An Update on the A′ Experiment (APEX) and Searches for New Vector Bosons

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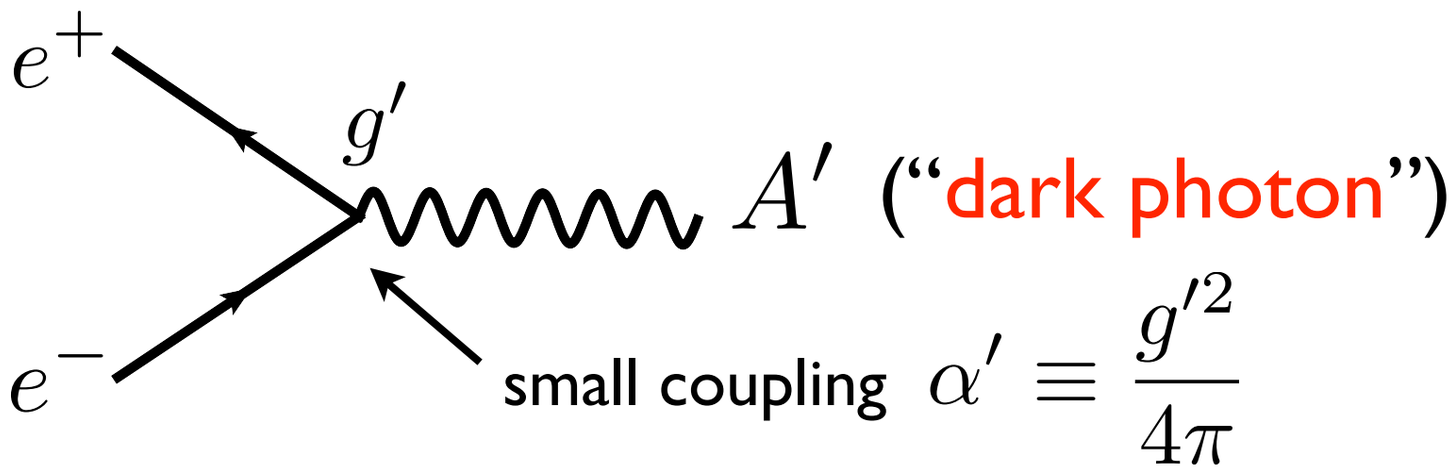
Hall A Collaboration Meeting
June 10, 2011

Outline

- An Update on Searches for (Dark Forces) GeV-Scale New Vector Bosons
  - e^+e^- colliders and e^- fixed-target
- Fixed-target Kinematics and Strategies
  - APEX, DarkLight, and HPS at JLab
- APEX Update
  - Proposed strategy for full experiment
  - Test-run update

Goal:

Search for new forces mediated by ~100 MeV vector boson A′ with weak coupling to electrons



Significant new reach in α' (~2-3 orders of magnitude)
Broad interest in particle physics community

- new gauge force
- dark matter interactions?
- $(g-2)_\mu$ anomaly

Physics motivation

Standard Model

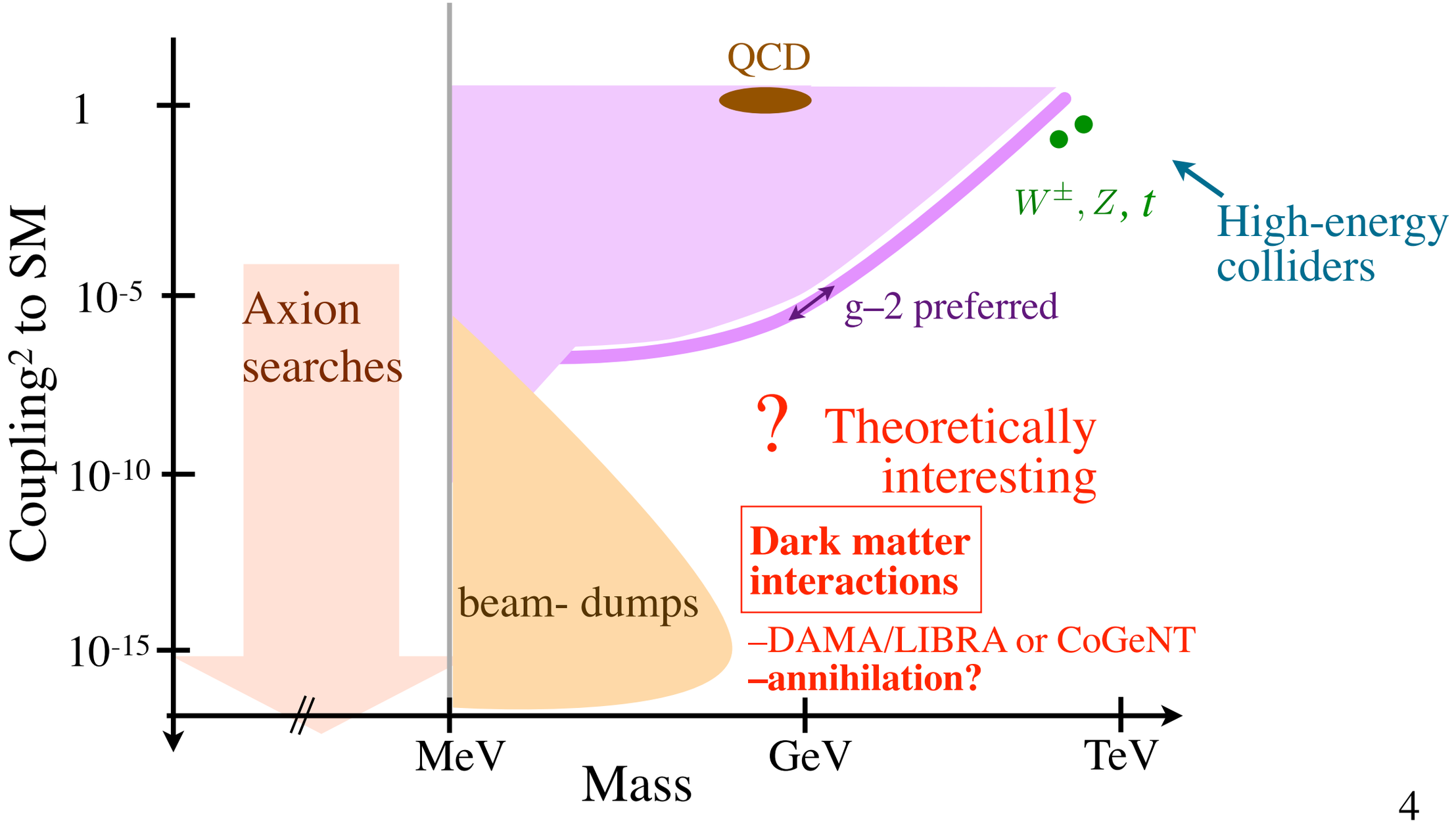
strong g

weak $W^{\pm}, Z$

electromagnetic γ

New Forces?

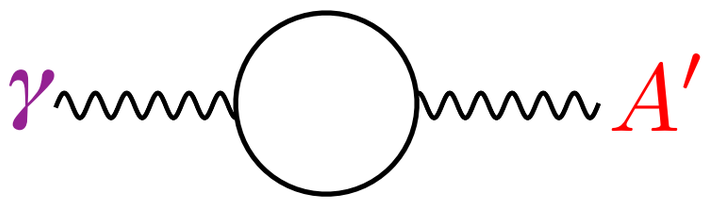
??? A'



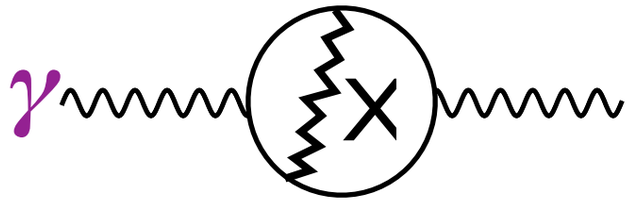
Physics motivation

Weak A' couplings are generic (generated as quantum corrections if **any** heavy particle interacts with γ and A')

[Holdom]



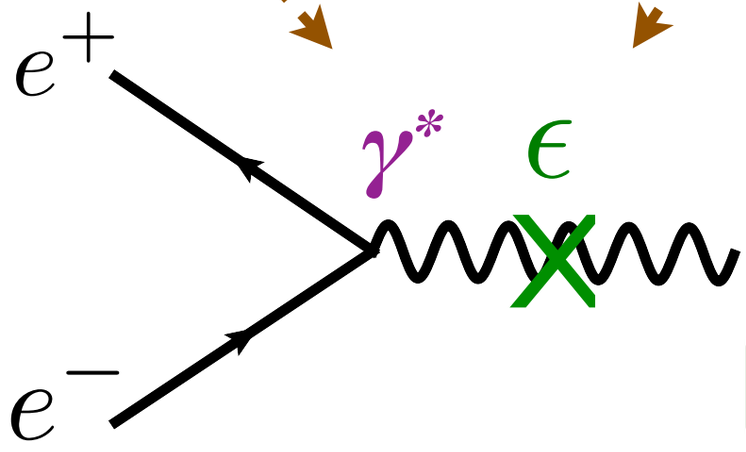
$\epsilon \sim 10^{-4} - 10^{-2}$



$\epsilon \sim 10^{-5} - 10^{-3}$
(if SM unifies in a GUT)

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

effective coupling:



$$\alpha'/\alpha = \epsilon^2 \sim 10^{-4} - 10^{-10}$$

In simple models:
[e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

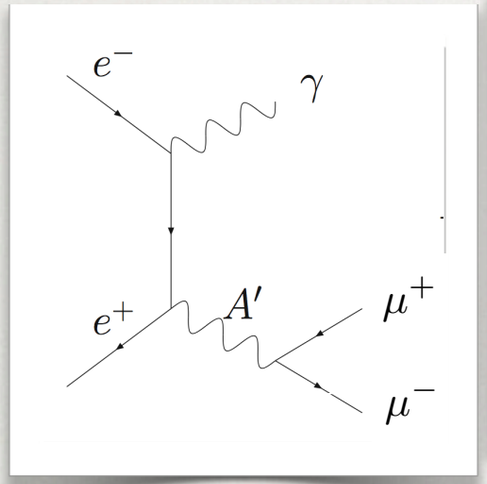
$$m^2_{A'} \sim \epsilon M^2_W \sim \mathrm{MeV}^2 - \mathrm{GeV}^2$$

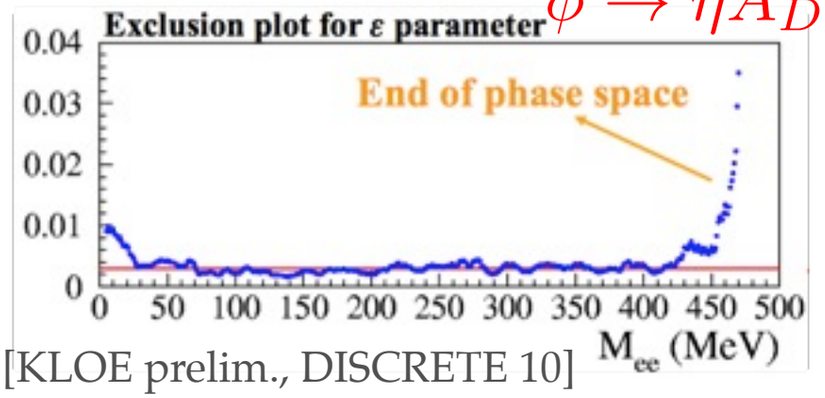
e^+e^- Collider Production and Searches

Minimal:

Reach:

$\epsilon \sim 3 \cdot 10^{-3}$





$\phi \to \eta A_D$

[KLOE prelim., DISCRETE 10]

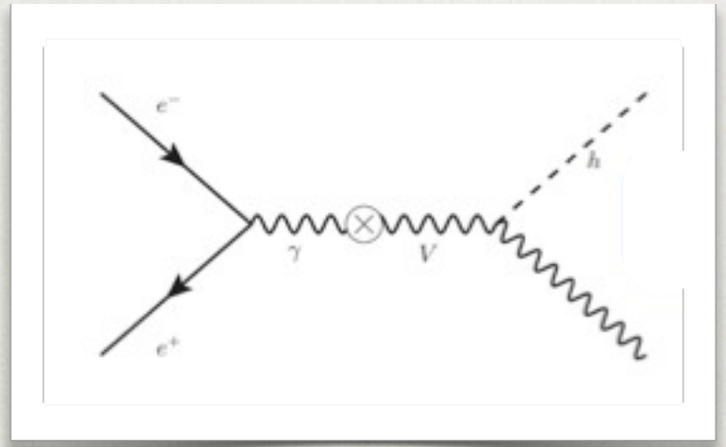
Limit extracted from BaBar 0902.2176; dedicated studies ongoing/planned at BES3, Belle

SuperB studies: 1103.0799

Vector + Higgs:

Reach: $\epsilon \sim 10^{-4}$

Batell, Pospelov, Ritz [0903.0363, PRD]



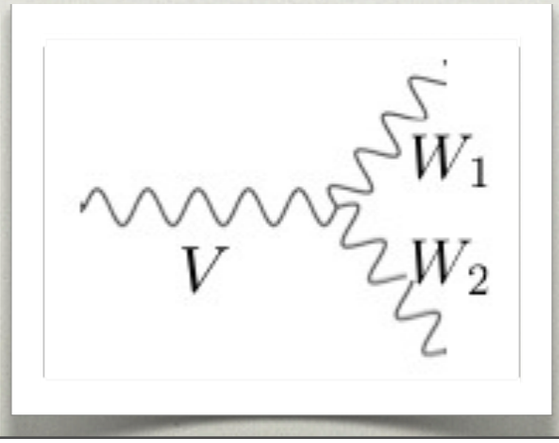
Ongoing studies in KLOE, BaBar, Belle

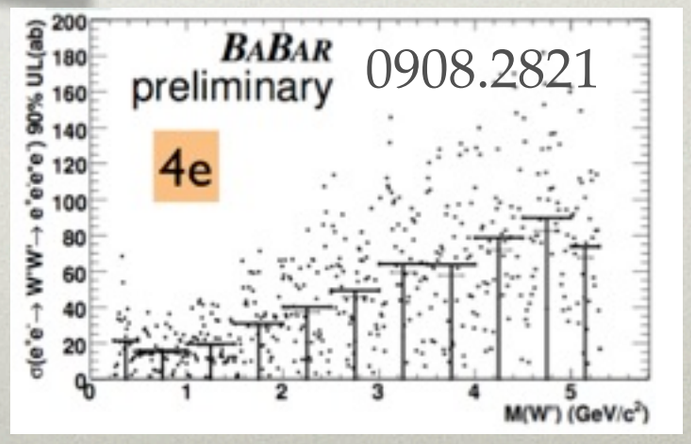
Non-minimal:

(e.g. non-Abelian)

[Essig, Schuster, NT]

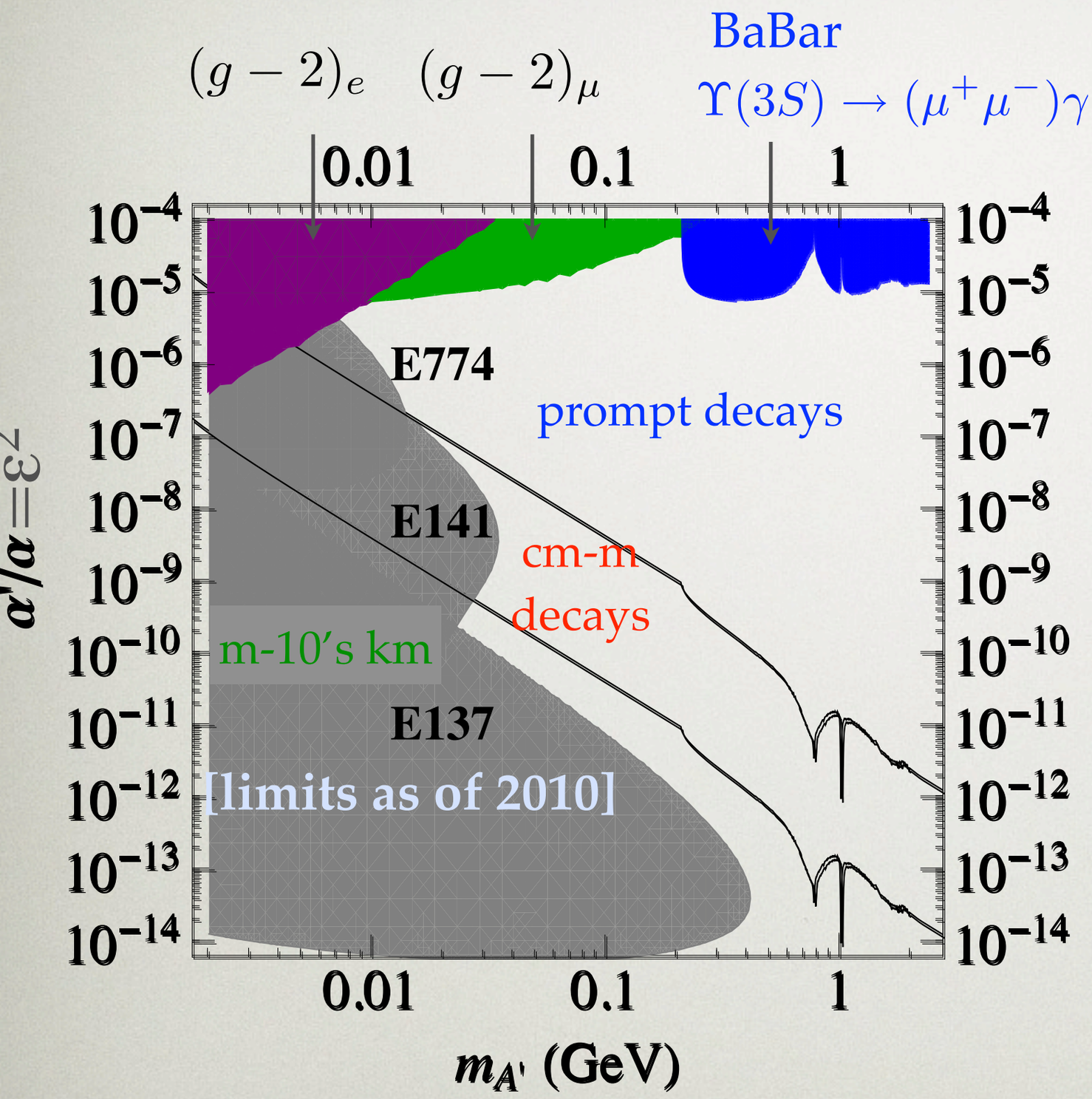
Reach: $\epsilon \sim 10^{-4}$





BaBar studying additional modes

Fixed-Target Territory

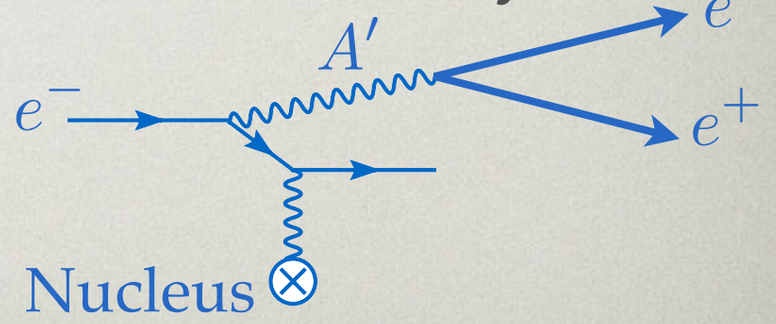


- Lifetime

$$\gamma c\tau \approx 1 \text{ mm}\,(\gamma/10)\,(10^{-8}\alpha/\alpha')\times(100 \text{ MeV}/m_{A'})$$

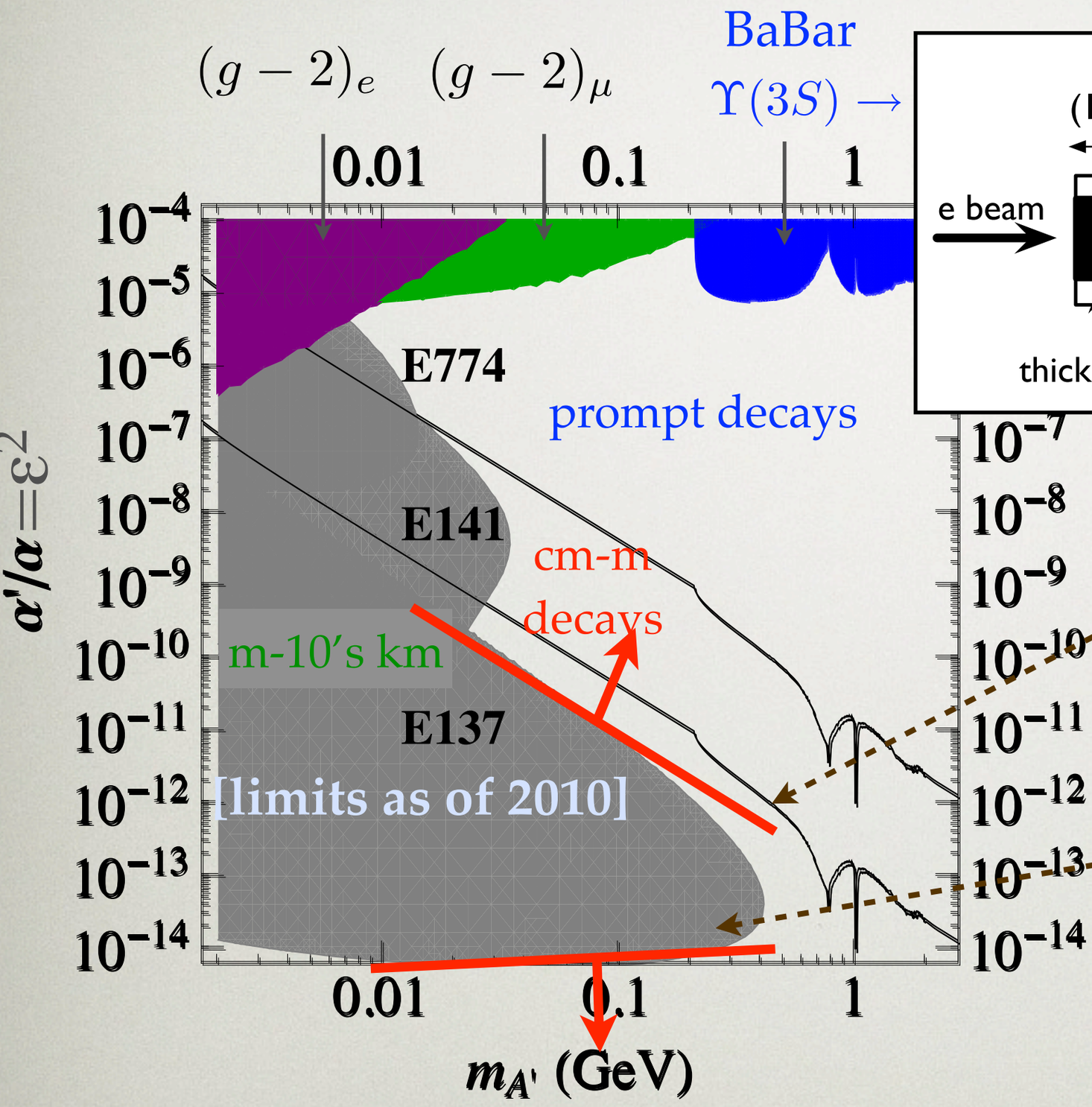
  varies over 15 decades

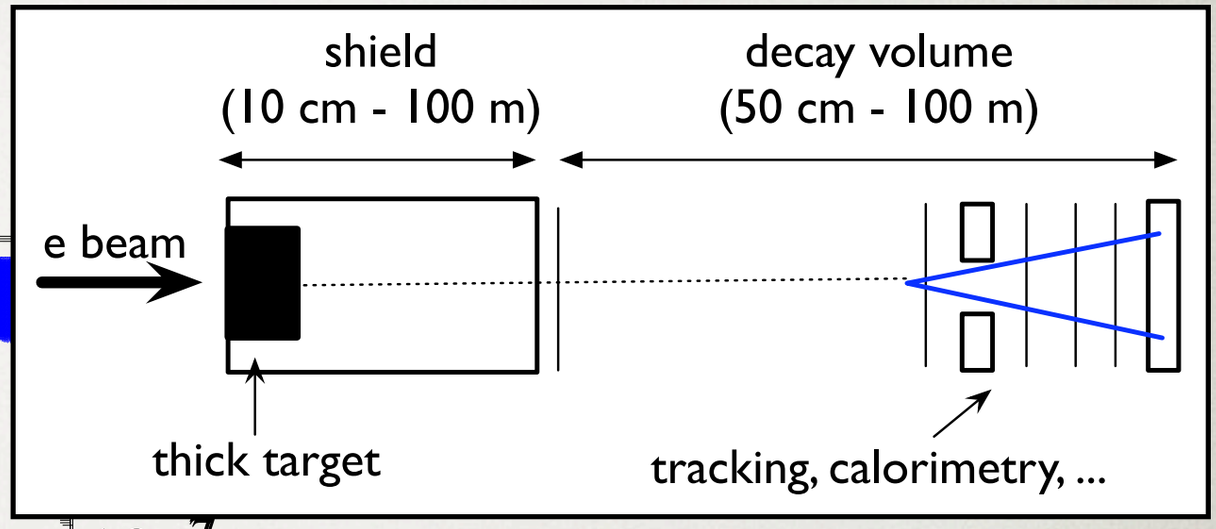
- Multiple detection strategies needed
  - mass-dependent kinematics
  - prompt, displaced, and far decays



[Bjorken, Essig, PS, Toro; see also: Reece and Wang; Batell, Pospelov, Ritz]

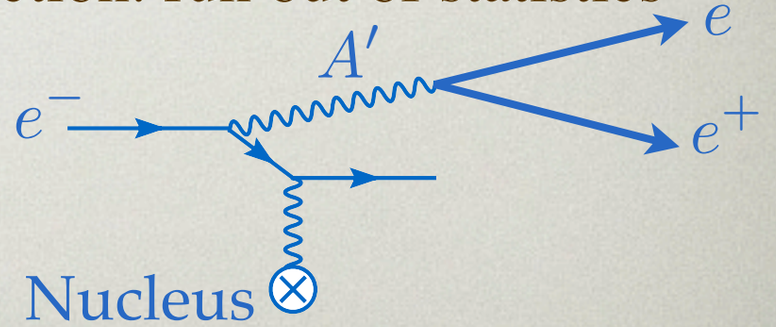
Fixed-Target Territory





Lifetime small compared to shield length: decay products stop

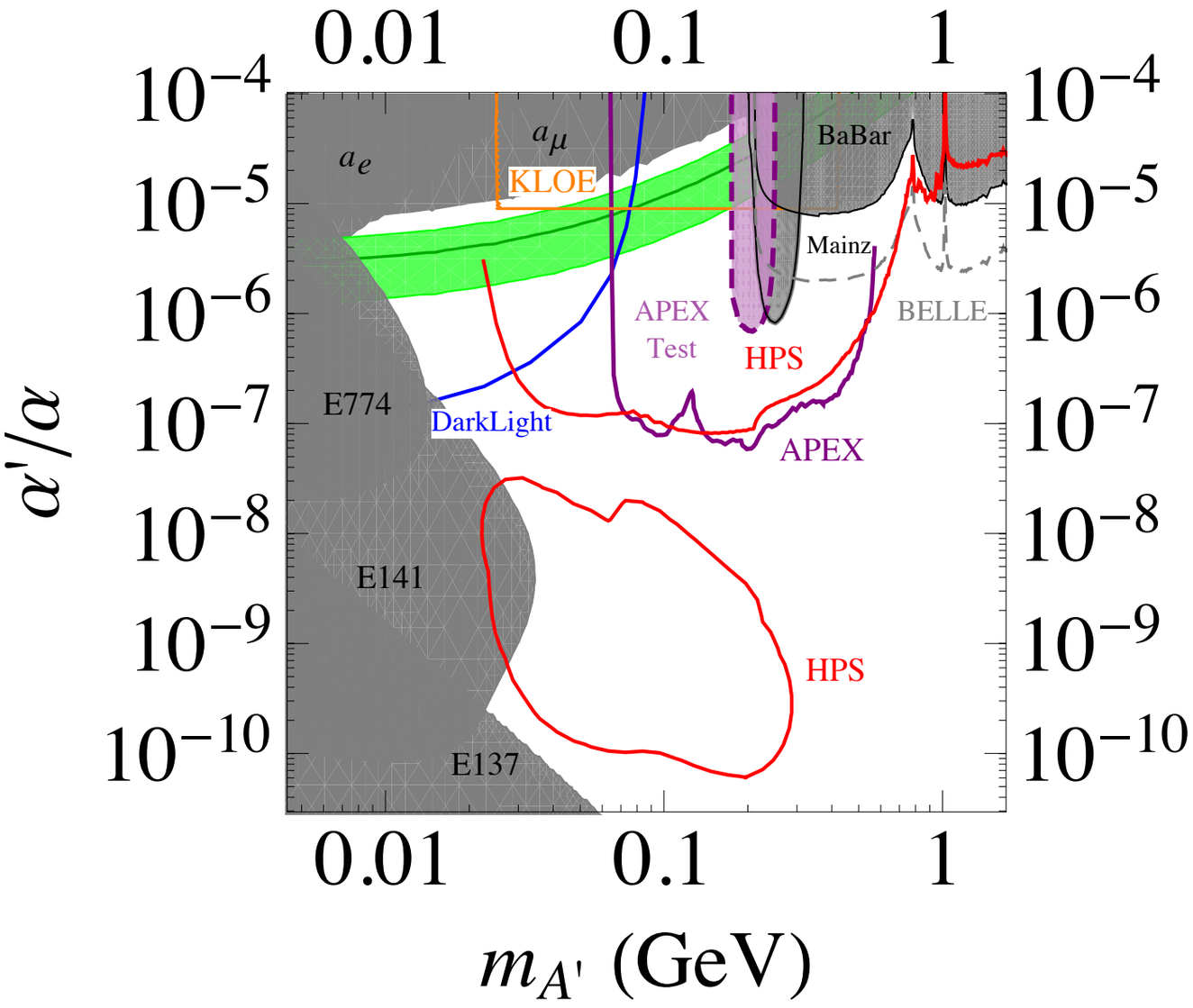
Lifetime large compared to shield length, and lower cross-section: run out of statistics



[Bjorken, Essig, PS, Toro; see also: Reece and Wang; Batell, Pospelov, Ritz]

Enormous potential for new sensitivity!

Experiments under development for next few years:



Significant new reach possible through search for small, narrow mass peaks (APEX, MAMI, DarkLight) and vertexing (HPS).

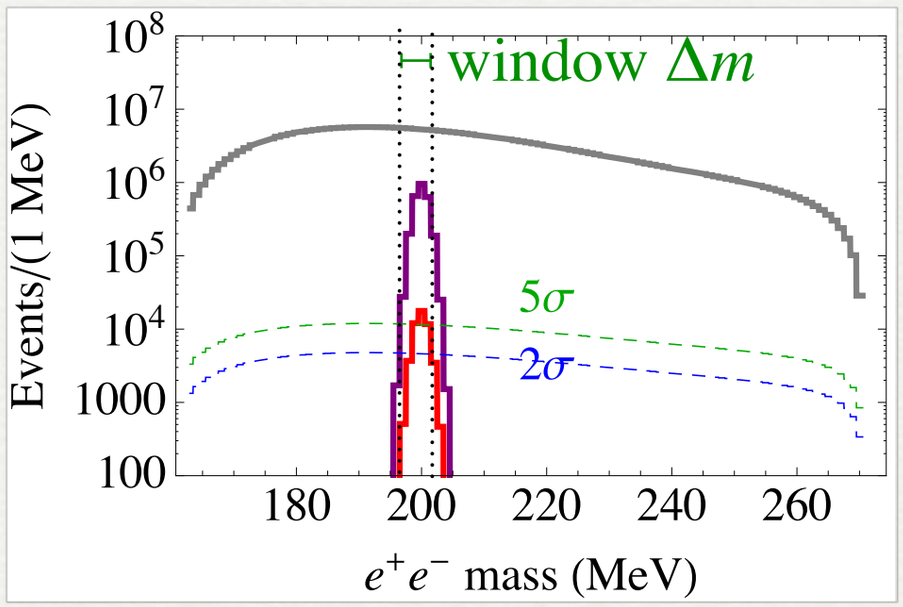
- explore most parameter space below 300 MeV, significant reach to 500 MeV
- beam-dump exploration @ DESY

Fixed-target experiments at JLab and Mainz ideally suited to look for new forces beyond the Standard Model!

Two Search Strategies

High-Statistics Resonance Search

(APEX, HPS, DarkLight)

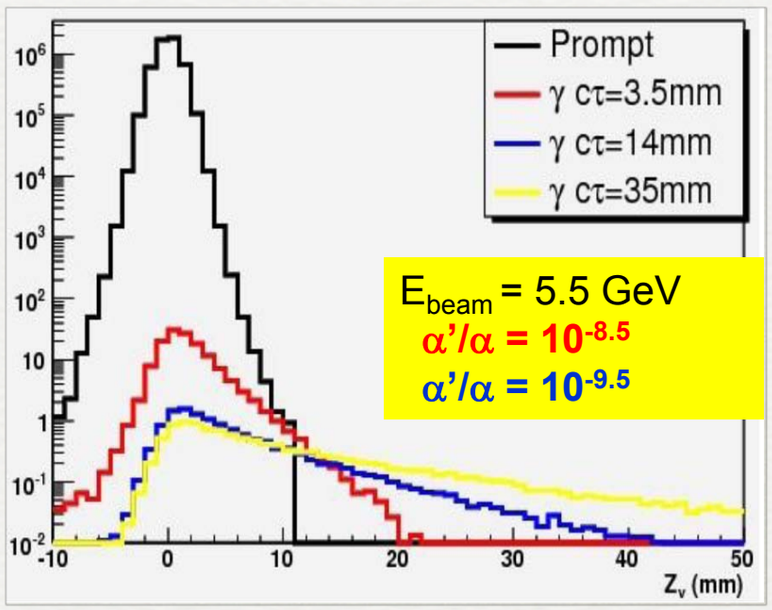


Demands high data-taking rate, background suppression and excellent mass resolution

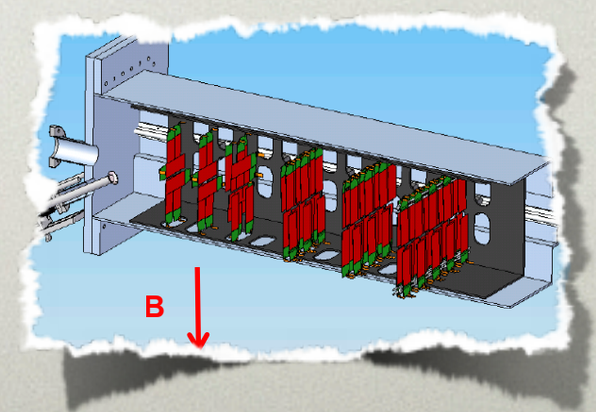
Demonstrated in test runs: Mainz (1101.4091) and APEX (analysis nearly complete)

Displaced Resonance search

(HPS)

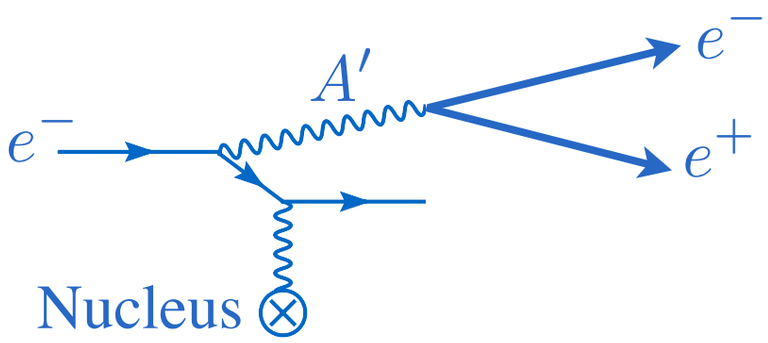


...and forward vertex resolution (well-controlled tails)



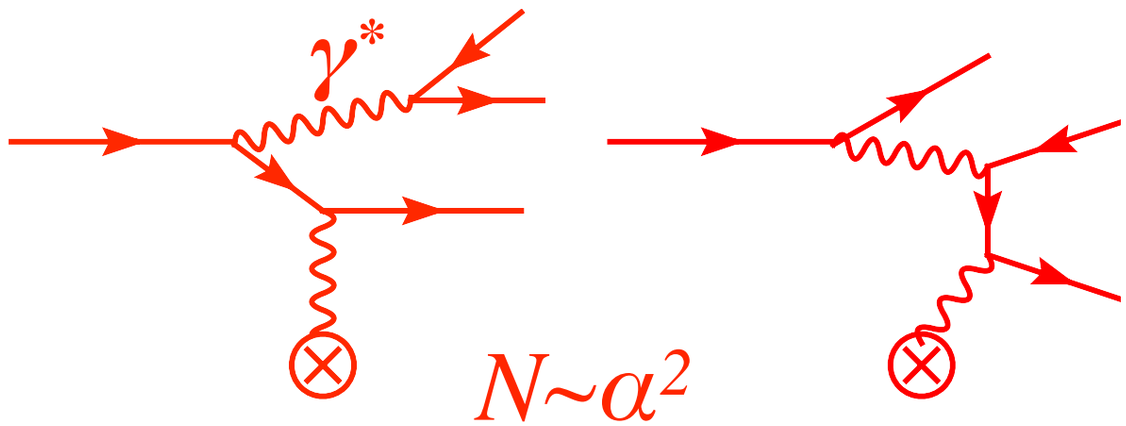
A′ Production and Background Kinematics ($m_{A'} \ll E_{beam}$)

Production diagrams analogous to photon bremsstrahlung



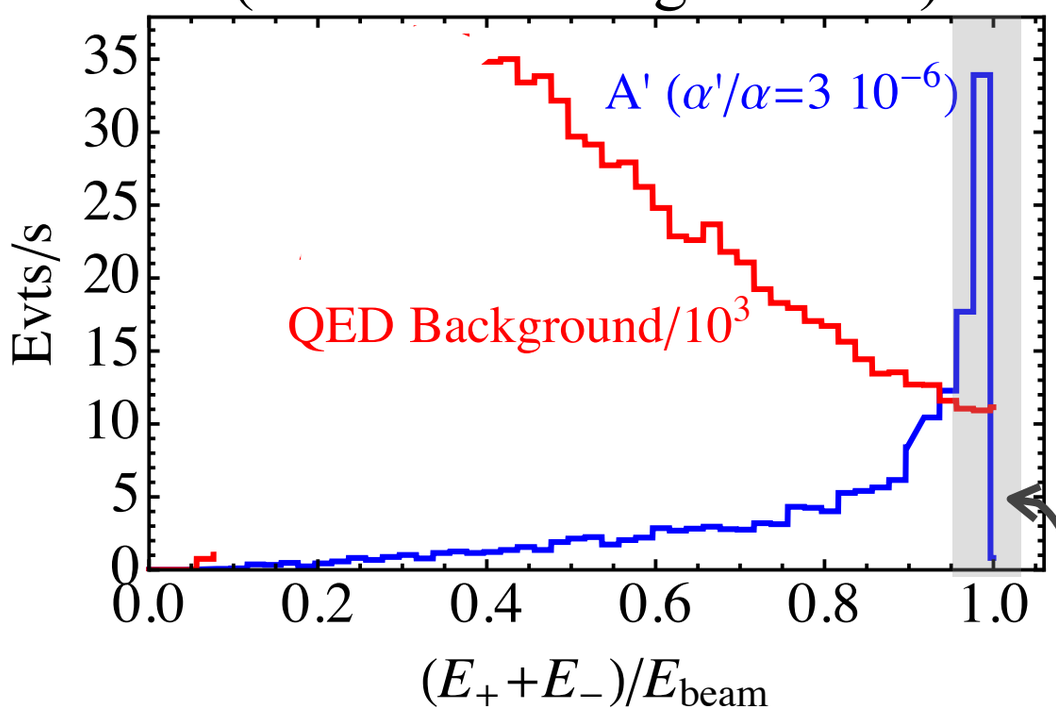
$N \sim \alpha'$ x Branching → O(1)

QED Backgrounds



$N \sim \alpha^2$

(rates before angular cuts)



– Distinctive kinematics:

A′ products carry (almost) full beam energy!

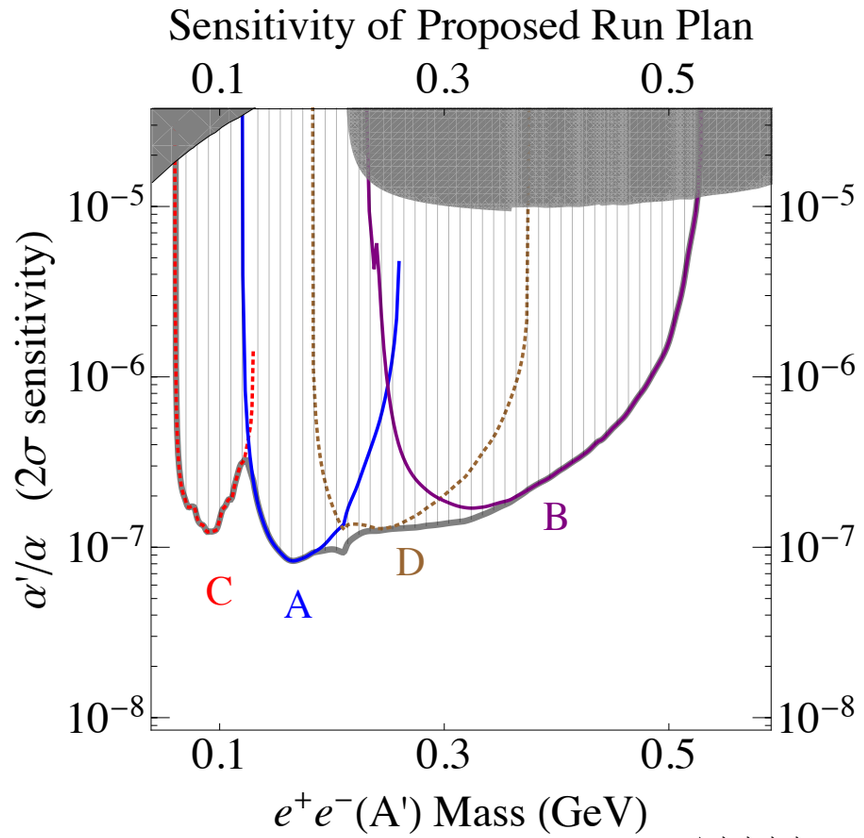
$$E^+ \approx E^- \approx E_{beam}/2$$

Symmetric energy, angles in two arms optimize acceptance

Optimal kinematic selection for A′ search

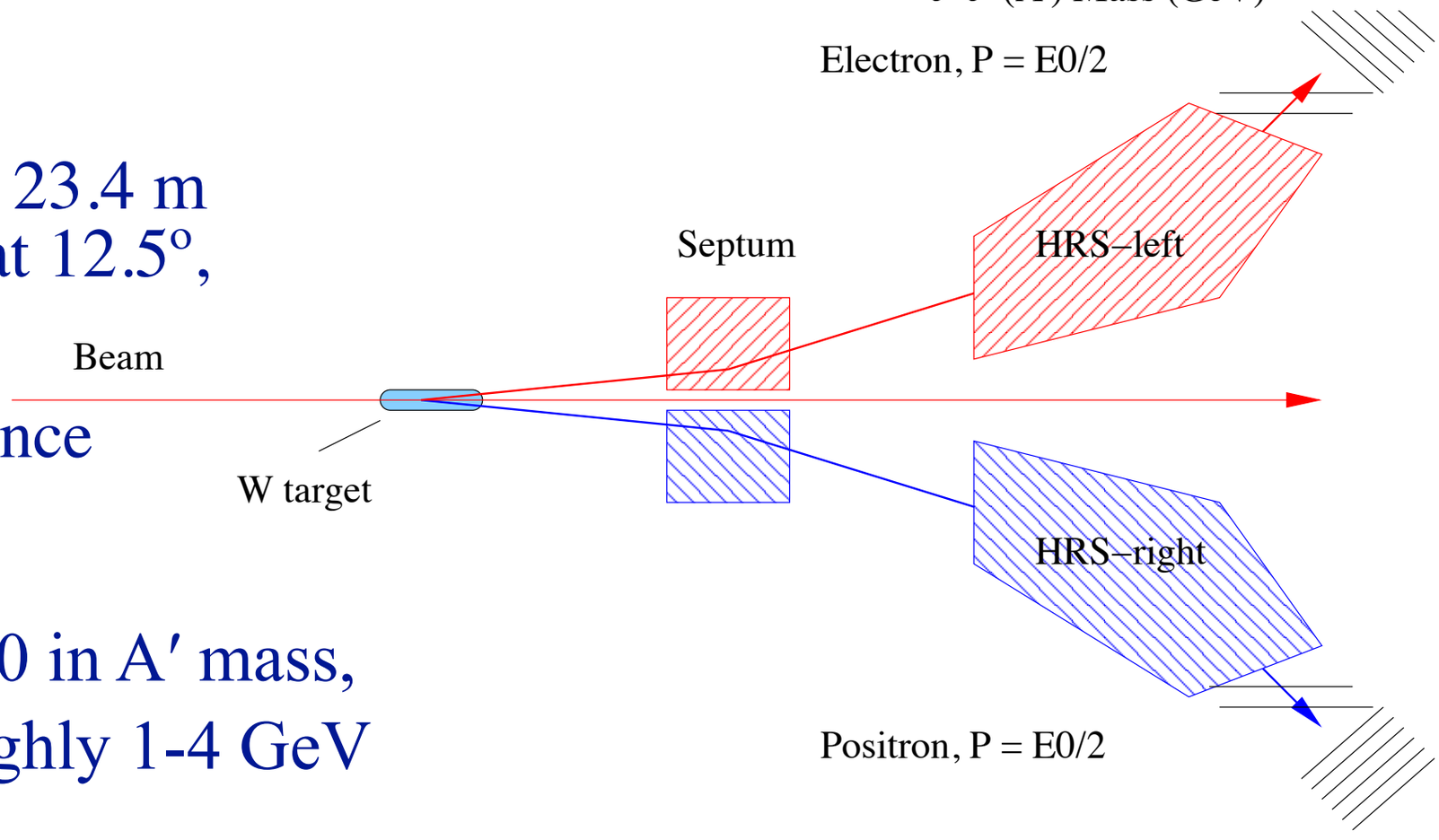
APEX Strategy: Hall A High Resolution Spectrometers (HRS)

- High-statistics resonance search
  - e^+ and e^- in magnetic spectrometer
    - trigger on S2 scintillators and GC
    - tracking in VDC
  - reconstruct invariant mass spectrum (>10^8 QED events in full run)
  - search for small (~ percent-level) resonance peak



HRS: 45° vertical-bend, 23.4 m magnetic spectrometer at 12.5°, lower to 5° with septum

±4% momentum acceptance



4 settings ⇒ factor of 10 in A′ mass, with beam energies roughly 1-4 GeV

APEX Status and Timeline

Jan. 2010: APEX conditionally approved by PAC 35.
Test run recommended.

June 2010 Test Run:

- installation and check-out of
  VDC and trigger electronics
- prepared target system (revised wrt. proposal)
- studied performance of coinc. trigger using gas Cherenkov
- studied high-rate performance of PID, and VDC tracking
- optics calibration with septum
- Measured electron, pion, and coincidence rates
- Last weekend: science data
  – (over 700K trident events within final acceptance)

Setup as specified in proposal, except
– thin Ta target (21.5 mg/cm^2)
– reduced spectrometer acceptance (collimators)
– only one setting (2 GeV) at lower statistics

Many thanks to JLab & Hall A staff for tremendous support!

Jan. 2011: APEX approved by PAC 37, pending radiation checks.

Spring 2011: Finishing test run analysis

Operating at High Charged Particle Rates

APEX running conditions require high singles rates:

- e^- (radiative elastic & inelastic) – about 10^4 x coincidence rate
- $\pi^\pm$ ~1/6 e^- rate, but up to 50 x **larger** than e^+

Cluster-finding and tracking in VDC become more challenging at MHz rates.

Test run: installed new electronics in VDC, checked tracking performance up to ~5 MHz (highest rate expected for PAC 37 proposal)

$\Rightarrow$ Obtained **60%** track reconstruction efficiency at 5 MHz singles rate, before known improvements.

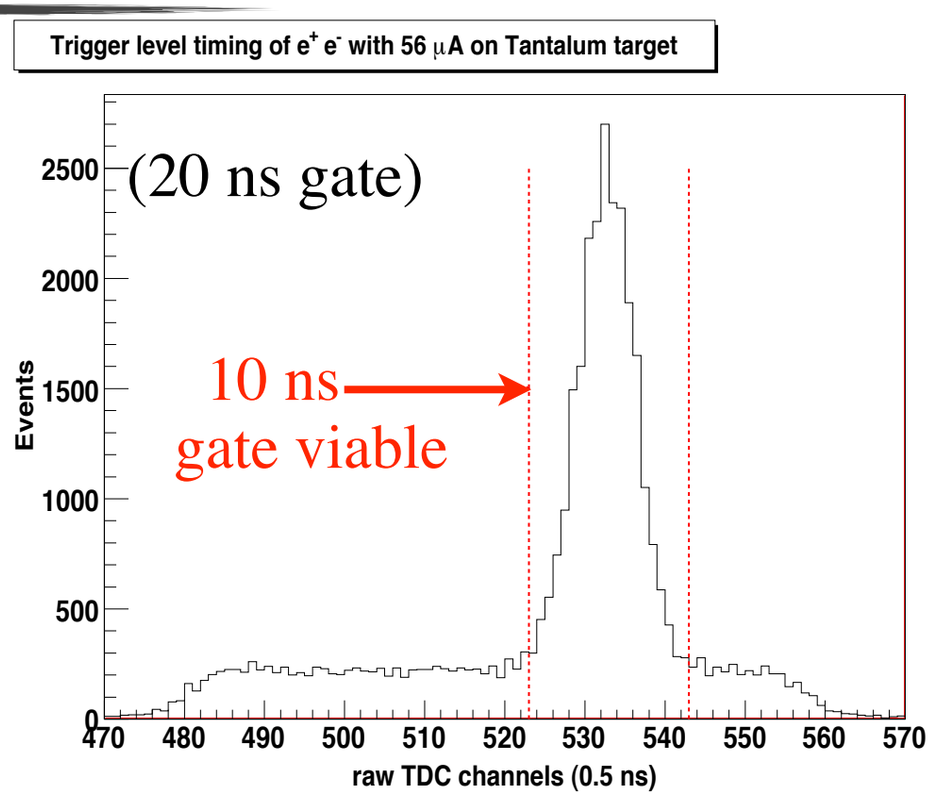
The Coincidence Trigger, PID, and Background Rates

Largest coincidence rates between L and R-HRS are accidentals:

- 10 ns online timing achieved in test run for "golden" trigger:

  Left S2m + Right S2m + Right Gas Cherenkov (e^+)

- Rate estimates [kHz]:



		1.1 GeV	2.2 GeV	3.3 GeV	4.4 GeV
N singles	e^-:	4500	4100	2200	700
	π^-:	25	90	350	250
P singles	e^+:	18	27	17	5
	$\pi+$ [p]:	25	90	350	250
Accidental	20 ns coinc:	4	10	17	5
	$1/30\pi^+$:	2.	2.5	1.4	0.3
True Coinc.	QED e^+e^-:	0.26	0.5	0.37	0.11

π rates – from 2 GeV test run data & SaGDH experiment – are much lower than earlier expectations!

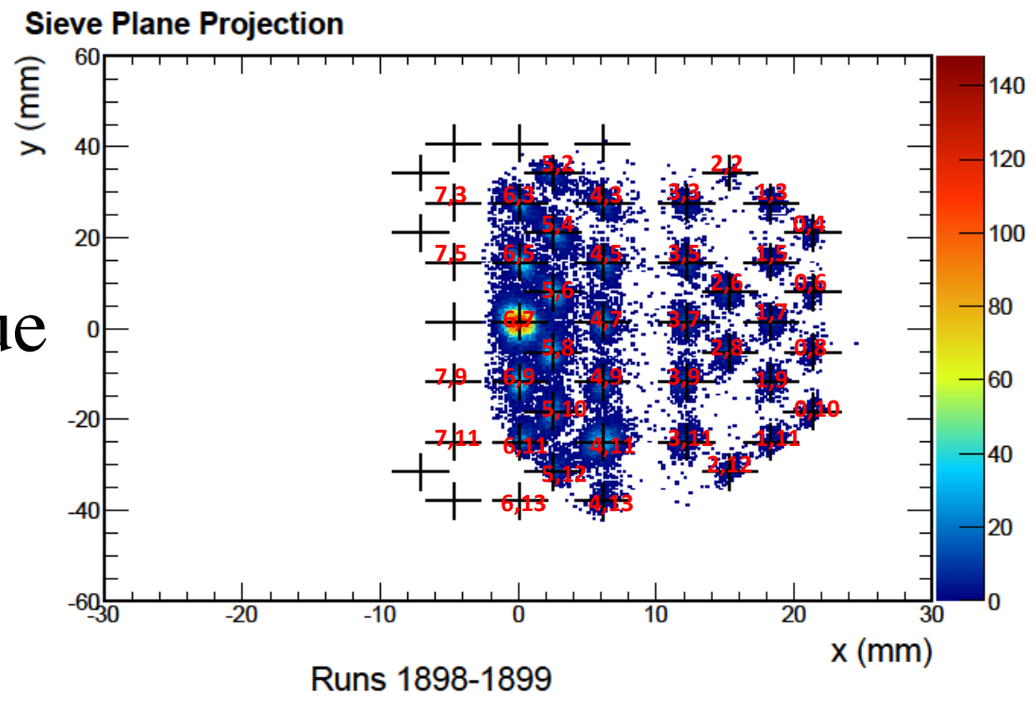
DAQ limit: ~4 kHz

Online π^+ rejection allows operation at higher current ⇒ increased sensitivity

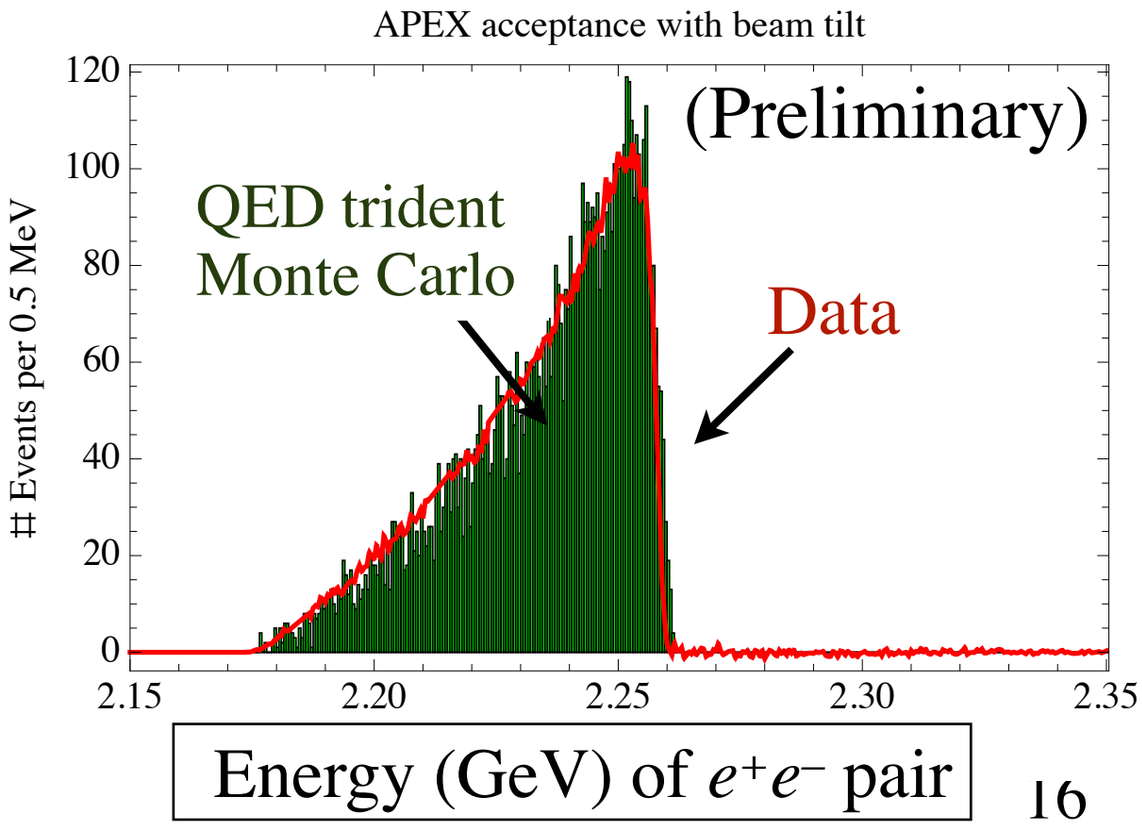
Offline, further rejection of e/π and e/e accidentals from Lead Glass PID, timing, and vertex position along target ⇒ accidentals <20% of coincidence dataset

Angular Resolution and Monte Carlo Analysis

- Optics calibration using sieve holes
  - L-HRS angular resolution measured across acceptance. Better than 0.3 mrad
  - R-HRS angular resolution poorly known due to test run conditions. We include 1 mrad uncertainty.
  - Include multiple scattering in target
  - **Resulting mass resolution: 1-1.1 MeV**



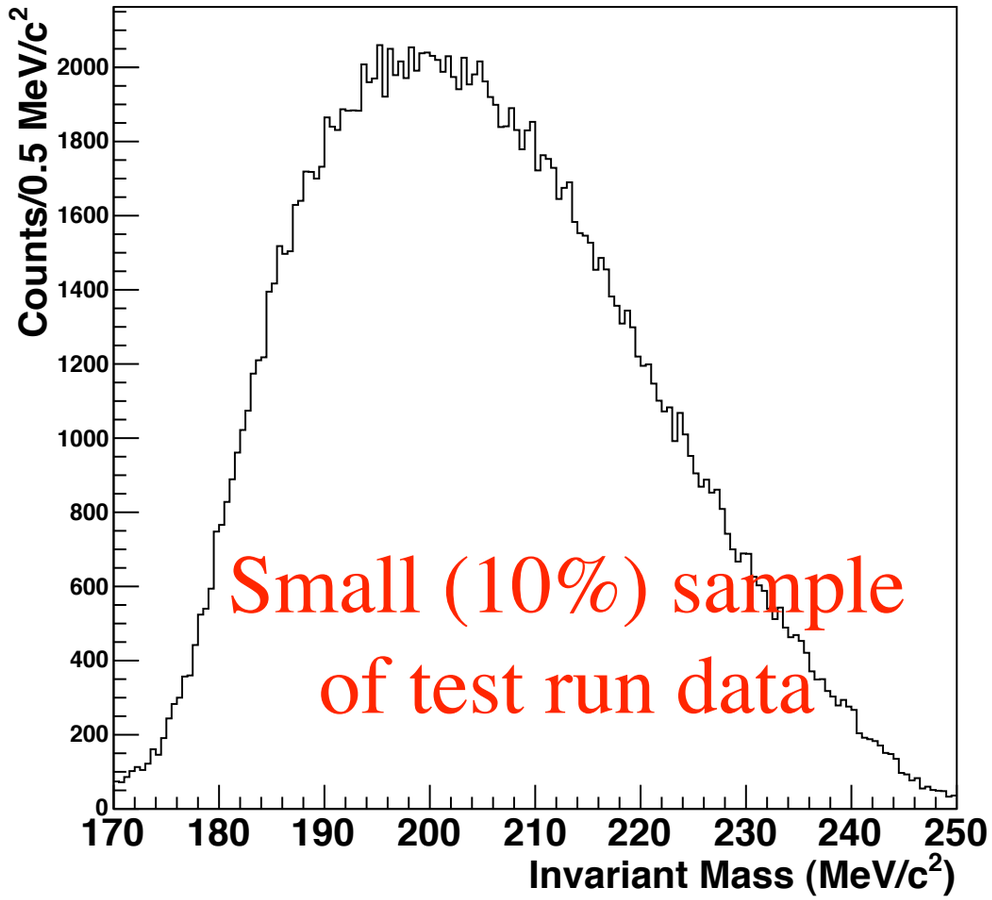
- Test run data compared to MadGraph Monte Carlo simulation with measured acceptance and efficiency corrections
  - **Very good agreement with e+e- trident predictions of rate (better than few %)**
  - Good agreement in shape for important kinematic distributions

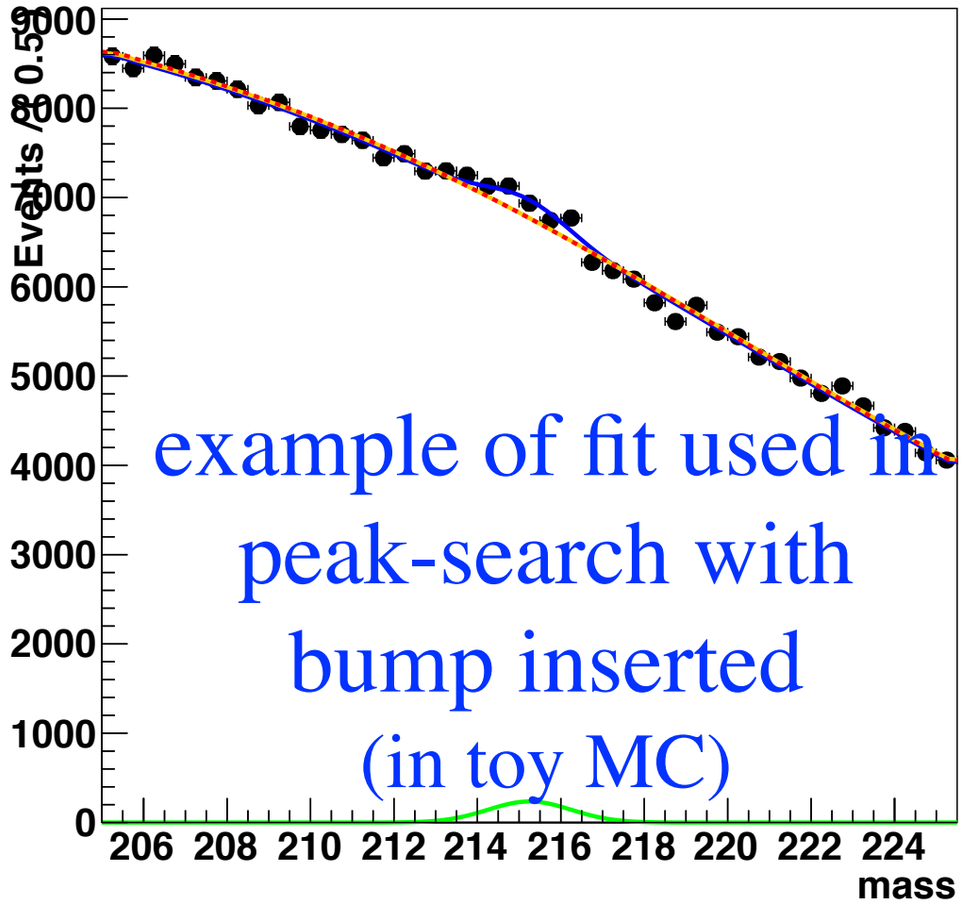


Using Test Run Data for a Resonance Search

Analysis procedure developed on test run data

(blind analysis; 10% unblinded)

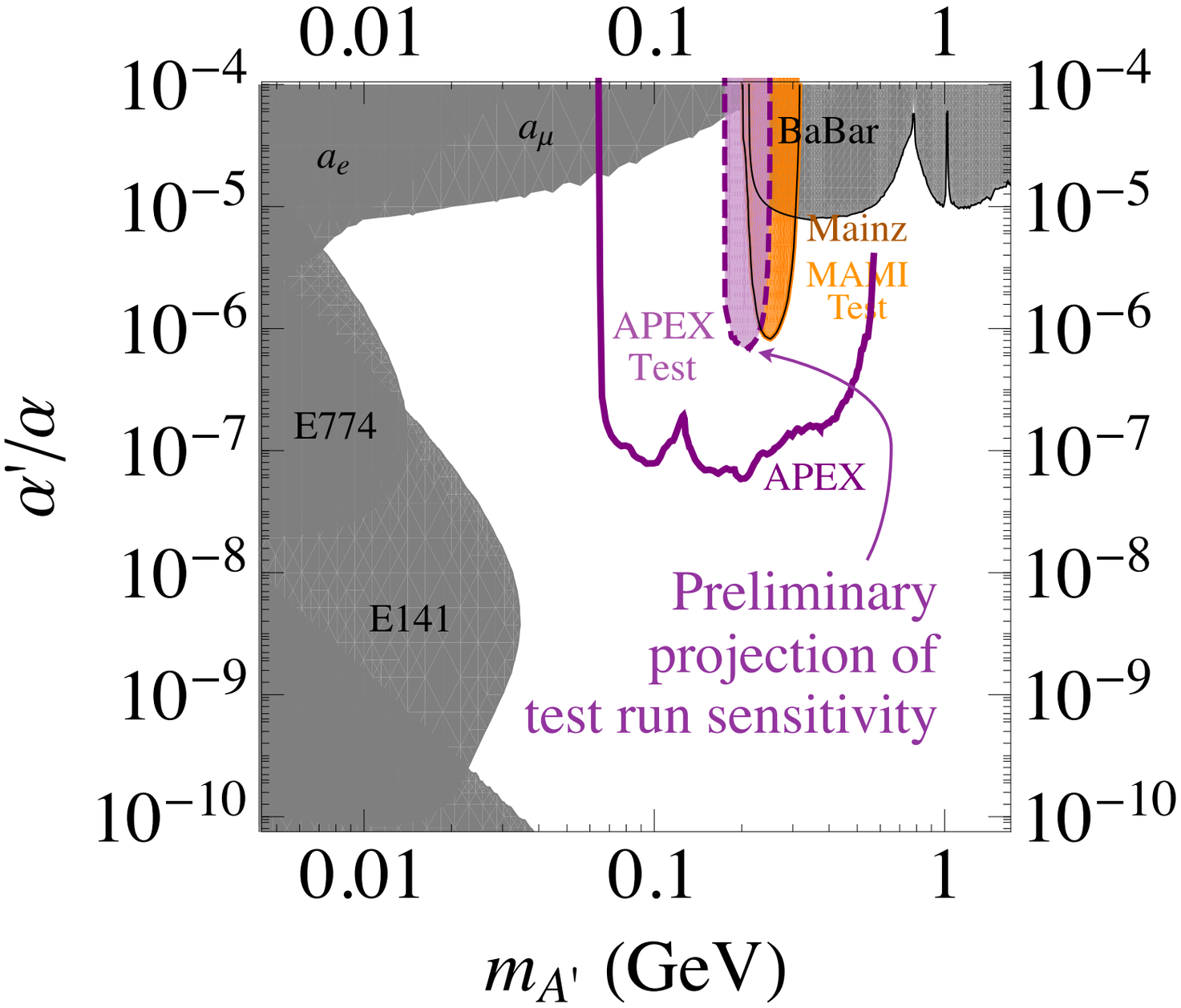




- Statistics is sufficiently large that higher order curvature in the background model must be included to remove systematic bias (noted but not included in Mainz study)
- Care is being taken to optimize our background model procedures and calibrate significance thresholds before unblinding our full test run data
- Final result will be presented in terms of (limit on) signal yield vs. mass and converted to a statement about coupling by normalizing to trident events

Projected APEX Sensitivity

Projected sensitivity based on existing test run analysis:



- **Test run sensitivity is expected to surpass all past experiments!**

Summary and Immediate Plans for APEX

- Finishing bump-hunt tools/approach that use a properly sophisticated background model
  - Working to minimize systematic errors
  - Firmly establish significance expectations and thresholds before unblinding full sample
- Finalized methods will be applied to the test run data (now!).
  - PRL in preparation
  - Expect to release public result this month (June)
  - Additional target preparation and calibration detector (for optics) needed prior to full run
- We're ready to run with short notice.
- APEX and other experiments are powerfully extending sensitivity to new forces beyond the Standard Model!

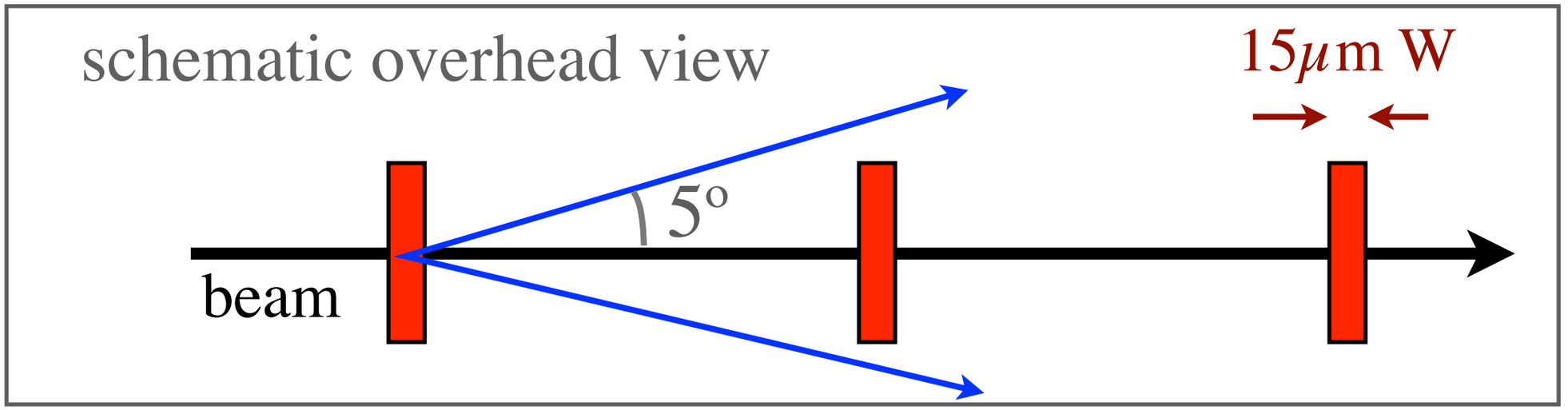
Backup Slides

Target Design: Minimizing Multiple Scattering

Target designed and built by SLAC APEX group for the test run, currently at JLab

Goals:

- $\sigma(\theta)_{\text{mult scat}} \leq 0.5$ mrad
  $\Rightarrow$ typical e^+e^- pair must only go through 0.3% X_0 (2-pass)
- Target thickness 0.7–8% X_0 (depending on E_{beam})

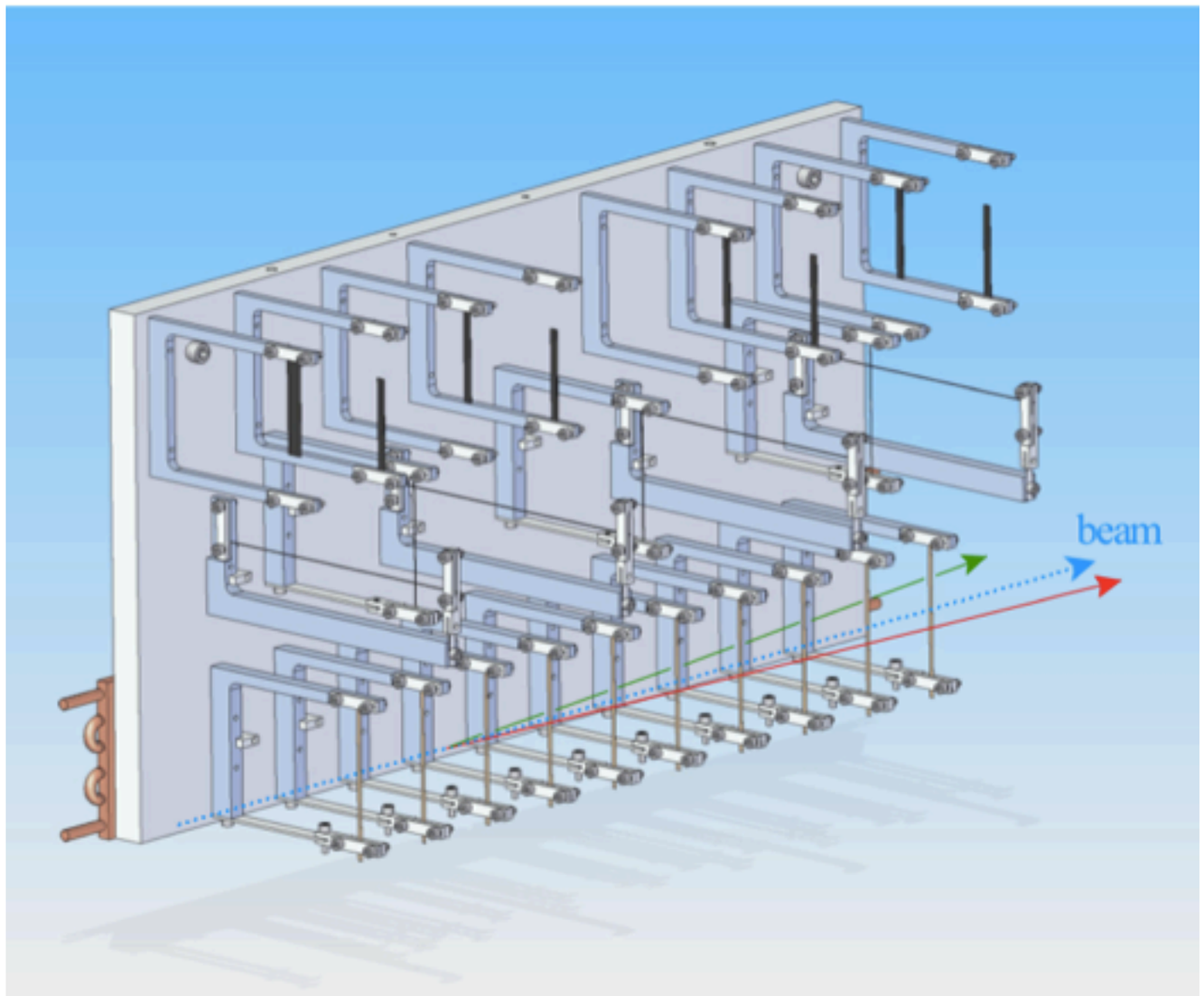


- High-Z target (reduce π yield for given QED rates)
- Stable under currents up to ~100 μA

long target $\Rightarrow$ wider single-run mass coverage

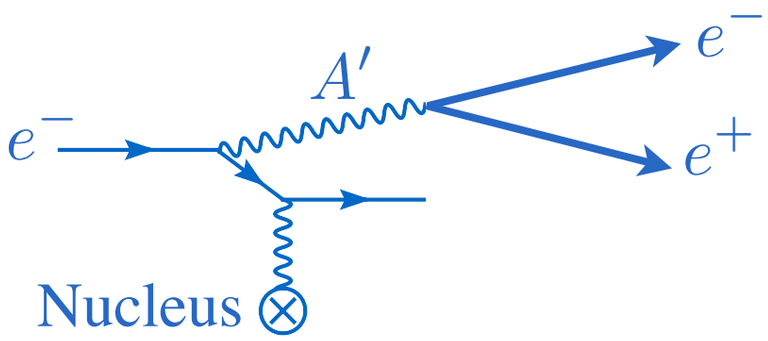
Target Design: Minimizing Multiple Scattering

Target designed and built by SLAC APEX group for the test run, currently at JLab



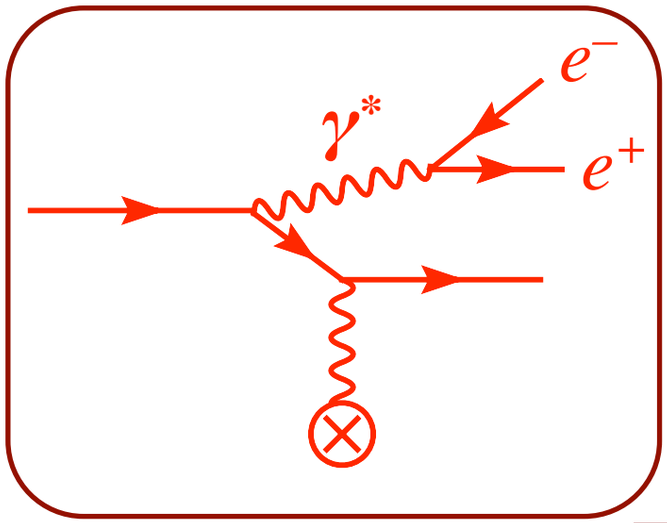
Normalizing Signal to Radiative Trident Background

Signal



$\propto$

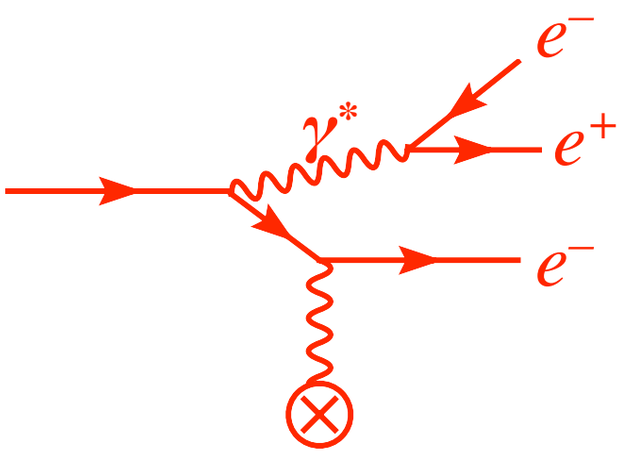
"Radiative" Trident

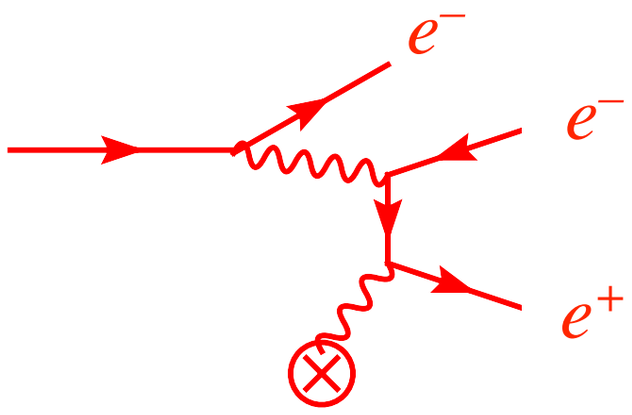


$$\times \quad \frac{3\pi}{2N_{eff}\alpha}\frac{\alpha'}{\alpha}\frac{m_{A'}}{\Delta m}$$

$$= f_{rad.}\frac{d\sigma}{dm}$$

Trident Backgrounds



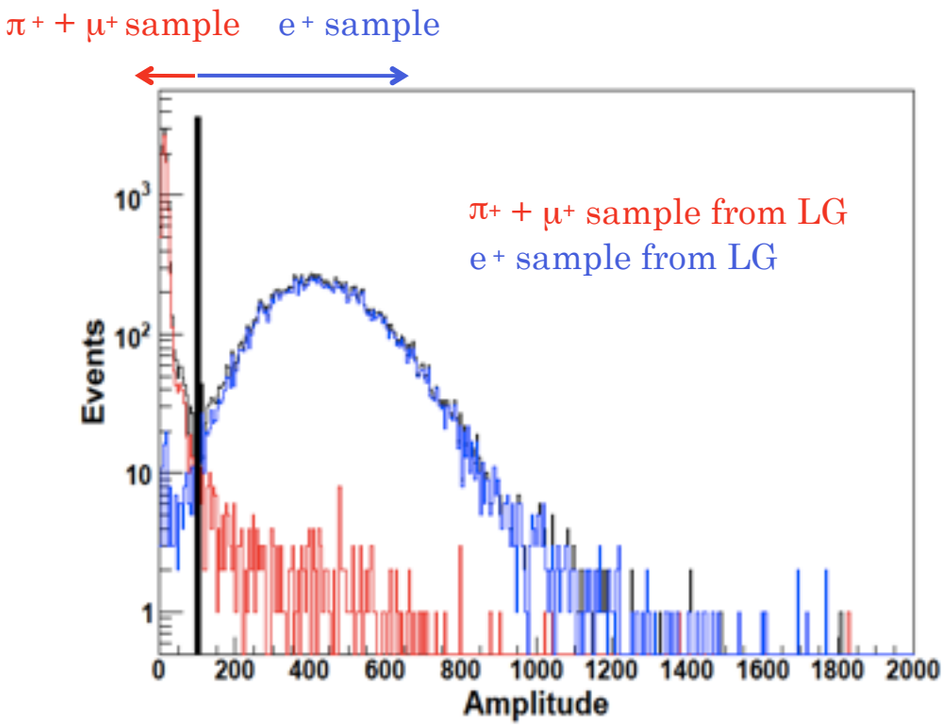


- 2nd "Bethe-Heitler" diagram significant (though not dominant)
- Background from *either* electron w/in acceptance

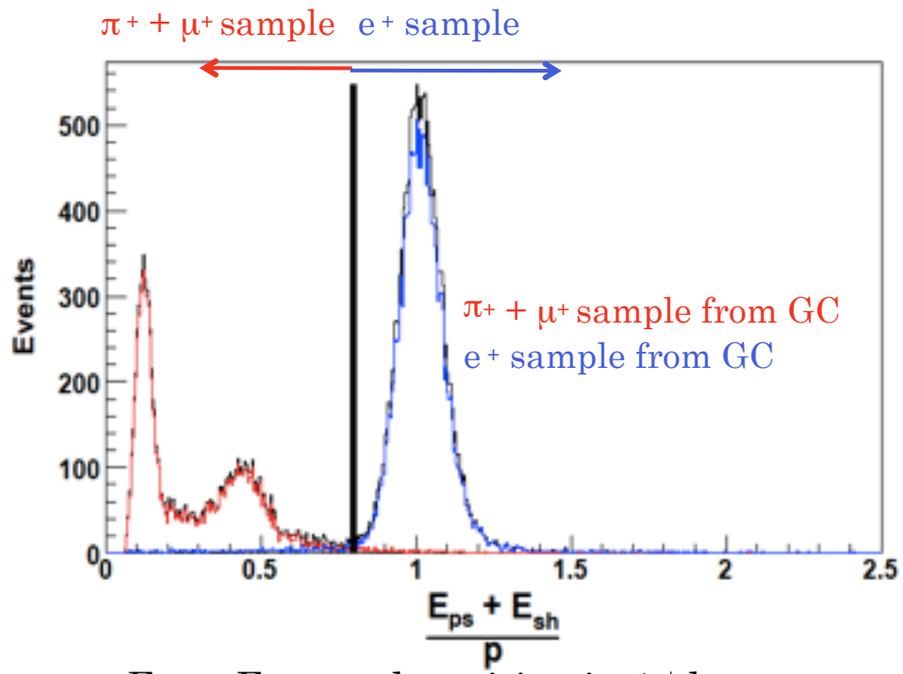
For APEX kinematics, $f_{rad.} \approx 0.22$

High Rate Particle Identification

30 μA on Pb Target, positron arm rate – 765 kHz
680 kHz pions & muons + 85 kHz positrons



Electron detection eff.	0.992
Pion rejection eff.	0.970



- E_{PS} – Energy deposition in 1st layer
- E_{SH} – Energy deposition in 2nd layer
- p – Particle momentum

Electron detection eff.	0.977
Pion rejection eff.	0.985

Online meson background rejected by a factor of 30; rejection of 50 possible with tighter threshold

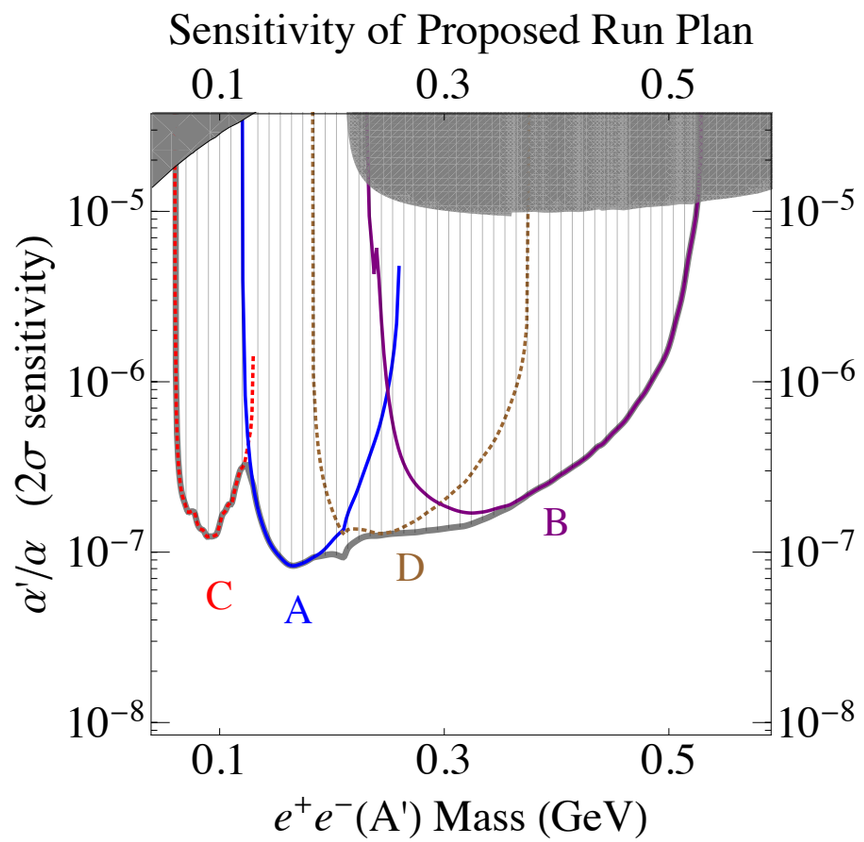
Offline meson background rejected by a factor of 60

Proposal **estimates**: 1/100 online (GC), 10^{-4} offline (GC & LG)

- **Require** 1/25 online (3-pass 1/90), no further offline rejection
- Demonstrated 1/50 (GC) x 1/60 (LG) in test run
  - ⇒ **pion rejection more than sufficient for 1-, 2-, and 4- pass running**
  - ⇒ might require lower current by 50% for 3-pass (but probably not!)

Run Plan

Settings	**A**	**B**	**C**	**D**
Beam energy (GeV)	2.2	4.4	1.1	3.3
Beam current (μA)	70	60	50	80
Nominal central angle	5.0°	5.0°	5.0°	5.0°
Time Requested (hrs)				
Energy change	–	4	4	4
Magnet setup	4	4	4	4
Optics calibration	16	16	16	16
10% $\mathcal{L}$	2	2	2	2
Normal $\mathcal{L}$	144	288	144	144
Total	166	314	170	170



6-12 days at 4 energy settings,

anticipate 8 days to swap target cartridges, check alignment, and calibrate optics

41 days total (33 days beam)