Center for Frontiers in Nuclear Science

Search for New Physics in e+e– Final States With an Invariant Mass of 10-20 MeV Using the ARIEL Electron Accelerator

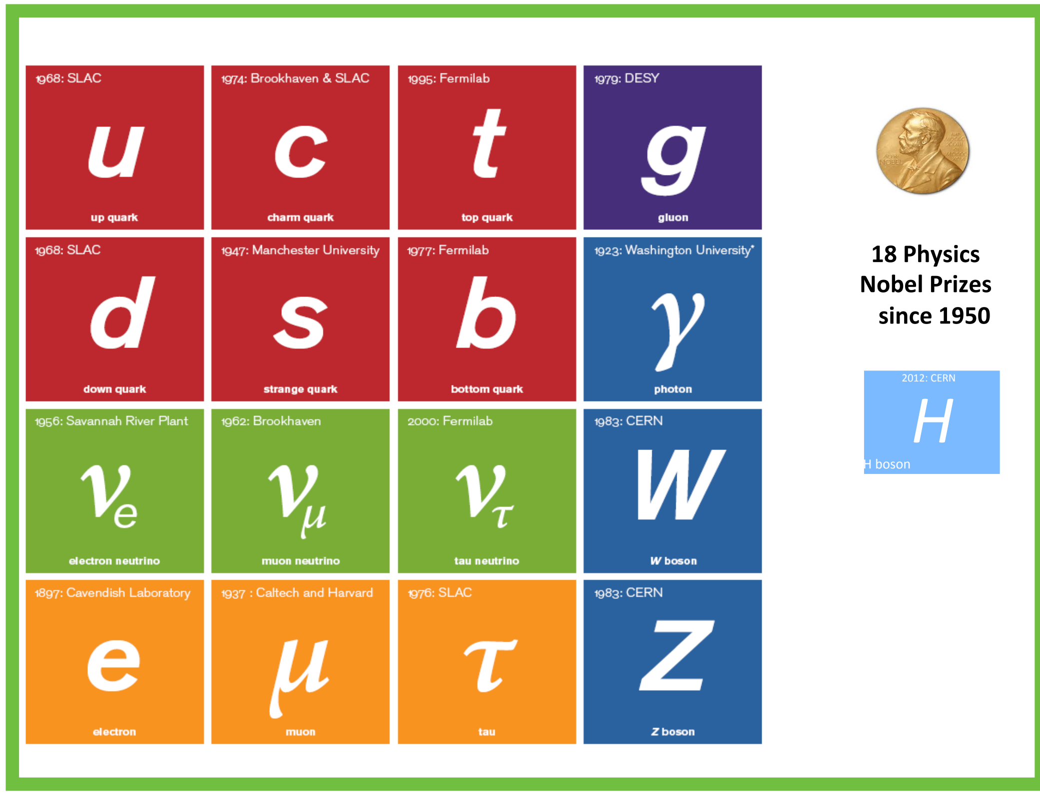
Ross Corliss

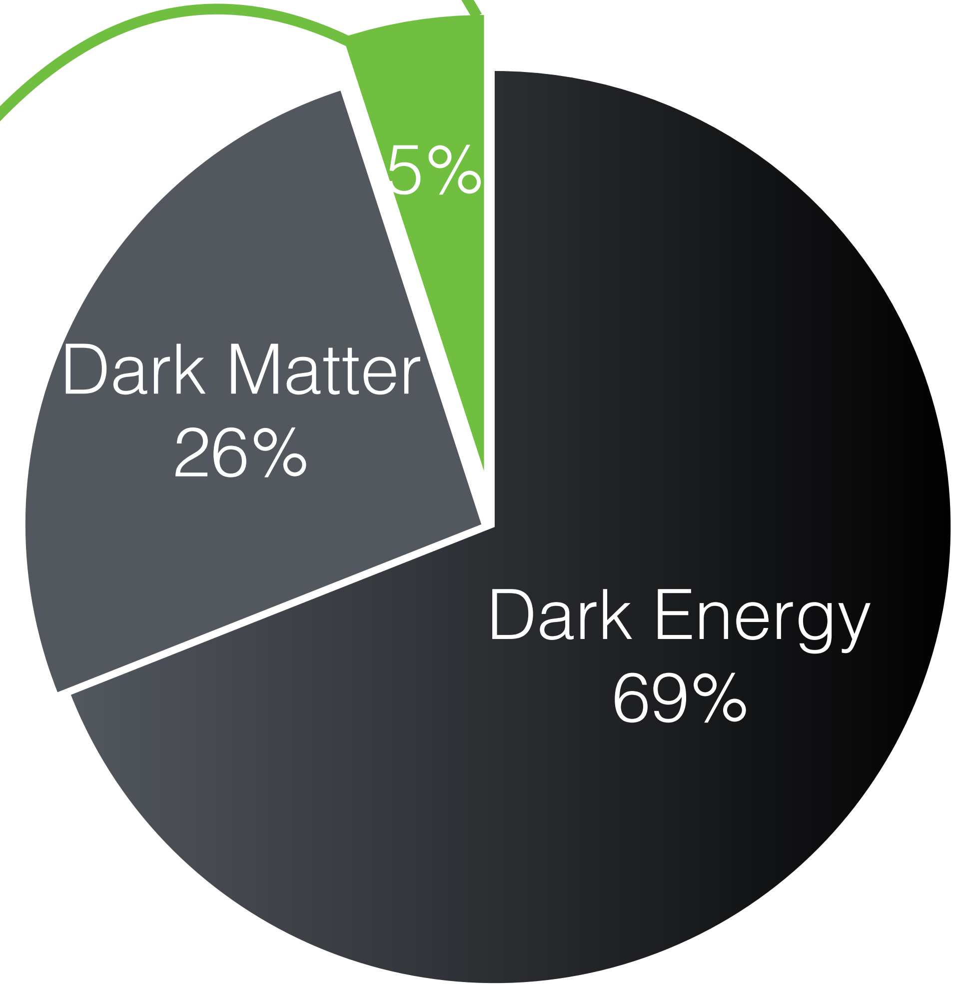
for the DARKLIGHT *Collaboration*

TRIUMF PP-EEC, April 2021

Stony Brook University

Beyond the Standard Model

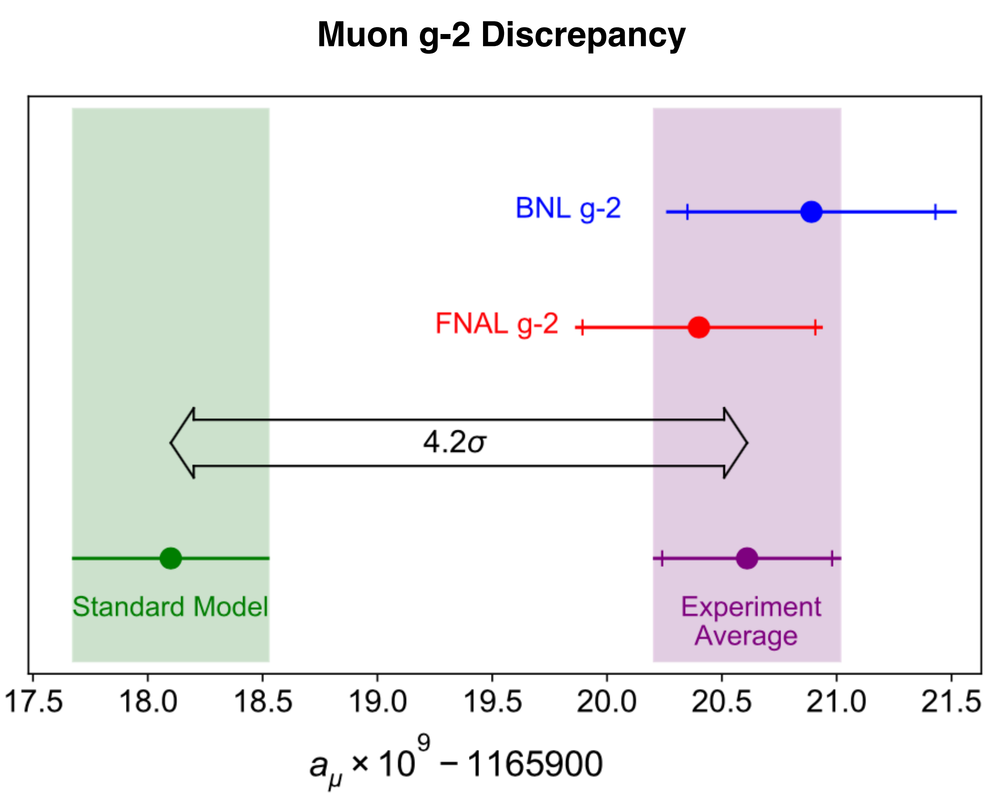


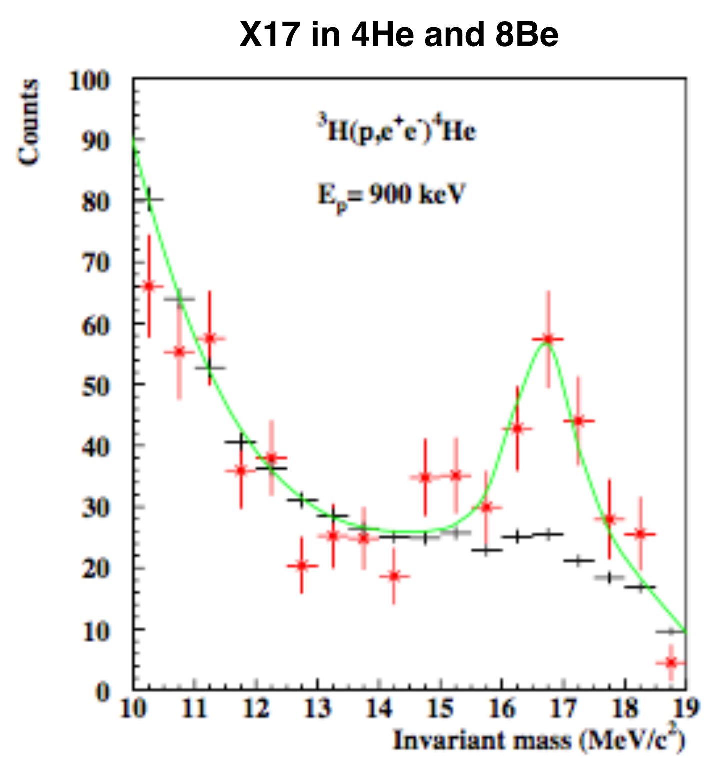


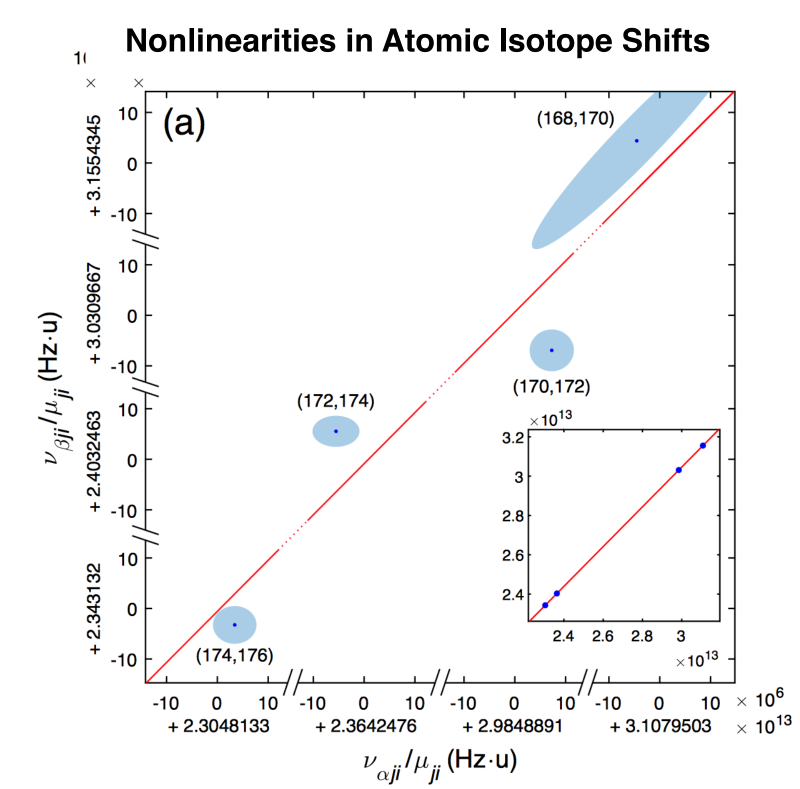
- Dark Matter: Massive + ???
- Dark Energy: ???
- Large parameter space even for simple models
- Evidence at smaller scales?

Anomalies as Lampposts

- May see hints of connection between Dark Matter and SM at lower energy
- ...or other BSM physics
- Anomalies in particle, nuclear, and atomic physics:

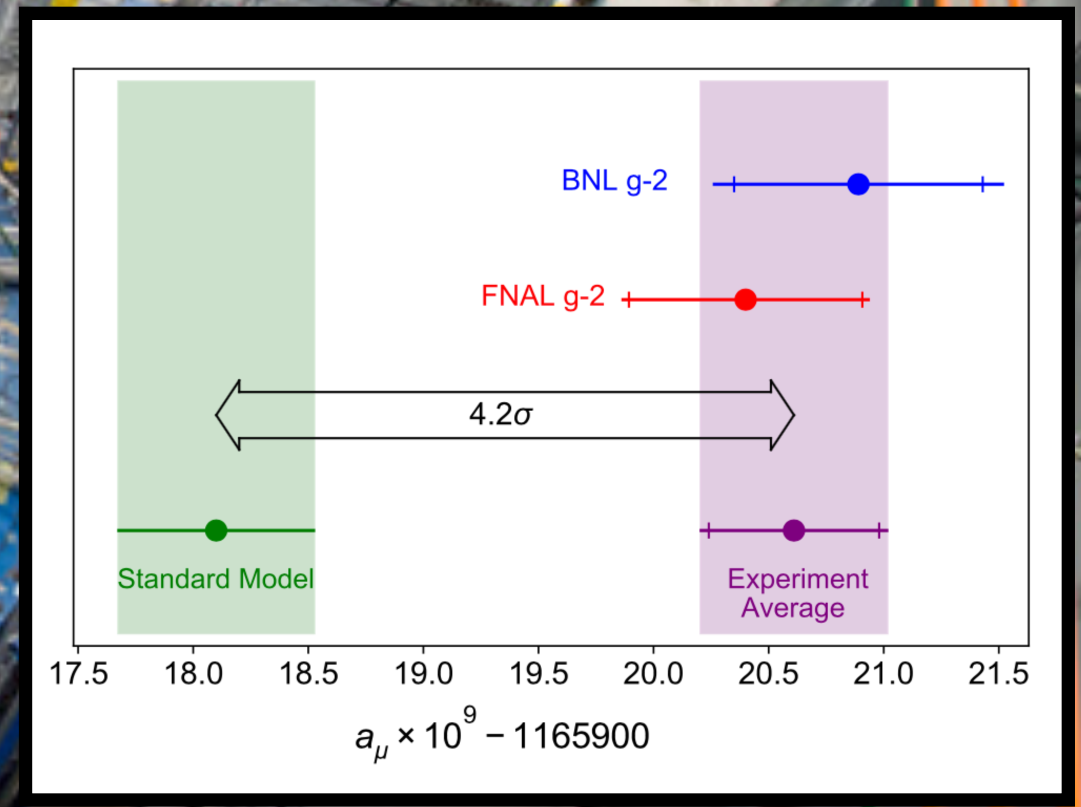






Muon g-2 Anomaly

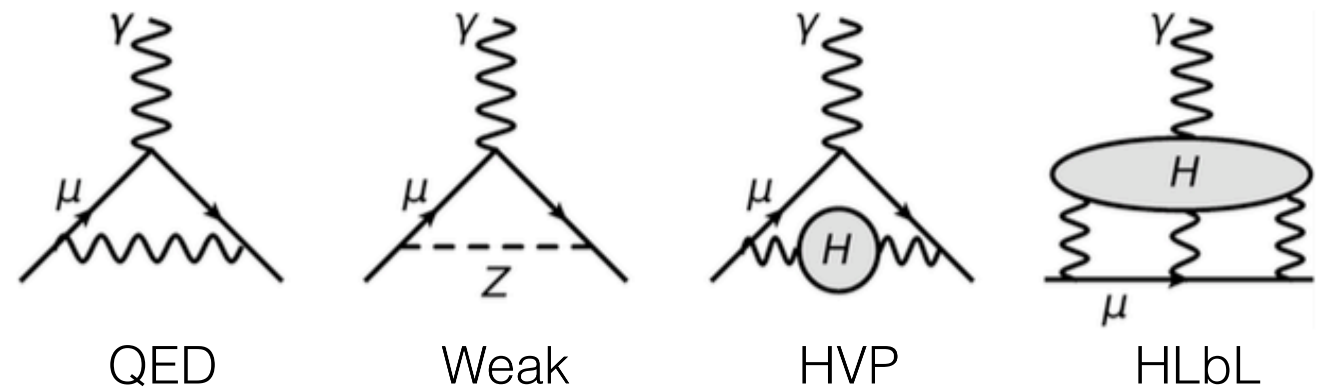
- FNAL result agrees with previous E821
- Large deviation from SM prediction!

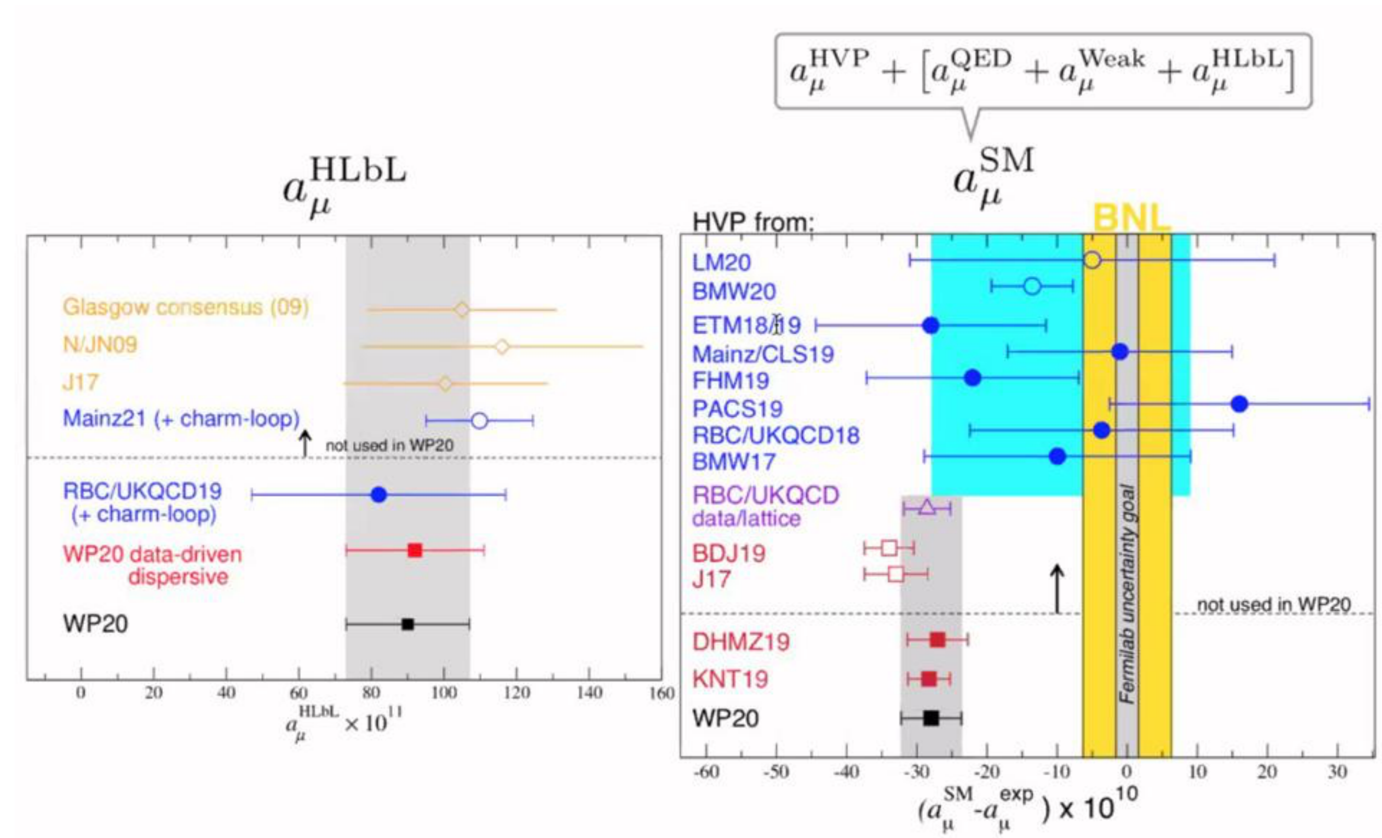


arxiv:2104.03281
PRL.126.141801 (2021)

Muon g-2 Anomaly

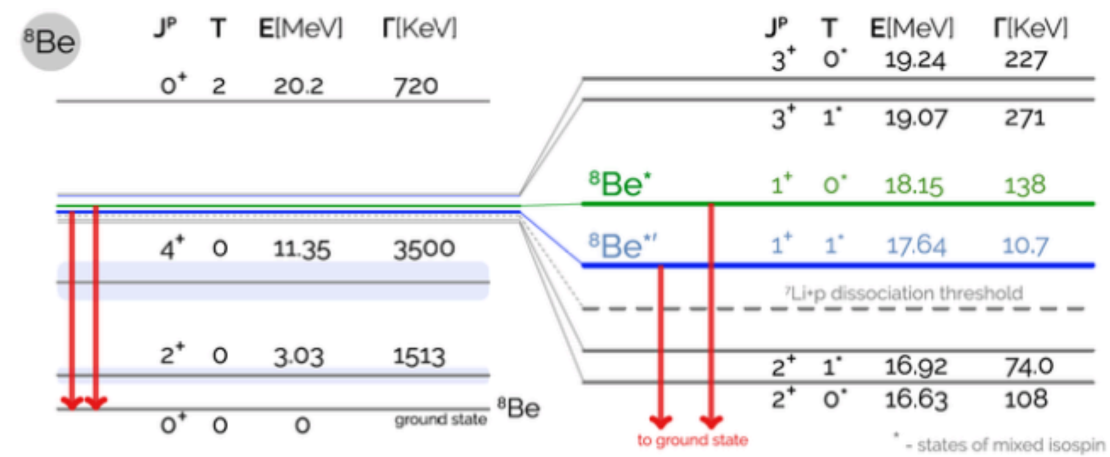
- Earlier uncertaintly in Hadronic Light-by-Light calculations now well constrained
- Consensus 'SM' point uses data-driven Hadronic Vacuum Polarization
- Lattice QCD (blue) suggests tension with 'SM' point, but error bars large
- New particle would add new QED-like term

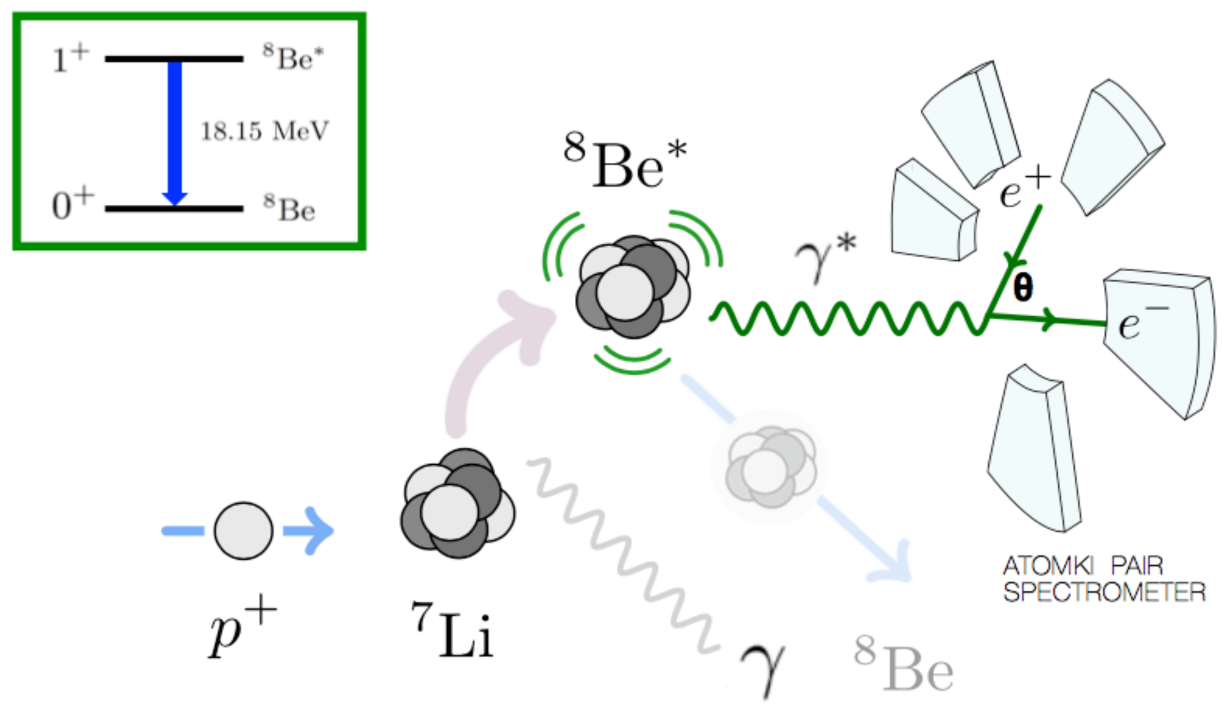




Beryllium Anomaly

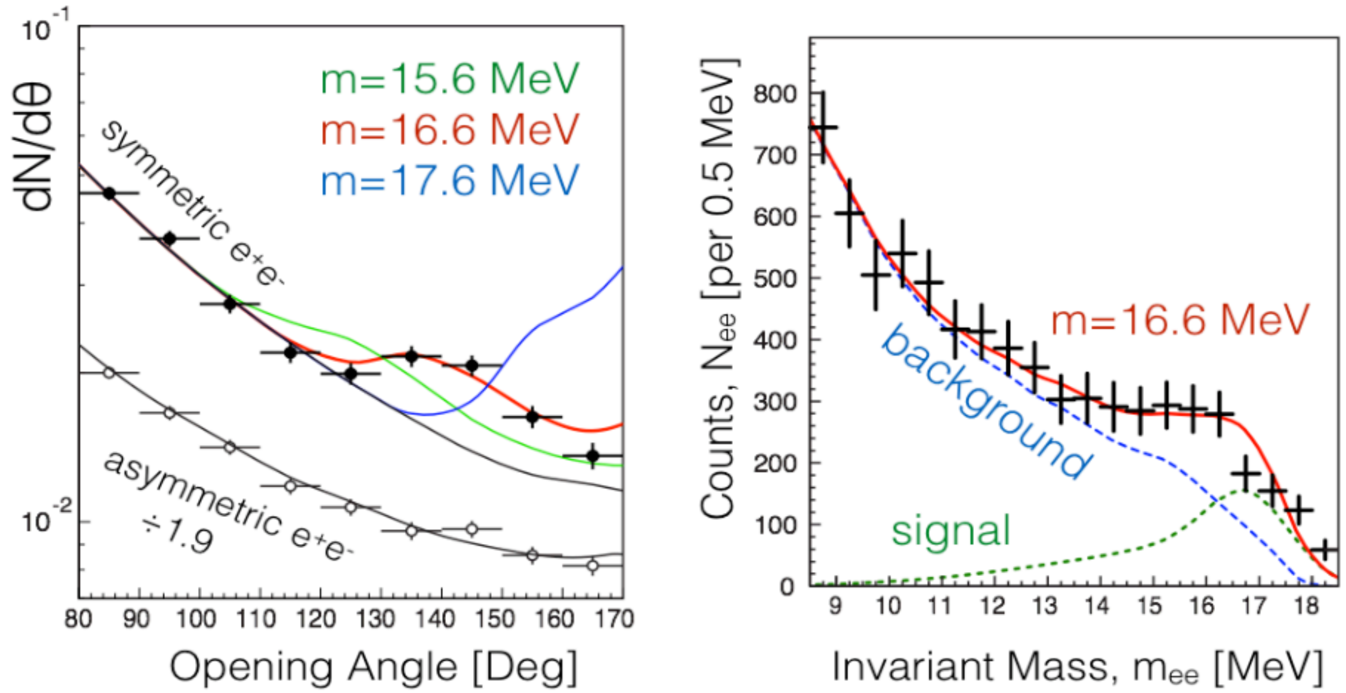
- Multiple narrow, high-E states -- excellent place to search for new MeV-scale physics
- p-beam produces $^{8}Be^{*}$, de-excitation through $e^{+}e^{-}$ recorded in 5-fold spectrometer set





(graphics from arxiv:1707.09749)

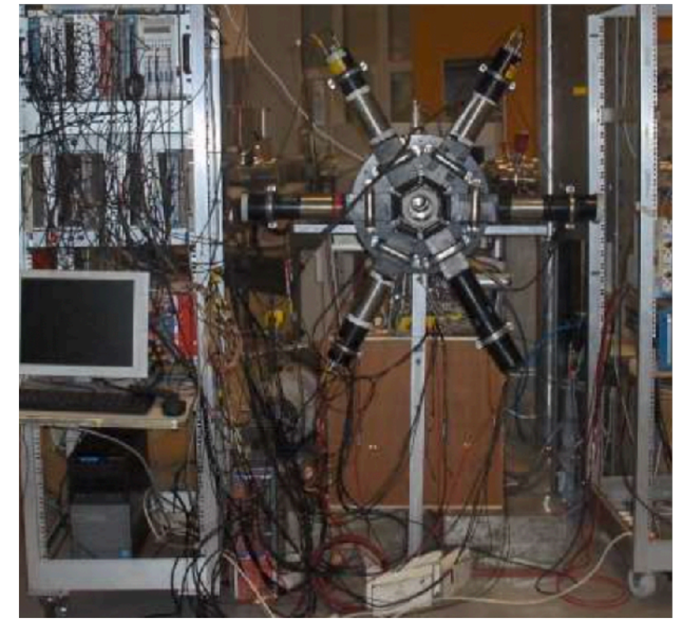
Beryllium Anomaly



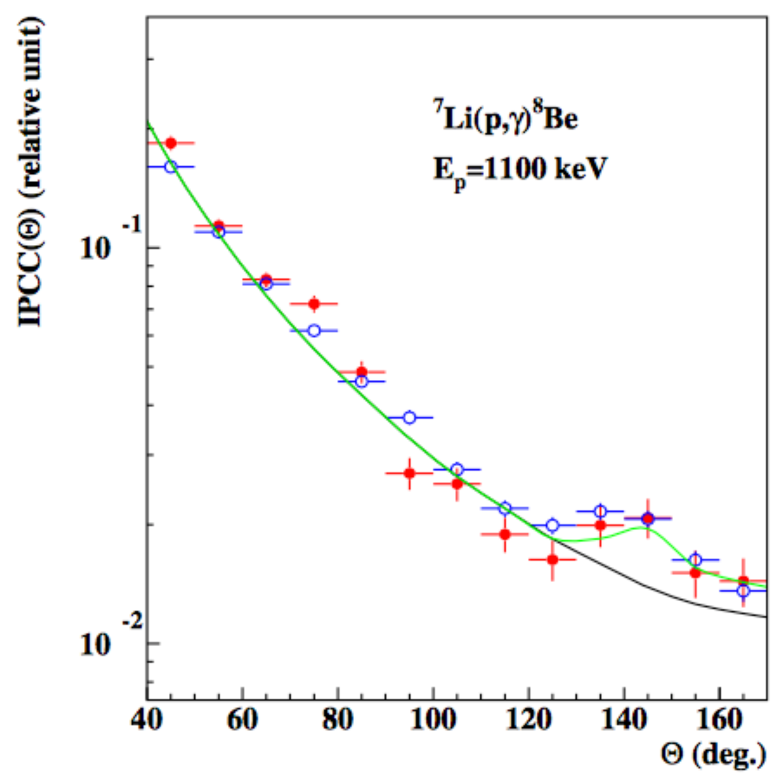
- Anomaly appears in mass and angular spectra
- No clear SM interpretation:
  - intermediate poles in nuclear propagator?
  - interaction of LO-NLO interference effects with detector acceptance?
  - Anomalous nuclear form factor?

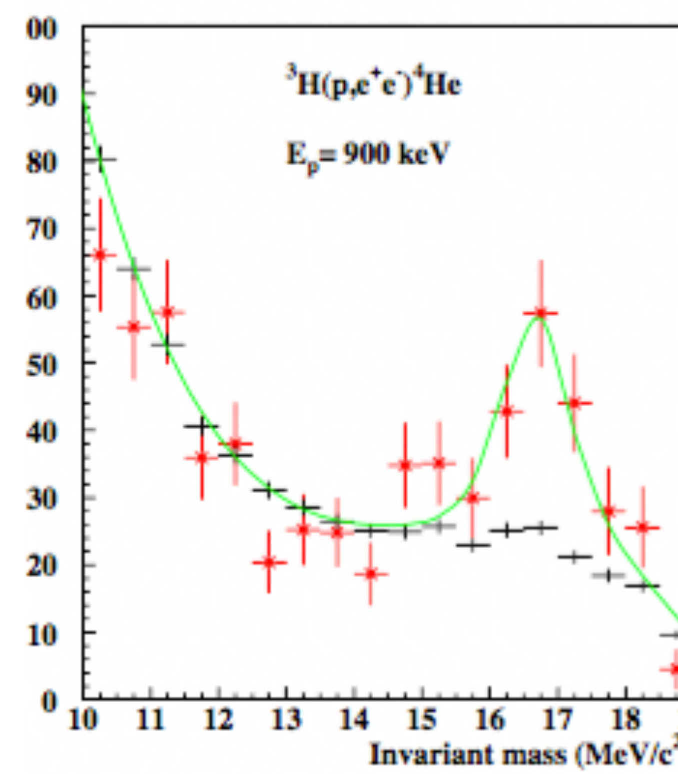
(graphics from arxiv:1707.09749)

Beryllium Anomaly



- ATOMKI group re-measured in 2019 with improved 6-fold detector, also consistent peak in $^4He^*$ decay
- No independent/similar measurements yet, but some interest (Montreal?)



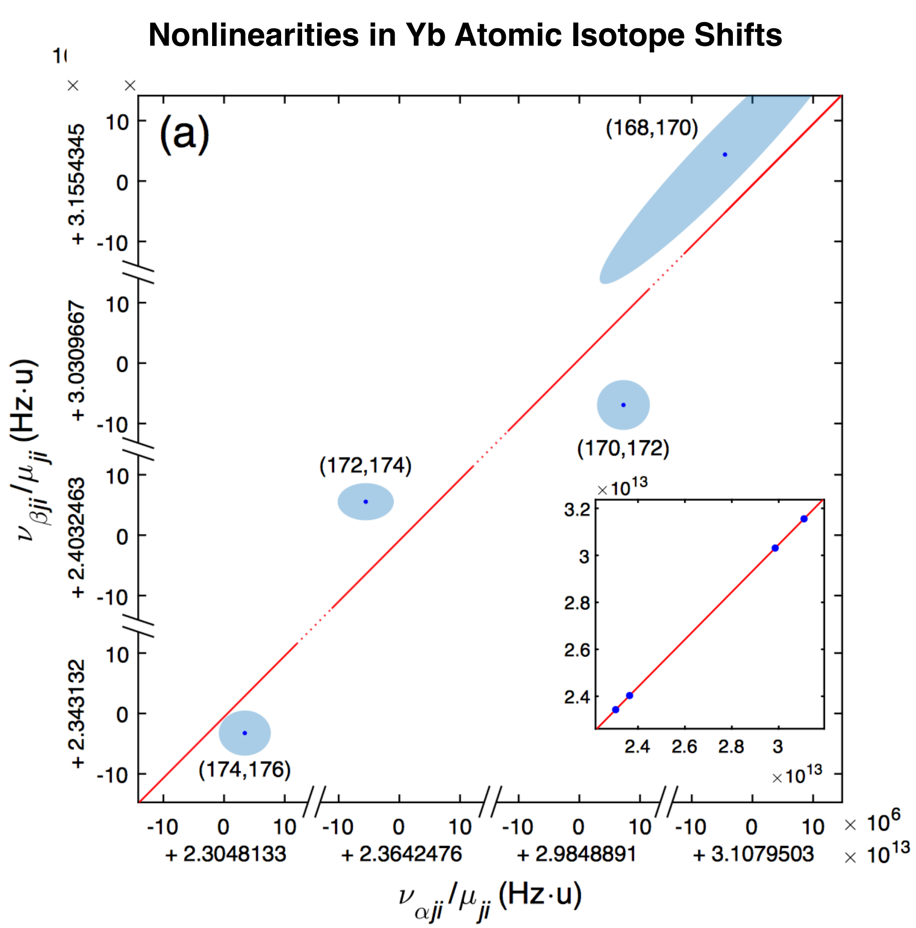


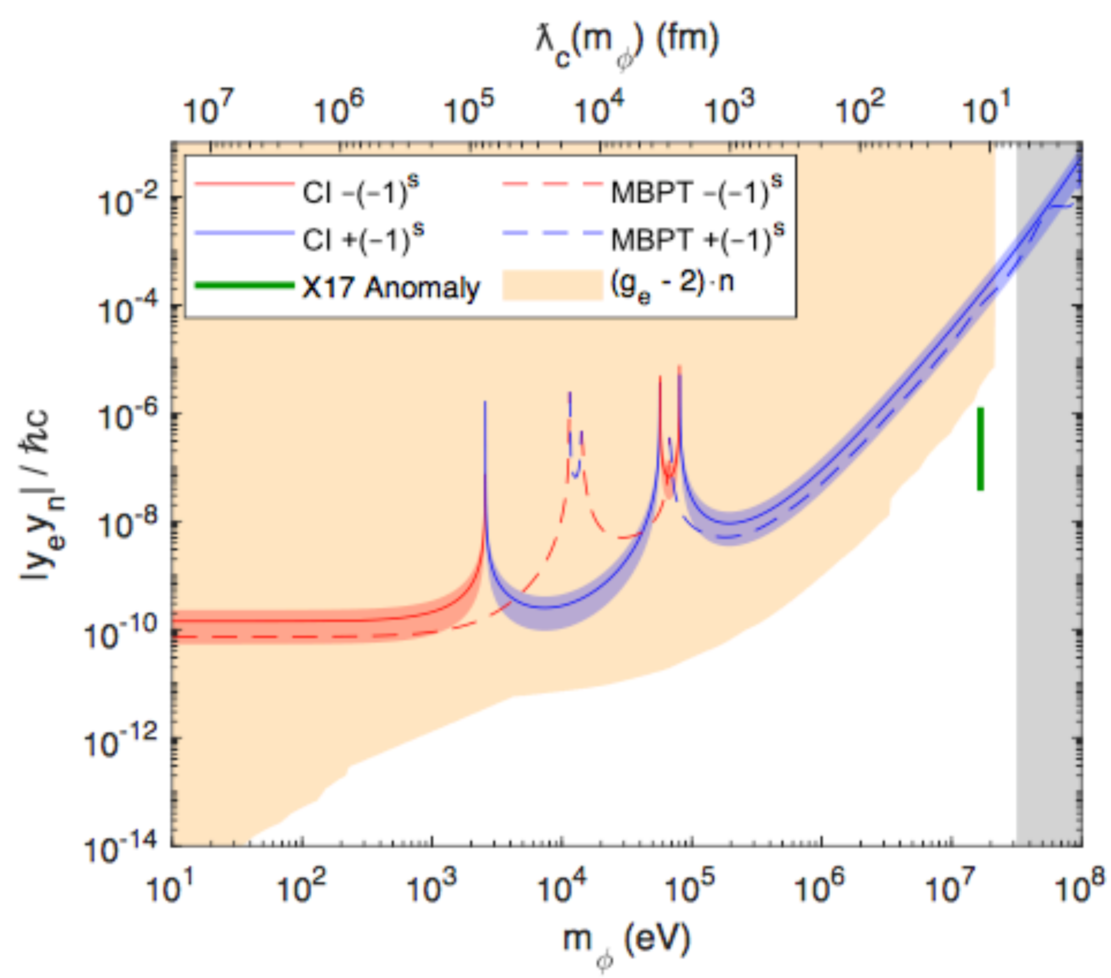
https://doi.org/10.1051/epjconf/202023204005

arxiv:1910.10459

Isotope Shift Anomaly

- King Plot: super-ratios of isotope transition frequencies should be linear
- Nonlinearities can be interpreted as new electron-neutron interactions

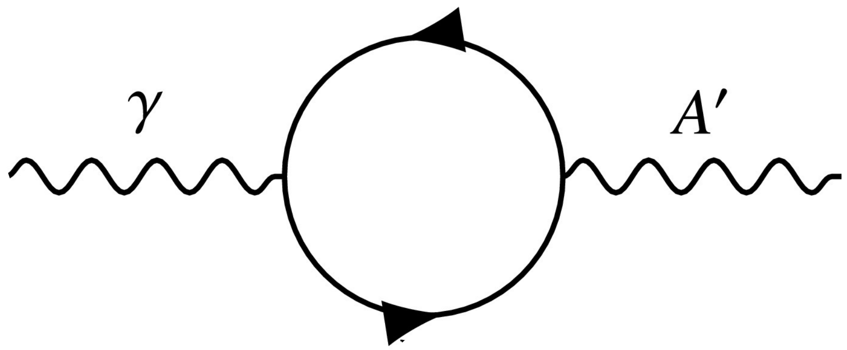




arXiv:2004.11383

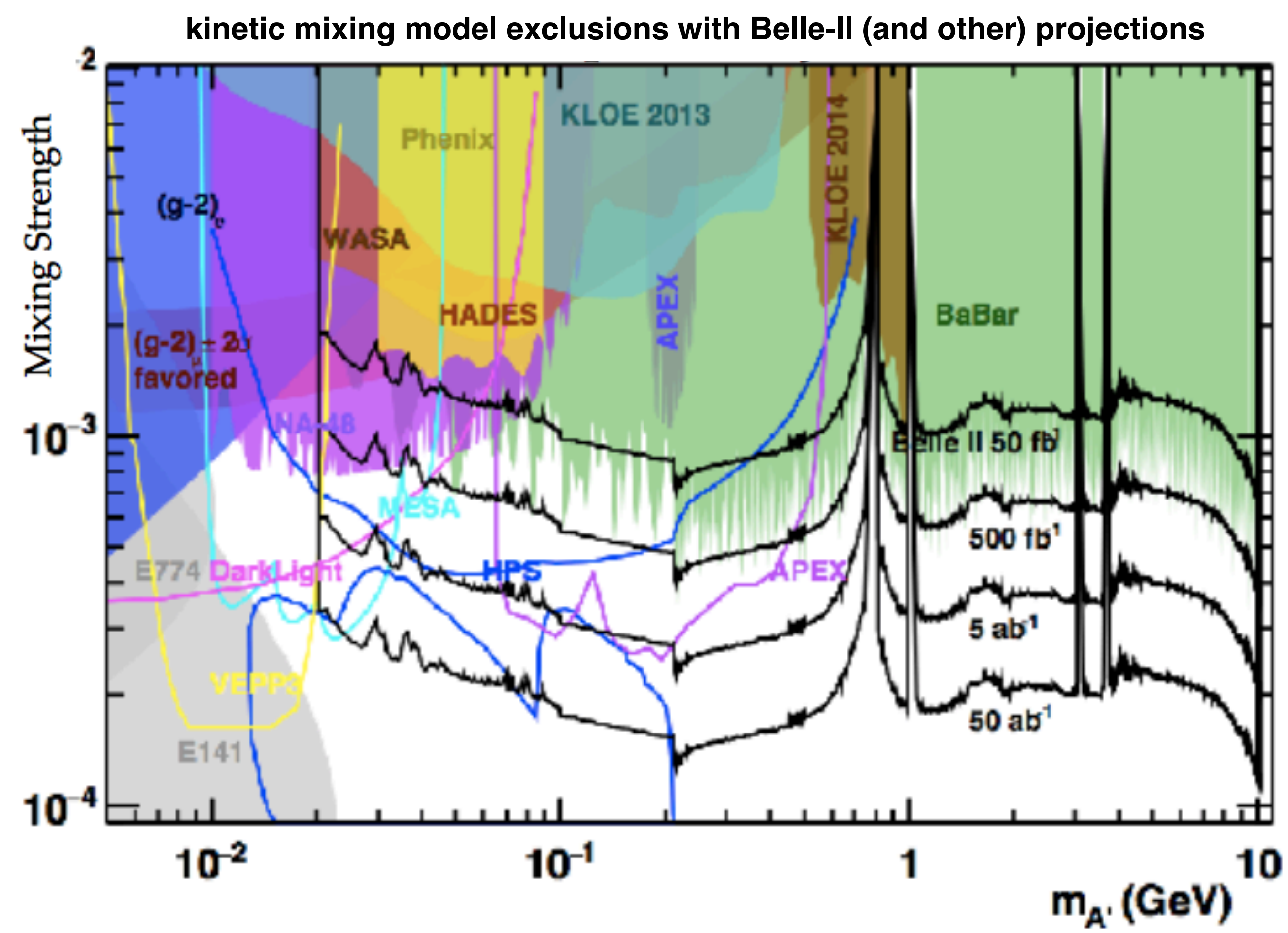
A New Interaction?

- Simplest coupling via Kinetic Mixing:



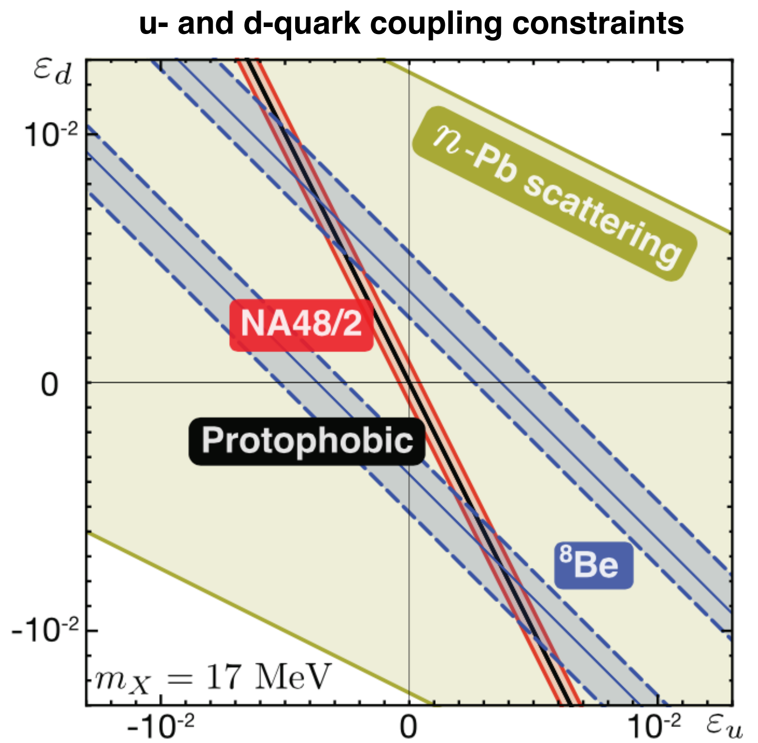
$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

- Parameterized by one coupling and mass
- Disfavored for X17 and g-2 areas of interest
- Hadronic ($\boldsymbol{\pi}^0$) probes strongest constraint

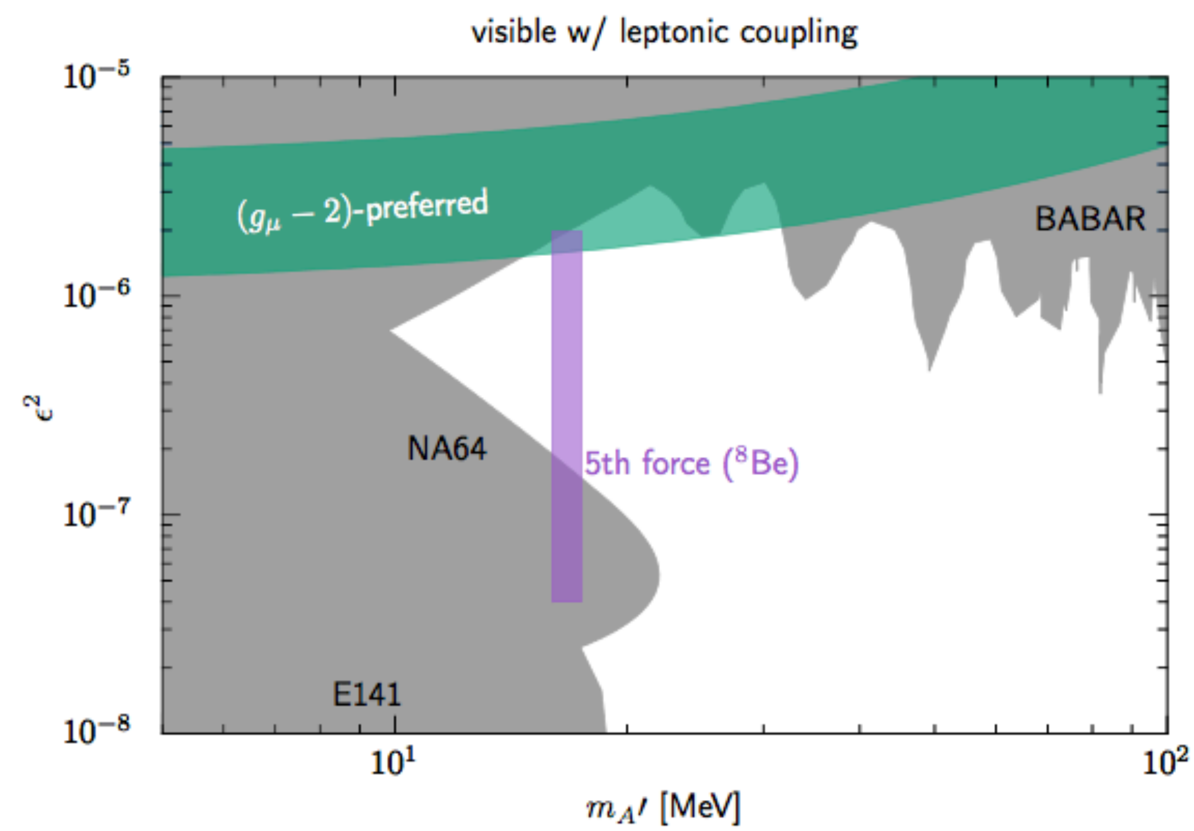


Protophobia?

- Generalized new force could have flavor-dependent coupling: $$X^{\mu}(\Sigma_f e\epsilon_f \bar{f}\gamma_\mu f)$$
- Moderately protophobic coupling combinations evades existing particle constraints, would generate an IS nonlinearity

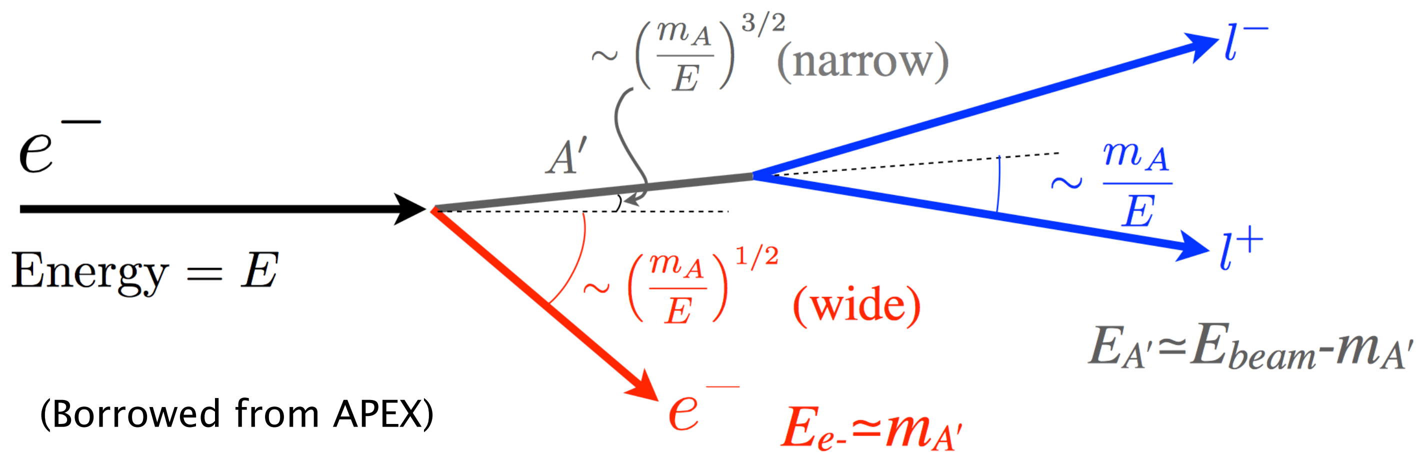


arXiv:1604.07411



- $|\epsilon_p/\epsilon_n| < 8\%$ -- similar scale as for Z^0
- ***Purely leptonic production*** provides an efficient way to probe

Searching at an e- Accelerator

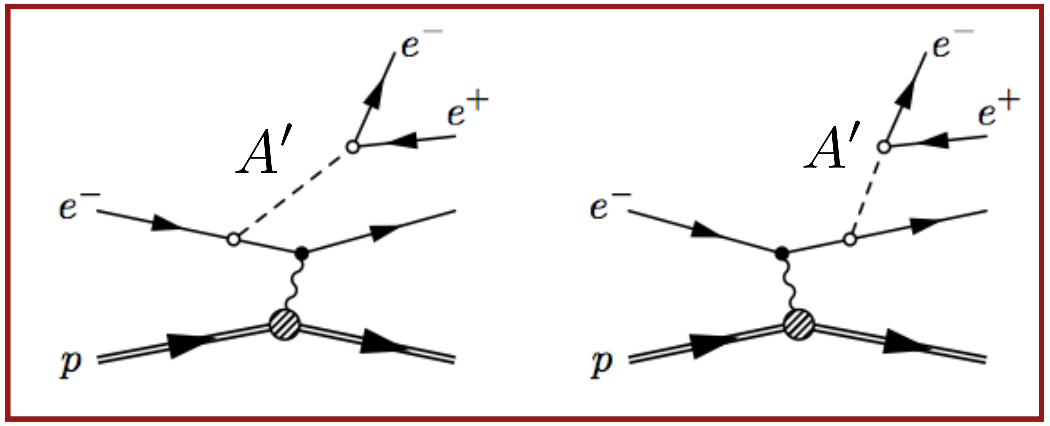


(Borrowed from APEX)

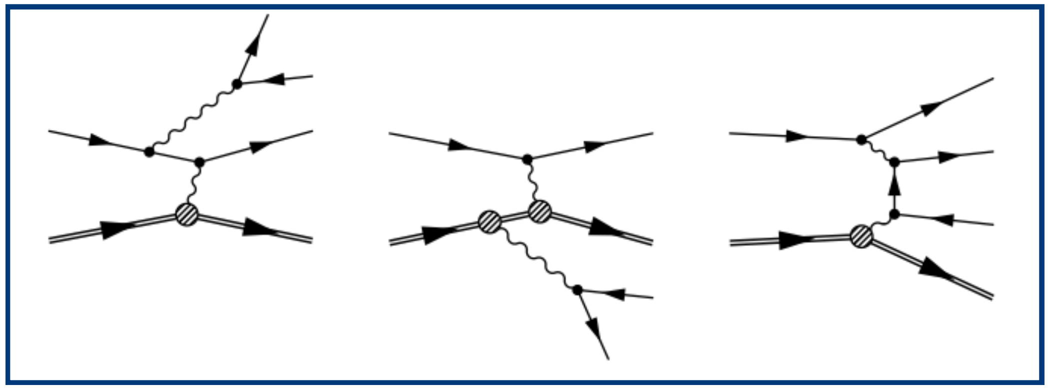
- Radiative production:

$$e^- + \text{Ta} \to e^- + \text{Ta} + A'$$

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



- Irreducible QED background similar, but no mass peak:



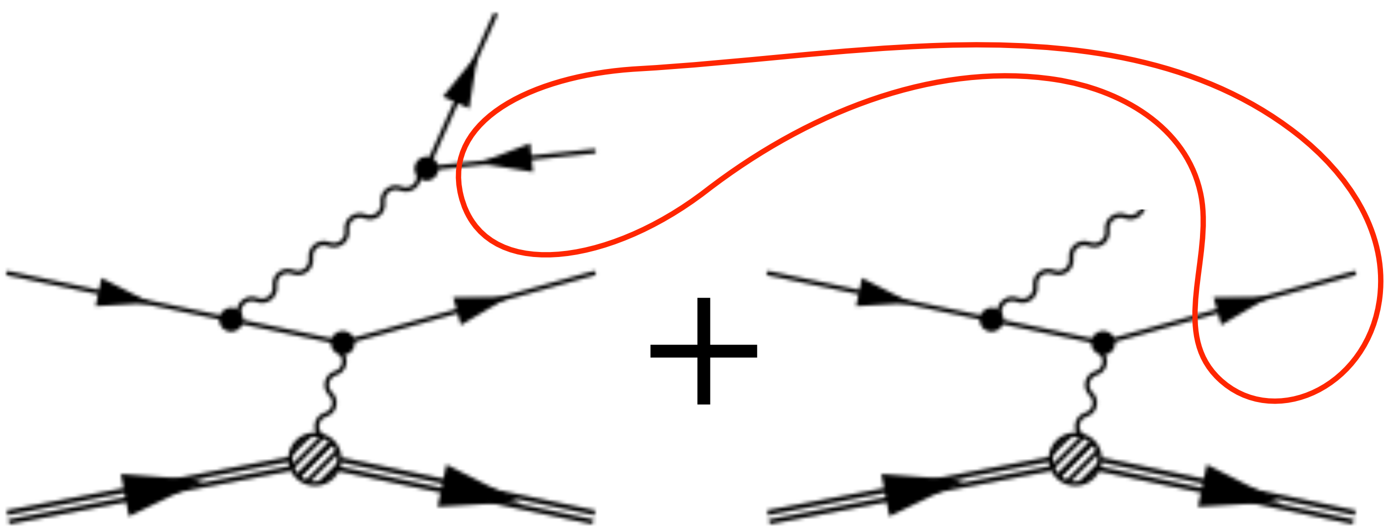
- Spectrometer pair:

  detect e+e- in coincidence

- $\text{FOM} \sim \frac{S}{\sqrt{B}}$

Combinatoric Background

- Limited acceptance: singles e^+ rate >> e^+e^- pair rate ➡ elastic e^- from same bunch acts as missing partner!



$$S \sim \mathcal{L}$$

$$B \sim \mathcal{L}^2$$

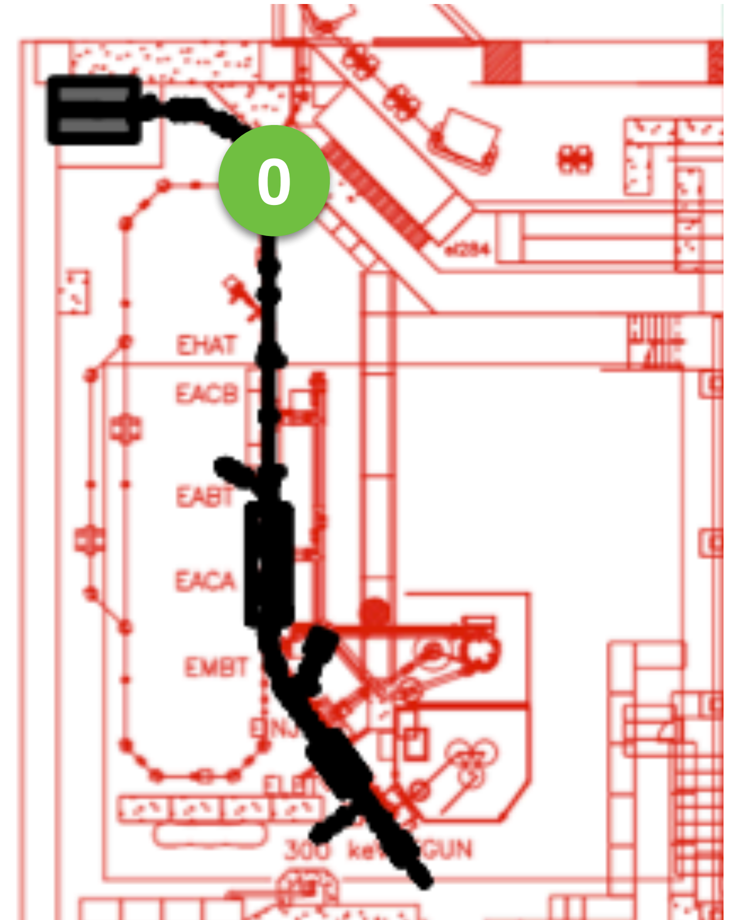
$$\mathrm{FOM} \sim \frac{S}{\sqrt{B}}$$

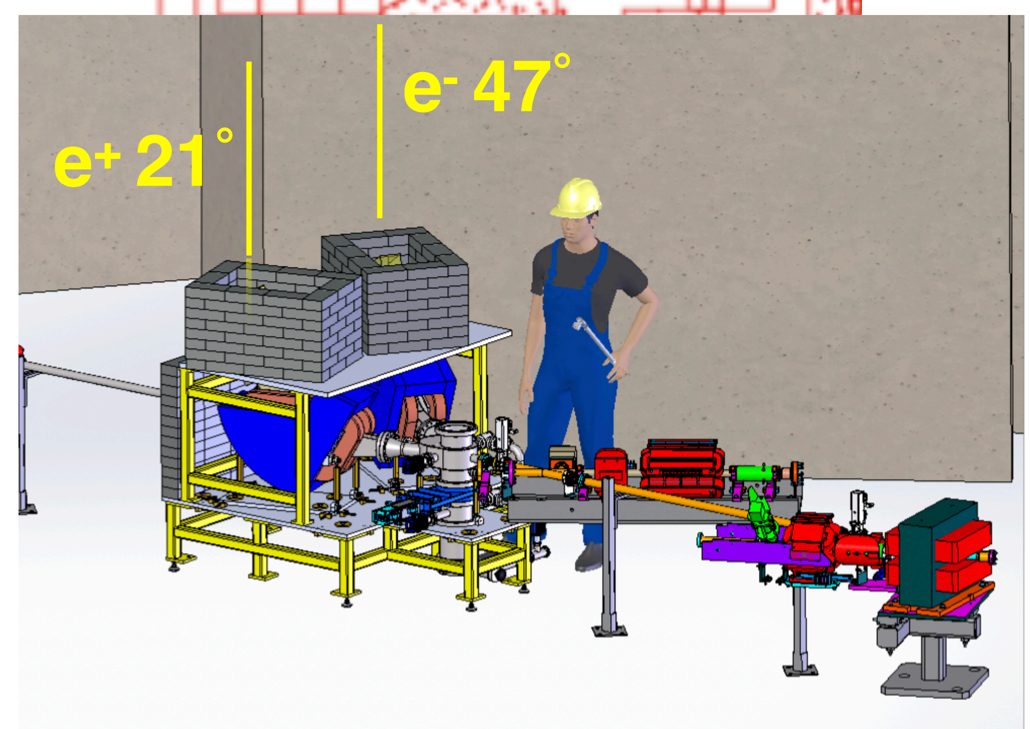
Irreducible QED	Singles e+	Singles e−	Random coin.
9.1 Hz	30.2 kHz	3.6 MHz	168 Hz

- At high $\mathcal{L}$, FOM scales with wall clock, not $\mathcal{L}$
- Optimize by moving e^- arm to larger angle

Proposed Design

- 1 um Tantalum foil target
- Adjustable twin-arm spectrometer
- Asymmetric angles and fields to optimize $S/\sqrt{B}$ of e^+e^- against combinatorics
- Final optimization still being studied
- Likely 'stage 0' placement near High-Power Beam Dump.



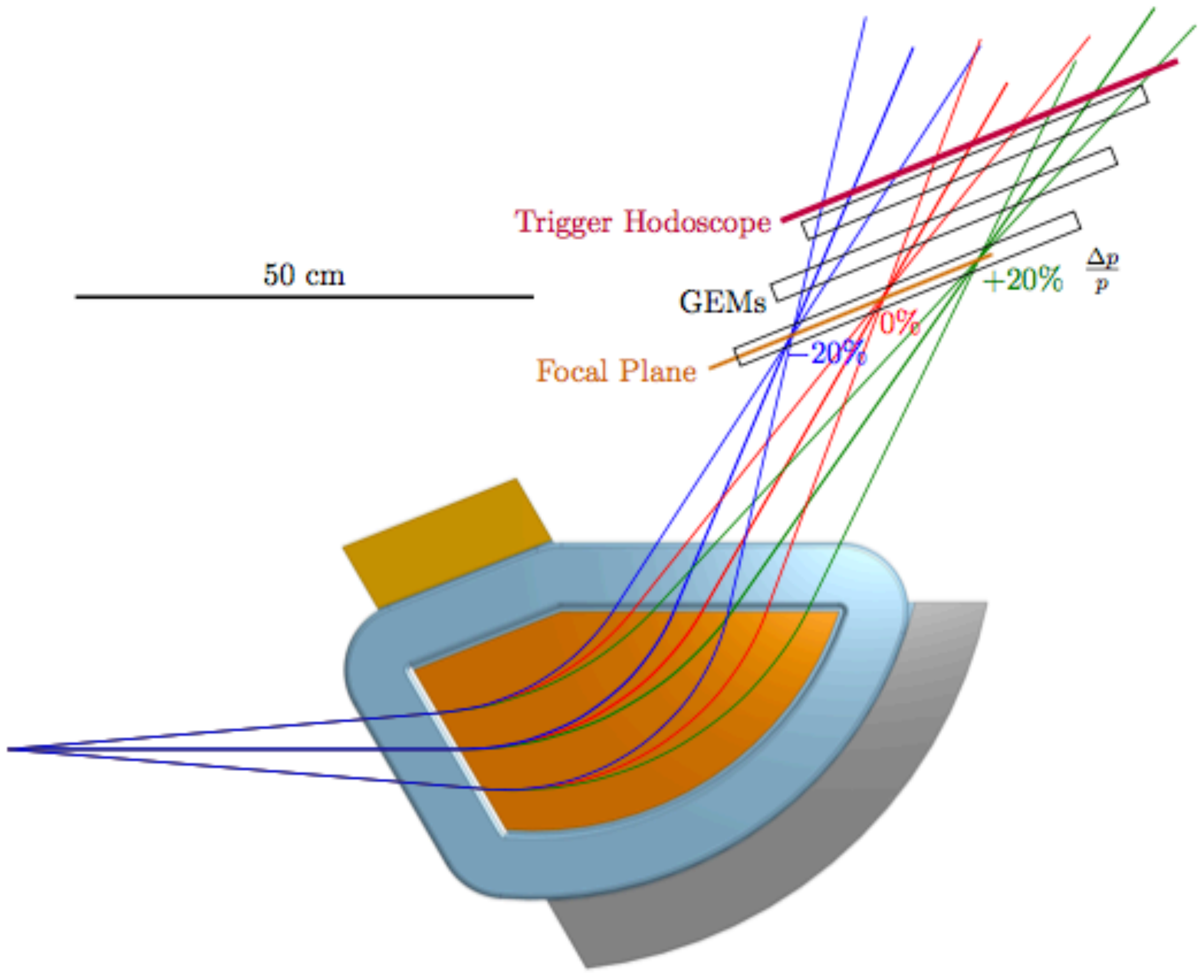


Target Details

- 1 um Ta foil
- ~0.5% beam spread from scattering
- Calculated heating of target is 4W
- Radiative cooling should be sufficient
- Spin target disk -- additional stability, spreads heat
- Interlock with accelerator to protect beamline
- Pass-through configuration of target possible

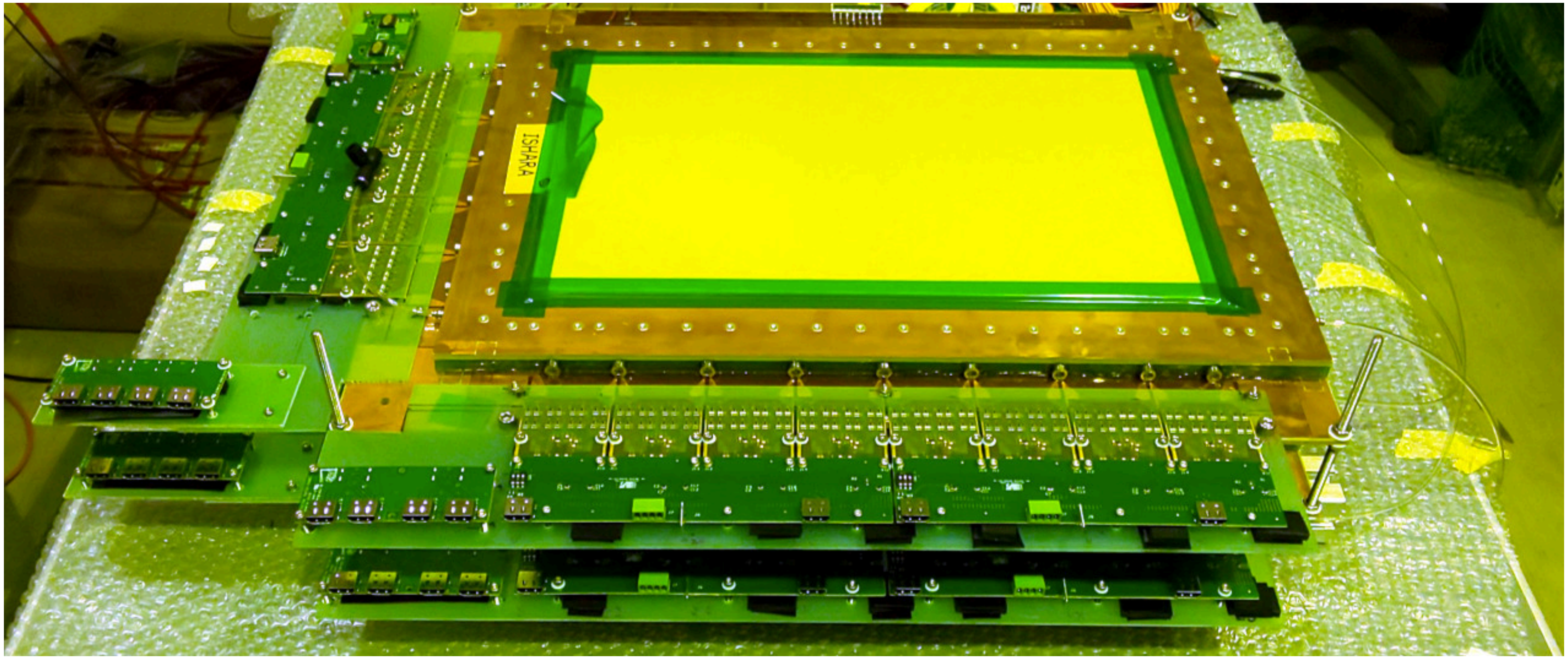
Spectrometers and Resolution

- Two single-dipole spectrometers
- Elastic line in acceptance
- 2/3 Triple-GEM detectors + Scintillators on each arm:
  - Layer 0: Momentum, in-plane angle
  - Layer 1: Out-of-plane angle
- MC sim with MS effects in target and detectors, magnetic optics reconstruction
  ➡ mass resolution 120keV @ 31 MeV beam



In-place acc.	±2°
Out-of-plane acc.	±5°
Momentum acc.	±20 %
Min. central angle	16°
Max. central mom.	28 MeV
Field strength	0.32 T
Nom. bend radius	30 cm
Pole gap	4 cm

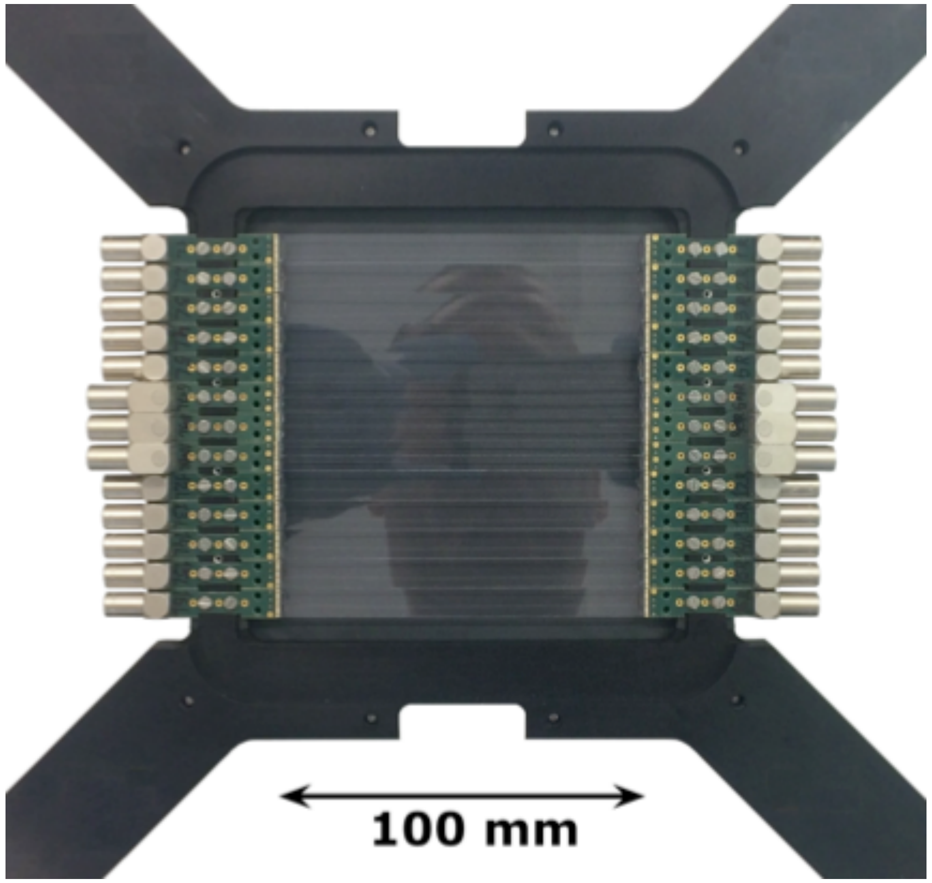
Focal Plane Detectors

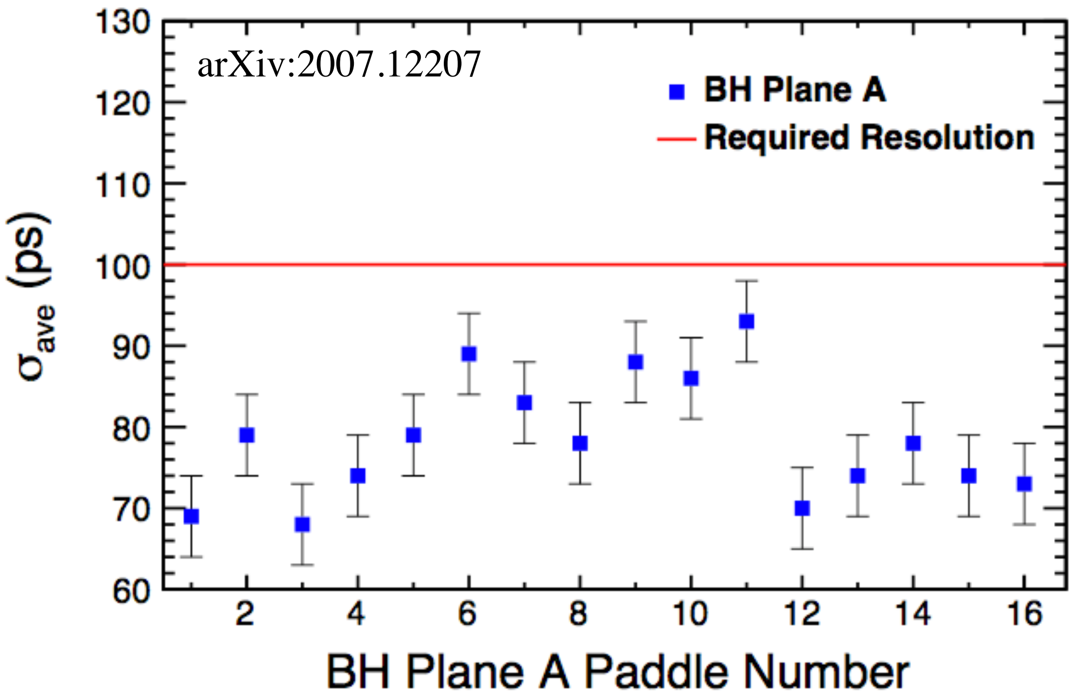


- 25x40cm Triple-GEM detector planes (modified CERN design) built through NSF MRI grant
- Readout via APV and MPD4
- Already built by Hampton group and in use
- Sufficient planes and readout electronics available

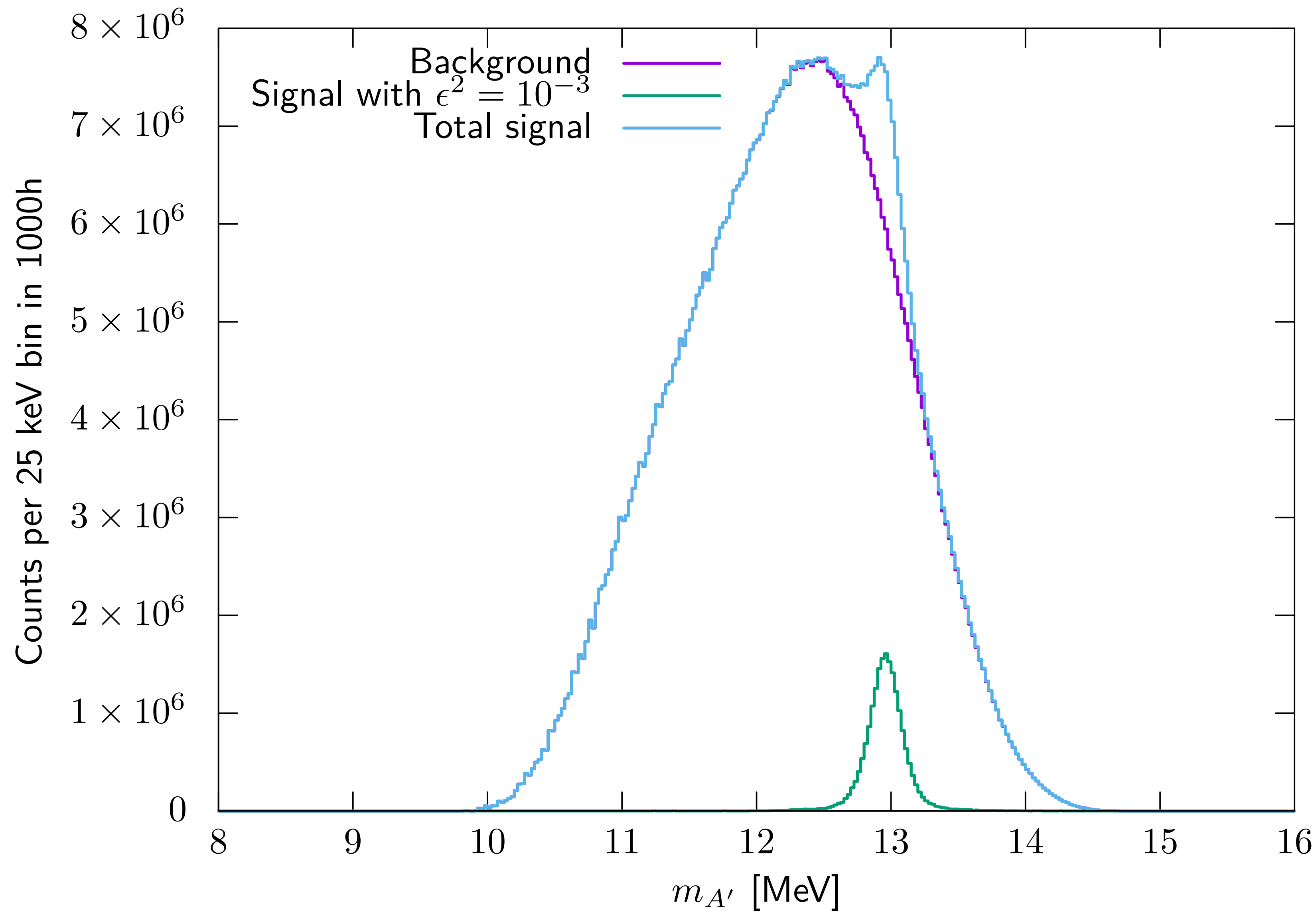
Trigger

- Triggered via segmented scintillator hodoscope
- Needs timing resolution < 500 ps
- Achieved at MUSE:
  - 2 mm thick scintillator, SiPM readout
  - Resolution < 100 ps
  - Tested up to 8mm wide, 15 cm long.



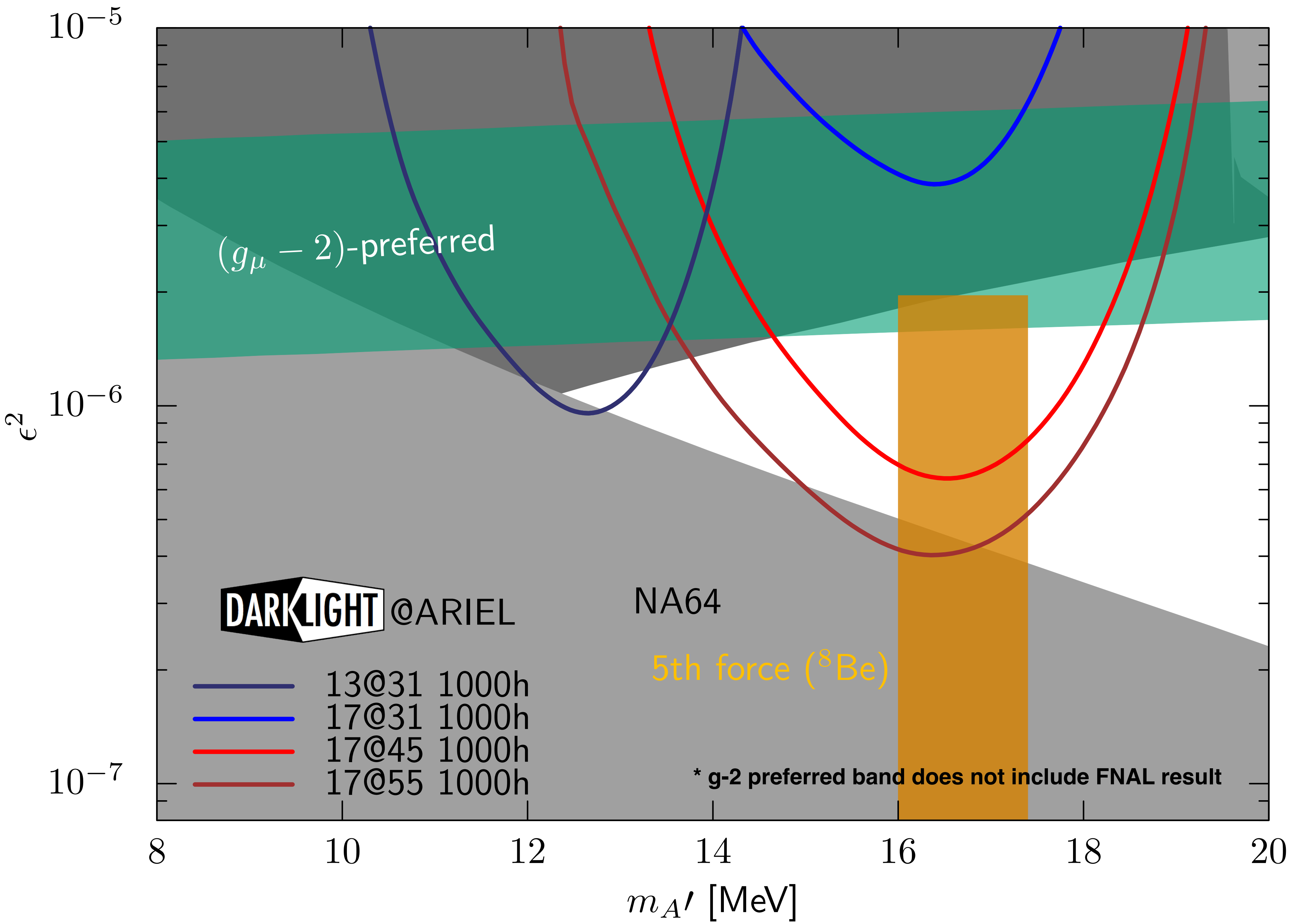


Simulated Signal and Analysis



- Combinatoric background smooth, estimated from mixed events
- Irreducible background smooth, calculated
- Signal significantly narrower
- Narrow, sliding fit region to seek excess

Projected Reach



- Showing limits with existing as well as upgraded ARIEL

Timeline

- Stage 0: Existing ARIEL Design
  - GEMs+electronics can be commissioned and available within 9-12 mo.
  - Final design+construction of magnets possible in same time frame (similar design used in DarkLight 1B)
  - Can begin commissioning at TRIUMF in 2022, ~12 mo after funding becomes available

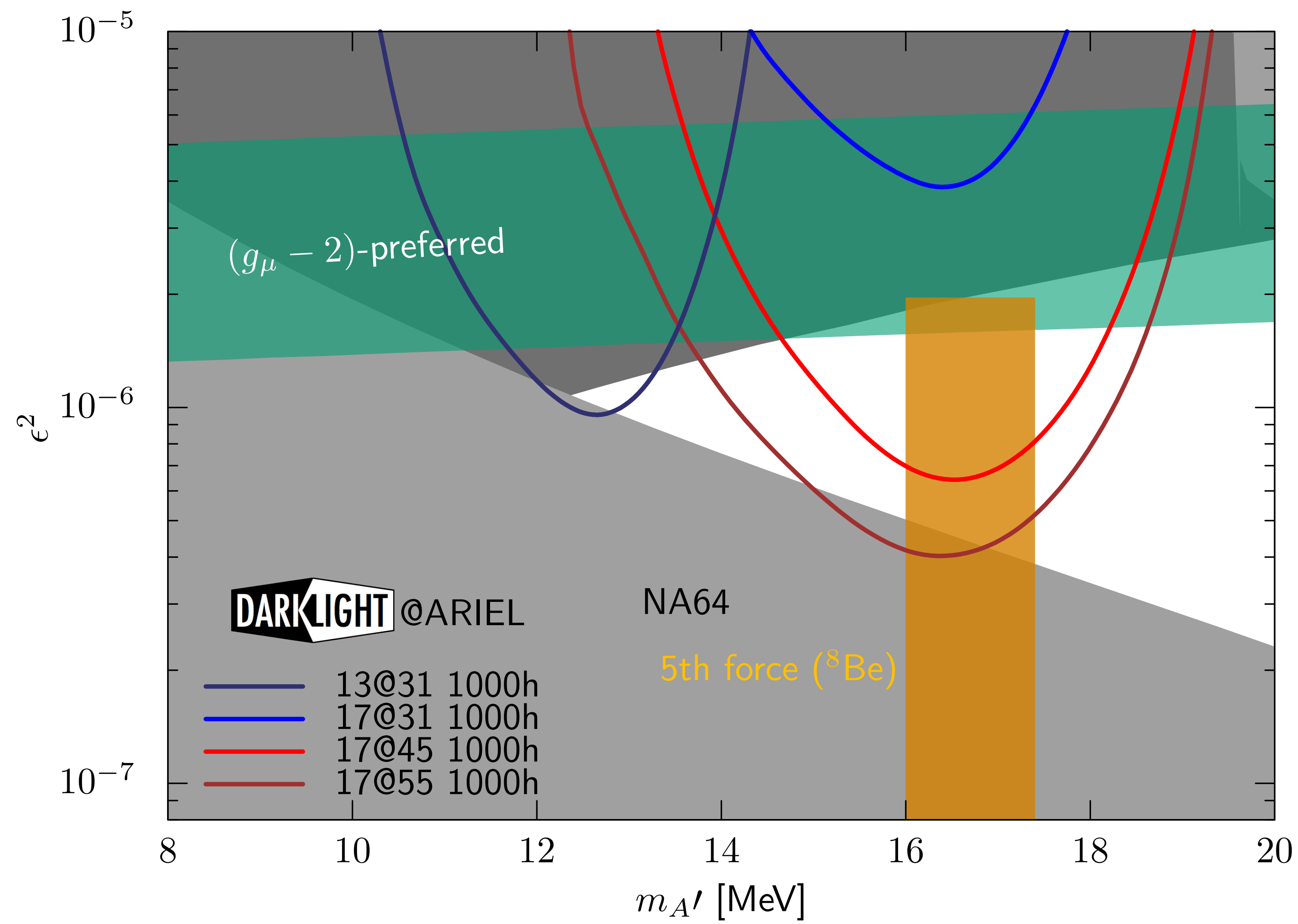
- Stage 1: Recirculation to reach 50 MeV beam, chicane possibly needed to separate 1st and 2nd pass beams through DarkLight target
- Stage 2: Additional cryo module added, DarkLight moved to allow simultaneous 50 MeV operation with ARIEL

Beamtime Request

- 2300 hours starting in 2022:
  - 1000h @ 31 MeV, 150 uA at 13 MeV spectrometer setting
  - 1000h @ 31 MeV, 150 uA at 17 MeV spectrometer setting
  - 300h for background studies and commissioning

Summary

- Several anomalies (including new g-2) are compatible with low-mass, nearly-protophobic force
- ***Purely leptonic production*** key aspect of expanded search
- Mixed-hadronic (LHCb etc) + pure-leptonic (this proposal) provide complementary coverage of X17 region



* g-2 preferred band does not include FNAL result

The DarkLight Collaboration

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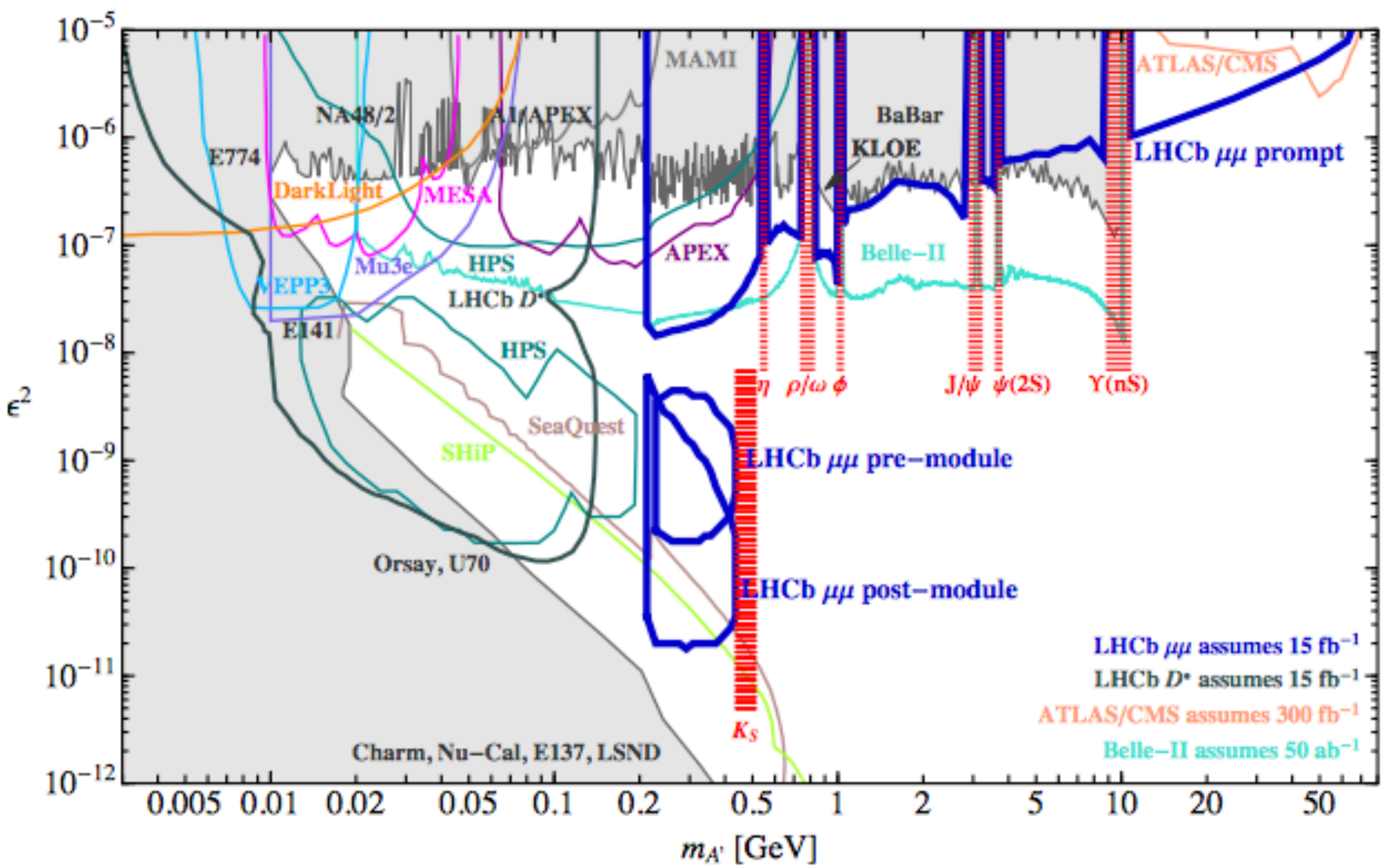
Other Accelerator Experiments

- LHCb - stats by ~2023, hadronic suppression in low-mass search
- Belle II - stats in 2025 or later

- LDMX - no timeline. data hungry
- NA64 - probably can't close the gap. data hungry
- HPS - can't reach
- PADME - very preliminary proposal to look for visible decays, no timeline
- MAGIX - 2023+
- APEX - can't reach
- Mu3e - initial timeline delayed.

LHCb

- Run3 upgrades, expect dataset by 2023
- probes $m_X \lesssim 100$ MeV via D^{0*} decay
- but additional model dependence



arxiv:1603.08926

8Be Apparatus

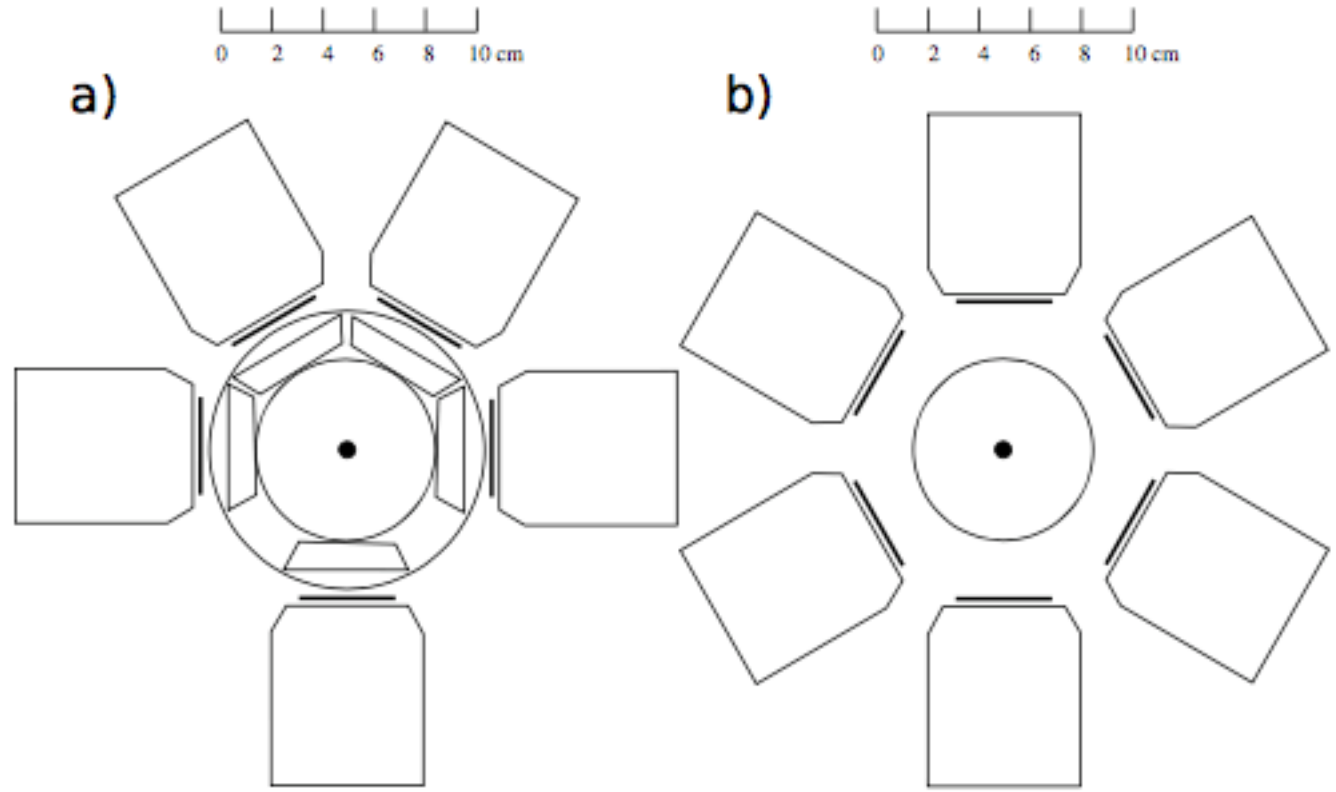
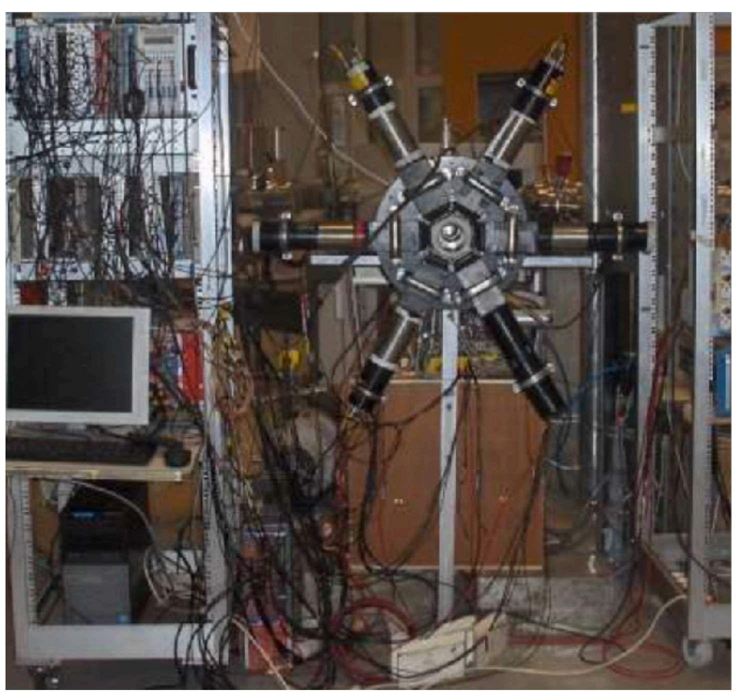


Figure 1. Comparison between the old and new setups. The previous setup (a) used 5 telescopes, each with a MWPC to gather the position of the particles and a thin scintillator in front of the main one to differentiate electrons and positrons from gammas. The new setup (b) consisted of 6 telescopes, and the MWPCs was replaced by DSSDs, which can be used for the particle identification, removing the need for the thin scintillators.



https://doi.org/10.1051/epjconf/202023204005

Additional Intermediate State?

$$U^{(2)}_{EM,\nu\mu} \sim \frac{1}{K_{\alpha\beta}\left(K^2_{\alpha\beta} - q^2\right)}\left(\frac{q}{K_{\alpha\beta}}\right)^L$$

$$\Theta = \arccos\left[\frac{K^2_{\alpha\beta} - \left(k^2_- + k^2_+\right)}{2k_-k_+}\right]$$

- Angular correlations natural for intermediate poles in the propagator
- Not clear if this can also match the observed mass resonances

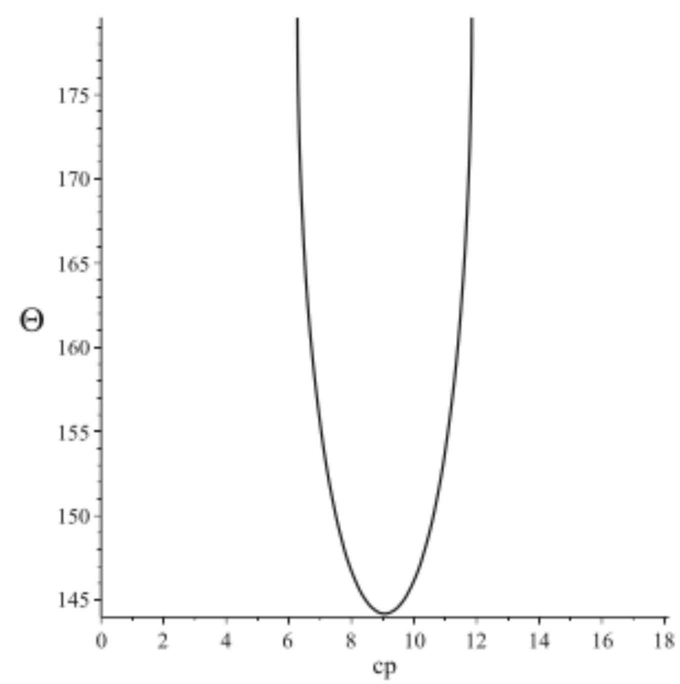
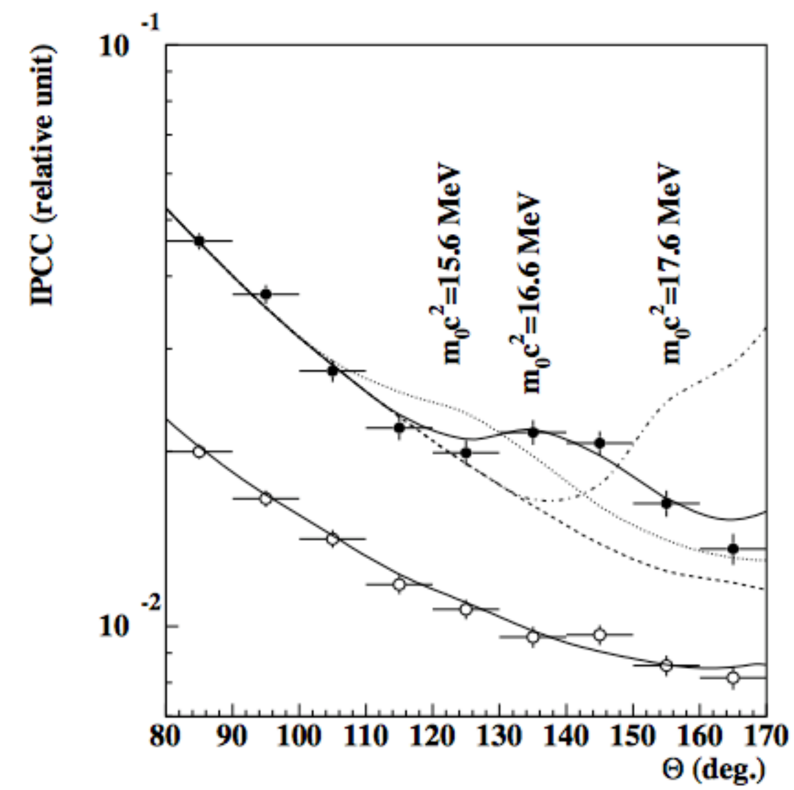


Fig. 1 The cp dependence (where p is momentum of the electron/positron) of Θ (given by (2)) of the expected peak in the coincident e^-e^+ pair counting rate in the case of an $E2$ transition of transition energy $\hbar c K_{31} = 5.572$ MeV of ^8Be. cp is measured in MeV units and Θ is given in degrees

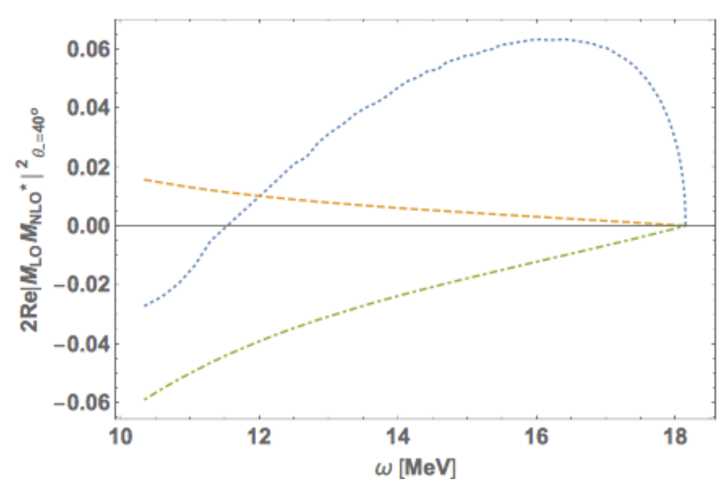


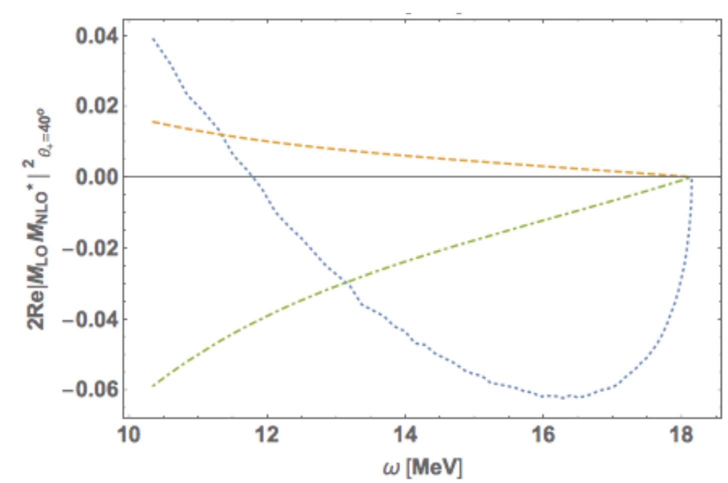
arxiv:2005.10643

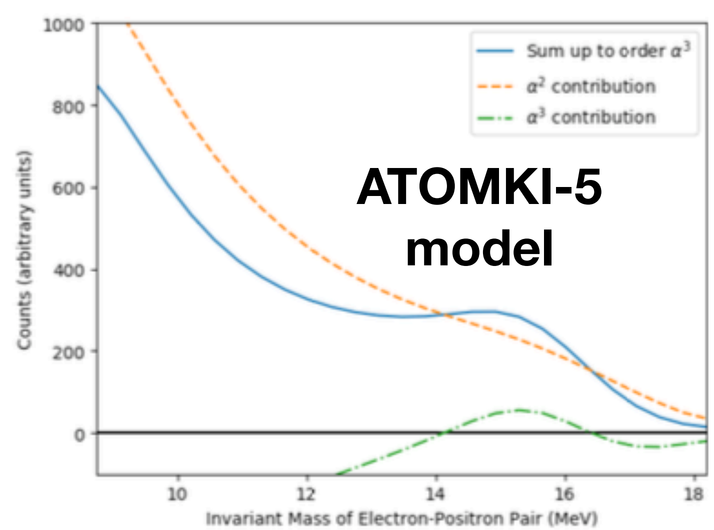
LO+NLO Inteference

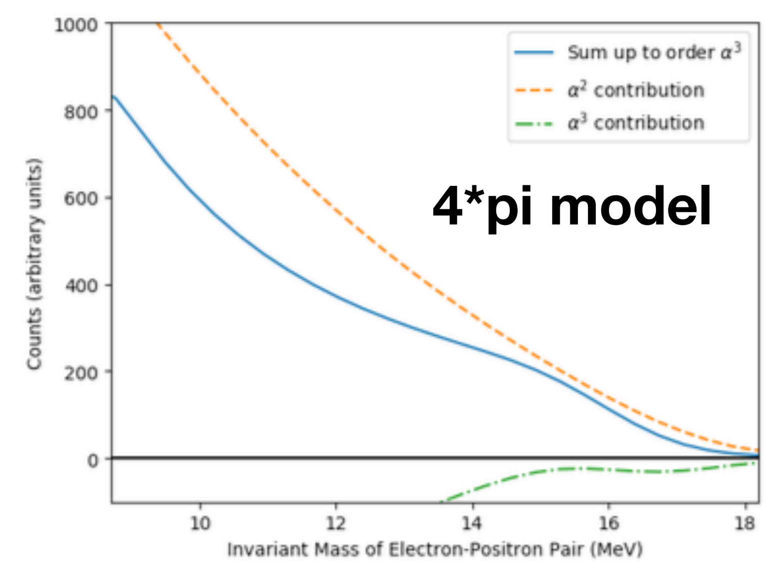
- Small charge sign asymmetry in interference term
- Interaction of LO+NLO assymetry with 5-fold detector acceptance can produce similar resonances
- Unclear if consistent approach can match new detector, ^{4}He result

$$\frac{d^2\Gamma}{d\theta_+ d\theta_-} = \left(|M_{LO}|^2 + 2\Re\left[M_{LO}M^*_{NLO}\right]\right)\Phi$$





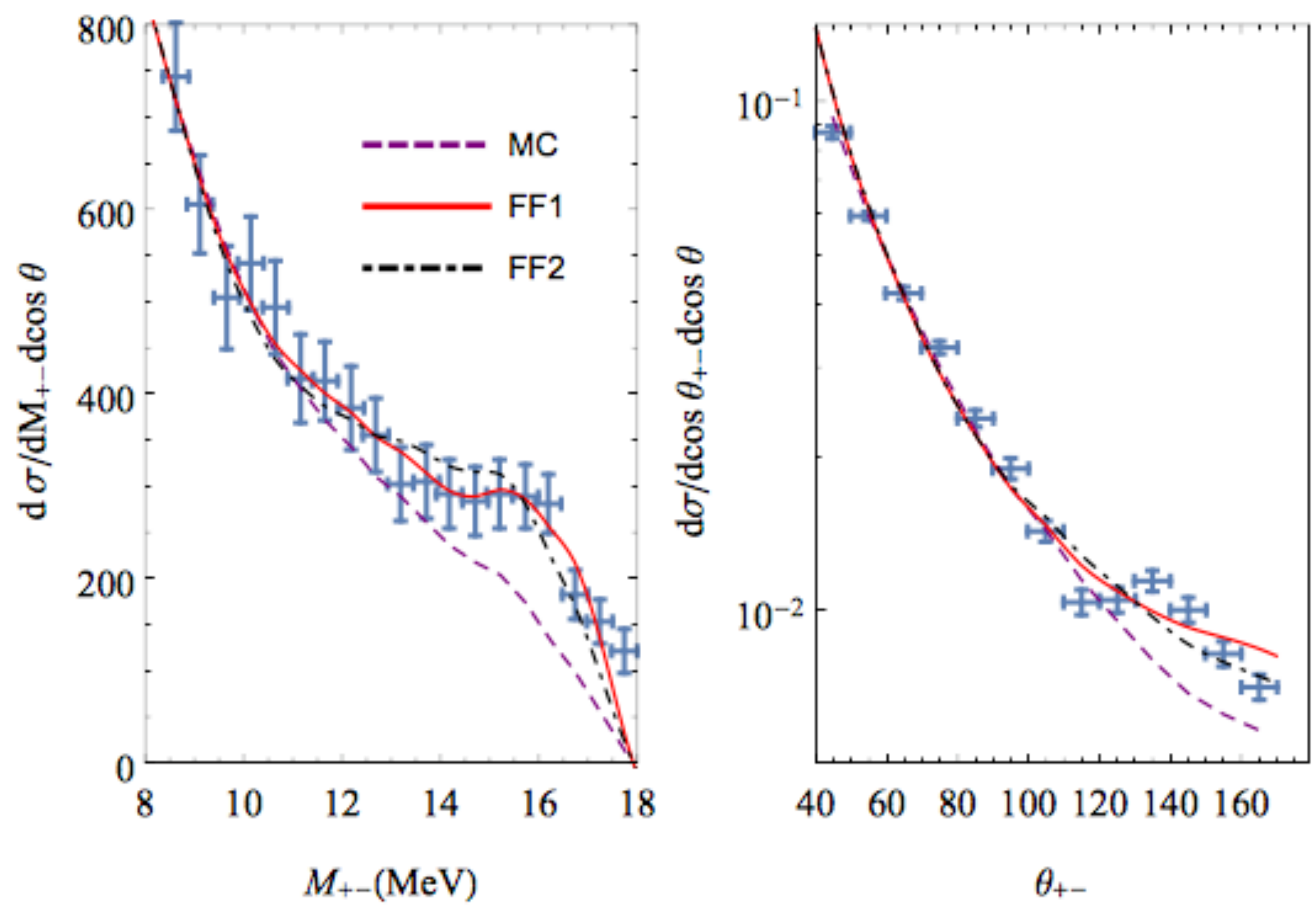




arxiv:2102.01127

Anomalous ^{8}Be Form Factor?

- Careful treatment of multipole interferences
- Introduction of form factor to M1 transition
- Good fit to mass peak, but difficult to match angular correlation
- Resulting FF has length scale O(10) fm -- much larger than charge radius



arxiv:1703.04588