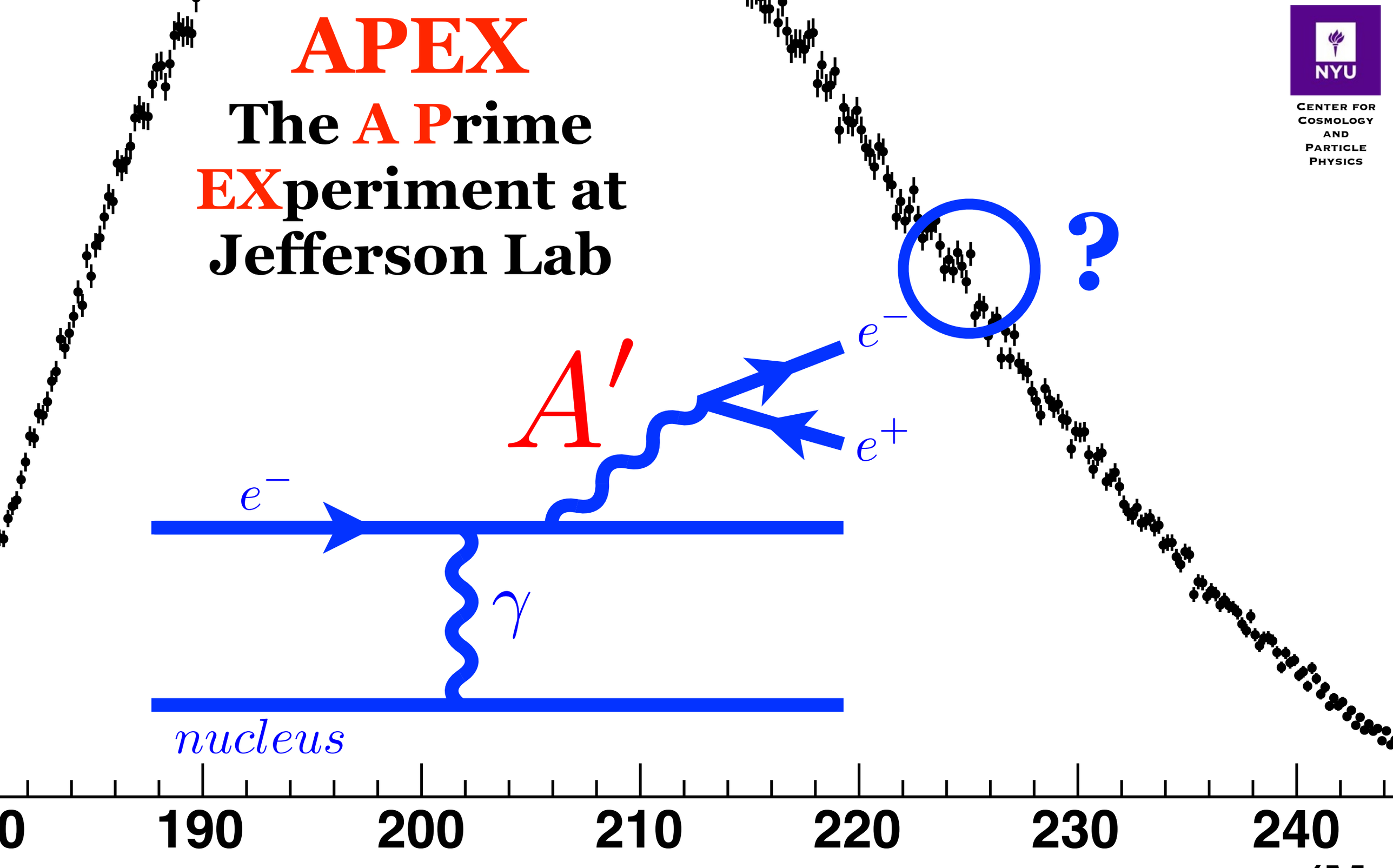
APEX

The A Prime EXperiment at Jefferson Lab



James Beacham

New York University

for the APEX Collaboration

NYU

Center for Cosmology and Particle Physics

Outline

Motivations

Existing constraints

APEX test run setup

Test run results

Full run plans

U(1) extension of the Standard Model

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- Common feature of many theories
- "Hidden gauge boson" ("dark photon", A') mixes kinetically with photon
  $\longrightarrow$ hidden sector coupled to SM
- Equivalent to assigning small EM charge

Kinetic mixing

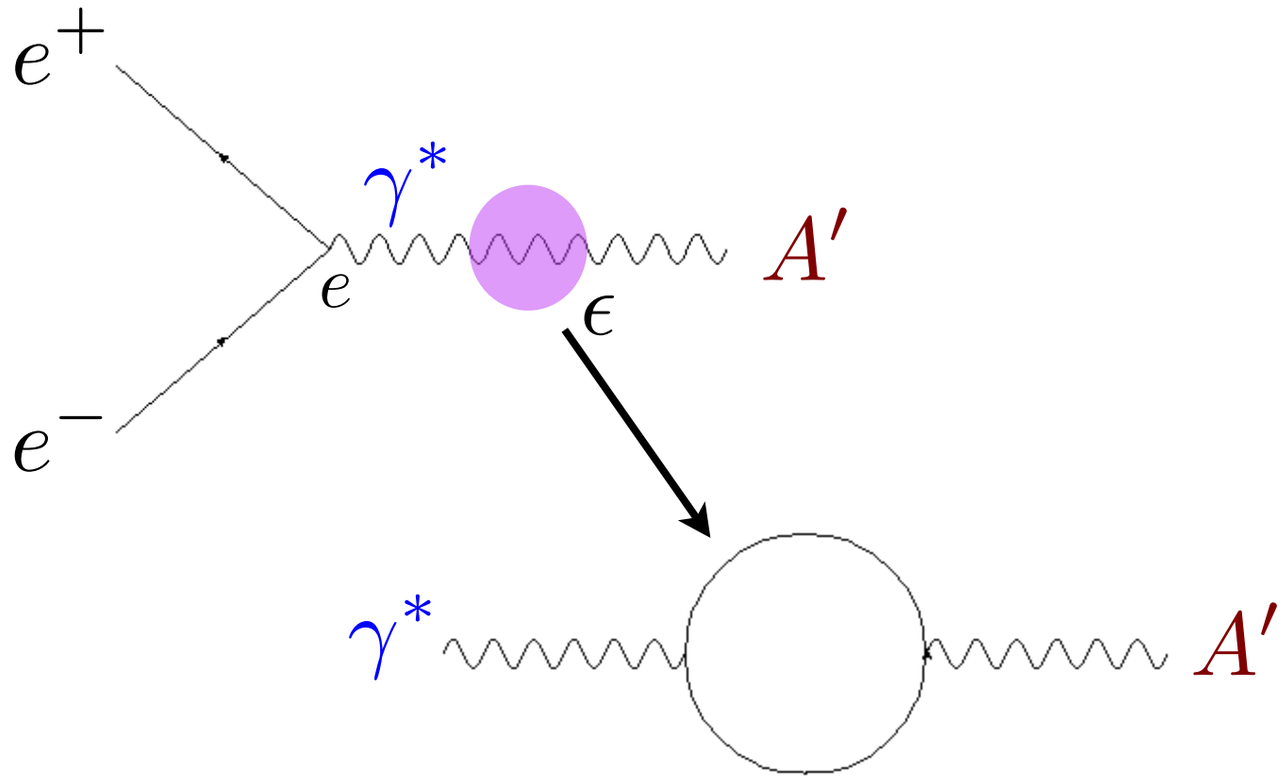
Holdom, Phys.Lett. B166 (1986) 196

- Lagrangian contains a term

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

$$\epsilon_Y = \epsilon \cos\theta_W$$

$$\epsilon = g'/e$$



$$\epsilon \sim 10^{-6} - 10^{-2}$$

$$m_{A'} \sim \text{MeV} - \text{GeV}$$

Note: $\alpha'/\alpha = \epsilon^2$

Additional motivations

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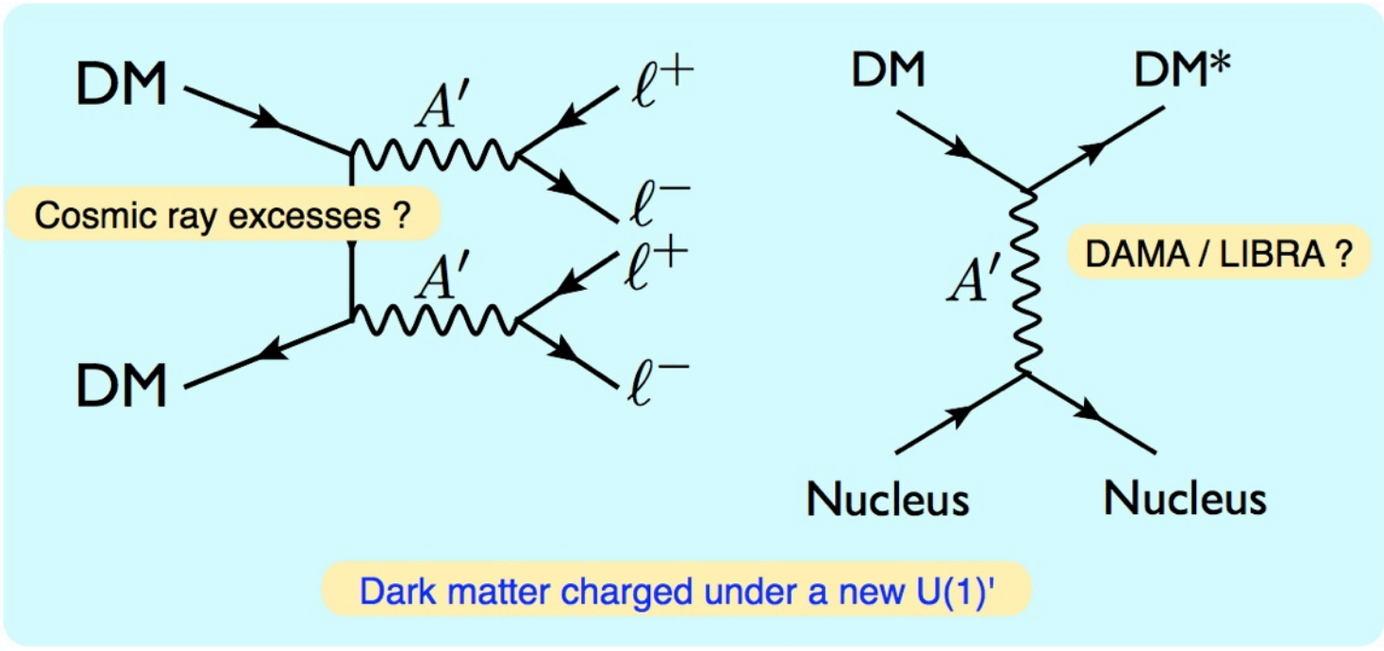
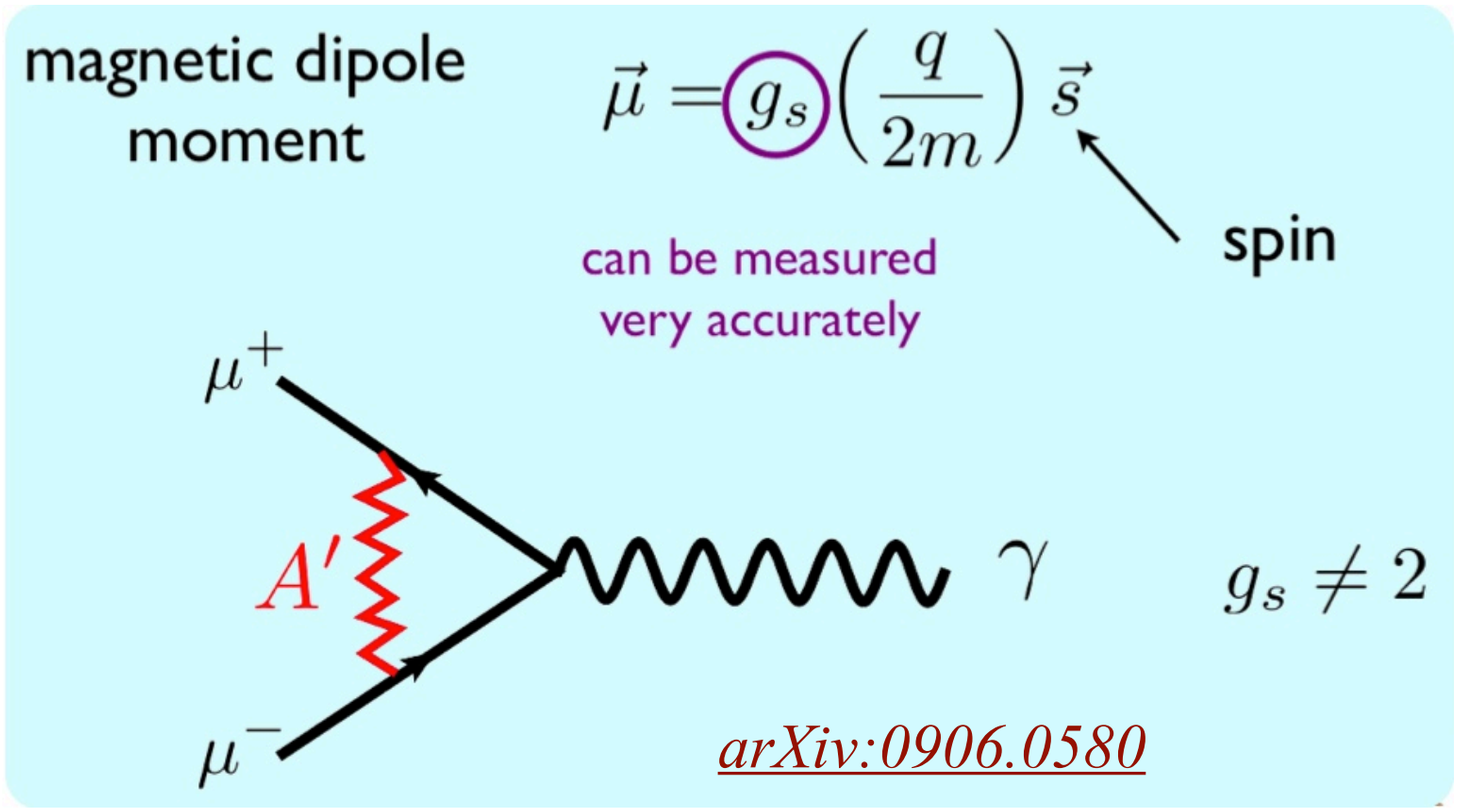
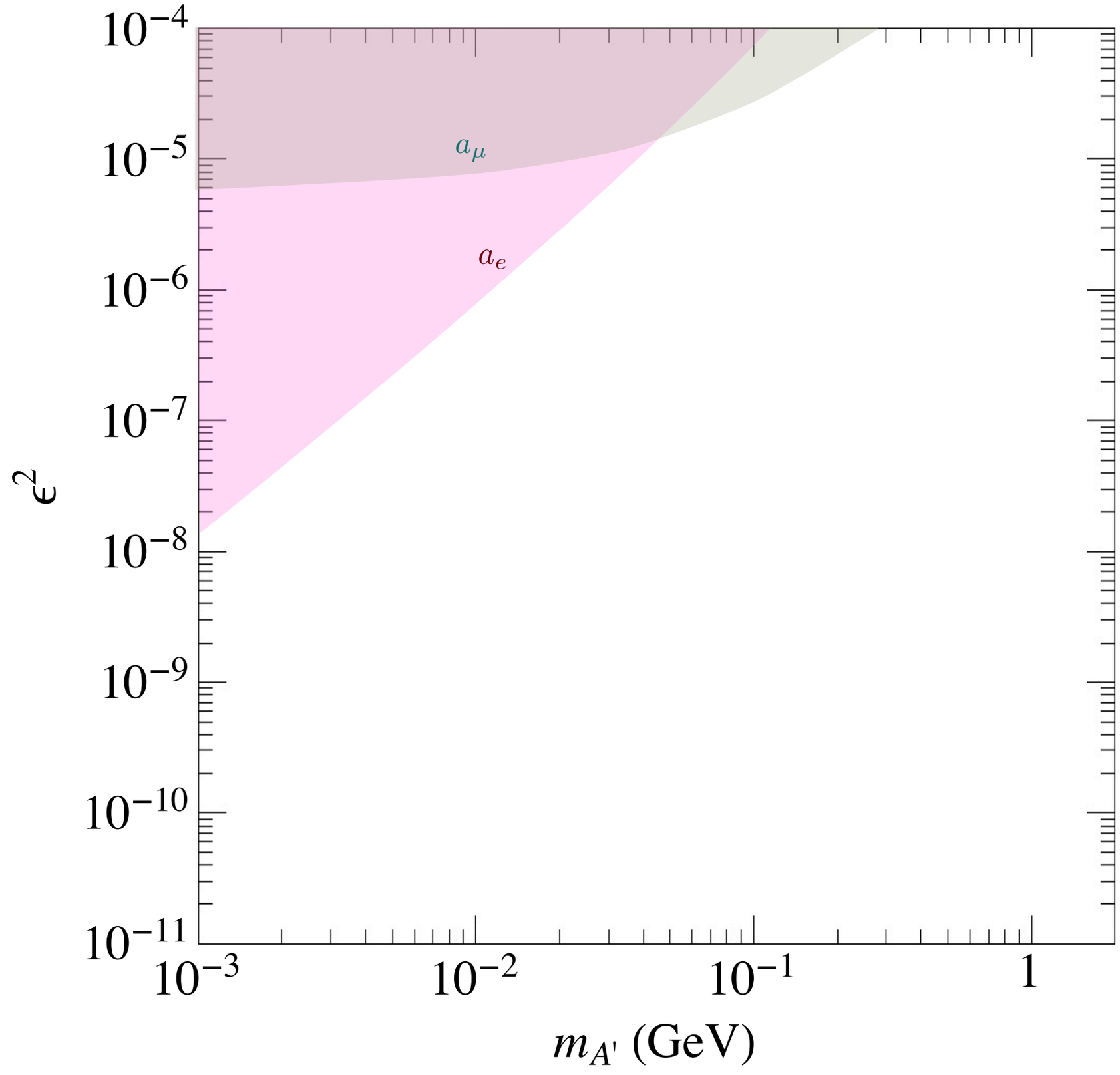
A sub-GeV mass for the A' could explain dark matter anomalies...





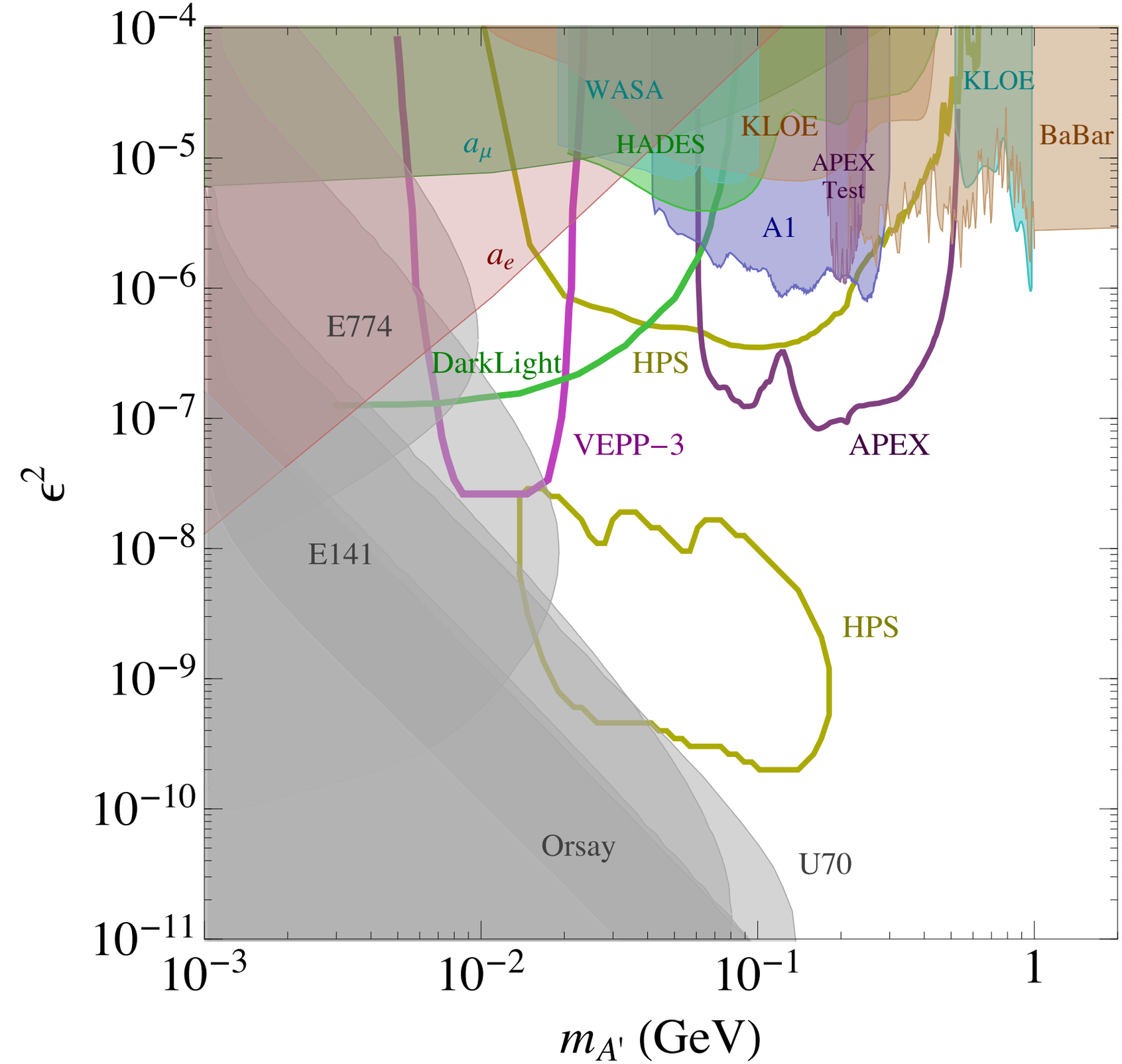
...and the anomalous magnetic moment of the muon

Existing constraints



2008

Existing constraints



Now

APEX: Dark photon search in fixed target experiment at Jefferson Lab

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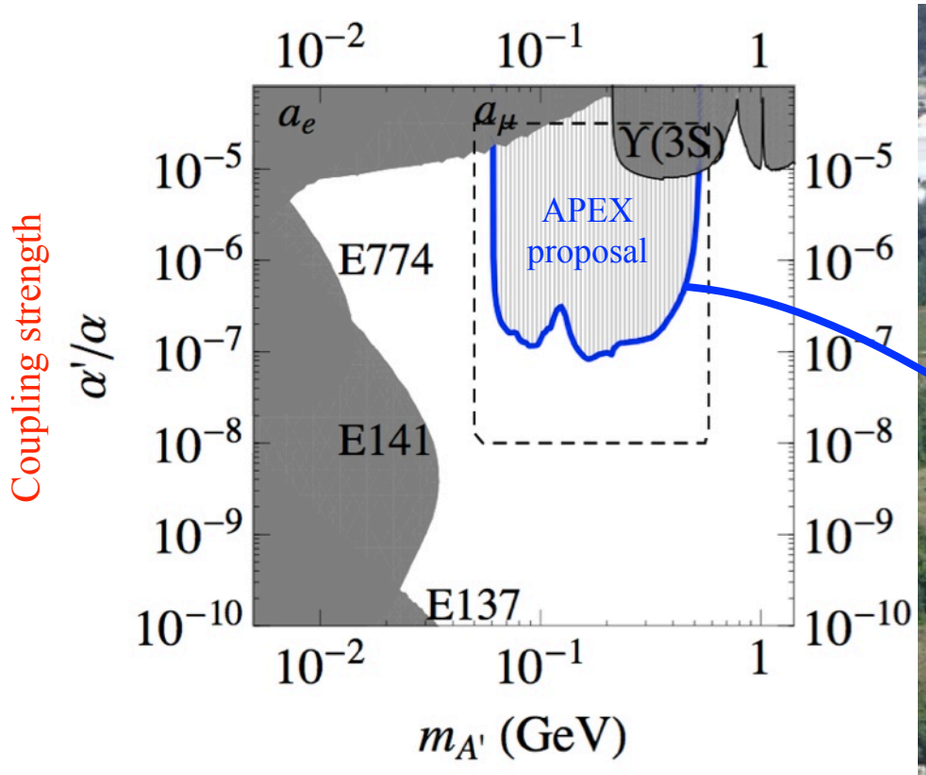
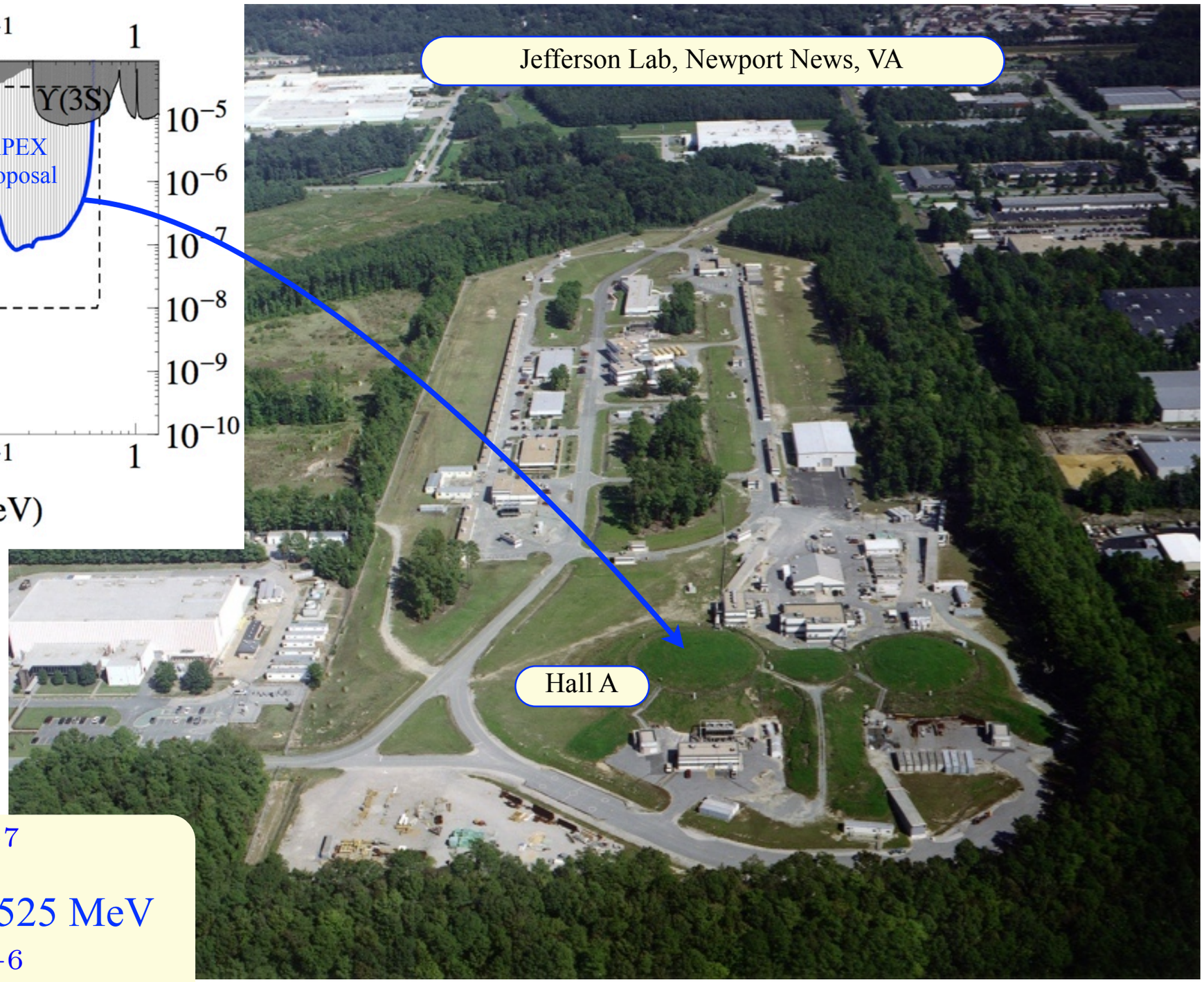


Bjorken, Essig, Schuster, Toro, Wojtsekhowski, et al. proposed a fixed target experiment to be conducted at Thomas Jefferson National Accelerator Facility, in Virginia; **test run for experiment in June/July 2010**



- Full run: $\alpha'/\alpha \gtrsim 10^{-7}$
  $m_{A'} = 65$ to 525 MeV
- Test run: $\alpha'/\alpha \gtrsim 10^{-6}$
  $m_{A'} = 178$ to 250 MeV

Experimental signature

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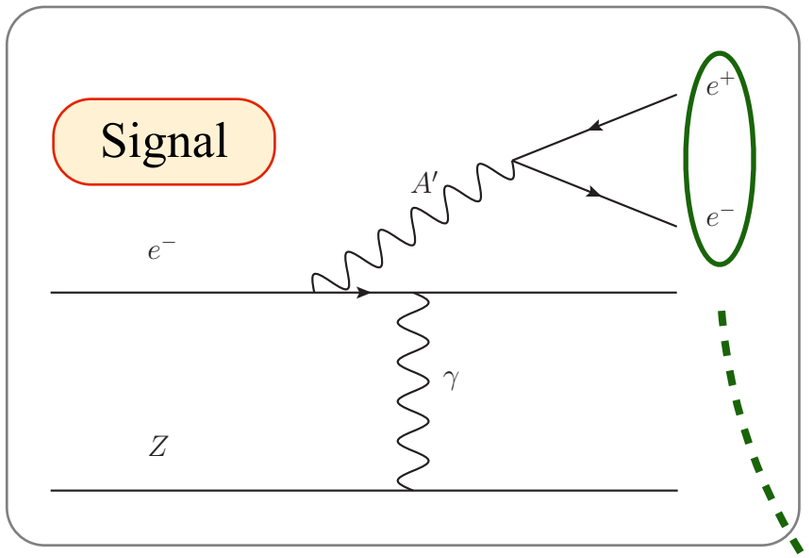
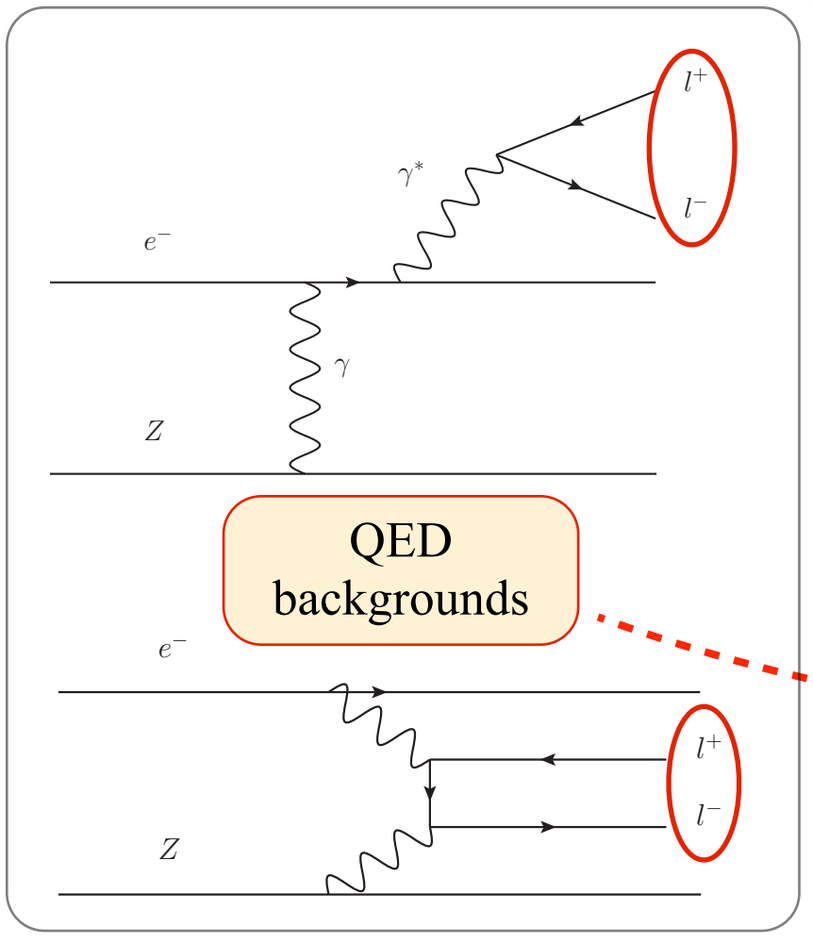
Direct production of A' at JLab

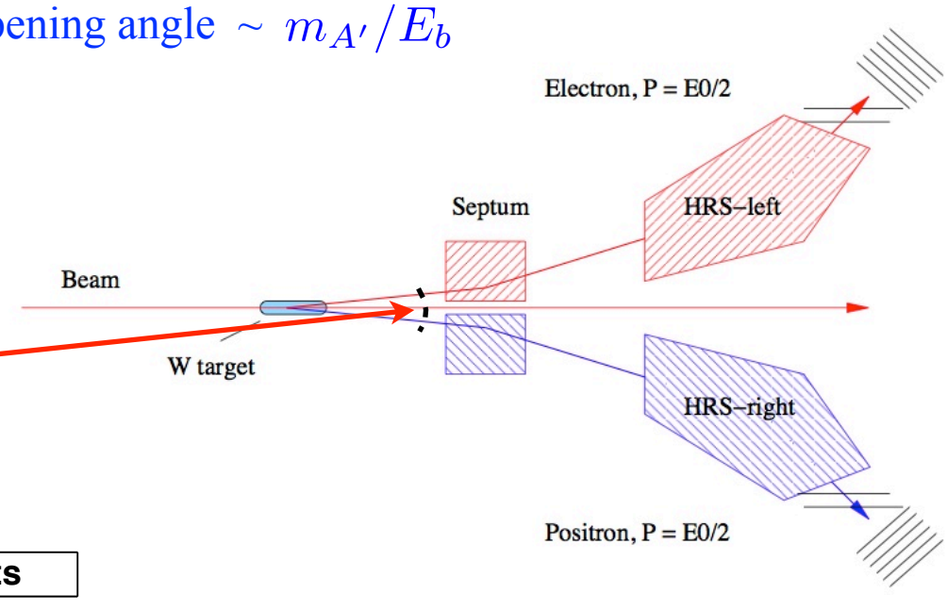
- Produced via high energy e- beam incident on fixed high-Z (Ta) target
- Decays to e^+e^- pair with opening angle $\sim m_{A'}/E_b$





Dipole septum magnets allow for detection of e^+e^- produced at small angles

$\Theta_0 \approx 5^\circ$



APEX Test Run Data, ~770K events

Looking for a small, narrow bump on top of a smooth histogram of QED processes; excellent mass resolution required

Jefferson Lab's Hall A experimental apparatus

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APEX test run:

Beam current up to 150μA

Target: Ta foil, 22 mg/cm^2

HRS Central momenta: 1.13 GeV

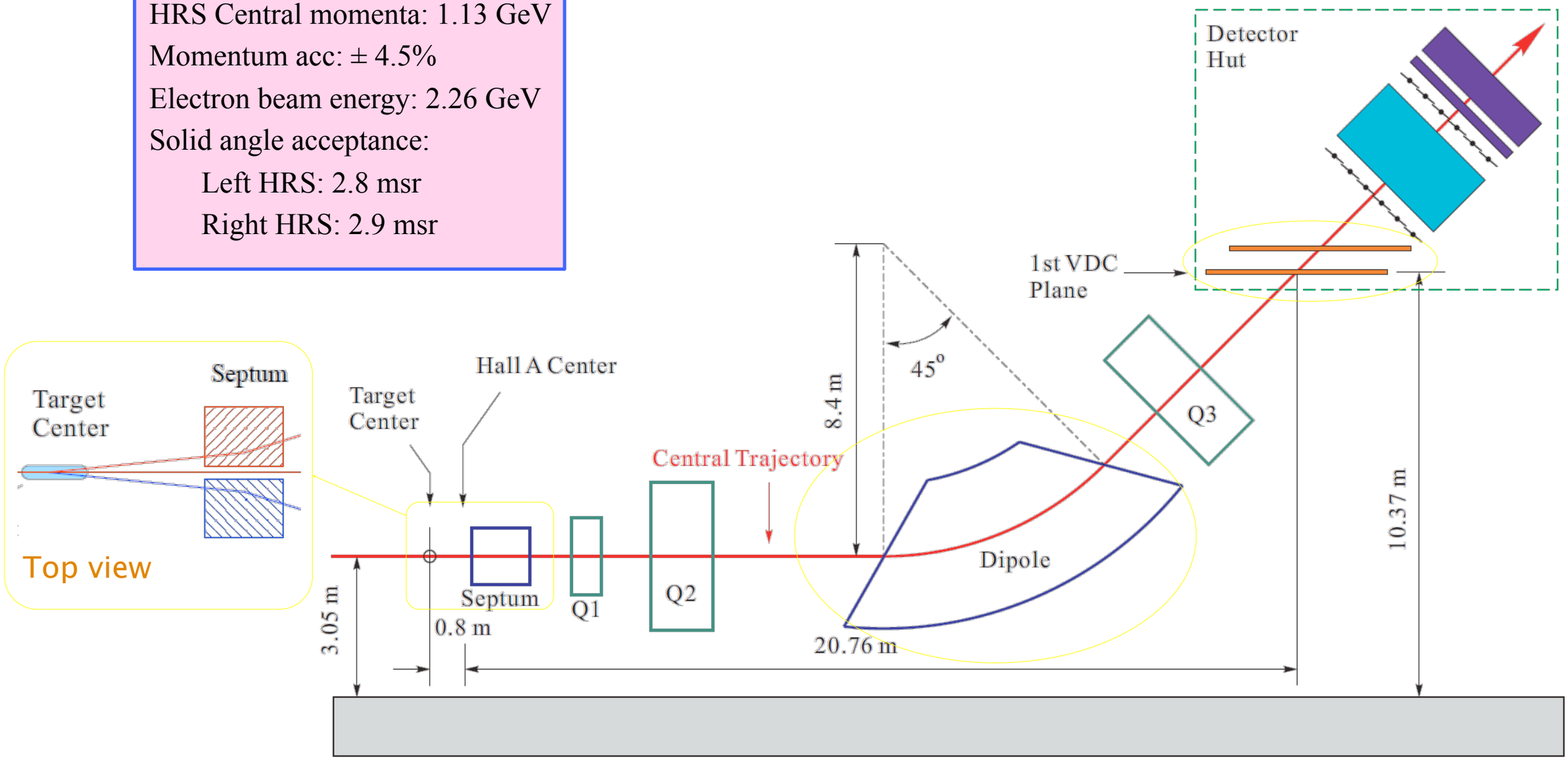
Momentum acc: ± 4.5%

Electron beam energy: 2.26 GeV

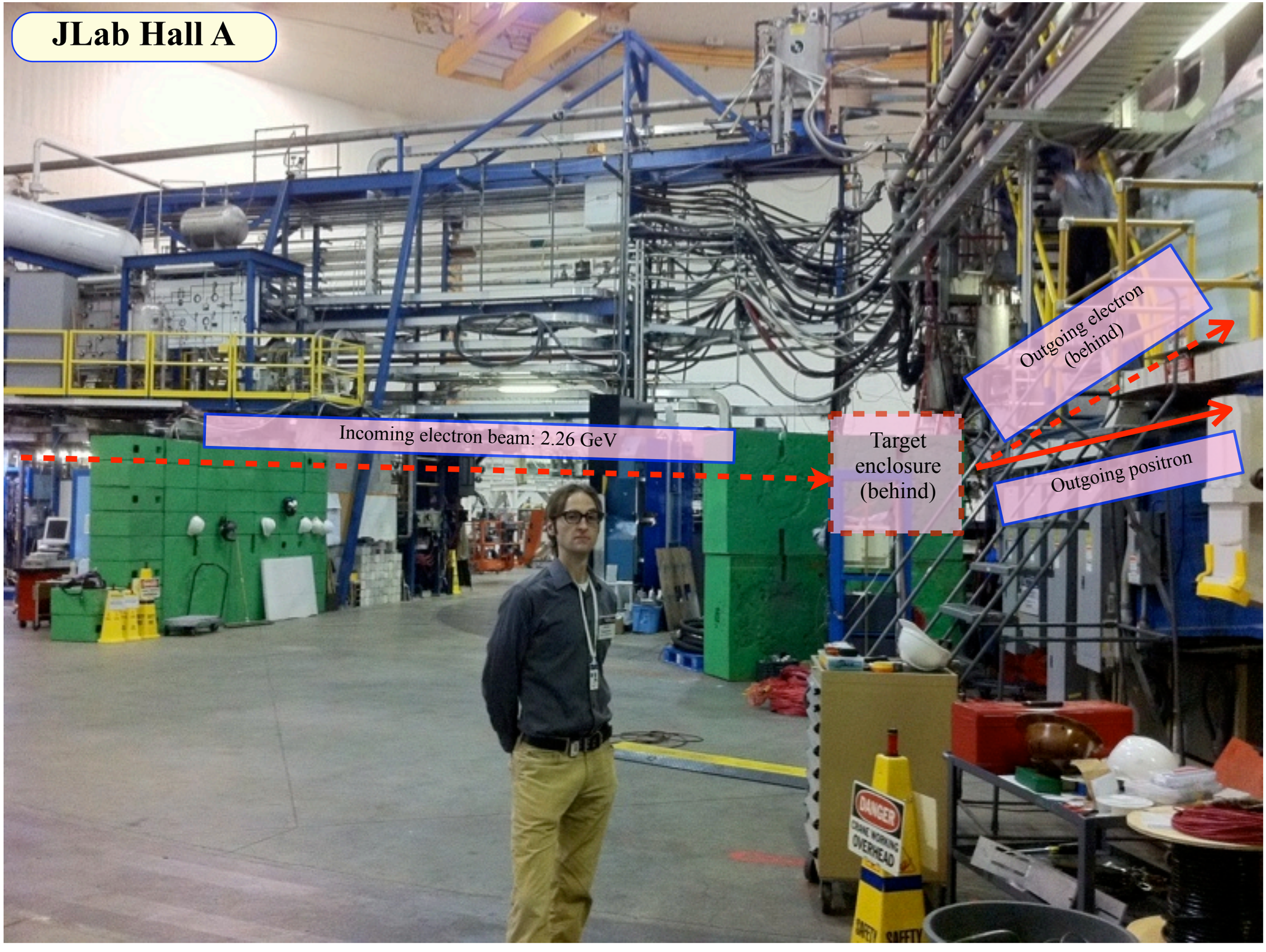
Solid angle acceptance:

Left HRS: 2.8 msr

Right HRS: 2.9 msr



J. Huang



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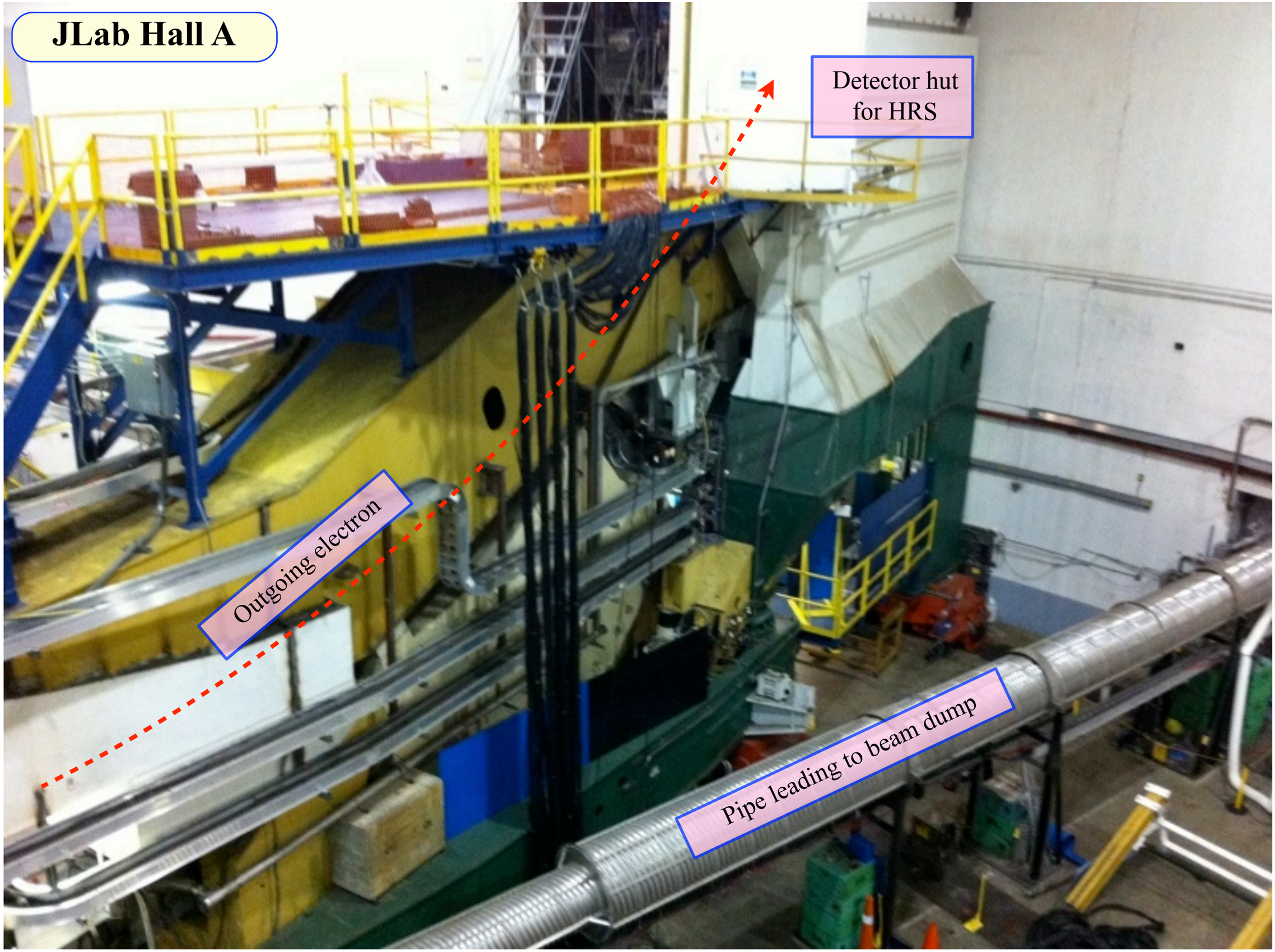
JLab Hall A



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Hall A High Resolution Spectrometers (HRSs)

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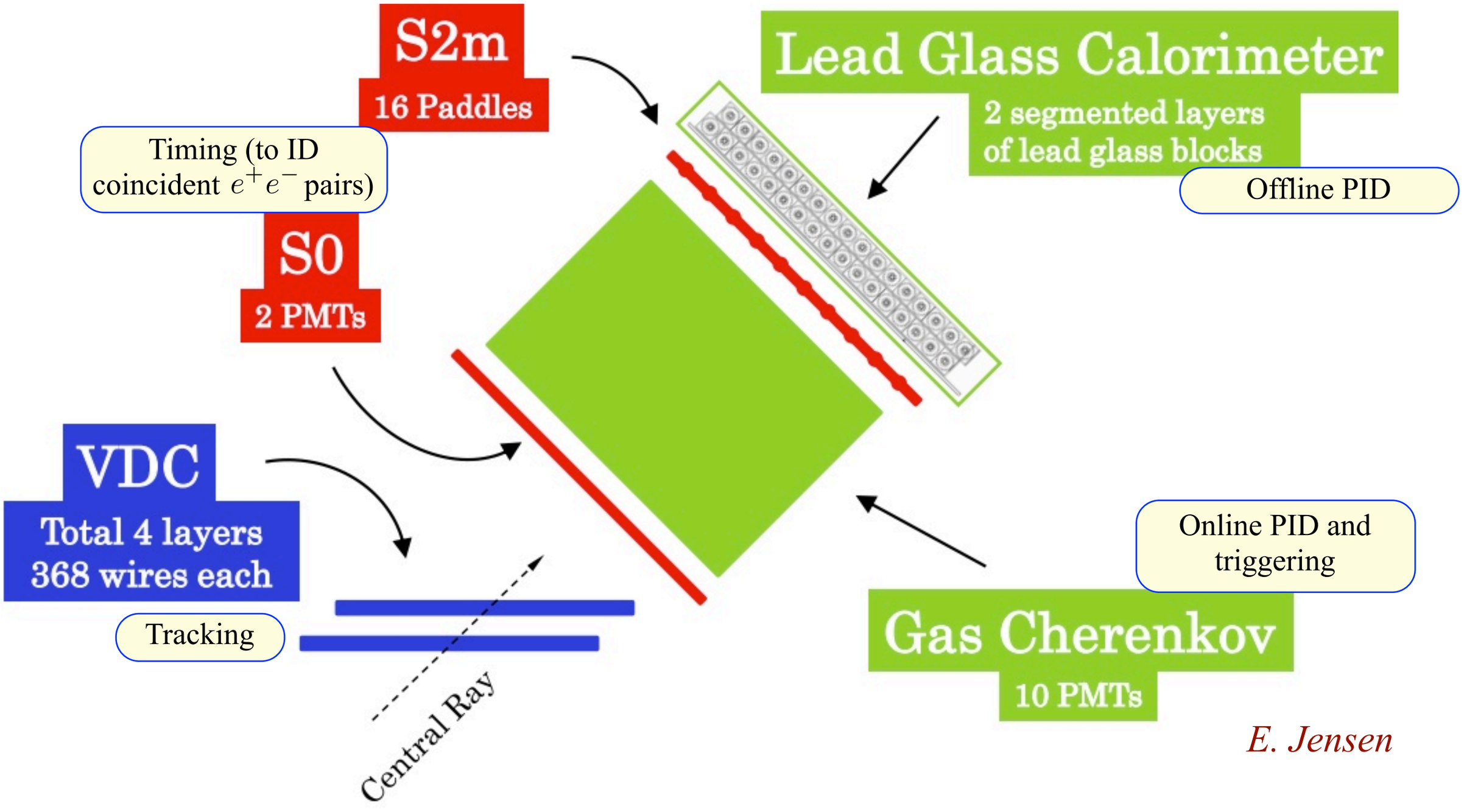
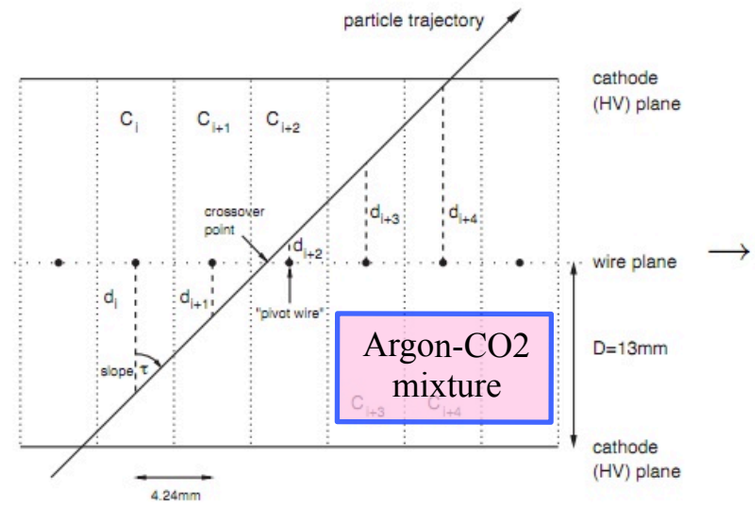


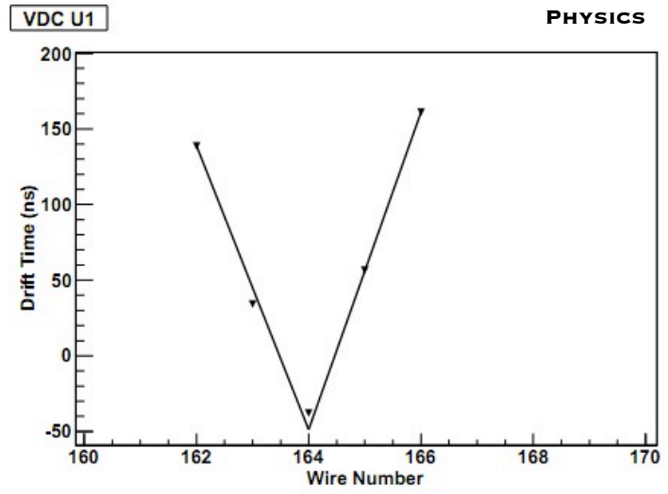
E. Jensen

Determining mass resolution

Two parallel VDCs provide accurate reconstruction of full 3D track of particle as it enters the HRS

- APEX: Electron singles rate from 0.7 to 5.8 MHz
- Rates are higher than ever used in Hall A -- 5 MHz (75 kHz/wire, 368 wires)



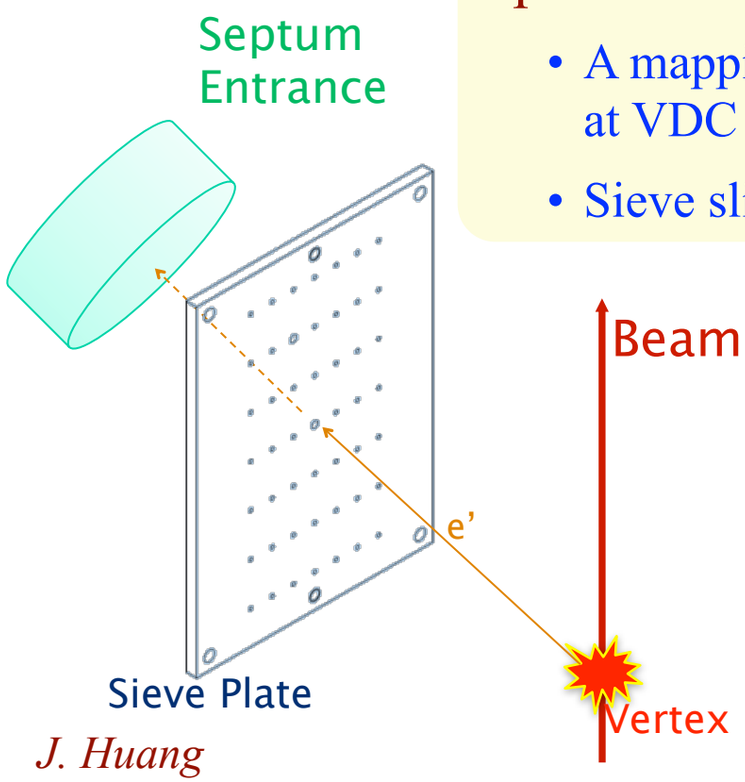


- Algorithm scans for 'V' shaped clusters in time

S. Riordan

Optics calibration

- A mapping from measured coord. at VDC to 3-momentum at target
- Sieve slit method



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Mass resolution depends on angular and momentum resolution

- HRS momentum resolution excellent, 10^{-4}; negligible
- **Angular resolution** and **multiple scattering in target** dominate

mrad	Optics	Tracking	MS in target
σ(horiz)	0.11	~0.4	0.37
σ(vert)	0.22	~1.8	0.37

Test run mass resolution: σ ~ 0.85 - 1.11 MeV (varies over mass range)

Background rejection and final dataset

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Reducible backgrounds

- Electron singles from inelastic or electron-nucleon scattering
- Pions from virtual photon decays
- Proton singles
- Accidental e^+e^- coincidences
- e^+e^- pairs from real photon conversions

Pion rejection:

- Production ratio in right HRS: $e^+/\pi^+ > 1/100$
- Online pion rejection: factor of 30
- Offline rejection > 1/100 using both gas Cherenkov and calorimeters

Final event sample trigger:

- Double coincidence gas Cherenkov signal within 12.5 ns window in each arm

Final data sample consisted of 770500 true e^+e^- coincident events with 0.9% (7.4%) meson (accidental e^+e^- coincidence) contamination

Bump hunt / resonance search

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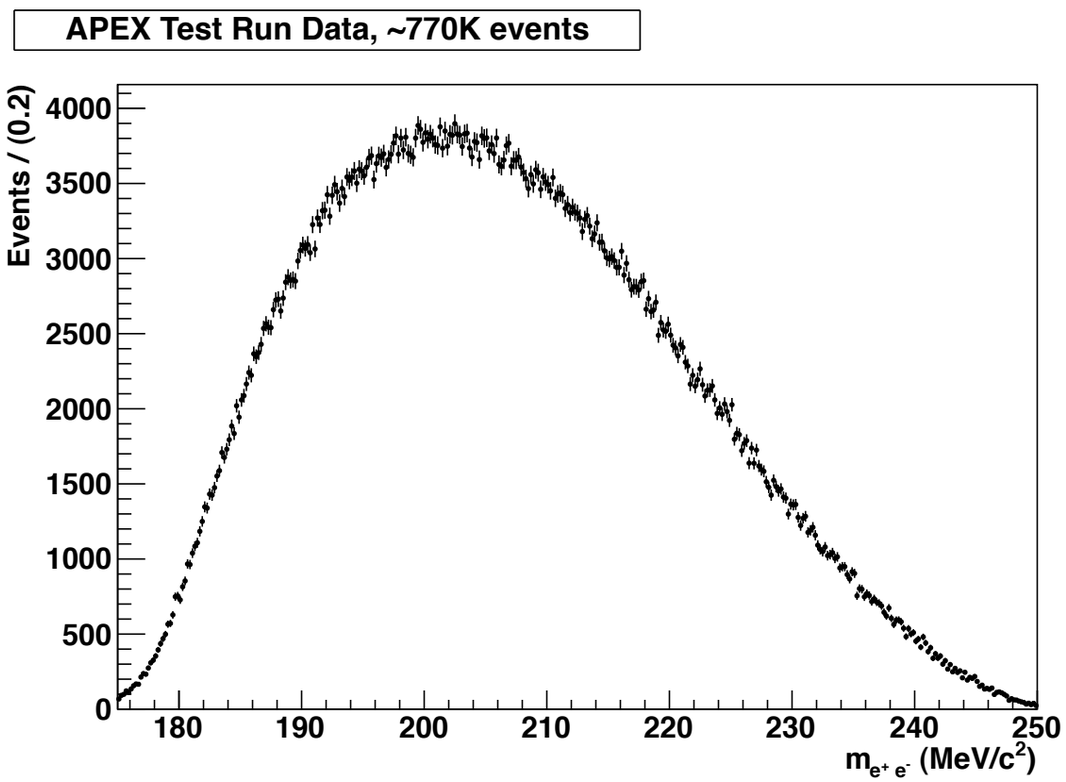
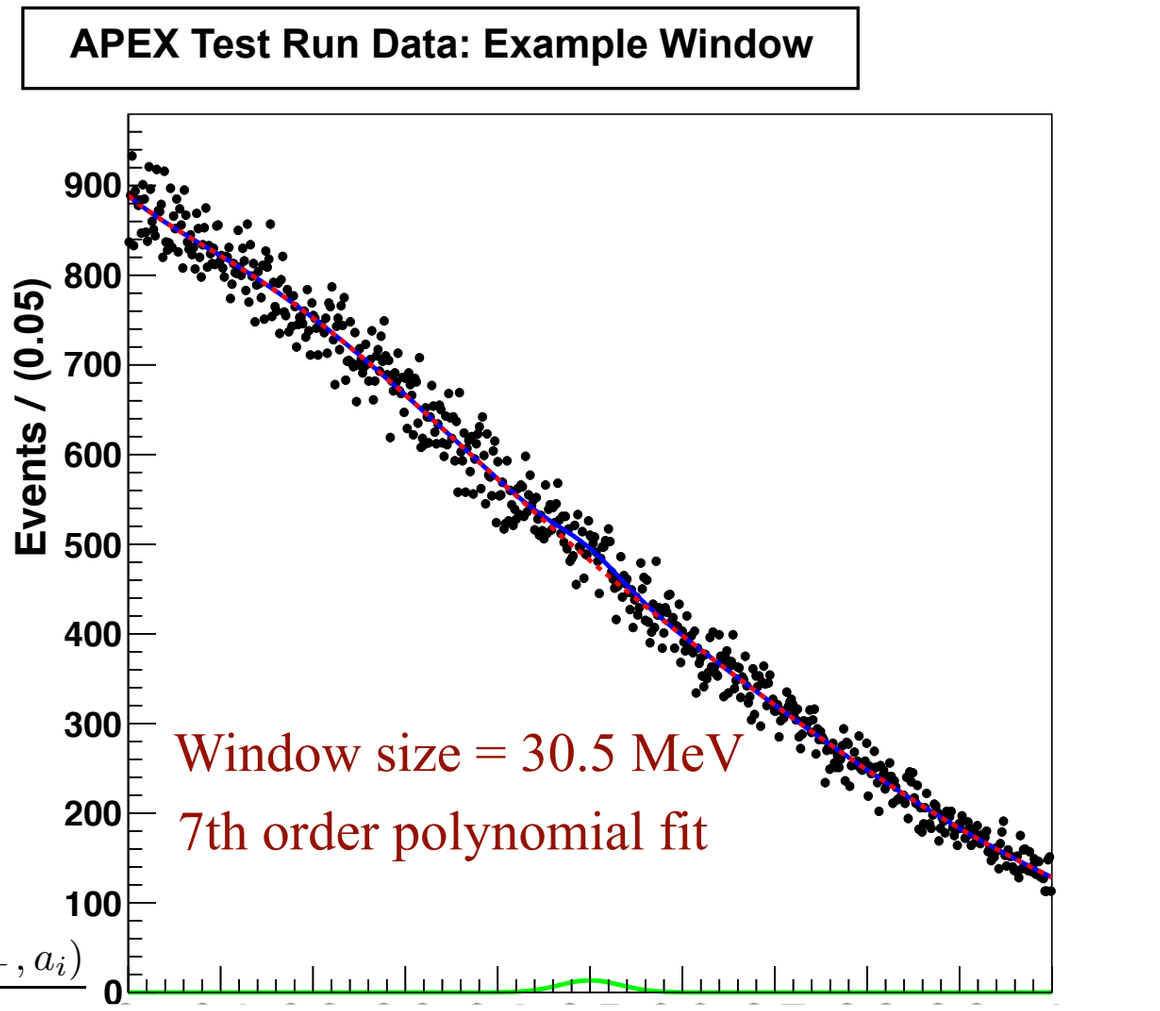
Final invariant mass spectrum QED radiative trident / Bethe-Heitler events

- Bump hunt for small, narrow resonance



Test run mass resolution: $\sigma \sim 0.85$ - 1.11 MeV



$$P(m_{e^+e^-} \mid m_{A'}, \sigma, S, B, a_i) = \frac{S \cdot \mathrm{N}(m_{e^+e^-} \mid m_{A'}, \sigma) \; + \; B \cdot \mathrm{Polynomial}(m_{e^+e^-}, a_i)}{S+B}$$

Probability model and profile likelihood ratio

$$\lambda(S) = \frac{L(S, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{S}, \hat{B}, \hat{a}_i)}$$

Results from scan of test run data: S, P-values

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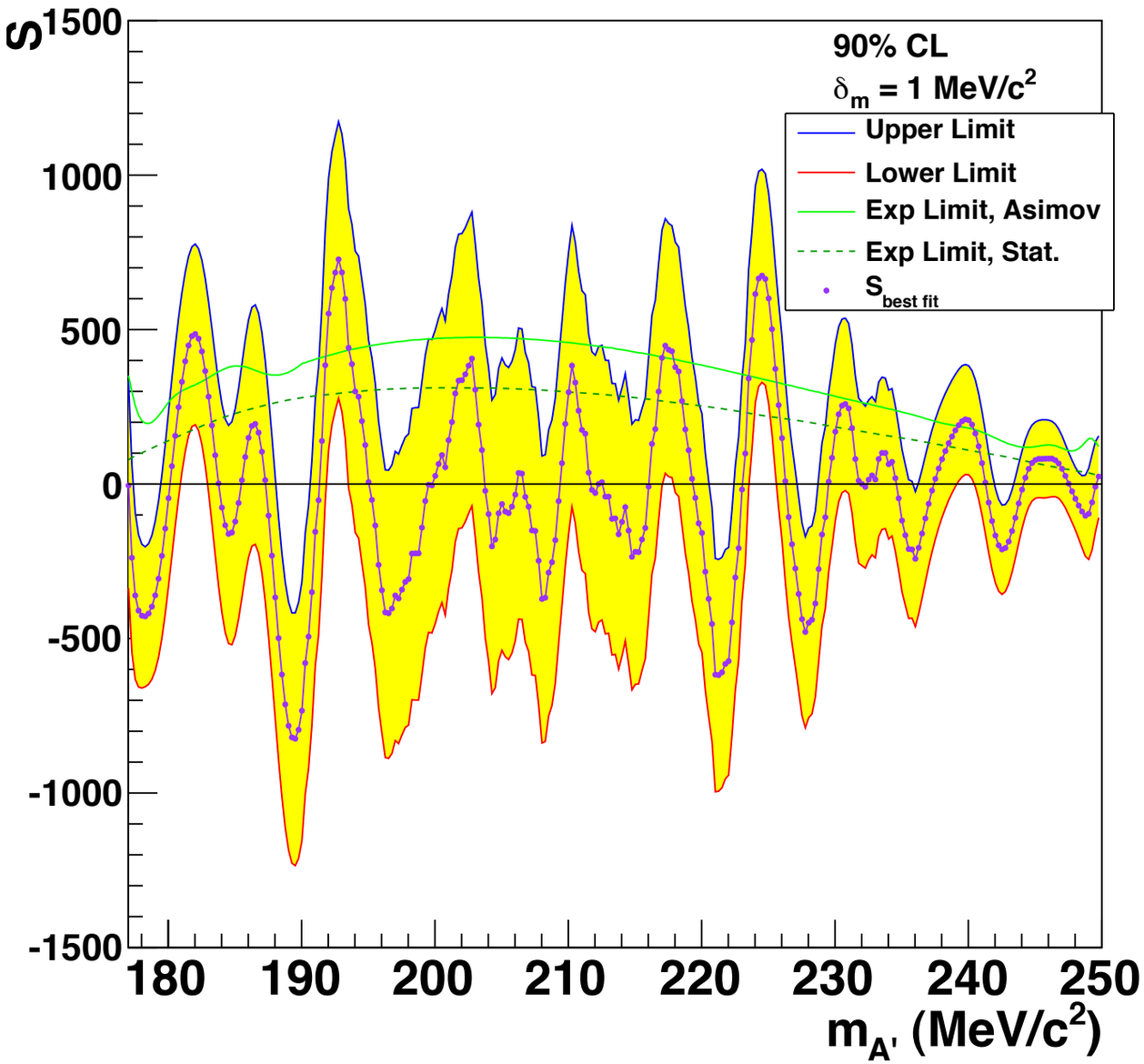
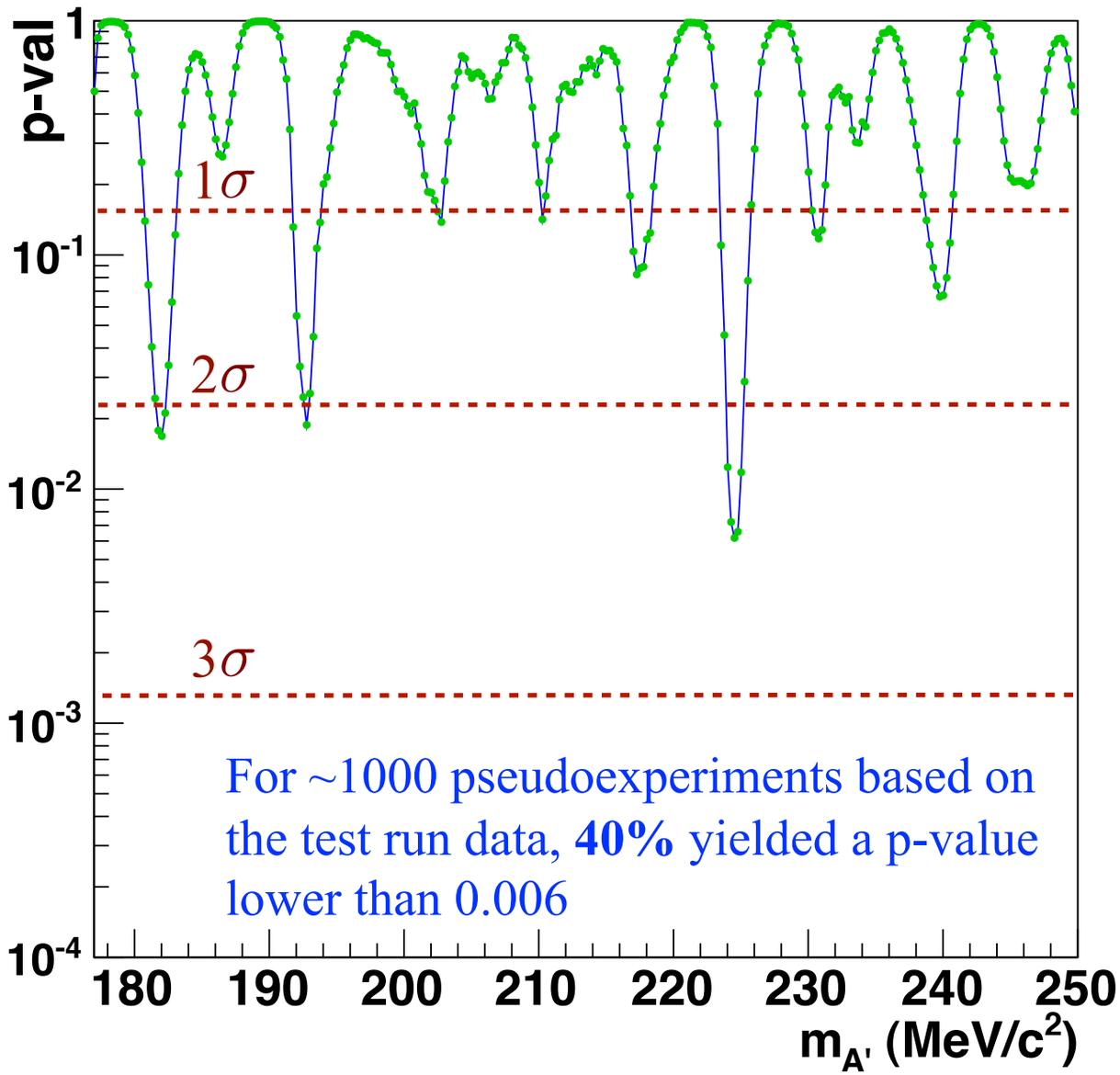
APEX Test Run Data, Two-Sided Central Limit



APEX Test Run Data, Raw Null P-values



Upper limit on S ⟶ upper limit on coupling

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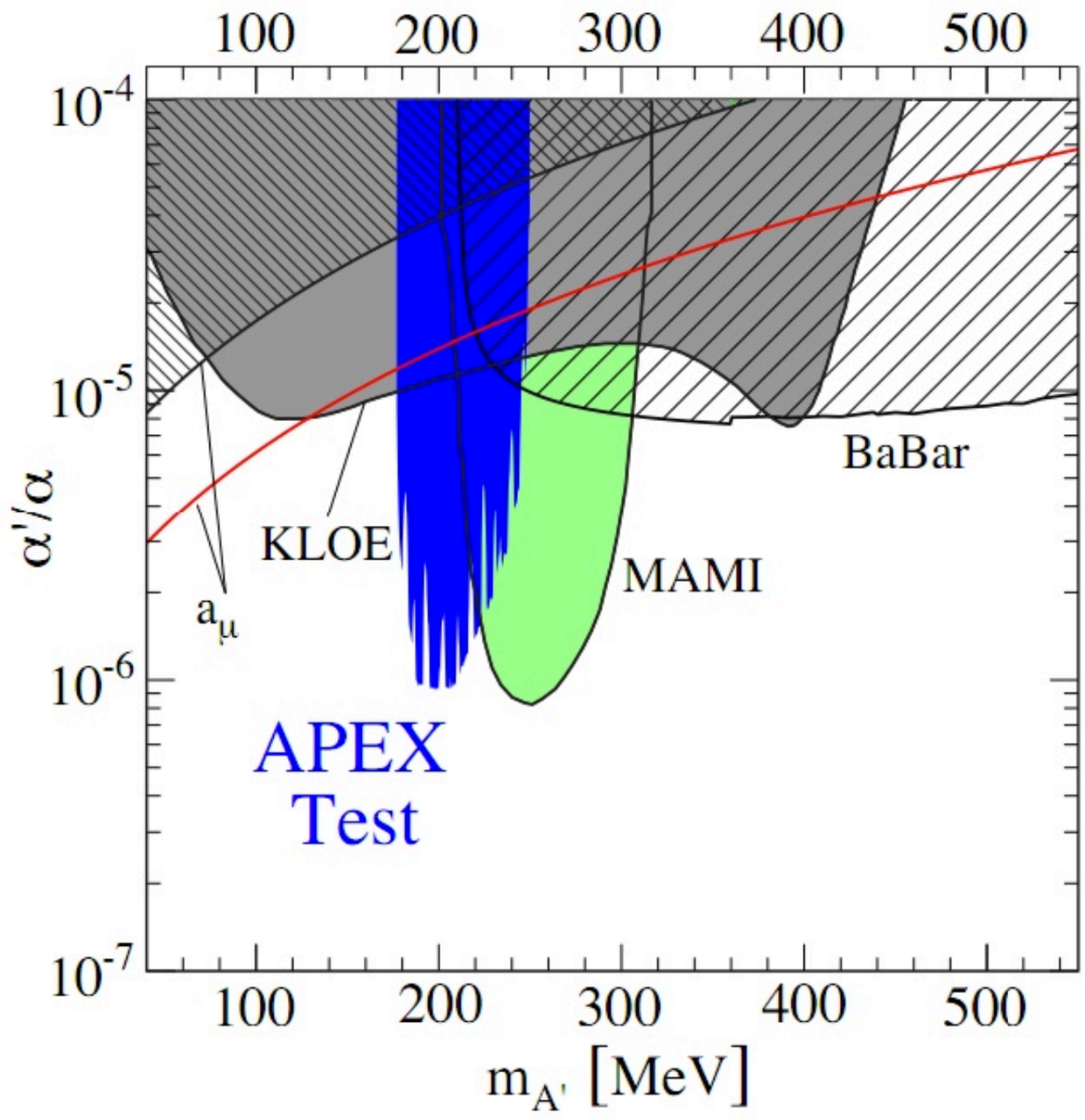
$$\frac{d\sigma(A')}{d\sigma(\gamma^*)} = \left(\frac{3\pi\epsilon^2}{2N_{\rm eff}\alpha}\right)\frac{m_{A'}}{\delta m} = \frac{S_{\delta m}}{B^{\gamma^*}_{\delta m}}$$

(See APEX proposal)

Normalize all backgrounds to γ^* background

- Ratio *f* of radiative-only cross section to full trident cross section determined via Monte Carlo to vary linearly from 0.21 to 0.25 across APEX mass range

$$\left(\frac{\alpha'}{\alpha}\right)_{max} = \left(\frac{S_{max}/m_{A'}}{f\cdot\Delta B/\Delta m}\right)\times\left(\frac{2N_{\rm eff}\alpha}{3\pi}\right)$$



Test run results and full run status

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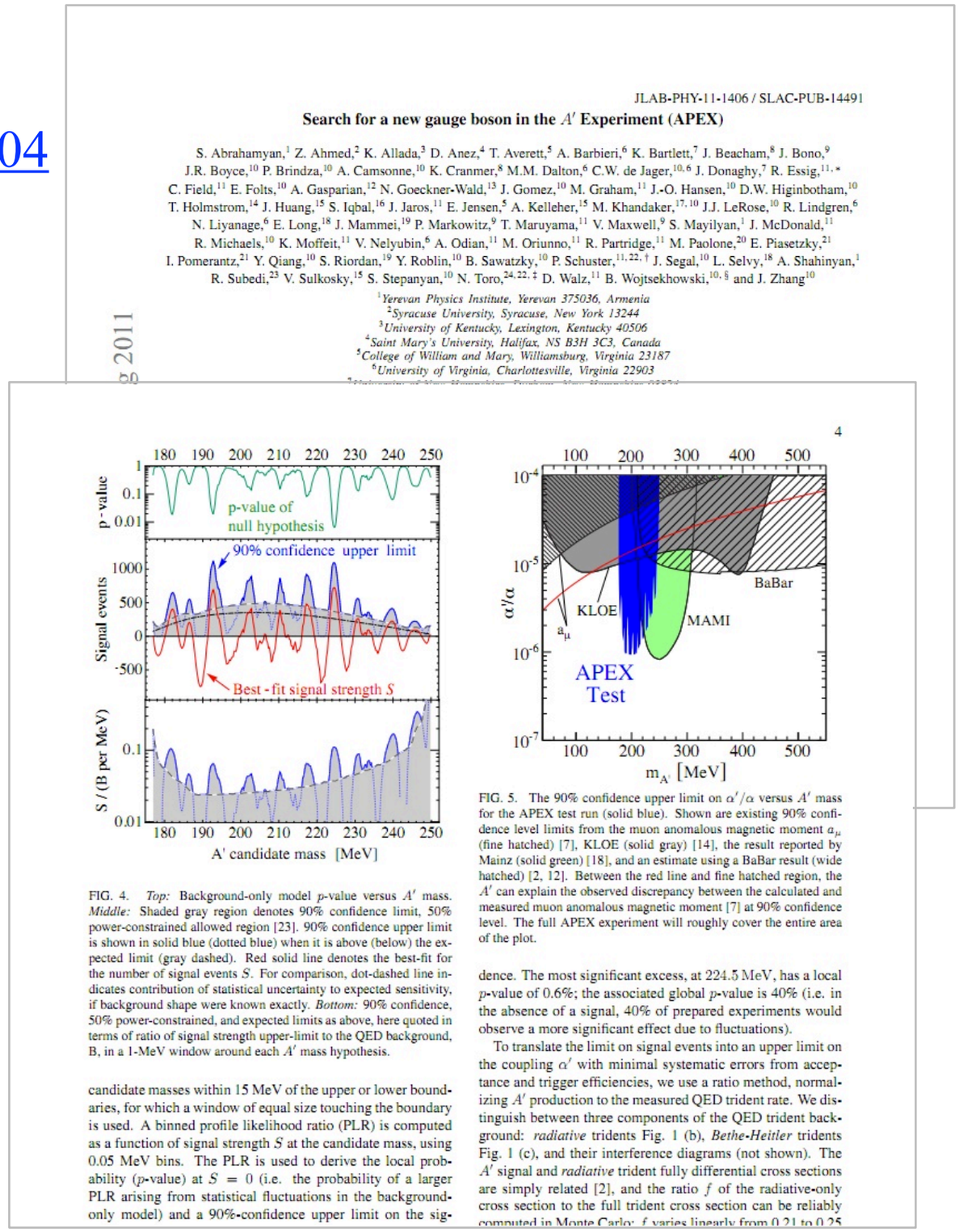
Test run results in PRL

- prl.aps.org/abstract/PRL/v107/i19/e191804
- arXiv:1108.2750



JLAB-PHY-11-1406 / SLAC-PUB-14491

Search for a new gauge boson in the A' Experiment (APEX)

S. Abrahamyan,[1] Z. Ahmed,[2] K. Allada,[3] D. Anez,[4] T. Averett,[5] A. Barbieri,[6] K. Bartlett,[7] J. Beacham,[8] J. Bono,[9] J.R. Boyce,[10] P. Brindza,[10] A. Camsonne,[10] K. Cranmer,[8] M.M. Dalton,[6] C.W. de Jager,[10,6] J. Donaghy,[7] R. Essig,[11,*] C. Field,[11] E. Folts,[10] A. Gasparian,[12] N. Goeckner-Wald,[13] J. Gomez,[10] M. Graham,[11] J.-O. Hansen,[10] D.W. Higinbotham,[10] T. Holmstrom,[14] J. Huang,[15] S. Iqbal,[16] J. Jaros,[11] E. Jensen,[5] A. Kelleher,[15] M. Khandaker,[17,10] J.J. LeRose,[10] R. Lindgren,[6] N. Liyanage,[6] E. Long,[18] J. Mammei,[19] P. Markowitz,[9] T. Maruyama,[11] V. Maxwell,[9] S. Mayilyan,[1] J. McDonald,[11] R. Michaels,[10] K. Moffeit,[11] V. Nelyubin,[6] A. Odian,[11] M. Oriunno,[11] R. Partridge,[11] M. Paolone,[20] E. Piasetzky,[21] I. Pomerantz,[21] Y. Qiang,[10] S. Riordan,[19] Y. Roblin,[10] B. Sawatzky,[10] P. Schuster,[11,22,†] J. Segal,[10] L. Selvy,[18] A. Shahinyan,[1] R. Subedi,[23] V. Sulkosky,[15] S. Stepanyan,[10] N. Toro,[24,22,‡] D. Walz,[11] B. Wojtsekhowski,[10,§] and J. Zhang[10]

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g 2011

FIG. 4. *Top:* Background-only model p-value versus A' mass. *Middle:* Shaded gray region denotes 90% confidence limit, 50% power-constrained allowed region [23]. 90% confidence upper limit is shown in solid blue (dotted blue) when it is above (below) the expected limit (gray dashed). Red solid line denotes the best-fit for the number of signal events S. For comparison, dot-dashed line indicates contribution of statistical uncertainty to expected sensitivity, if background shape were known exactly. *Bottom:* 90% confidence, 50% power-constrained, and expected limits as above, here quoted in terms of ratio of signal strength upper-limit to the QED background, B, in a 1-MeV window around each A' mass hypothesis.

candidate masses within 15 MeV of the upper or lower boundaries, for which a window of equal size touching the boundary is used. A binned profile likelihood ratio (PLR) is computed as a function of signal strength S at the candidate mass, using 0.05 MeV bins. The PLR is used to derive the local probability (p-value) at $S = 0$ (i.e. the probability of a larger PLR arising from statistical fluctuations in the background-only model) and a 90%-confidence upper limit on the sig-

FIG. 5. The 90% confidence upper limit on α'/α versus A' mass for the APEX test run (solid blue). Shown are existing 90% confidence level limits from the muon anomalous magnetic moment a_μ (fine hatched) [7], KLOE (solid gray) [14], the result reported by Mainz (solid green) [18], and an estimate using a BaBar result (wide hatched) [2, 12]. Between the red line and fine hatched region, the A' can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [7] at 90% confidence level. The full APEX experiment will roughly cover the entire area of the plot.

dence. The most significant excess, at 224.5 MeV, has a local p-value of 0.6%; the associated global p-value is 40% (i.e. in the absence of a signal, 40% of prepared experiments would observe a more significant effect due to fluctuations).

To translate the limit on signal events into an upper limit on the coupling α' with minimal systematic errors from acceptance and trigger efficiencies, we use a ratio method, normalizing A' production to the measured QED trident rate. We distinguish between three components of the QED trident background: *radiative* tridents Fig. 1 (b), *Bethe-Heitler* tridents Fig. 1 (c), and their interference diagrams (not shown). The A' signal and *radiative* trident fully differential cross sections are simply related [2], and the ratio f of the radiative-only cross section to the full trident cross section can be reliably computed in Monte Carlo: f varies linearly from 0.21 to 0.25

APEX is approved; JLab currently commissioning beam after shutdown for upgrade to 12 GeV

- Physics in 2015
- **Both APEX and HPS selected by JLab PAC 41 for priority running (next few years)**
- Equipment fully funded

Dataset now public

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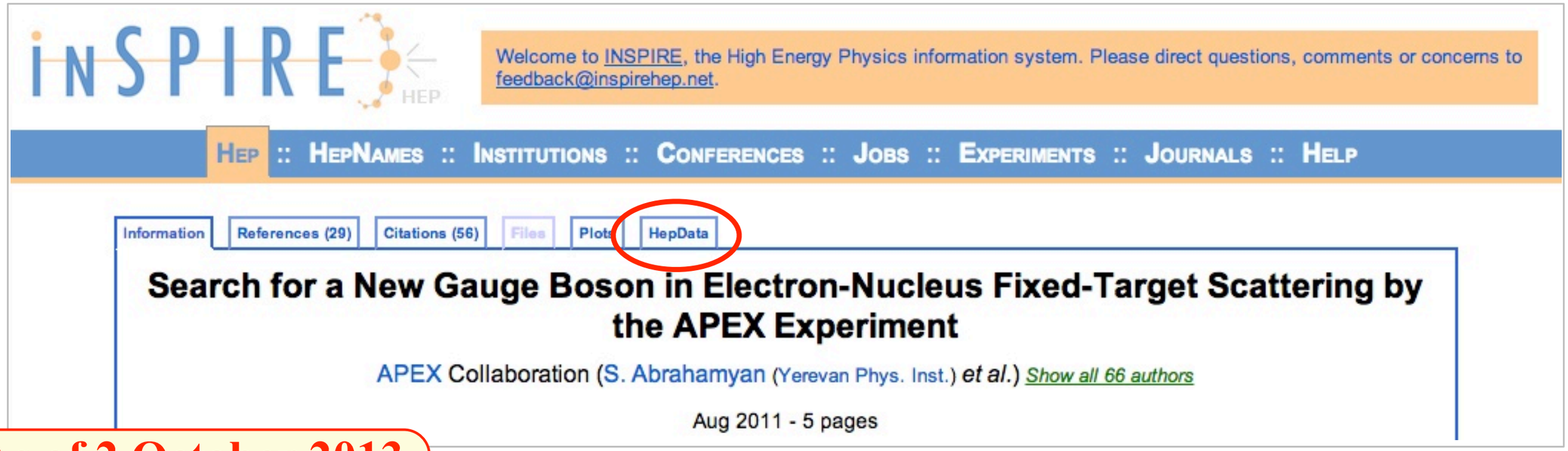
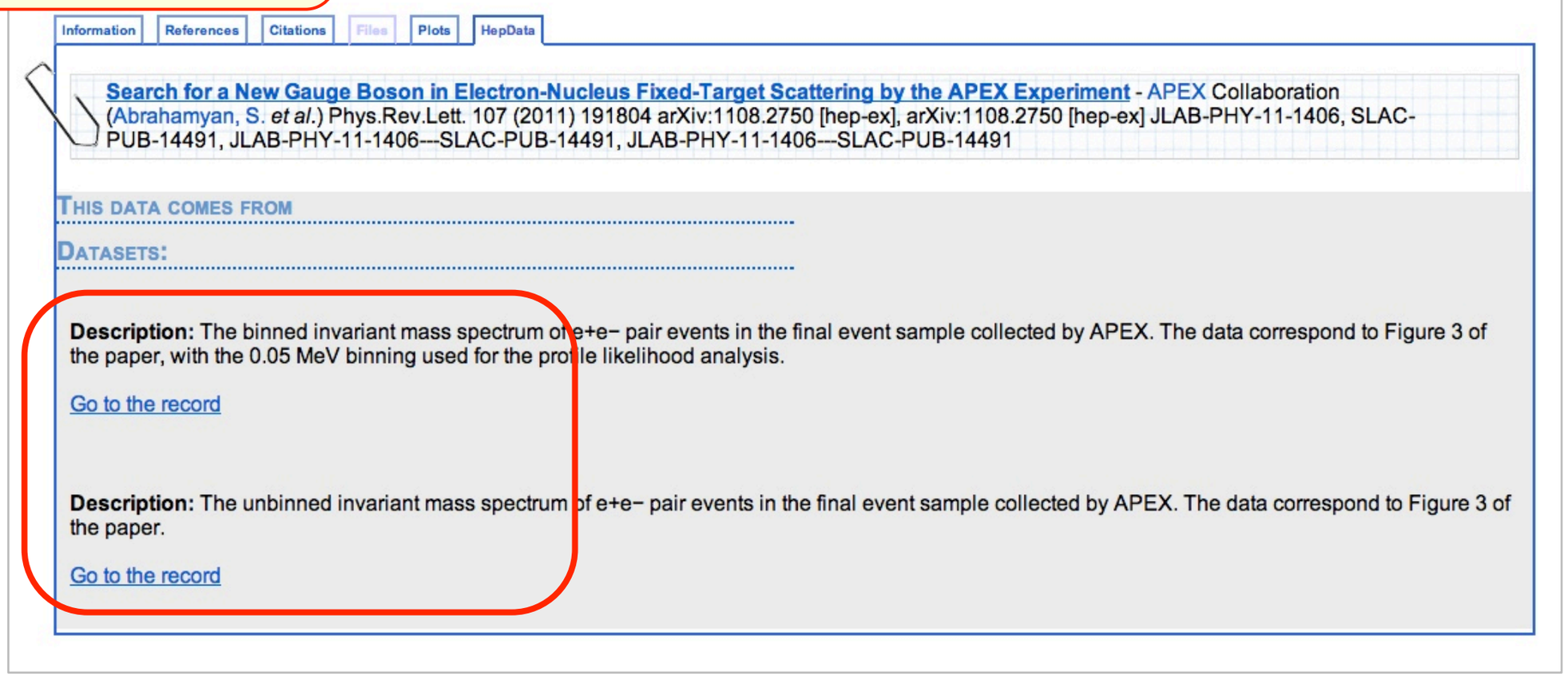


As of 2 October 2013



Plan for full run

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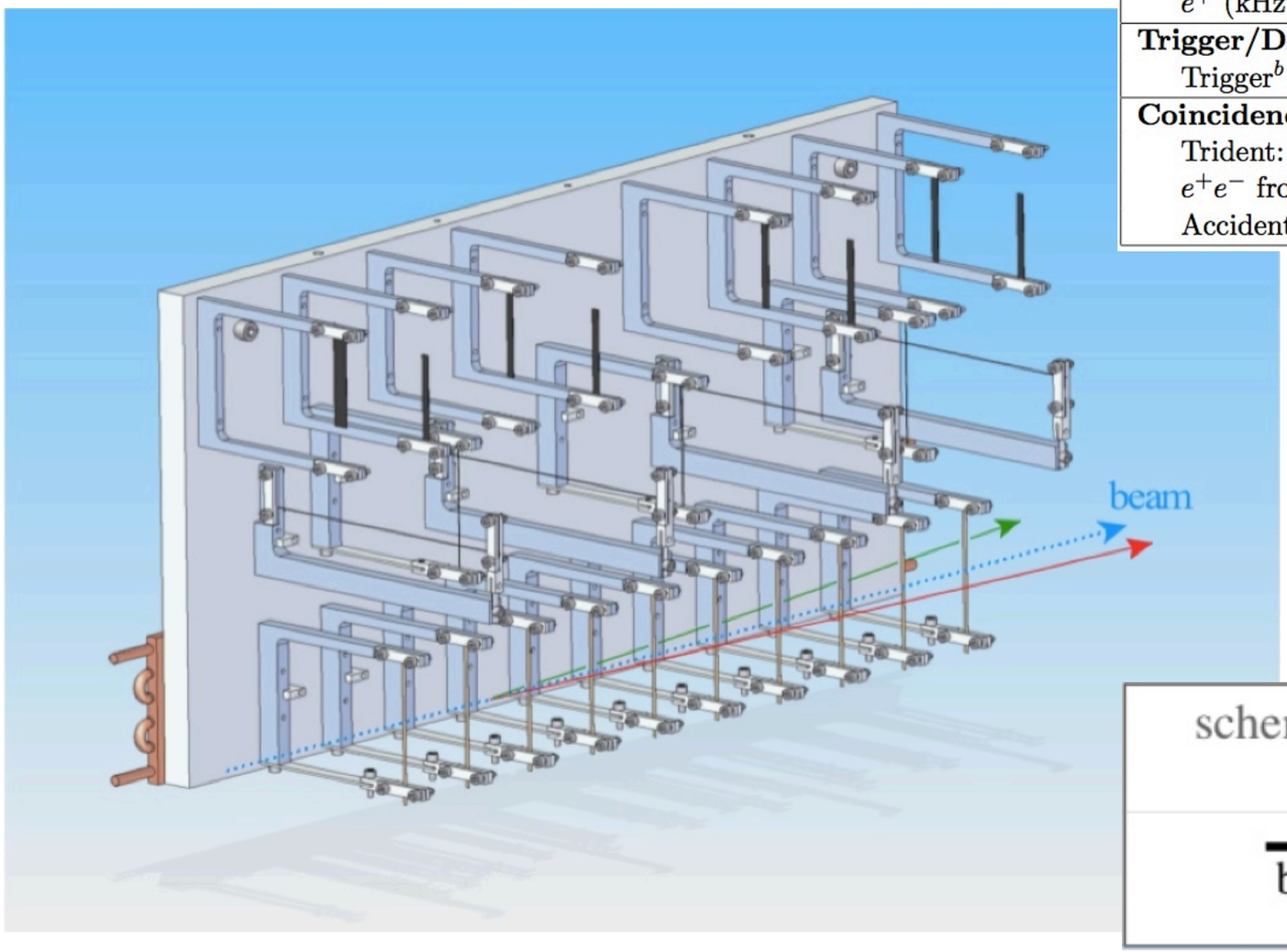
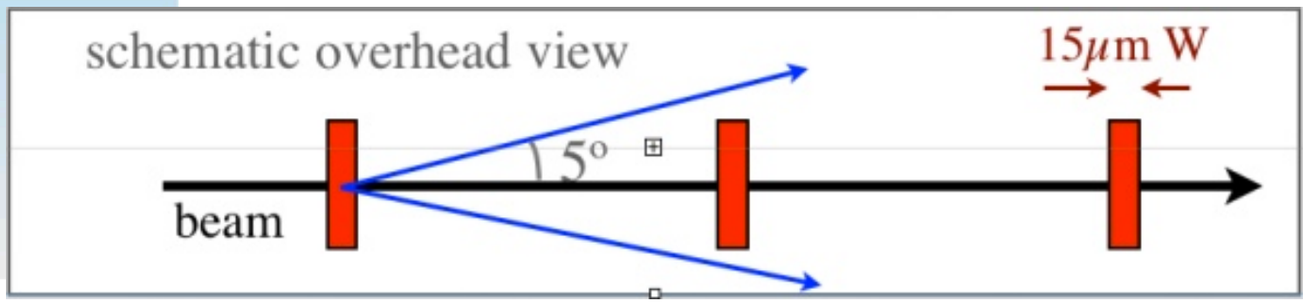
Full run at JLab will take data for ~34 days at several energy and spectrometer settings

- Possible modifications to original run plan could take advantage of higher beam energies and wider angles (with adjustment of septum magnets) to access higher $m_{A'}$ region

Settings	A	B	C	D
Beam energy (GeV)	2.2	4.4	1.1	3.3
Central angle	5.0°	5.0°	5.0°	5.0°
Effective angles	4.5–5.5	4.5–5.5	4.5–5.5	4.5–5.5
Target T/X_0 (ratio[a])	4%	8%	0.69% (1:3)	8%
Beam current (μA)	70	60	65	80
Central momentum (GeV)	1.095	2.189	0.545	1.634
Singles (negative polarity)				
e^- (MHz)	4.1	0.7	5.8	2.2
π^- (MHz)	0.1	1.7	0.03	0.9
Singles (positive polarity)				
$\pi+$ [p] (kHz)	90	1700	30	900
e^+ (kHz)	27	5	23	17
Trigger/DAQ:				
Trigger[b] (kHz)	3.0	3.1	3.15	3.3
Coincidence Backgrounds:				
Trident: $e^-Z \rightarrow e^-e^+e^-Z$ (Hz)	500	110	330	370
e^+e^- from real γ conversion (Hz)	30	16	4	45
Accidentals [c] (Hz)	55	30	70	40



Cover a larger mass range using a 50-cm long multifoil target



Work in progress for full run

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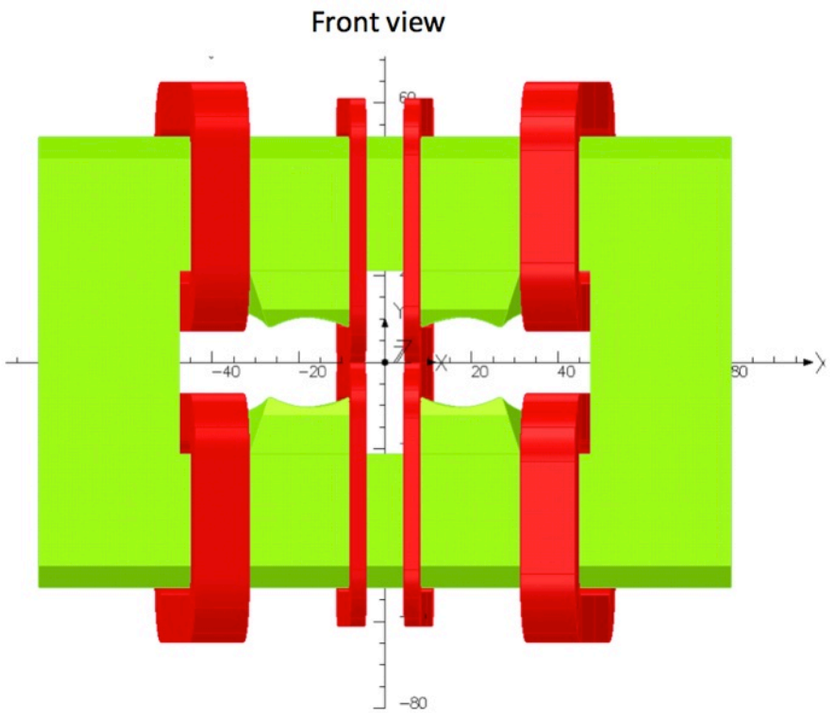
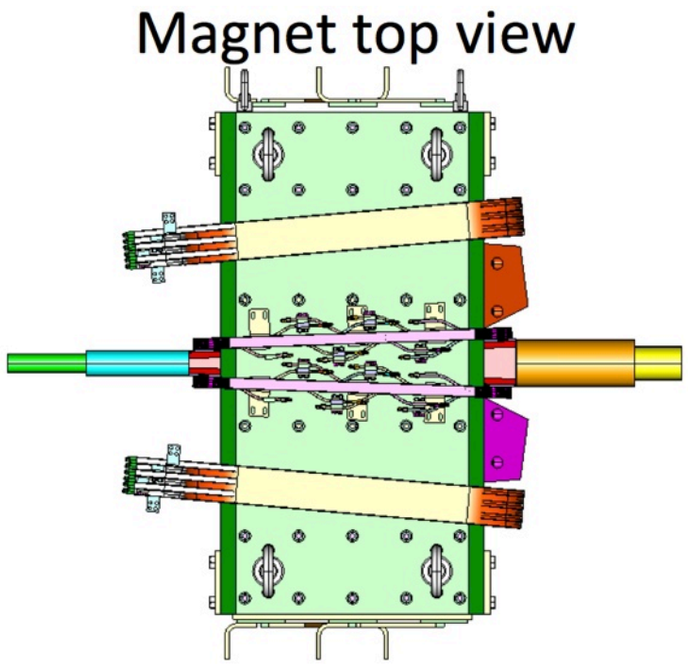


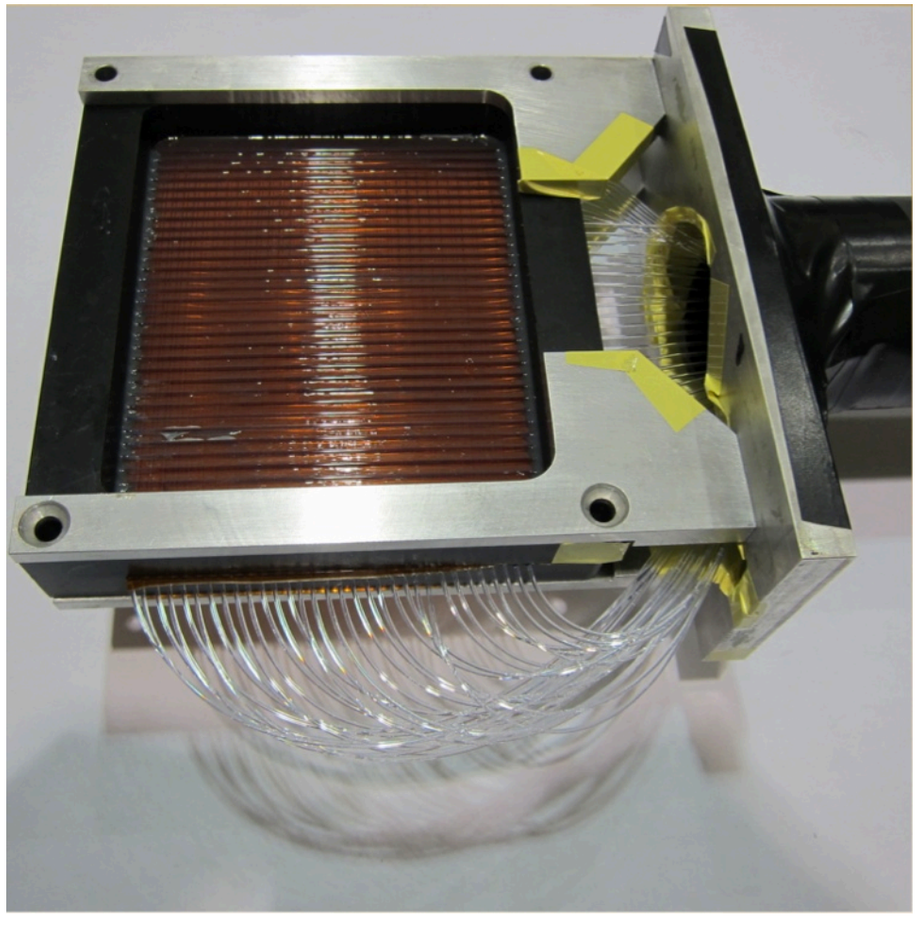


New septum magnets

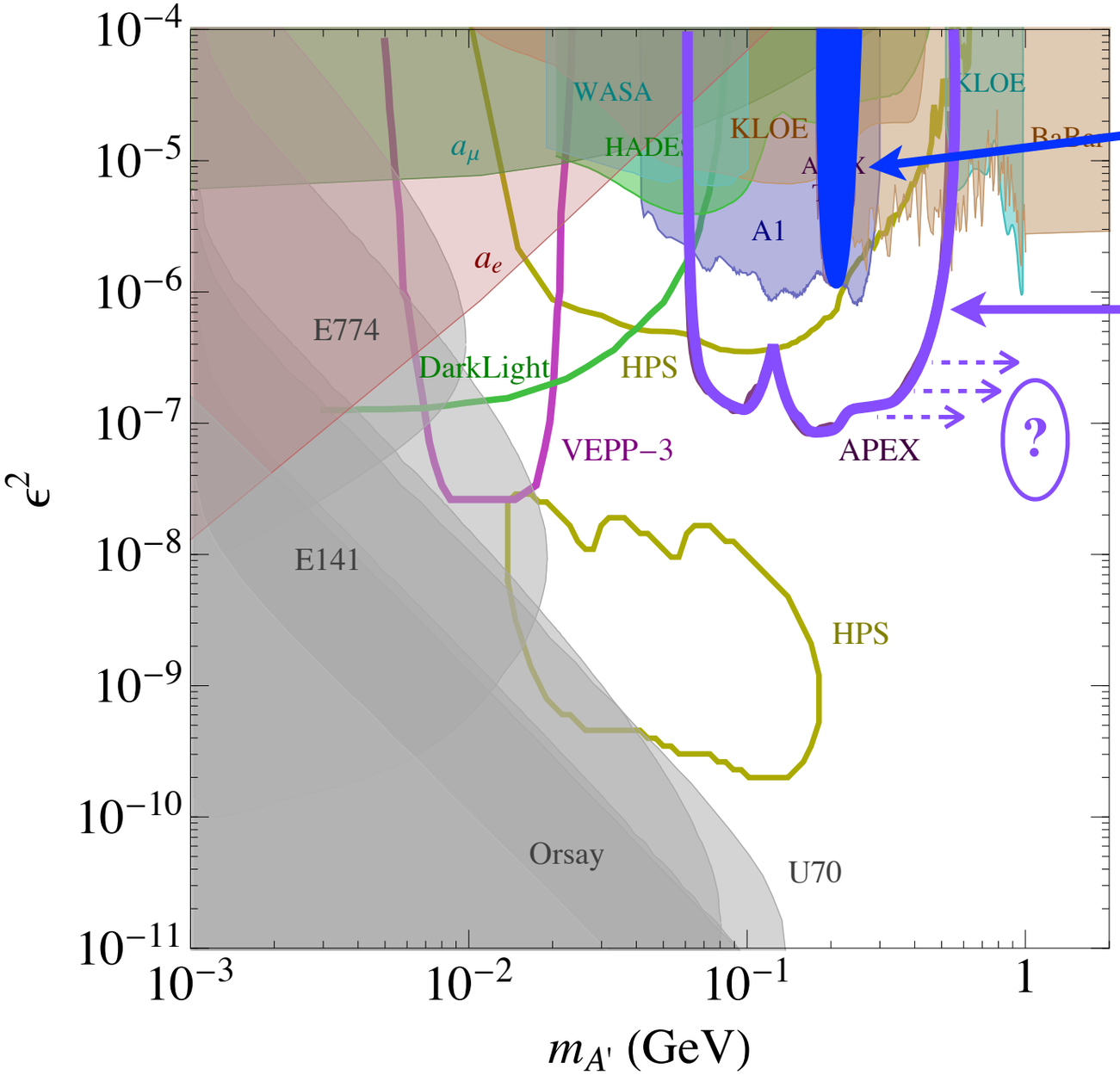
- Magnet parts produced
- Contractor currently testing coils
- Sensitivity projections currently being updated with new acceptance

New optics method

- Scintillating fiber (SciFi) hodoscope



Plan for full run



APEX Test Run Results

Full Run Projected Sensitivity

Full run statistics of e^+e^- pairs will be ~200x larger than test run, allowing sensitivity to $\alpha'/\alpha = \epsilon^2$ 1-2 orders of magnitude below current limits

JLab commissioning 12 GeV beam now -- physics in 2015

- Hall A schedule still being finalized; APEX ready to run in the first or second year
- New SciFi optics calibration method and septum magnets
- Data acquisition rate improvements (up to 5 kHz)

Hidden forces in public

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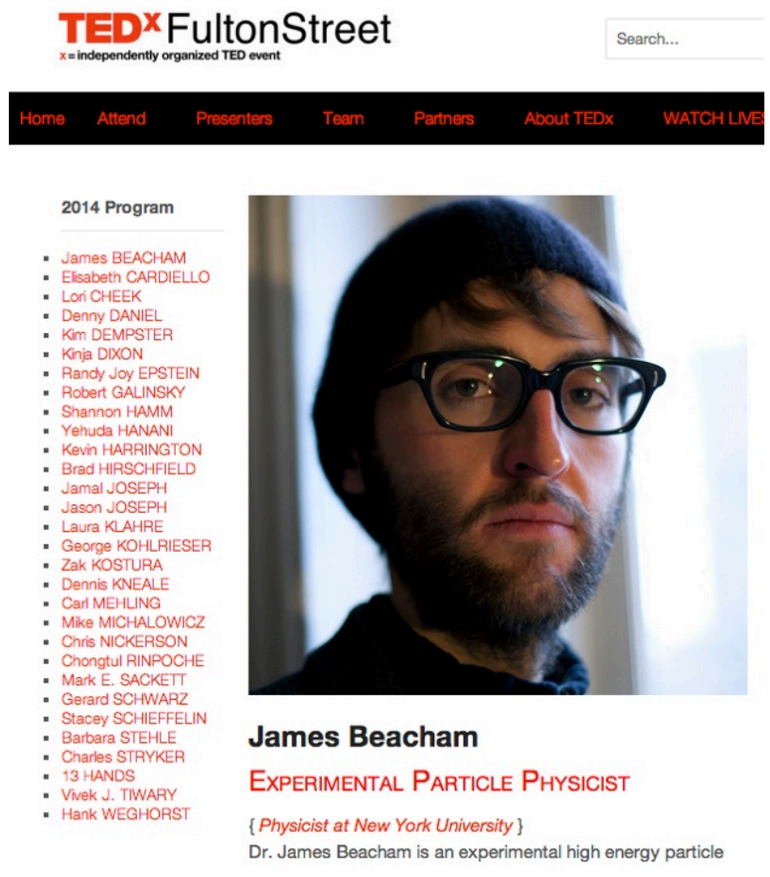
Yesterday



Acknowledgments

APEX spokespeople

- Rouven Essig (Stony Brook)
- Philip Schuster (Perimeter)
- Natalia Toro (Perimeter)
- Bogdan Wojtsekhowski (Jefferson Lab)

Core test run analysis team

- Sergey Abrahamyan (Jefferson Lab)
- Eric Jensen (William & Mary)
- Jin Huang (MIT)
- Kyle Cranmer, J.B. (NYU)

The Hall A Collaboration

Jefferson Lab staff

Backups

Hall A High Resolution Spectrometers (HRSs)

NYU
Center for Cosmology and Particle Physics

Table 1: Main design characteristics of the Hall A High Resolution Spectrometers at nominal target position. The resolution values are for the FWHM.

Configuration	QQD_nQ Vertical bend
Bending angle	45°
Optical length	23.4 m
Momentum range	0.3 - 4.0 GeV/c
Momentum acceptance	-4.5% < δp/p <+4.5%
Momentum resolution	1×10^{-4}
Dispersion at the focus (D)	12.4 m
Radial linear magnification (M)	-2.5
D/M	5.0
Angular range HRS-L	12.5° - 150°
HRS-R	12.5° - 130°
Angular acceptance: Horizontal	±30 mrad
Vertical	±60 mrad
Angular resolution : Horizontal	0.5 mrad
Vertical	1.0 mrad
Solid angle at δp/p = 0, $y_0 = 0$	6 msr
Transverse length acceptance	±5 cm
Transverse position resolution	1 mm