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Search for a New Vector Boson A' Decaying to e^+e^-

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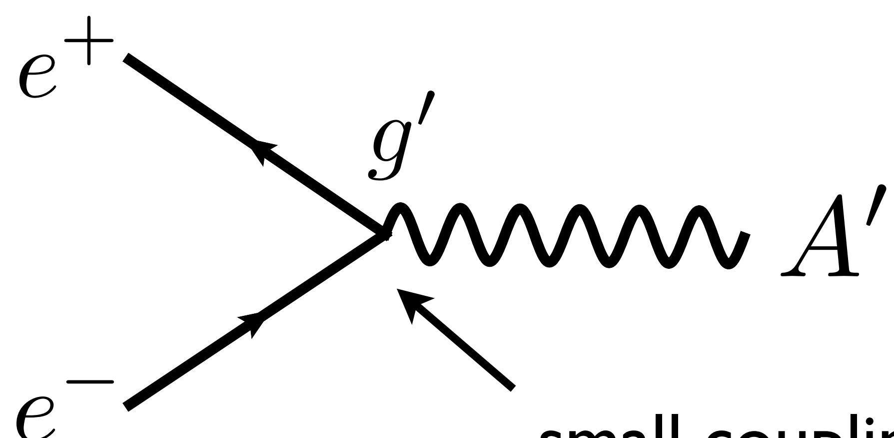
and The Hall A Collaboration

(arXiv:1001.2557)

Goal:

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



("dark photon")

small coupling $\alpha' \equiv \frac{g'^2}{4\pi}$

Significant new reach in $\boldsymbol{\alpha'}$ (~2-3 orders of magnitude)

Broad interest in particle physics community

- new gauge force
- dark matter interactions?
- **$(g\text{–}2)_\mu$** and HyperCP anomalies

see also Dark forces workshop, SLAC Sept. 2009:
http://www-conf.slac.stanford.edu/darkforces2009/

Physics motivation

Standard Model

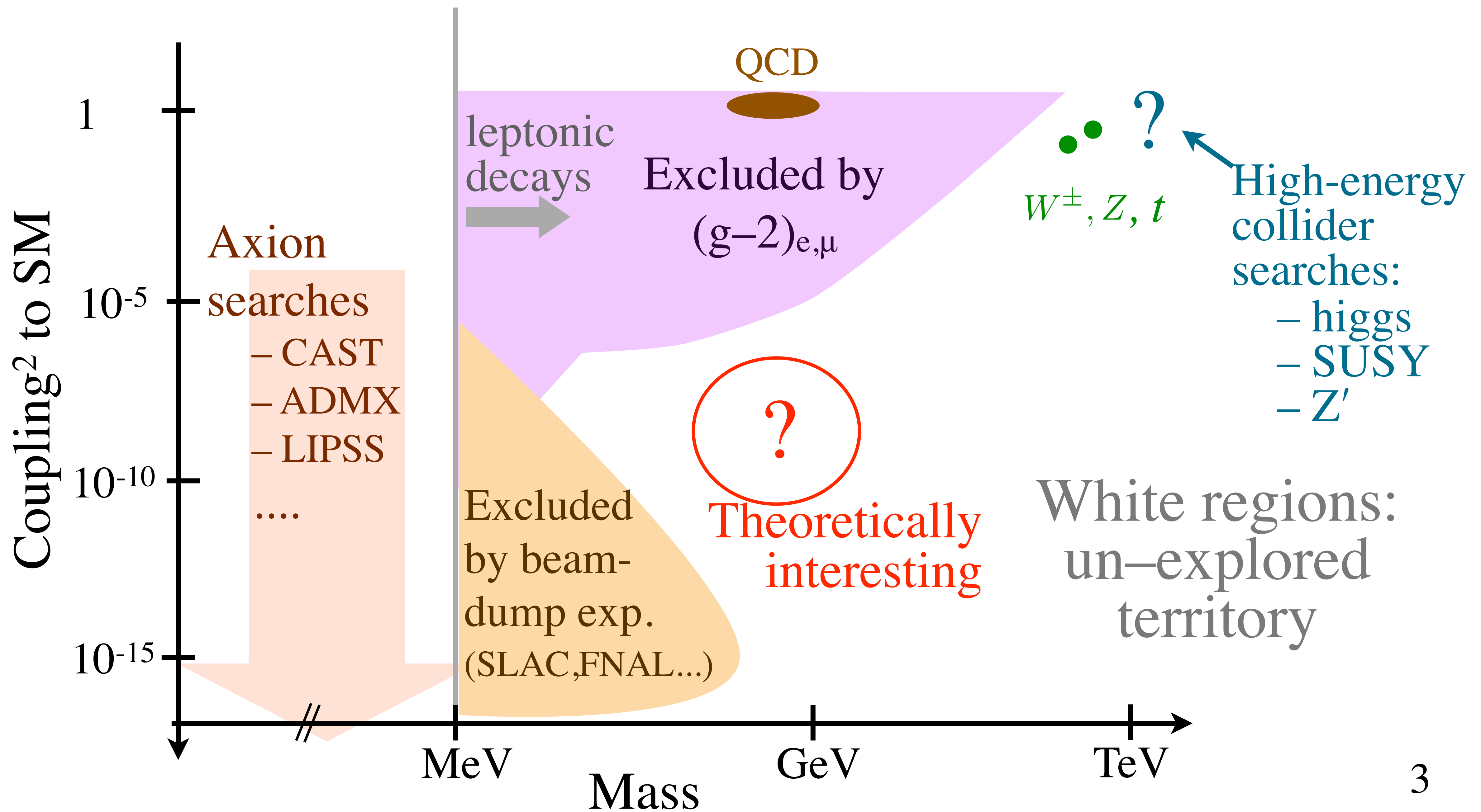
strong — g

weak — $W^{\pm}, Z$

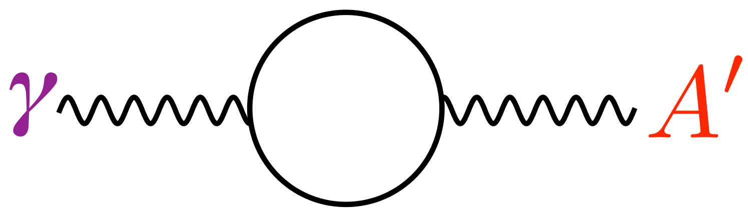
electromagnetic — γ

New Forces?

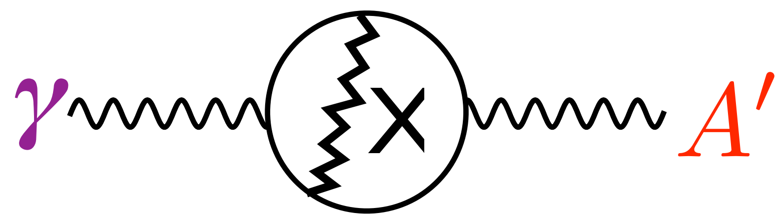
??? — A'



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



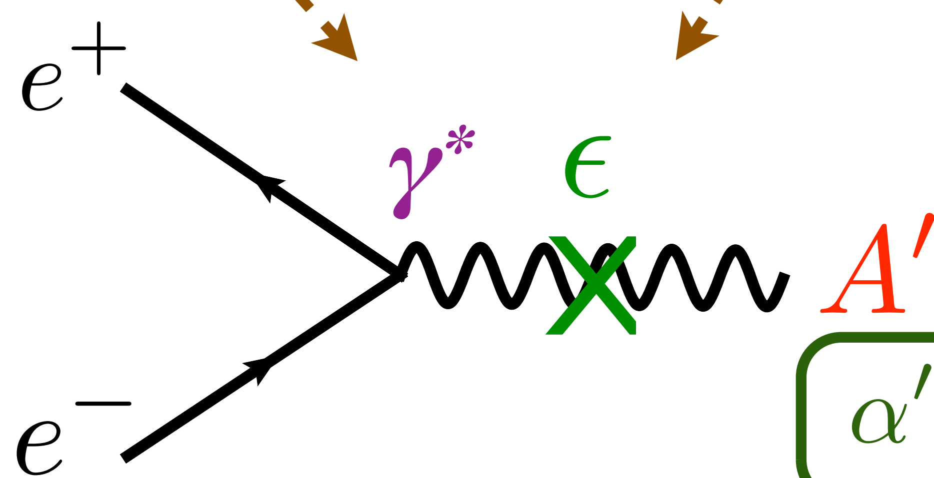
$\epsilon \sim 10^{-4} - 10^{-2}$



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

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

effective coupling:



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

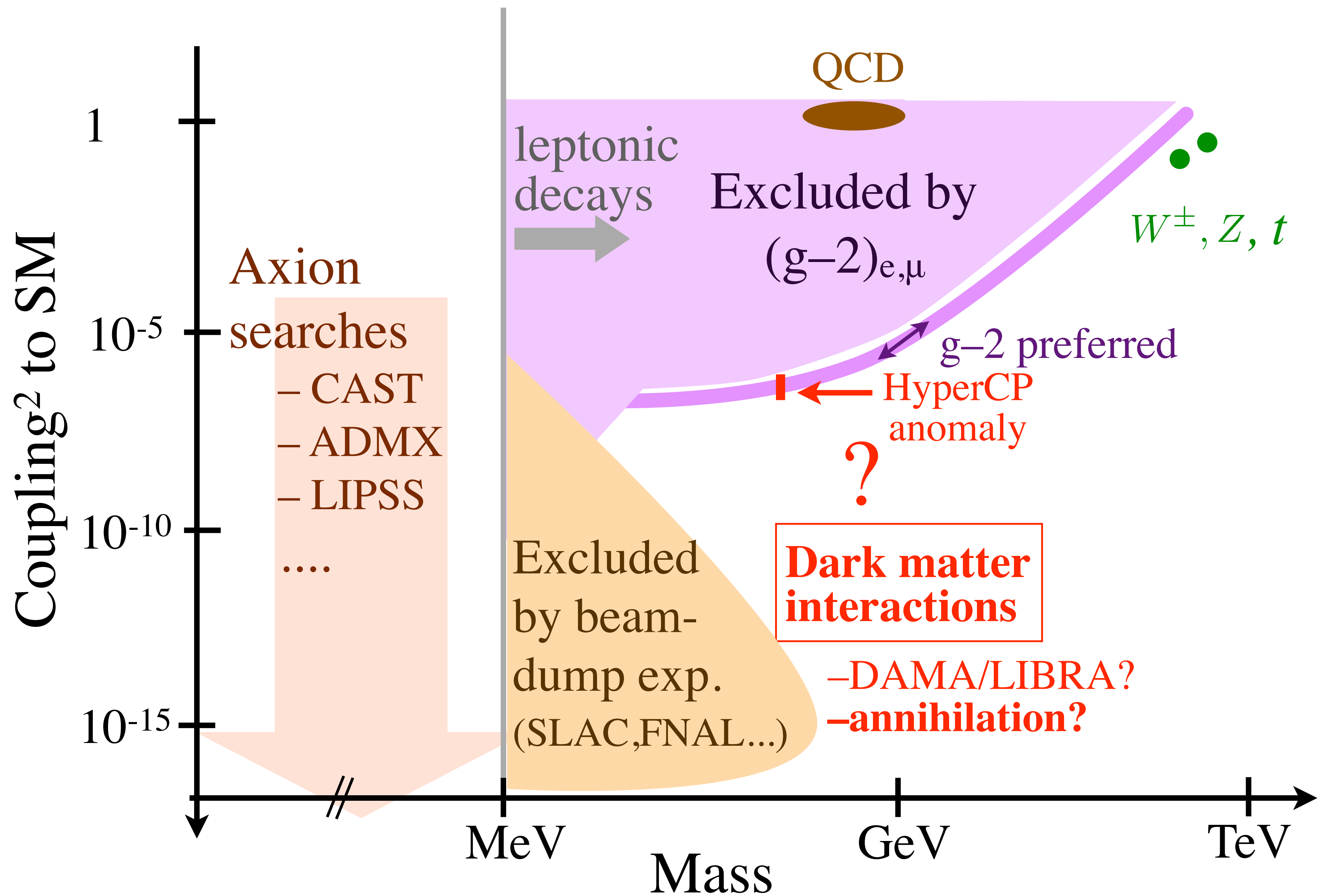
In simple models:
[e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

$$m_{A'}^2 \sim \epsilon M_W^2 \sim \text{MeV}^2 - \text{GeV}^2$$

Physics motivation

Standard Model — New Forces?

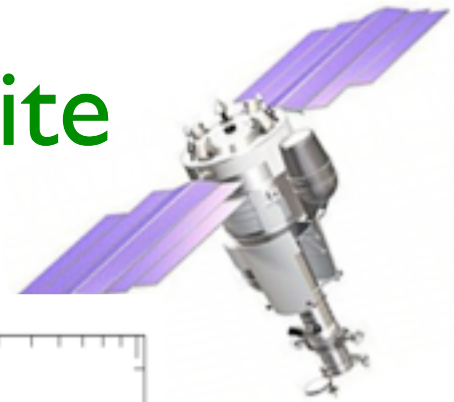
strong	weak	electromagnetic	???
g	$W^\pm, Z$	γ	A'

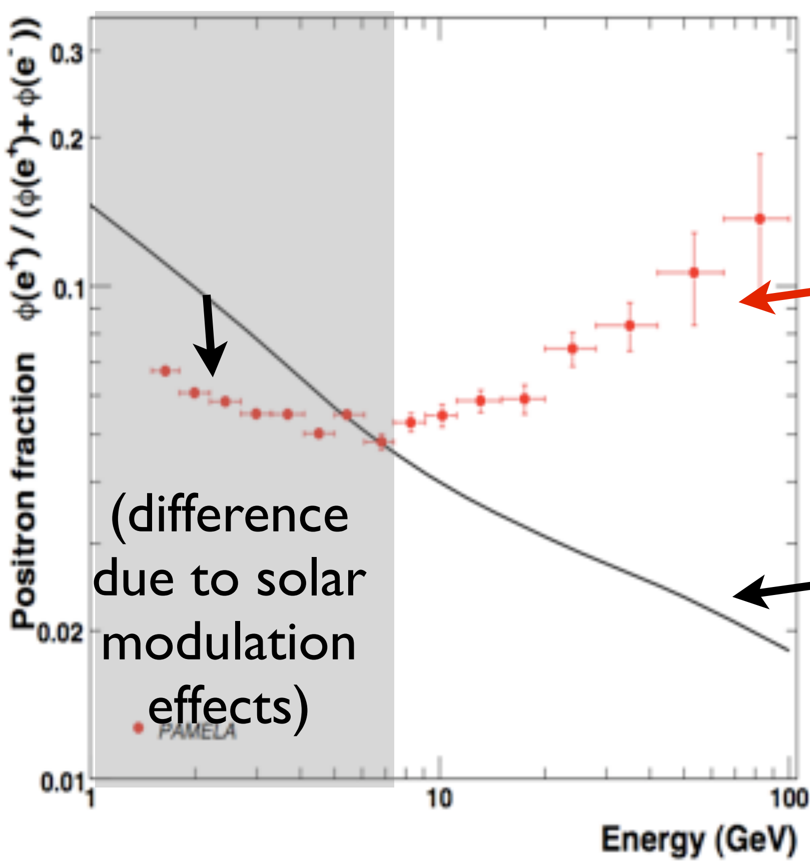


Physics motivation – Dark Matter Anomalies

PAMELA satellite

Nature, 2009
(~1 citation/day)

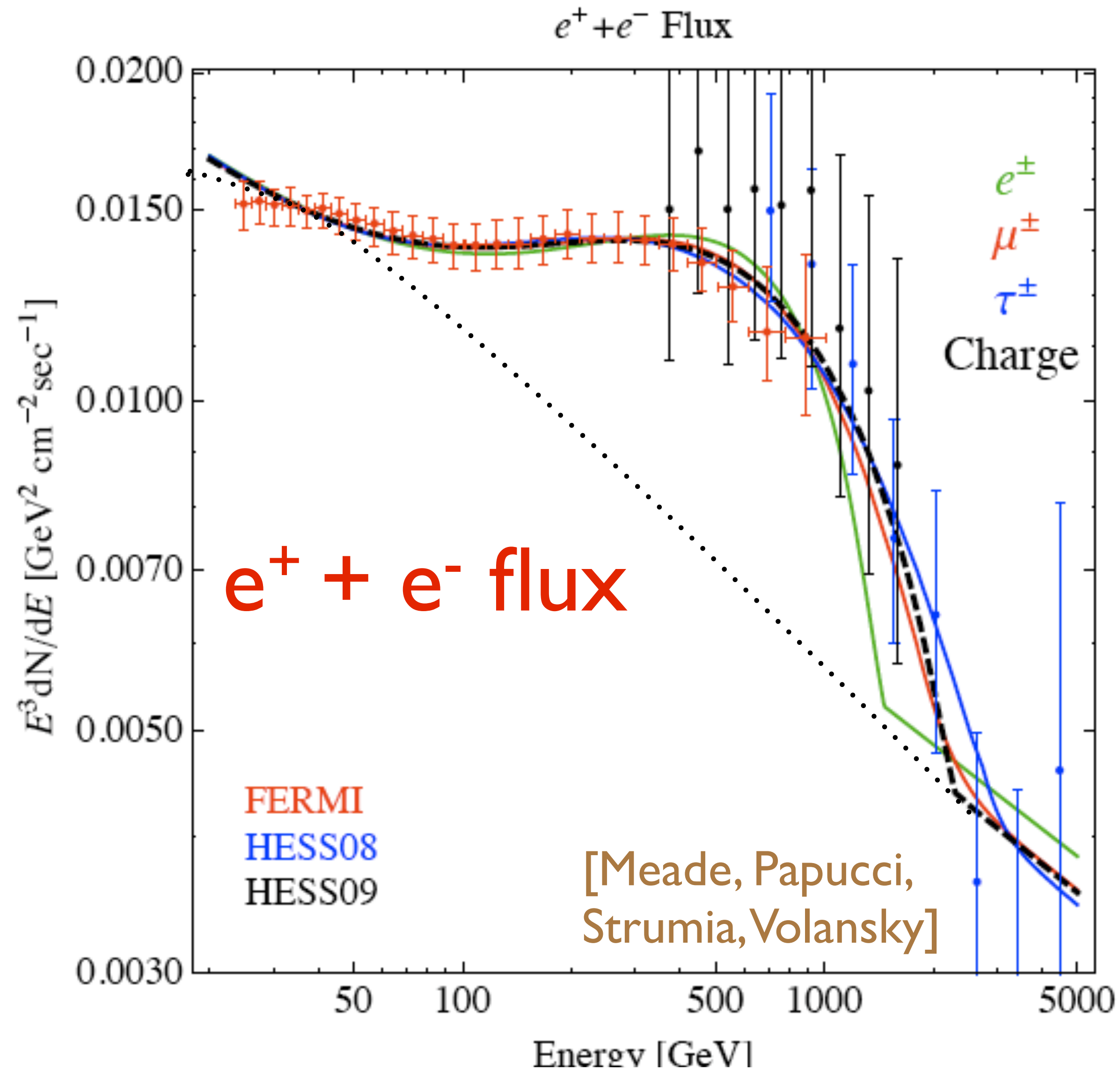


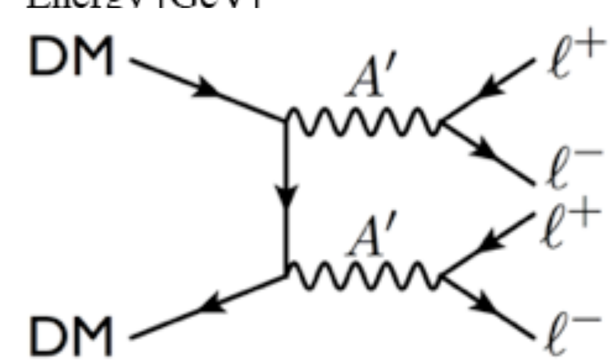


New e+ source

theory expectation

Fermi satellite, HESS





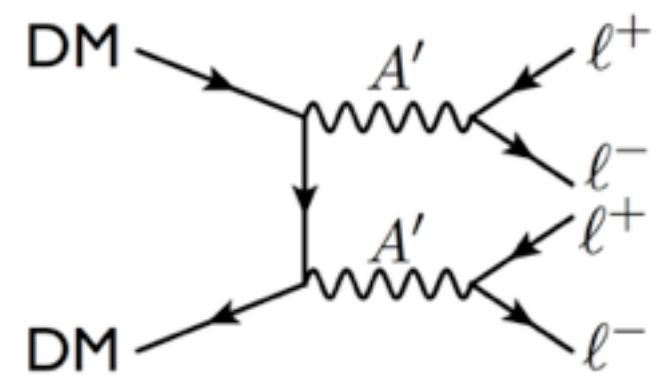
These and related anomalies are compatible with annihilation of ~TeV dark matter into Standard Model leptons.

e^+, e^- energy ~m_{DM}~TeV

(More info: N. Weiner, seminar Feb. 19)

Dark Matter Anomalies – why a new force?

1) No antiproton excess observed!
   – not consistent with annihilation into g, $W^\pm$, Z
      $\Rightarrow$ new force?
   – suggests $m_{A'} \lesssim 1$ GeV
      $\Rightarrow$ decay to protons is kinematically forbidden,
      $A' \to \ell^+\ell^-, \pi^+\pi^-$

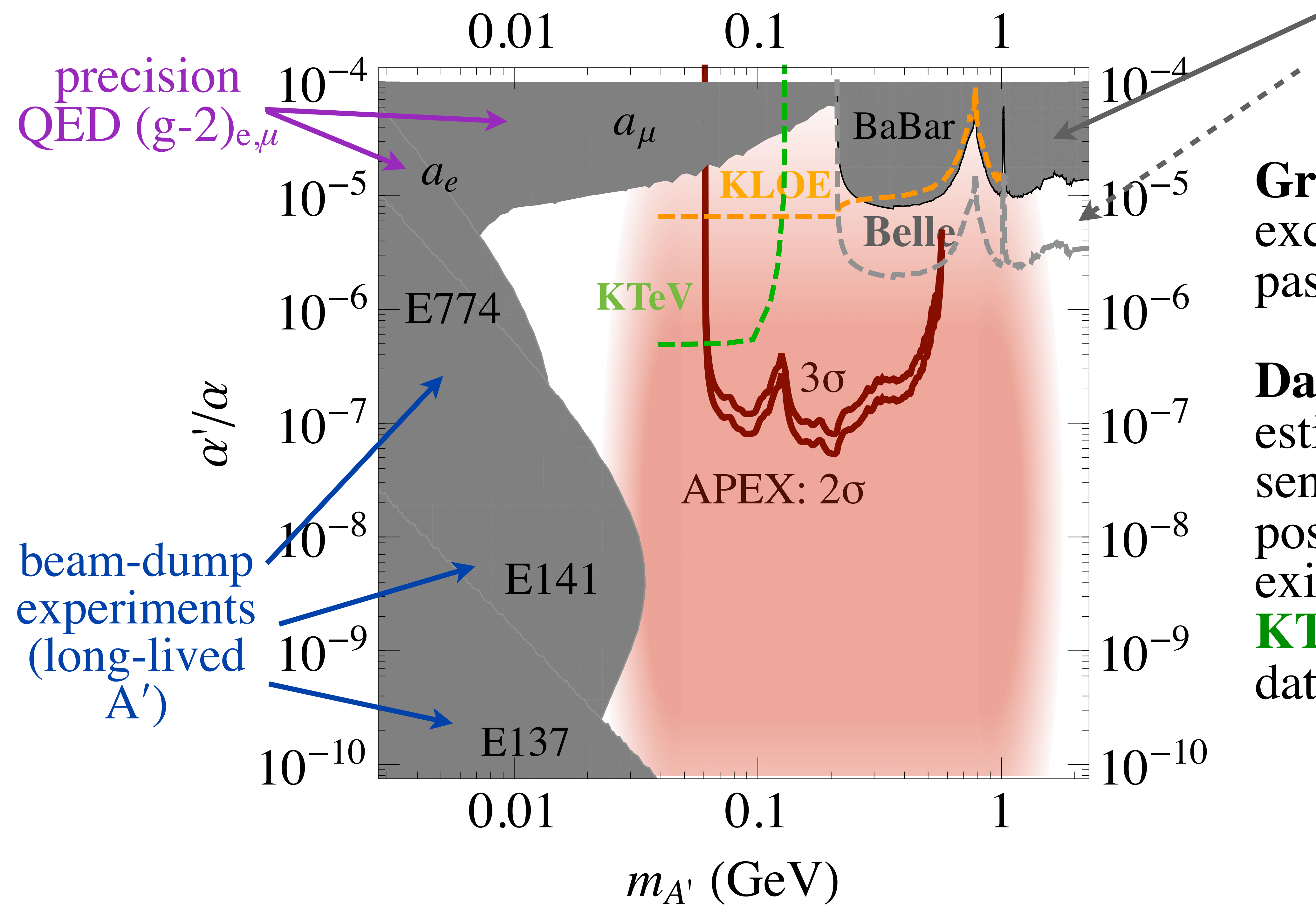


2) Observed annihilation rate is large!
   – consistency with standard cosmology requires attractive force with range $\gg 1/m_{DM}$ $\Rightarrow$ again suggests $m_{A'} \lesssim 1$ GeV

[Cholis, Goodenough, Weiner;
Arkani-Hamed, Finkbeiner, Slatyer, Weiner;
Pospelov & Ritz]

Irrespective of anomalies: New ~GeV–scale force carriers are important category of physics beyond the Standard Model.
Fixed-target experiments have unique capability to explore this vast territory!

Existing limits and APEX Sensitivity



Gray regions: excluded (2σ) by past experiments

Dashed lines: estimated 2σ sensitivity of other possible searches in existing **KLOE**, **KTeV**, and **Belle** data.

No past experiment has **sufficient statistics and mass resolution** to see A′ if its coupling is below the dotted lines.

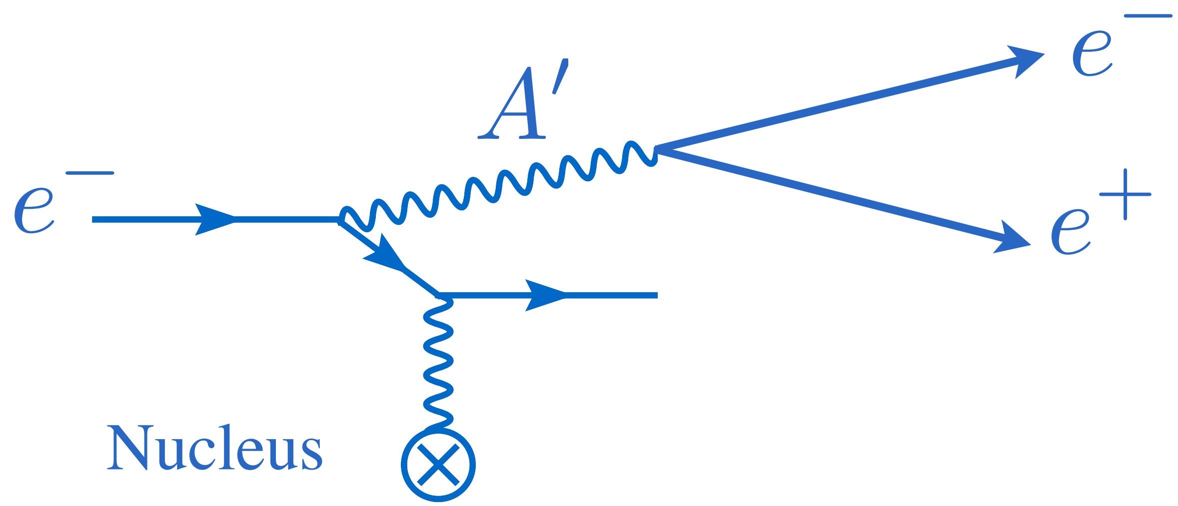
This is a theoretically motivated region

– relevant for dark matter

– predicted by grand unification

A′ Properties in APEX Search Region ($\alpha'/\alpha > 10^{-7}$)

- Produced abundantly through bremsstrahlung
  (e.g. >1/second for 75 μA beam, 0.1 X_0)

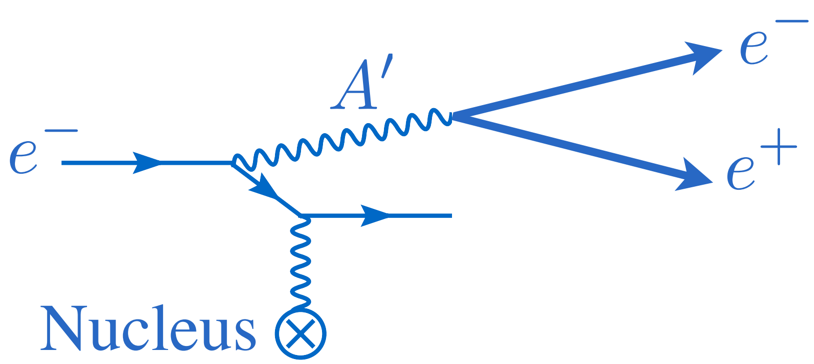


- A′ decays promptly to e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$
  ⇒ large QED background

Strategy: measure e^+e^- mass spectrum precisely, in kinematic region optimized for A′ acceptance and QED background suppression

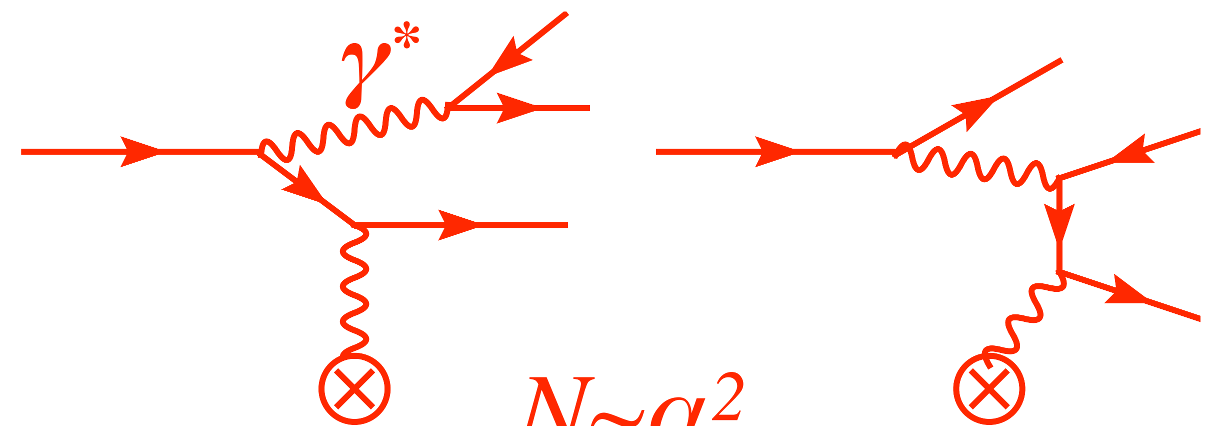
Approach: A′ Production and Background Kinematics

Production diagrams analogous to photon bremsstrahlung



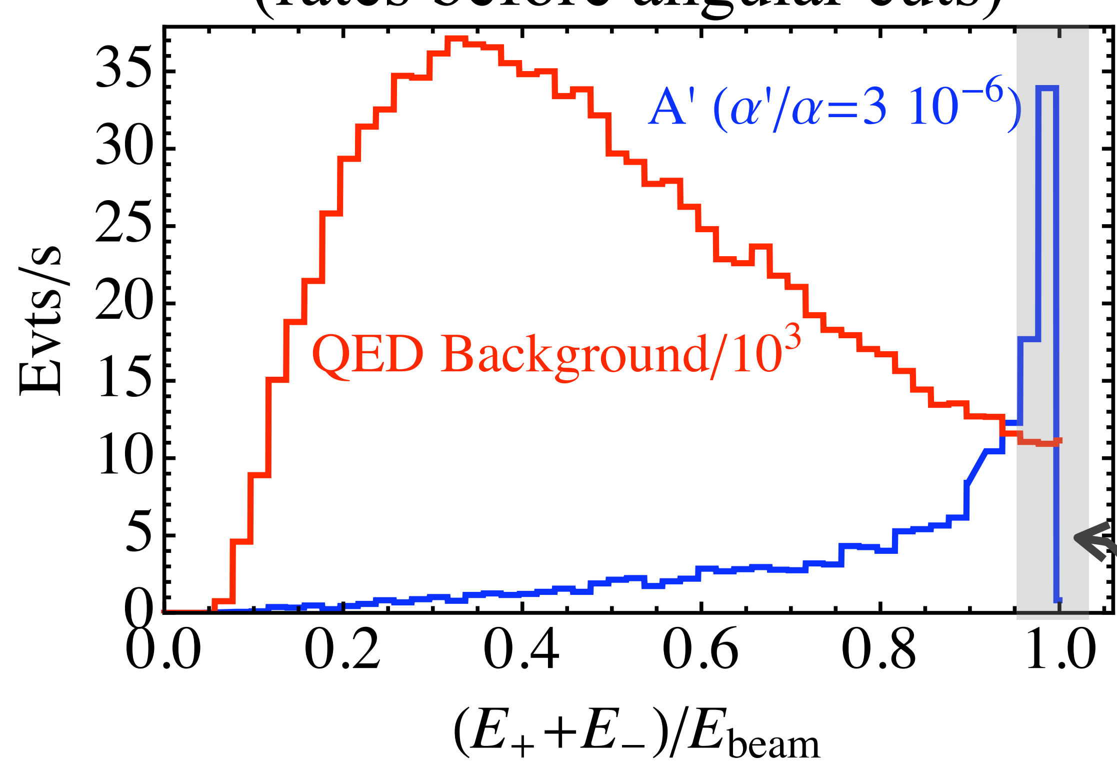
$N \sim \alpha'$ x Branching → O(1)

QED Backgrounds



$N \sim \alpha^2$

(rates before angular cuts)



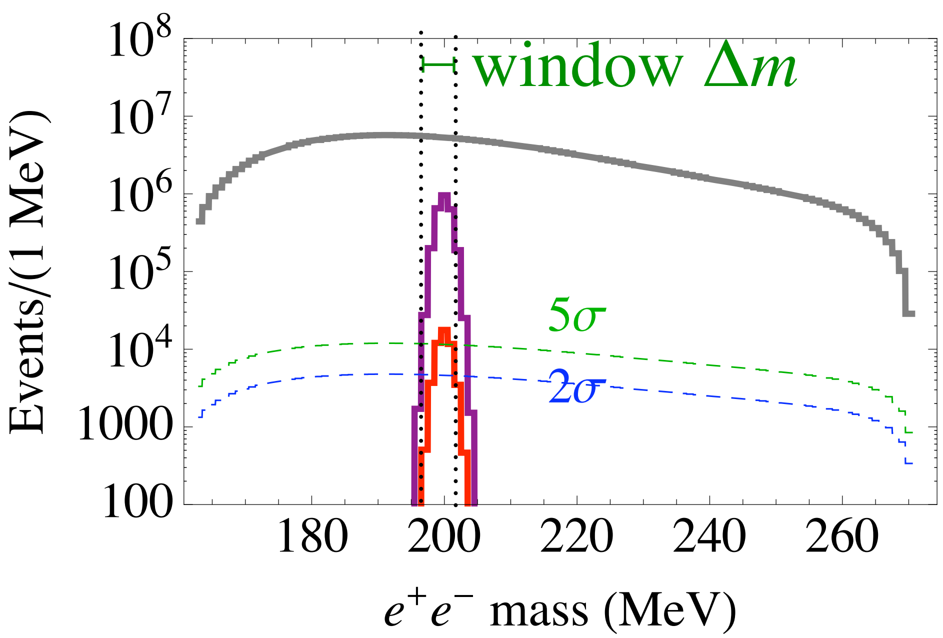
A′ products carry full beam energy!

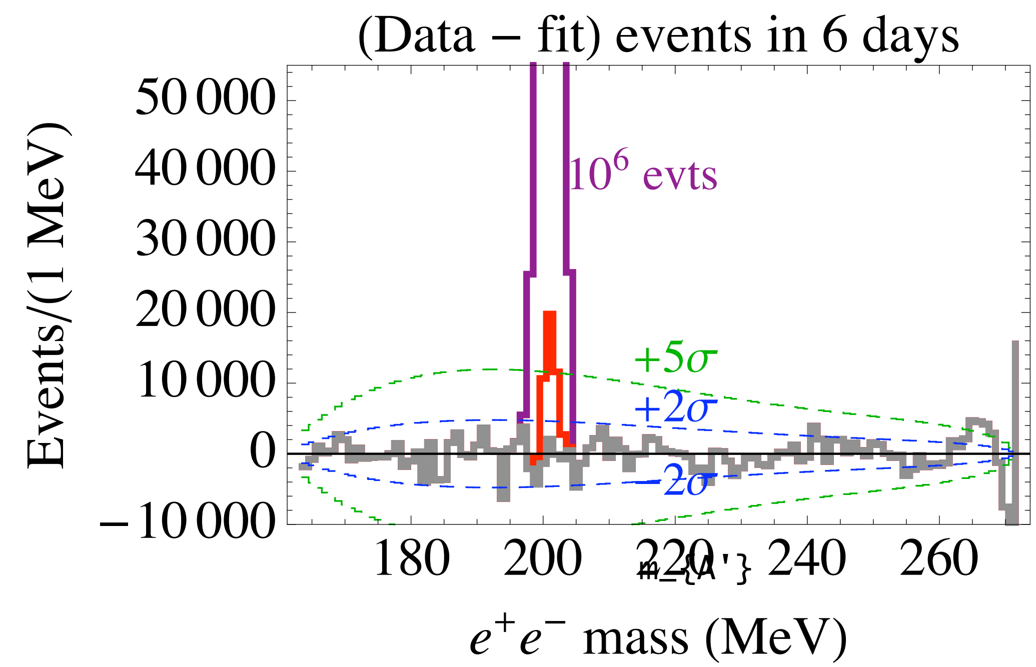
– Distinctive kinematics
– Assists in background suppression

Best kinematics to select events for A′ 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

Approach: Maximizing Statistics & Sensitivity

N_{QED} ~ Luminosity x Acceptance x $1/(m_{pair})^2$

(falling cross-section)

⇒ Best statistics at **low masses** $m_{A'} \lesssim 600$ MeV

Two ways to reach low mass: $m(e^+, e^-) \approx \sqrt{E_+ E_-}(\theta_+ + \theta_-)$

Lower energies E_+, E_-

- lose rate (lose nuclear coherence)
- worse multiple scattering
- reduced spectrometer performance (for E ≲ 500 MeV)

or

Small angles θ_+, θ_-

- $\delta\theta/\theta$ worse, but ok at 5°
- higher acceptance

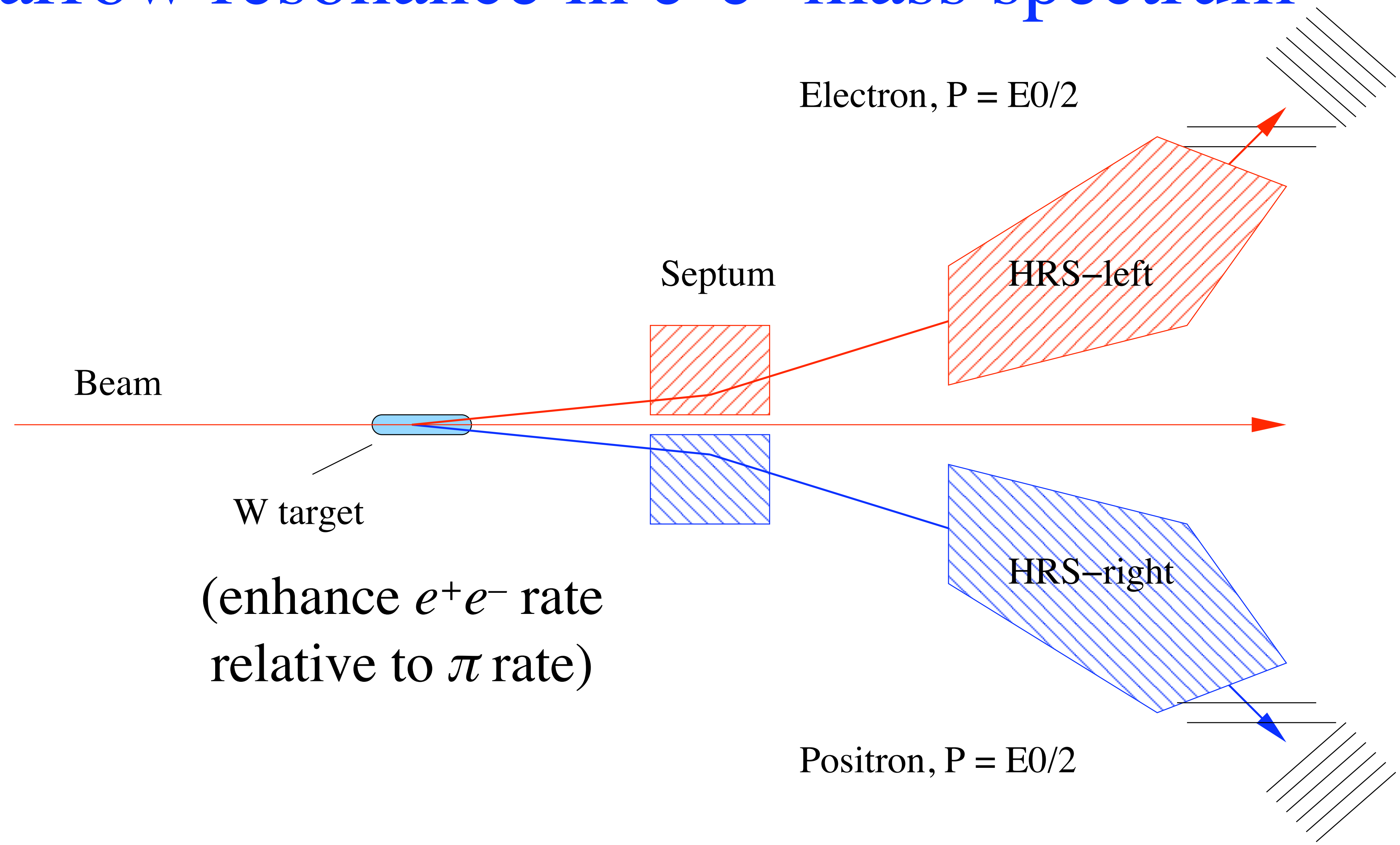
Preferred

Spectrometer kinematics:

- Select symmetric angles $\theta_+ = \theta_-$ (for best mass resolution)
- In this case, signal dominated at equal momenta: $E_+ = E_- = E_{beam}/2$

(see backup slides)

Search for narrow resonance in e^+e^- mass spectrum



- Signal dominated at $E_+ = E_- = E_{\text{beam}}/2$
- Use septa to achieve 5° central angles ⇒ high statistics
- Mass resolution is critical, controls target design

Experimental Design: HRS Spectrometer Setup

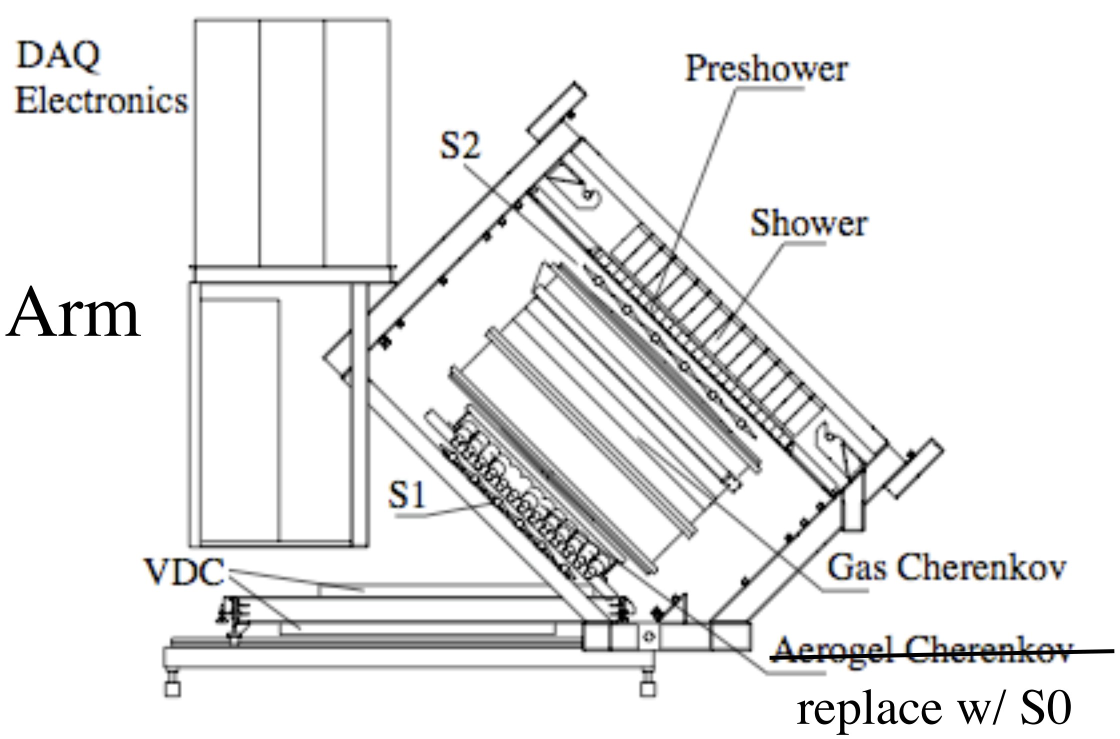
Configuration	QQD_nQ Vertical bend
Bending angle	45°
Optical length	23.4 m
Momentum range	0.3 - 4.0 GeV/c
Momentum acceptance	-4.5% < $\delta p/p$ <+4.5%
Momentum resolution	1×10^{-4}
Angular range HRS-L	12.5° - 150°
HRS-R	12.5° - 130°
Angular acceptance: Horizontal	±30 mrad
Vertical	±60 mrad
Angular resolution : Horizontal	0.5 mrad
Vertical	1.0 mrad
Solid angle at $\delta p/p = 0$, $y_0 = 0$	6 msr

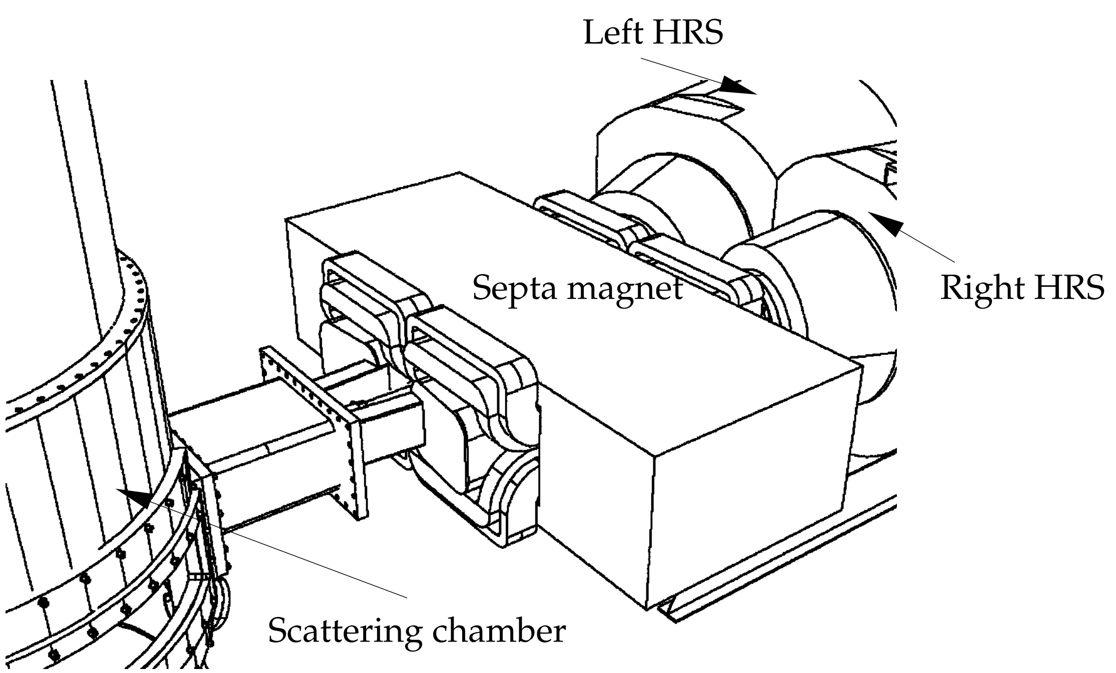
Use PREX septa to achieve smaller central angle (5°)

Excellent momentum and angular resolution

⇒ mass resolution controlled by multiple scattering in target

HRS Right Arm





Experimental Design: Tilted wire mesh target

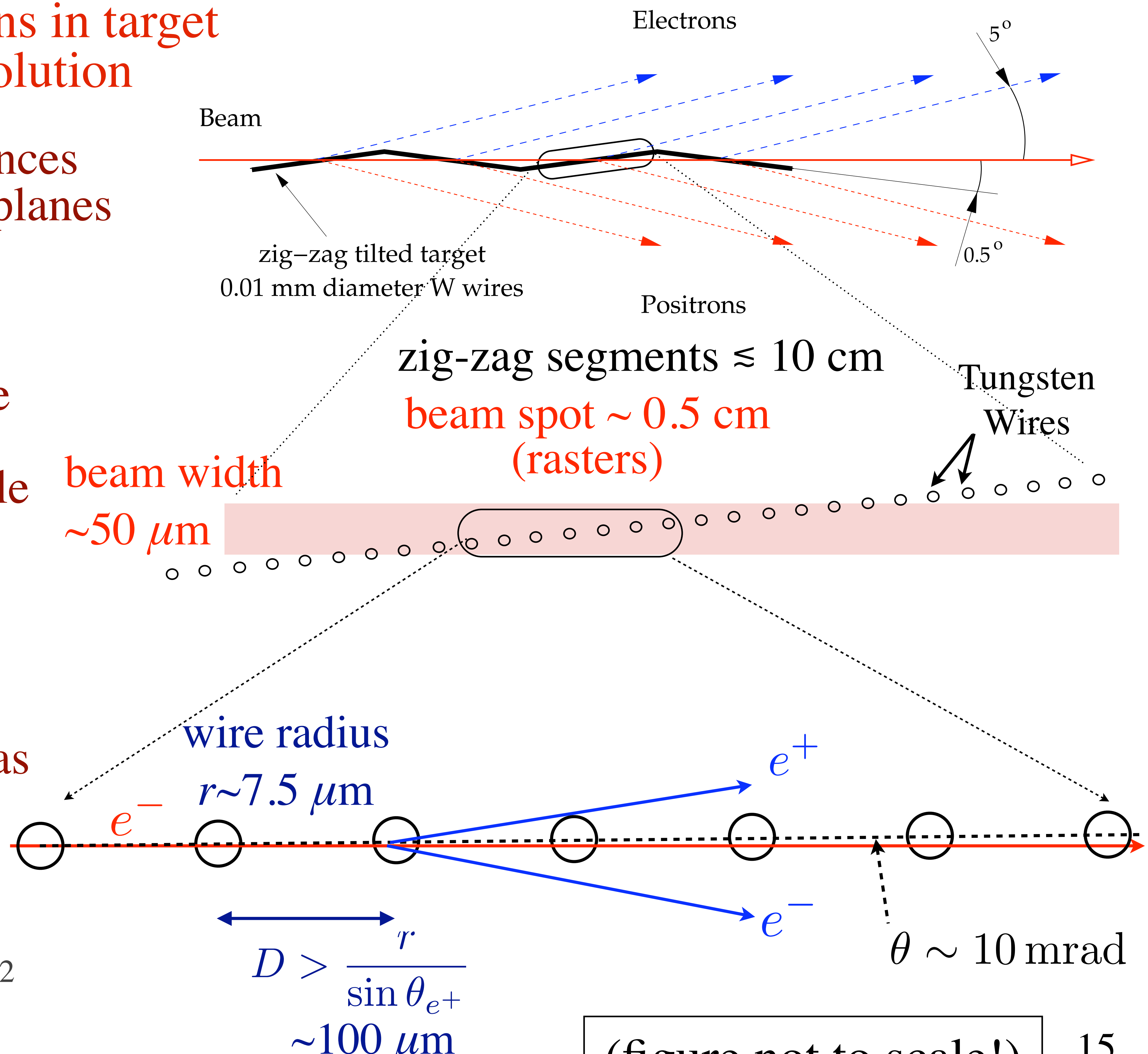
Multiple interactions in target dominate mass resolution

Accidental coincidences from different wire planes rejected off-line

Long target
⇒ range of effective angles ±15% from nominal central angle
⇒ broader mass range accessible at each setting

Angled wire plane has $T_{\mathbf{beam}} \gg T_{\mathbf{products}}$

Heat load ~25 W/cm² of wire surface



(figure not to scale!)

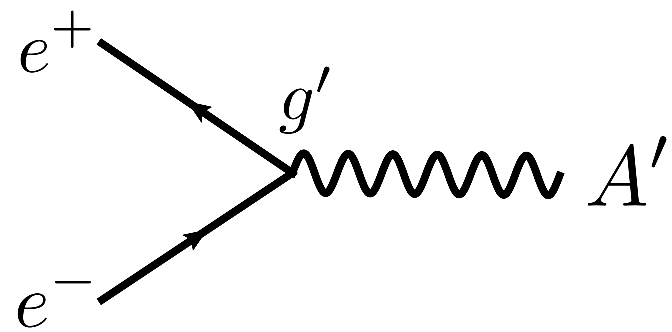
Experimental Design: Run Plan and Sensitivity

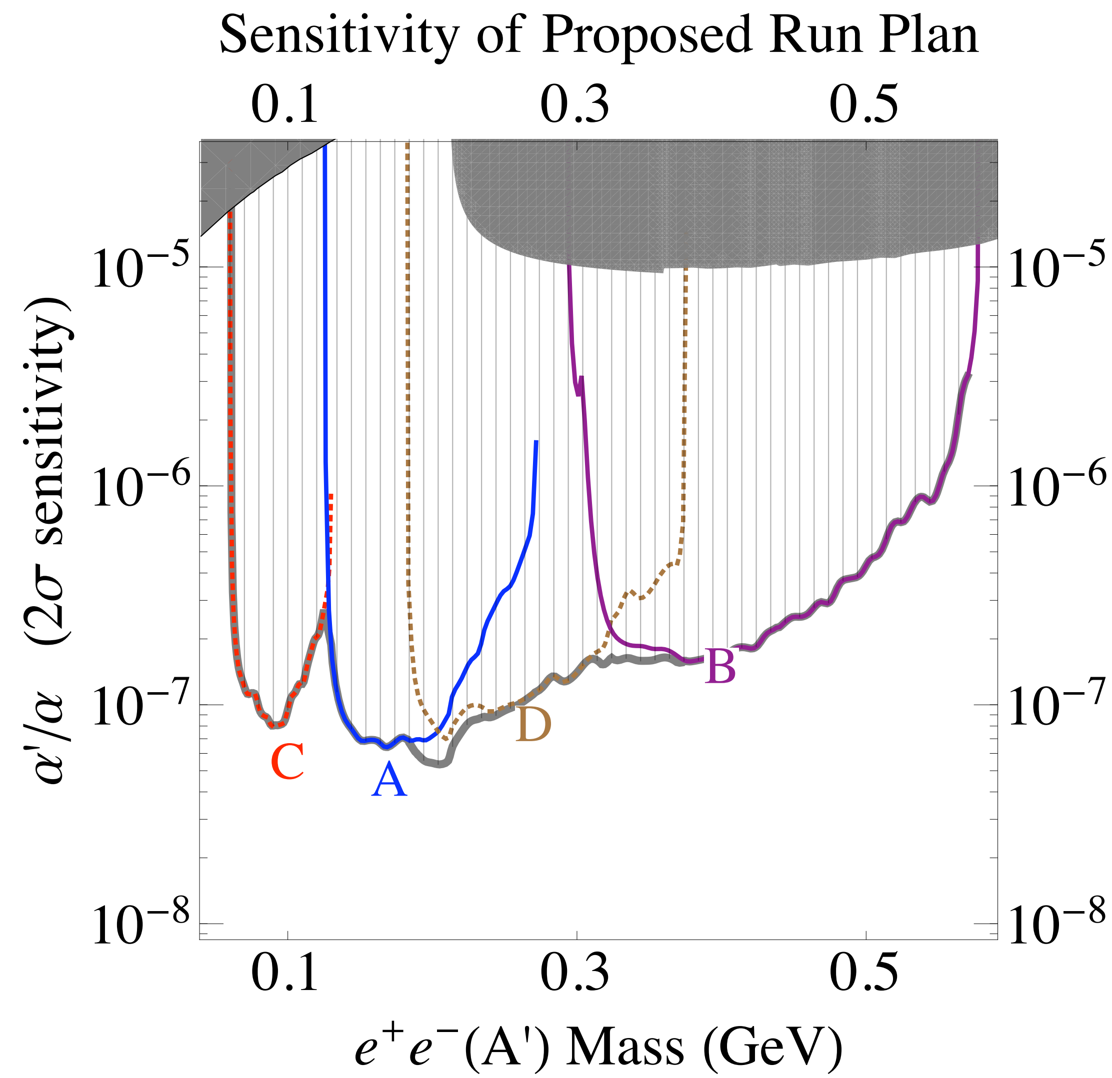
Settings	A	B	C	D
Beam energy (GeV)	2.302	4.482	1.1	3.3
Beam current (μA)	75	75	75	75
Nominal central angle	5.0°	5.5°	5.0°	5.0°
Time Requested (hrs)				
Energy change	–	4	4	4
Angle change	–	16	–	–
Magnet setup	4	4	4	4
Optics calibration	4	4	4	4
10% $\mathcal{L}$	2	2	2	2
Normal $\mathcal{L}$	144	288	144	144
Total	154	318	158	158

4 energy settings
2 angle settings [could be reduced to one]

33 days total (30 days beam)

Conclusions





- An MeV–GeV gauge boson A′ may explain a wide range of new-physics and dark matter anomalies, and arises naturally in simple models
- Experiment would have **enormous** impact; great interest from theory community.
- **JLab Hall A is ideal:** ready equipment, high resolution, momentum selectivity, unprecedented statistics.
- In 30 beam-days, achieve 10,000 x statistics, 100 x cross-section sensitivity of previous searches. **Excellent discovery potential!**

Backup Slides

Experimental Design: Count Rates and Trigger (75 μA current)

Settings	A	B	C	D
Beam energy (GeV)	2.302	4.482	1.1	3.3
Central angle	5.0	5.5	5.0	5.0
Target T/X_0	4.25%	10%	0.58%	10%
Central momentum (GeV)	1.145	2.230	0.545	1.634
Singles (negative polarity)				
e^- (MHz)	4.5	0.7	6.	2.9
π^- (MHz)	0.64	2.20	0.036	2.50
Singles (positive polarity)				
$\pi+$ $[p]$ (kHz)	640.	2200	36.	2500.
e^+: QED (kHz)	31.	3.6	24.	23.
e^+: π^0 decay (kHz)	2	7	0.03	9
Total e^+ (kHz)	33.	10.6	24.03	32.
Trigger/DAQ				
Accidental trigger(kHz)	3.55	0.47	2.93	3.33
True coinc. trigger (kHz)	0.65	0.09	0.36	0.6
Total trigger (kHz)	4.20	0.56	3.29	3.93
Offline Signal & Background Rates				
QED e^+e^- (Hz)	610	70	350	530
Two-step (Hz)	35	15	5	75
Accidental Background (Hz)	74	3.8	72	47

Main Trigger:
Coincidence of S0 signals in both arms (20 ns)
and
between S0 and Gas Cherenkov signals in positive arm (40 ns)

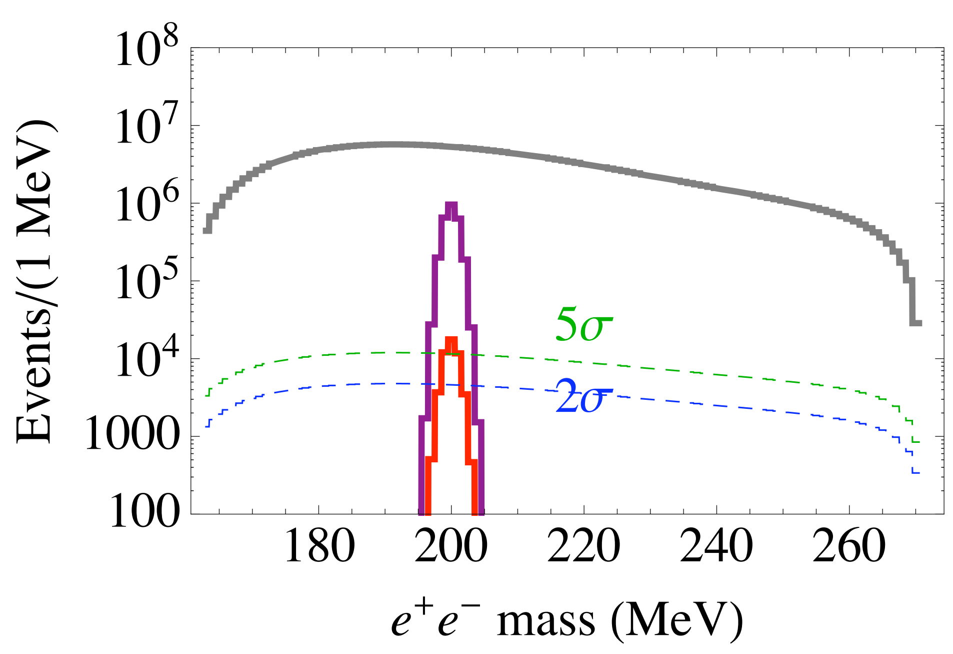
Each setting:
~10^8 QED e^+e^- events in 6–12 days

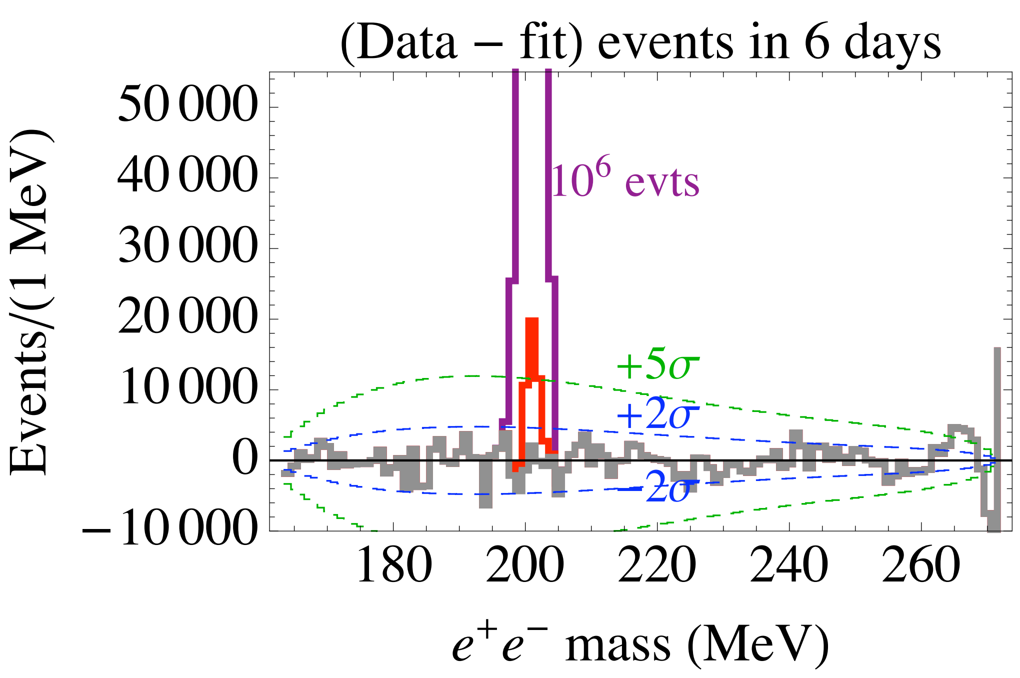
10,000 x more statistics than existing A′ searches in this mass range!

With offline analysis, **QED e^+e^- pairs dominate** over accidentals by factor of 5–20

Search requires uniformity at 10^{-3} level in 1% mass intervals – How can this be achieved?

- Accidental coincidence events allow measurement of smoothness of acceptance in accidental events with 20 ns window (10x more than signal), to level <1%
- Instrumental effects non-uniform in ***momentum*** or ***angle***, and get smoothed out in invariant mass





Is the 6 MHz rate a problem?

A) **Could the chamber operate?** – Yes, because:

- At 6 MHz the rate on individual wires of VDC is: (6000/368)*4.5 = 74 kHz per 15 cm active length. During elastic C-12(e,e') calibrations, VDC was used with the rate per wire of 30-100 kHz.
- New amplifier-discriminator cards allow to reduce gas multiplication by a factor of 10, so the saturation limit will be higher by a factor of 10.
- New A/D were used successfully with the rate per wire up to 250 kHz in BigBite.

B) **How many tracks will be observed?** – Two

- The maximum drift time is about 350 ns $\Rightarrow$ 2 extra tracks per event.

C) **How will the false tracks be identified?** A rejection factor > 100

- Timing scintillator plane is segmented to 16 paddles and the shower detector segmented to 48 counters $\Rightarrow$ rejection factor > 10
- The correlation between "upper" and "lower" segments of the track provides a rejection factor of 10

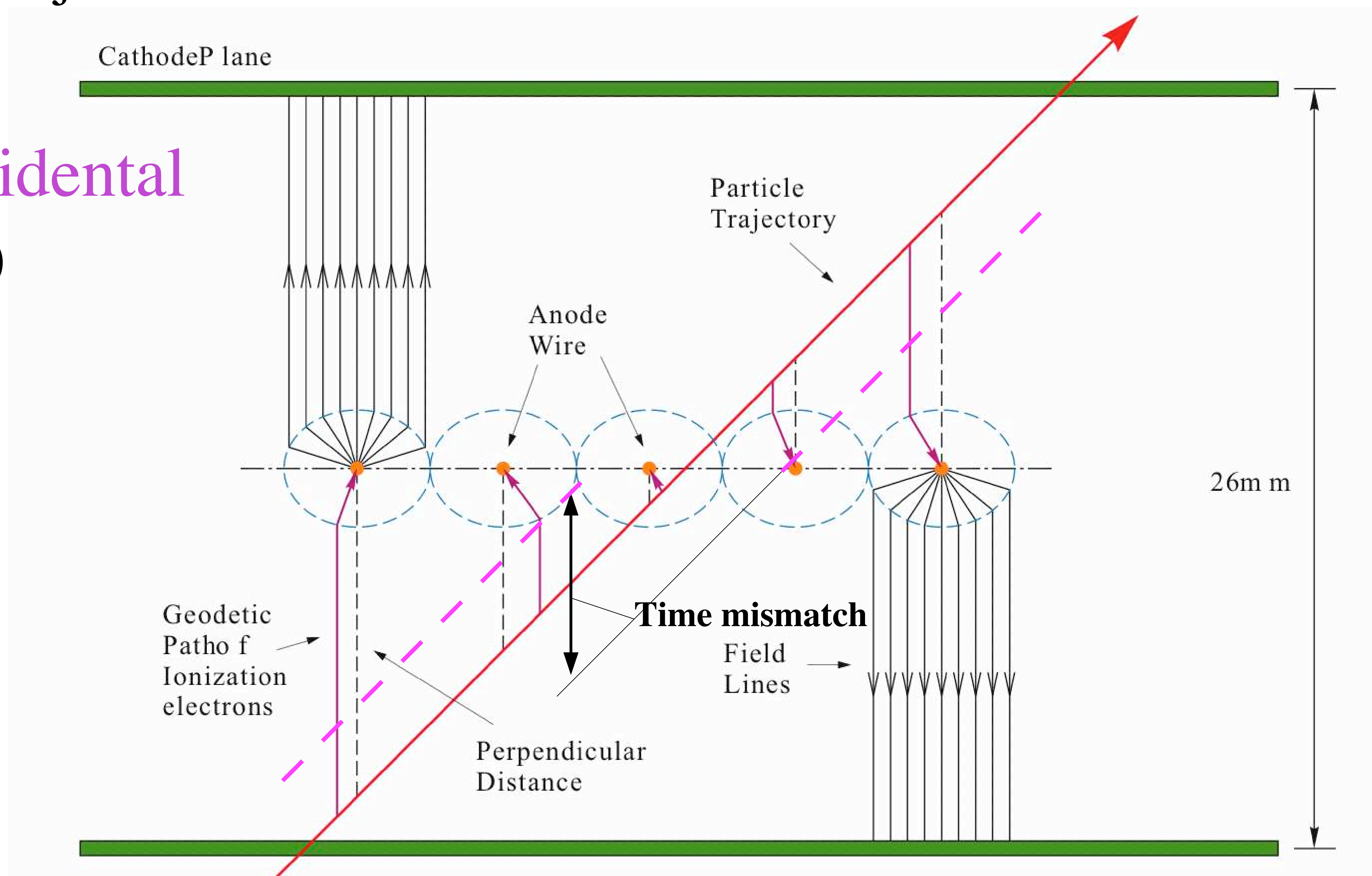
  (see figure on next slide)

VDC Drift Scheme and False Track Identification

C) **How will the false tracks be identified?** A rejection factor > 100

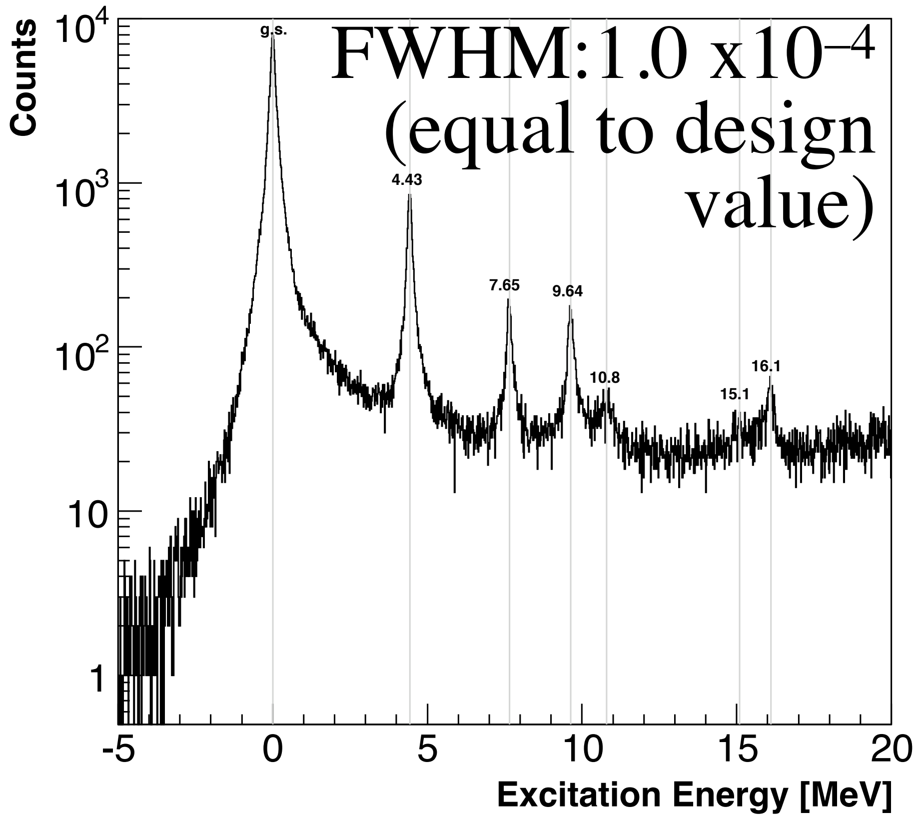
- Timing scintillator plane is segmented to 16 paddles and the shower detector segmented to 48 counters ⇒ rejection factor > 10
- The correlation between "upper" and "lower" segments of the track provides a rejection factor of 10

(Real and accidental tracks shown)

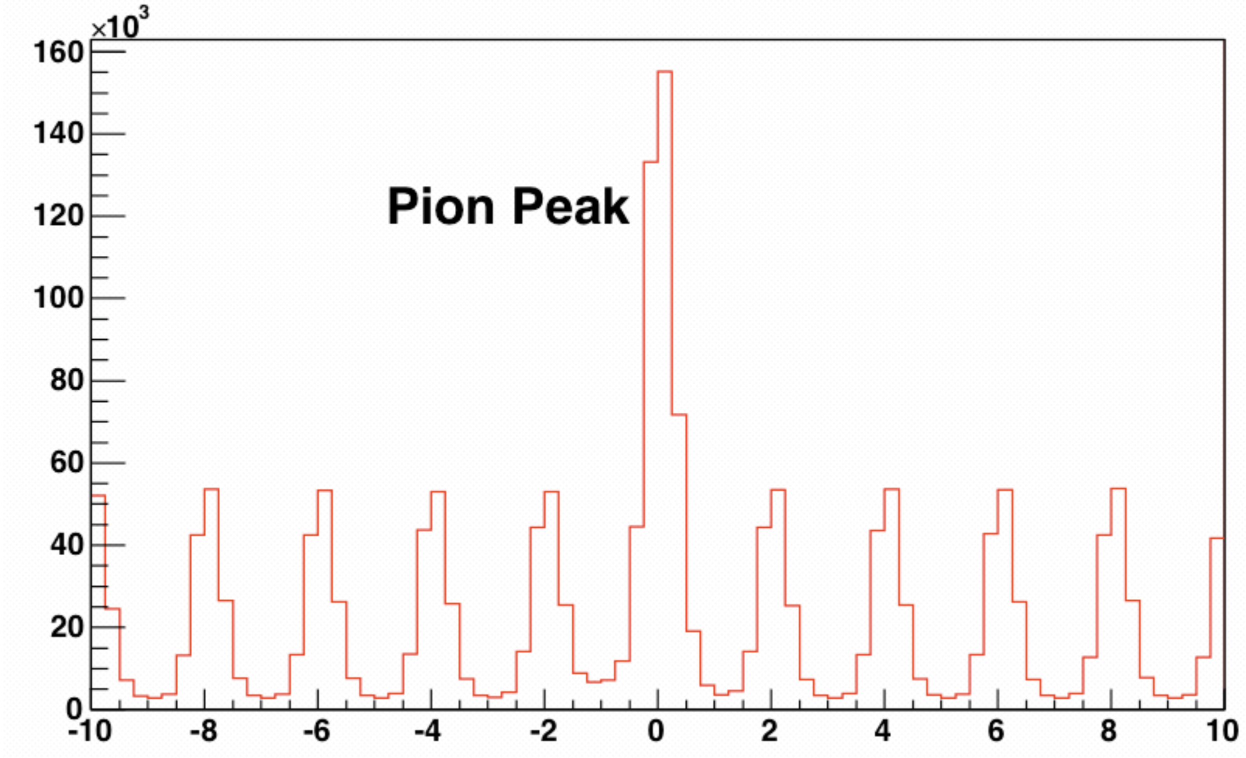


Experimental Design: HRS Performance with Septa

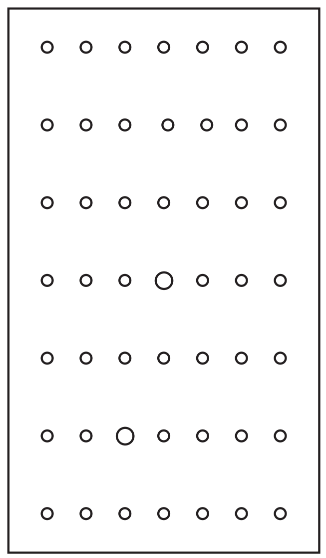
Energy resolution at 6°:

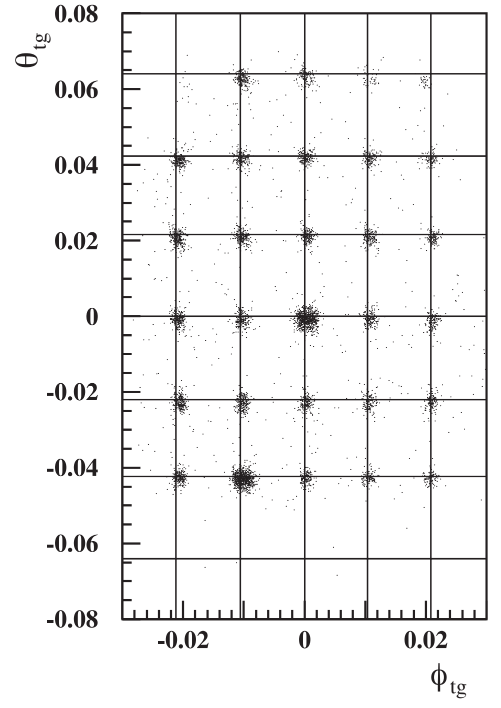


2ns beam structure is resolvable:

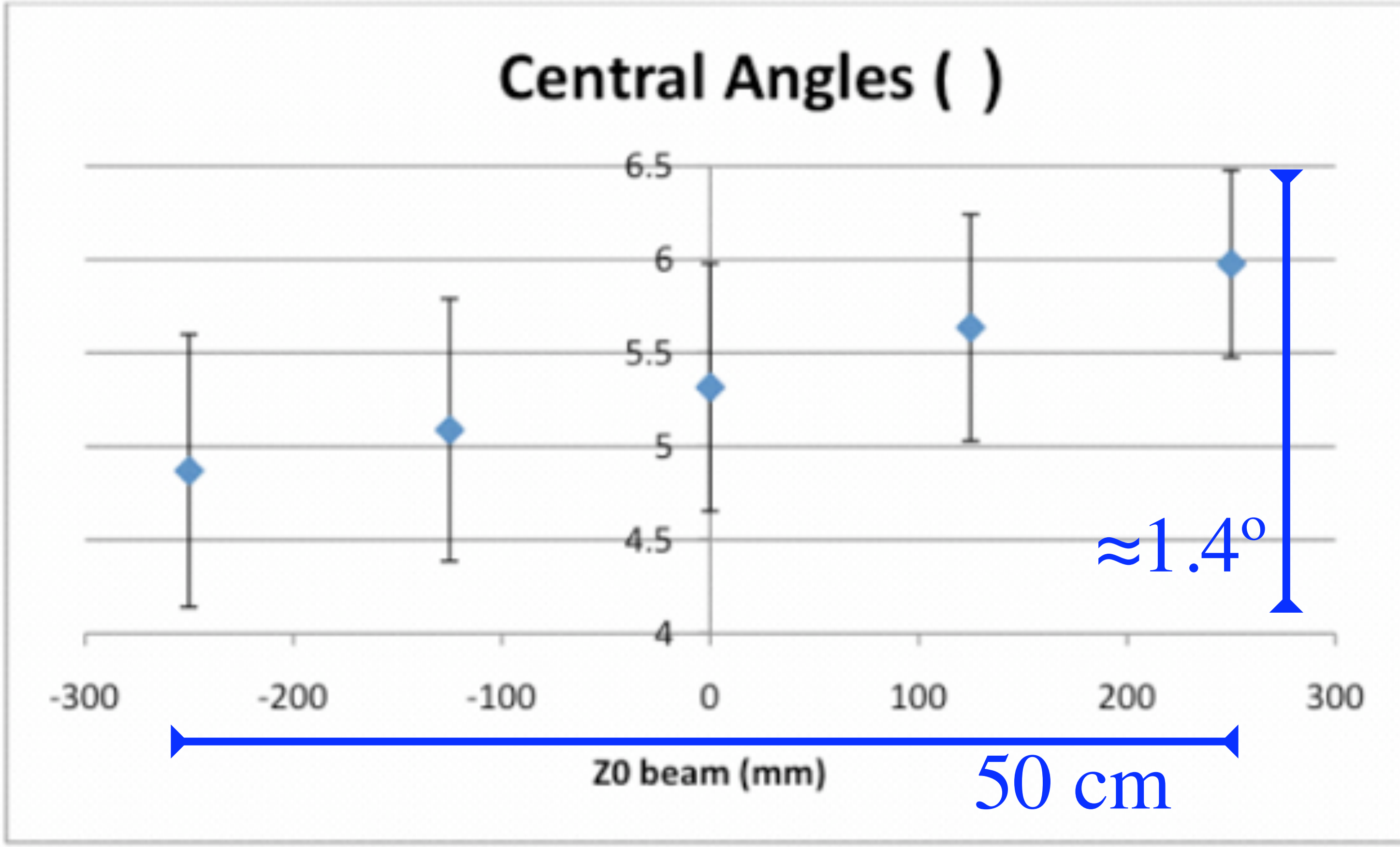


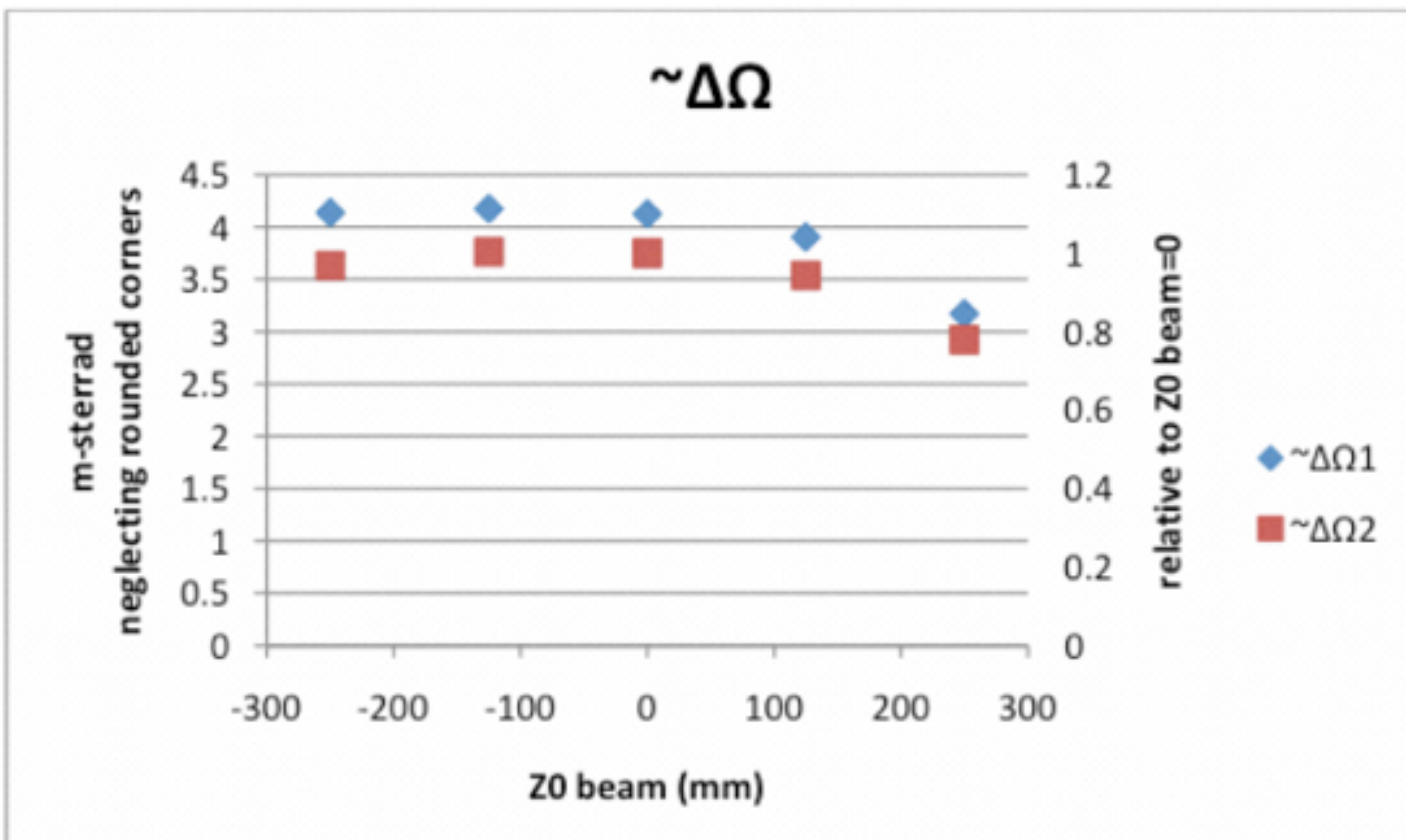
Angular calibration method:





Experimental Design: Performance for Long Target



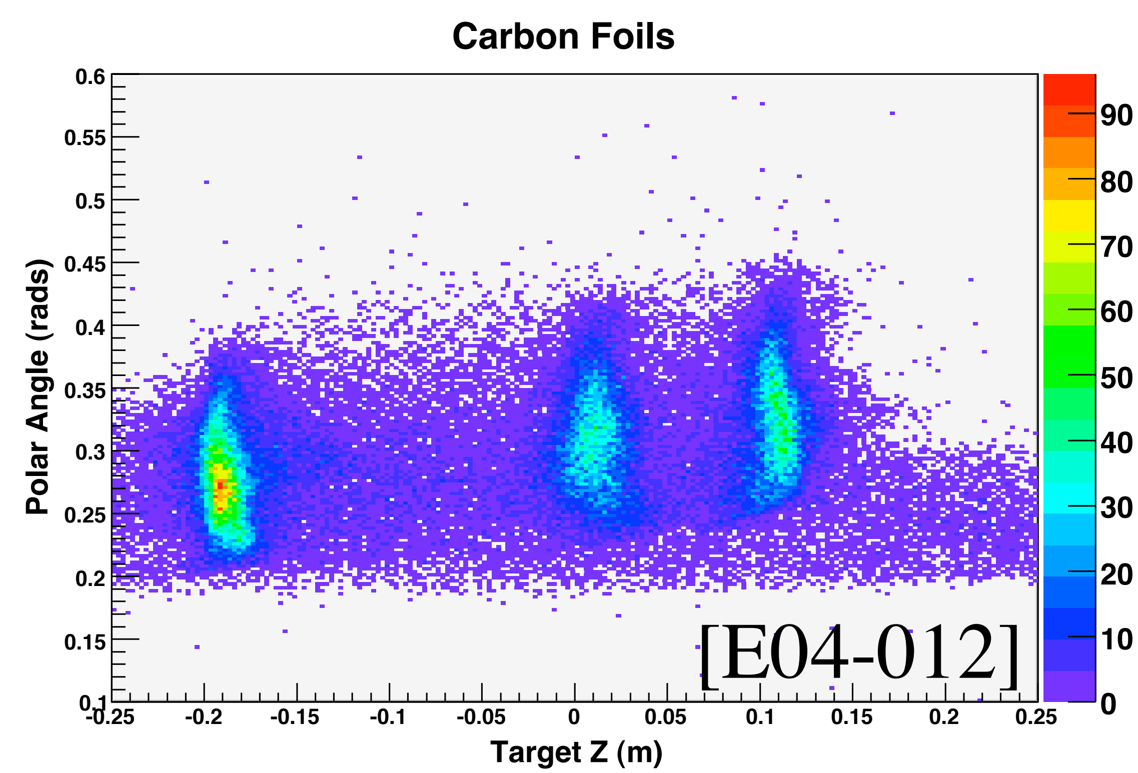


(MC simulation by J. LeRose)

Cover ±15% from nominal central angle – broadens mass range accessible at each setting

Good acceptance throughout angular range

Tracks pointing back to single mesh plane → can identify collision point for each event,



Difficulties searching at higher A′ mass ($\gtrsim$ 600 MeV)

Loss of statistics from:

A) Production rate ~ $1/(m_{A'})^2$

B) Larger mass ⇒ larger fraction of decays to $\mu^+\mu^-$, $\pi^+\pi^-$
⇒ lower efficiency in electron channel

C) Wider e^+e^- angles ⇒ lower acceptance in spectrometer

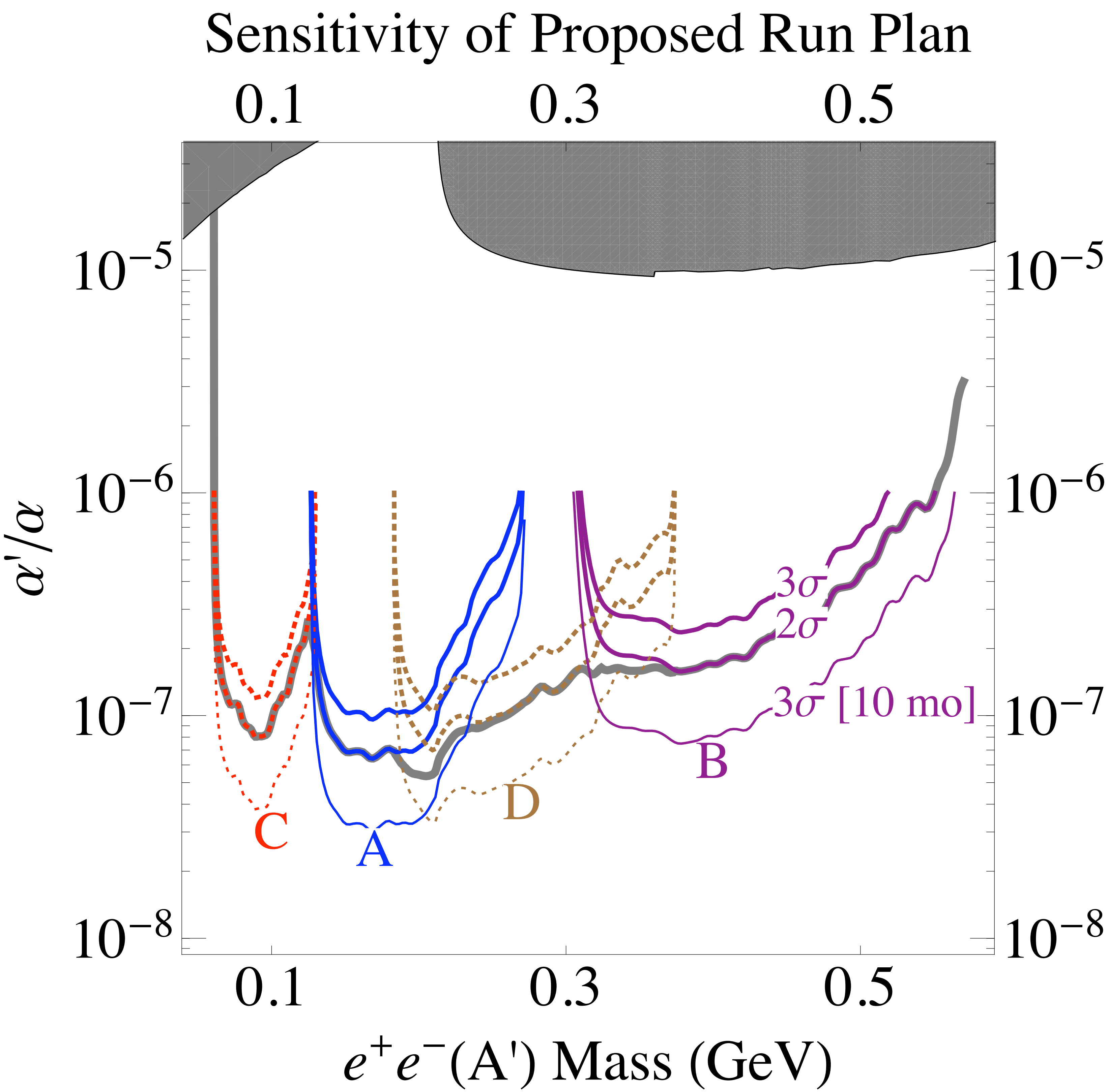
To maximize statistics, need experiment with:

A) Larger luminosity tolerance

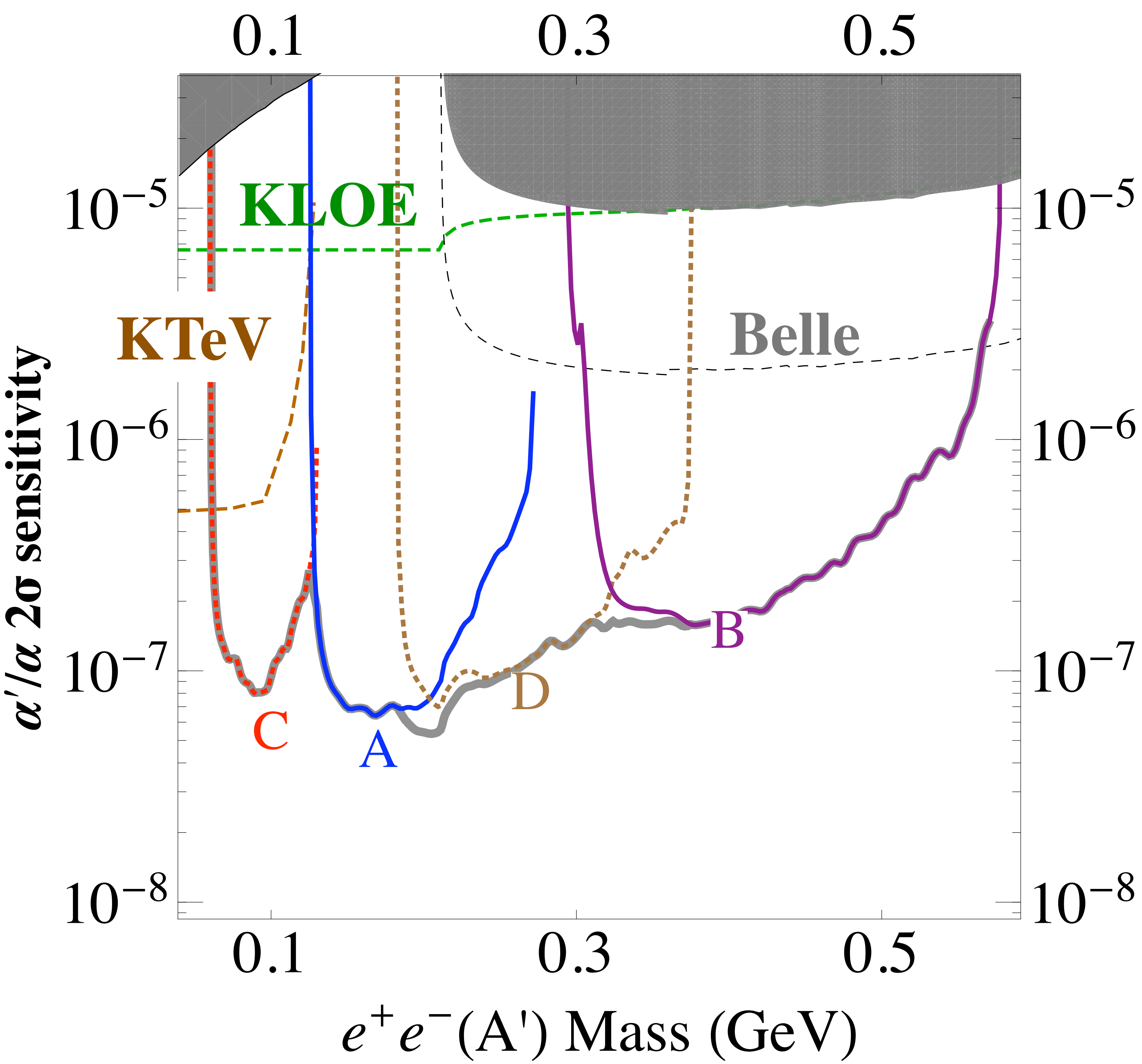
B) Sensitivity and Particle ID for μ, π

C) Larger-acceptance spectrometers

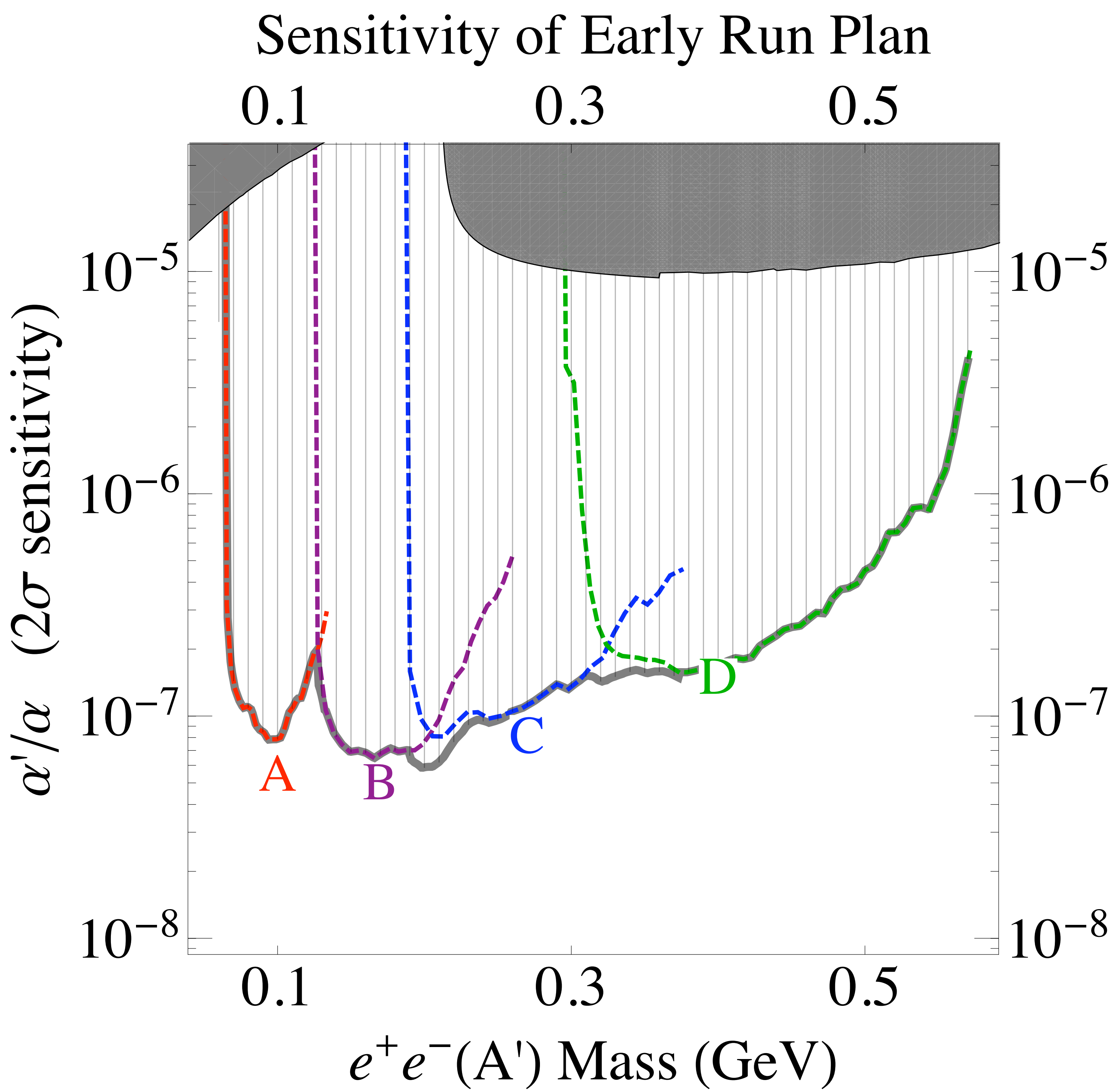
Detailed Sensitivity Plot and Comparison to 10-Month Run



Detailed Sensitivity Comparison to Potential Searches



Possible Results with 6 GeV energies



Symmetric momenta

- After restricting to symmetric angles $\theta_+ = \theta_-$, and total momentum $E_+ + E_- \approx E_{beam}$, signal is peaked at symmetric momenta:

(same distribution for QED coincidence backgrounds)