

*The Heavy Photon Search experiment
at Jefferson Laboratory*



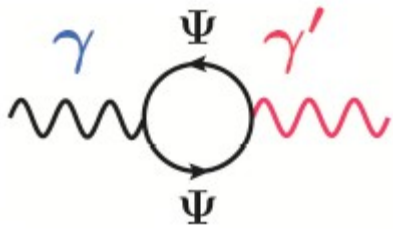
*A. Celentano
(INFN – Genova)
on behalf of the HPS collaboration*

Outline

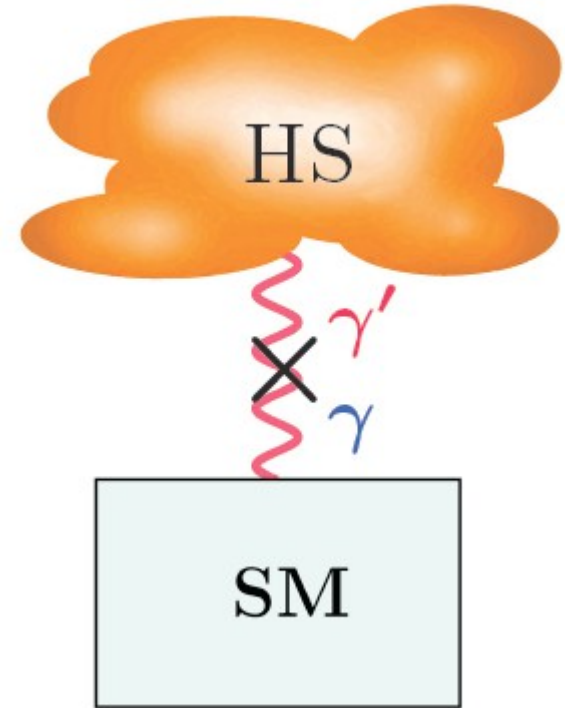
- **Dark photons: introduction**
 - Theoretical motivations
 - Experimental hints for dark photons existence
 - Results from previous experiments
- **Dark photons searches with fixed-target experiments**
 - Experimental overview
 - Signal and background signatures
- **The HPS experiment at Jefferson Laboratory**
 - Experimental reach
 - The HPS detector in Hall-B at Jefferson Laboratory
 - Results from the 2012 test run

Dark photons

- Consider an additional U(1) hidden symmetry in nature: this leads to a kinetic mixing between the photon and the new gauge boson A'



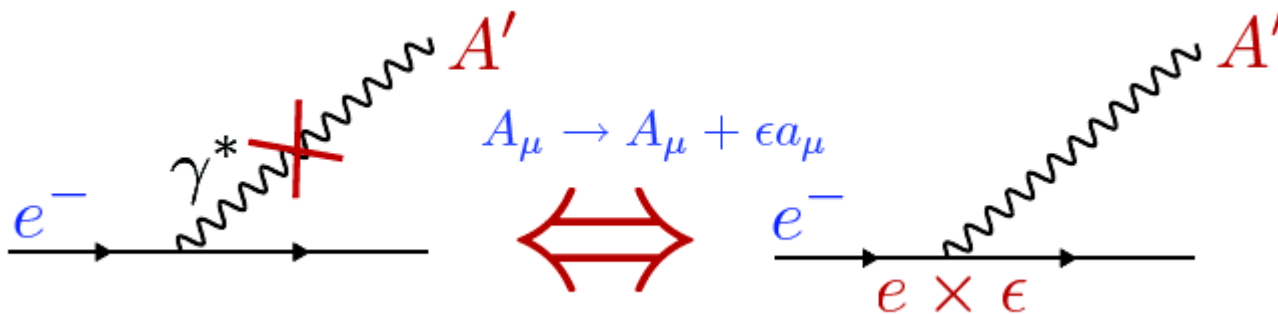
Ψ is a huge mass scale particle ($M \sim 1 \text{ EeV}$) coupling to both SM and HS



- General hypothesis to incorporate new physics in the SM: the A' acts as a “portal” between the SM and the new sector

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m_A^2 A'^\mu A'_\mu$$

- Under A' interaction, ordinary charged matter acquires a new charge ϵe :



New interaction term:

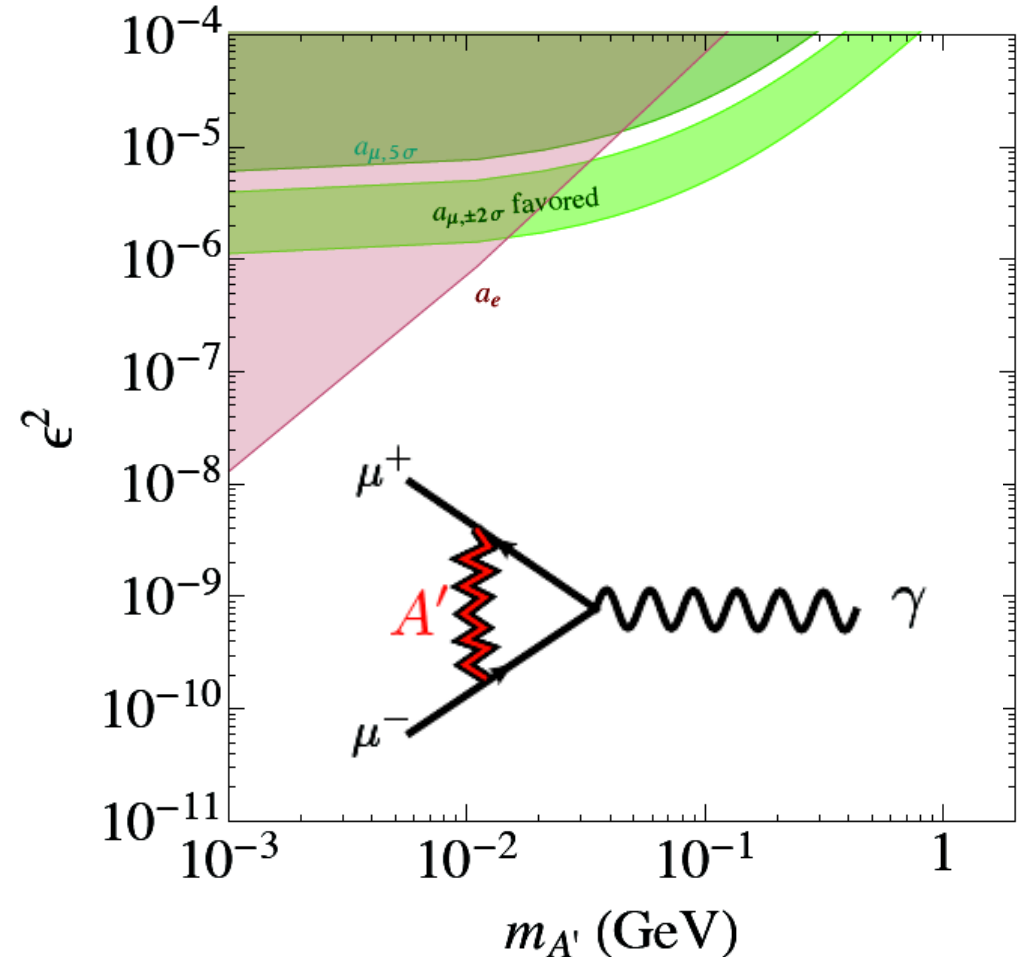
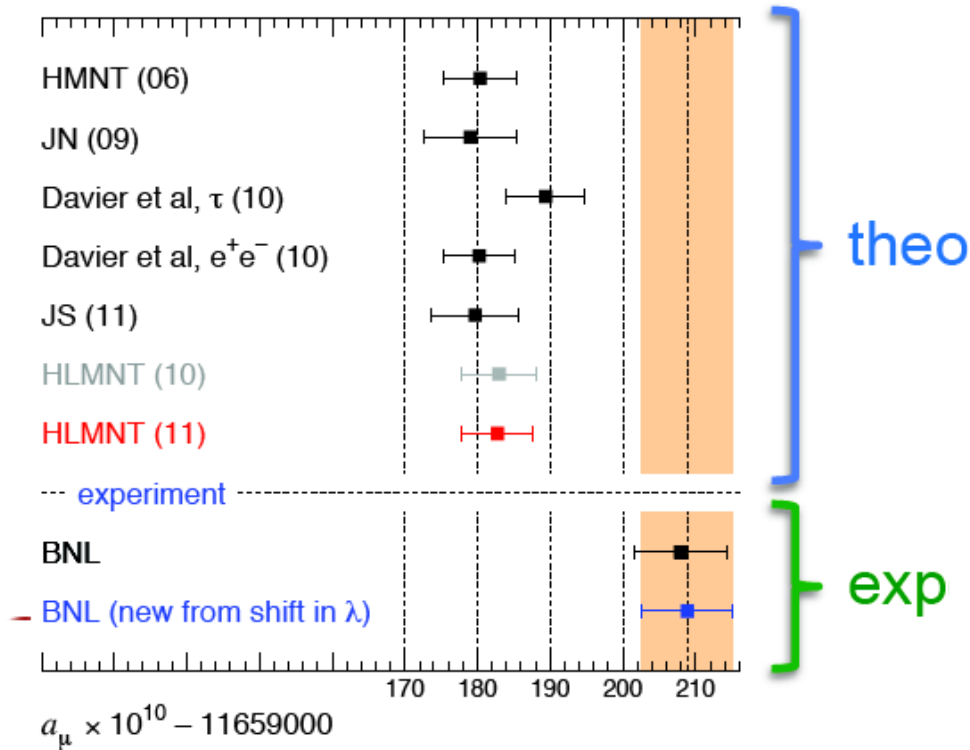
$$\epsilon A'_\mu J_{EM}^\mu$$

Hints for A' existence: precision physics

Muon anomalous magnetic moment ($g-2$)

- $> 3 \sigma$ deviation experiment – SM prediction
- 10-100 MeV A' could explain the anomaly

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

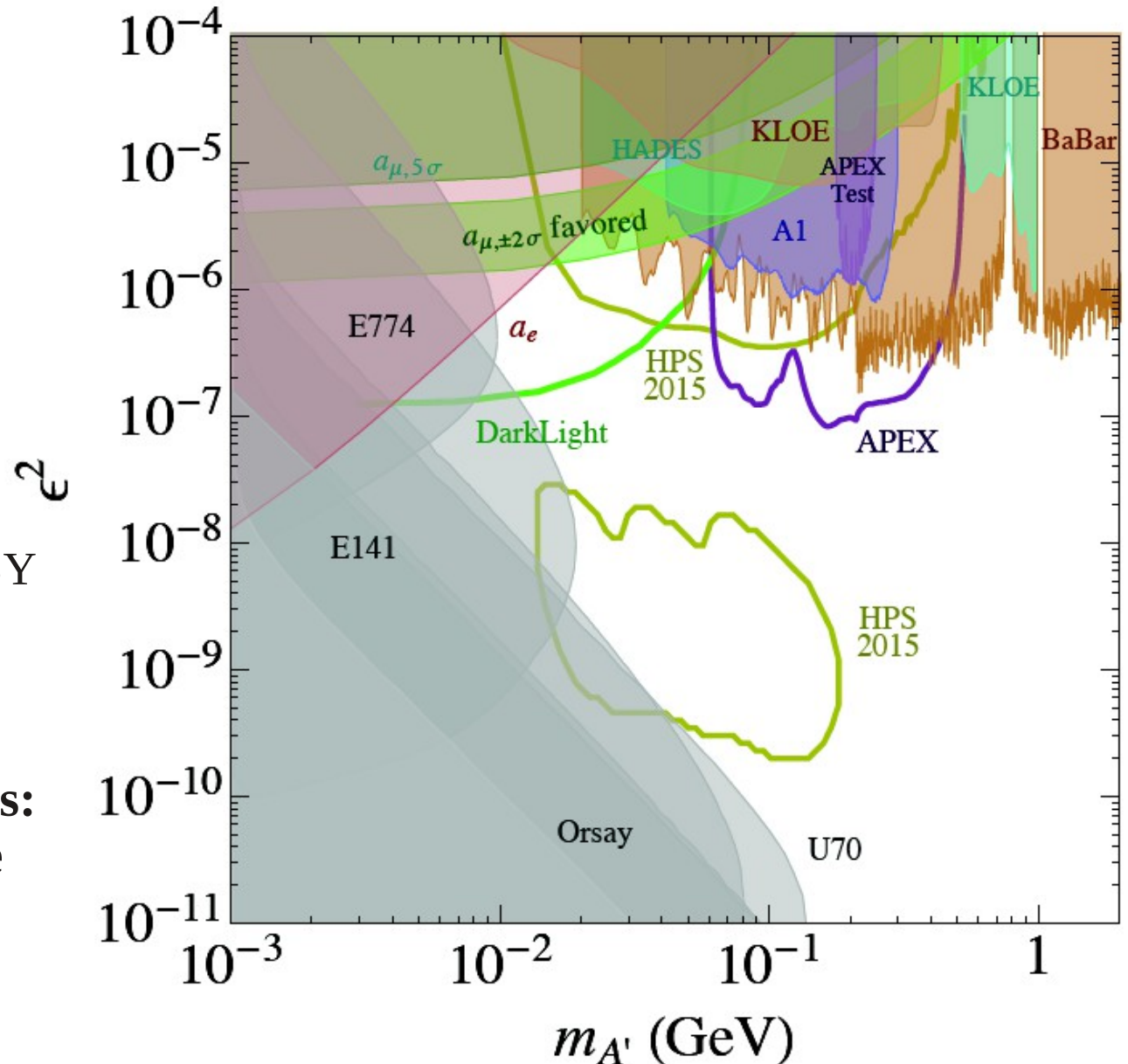


A' current searches and constrains

Any γ -rich environment is suitable for A' searches.

- Fixed target with e^- beam
 - JLab, Mainz
- Fixed target with p beam
 - Fermilab
- Annihilation
 - BABAR, BELLE, KLOE
- Meson decay
 - KLOE, BES-3, WASA-COSY

So far, no positive A' evidences:
limits in the parameters space

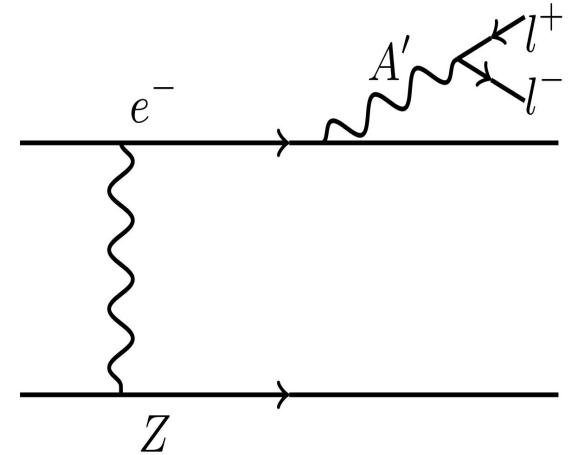


A' searches with fixed target experiments

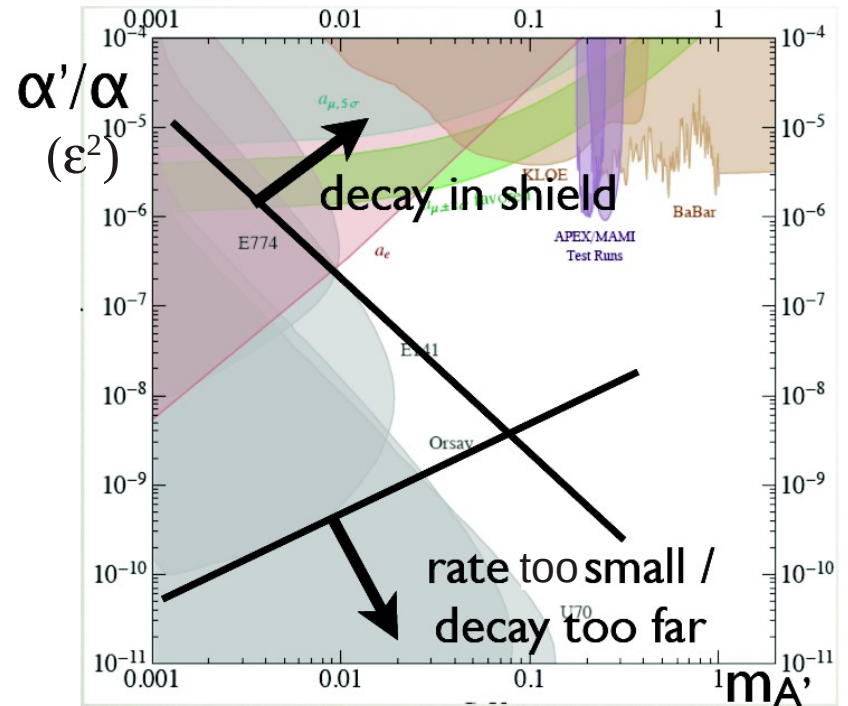
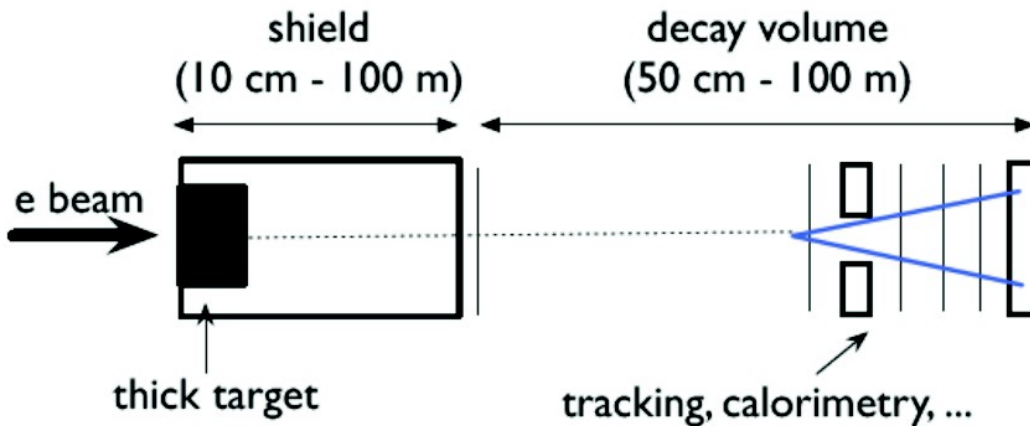
First generation fixed-target experiments: beam dump

$$\sigma \simeq \frac{\alpha^3 Z^2 \epsilon^2}{M^2} \simeq O(pb)$$

- e^- beam incident on thick target
- A' is produced in a Bremsstrahlung-like process
- A' emitted forward at small angle:
 - Carries most of the beam energy
 - Decays before the detector
- A' decay products are measured in the detector



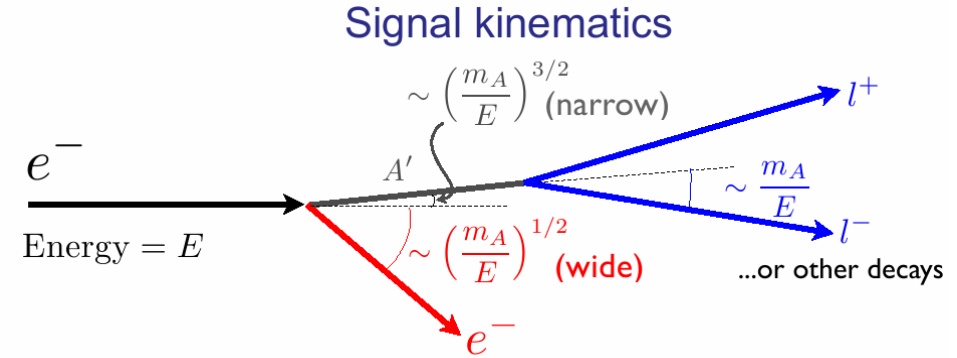
$$\gamma c\tau \approx 1 \text{ mm } (\gamma/10) (10^{-8} \alpha/\alpha') \times (100 \text{ MeV}/m_{A'})$$



Fixed target experiments: kinematics and backgrounds

A' signal kinematic features:

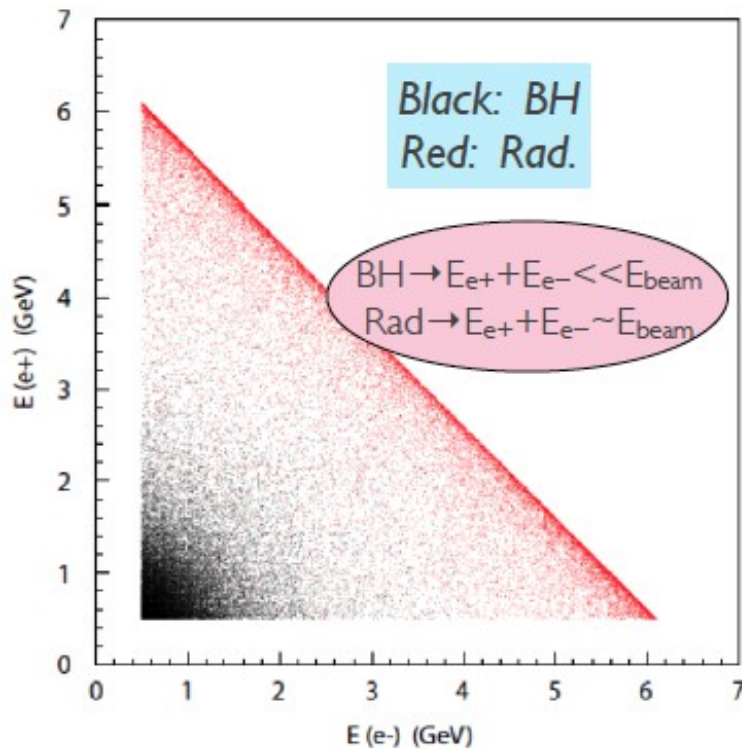
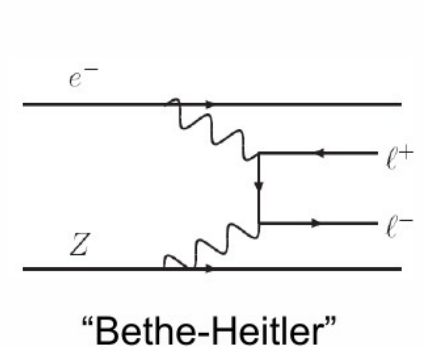
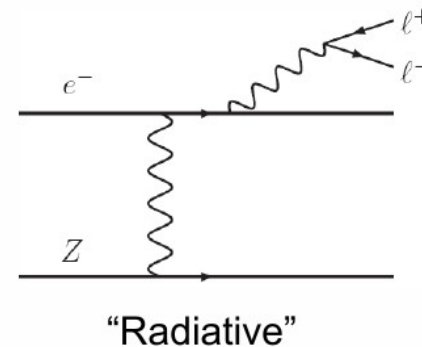
- Very forward A' emission angle, $E_{A'} \sim E$
- Decay products opening angle $\sim m_{A'}/E$
- Possible detached decay vertex



Main background sources:

- Radiative $l^+ l^-$ emission (irreducible)
- Bethe-Heitler processes (different kinematics)

Trident backgrounds



Signal searches:

- "Bump hunting" in narrow invariant mass windows
- Detached vertexing

The HPS experiment at JLab

The HPS experiment at JLab:

- Search for A' in a fixed tungsten-target setup with an e^- beam.
- Two complementary approaches:
 - Resonance search (traditional “bump hunting”)
 - **Detached vertex search**
- Use a high-rate, high-acceptance, high-resolution detector.

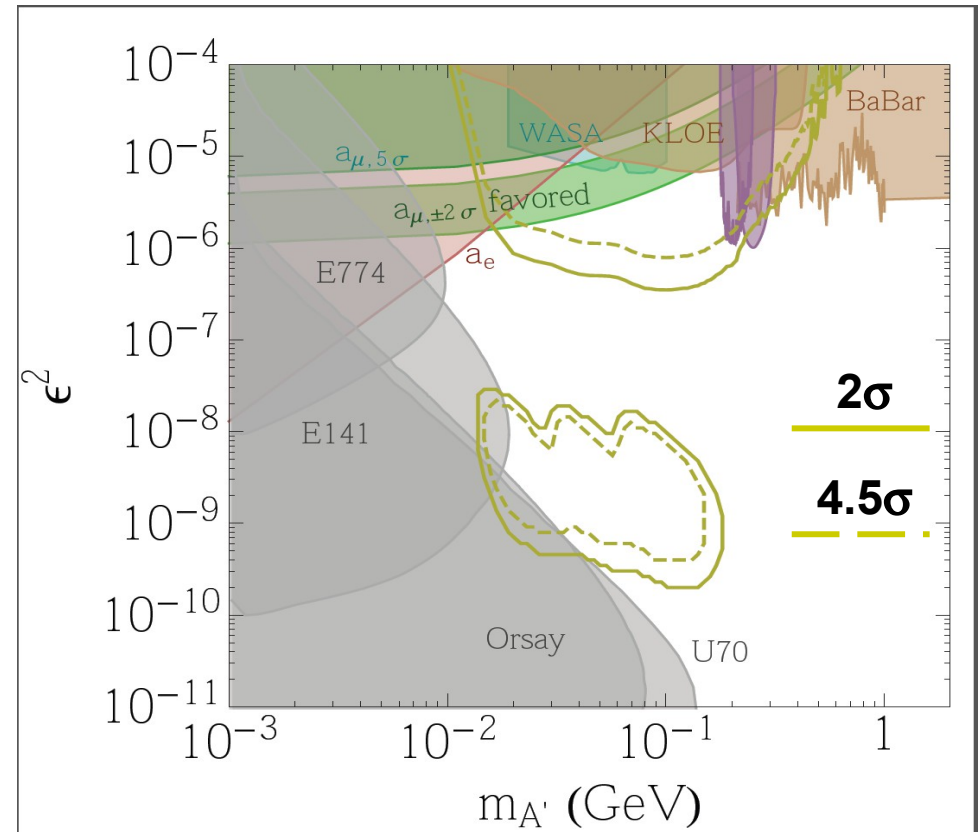
**JLAB officially approved experiment.
PAC41: high impact experiment!**

Data taking starts in Spring 2015.

Experimental reach:

- 1 week @ 1.1 GeV
- 1 week @ 2.2 GeV
- 2 weeks @ 4.4 GeV

Within few years HPS will explore a unique region in the A' parameter space.

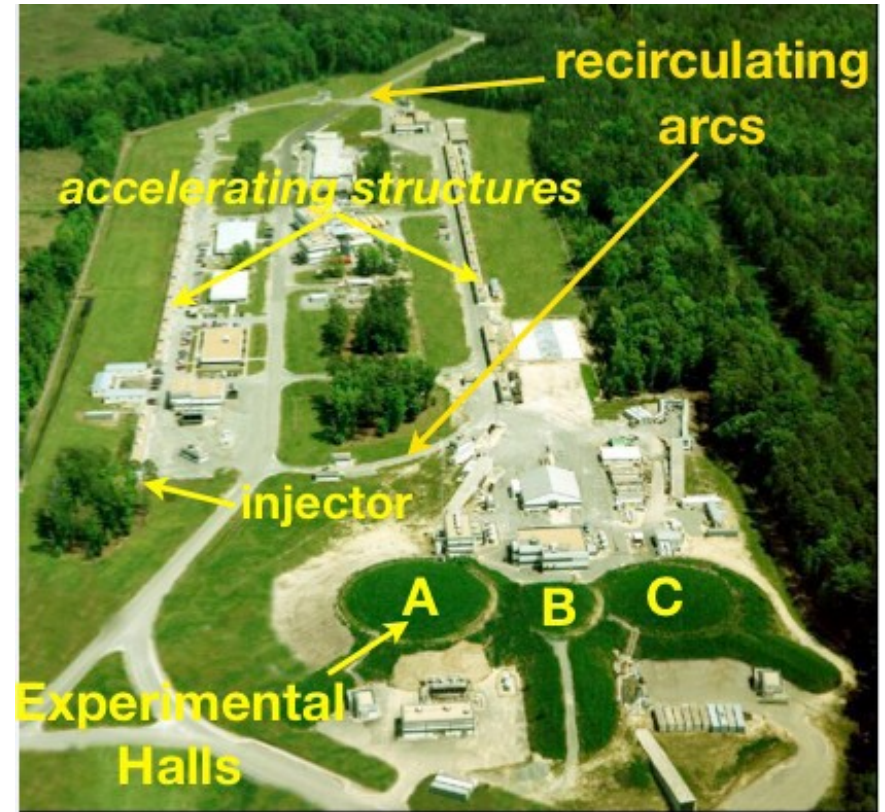
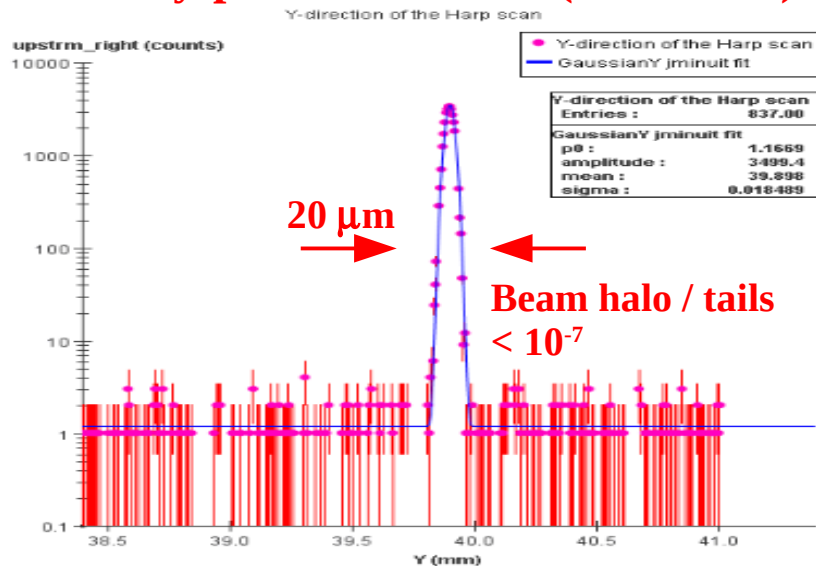


HPS in Hall B at Jefferson Laboratory

HPS will run in the Hall B of Jefferson Laboratory (Newport News, Virginia)
JLab recently completed the energy upgrade: from 6 to 12 GeV e^- beam

- Variable electron beam energy and intensity
 - $E_{\text{beam}} = n \times 2.2 \text{ GeV}$, $n < 5$
 - $I_{\text{beam}} < 800 \text{ nA}$ @ Hall B
 - $I_{\text{beam}} < 100 \mu\text{A}$ @ Hall A, C
- Quasi-continuous beam, 2ns bunches
- Excellent beam quality and stability

Beam y-profile in Hall B (6 GeV era)



Accelerator currently being commissioned
First beam in Hall-B expected in Nov. 2014

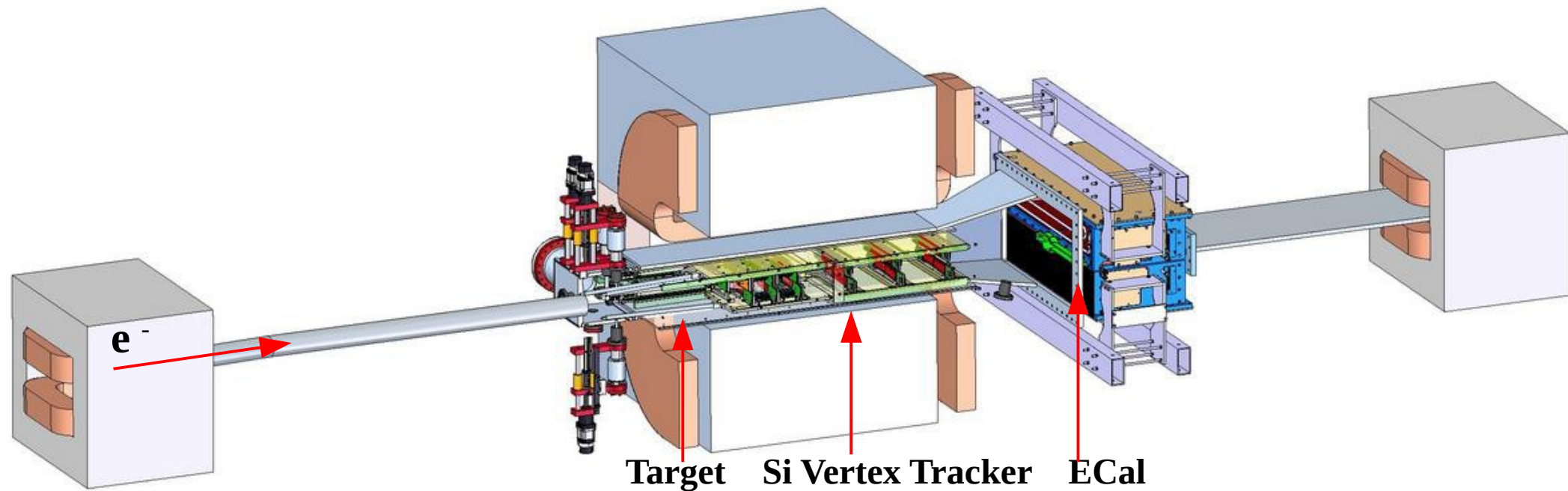
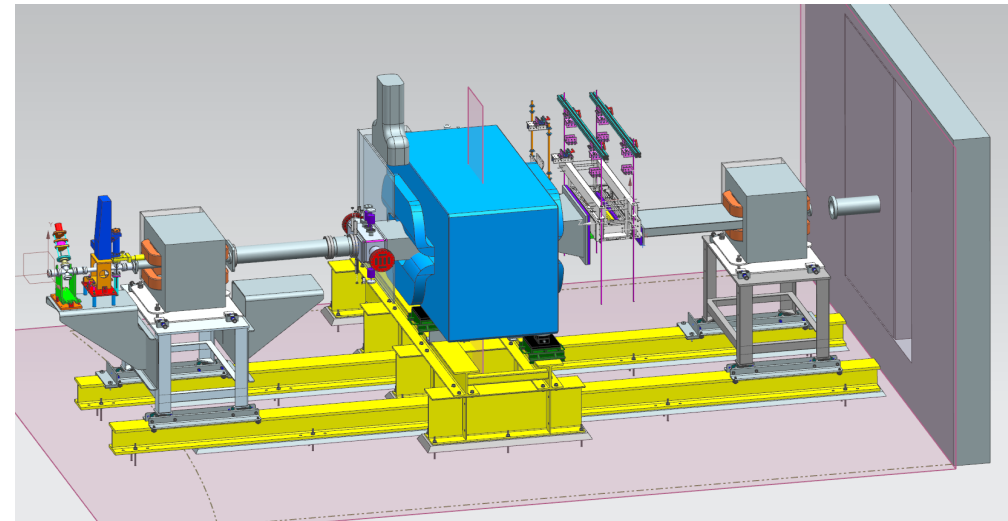
HPS detector

HPS will reside in the Hall B alcove, directly behind the general purpose CLAS12 detector, and before the Hall B dump.

HPS detector:

- Thin W target ($\sim 10^{-3} X_0$)
- Dipole magnet
- Si-tracker (6 layers w. axial/stereo modules)
 - Momentum analysis
 - Vertexing
- PbWO_4 calorimeter
 - Triggering

Hall B Alcove



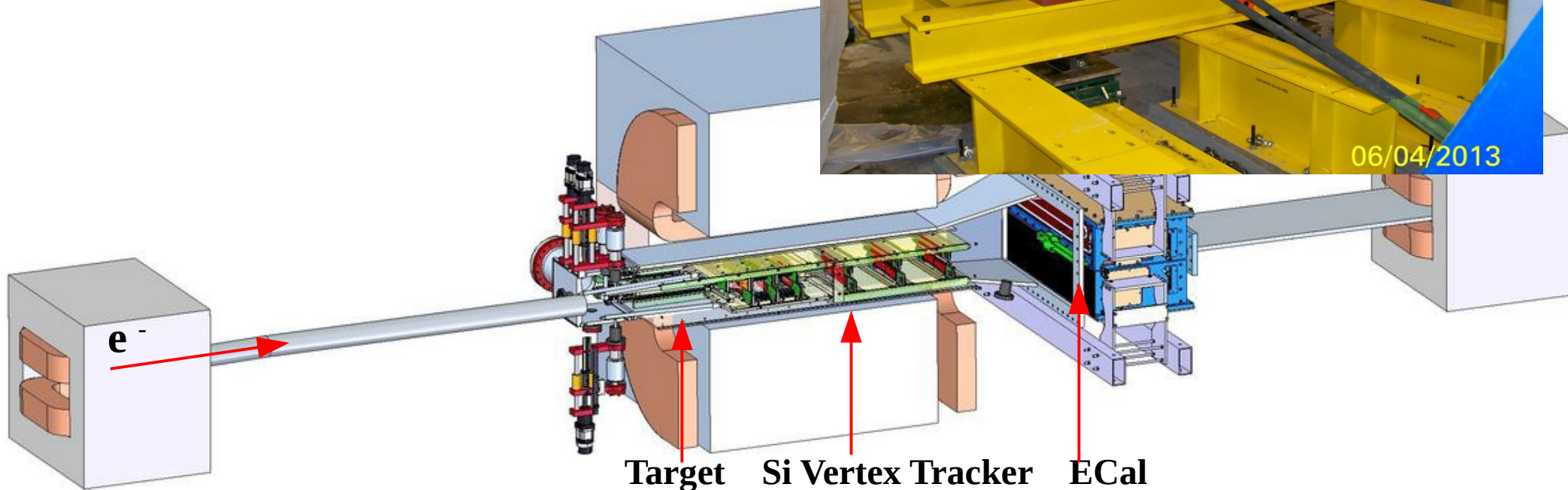
HPS detector

HPS will reside in the Hall B alcove, directly behind the general purpose CLAS12 detector, and before the Hall B dump.

HPS detector:

- Thin W target ($\sim 10^{-3} X_0$)
- Dipole magnet
- Si-tracker (6 layers w. axial/stereo modules)
 - Momentum analysis
 - Vertexing
- PbWO_4 calorimeter
 - Triggering

June 2014: first magnet installed in alcove!



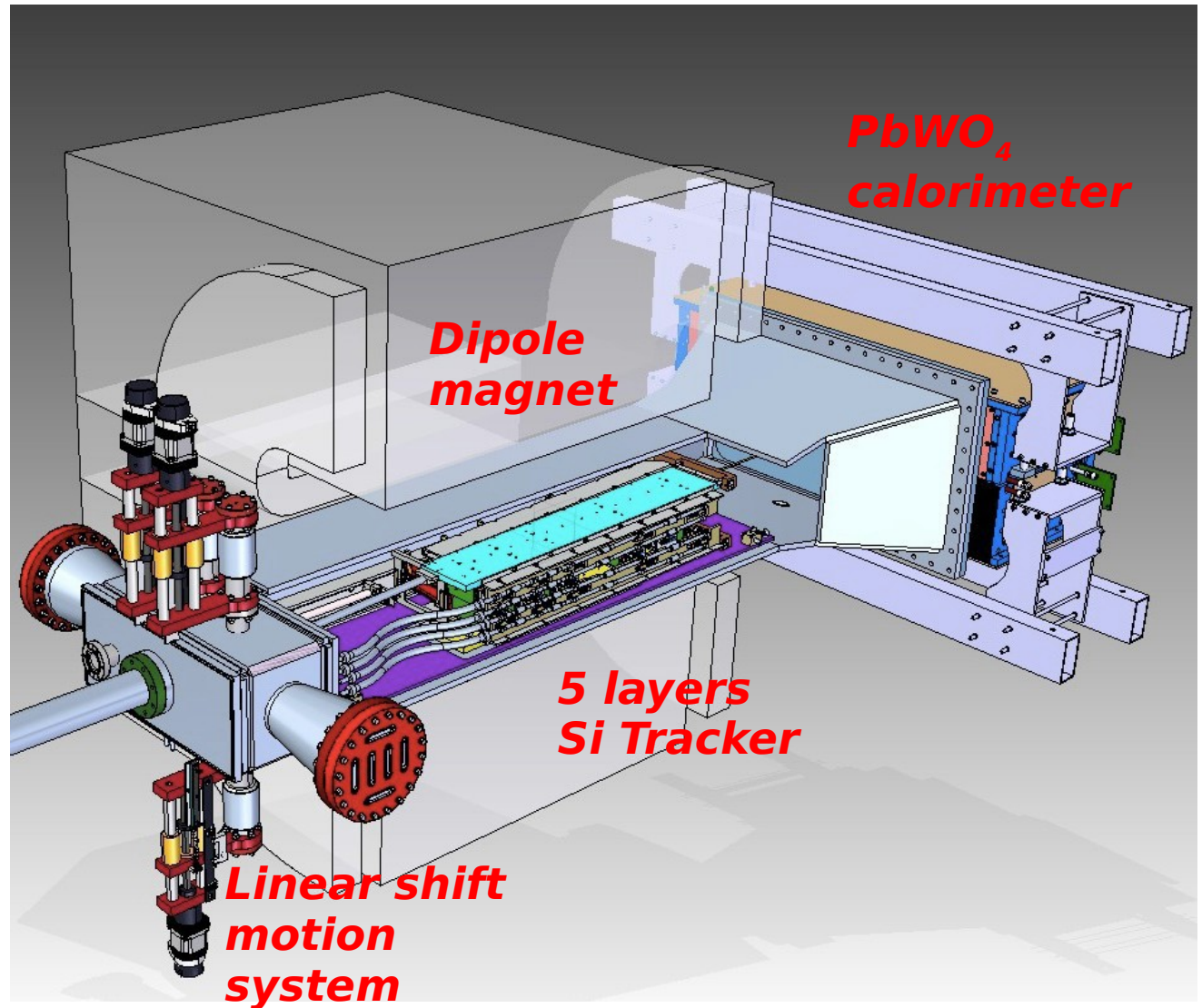
HPS 2012 test run

**First HPS phase:
the May 2012 test run.**

Test run goals:

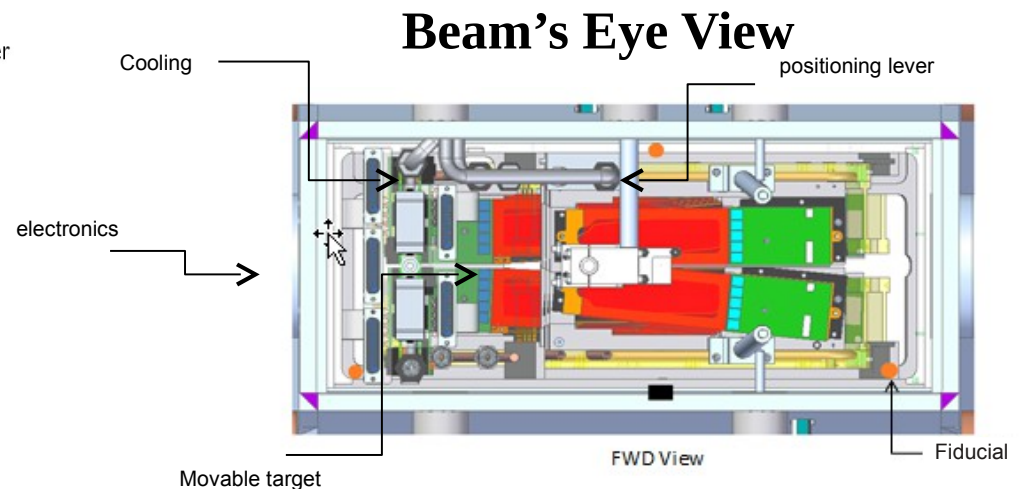
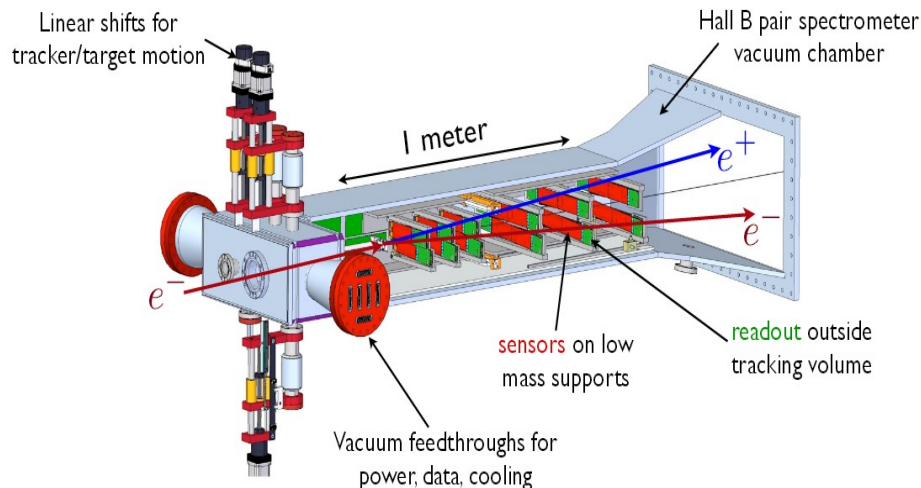
- Develop technical solutions
- Demonstrate operational principles
- Test detector performances
- Measure backgrounds

**Run in Hall B with photon
beam: parasitically + 8 hours
dedicated time.**



Si tracker

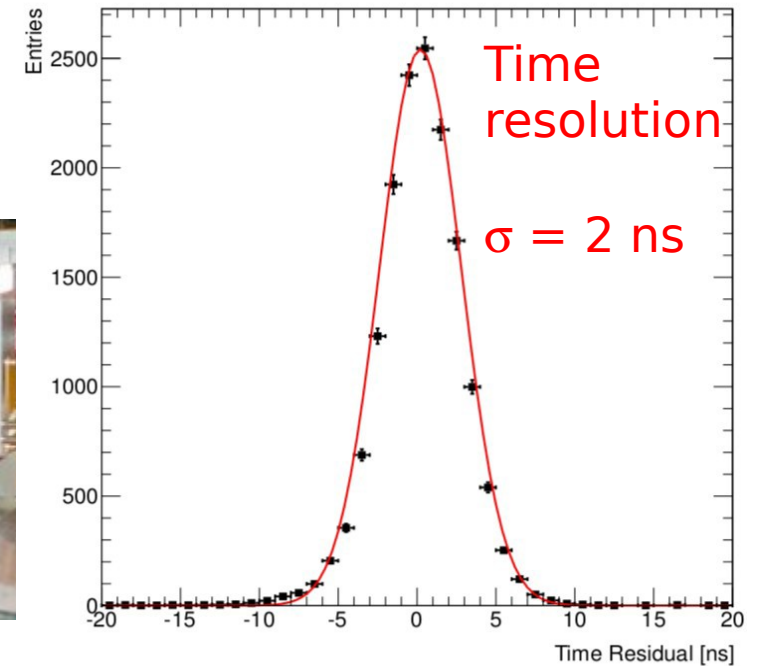
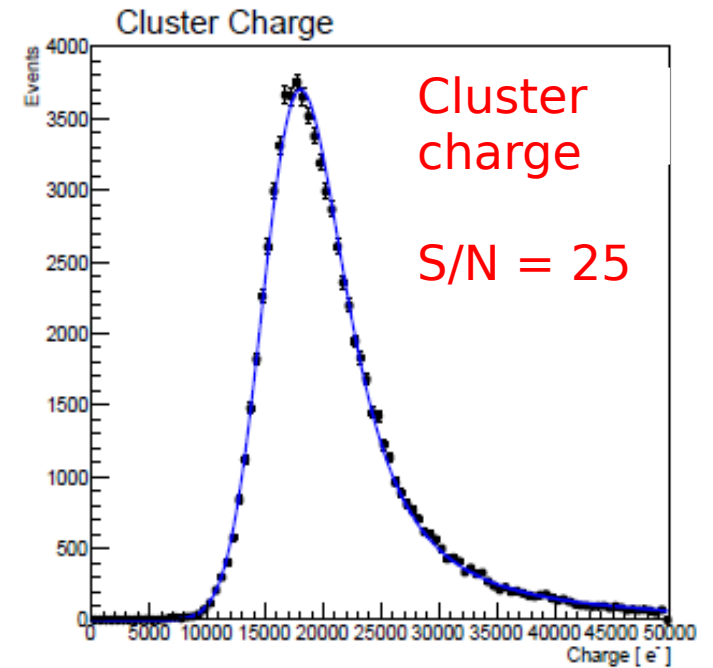
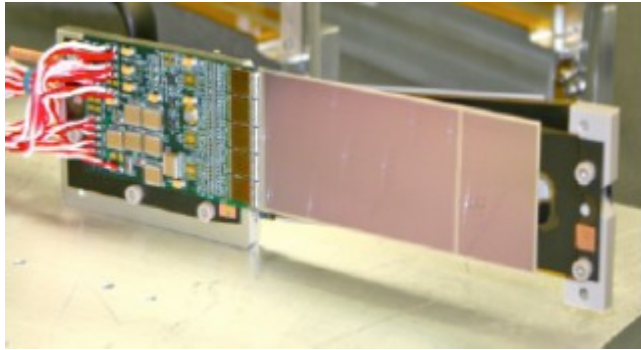
- **SVT Design:**
 - 6 layers of Si modules (top-bottom) each with two sensors: axial and stereo
 - 4x10 cm² Hamamatsu microstrip detector with 60 μm sense pitch.
- **Fast Readout:**
 - CMS APV25, 40 MHz continuous sampling, 3 μsec latency.
 - Power and control in/data out through vacuum feedthroughs.
 - Electronics and sensors cooled < 0° C to remove heat and boost radiation hardness.
- **Precision Movers:** position layers 1-3 close to the beam, do wire scans, and insert targets as needed.



HPS 2012 test run: Si tracker performances

HPS-2012 Si Vertex Tracker:

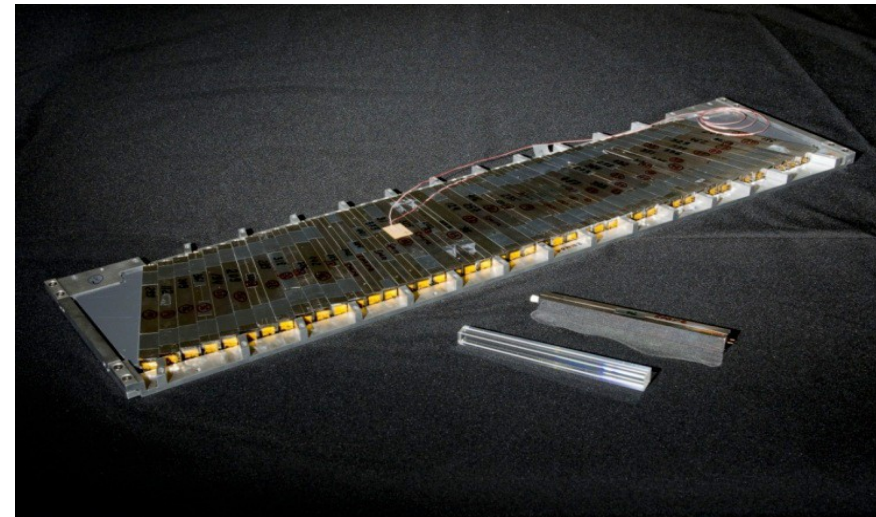
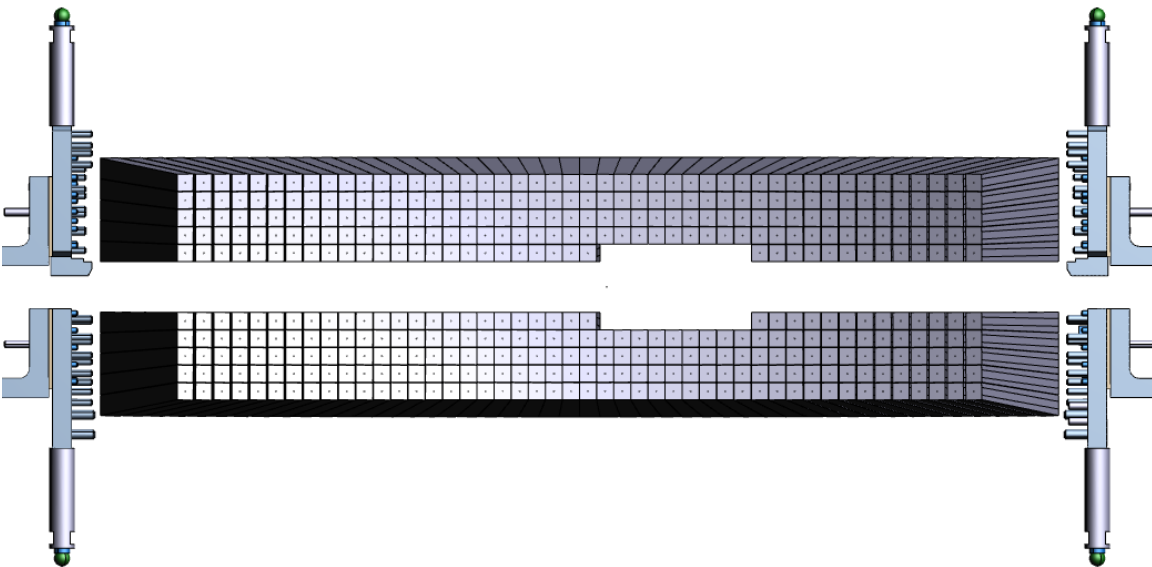
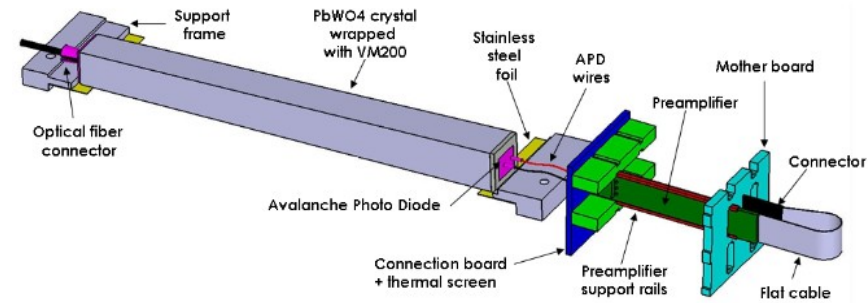
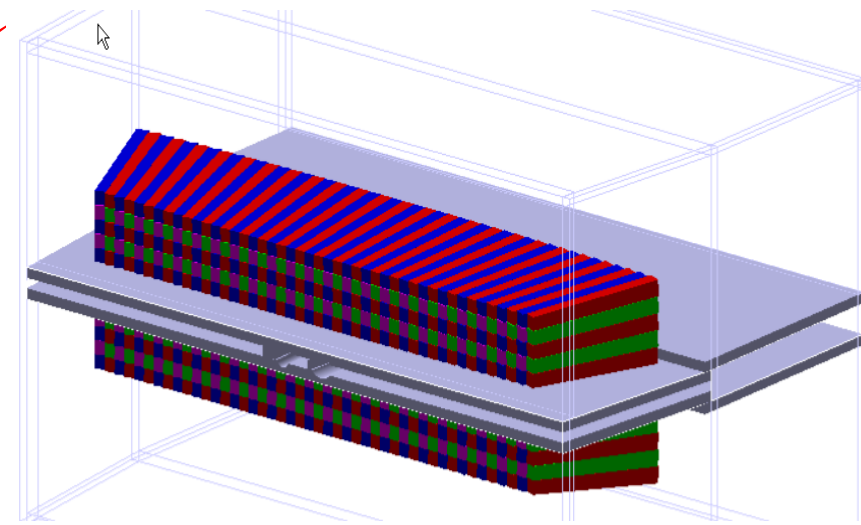
- Same configuration as in the final run, 5 layers only
- **Very good agreement data/MC**
- **Single hit resolution: 6 μm , 2 ns**



HPS Ecal

Ecal design: PbWO_4 crystals with LA-APD readout

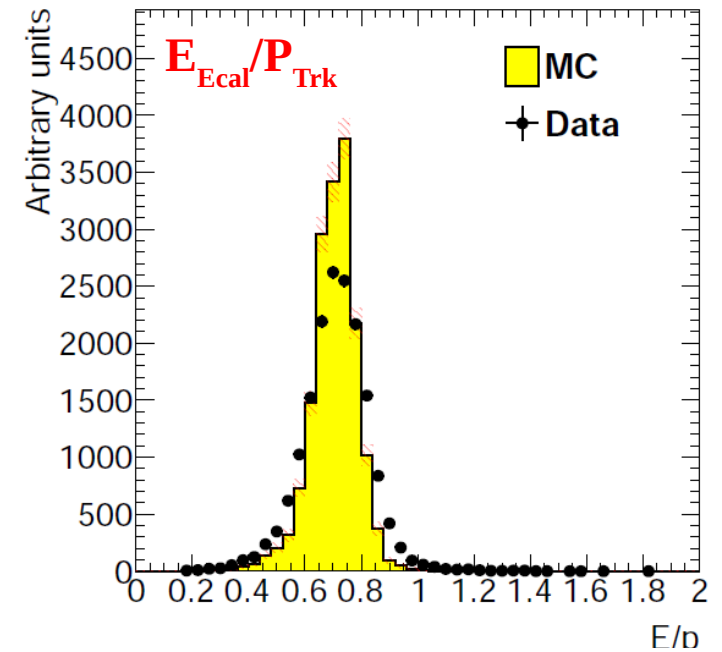
- Top and bottom modules
 - 5 layers each
 - 442 crystals in all
- APD readout through custom preamplifiers
 - Data recorded with 250 MHz 12 bit FADCs
- Thermal enclosure to hold crystal temperature to 18 °C to stabilize gains



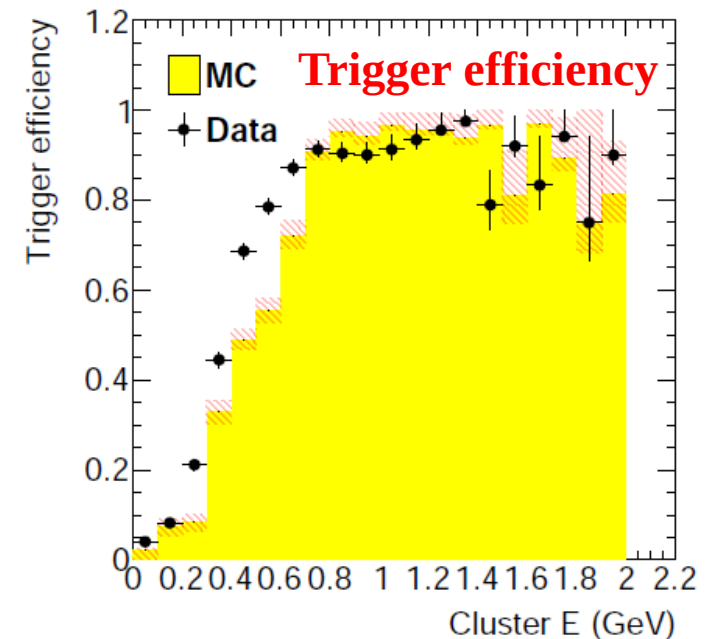
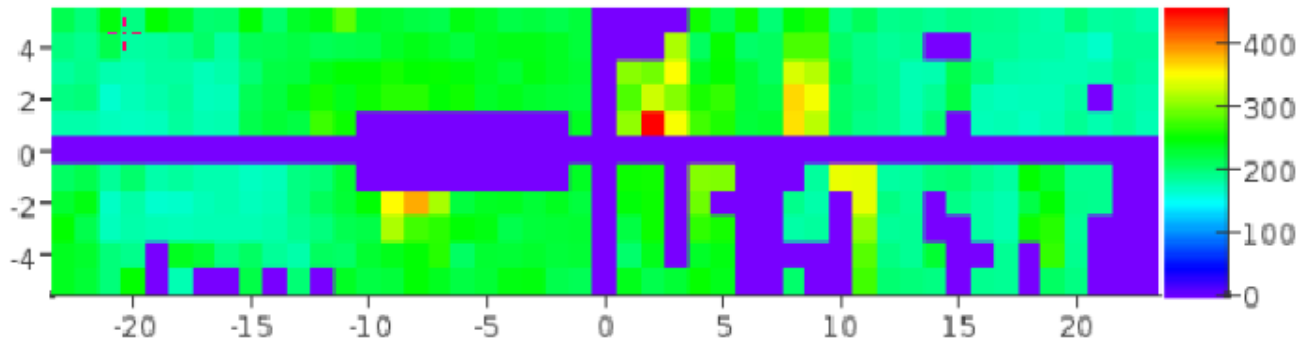
HPS 2012 test run: Ecal performances

HPS-2012 Ecal:

- 5x5 mm² APD-readout
- **Good agreement between data and MC for both energy reconstruction / trigger performances.**
- Ecal upgrade in the production run driven by test-run measured performances.
 - New 10x10 mm² LA-APDs (gain matched) for better uniformity and higher S/N ratio.
 - New read-out chain matched to the new sensors



Mean pulse amplitude per channel



Conclusions

- HPS is a new experiment at JLab, dedicated to searching for heavy photons in the mass range 10-200 MeV and with couplings $10^{-3} < \epsilon < 10^{-5}$.

HPS will cover a new, unexplored region in the parameters space.

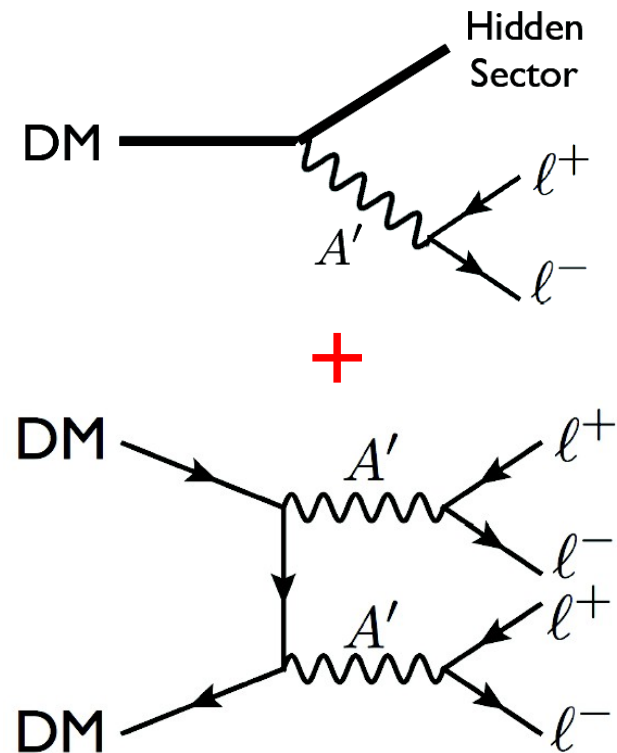
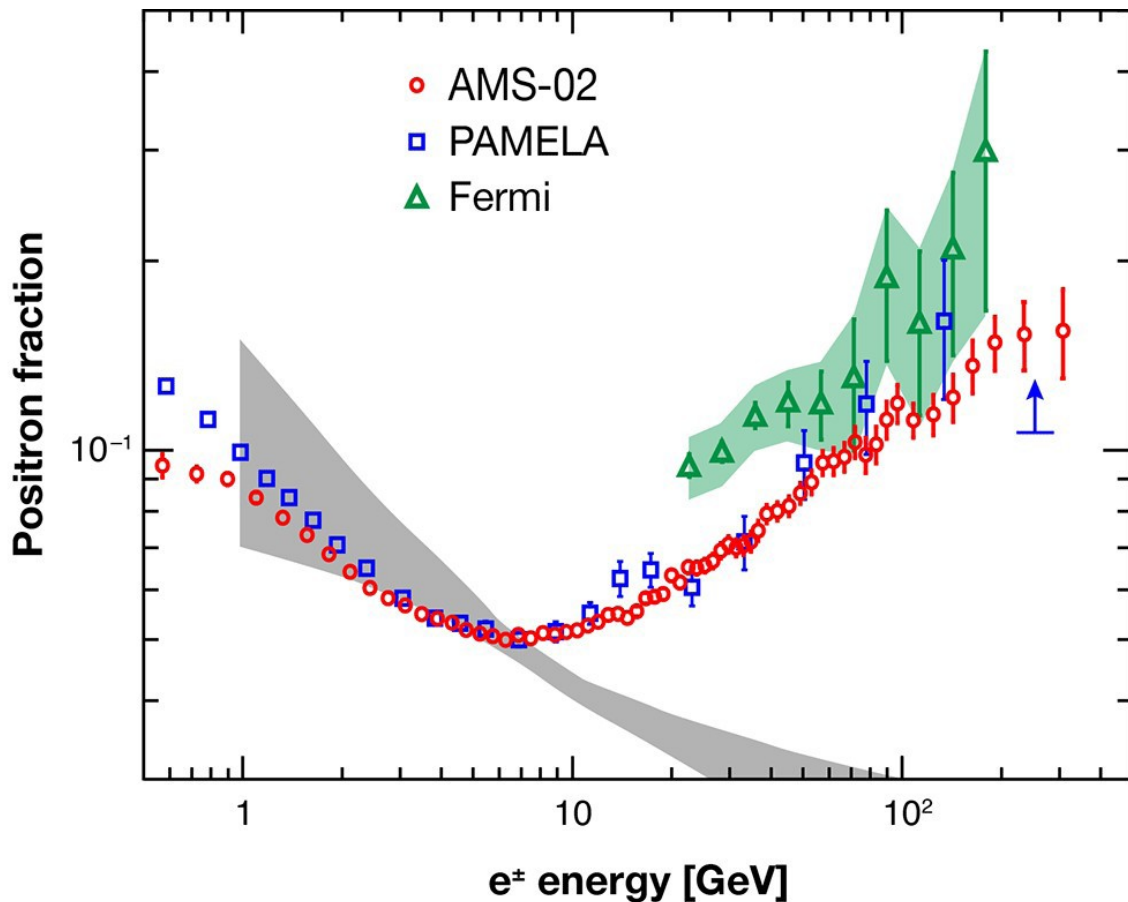
- HPS will employ two complementary searches:
 - Resonance search in $e^+ e^-$ invariant mass (traditional “bump hunting”).
 - **Detached vertex search.**
- **HPS detector:** large acceptance forward spectrometer
 - Calorimeter for PID and triggering.
 - Si tracker for momentum analysis and vertexing.
- Successful 2012 test run demonstrated operational principles and validated the detector design.
- HPS is completing construction this summer, and will be installed in Hall B this fall.
First data taking is scheduled for Spring 2015.

Backup

Hints for A' existence: astrophysics

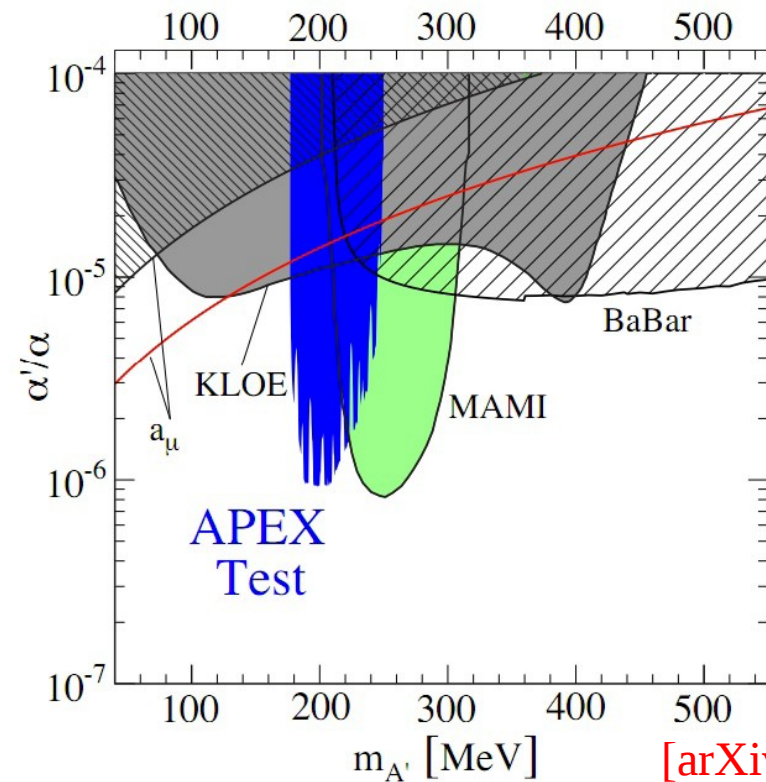
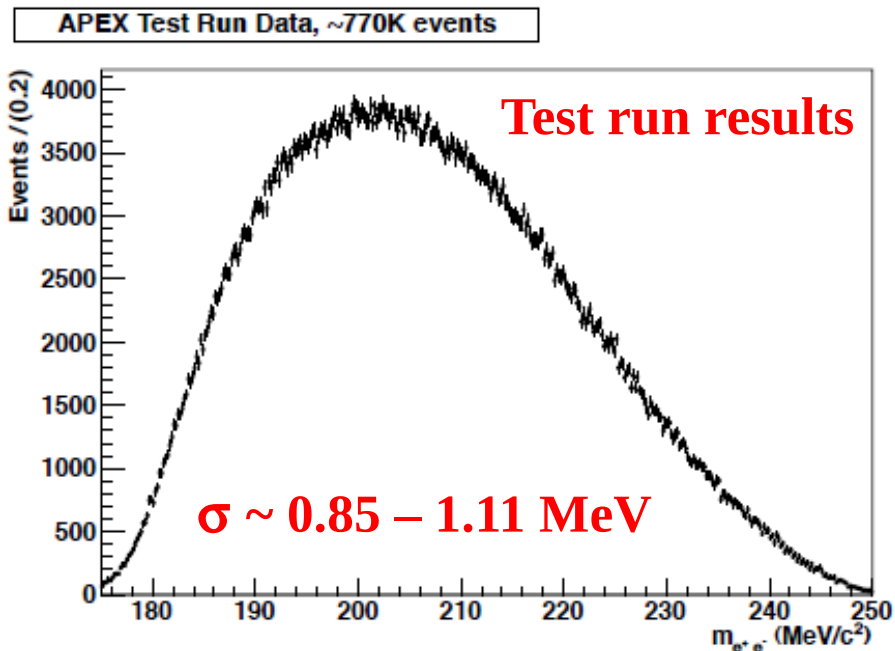
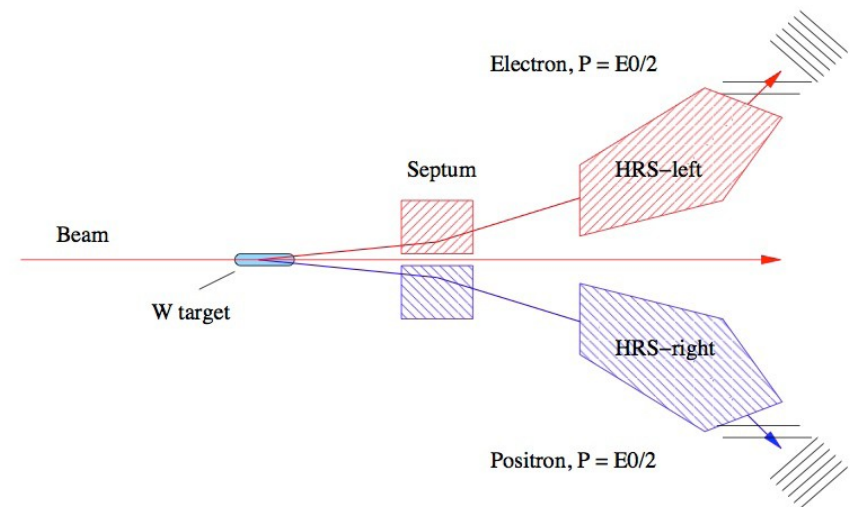
Cosmic positron fraction excess (AMS, FERMI, PAMELA)

- This anomaly could be explained by dark matter decaying or annihilating in A' , which then decays to $e^+ e^-$
- No excess measured in anti-proton fraction: light A' ($M_{A'} < \sim 2$ GeV)



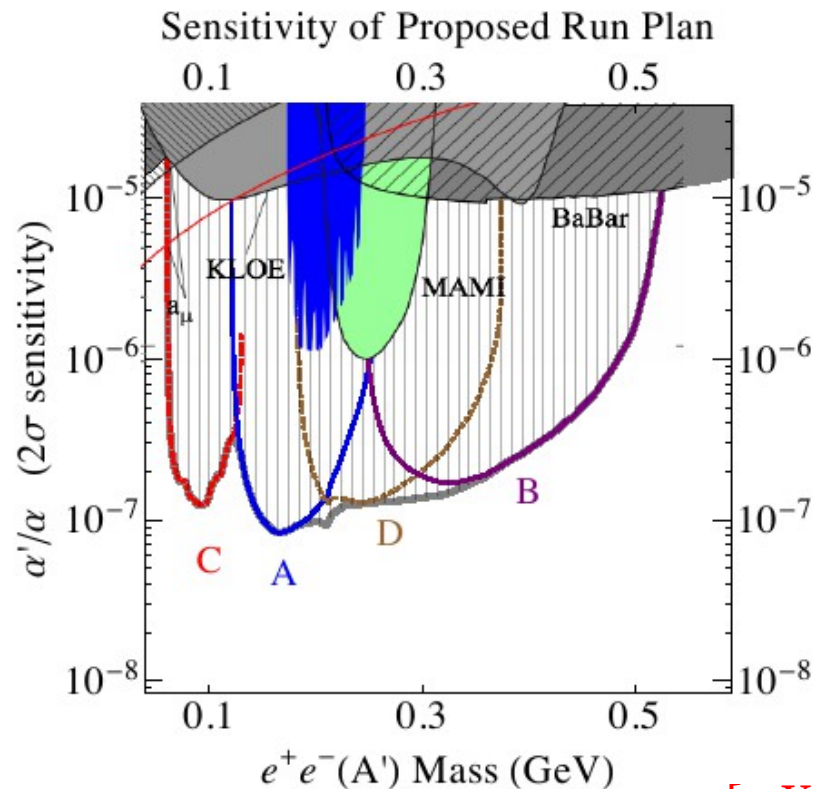
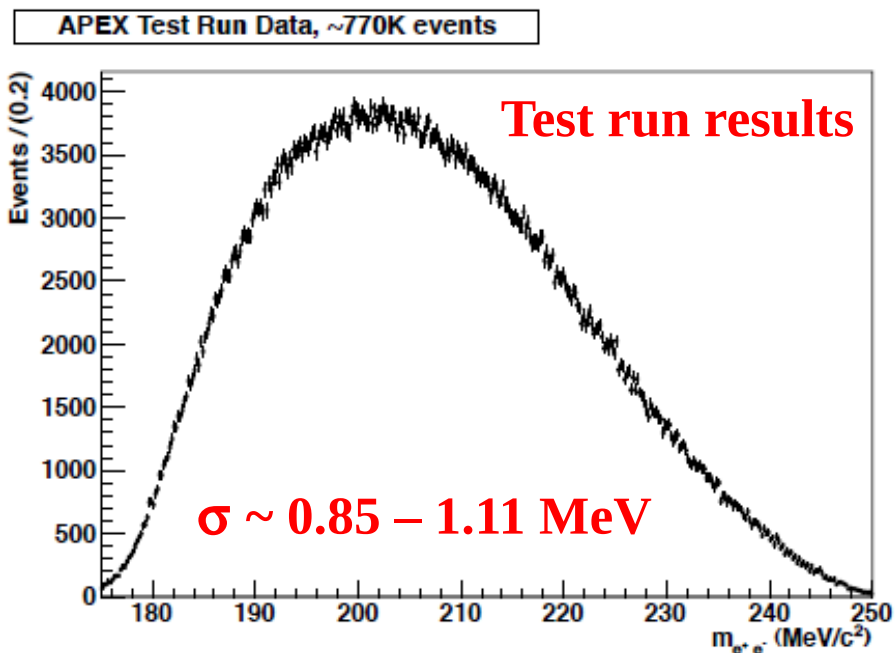
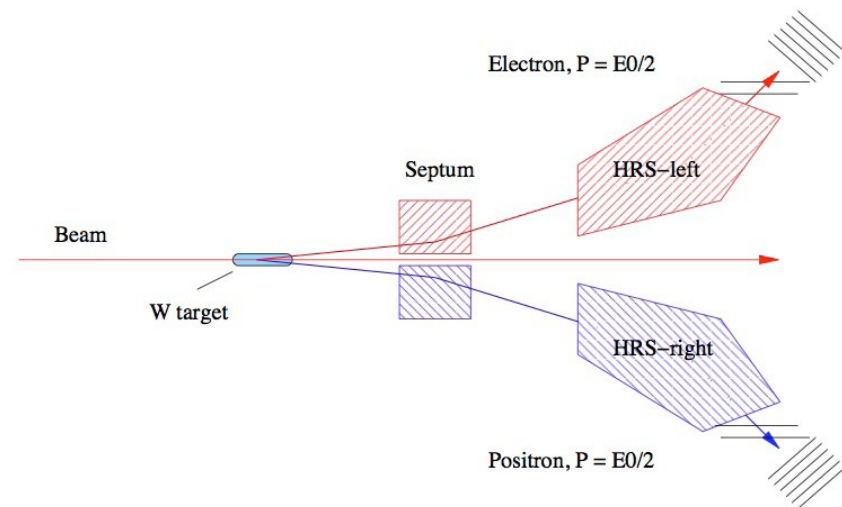
Direct production of A' at JLab (Hall-A)

- Fixed target experiment with W target.
- A' search in invariant $e^+ e^-$ mass.
- Measure $e^+ e^-$ pairs with Hall-A High-resolution spectrometer.
- Dipole septum magnets allow for detection of produced pairs at small angles ($\sim 5^\circ$)
- **Successful 2012 test-run: ~ 770 k events**
- **Plans for 2015 run (200x statistics)**



Direct production of A' at JLab (Hall-A)

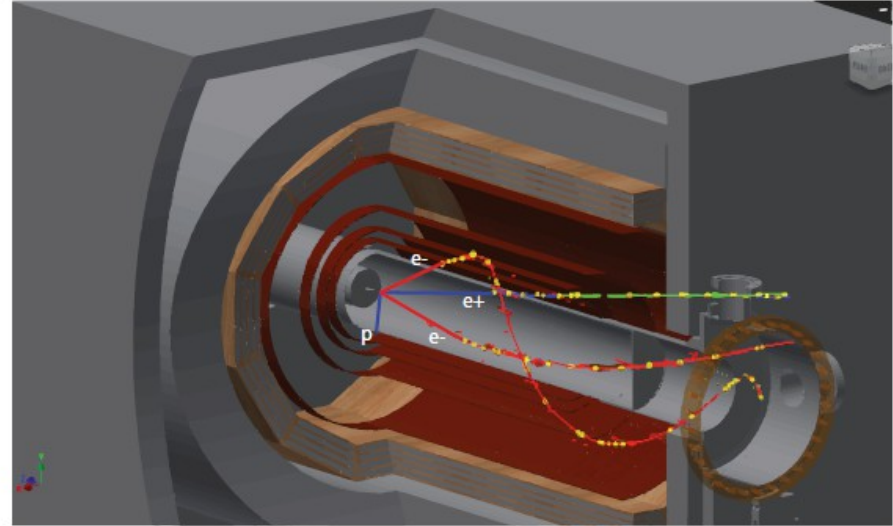
- Fixed target experiment with W target.
- A' search in invariant $e^+ e^-$ mass.
- Measure $e^+ e^-$ pairs with Hall-A High-resolution spectrometer.
- Dipole septum magnets allow for detection of produced pairs at small angles ($\sim 5^\circ$)
- **Successful 2012 test-run: ~ 770 k events**
- **Plans for 2015 run (200x statistics)**



DarkLight

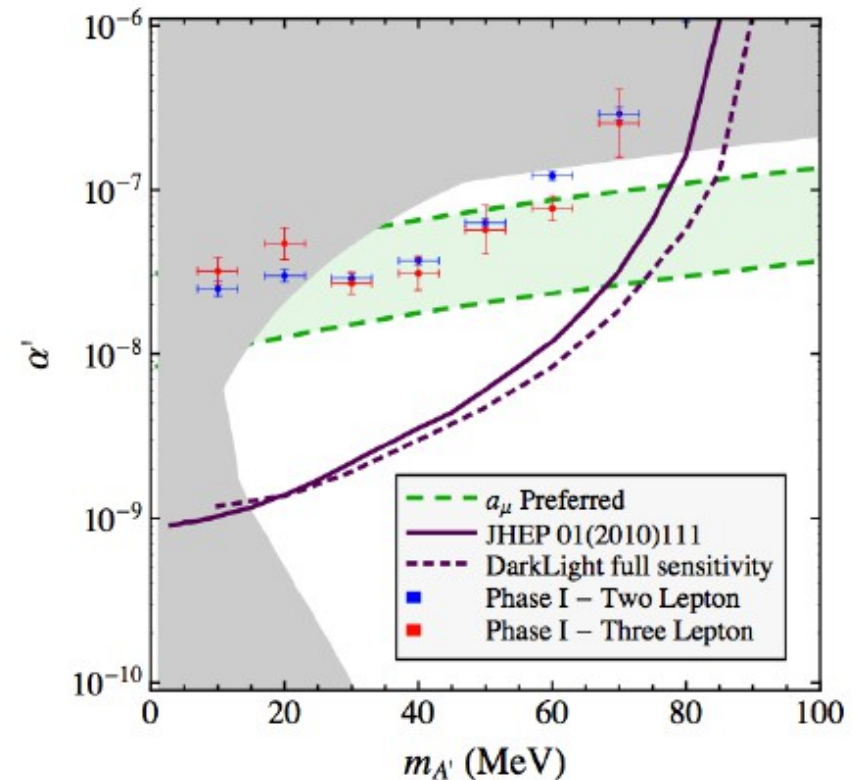
Direct production of A' at JLab Free Electron Laser

- 100 MeV, 10 mA beam
- Internal H_2 target in 0.5 T solenoid
- Successful 2012 technical test run demonstrated FEL has the required performances and stability



Experiment status:

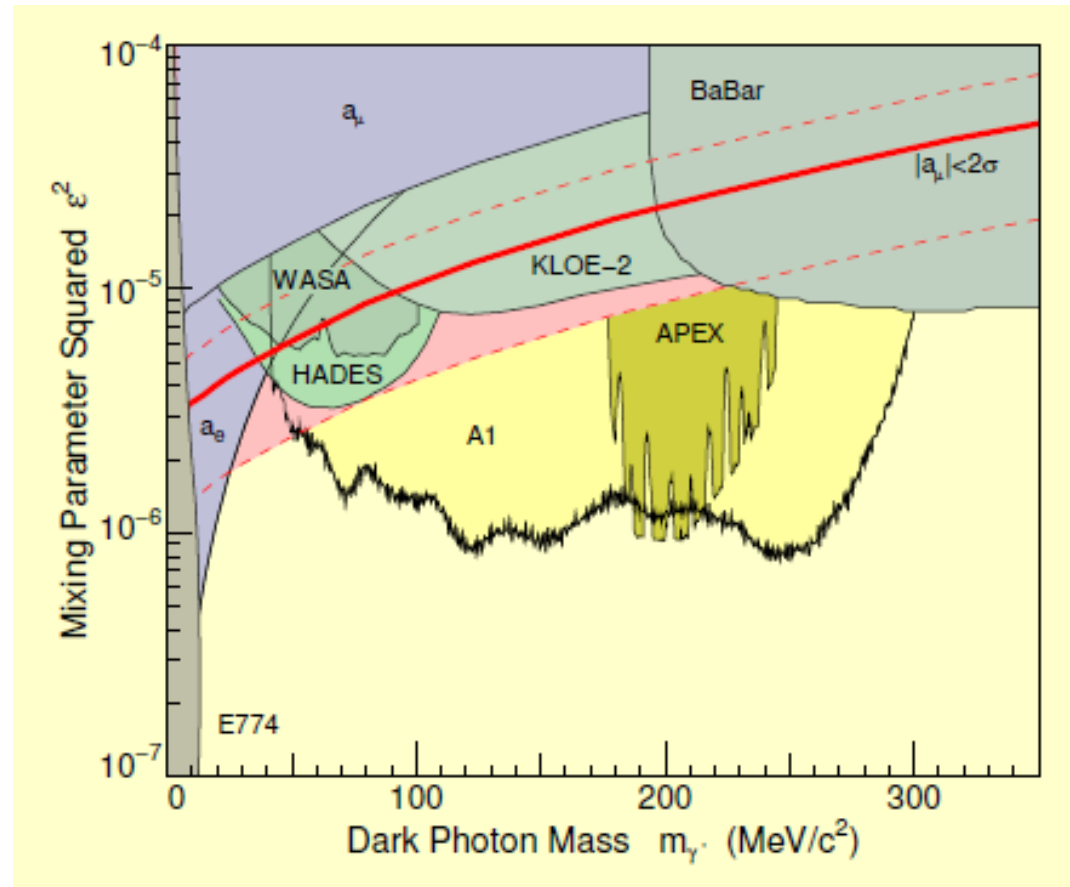
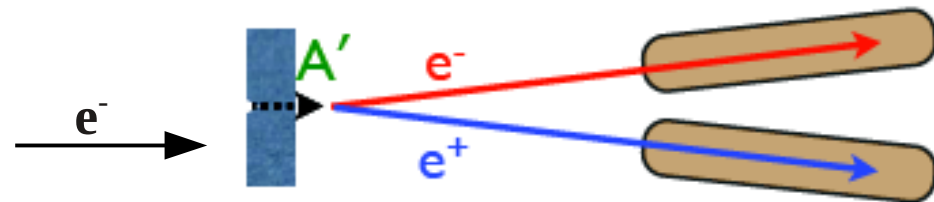
- Full scientific approval from Jefferson Lab received in June 2013
- January 2014: NFS MRI proposal submitted for Phase 1 (2015)
- Work in progress to finalize full design by summer 2014



A1 (Mainz)

Search for A' in fixed-target experiment

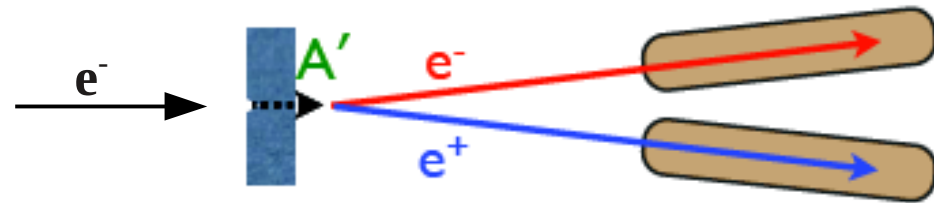
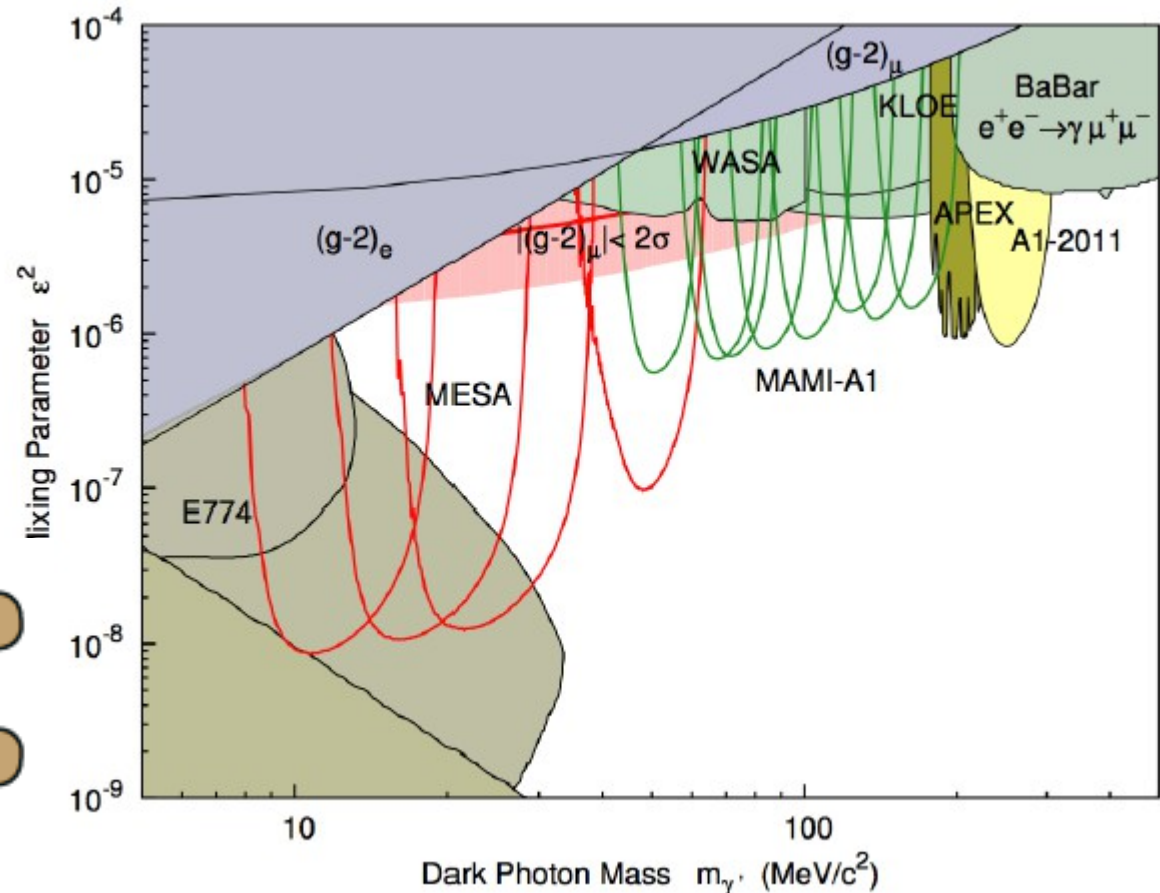
- APEX-style experiment, double-arm A1 spectrometer
- 2012-2013 run: 0.05 mm ^{151}Ta target, $E_0=855$ MeV, 22 kinematic settings
- Idea for detached-vertex search through variable beam-stoppers abandoned (too much background)
- Future search: low A' mass



A1 (Mainz)

Search for A' in fixed-target experiment

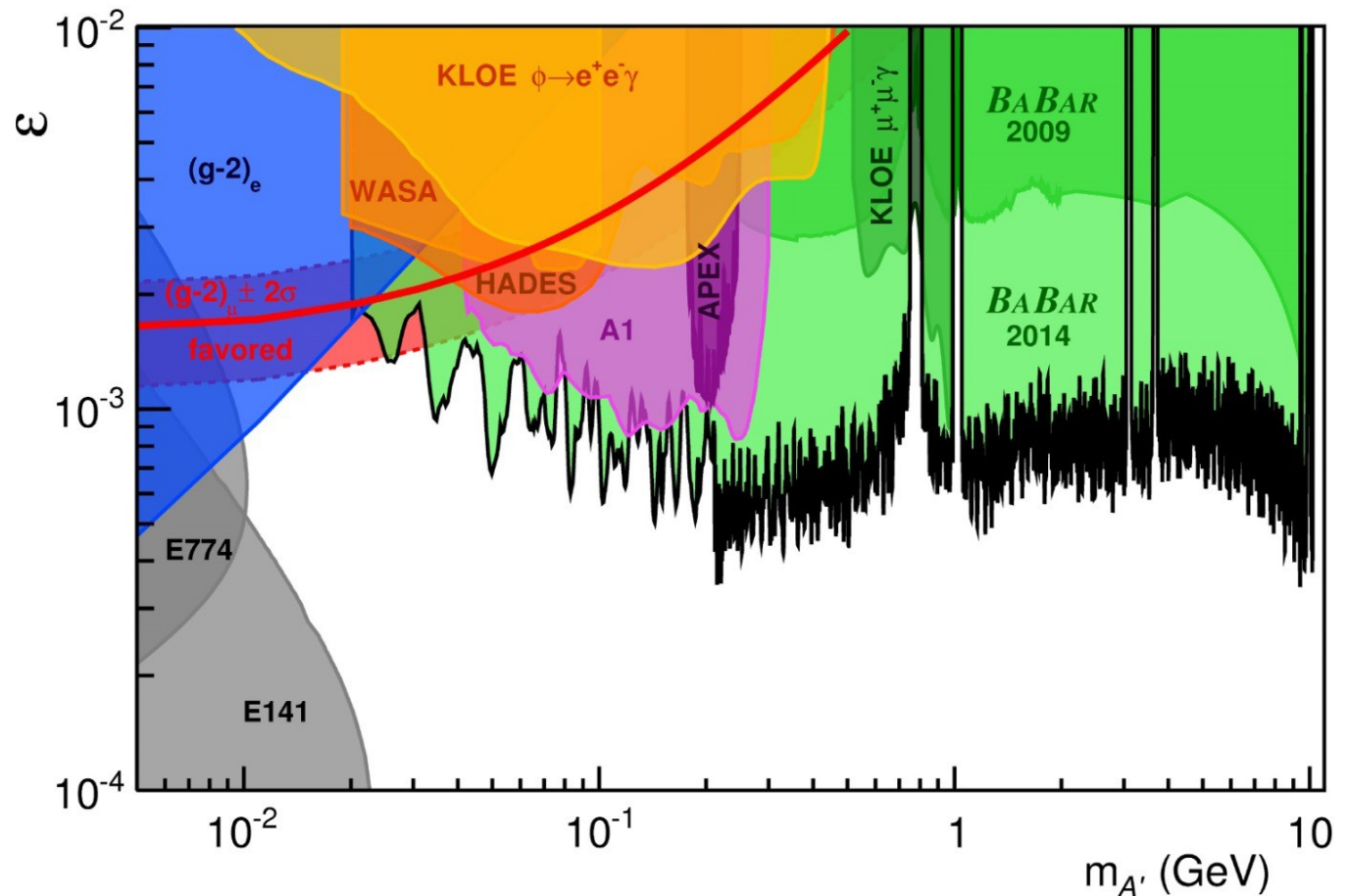
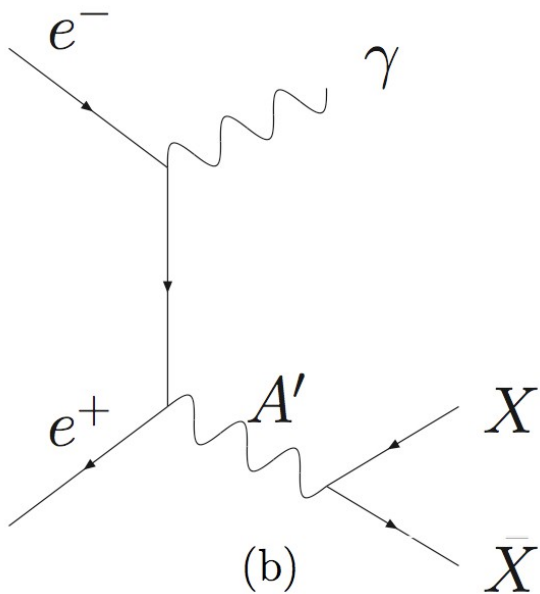
- APEX-style experiment, double-arm A1 spectrometer
- 2012-2013 run: 0.05 mm ^{151}Ta target, $E_0 = 855$ MeV, 22 kinematic settings
- Idea for detached-vertex search through variable beam-stoppers abandoned (too much background)
- Future search: low A' mass (MESA accelerator)



BaBar

Search for A' in $e^+ e^-$ annihilation: $e^+ e^- \rightarrow \gamma A' \rightarrow \gamma e^+ e^- / \gamma \mu^+ \mu^-$

- Select events with 1 γ and two opposite charged leptons.
- Scan the di-lepton mass and fit a background plus signal function at each step.
 - Background includes resonances – $\rho^0, \phi, J/\psi$



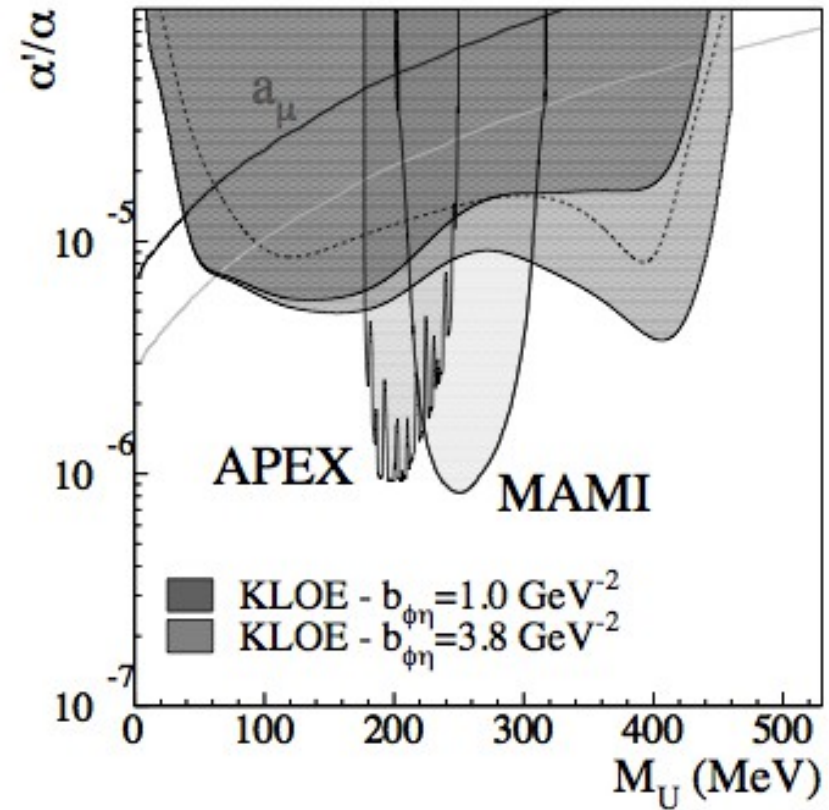
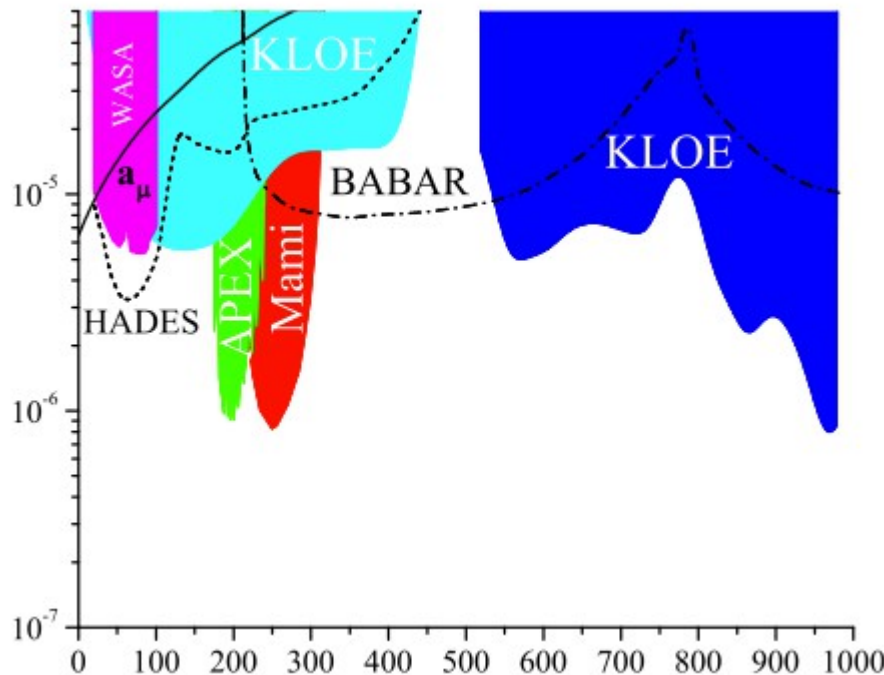
KLOE

Search for A' in ϕ decay: $\phi \rightarrow A' \eta \rightarrow e^+ e^- \eta$

- Search for excess in electron-positron invariant mass distribution of irreducible $\Phi \rightarrow \eta e^+ e^-$ background
- $\sigma_M < 2 \text{ MeV}$

Search for A' in $e^+ e^-$ annihilation (Babar-like)

- Search for peak in $\mu^+ \mu^-$ invariant mass distribution

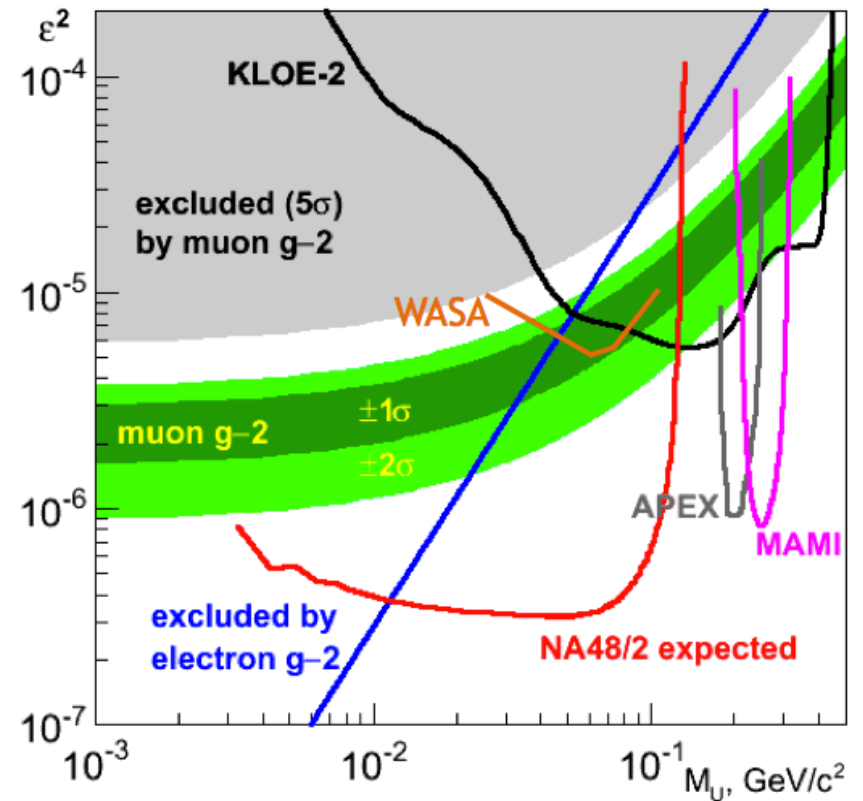
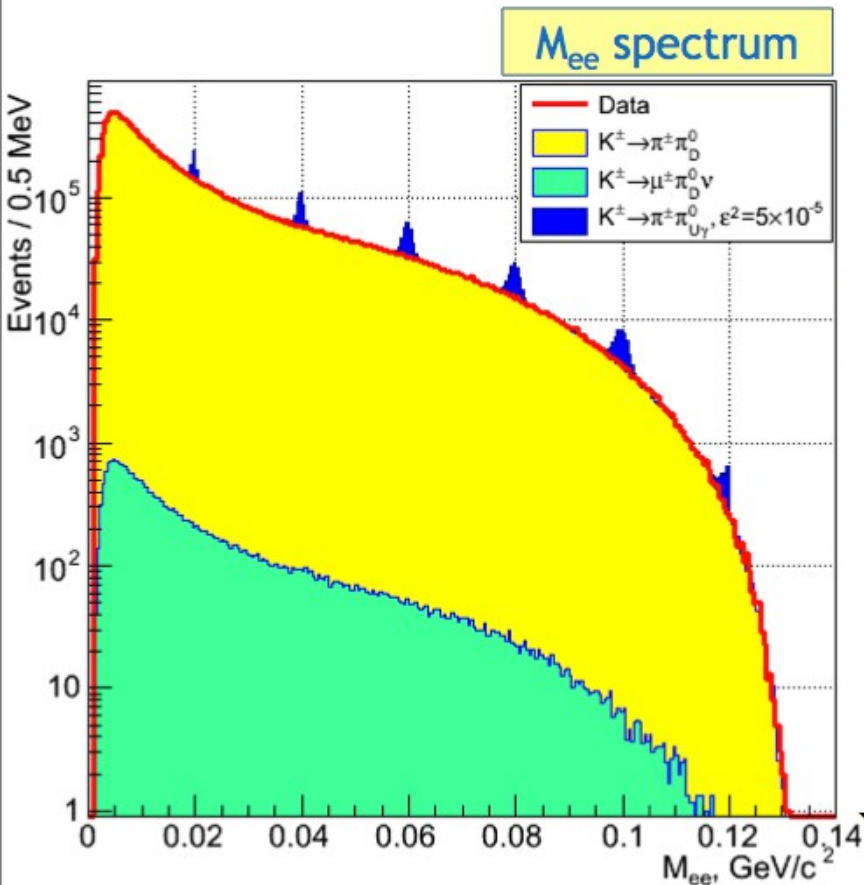


Note: limit depends on the meson form factor, $b = dF/dq^2(q^2=0)$

NA48/2

Search for A' in π^0 Dalitz decay: $\pi^0 \rightarrow A' \gamma \rightarrow e^+ e^- \gamma$

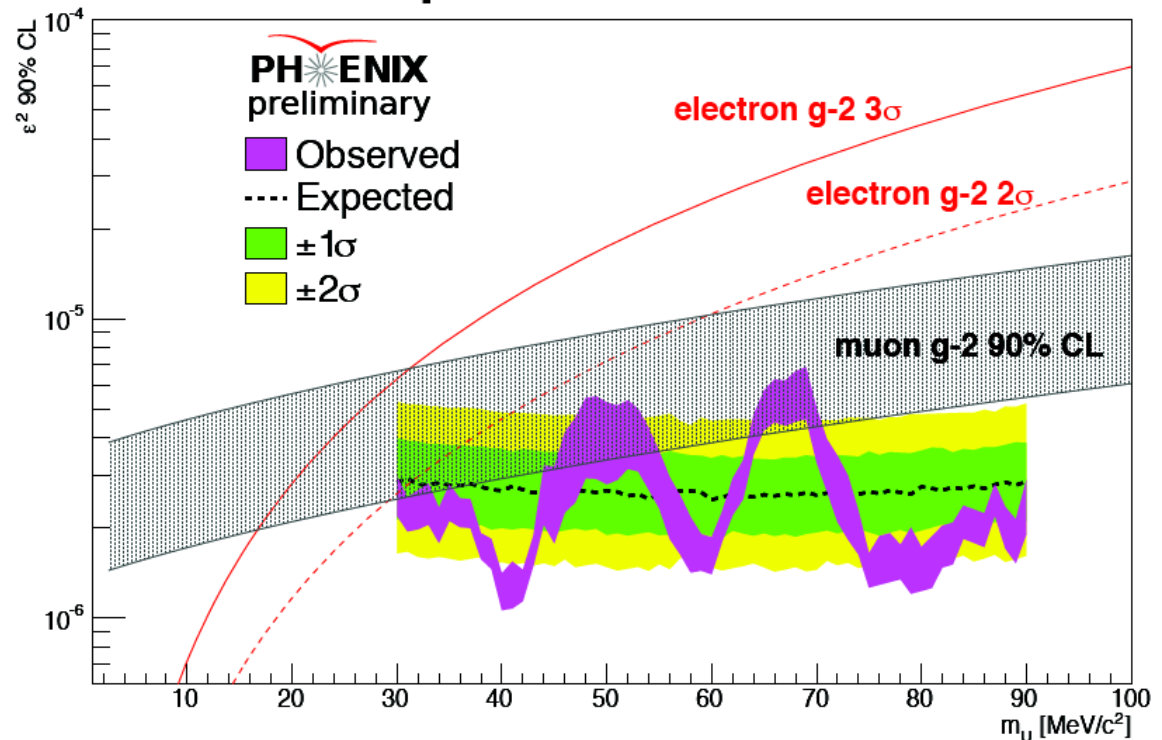
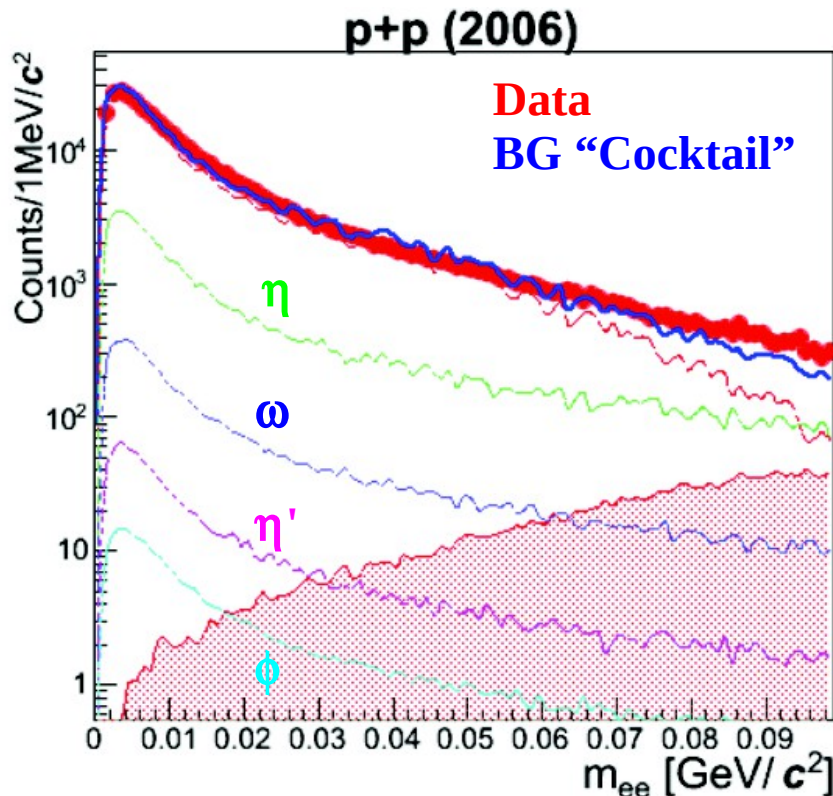
- Data from 2003-2004 run, large flux of tagged π^0 from $K^\pm \rightarrow \pi^\pm \pi^0$
- Search for A' in invariant $e^+ e^-$ mass ($\sim 1.2\%$ mass resolution): analysis in progress
- Searches from $K^+ \rightarrow \pi^+ A' \rightarrow \pi^+ l^+ l^-$ are also in progress [arXiv: 0903.3130]



PHENIX

PHENIX detector @ BNL RHIC : Search for A' in π^0 / η Dalitz decay

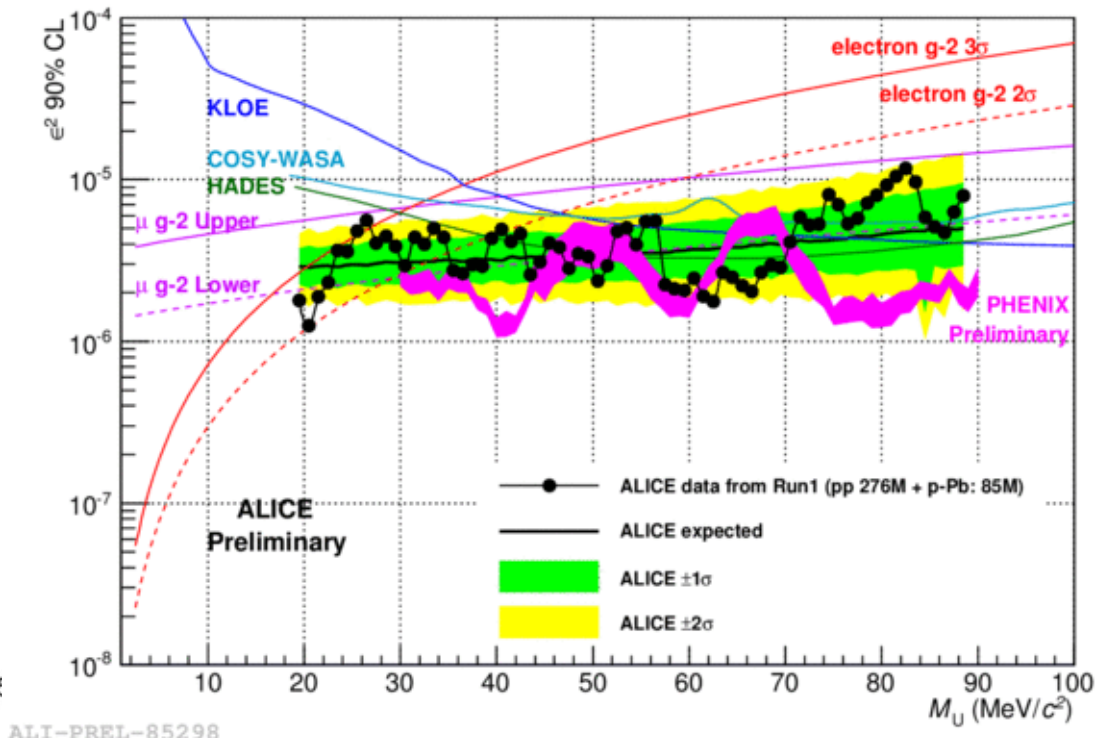
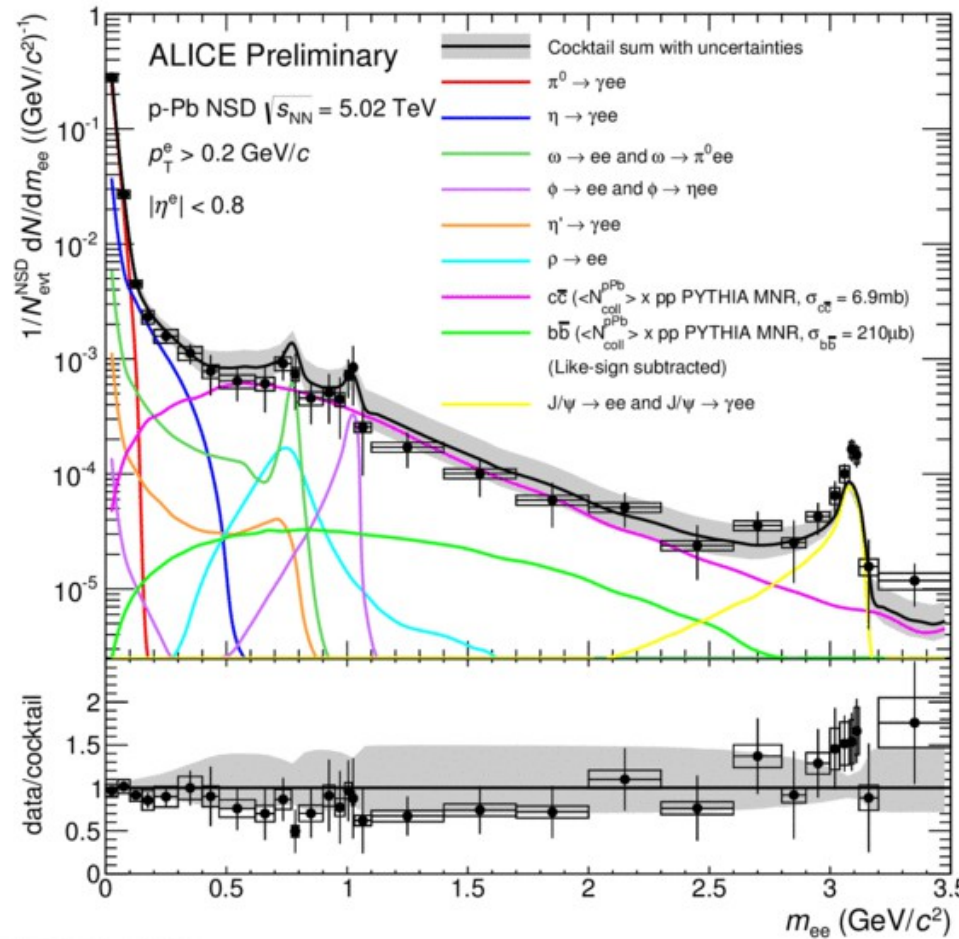
- 1.4M $e^+ e^-$ pairs in p+p(2006) and d+Au (2008) datasets
- Mass resolution ~ 3 MeV
- **Background well under control:** “cocktail” of hadron decays
- Future plans:
 - Increase statistics adding 2009 p+p dataset
 - Use 2014 Au + Au dataset for vertex search



ALICE

ALICE detector @ CERN LHC: search for A' in π^0 / η Dalitz decay

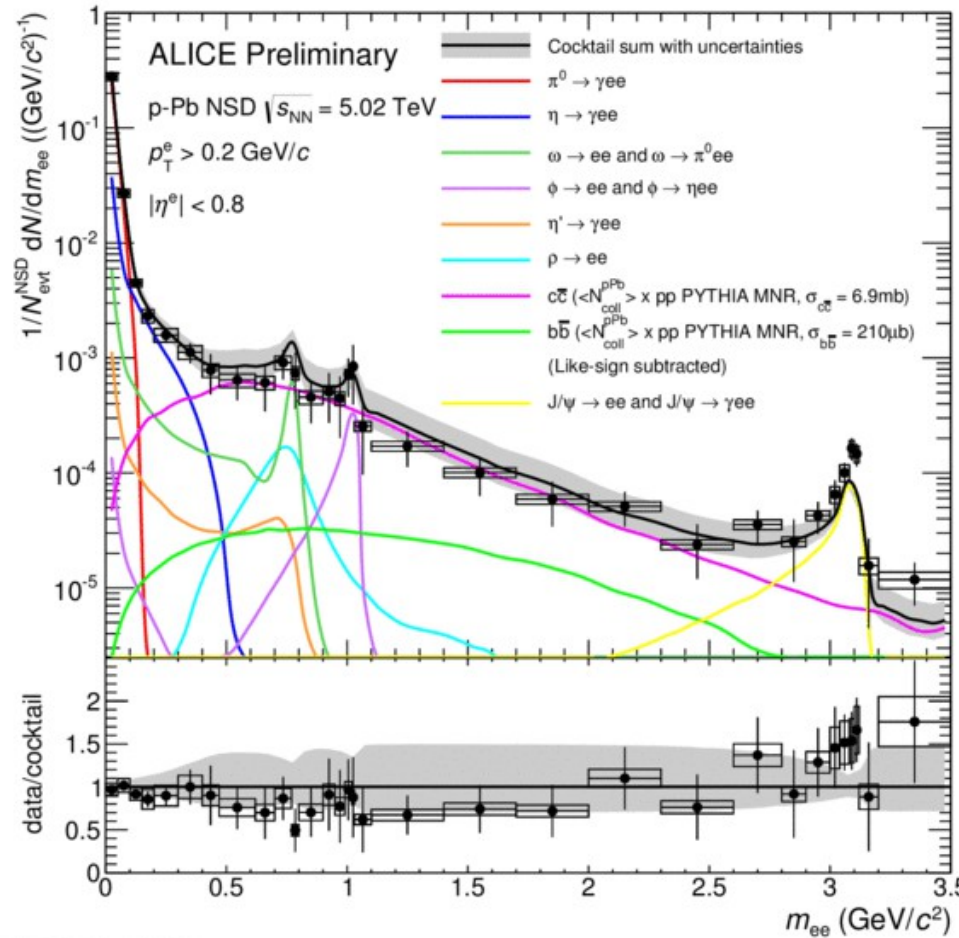
- $e^+ e^-$ pairs from p+p (276M) and p+Pb (85M) datasets
- Mass resolution $\sim 1\%$
- **Background well under control:** “cocktail” of hadron decays



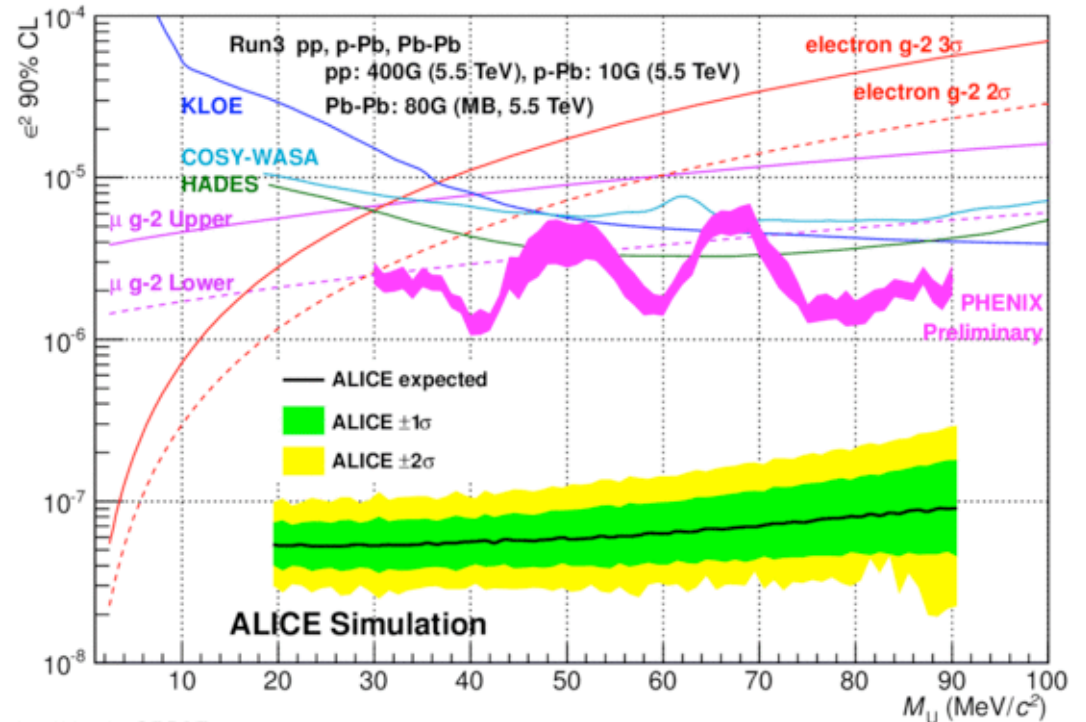
ALICE

ALICE detector @ CERN LHC: search for A' in π^0 / η Dalitz decay

- $e^+ e^-$ pairs from p+p (276M) and p+Pb (85M) datasets
- Mass resolution $\sim 1\%$
- **Background well under control:** “cocktail” of hadron decays



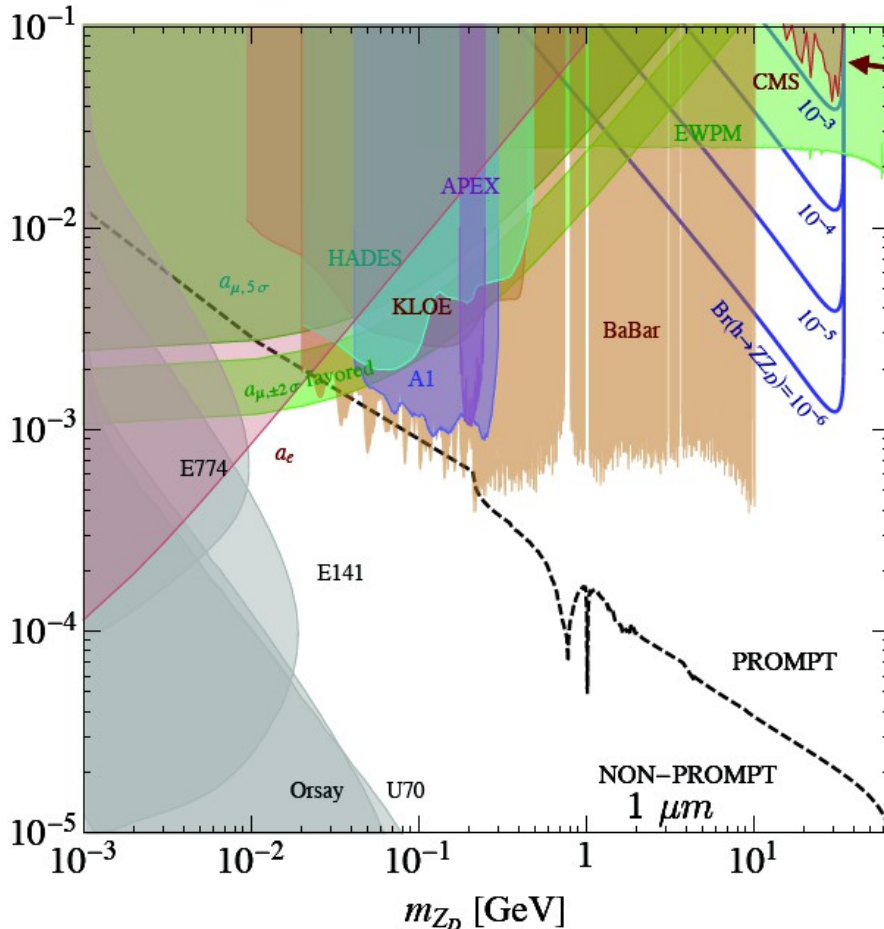
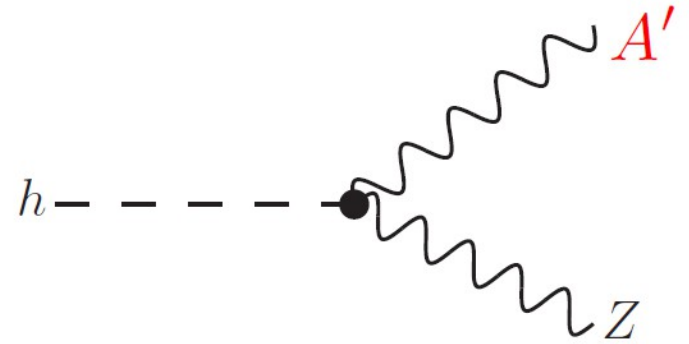
Very promising sensitivity from ALICE upgrade



CMS/ATLAS

Search for A' in exotic Higgs Decay

- Kinetic mixing Z - A'

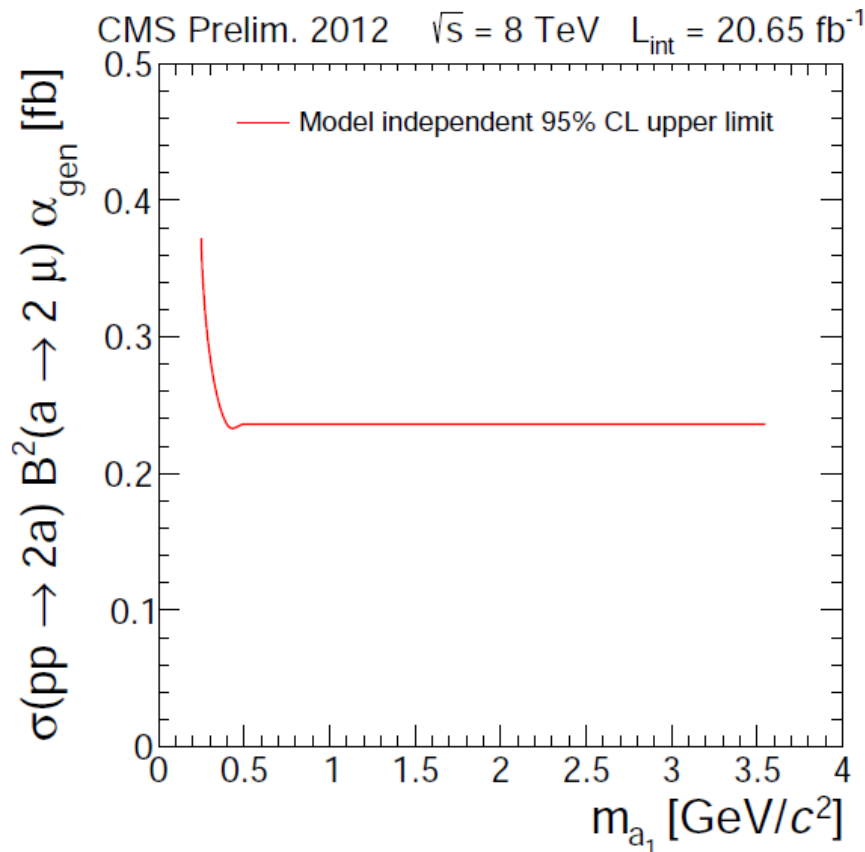
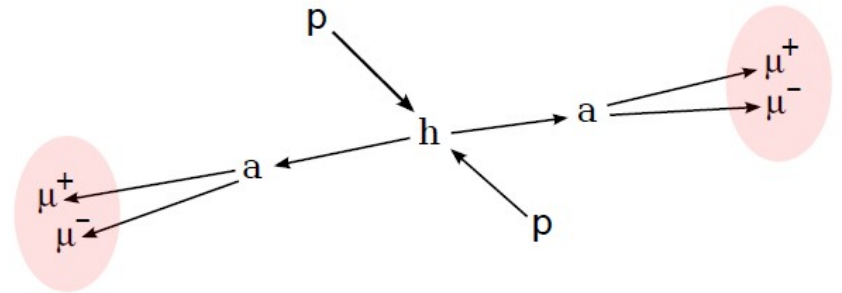


CMS limits
(ATLAS similar)

- Unoptimized limit almost competitive with dedicated precision measurements
- 14 TeV run with 300 fb^{-1} may be sensitive to very low BR

Search for A' in exotic Higgs Decay

- Kinetic mixing Z-A'
- Non-SM Higgs decay to an A' pair, each decays to an isolated lepton pair



95 % CL limit (model-independent!) on
 $\sigma(pp \rightarrow h \rightarrow 2a) \times \mathcal{B}^2(a \rightarrow 2\mu) \times \alpha_{gen}$

α_{gen} : kinematic and geometric acceptance (on generator level)

Dark photons and dark matter

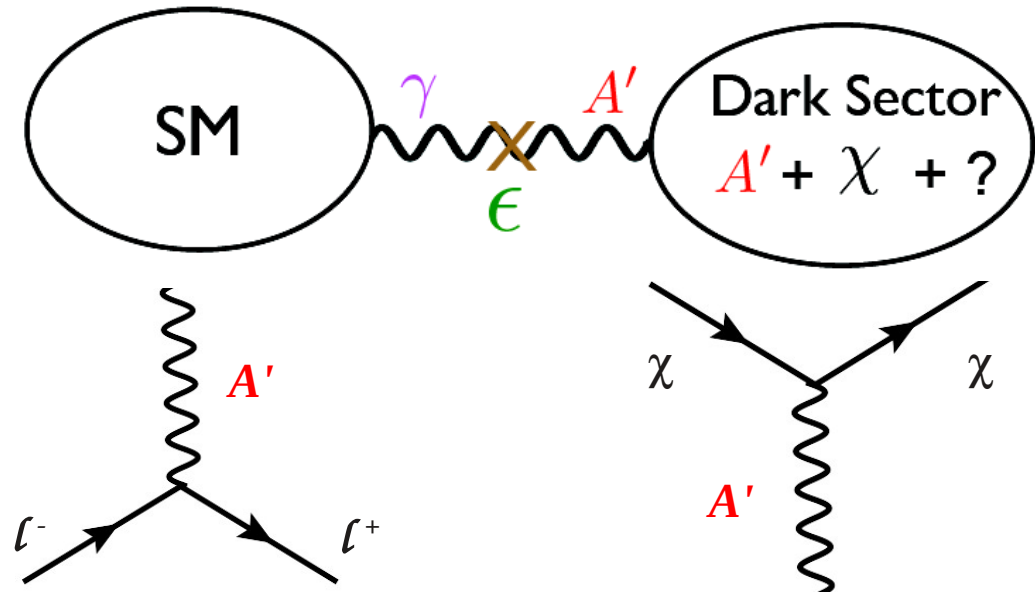
Model:

- A' interacts with SM γ through kinetic mixing
- Dark sector particle χ interacts with A'

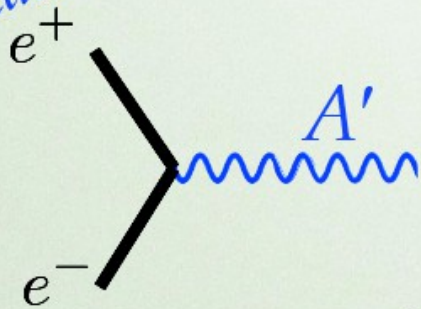
4 parameters: $M_{A'}$, M_χ , ϵ , g_d

A' production: $\sigma \propto \epsilon^2$

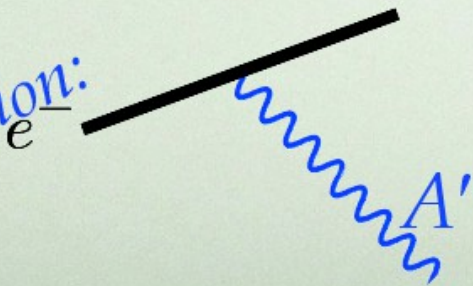
A' decay:



Annihilation:

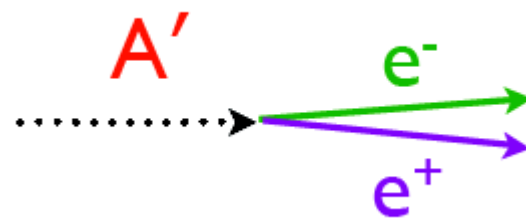


Radiation:



Visible

First scenario



$$\Gamma \propto \epsilon^2$$

- Minimal scenario
- Decay suppressed by small mixing ϵ
- Valid for any M_χ value

Second scenario: invisible decay

(not discussed in this talk)