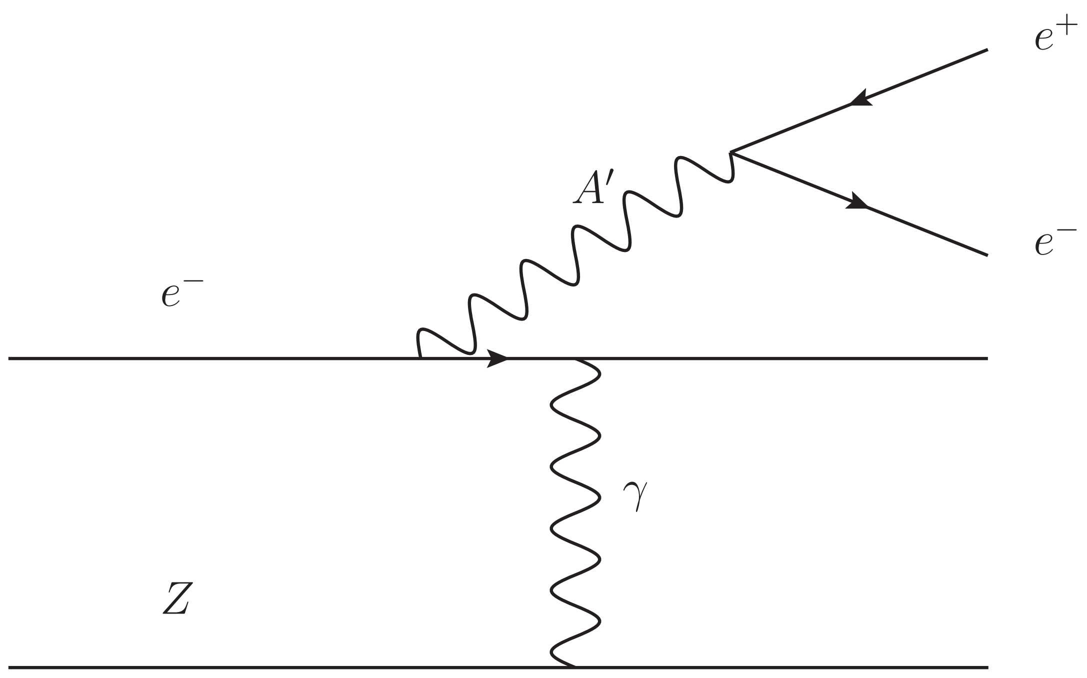
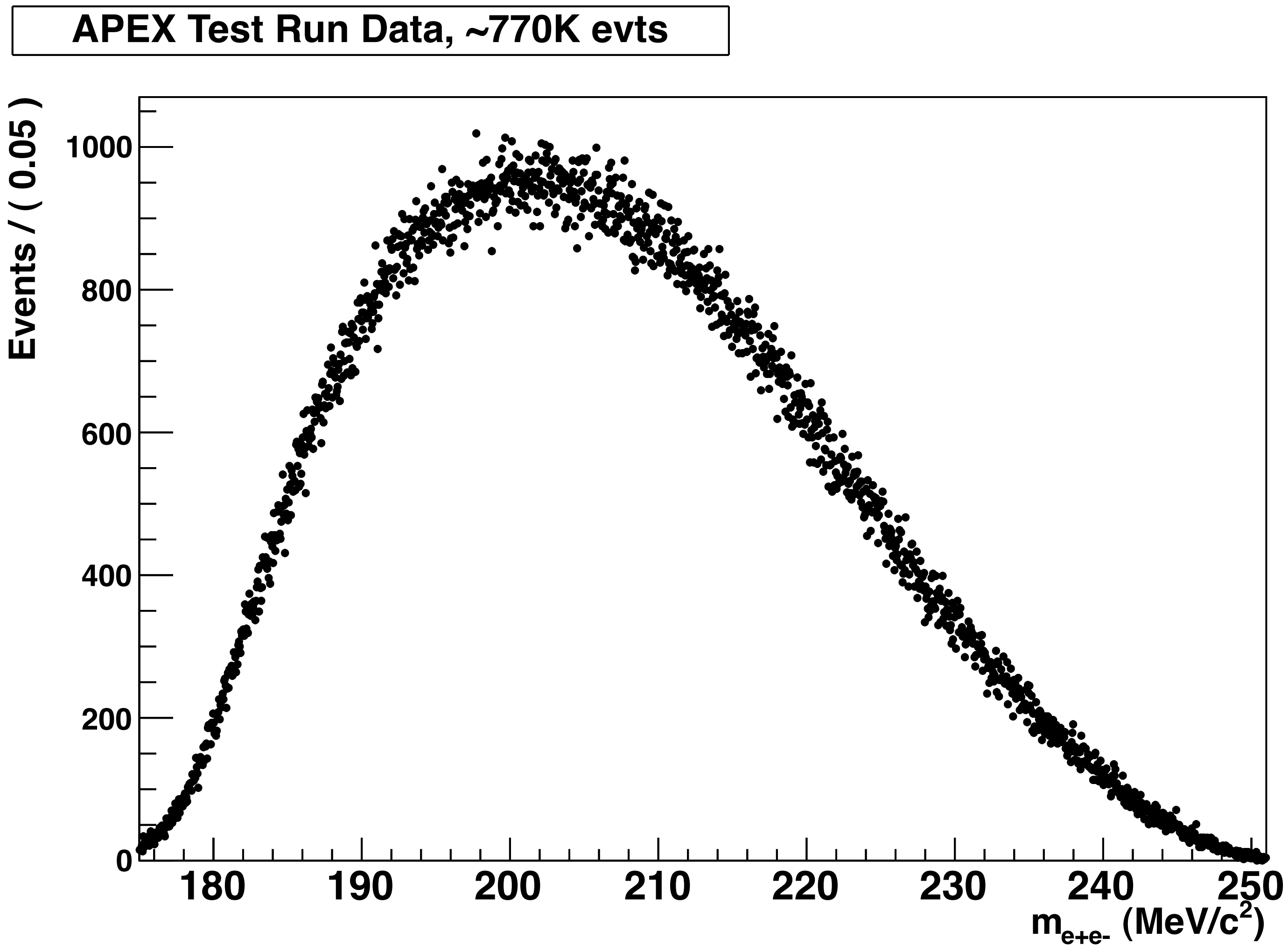
Center for Cosmology and Particle Physics

APEX: A Prime EXperiment at Jefferson Lab





James Beacham
New York University
for the APEX Collaboration

Outline

Motivations

Existing constraints

APEX test run setup

Test run results

Full run plans

U(1) extension of the Standard Model

Common feature of many theories, e.g.,

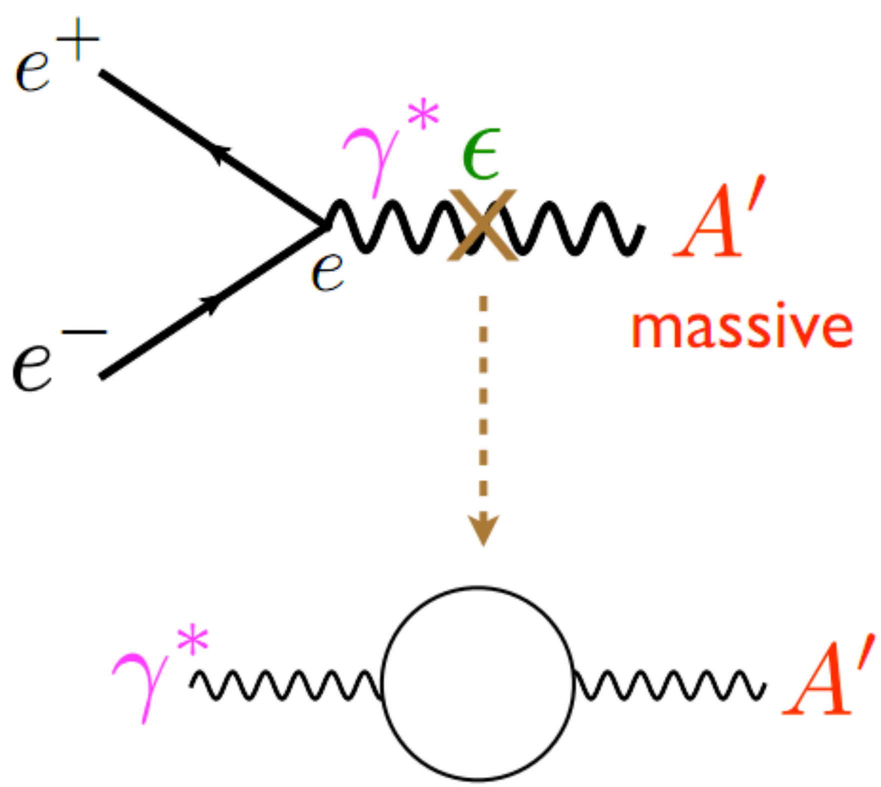
- Holdom
  - *Two U(1)'s and Epsilon Charge Shifts,* Phys. Lett. B166 (1986) 196
- Strassler/Zurek
  - *Echoes of a hidden valley at hadron colliders,* Phys. Lett. B651 (2007) 374-379

Generically, hidden gauge sector talks to visible sector via kinetic mixing terms in Lagrangian; simplest extension is a $U(1)'$

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

U(1) extension of the Standard Model

- "Hidden gauge boson" ("dark photon", A') mixes with photon
  → hidden sector coupled to SM
- Equivalent to assigning small EM charge



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

Generated by heavy particles interacting with γ and A'

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

$$\epsilon = g'/e$$

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

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

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

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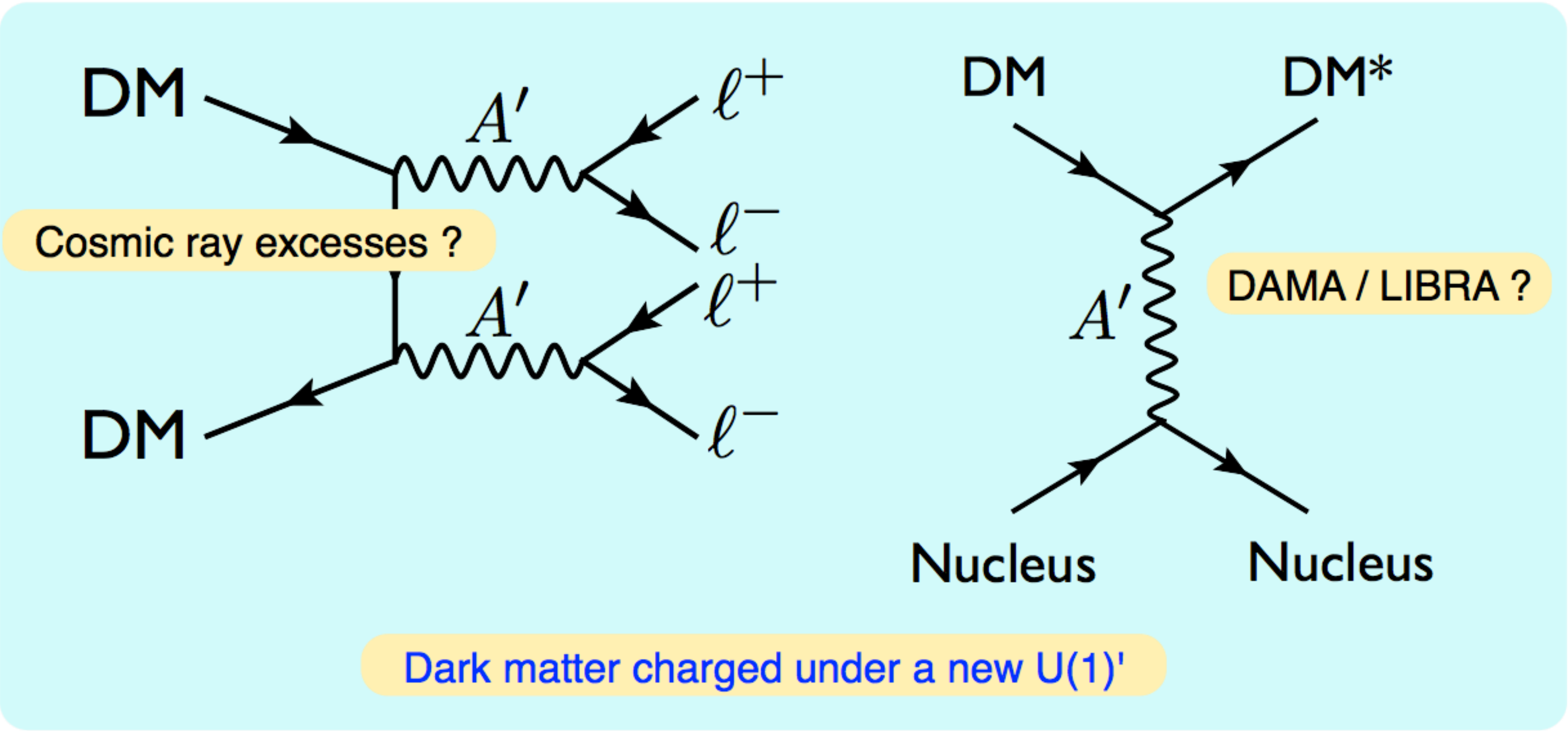
Additional motivations

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



- PAMELA sees positron excess but no antiproton excess ⟶ preferential decay of a sub-GeV mass gauge boson into leptons
- Fermi, ATIC, HESS: Annihilation or decay of dark matter charged under new $U(1)'$ with sub-GeV mass A', to explain e^+e^- excesses
- DAMA/LIBRA, INTEGRAL, CoGeNT

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Additional motivations

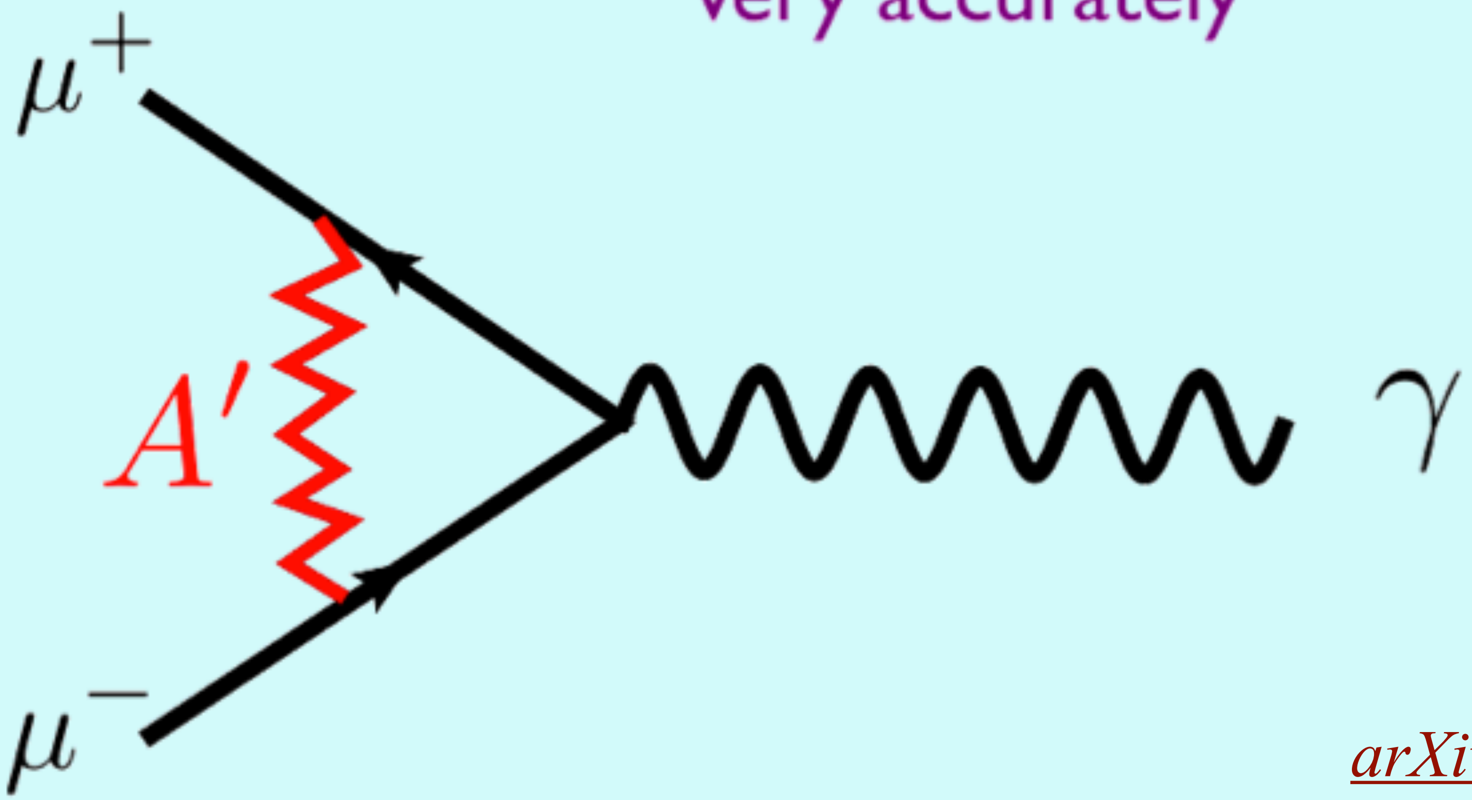
...and the anomalous magnetic moment of the muon

magnetic dipole moment

$$\vec{\mu} = g_s \left(\frac{q}{2m}\right) \vec{s}$$

spin

can be measured very accurately

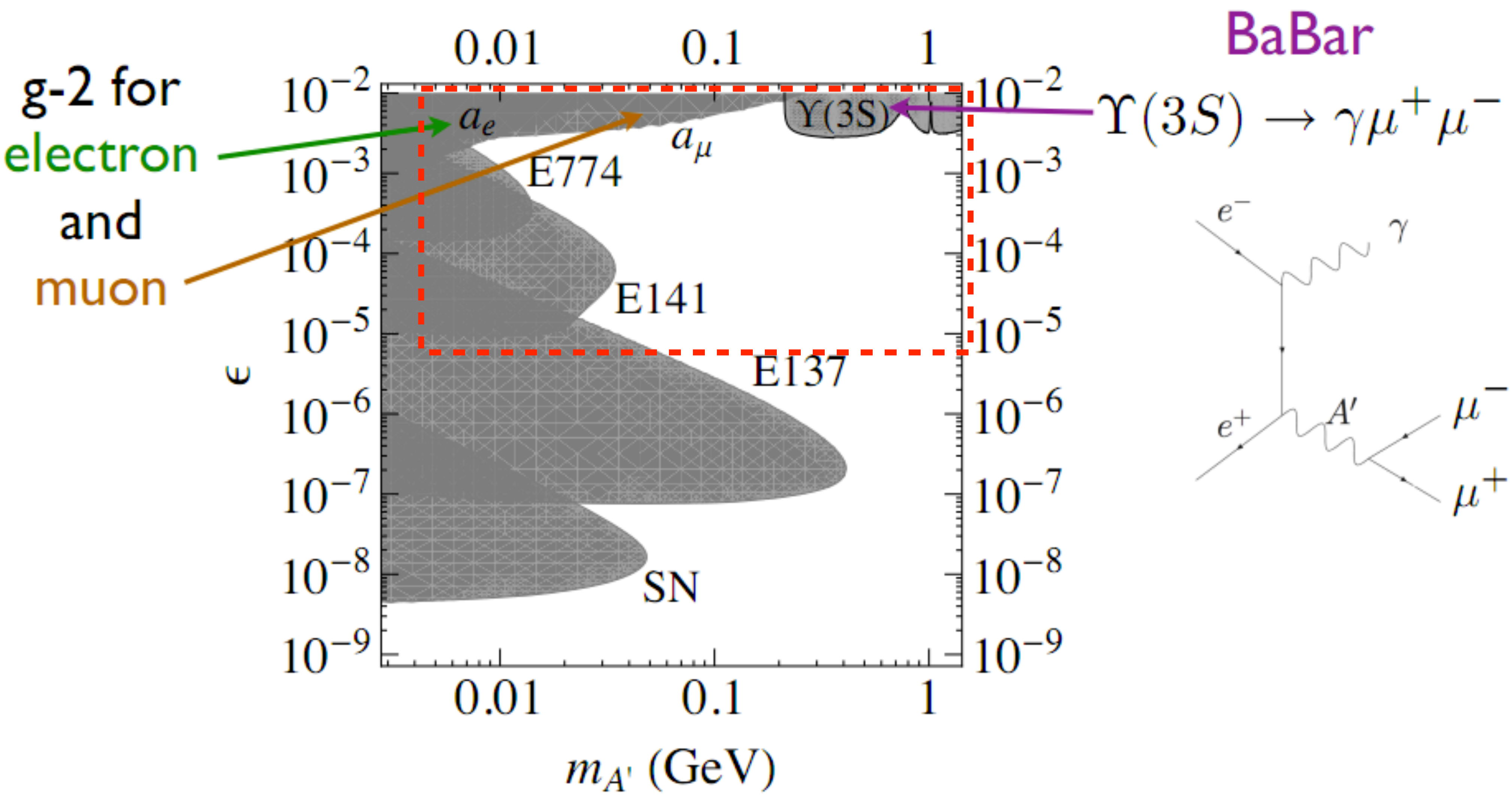


$g_s \neq 2$

arXiv:0906.0580

Existing constraints

- Beam dump experiments
- BaBar $\Upsilon(3S)$ experiment
- Supernova data
- g-2 of muon and electron

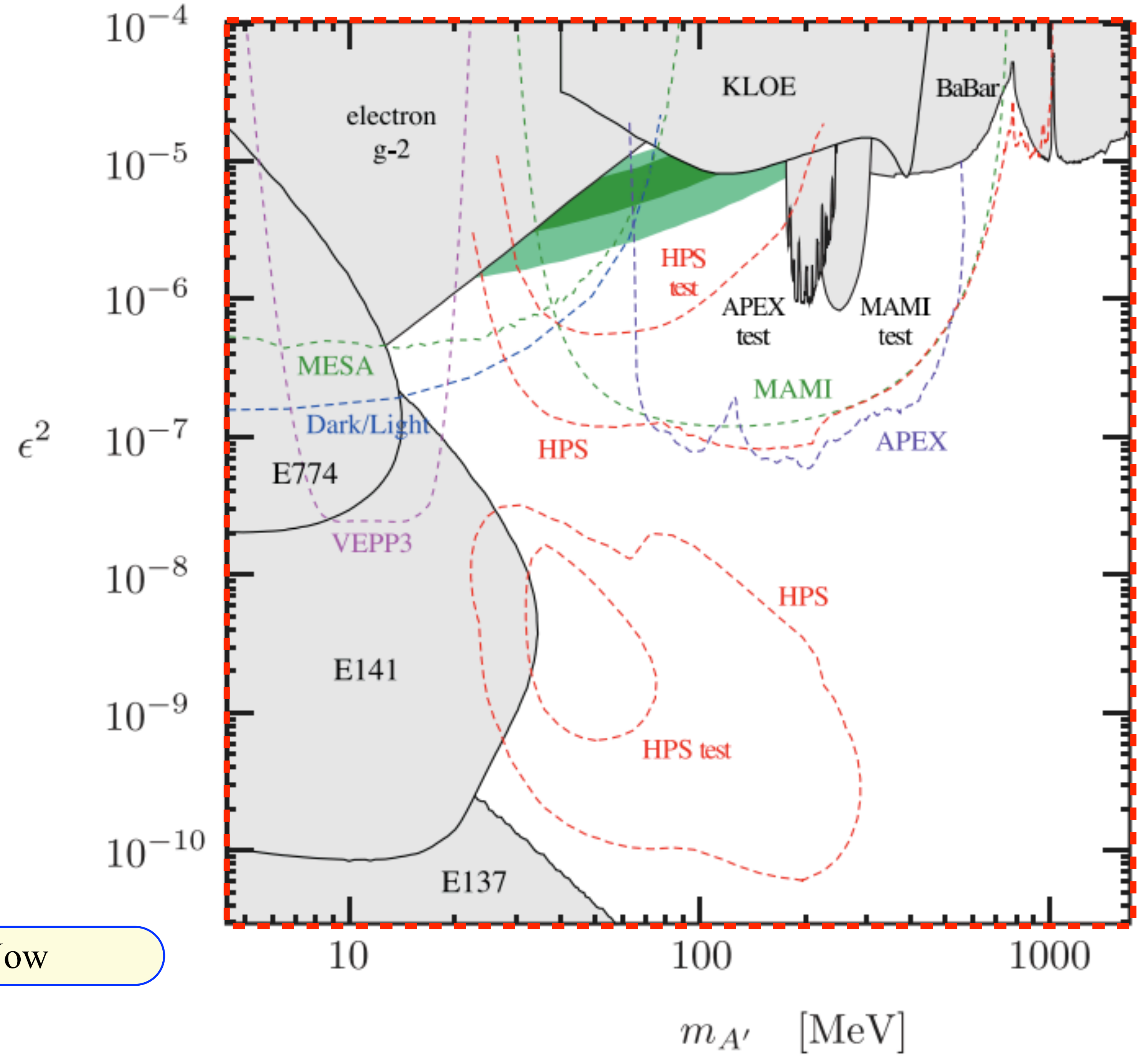


As of 2009

arXiv:0906.0580

Existing constraints

- Beam dump experiments
- BaBar $\Upsilon(3S)$ experiment
- Supernova data
- g-2 of muon and electron



Now

arXiv:1209.2558

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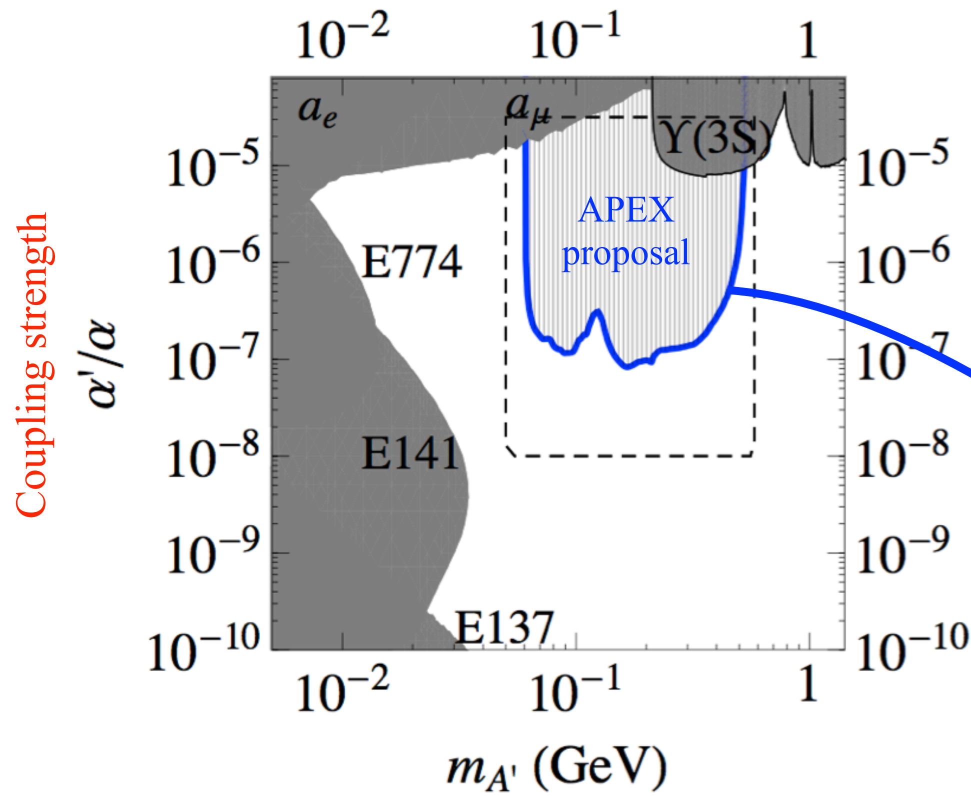
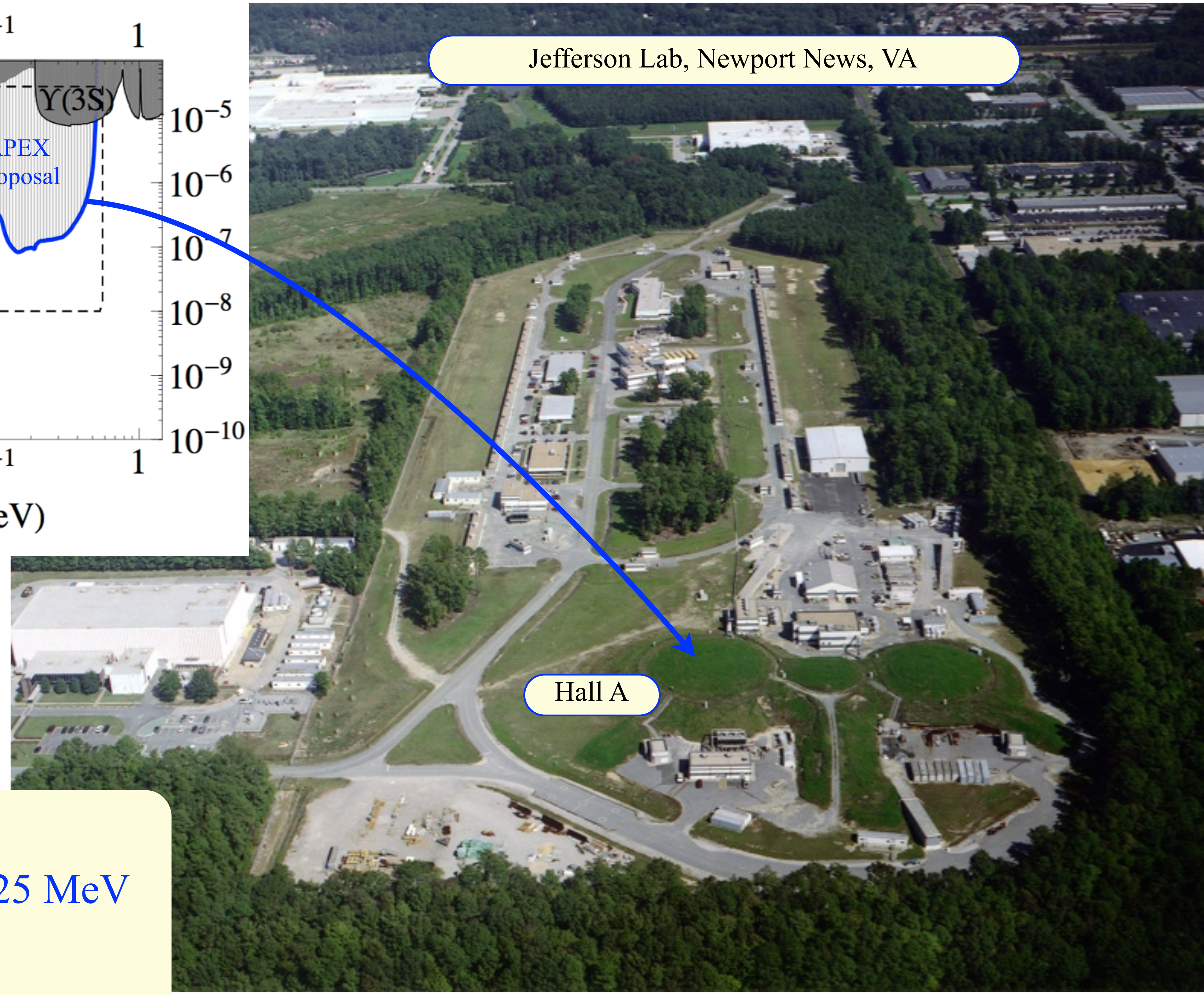
APEX: Dark photon search in fixed target experiment at Jefferson Lab





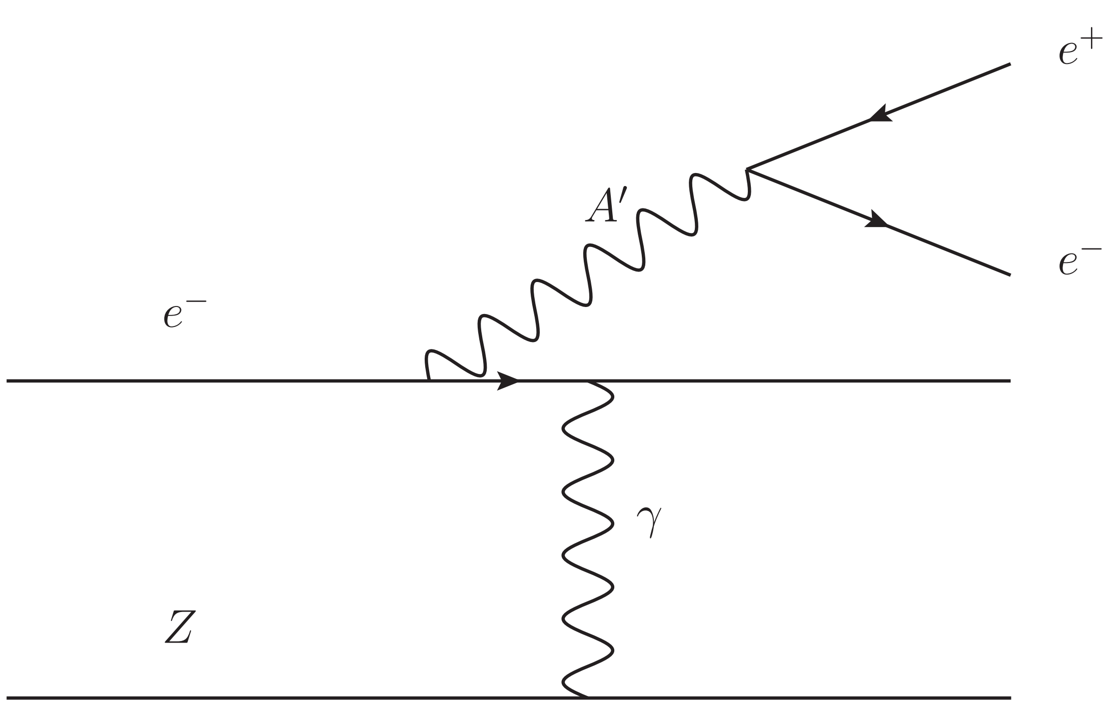
Bjorken, Essig, Schuster, Toro, Wojtsekhowski, et al. proposed a fixed target experiment to be conducted at Thomas Jefferson National Accelerator Facility, in Virginia; **test run for experiment in June/July 2010**

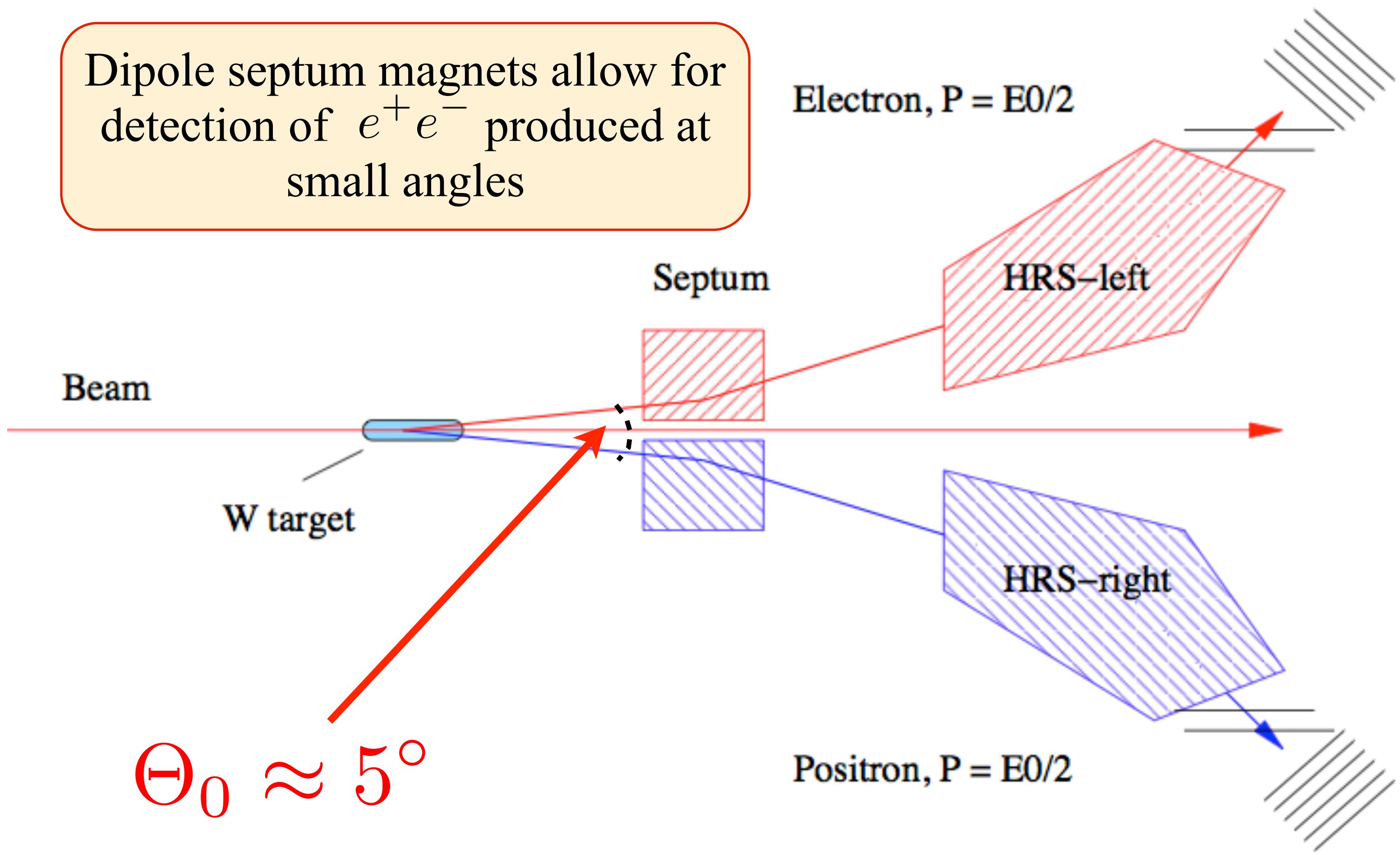
- Full run: $\alpha'/\alpha \gtrsim 10^{-7}$
  $m_{A'} = 65$ to 525 MeV
- Test run: $\alpha'/\alpha \gtrsim 10^{-6}$
  $m_{A'} = 178$ to 250 MeV

Experimental signature

Direct production at JLab

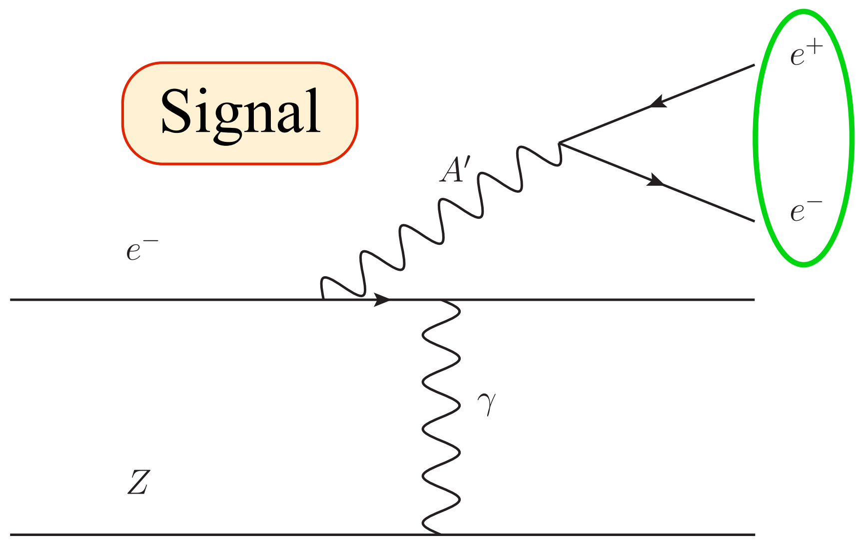
- Produce low mass hidden gauge bosons with weak coupling to SM via high energy electron beam incident on fixed high-Z (Ta) target
- A' decays to e^+e^- pair with opening angle $\sim m_{A'}/E_b$

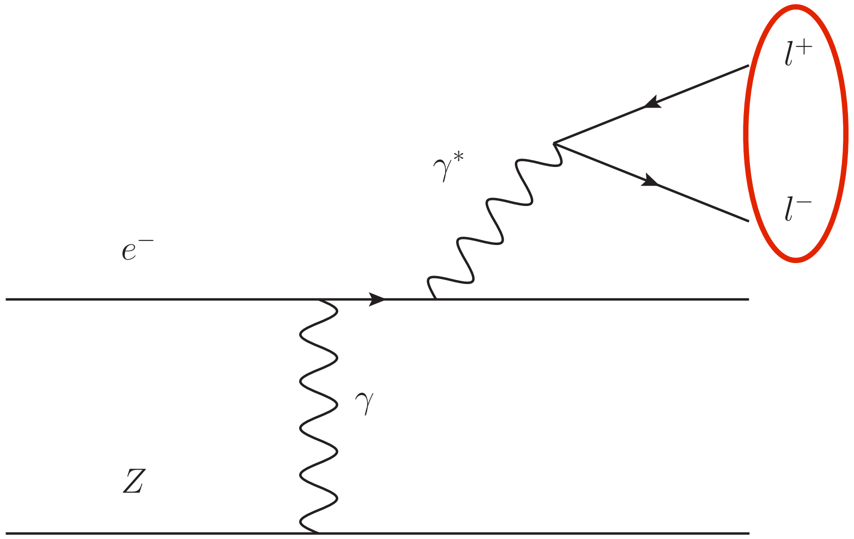




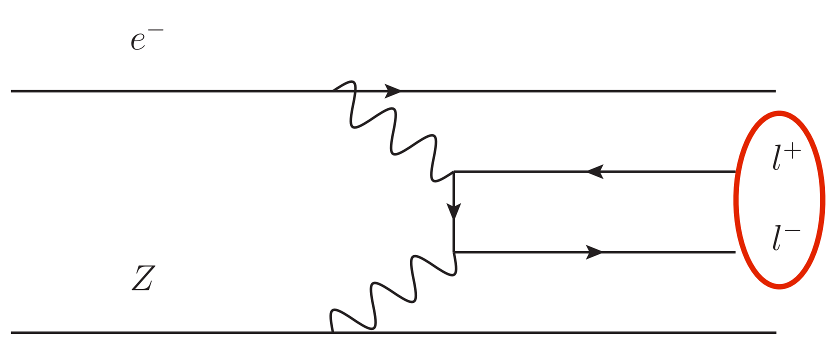
Experimental signature

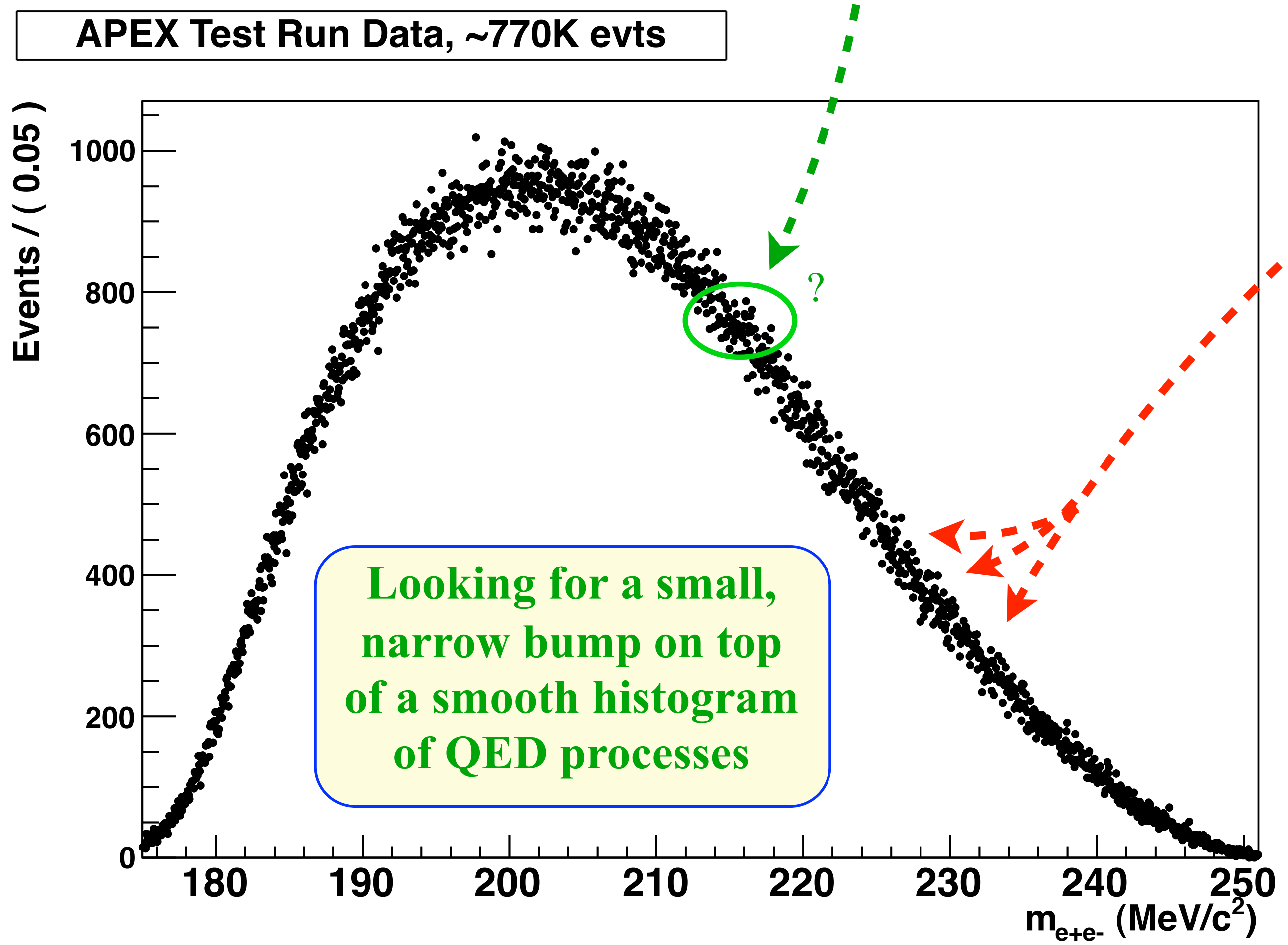
Signal





QED backgrounds





Looking for a small, narrow bump on top of a smooth histogram of QED processes

Excellent mass resolution required

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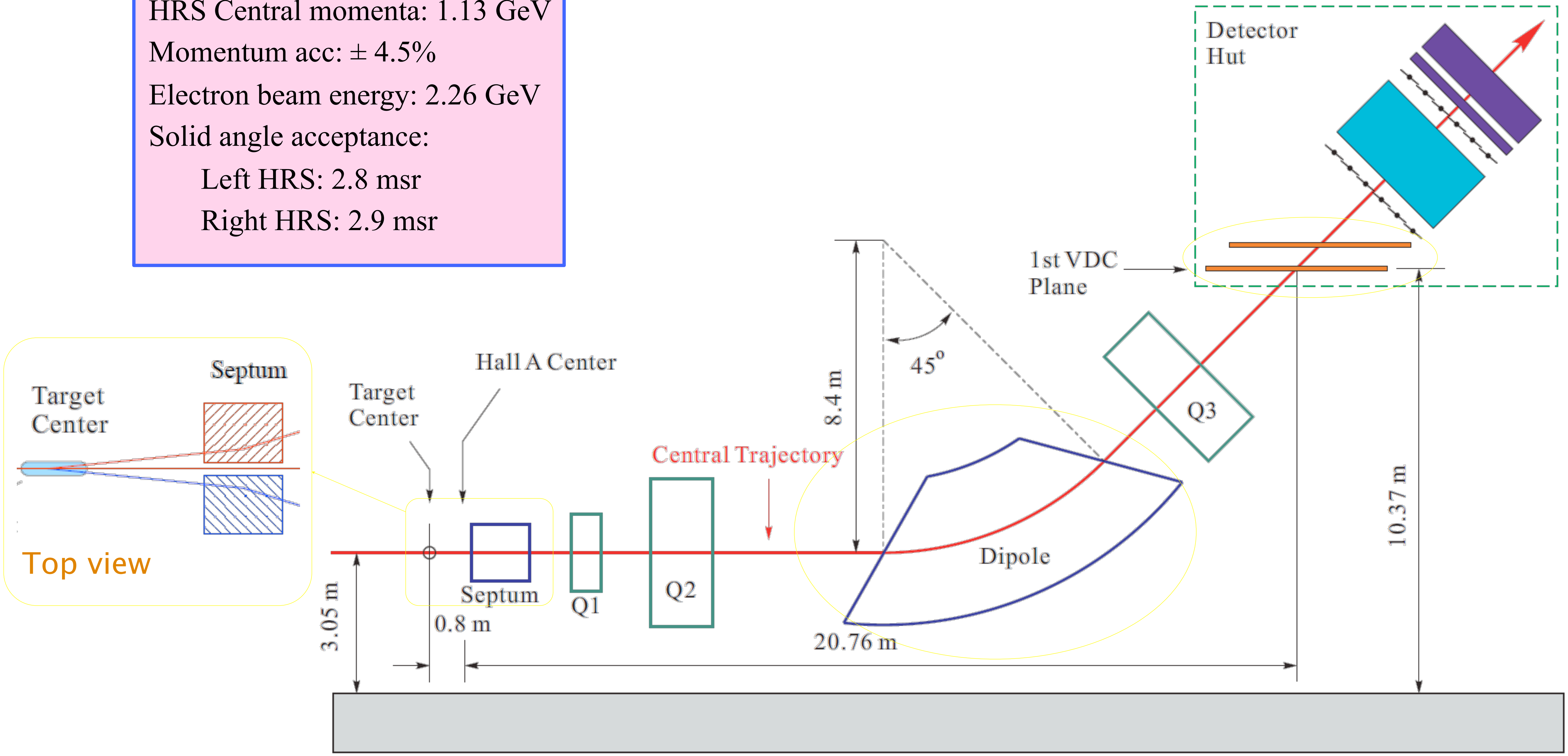
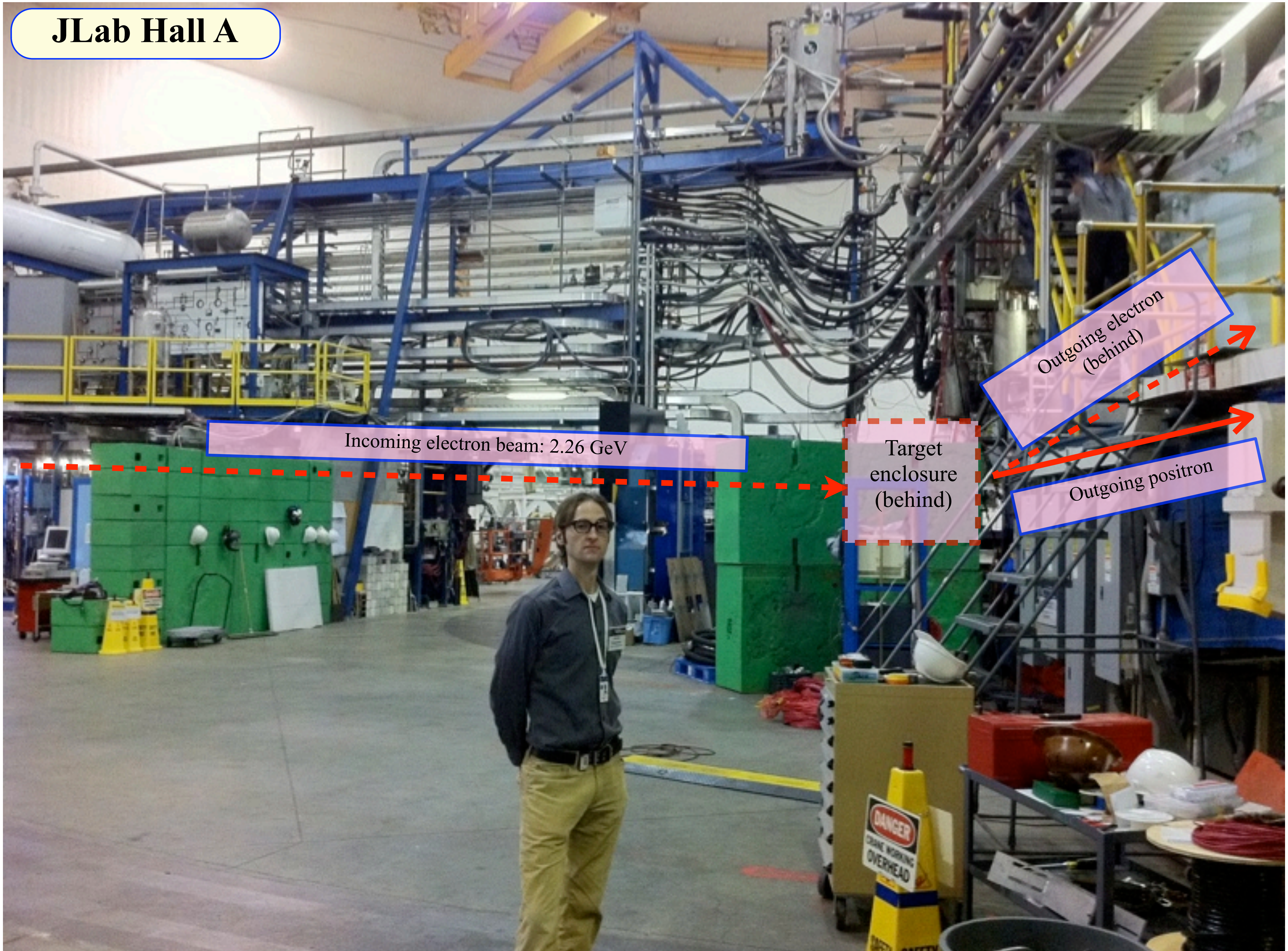
Jefferson Lab's Hall A experimental apparatus

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


JLab Hall A
Incoming electron beam: 2.26 GeV
Target enclosure (behind)
Outgoing electron (behind)
Outgoing positron

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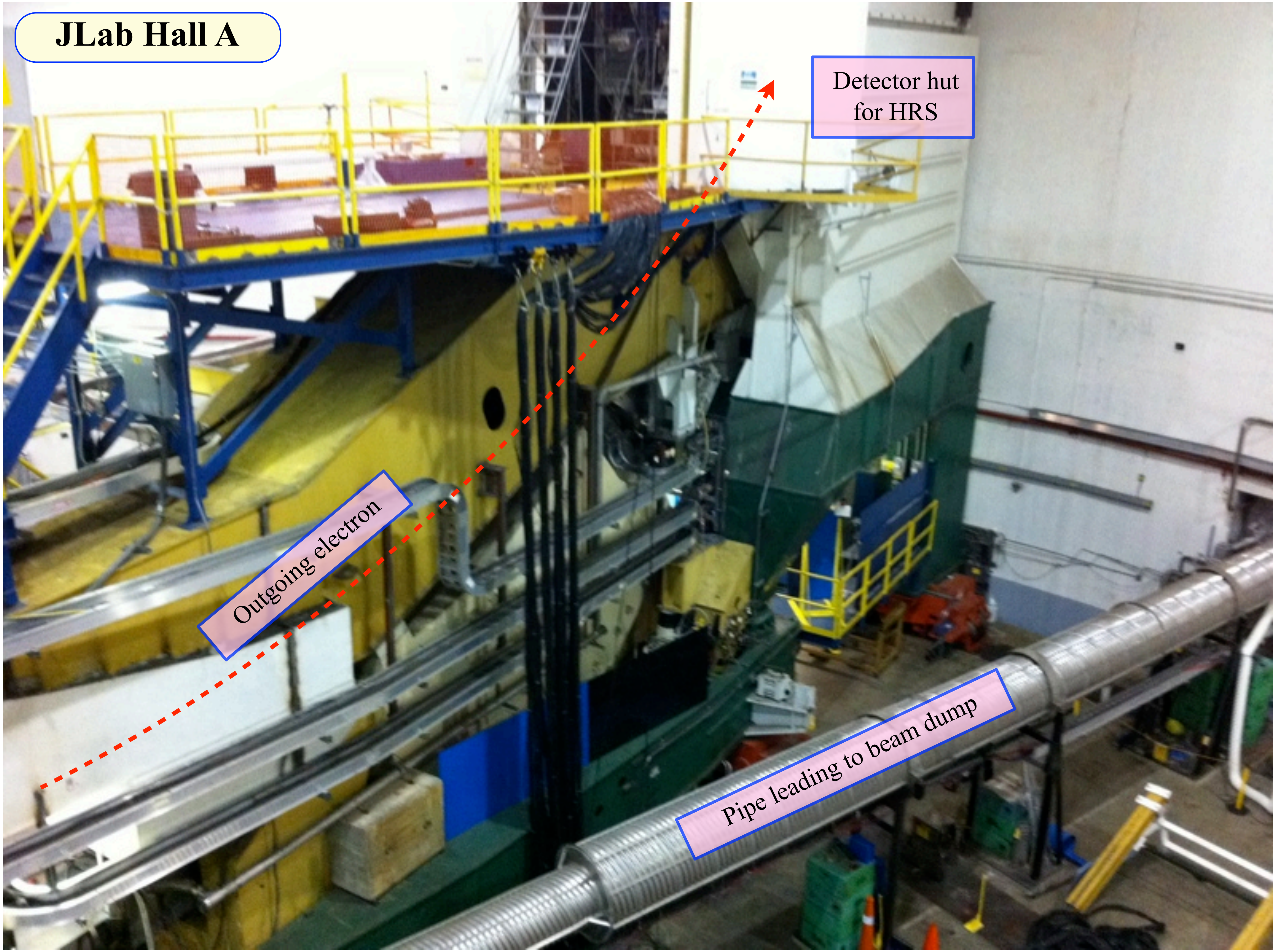
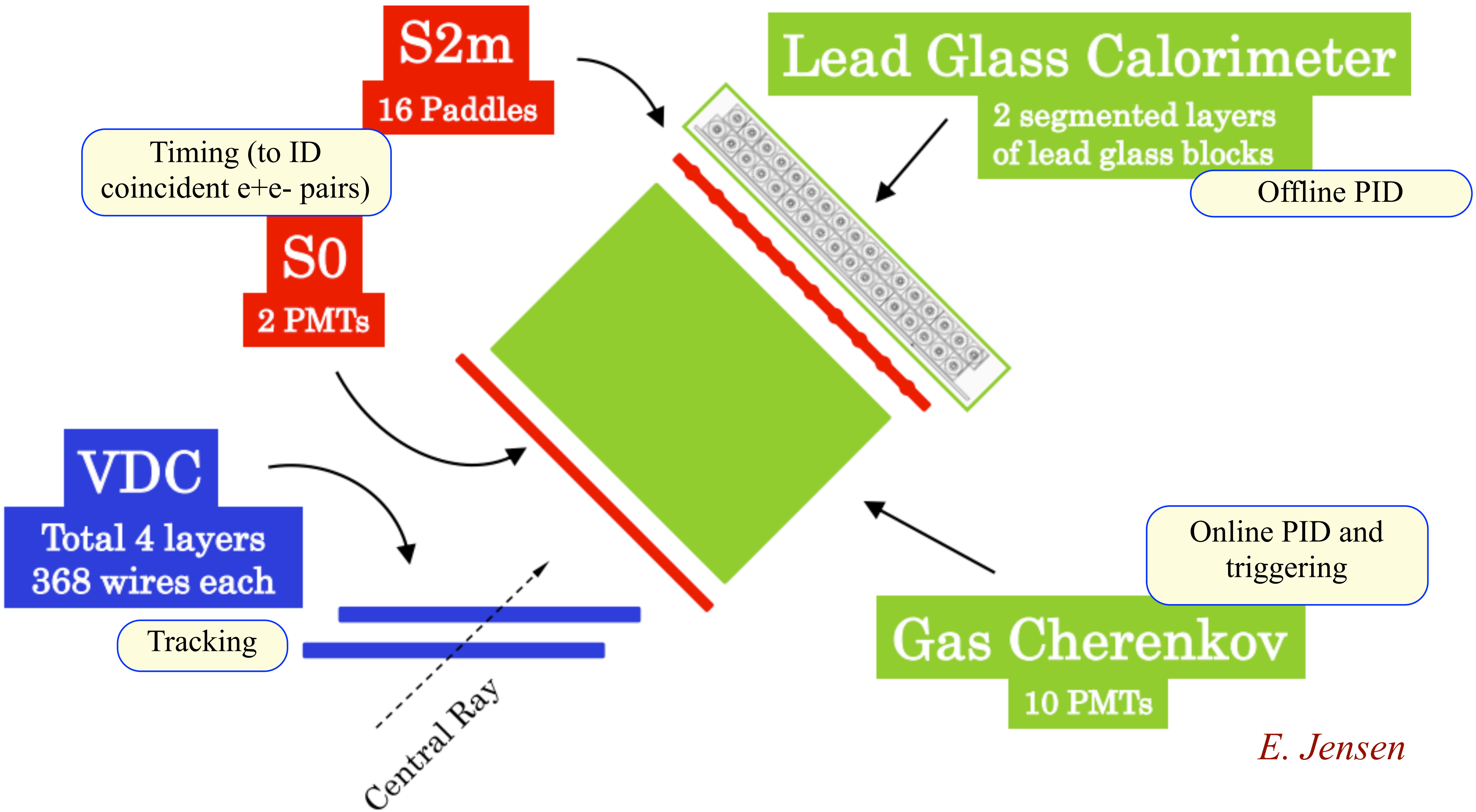
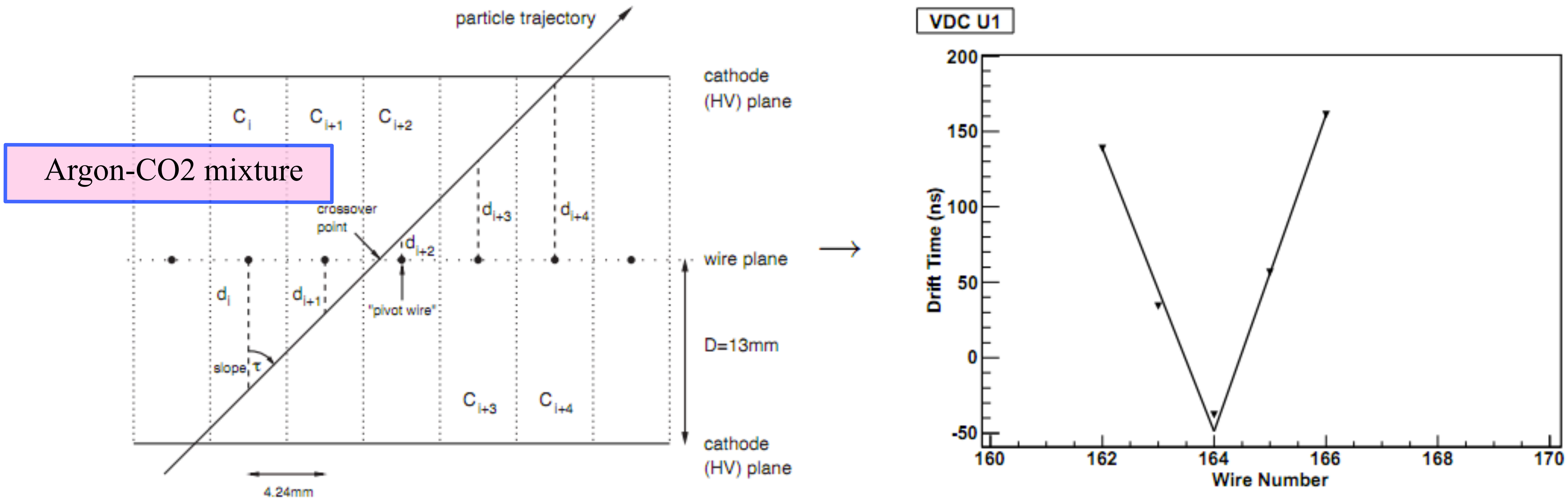


Hall A High Resolution Spectrometers (HRSs)



E. Jensen

Vertical Drift Chambers



S. Riordan

- Algorithm scans for 'V' shaped clusters in time

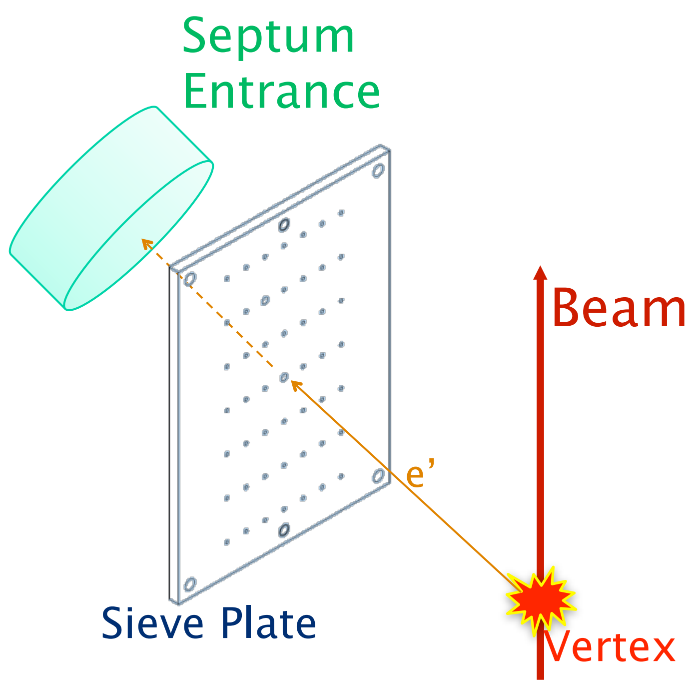
Two parallel VDCs provide accurate reconstruction of full 3D track of particle as it enters the HRS

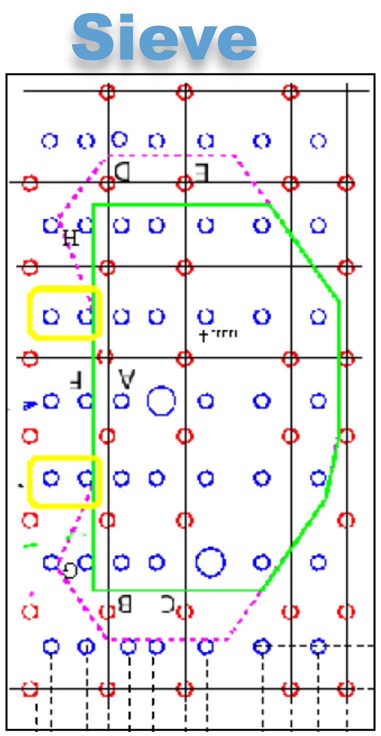
- APEX: Electron singles rate from 0.7 to 5.8 MHz
- Rates are higher than ever used in Hall A -- 5 MHz (75 kHz/wire, 368 wires)

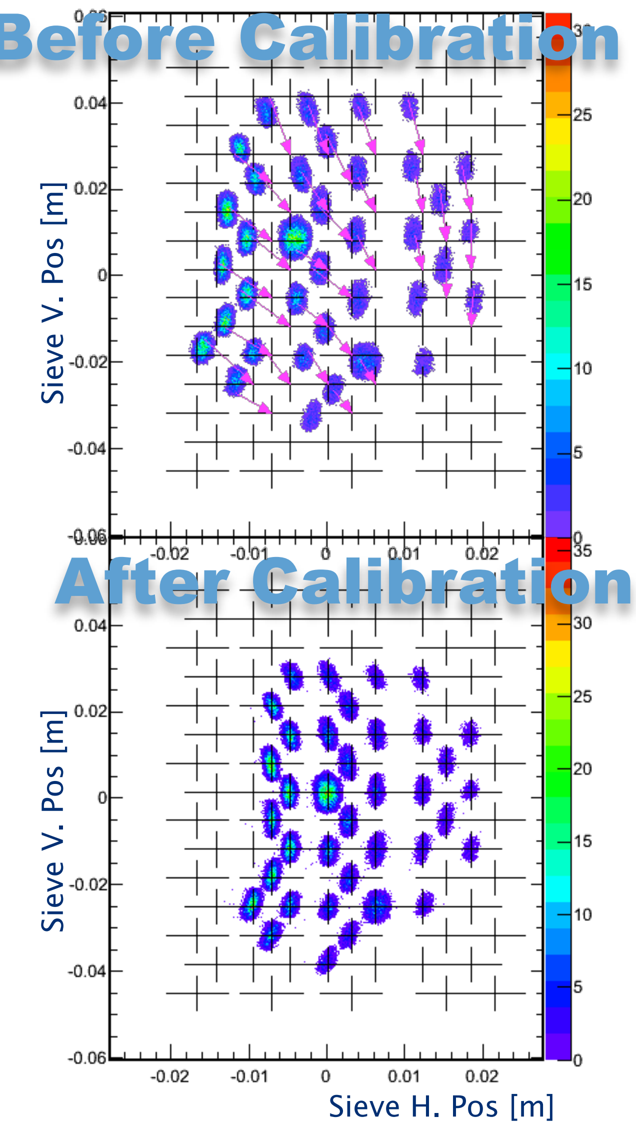
Optics calibration

Accurate determination of momentum requires knowledge of position at target in addition to position at HRS

- Sieve slit method







J. Huang

- Use elastic scattering events during calibration run; know position and angle at target very well ⟶ optics matrix
- Optics is a mapping from measured coord. at VDC to 3-momentum at target
- Optics data separately used to determine angular resolution

Mass resolution

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

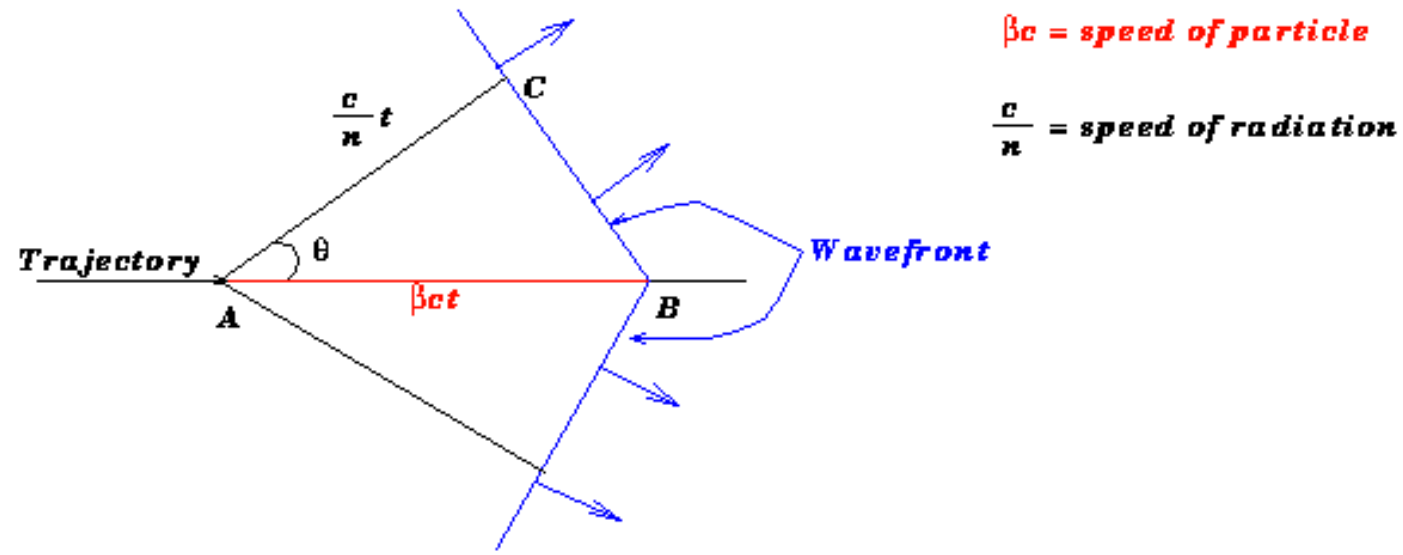
$\Rightarrow$ **Test run mass resolution: σ ~ 0.85 - 1.11 MeV**

(varies over mass range)

Background rejection and final data set

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



$$\cos\theta_c = \frac{c}{nv}$$ Measure p separately ==> $$m = \frac{p}{\gamma v}$$

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

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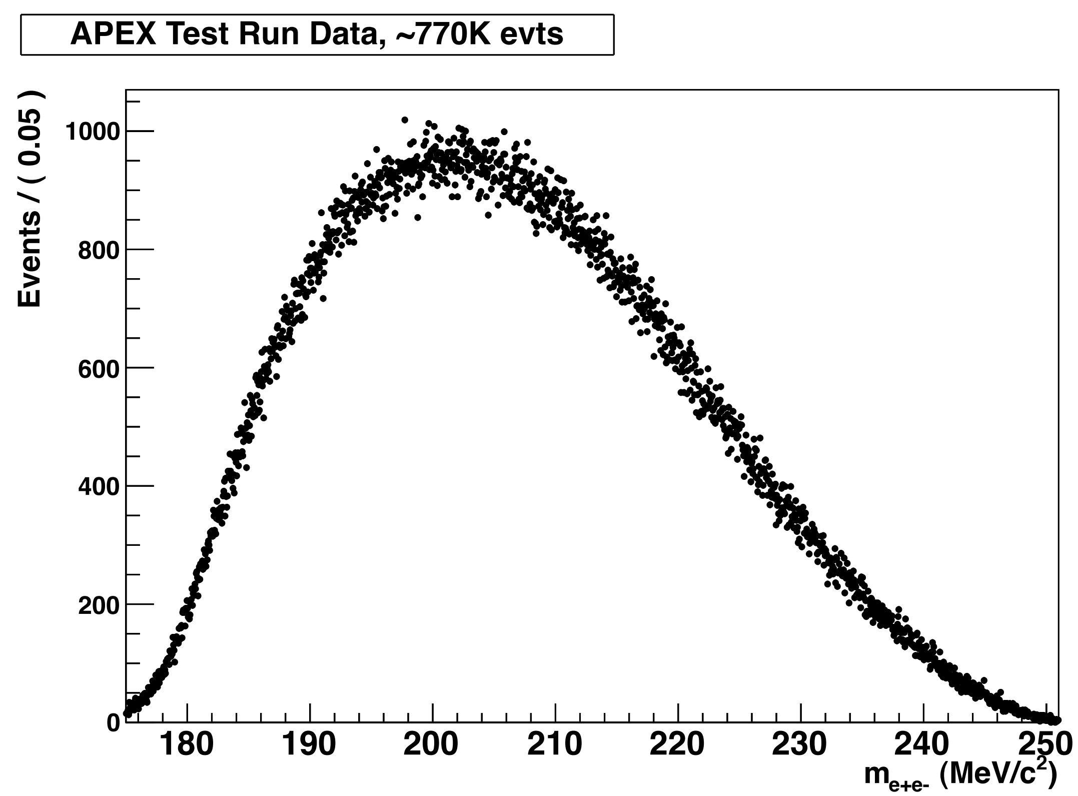
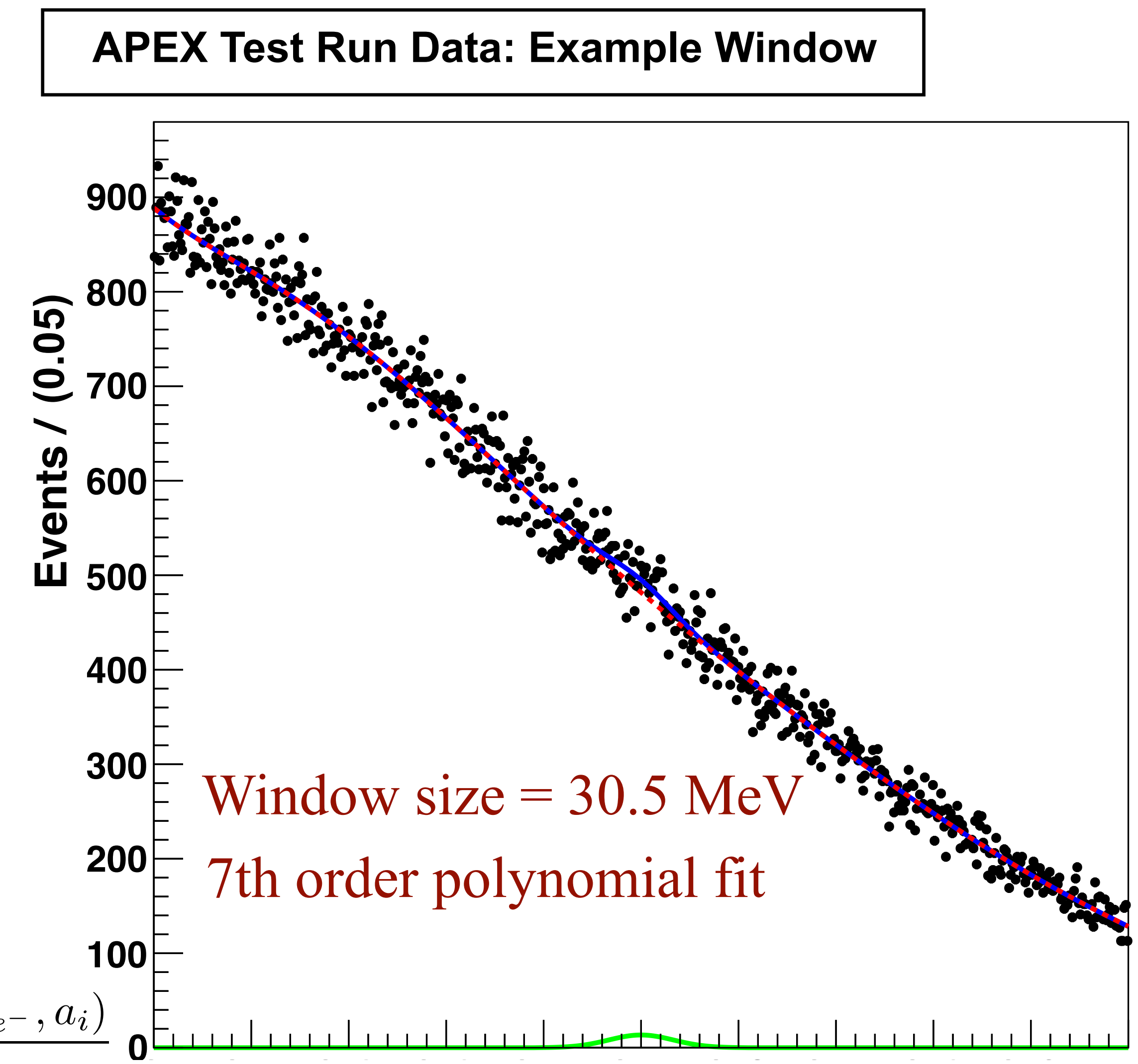
Bump hunt / resonance search

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



209.525 MeV

240.025 MeV

Test mass:

$m_{A'}$= 224.525 MeV

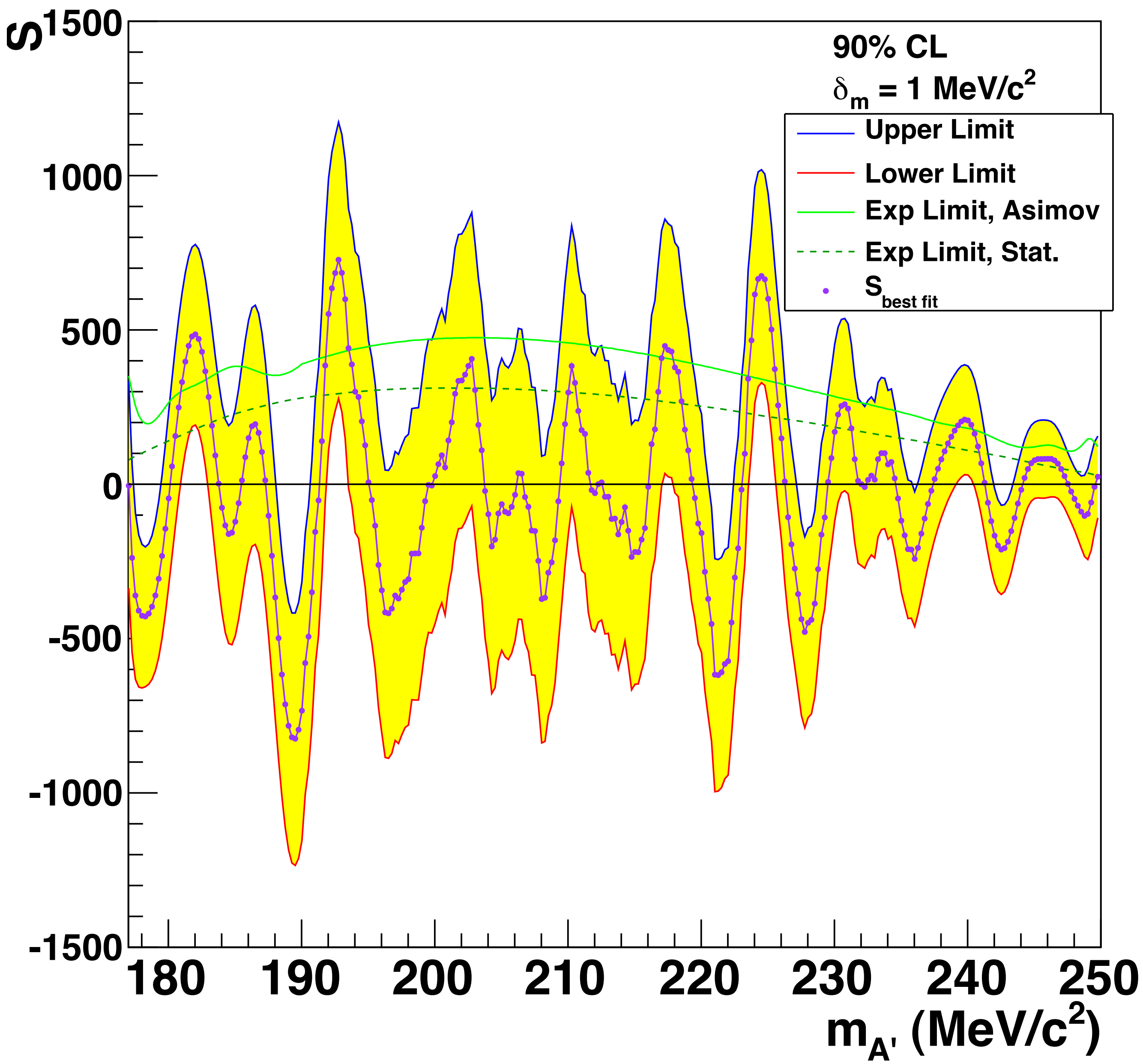
$$P(m_{e^+e^-} \mid m_{A'}, \sigma, S, B, a_i) = \frac{S \cdot \mathrm{N}(m_{e^+e^-} \mid m_{A'}, \sigma) \; + \; B \cdot \mathrm{Polynomial}(m_{e^+e^-}, a_i)}{S + B}$$

Probability model and profile likelihood ratio

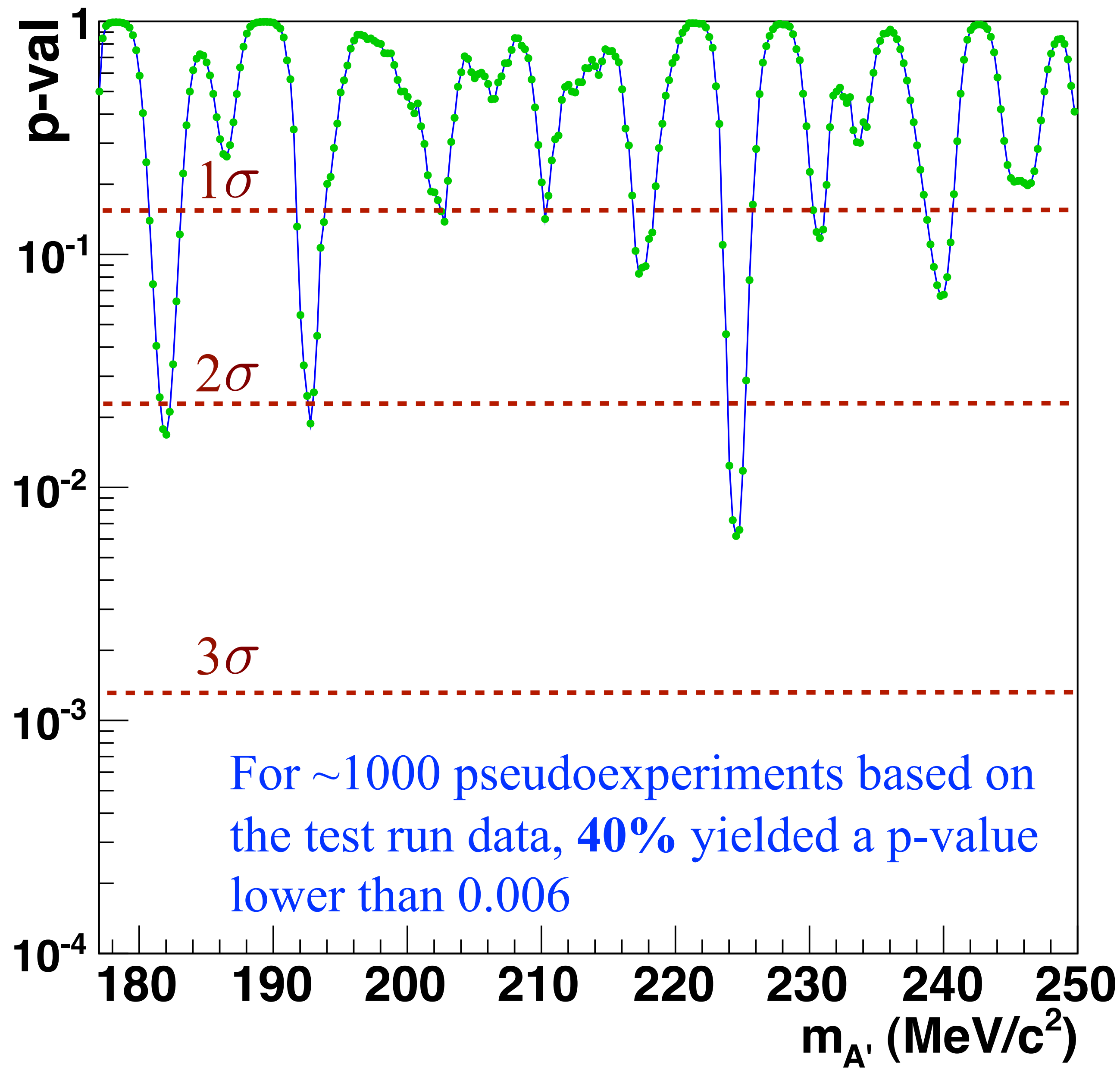
$$\lambda(S) = \frac{L(S, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{S}, \hat{B}, \hat{a}_i)}$$

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

APEX Test Run Data, Two-Sided Central Limit



APEX Test Run Data, Raw Null P-values



Upper limit on S ⟶ upper limit on coupling

The A' cross section is related to the radiative trident cross section by

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

(See APEX proposal)

within a mass window of width δm

$\Rightarrow$ **S/B independent of detector acceptance within 1 MeV window around A' mass**

- Exploit the kinematic similarities between A' and γ^* production
- 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

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

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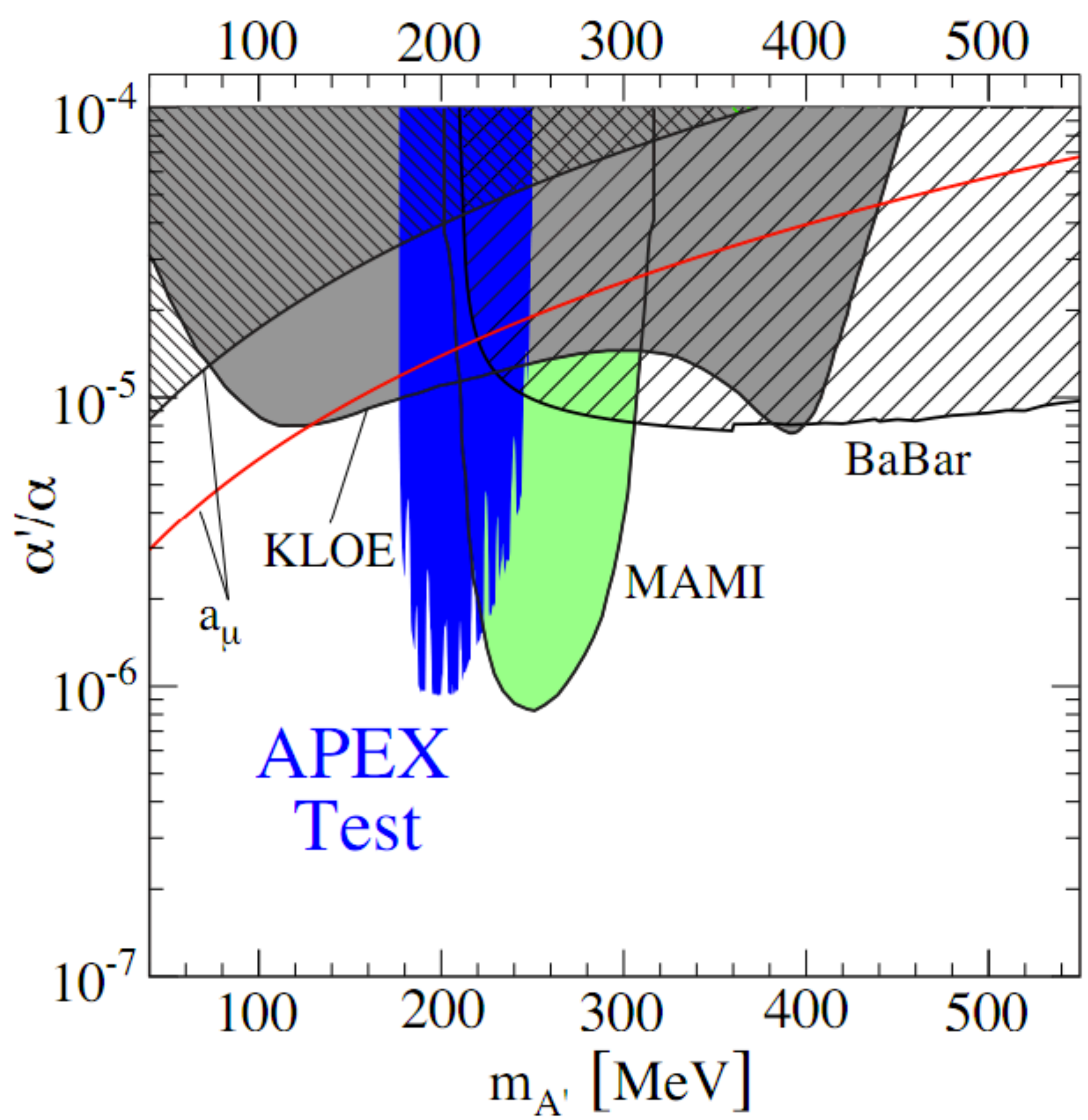
Upper limit on S ⟶ upper limit on coupling

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

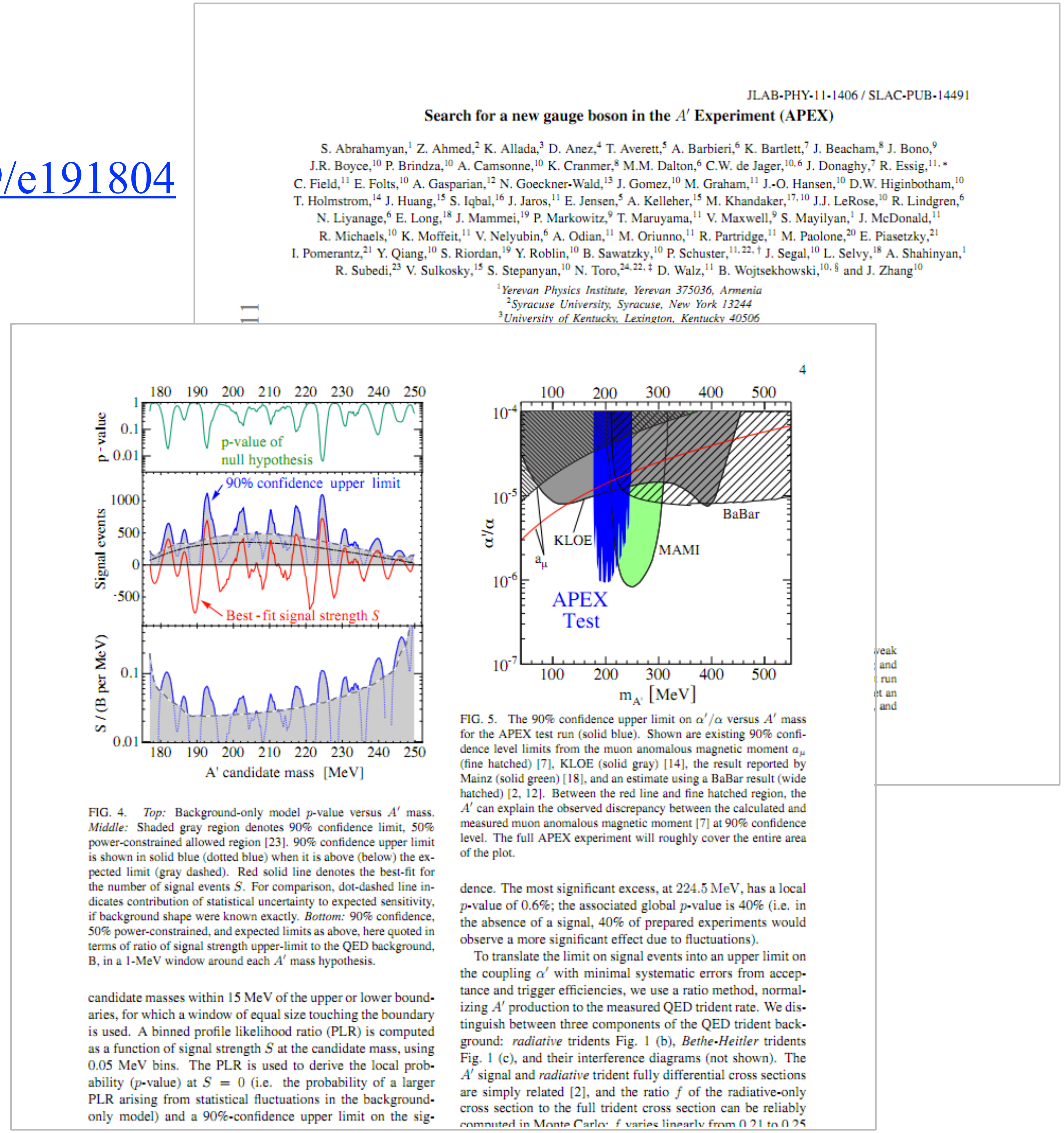


Test run results and full run status

Test run results in PRL

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

Experiment is approved; JLab currently shut down for upgrade of beam to 12 GeV



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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[2]Syracuse University, Syracuse, New York 13244
[3]University of Kentucky, Lexington, Kentucky 40506

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.

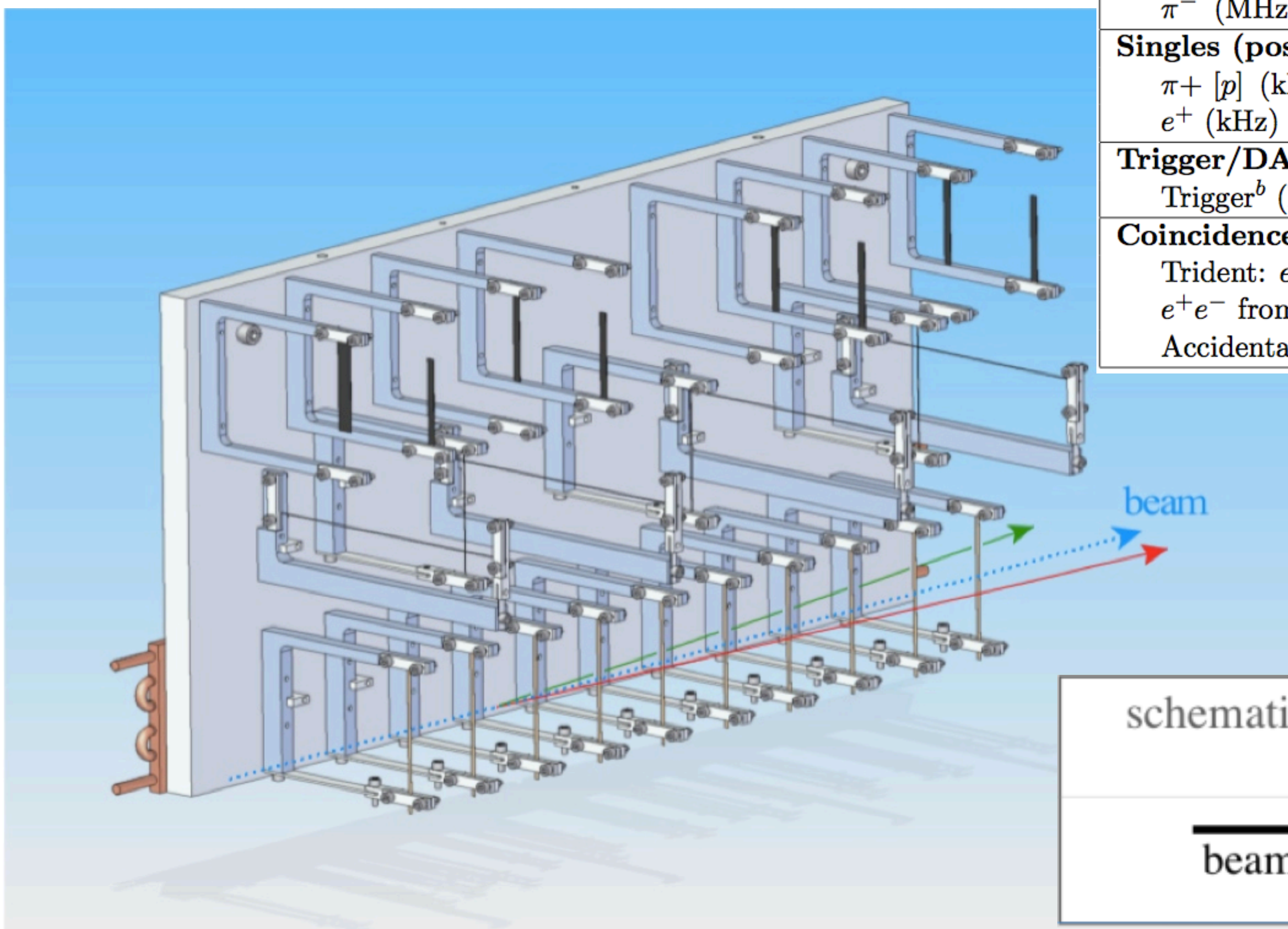
dence. The most significant excess, at 224.5 MeV, has a local p-value of 0.6%; the associated global p-value is 40% (i.e. in the absence of a signal, 40% of prepared experiments would observe a more significant effect due to fluctuations).

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

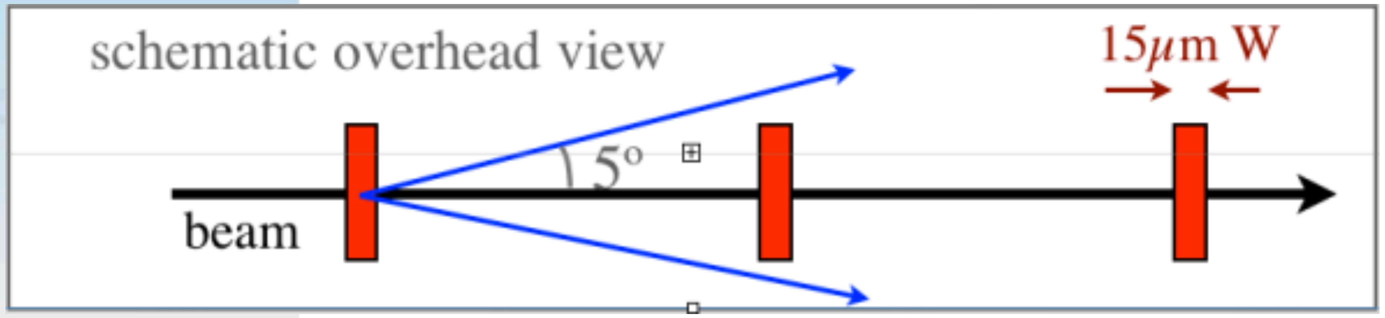
Plan for Full Run

Full run at JLab will take data for ~34 days at 4 different energy and spectrometer settings

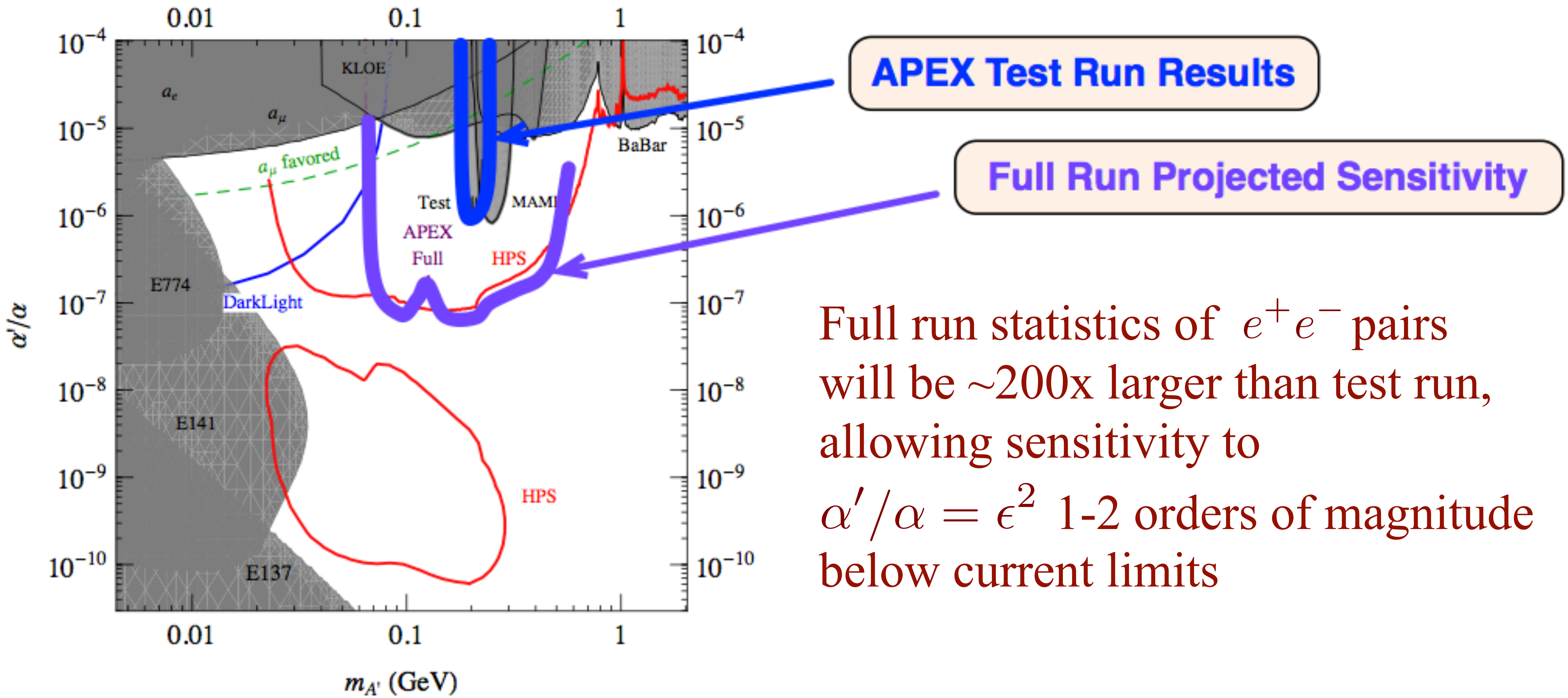
Settings	A	B	C	D
Beam energy (GeV)	2.2	4.4	1.1	3.3
Central angle	5.0°	5.0°	5.0°	5.0°
Effective angles	4.5–5.5	4.5–5.5	4.5–5.5	4.5–5.5
Target T/X_0 (ratio^a)	4%	8%	0.69% (1:3)	8%
Beam current (μA)	70	60	65	80
Central momentum (GeV)	1.095	2.189	0.545	1.634
Singles (negative polarity)				
e^- (MHz)	4.1	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: $e^-Z \to e^-e^+e^-Z$ (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



Plan for Full Run



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 first beam after shutdown for 12 GeV upgrade projected for February 2014

- APEX ready for first beam in Hall A
- Currently testing new optics calibration method
- Data acquisition rate improvements (up to 5 kHz)

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)

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 $\delta p/p = 0$, $y_0 = 0$	6 msr
Transverse length acceptance	±5 cm
Transverse position resolution	1 mm