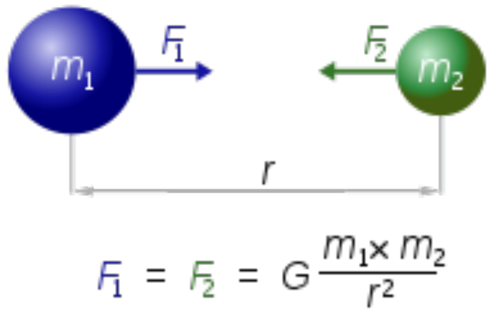
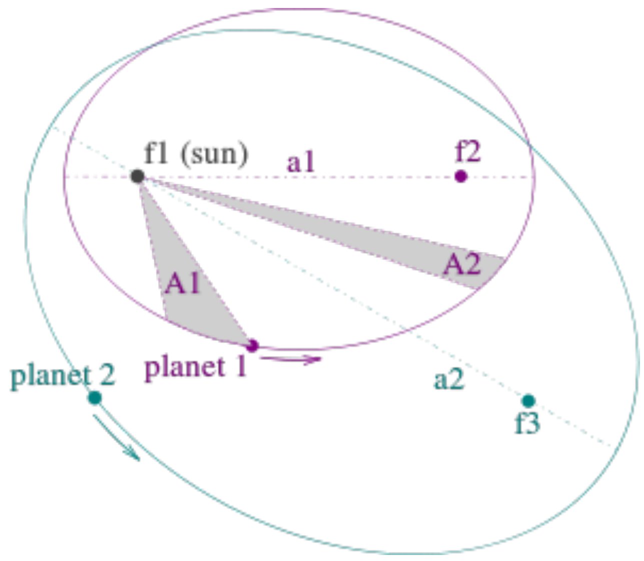
A Prime EXperiment:
Sensitive search for a heavy photon

Bogdan Wojtsekhowski, Jefferson Lab

- Motivation
  - Physics beyond SM
  - Dark matter astronomical observations
  - Heavy photon as a DM force mediator
- Axion-like/Heavy photon searches
- APEX-2019 data quality and sensitivity

Where is new physics?





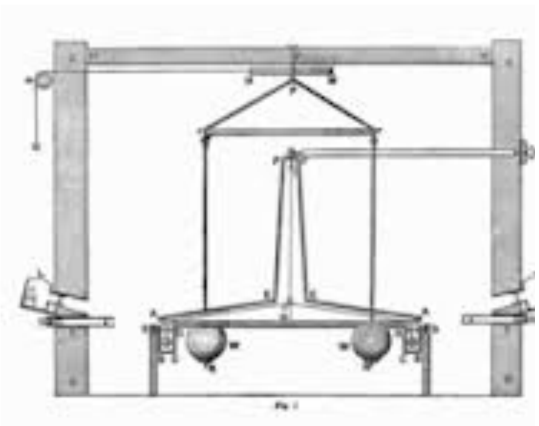
In the middle of the 18th century:

Clairaut suggested that the strength of gravity was proportional not to $\frac{1}{r^2}$, but the more complicated

$$\frac{1}{r^2} + \frac{c}{r^4}$$

for some constant c. Over large distances, the c/r^4 term would effectively disappear, accounting for the utility of the inverse square law over large distances. He then began

Where is new physics?



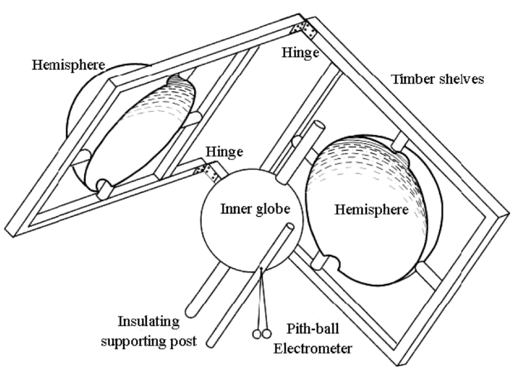


Table I. Results of various tests of Coulomb's law and tests for a nonzero photon rest mass.

	Coulomb's Law violation of form r^{2+q}		Photon rest mass
	q	$\mu^2 = \left(\frac{m_o c}{\hbar}\right)^2$	m_o
Cavendish (1773)	2×10^{-2}		
Coulomb (1785)	4×10^{-2}		
Maxwell (1873)	4.9×10^{-5}		
Plimpton and Lawton (1936)	2.0×10^{-9}	$1.0 \times 10^{-12}\ cm^{-2}$	$\leq 3.4 \times 10^{-44}\ g$
Cochran and Franken (1967)	9.2×10^{-12}	$7.3 \times 10^{-15}\ cm^{-2}$	$\leq 3 \times 10^{-45}\ g$
Bartlett, Goldhagen, Phillips (1970)	1.3×10^{-13}	$1 \times 10^{-16}\ cm^{-2}$	$\leq 3 \times 10^{-46}\ g$
Williams, Faller, Hill	$(2.7 \pm 3.1) \times 10^{-16}$	$(1.04 \pm 1.2) \times 10^{-19}\ cm^{-2}$	$\leq 1.6 \times 10^{-47}\ g$
Schroedinger (1943)	Test of Ampere's Law from Geo-magnetic Data	$3 \times 10^{-19}\ cm^{-2}$	$\sim 2 \times 10^{-47}\ g$
Gintsburg (1963)		$5 \times 10^{-20}\ cm^{-2}$	$\leq 8 \times 10^{-48}\ g$
Nieto and Goldhaber (1968)		$1.3 \times 10^{-20}\ cm^{-2}$	$\leq 4 \times 10^{-48}\ g$
Feinberg (1969) [a]	Dispersion of light	$8 \times 10^{-14}\ cm^{-2}$	$10^{-44}\ g$

10^{-11} eV

SM tests, constraints on new physics (per PDG)

column denoted Pull gives the standard deviations for the principal fit with M_H free, while the column denoted Dev. (Deviation) is for $M_H = 124.5$ GeV [215] fixed.

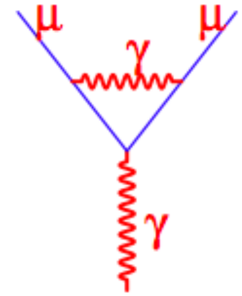
Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	-0.1	-0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		-0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

Photon mass < 10^{-18} eV

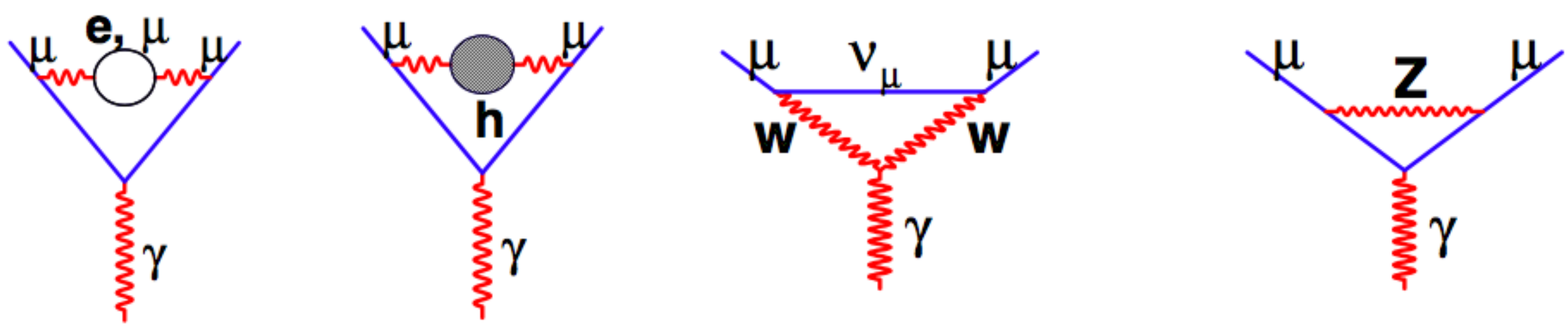
SM tests, constraints on new physics (per PDG)

g - 2 for the muon

Largest contribution : $$a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$$



Other standard model contributions :



QED hadronic weak

from STORY05, Y. Semertzidis

Where is new physics?

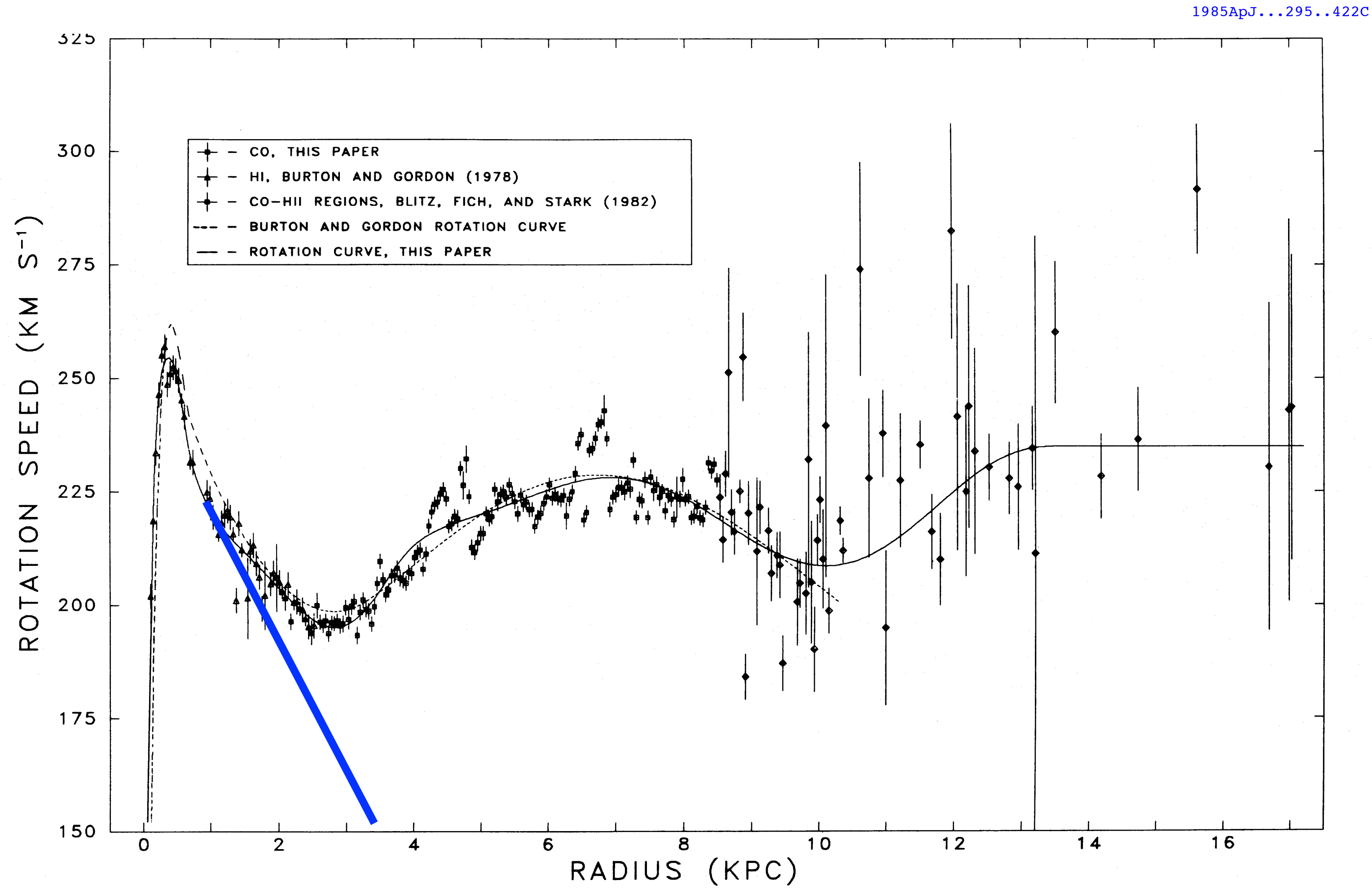


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)(R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

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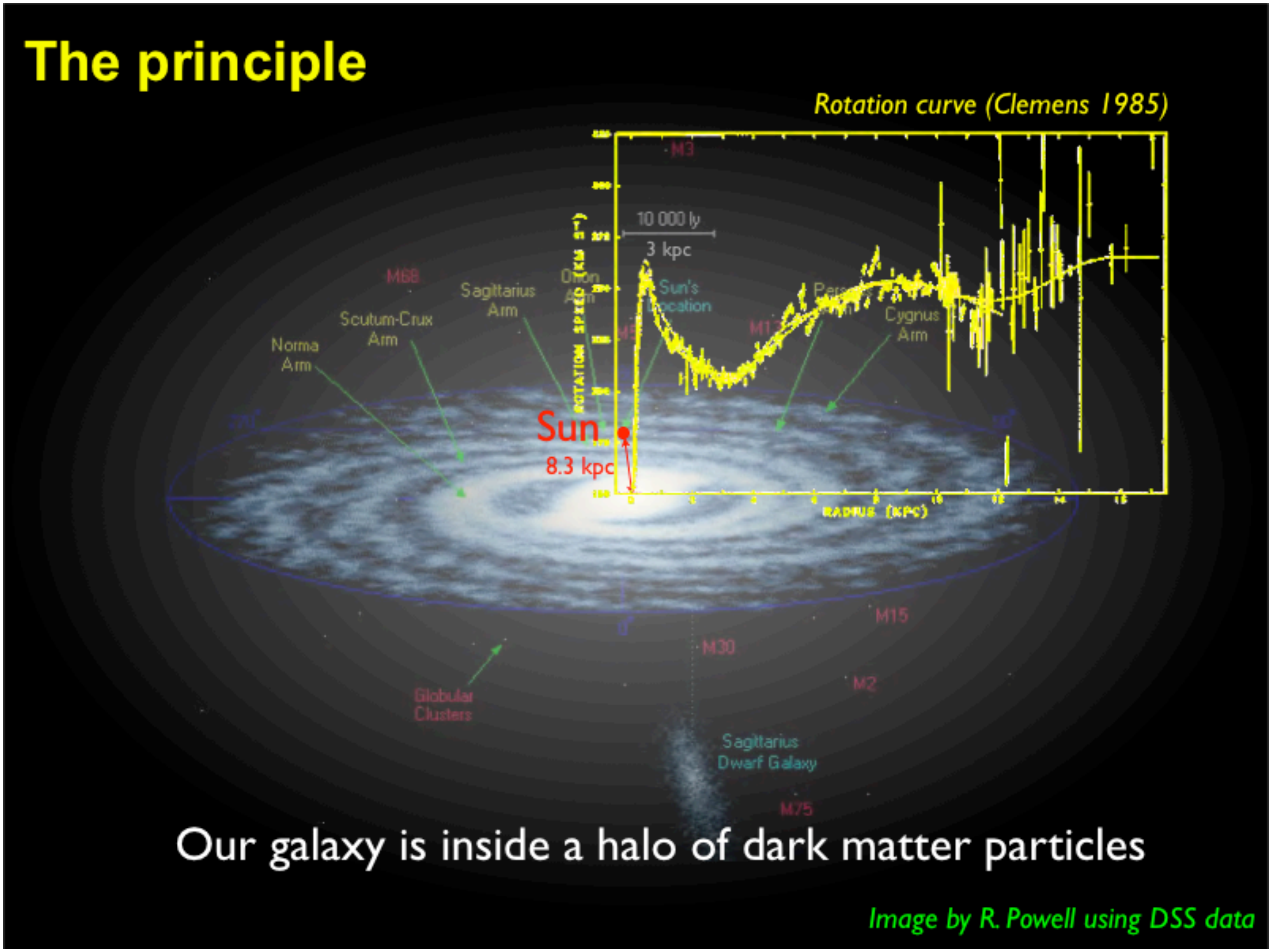
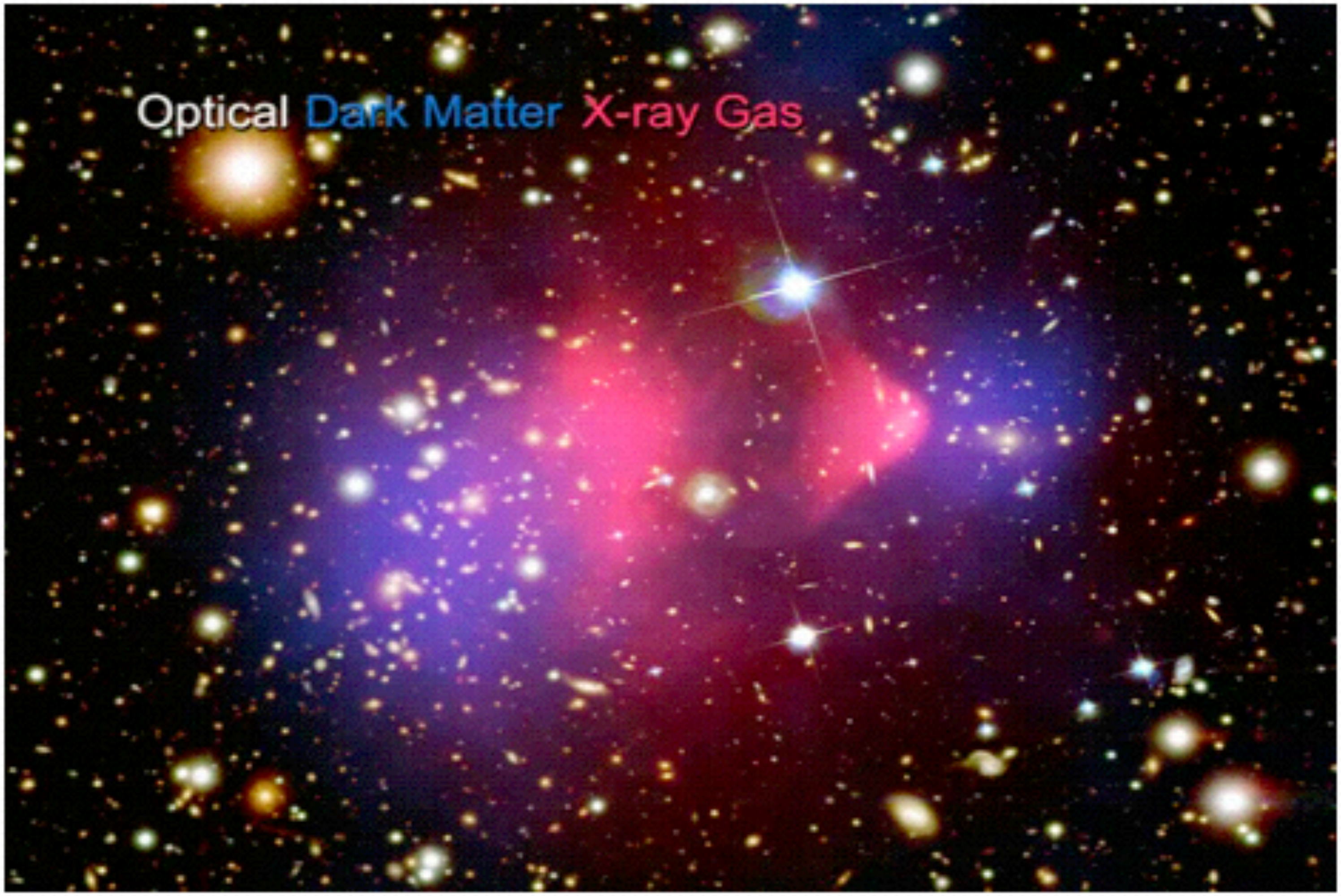
DM in 1933 by F. Zwicky. The plot from D. Clemens, 1985

The motivation is the nature of dark matter



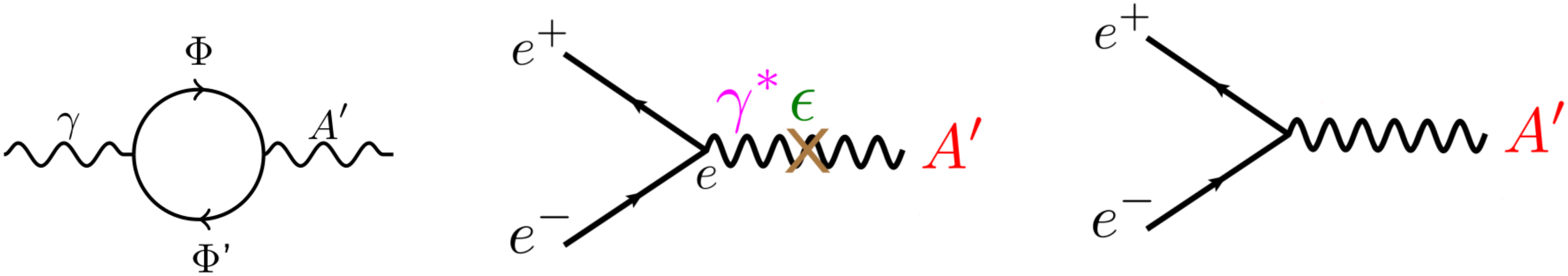
The motivation is the nature of dark matter



D. Clowe et al., ”A direct empirical proof of the existence of dark matter”,
Astrophys. J., Vol.648, L109 (2006). doi:10.1086/508162

The connection of dark matter to SM

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$



Search for DM particles

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

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(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Search for a Short-Lived Neutral Particle Produced in Nuclear Decay

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We report on a search for a short-lived neutral particle ϕ produced in the decay of the 9.17-MeV $J^\pi=2^+$ state in ^{14}N. The experiment is sensitive to decays into an e^+e^- pair with $\tau_\phi \lesssim 10^{-11}$ s. For $m_\phi = 1.7$ MeV we place a limit on the branching ratio of $\Gamma_\phi/\Gamma_\gamma \leqslant 4\times10^{-4}$ at the 90% confidence level.

PACS numbers: 14.80.Gt, 23.90.+w

Anomalous narrow peaks have been observed in the spectra of positrons emitted in heavy-ion collisions in several recent experiments at Gesellschaft für Schwerionenforschung Darmstadt (GSI).[1-3] In addition, a new experiment[4] has revealed that the positrons associated with these peaks are correlated with electrons whose energy spectrum also contains a narrow peak at the same energy as the positron peaks. One explanation[4-6] for these peaks is the production and subsequent decay of a previously unobserved neutral particle ϕ of mass ~ 1.7 MeV. Monte Carlo simulations[4] of such a particle decay, assuming the particle to be produced at rest in the center-of-mass system iments, if attributed to this new neutral particle, indicate a large branching ratio for decay to e^+e^-. To observe these pairs emitted from a particle produced in nuclear decay we must separate them from the ordinary internal pairs produced in the electromagnetic decay of the nuclear state (a virtual photon converts internally to e^+e^-). It has been suggested previously[16] that pairs produced from the decay of a pseudoscalar particle can be distinguished from internal pairs by their angular correlation. Previous detailed studies[17] of the angular correlation of nuclear pairs, which were used to extract transition multipolarities, indicate that $\Gamma_\phi/\Gamma_\gamma$ is likely to be small, although estimates are

VOLUME 52, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1984

Search for a Light Scalar Boson Emitted in Nuclear Decay

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and

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(Received 6 September 1983)

The possibility that a scalar boson is sometimes emitted in the decay of ^{4}He(20.1 MeV, 0^+) is examined experimentally. Finding no positive evidence the authors exclude scalars with Higgs-like couplings for $3 \lesssim m_\varphi \lesssim 14$ MeV/c^2, where the precise range depends upon the model.

PACS numbers: 14.80.Gt, 14.80.Pb, 23.90.+w

One exciting aspect of gauge theories is the notion that new scalar bosons may await experimental discovery.[1,2] For example, the standard model of electroweak interactions requires a new neutral scalar, the Higgs boson. Simple assumptions imply a heavy scalar, $m_\varphi \gtrsim 6-7$ GeV/c^2,[3] but complications could spoil the bound. Moreover, scalars seem ubiquitous in gauge theories and it is prudent to search for them regardless of mass.[2]

An early suggestion of a light scalar was based on anomalous muonic x-ray shifts.[3,4] Resnick *et al.*[5] argued that the relative shifts of Ba $4f-3d$ and Pb $5g-4f$ could be accounted for by a force mediated by a scalar with mass in the range $0 \lesssim m_\varphi \lesssim 22$ MeV/c^2 and Higgs-like couplings. This possibility motivated Kohler *et al.*[6] to search directly in the decays ^{16}O(6.05 MeV, 0^+) $\to$ ^{16}O(g.s., 0^+) + φ and ^{4}He(20.1 MeV, 0^+) $\to$ ^{4}He(g.s., 0^+) + φ. The evidence for x-ray anomalies has not held

ed NaI detector in which the signal approximates that of a 20-MeV γ ray. Higgs-like scalars should be semiweakly interacting and, unlike direct-capture photons, able to penetrate thick shielding material. In this Letter we describe the experiment and we compare the results to available theory.

Figure 1 shows the experimental arrangement. A 600-keV proton beam from the Argonne National Laboratory Dynamitron bombards a tritium target. The target is ≈ 30 μg/cm^2 tritium implanted in ≈ 1 mg/cm^2 erbium deposited over a 5-cm circle inside a tantalum "wobbler-target cup." The wobbler spreads the irradiation on the perimeter of a 4-cm circle mitigating tritium loss from excessive heating. With the wobbler an average power dissipation of $\lesssim 70$ W can be tolerated. The maximum obtainable beam current is 100–120 μA and the beam is pulsed on and off during alternate 100-msec periods. The prin-

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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(Received 7 April 2015; pu

Electron-positron angular correlations were meas
($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, T
($J^\pi = 1^+$, $T = 0$) state → ground state transitions in
pair creation was observed at large angles in the an
confidence level of $> 5\sigma$. This observation could possi
might indicate that, in an intermediate step,
$16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV/c^2 and $J^\pi = 1^+$

^{7}Li+p -> ^{8}Be*-> ^{8}Be + e+e-

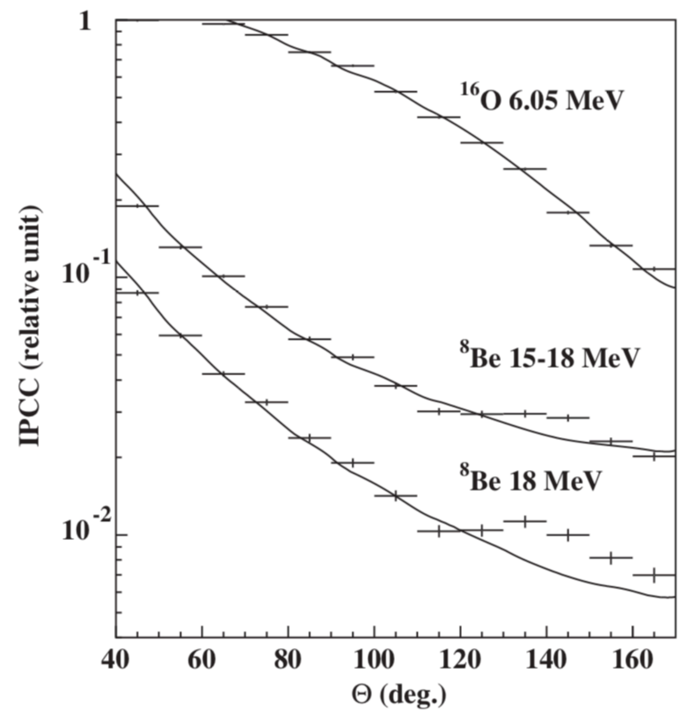
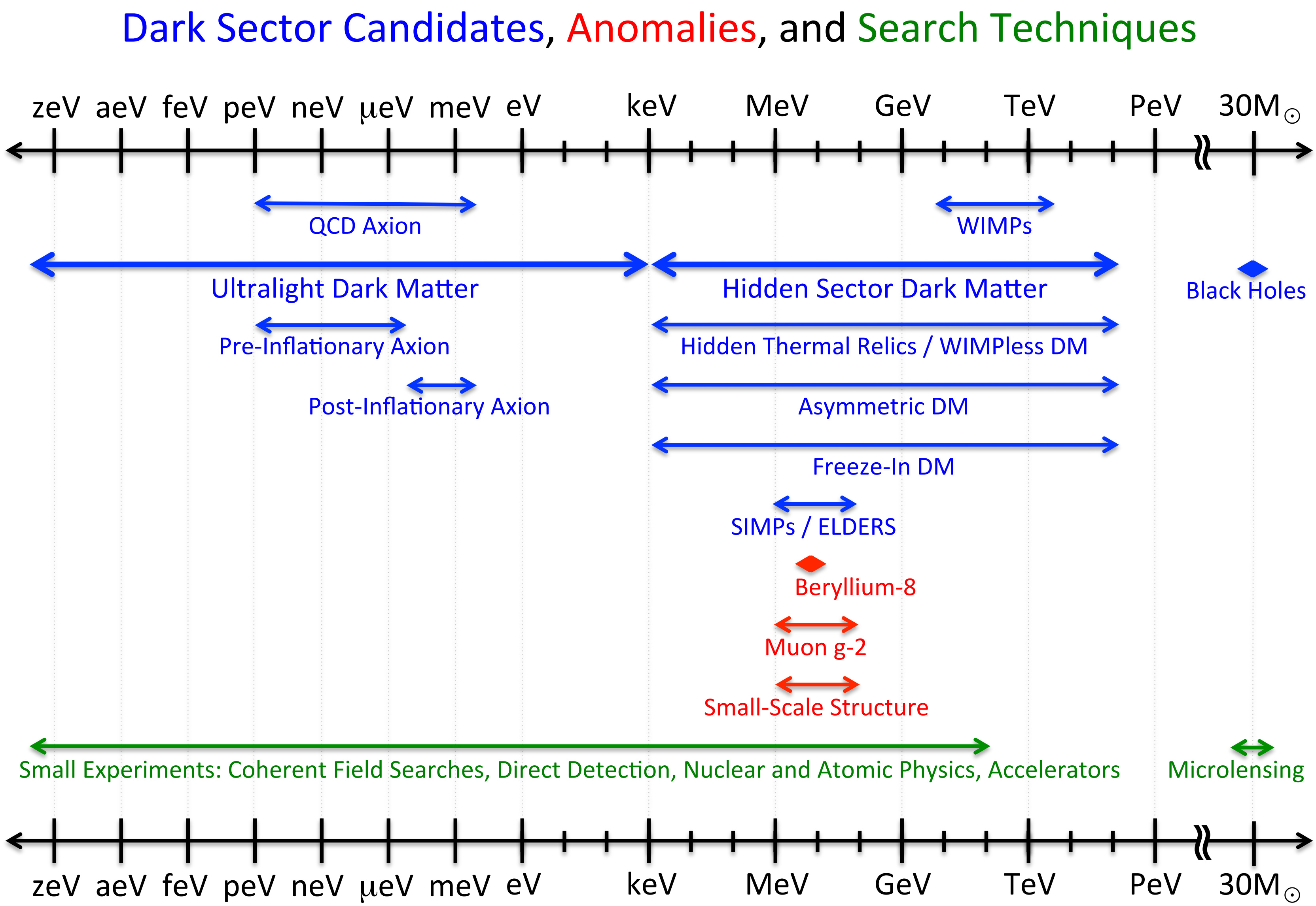
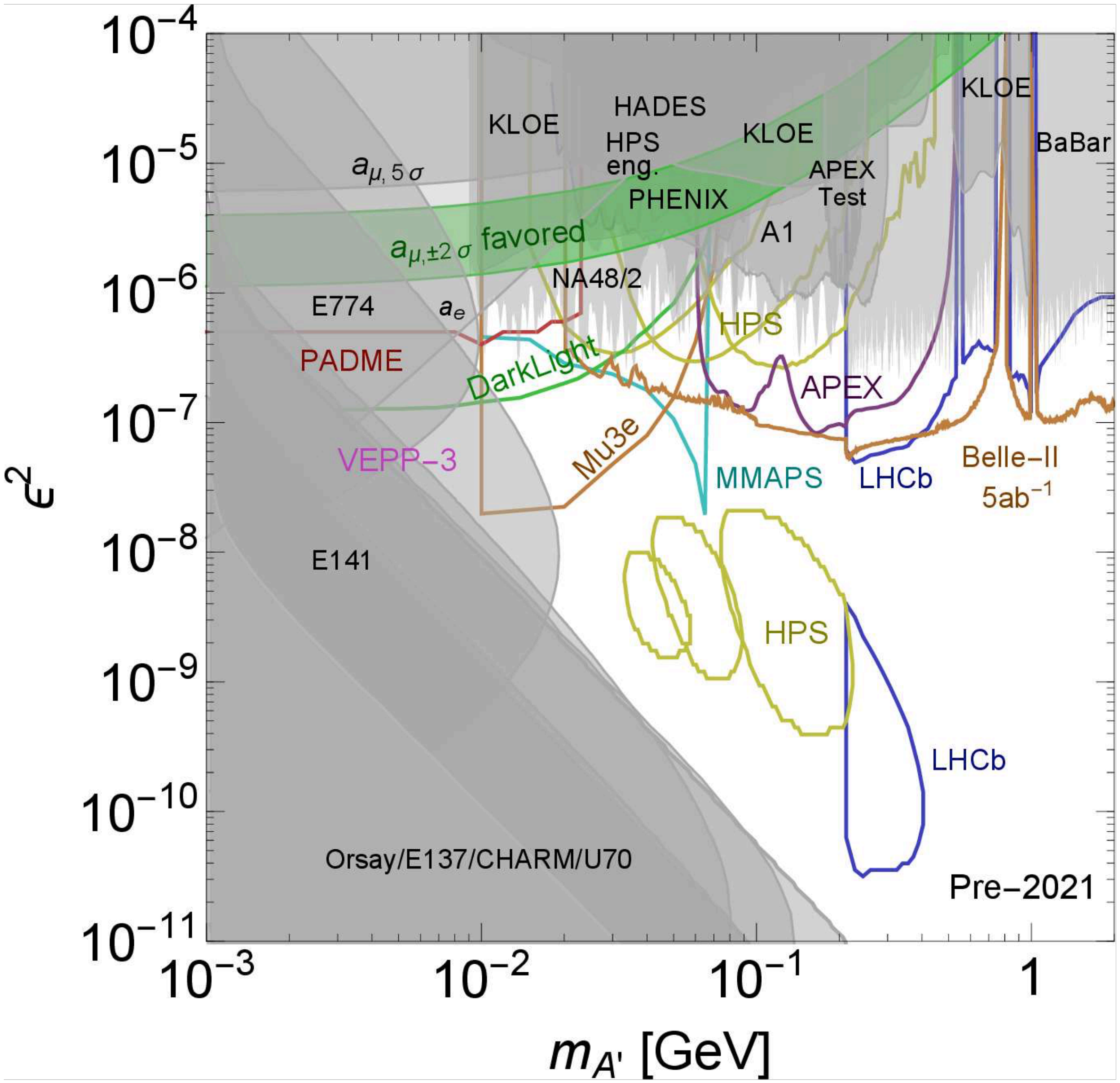


FIG. 2. Measured angular correlations ($E_P = 1.10$ MeV) of the e^+e^- pairs created in the different transitions labeled in the figure, compared with the simulated angular correlations assuming $E0$ and $M1 + E1$ mixed transitions.

The DM overview



The DF mediator parameter space



Ways to search for a new particle

$$e^+e^- \leftrightarrow \gamma^* \text{ and } e^+e^- \leftrightarrow A'$$

- Search for a bump in the mass spectra

  as it was done - Vector Mesons, Z/W, H

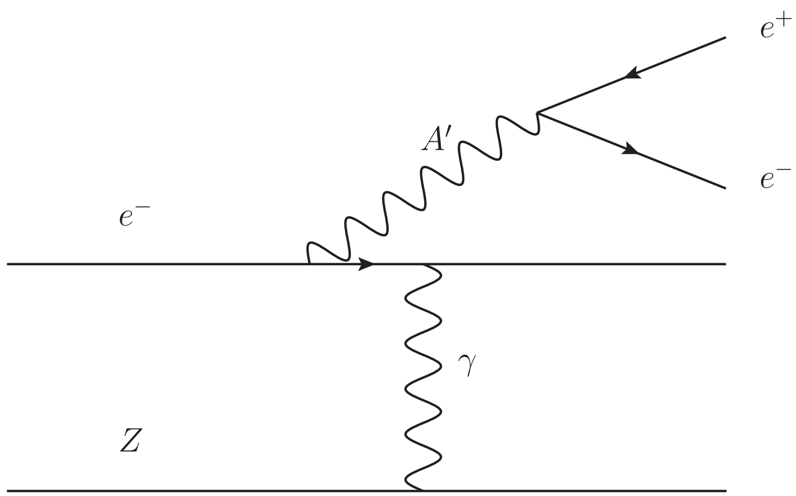
- Impact of "invisible" modes in decay products

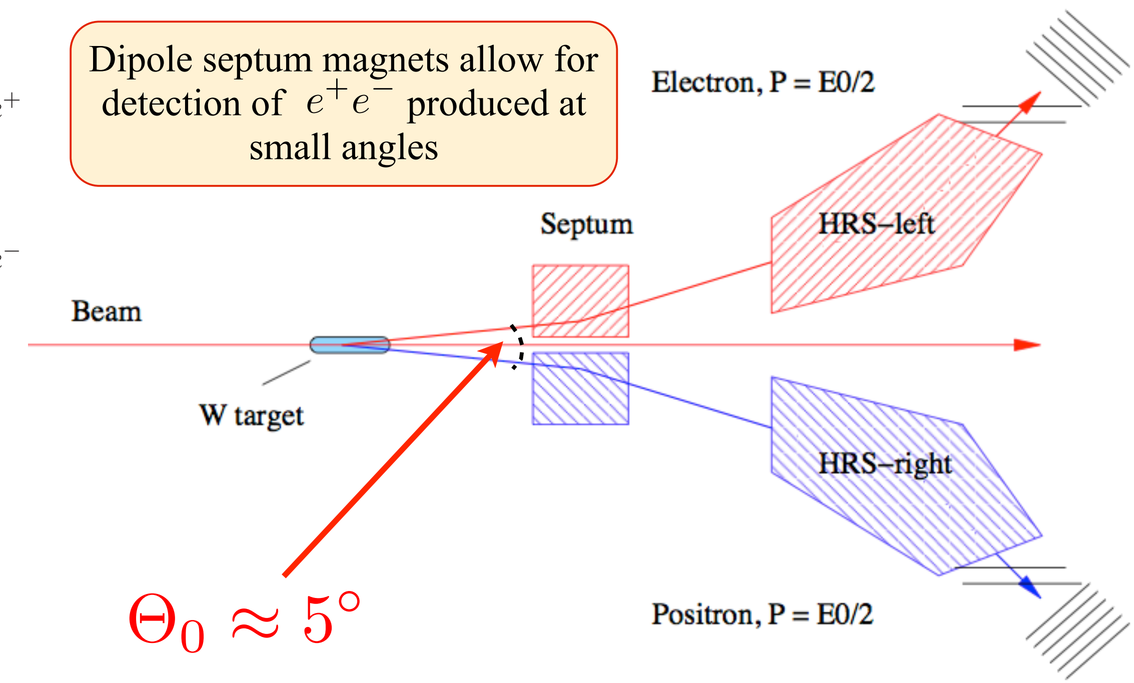
  How small is the e+e- decay branching fraction?

Searches for a gauge boson A’ in Hall A

Direct production at JLab

- Produce low mass hidden gauge bosons with weak coupling to SM via high energy electron beam incident on fixed high-Z (Ta) target
- A' decays to e^+e^- pair with opening angle $\sim m_{A'}/E_b$



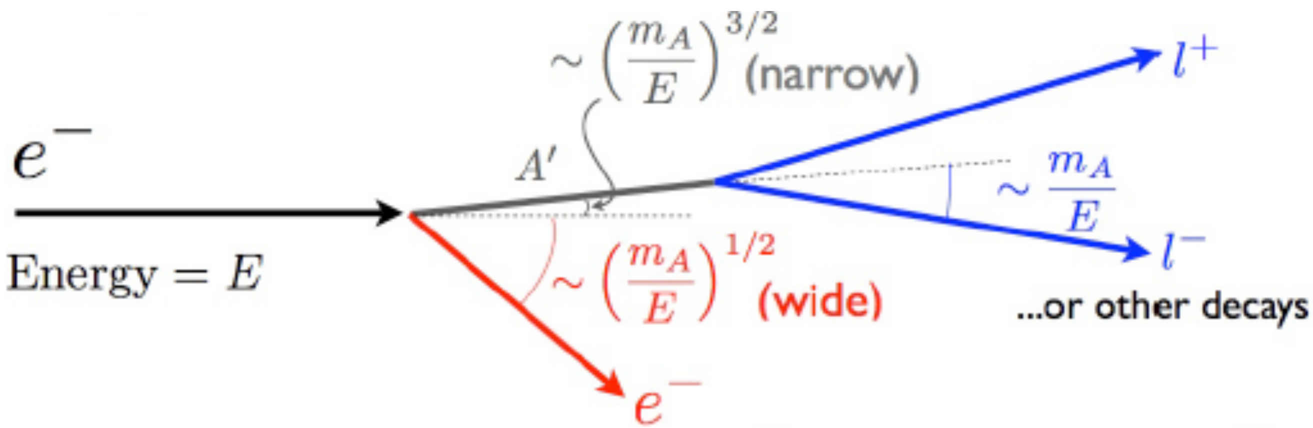


A' radiation and decay

- Like photon Bremstrahlung, production is enhanced by high Z target, but suppressed by ~ $(\varepsilon m_e/m_{A'})^2$

- Emitted mostly at beam energy ($E_{A'} \approx E$)

  and at small angles



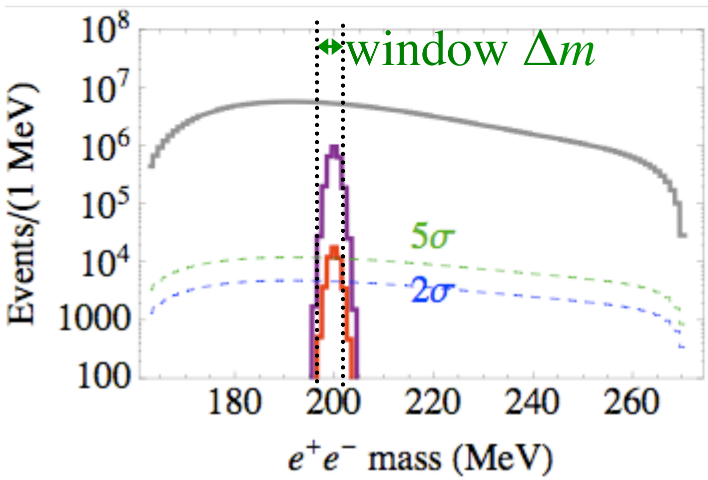
- Huge QED background (reduced for displaced decay vertex)

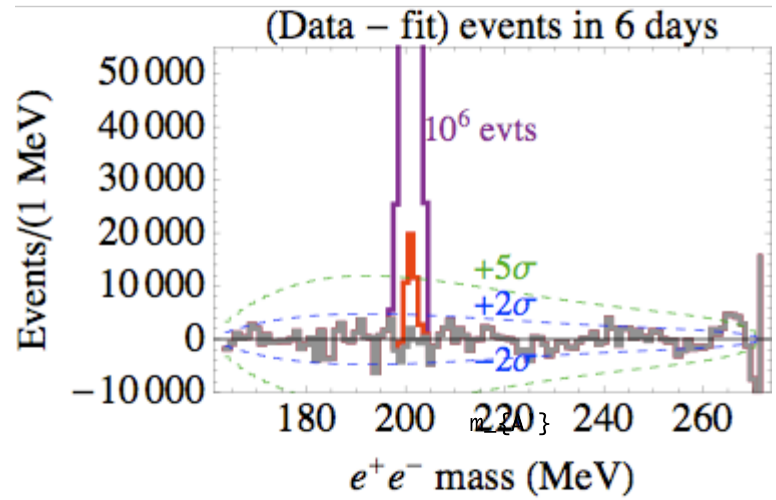
 Bjorken et al., PRD 80 (2009) 075018

Narrow Resonance Search

To identify A′ signal, must study invariant mass distribution

$$m_{A'} \approx \sqrt{E_+E_-}(\theta_+ + \theta_-)$$





In mass window Δm:

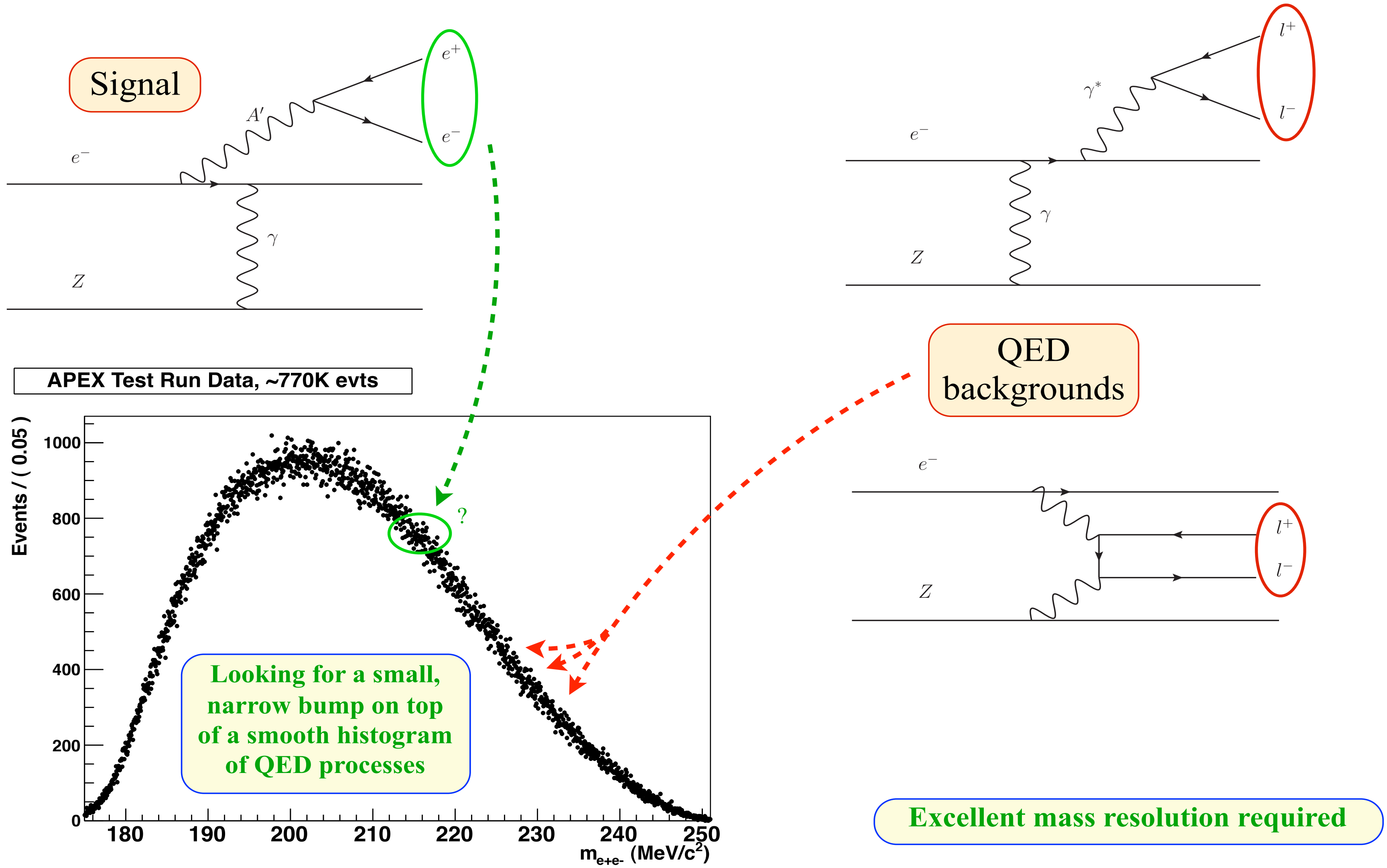
$$\frac{S}{\sqrt{B}} \sim \frac{\alpha'}{\alpha^2}\sqrt{N_{QED}\left(\frac{m_{A'}}{\Delta m}\right)}$$

To search at small α′, need:

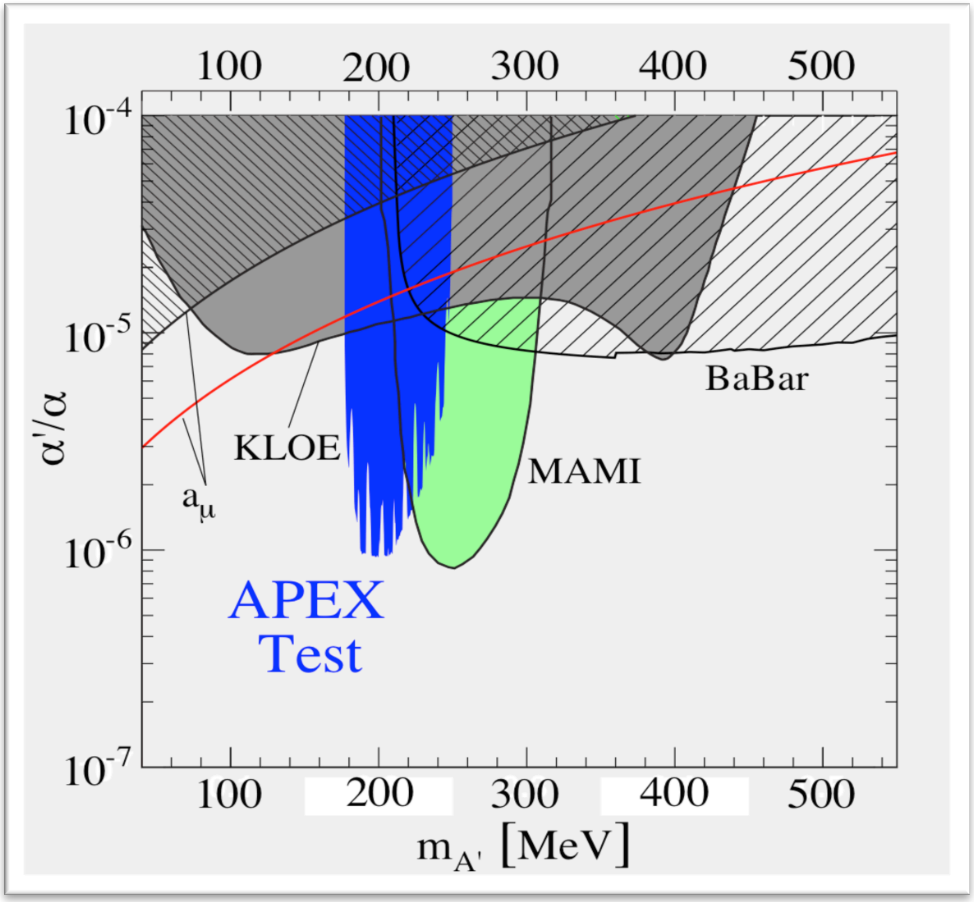
★High e^+e^- statistics

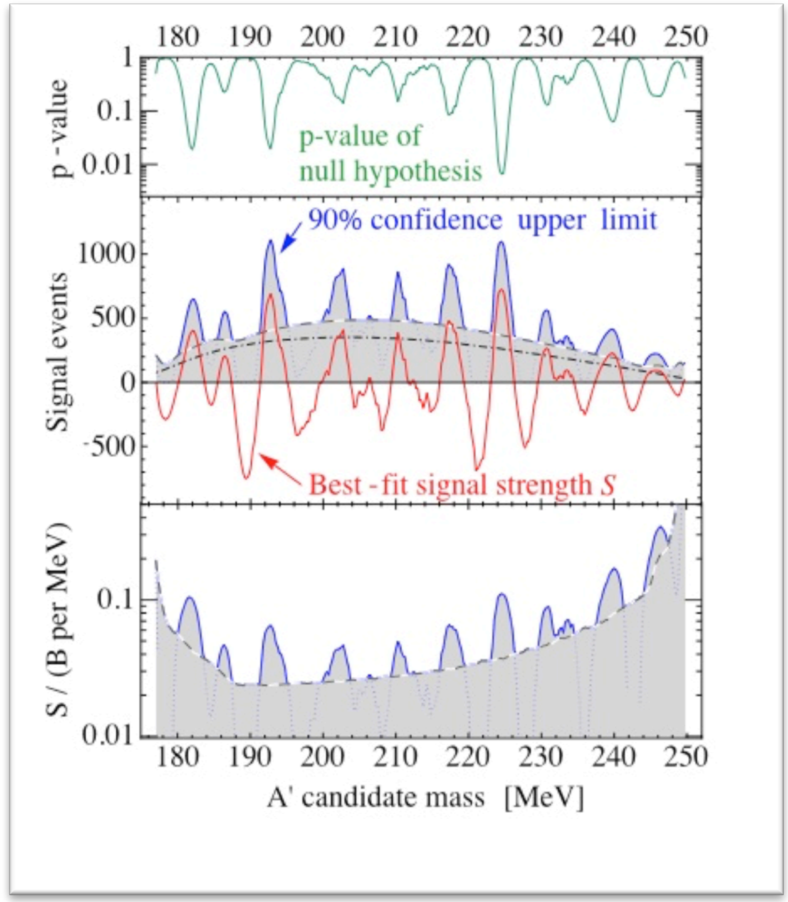
★Excellent mass resolution

A’ radiation and decay => bump search



Example of the APEX-2010 analysis

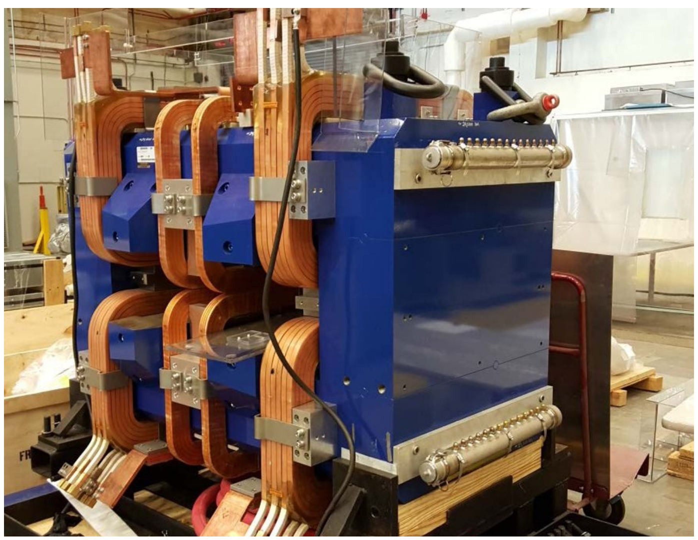


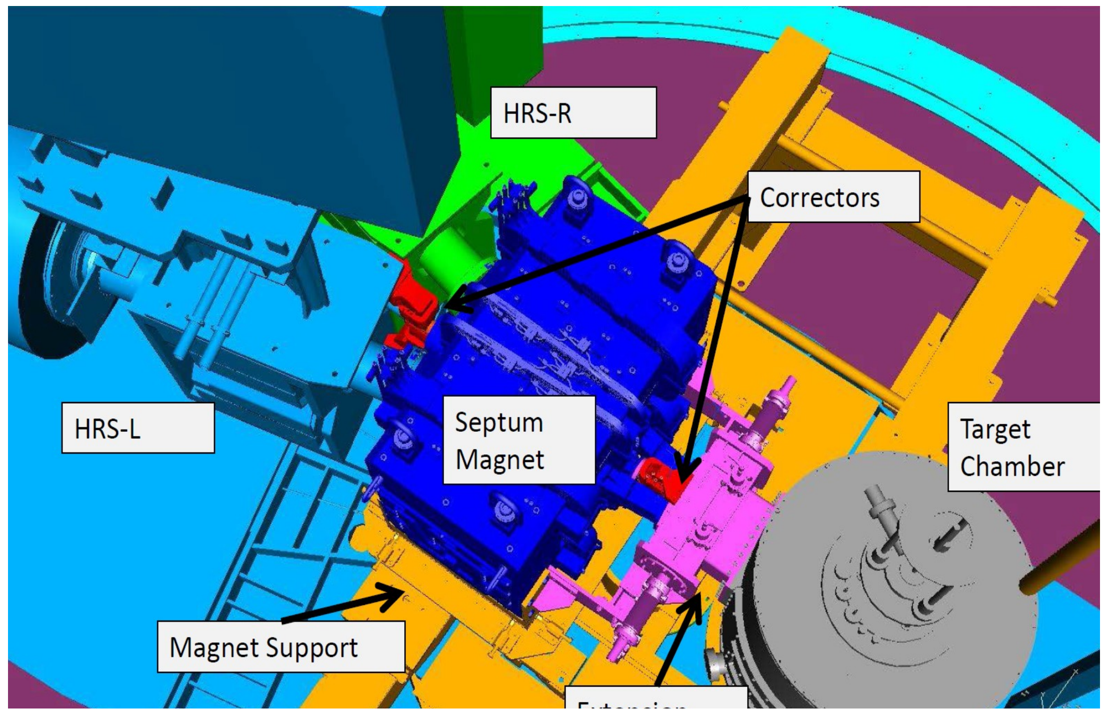


Layout of the APEX experiment

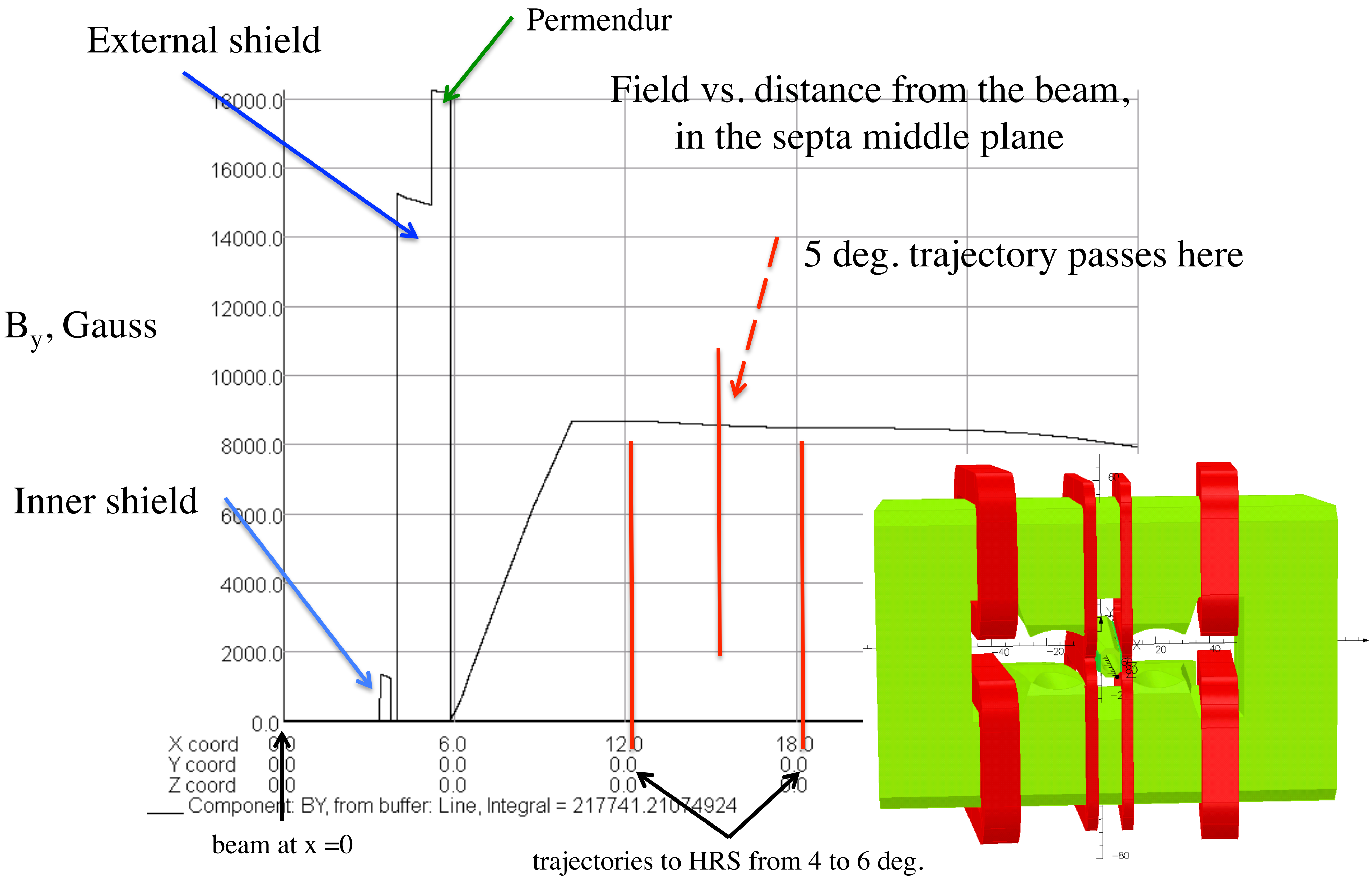
New septum:

- allows registration of small-angle e^+e^- pairs in HRS;
- provides operation for full momentum range of the experiment (up to 2.2 GeV);
- has a good magnetic shielding of the beam line.

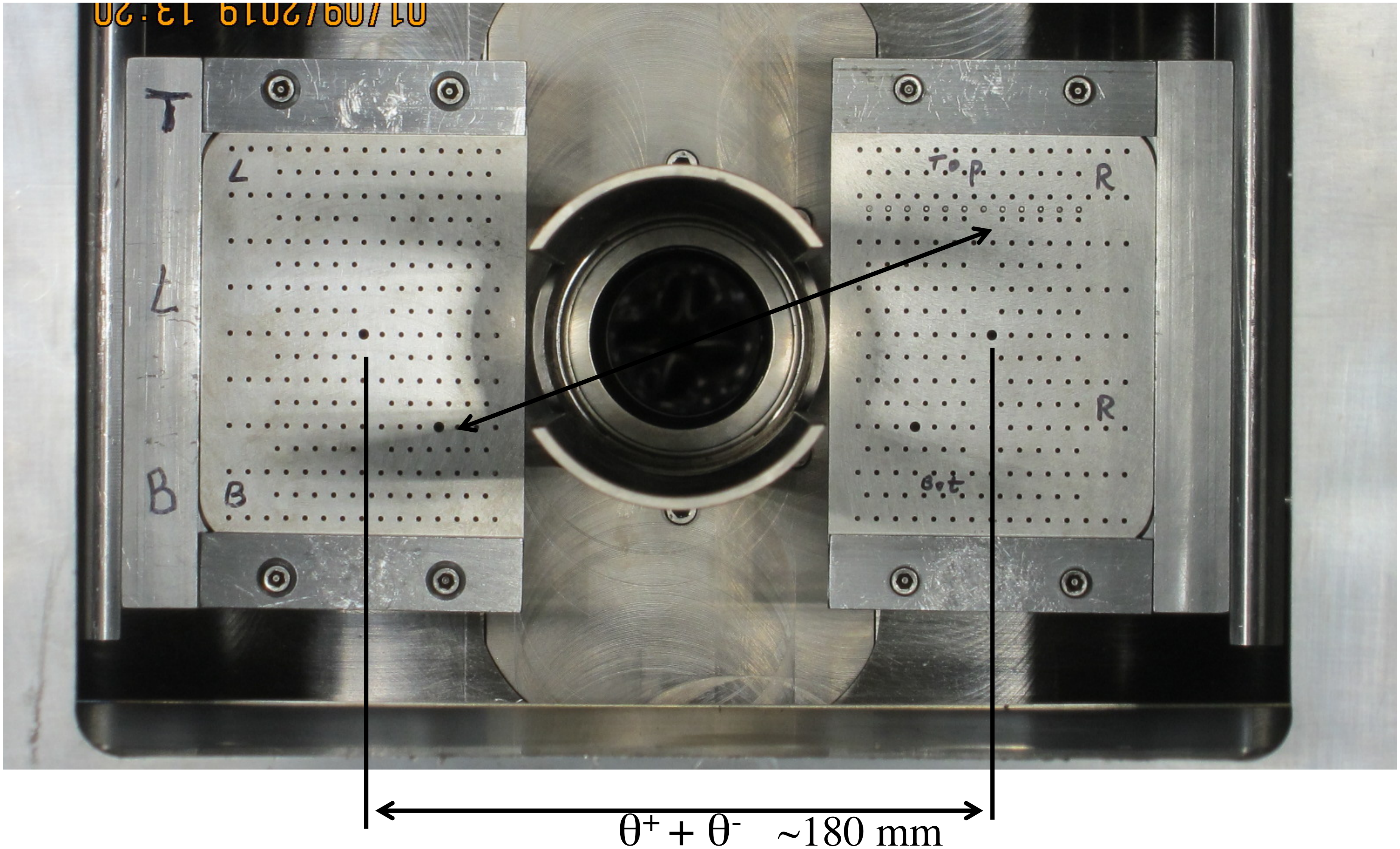




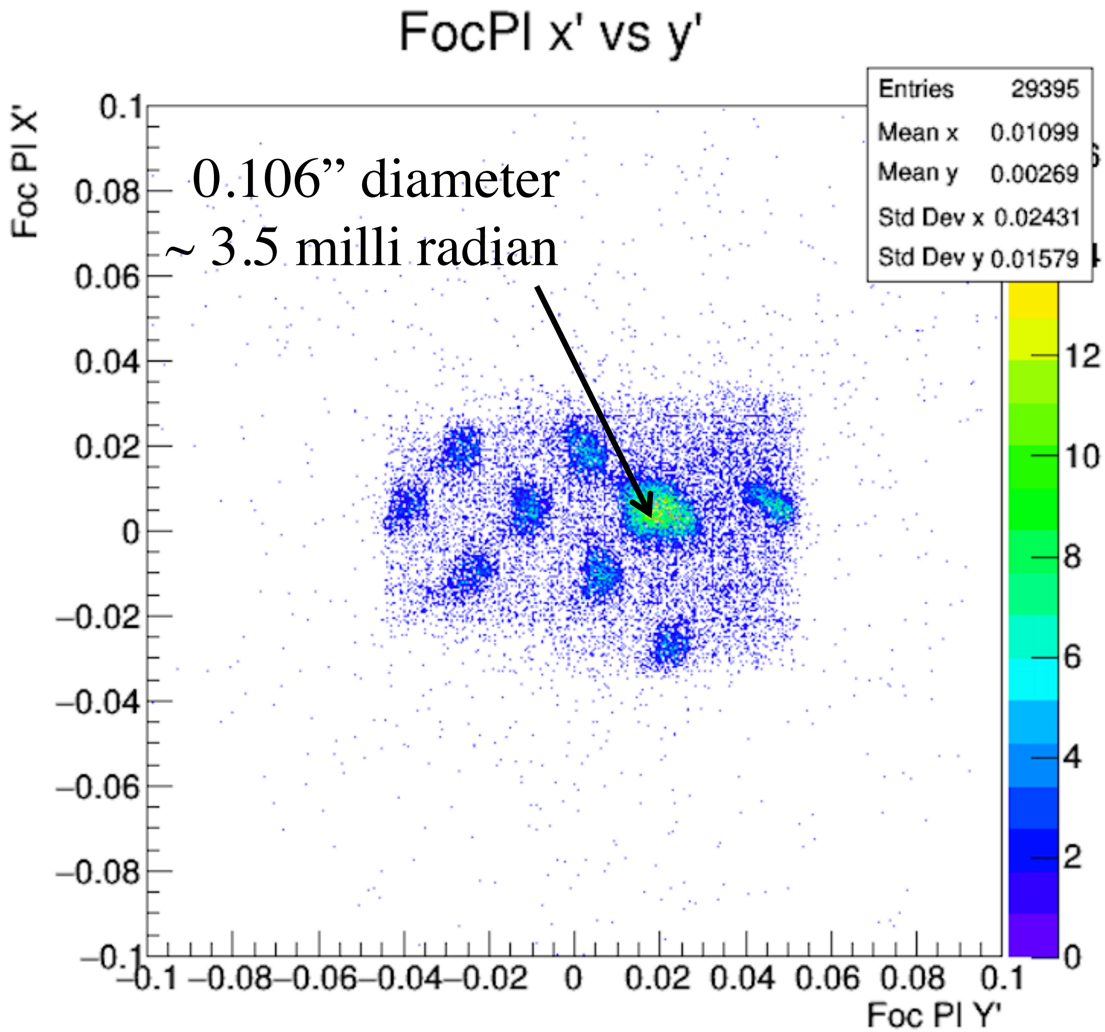
Specialized APEX hardware: Septa magnet



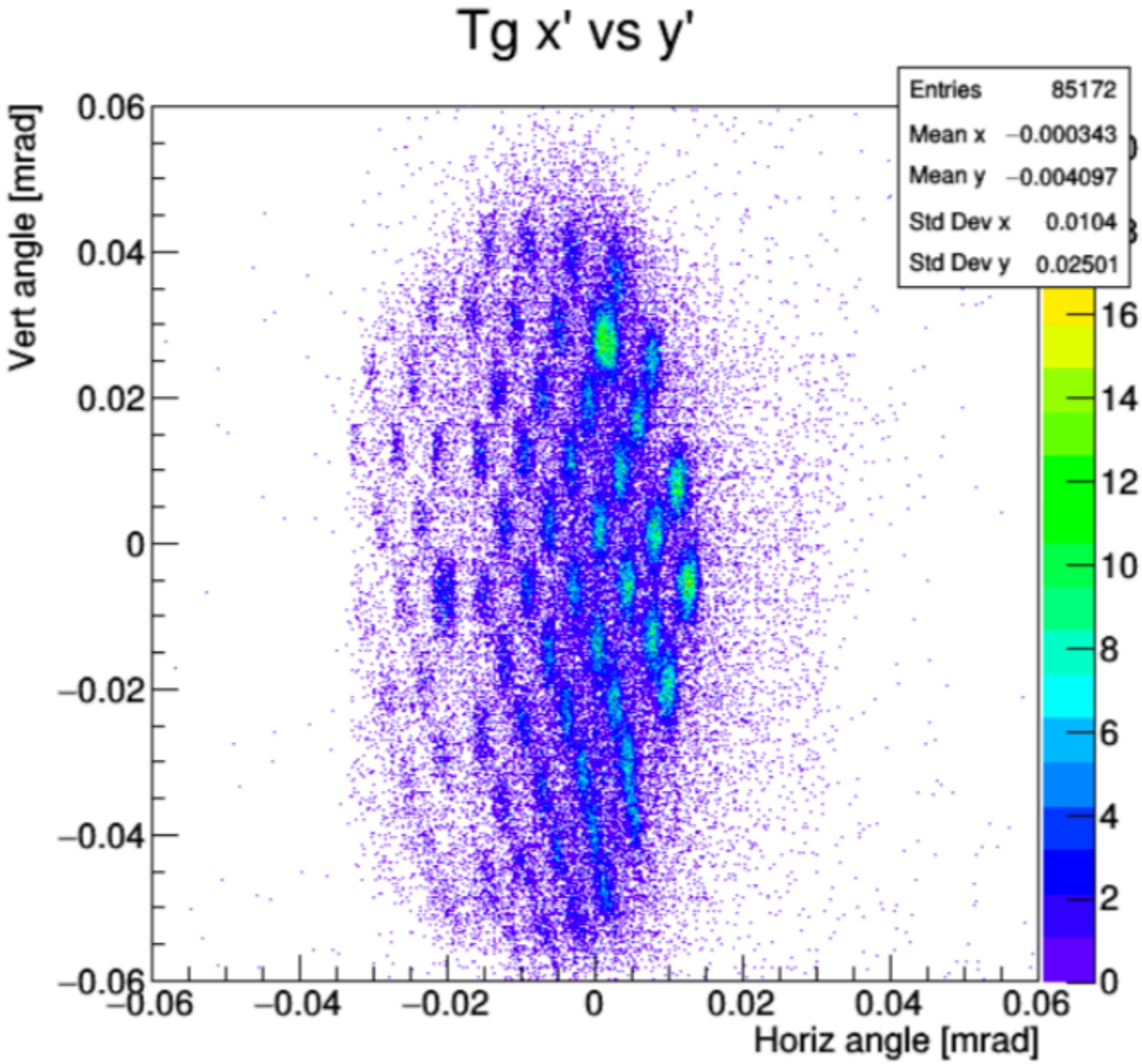
Optics calibration



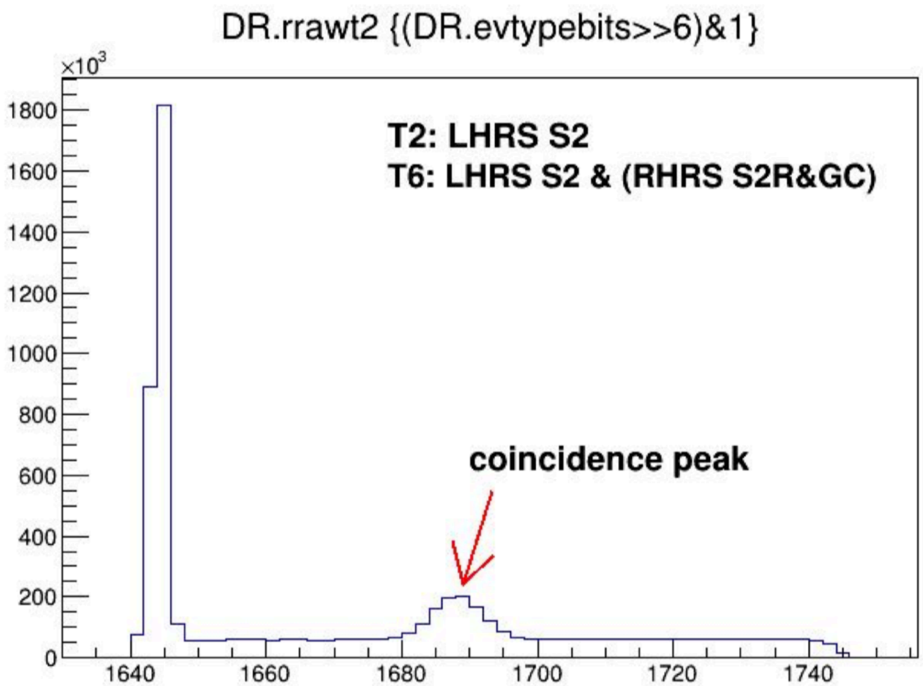
The first optics plot

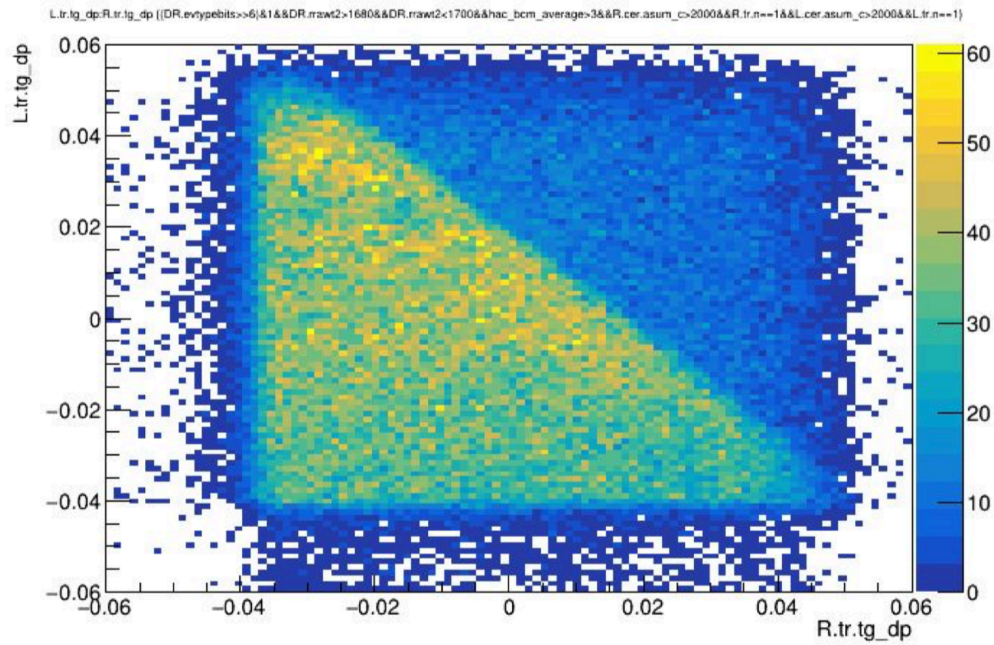


Optics calibration with correct Q1



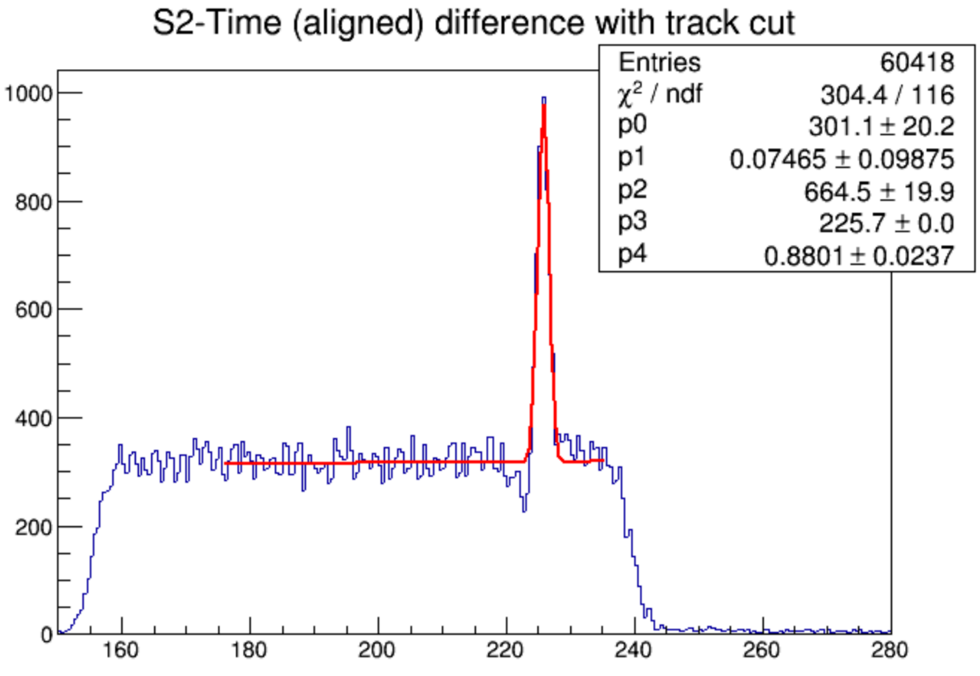
Online data analysis plots

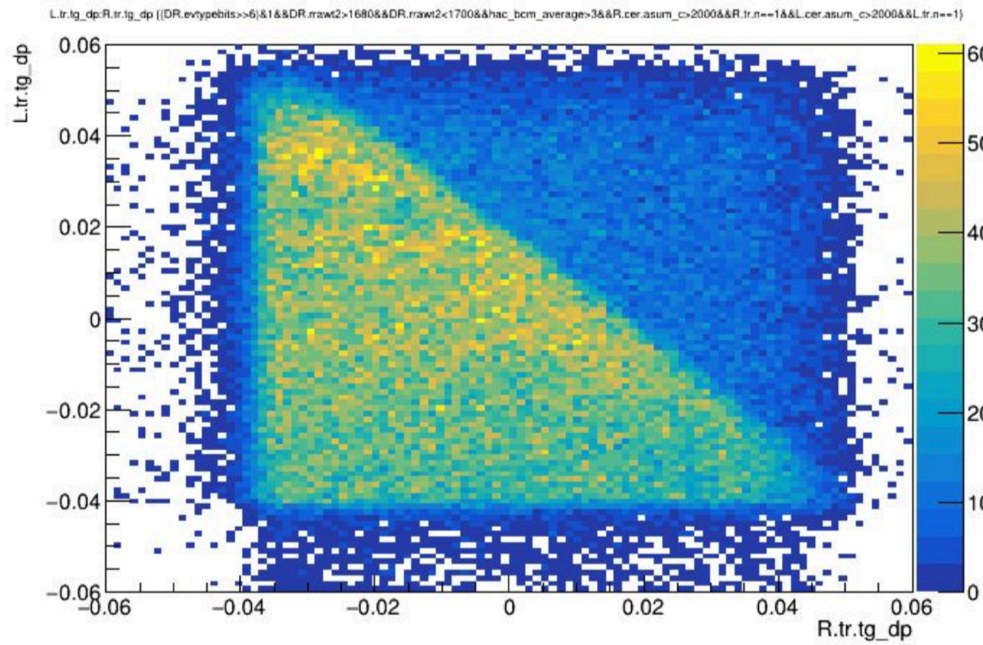




Online data analysis plots

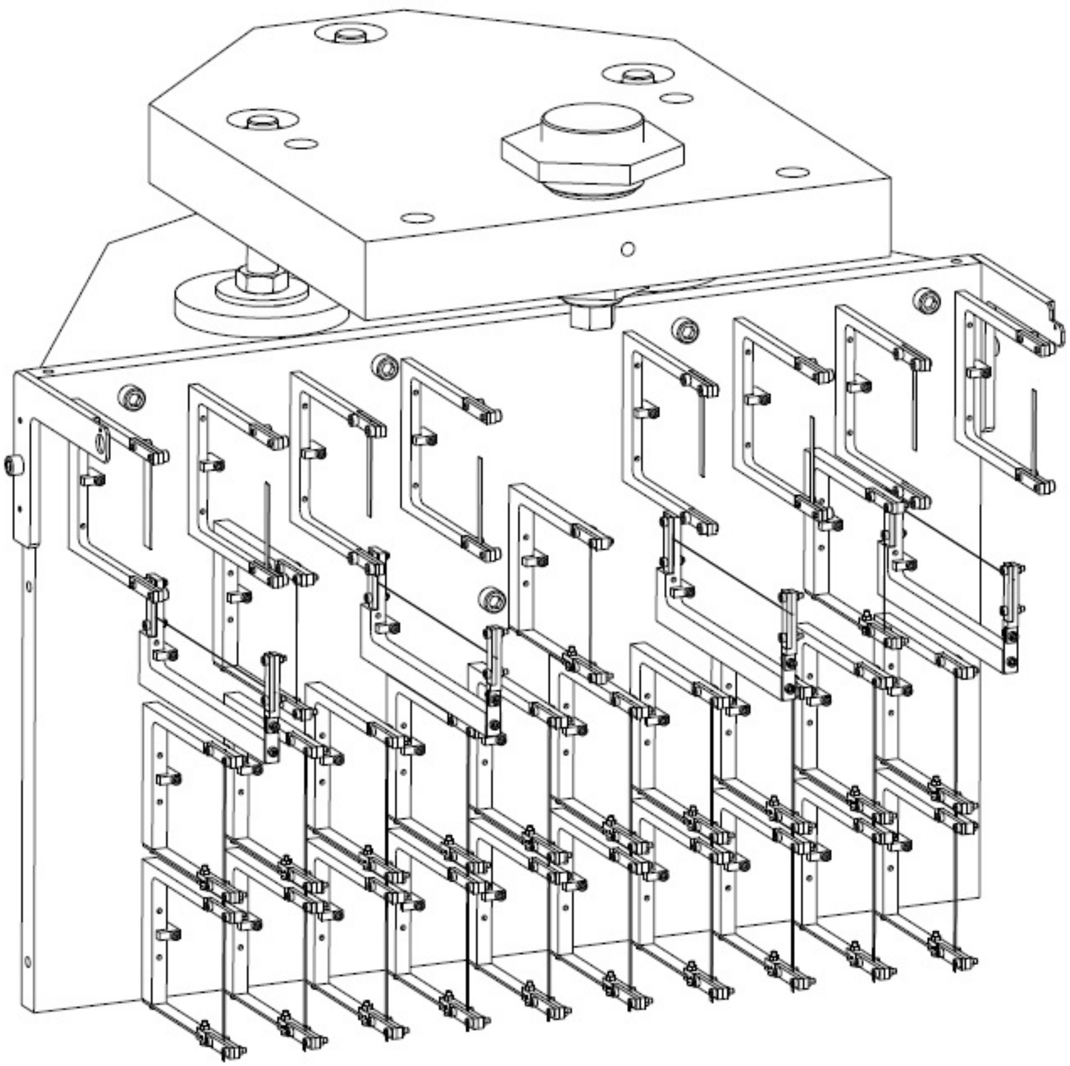
S2m time alignment



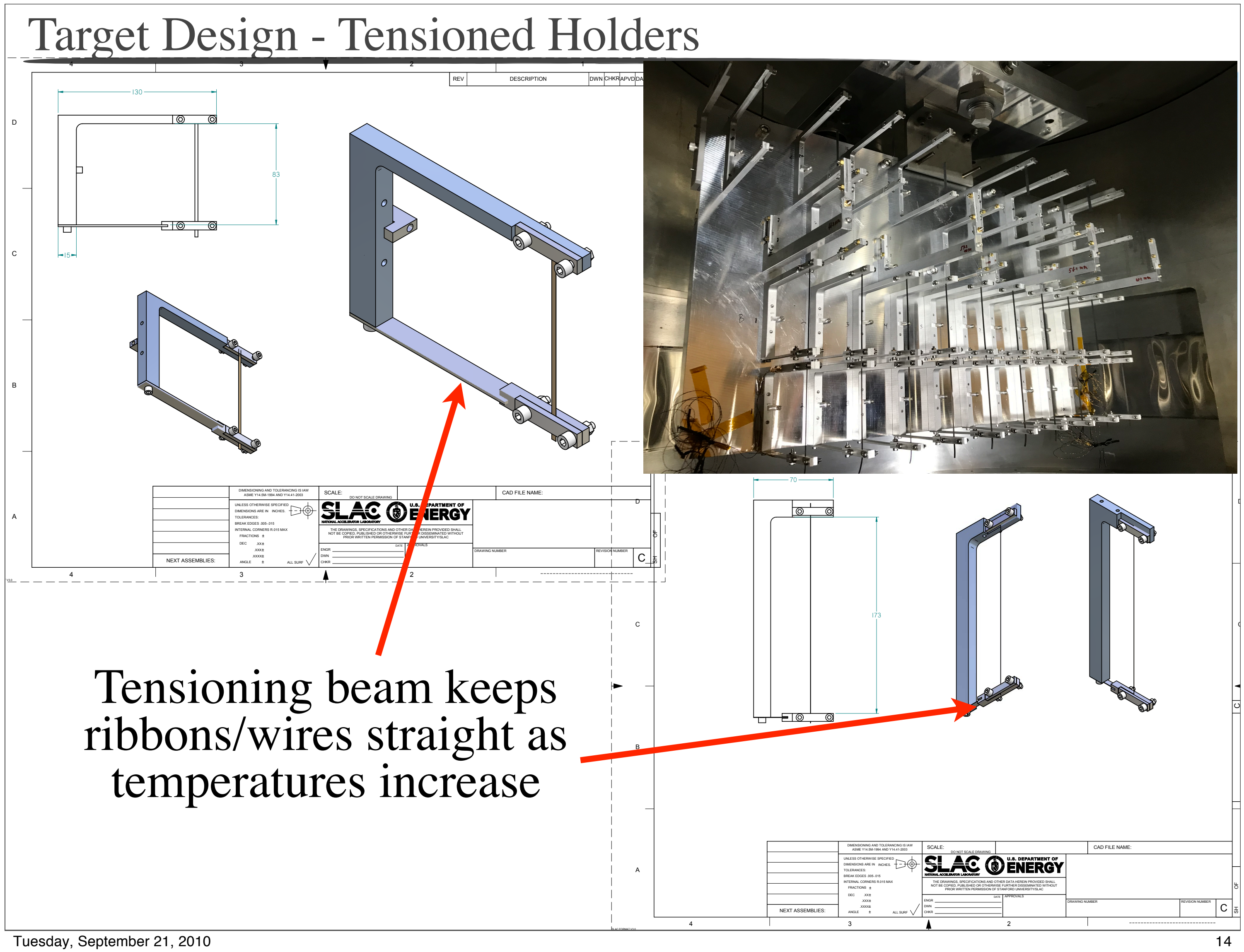


Resolution 1.4 ns => 0.9 ns

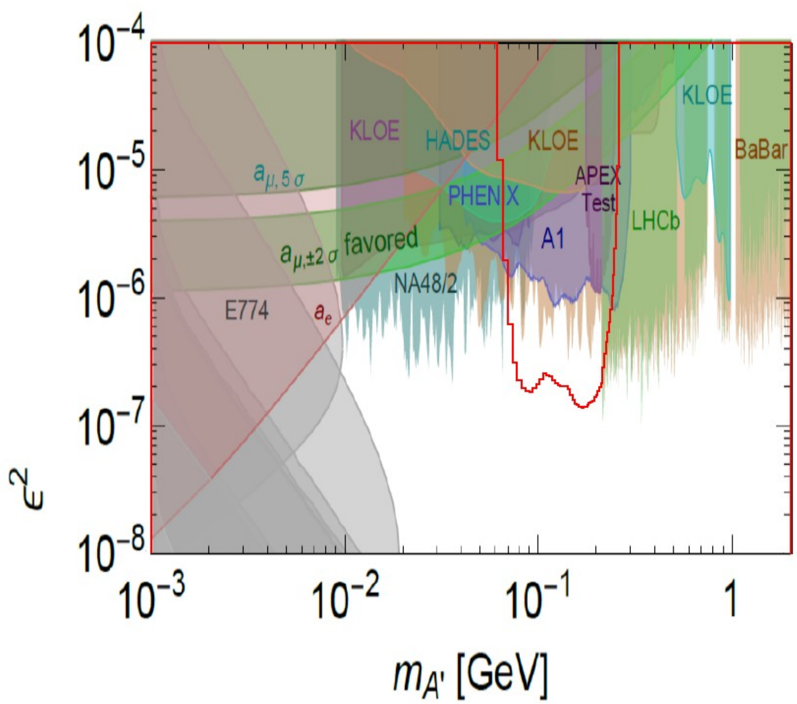
Specialized APEX target



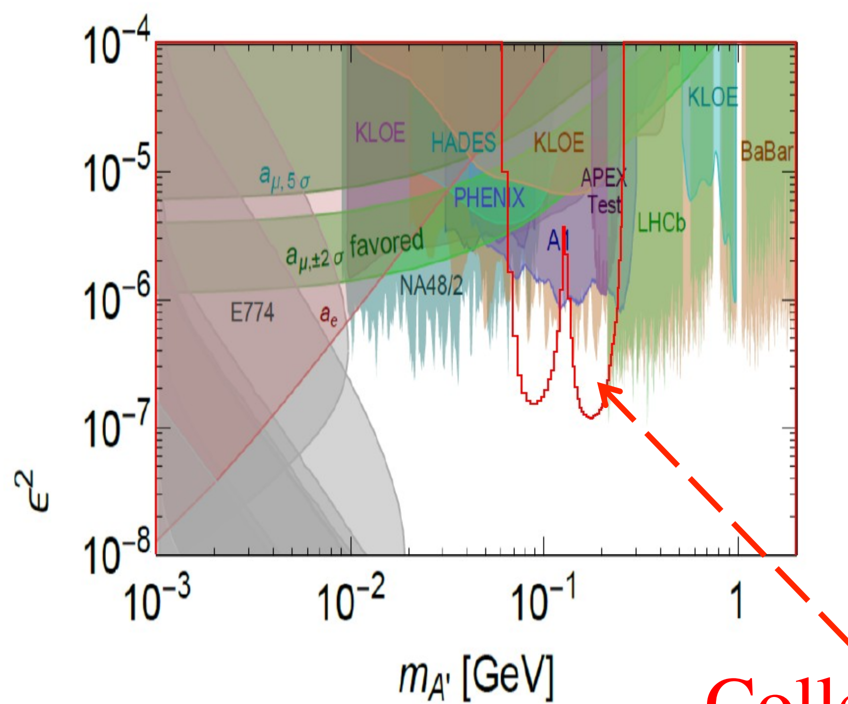
Specialized APEX target



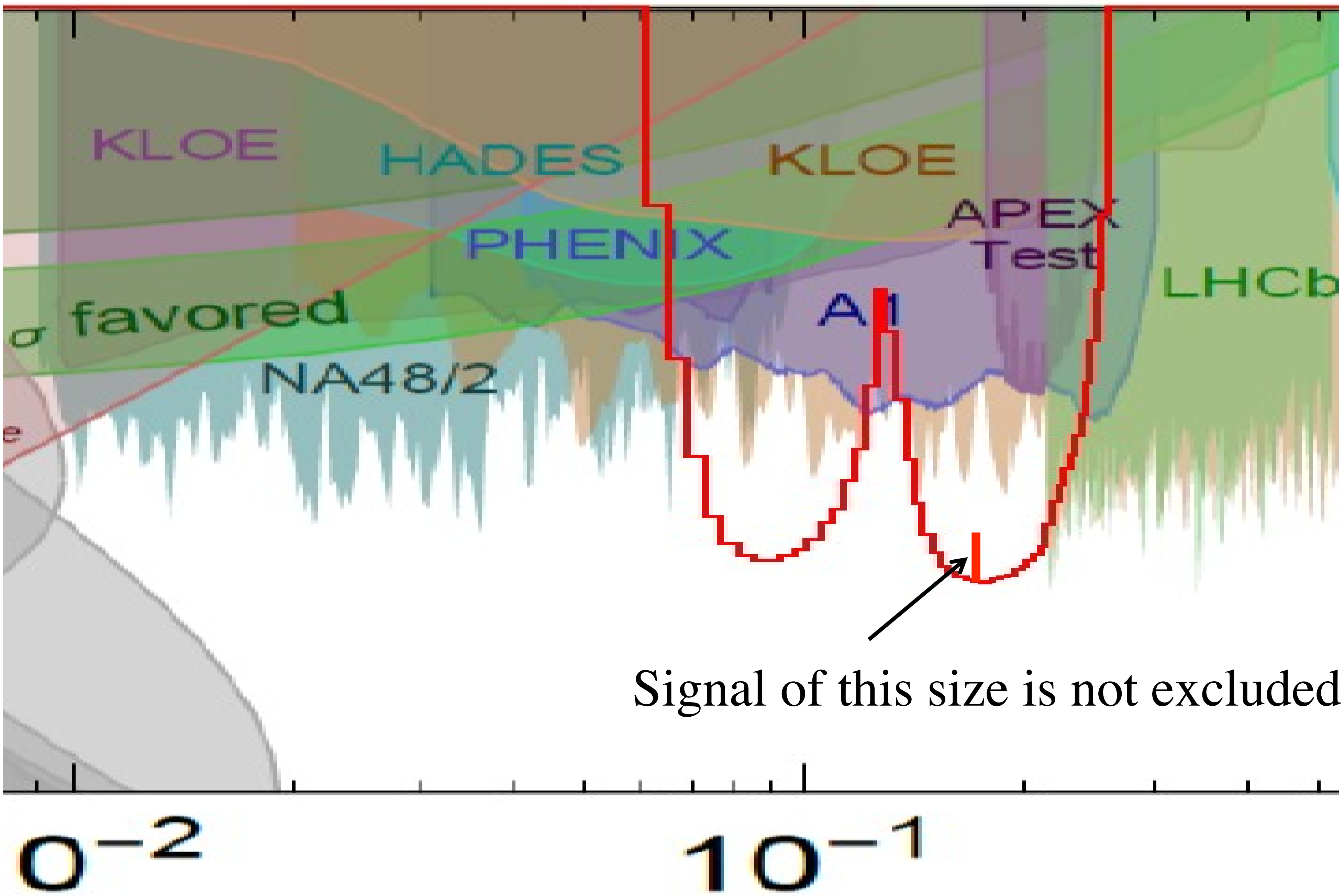
Updated plan (all energies)



10 days at 1.1 GeV beam
10 days at 1.65 GeV beam
10 days at 2.2 GeV beam



Collected


KLOE
HADES
KLOE
APEX
Test
PHENIX
LHCb
favored
A1
NA48/2
Signal of this size is not excluded
10^{-2}
10^{-1}

Summary

- APEX took a very good data sample. We welcome new collaborators for data analysis and future runs.

- Data analysis of collected statistics is on the way with the goal of producing final results by next June.