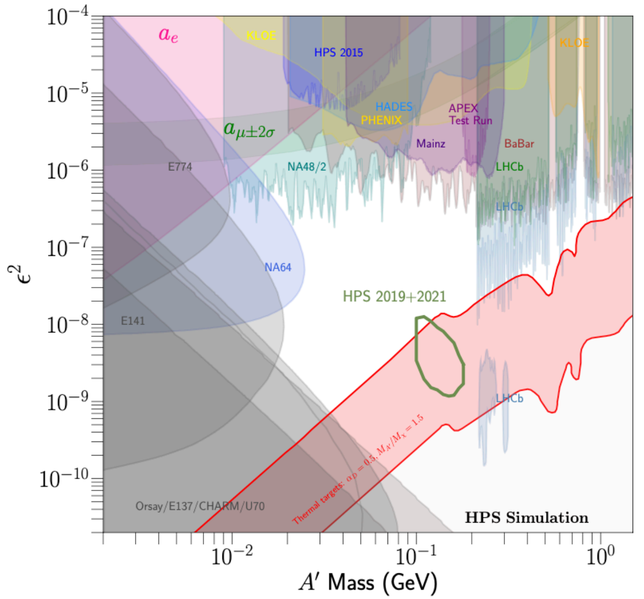
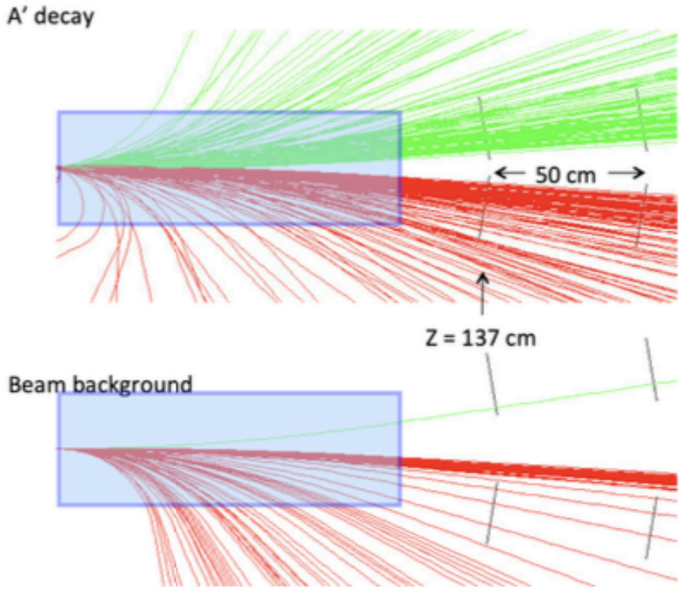
HPS



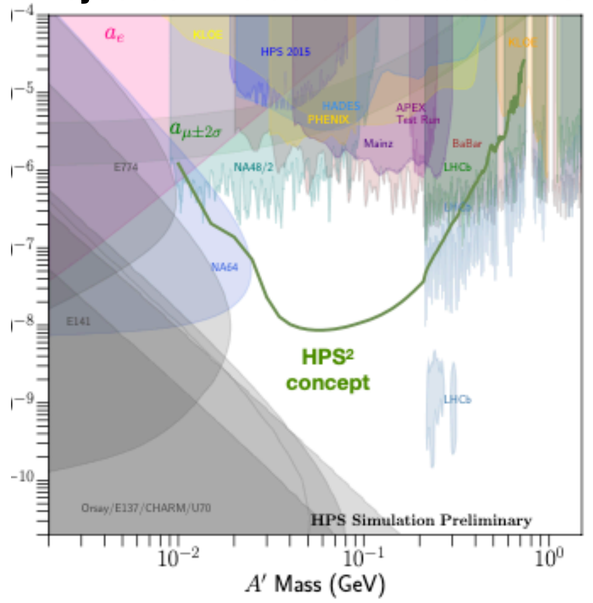
- Tracking very close to target+beam
- Prompt and displaced vertices for SM decay
- 107 of 180 run-days remaining.
- studying HPS² concept to reach low mass:
  - new trackers behind the magnet trade vertex resolution for mass resolution

Projected Exclusion w/ Existing Data





Projected Exclusion w/ 150d HPS²



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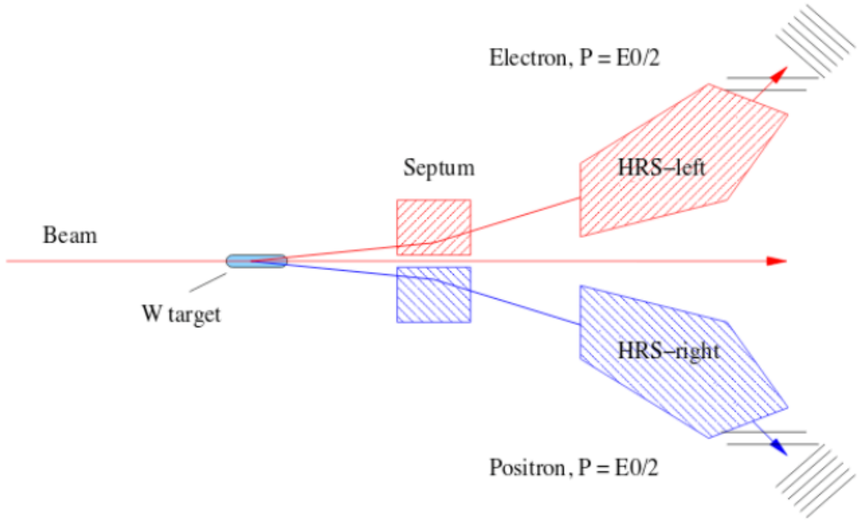
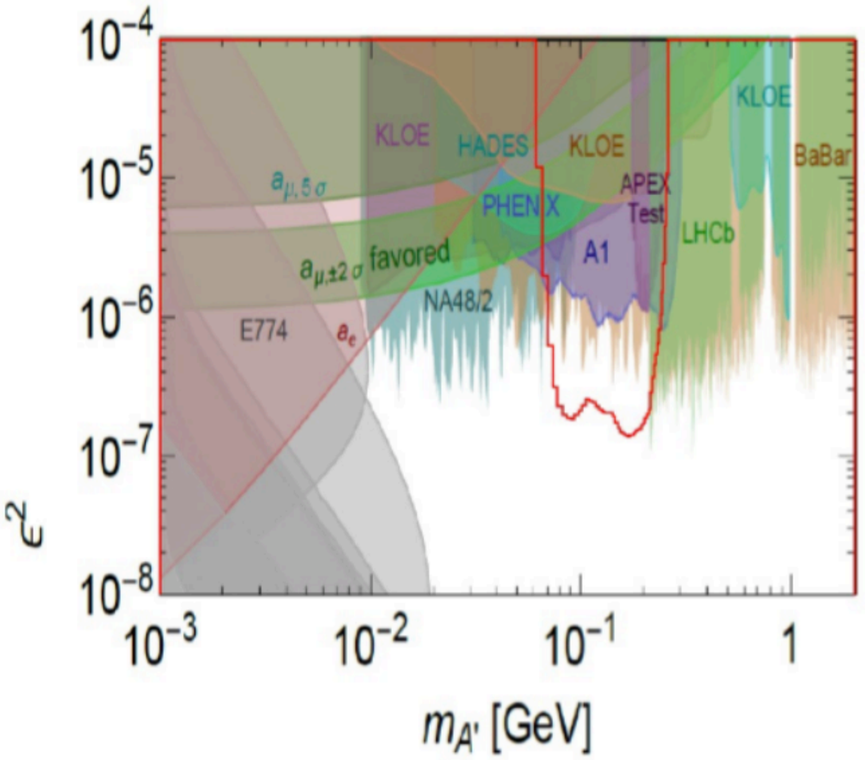
APEX





- e+e- mass resonance, very low opening angles
- Plot includes 2020 data and future proposed settings -- current design can't reach X17

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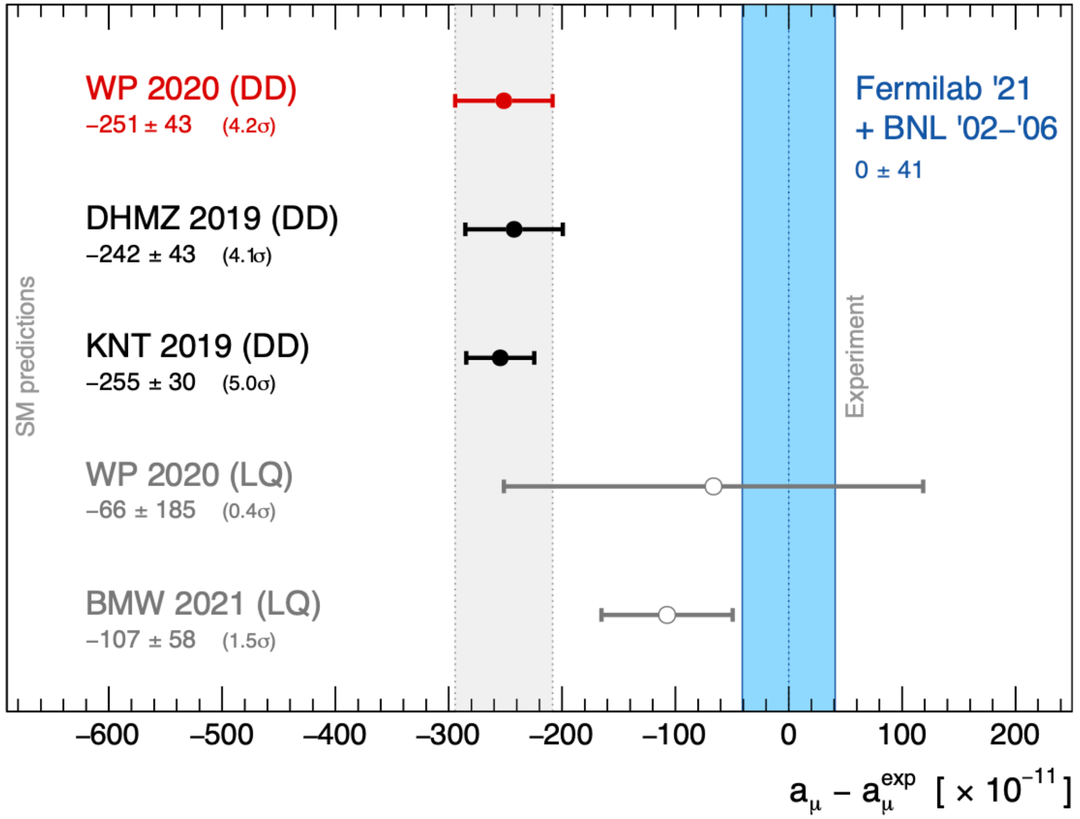
g-2 Lattice Issues

- Data-driven calculations suggest smaller hadronic contribution to magnetic anomaly
- Lattice QCD suggests larger, but caveats. Hence not used in PDG average



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Inferring X17 properties

- 8Be 18.15 MeV 1+ -> 0+:
  - If J_X=0, then L=1 and P=-1 ==> X can be a **pseudoscalar** produced in P-wave.
  - If J_X=1, then L=0,1,2 and P=+1,-1,+1 respectively ==> X can be ~~vector in P-wave~~ or **axial vector** in S- or D-wave.
- 4He 20.21 MeV 0- -> 0+:
  - If J_X=0, then L=0 and P=-1 ==> X can be a **pseudoscalar** produced in S-wave.
  - If J_X=1, then L=1 and P=+1 ==> X can be an **axial vector** in P-wave.

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from Daniel Firak (SBU)

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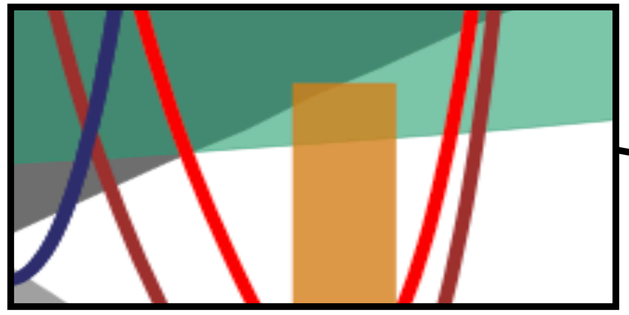
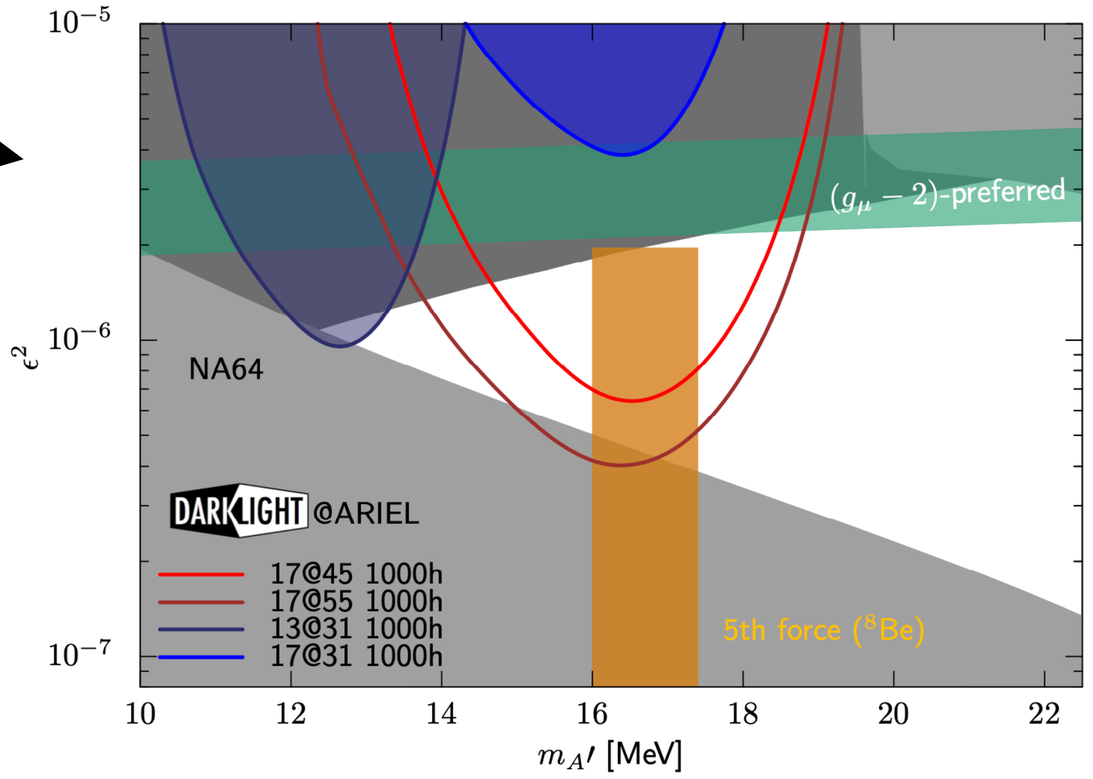
Revised g-2 region

Before Fermilab 2021





- 2021 Fermilab+BNL reduces preferred band somewhat: no longer touches X17
- *Some* increase from LQCD and CMD-3 would move this substantially (or all the way to zero)

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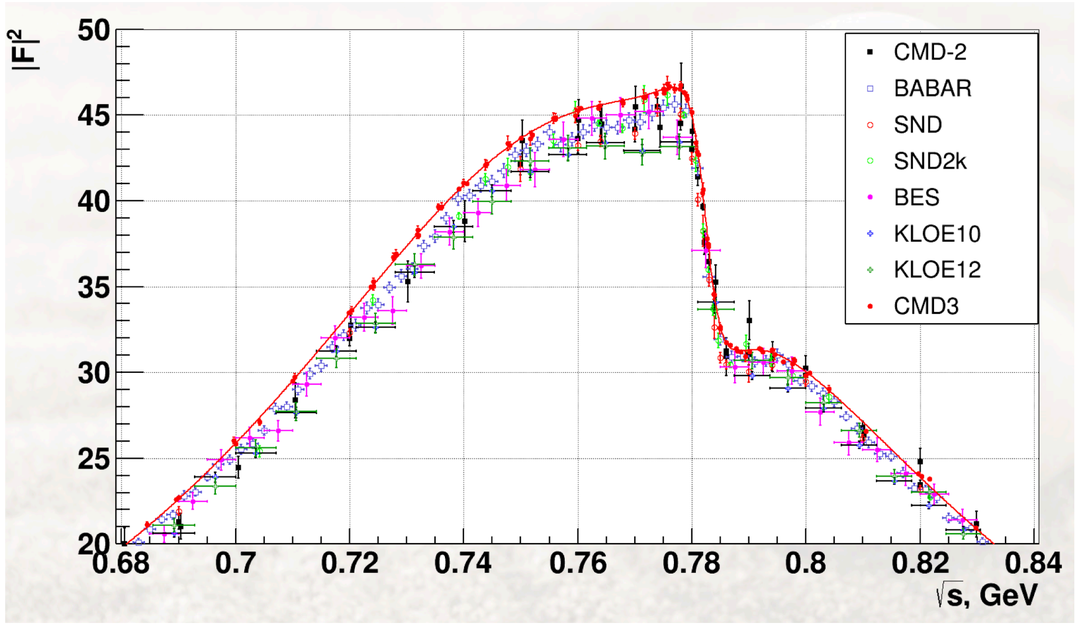
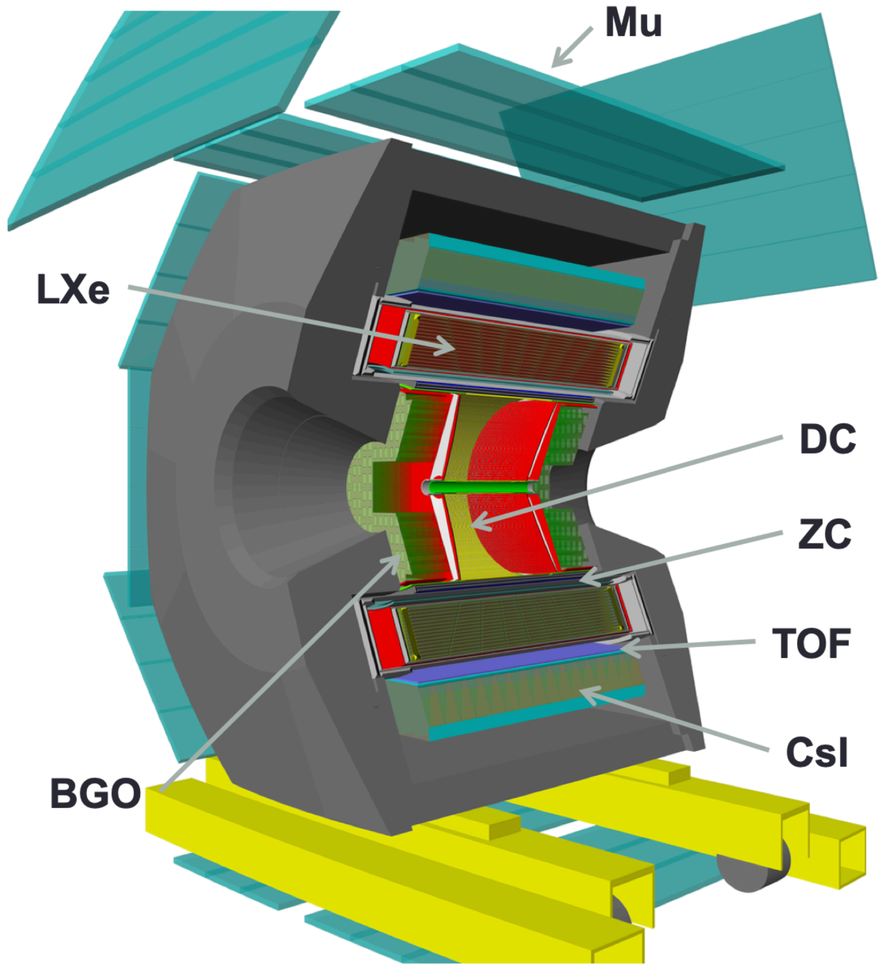
CMD-3

- VEPP-2000
- Program to measure $e^+e^- \rightarrow$ hadrons
- $e+e- \rightarrow \pi+\pi-$ form factor disagrees with all prior results





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Other Nuclear Excitement

- **N_Tof**: Proposal at EAR2/CERN to look for X17 in $^{3}He(n, X17)^{4}He$. Peak height vs beam energy can distinguish quantum numbers
- **NUCLEX: ΔE-E detectors for 12C and 8Be at INFN Legnaro**: Studying 5-fold layout like ATOMKI, but 1% mass resolution. If peak does not sharpen, then it has the wrong intrinsic width to be the assumed particle. Still in early stages as of Nov, 2023.

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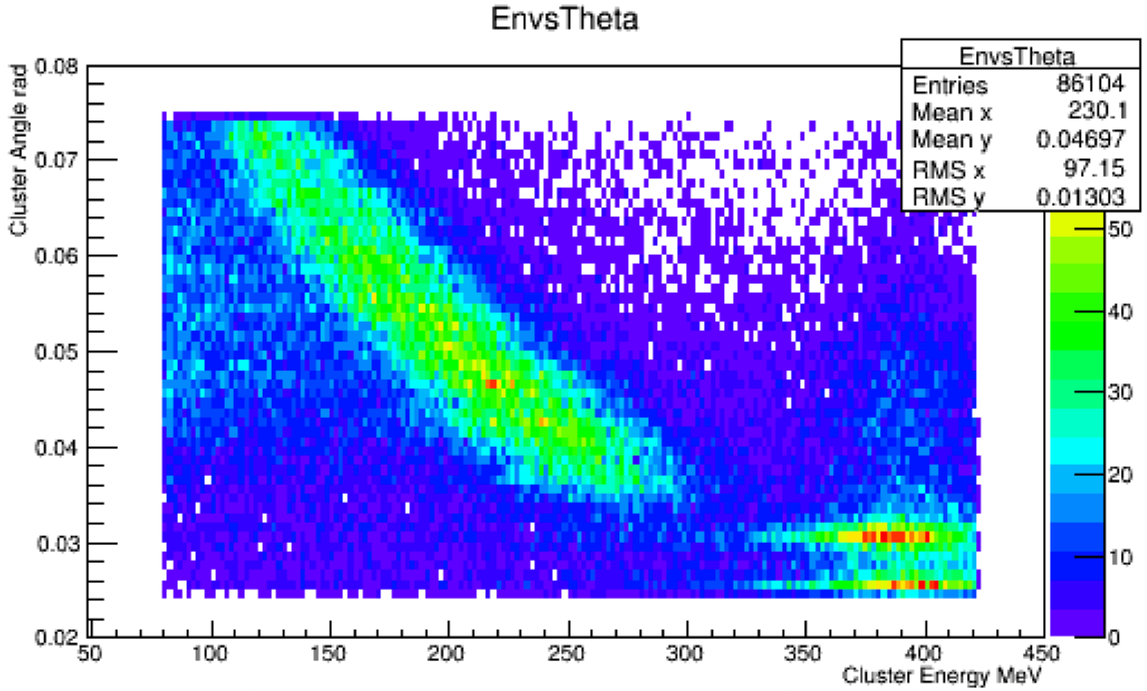
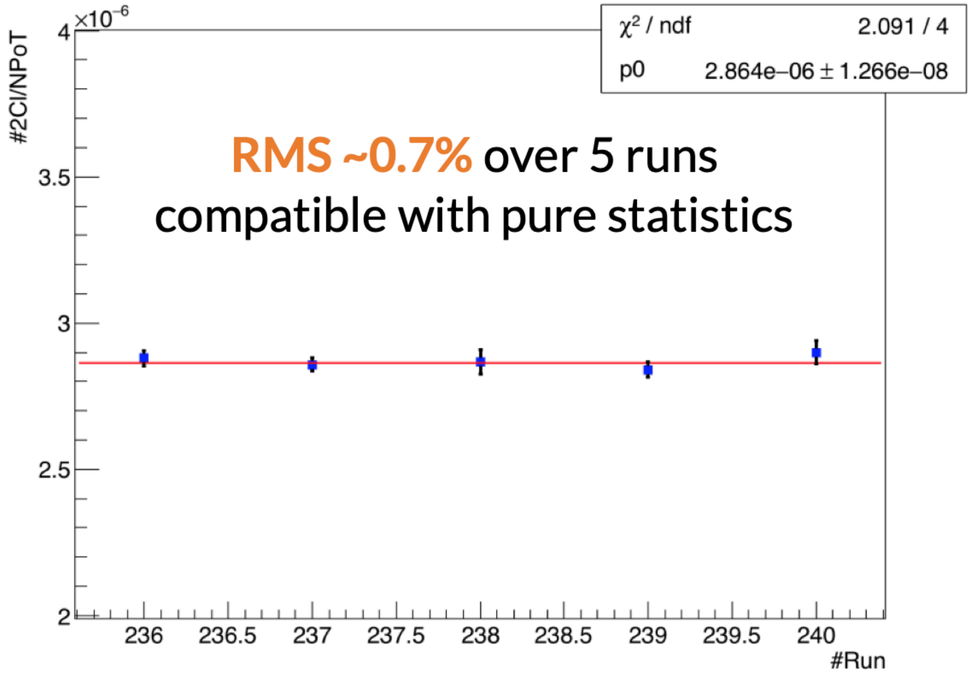
PADME Resolution?



Above Resonance: 402 MeV



RMS ~0.7% over 5 runs
compatible with pure statistics

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