Center for Frontiers in Nuclear Science

Dark Photons at the EIC

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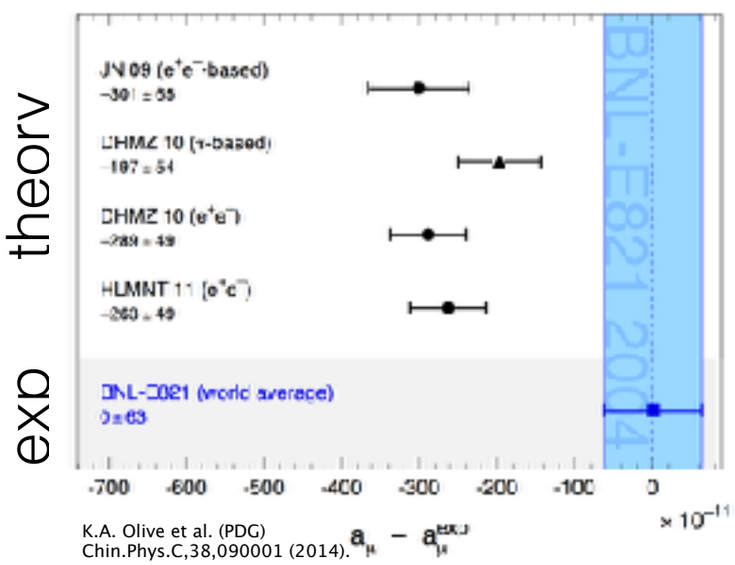
Outline

- Motivation
- Channels
- Kinematics
- Monte Carlo Studies
- Ongoing Work

Why a Dark Photon?

- Dark Matter Decay Mechanism?
- Anomalies:

Muon g-2



K.A. Olive et al. (PDG)
Chin.Phys.C,38,090001 (2014).

X17 in 4He and 8Be

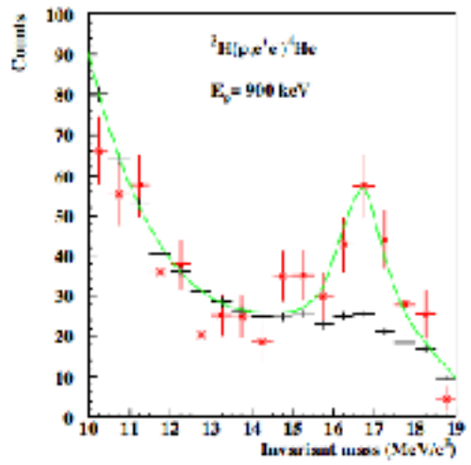
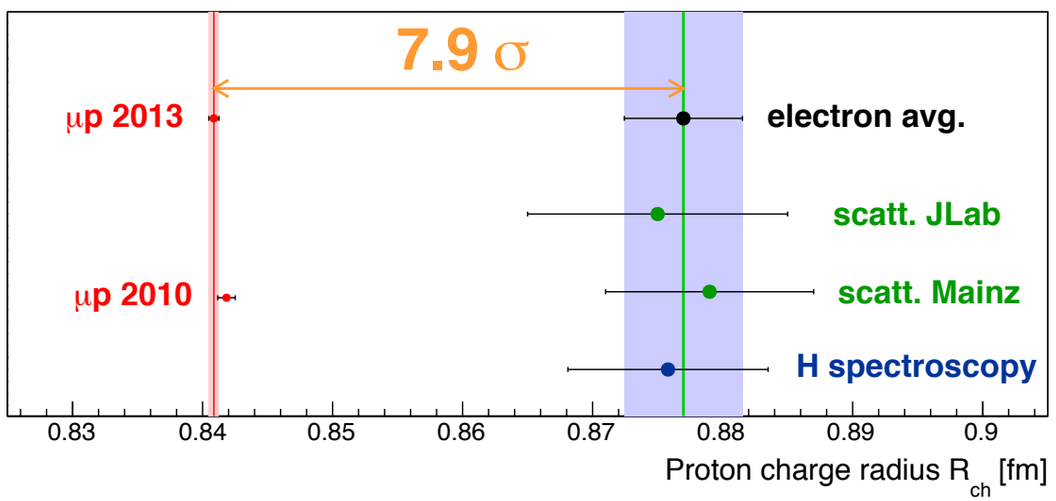


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in* ^{8}*Be.*

Proton radius puzzle

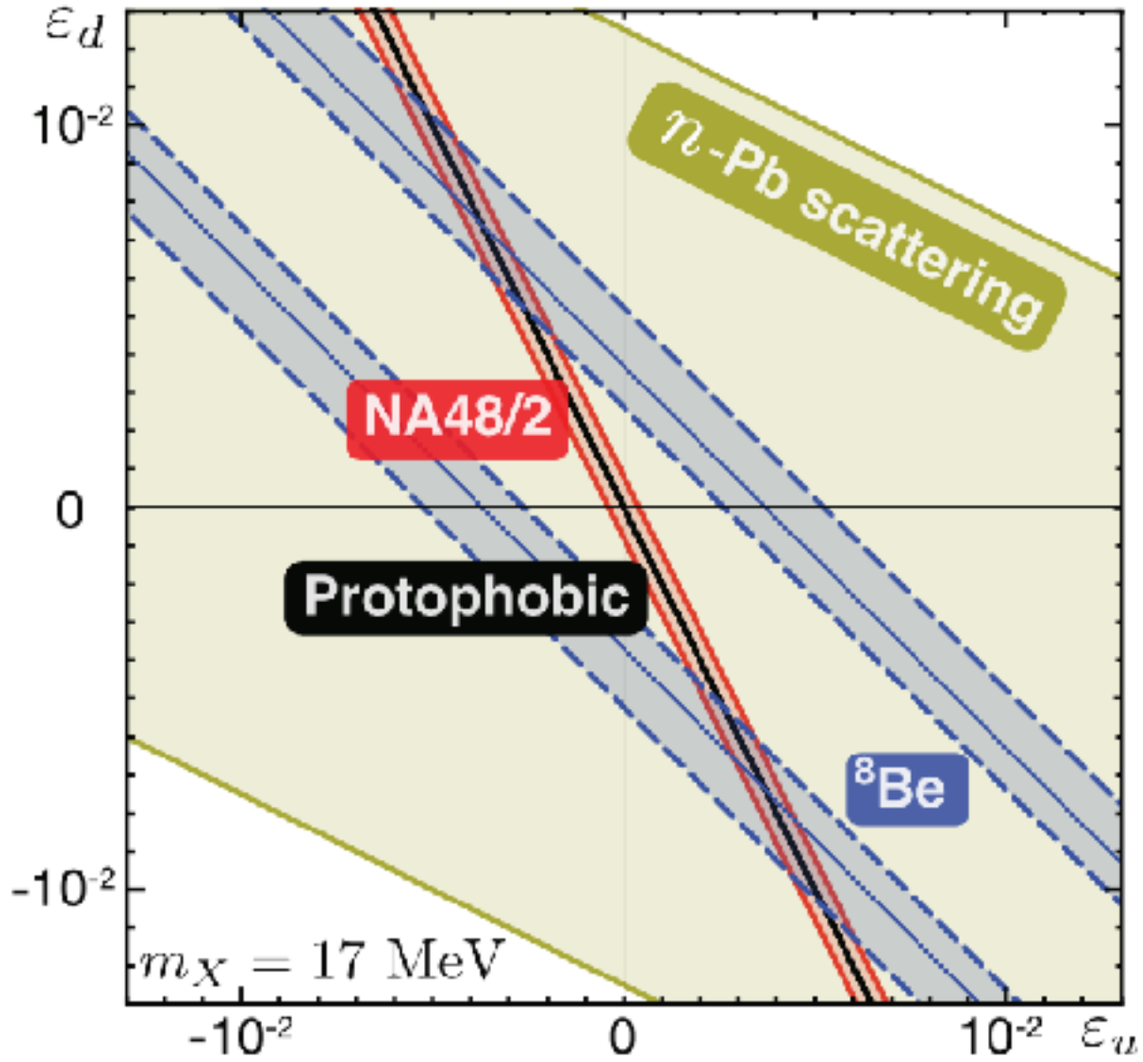


- Because we can write it:

$$L \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

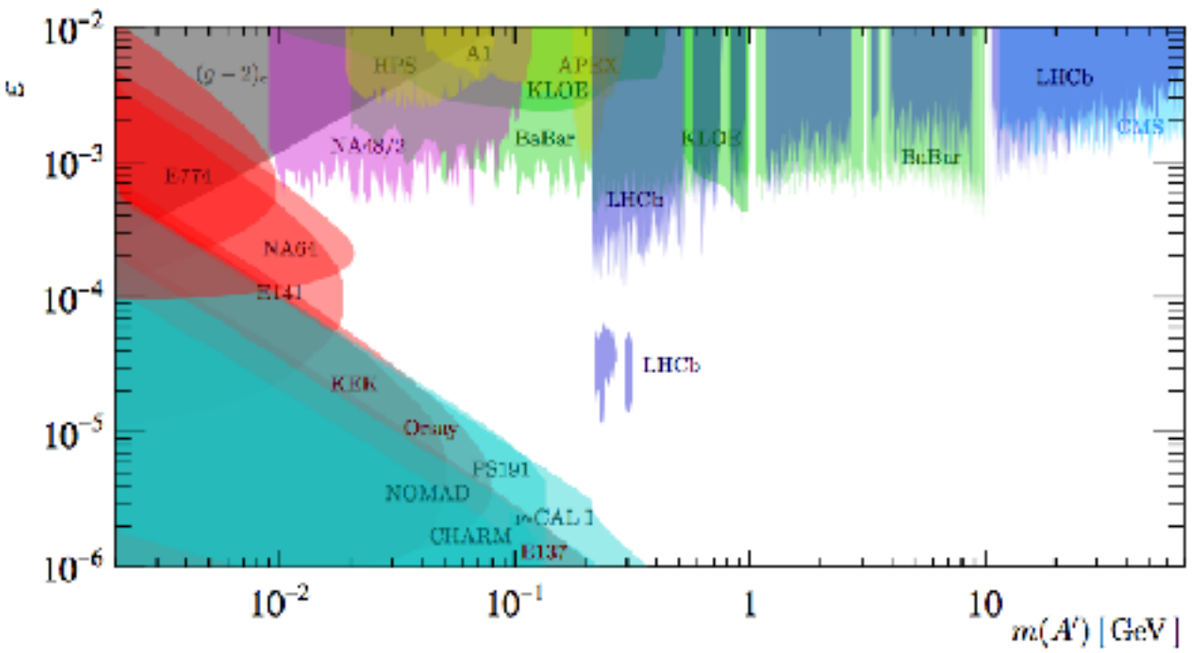
8Be/4He Anomalies

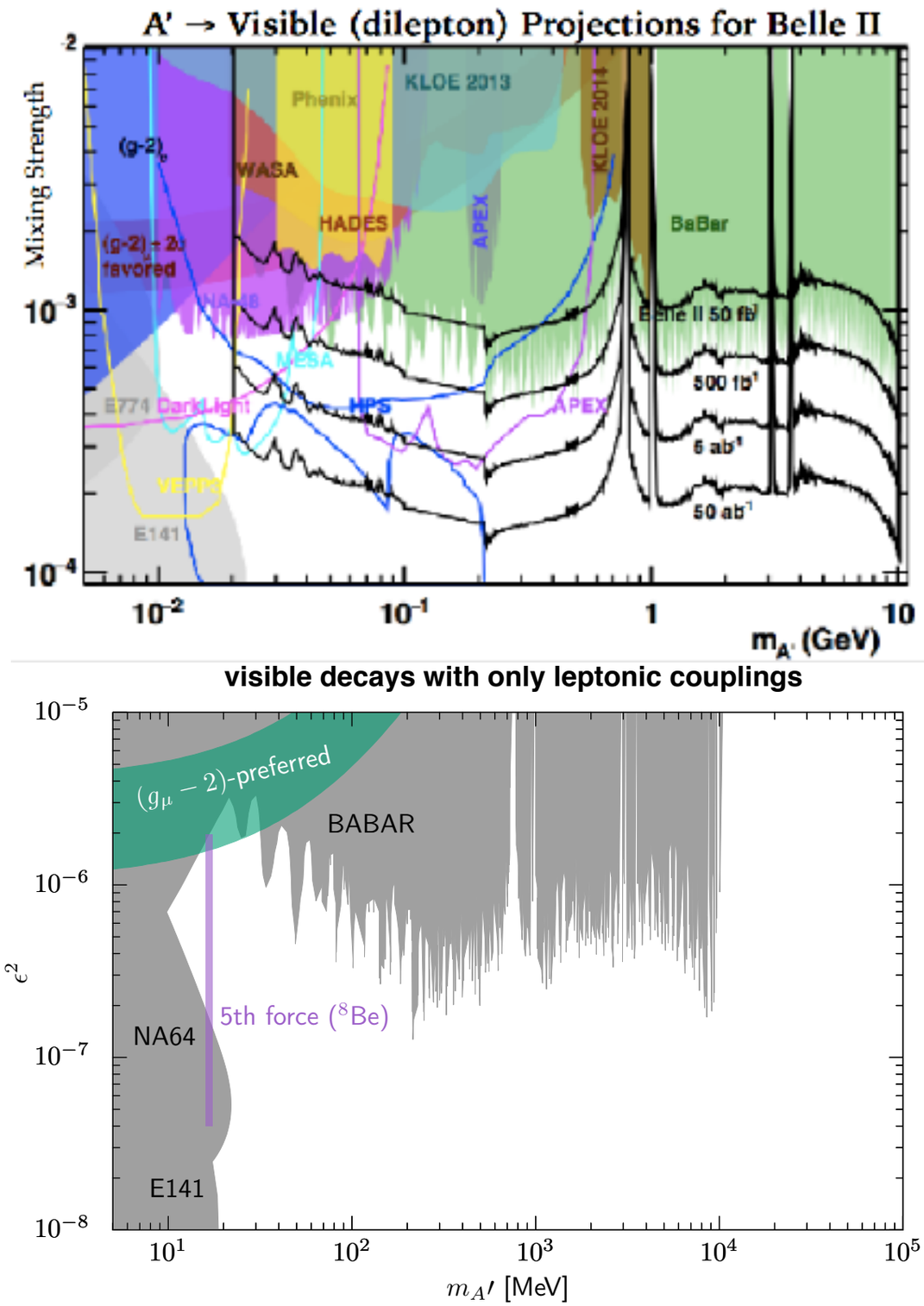
- Signal conflicts with simple charge-coupling model
- Allow particles to have independent couplings:
  - Simple Lagrangian term modified
  - Pion couplings suppressed
- Ratio of proton and neutron couplings no less 'natural' than for Z



arXiv:1604.07411

Existing Limits and Projections





- In simple Kinetic Mixing Model:

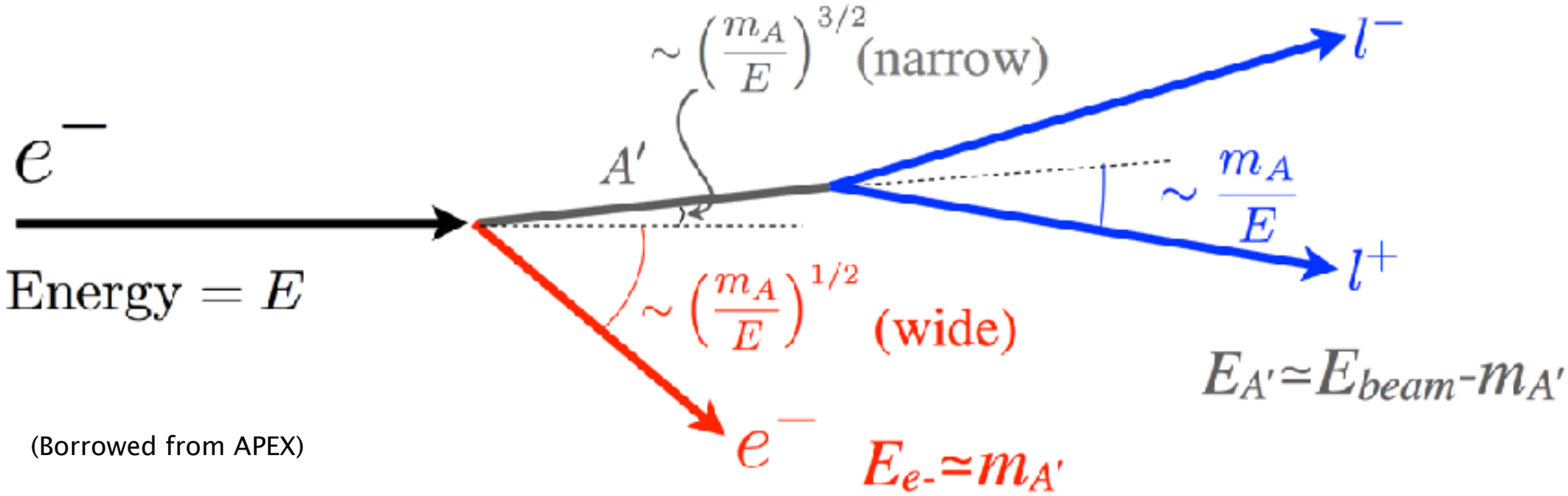
$$\alpha_D = \epsilon^2 \alpha_{EM}$$

- Want to explore the parameter space with purely leptonic couplings as well!
- (But keep the notation and name.)

A' Channels

- Production:
  - ISR (A'-strahlung from e- beam) ($m_A < \sqrt{s}$))
  - Decay (on-shell A' replaces photon in decay chain) ($m_A <$ parent)
- Final States:
  - e+ e- pair ($m_A > 2m_e$)
  - μ+ μ- pair ($m_A > 2m_\mu$, cleaner signal)
  - q qbar pair (messier, harder)
  - invisible (much harder)
  - displaced vertices (cleaner, much harder)

Fixed-Target Kinematics

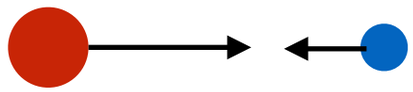


(Borrowed from APEX)

- A' carries large fraction of beam energy -- at large boost, decay products go forward.
- Recoil proton carries little energy

EIC Kinematics

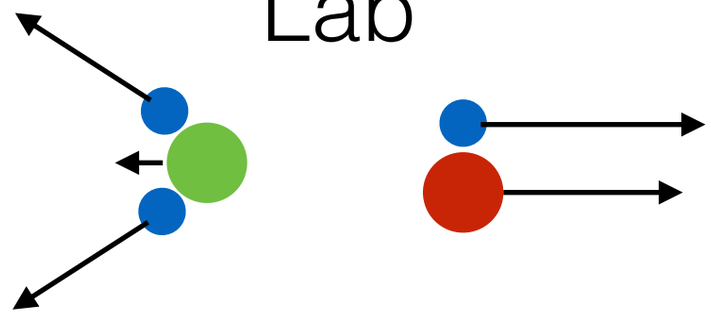
- at 20GeV x 250GeV, CM Boost substantially opens the angle between decay leptons:



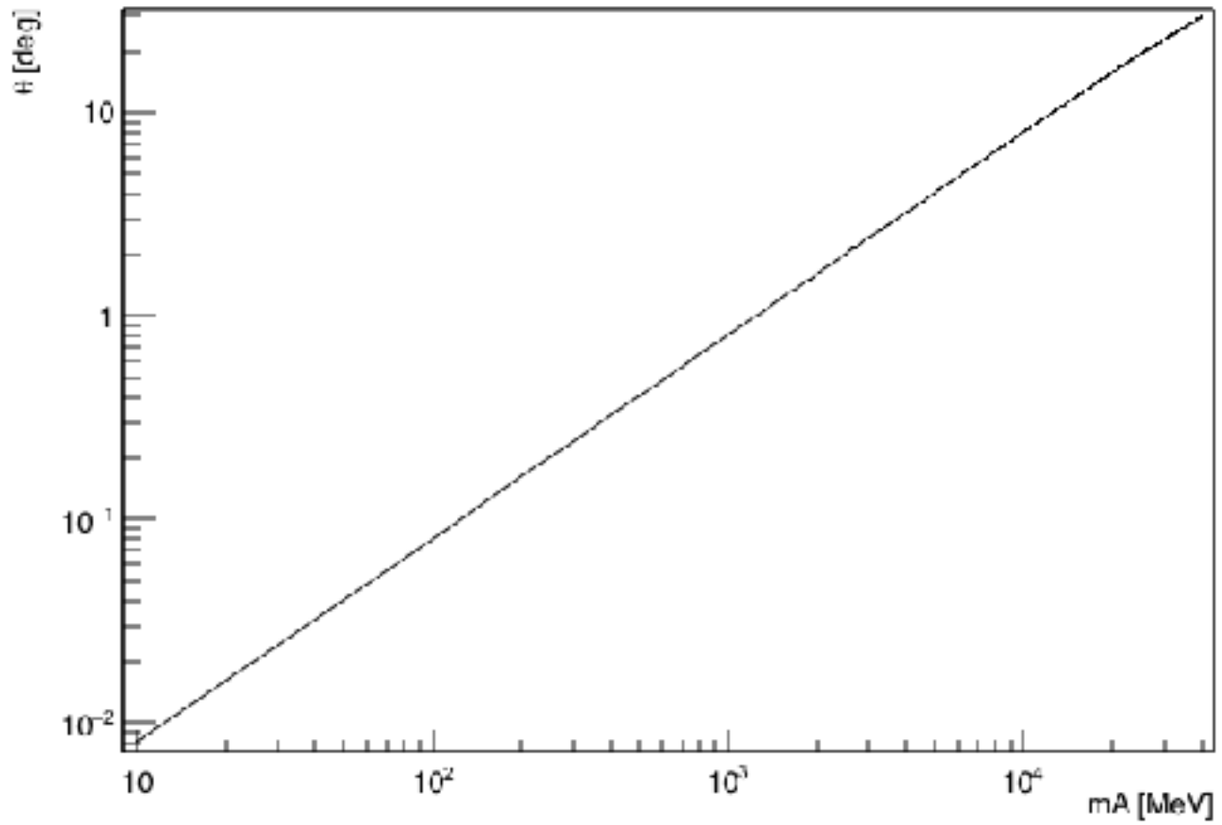
CM

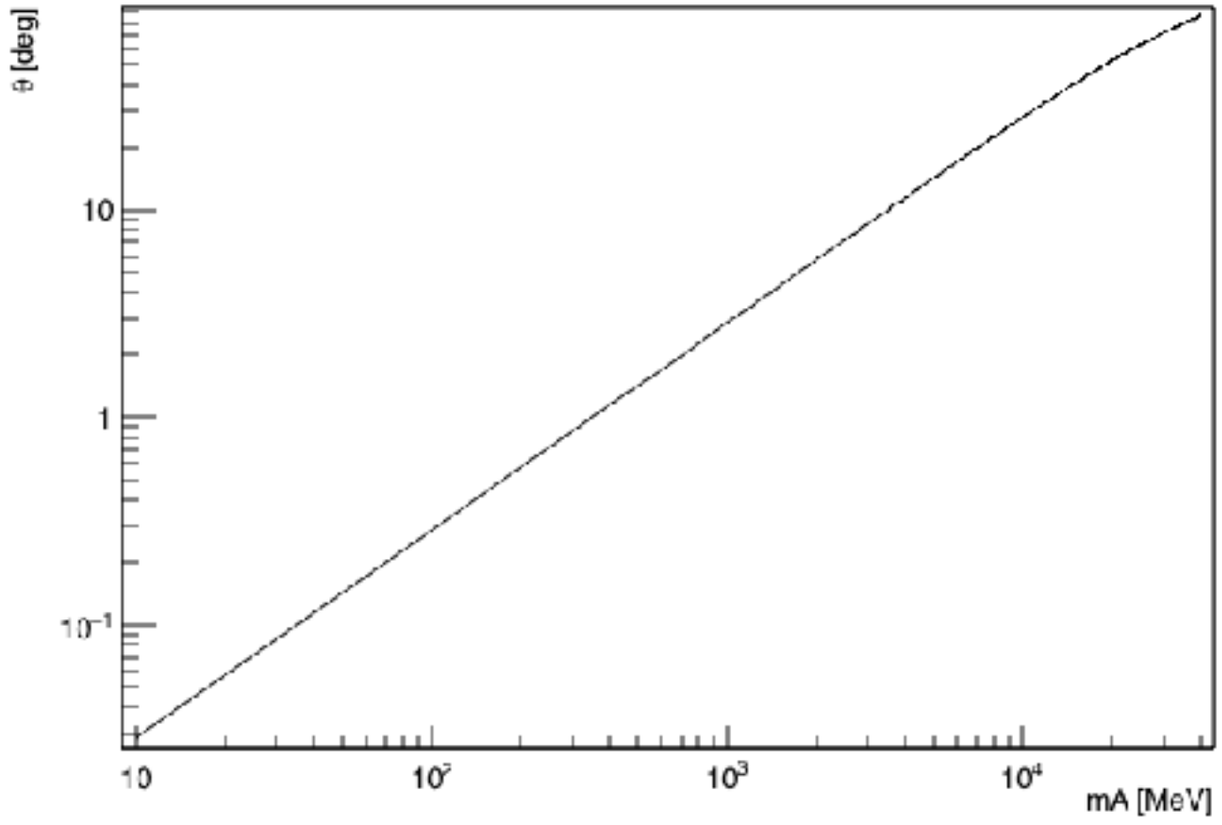
CM frame symmetric θ for A' decay

Lab

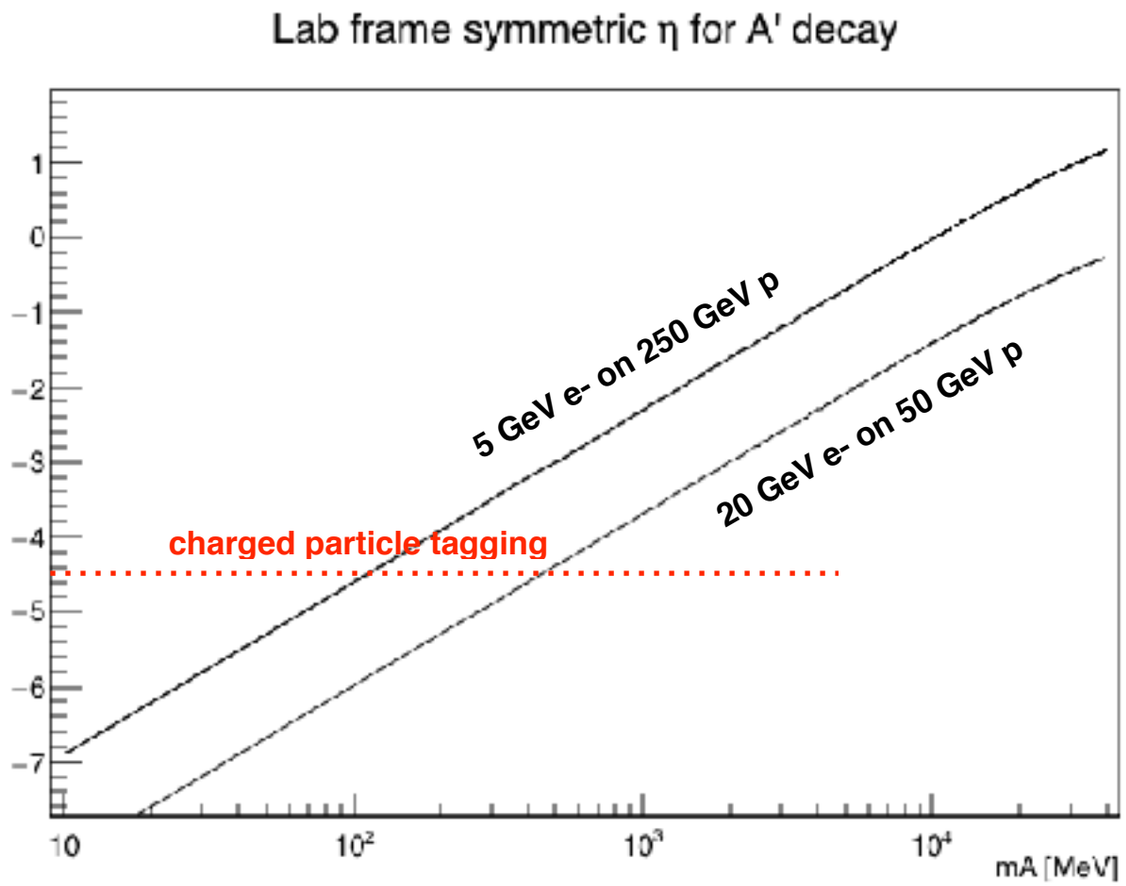


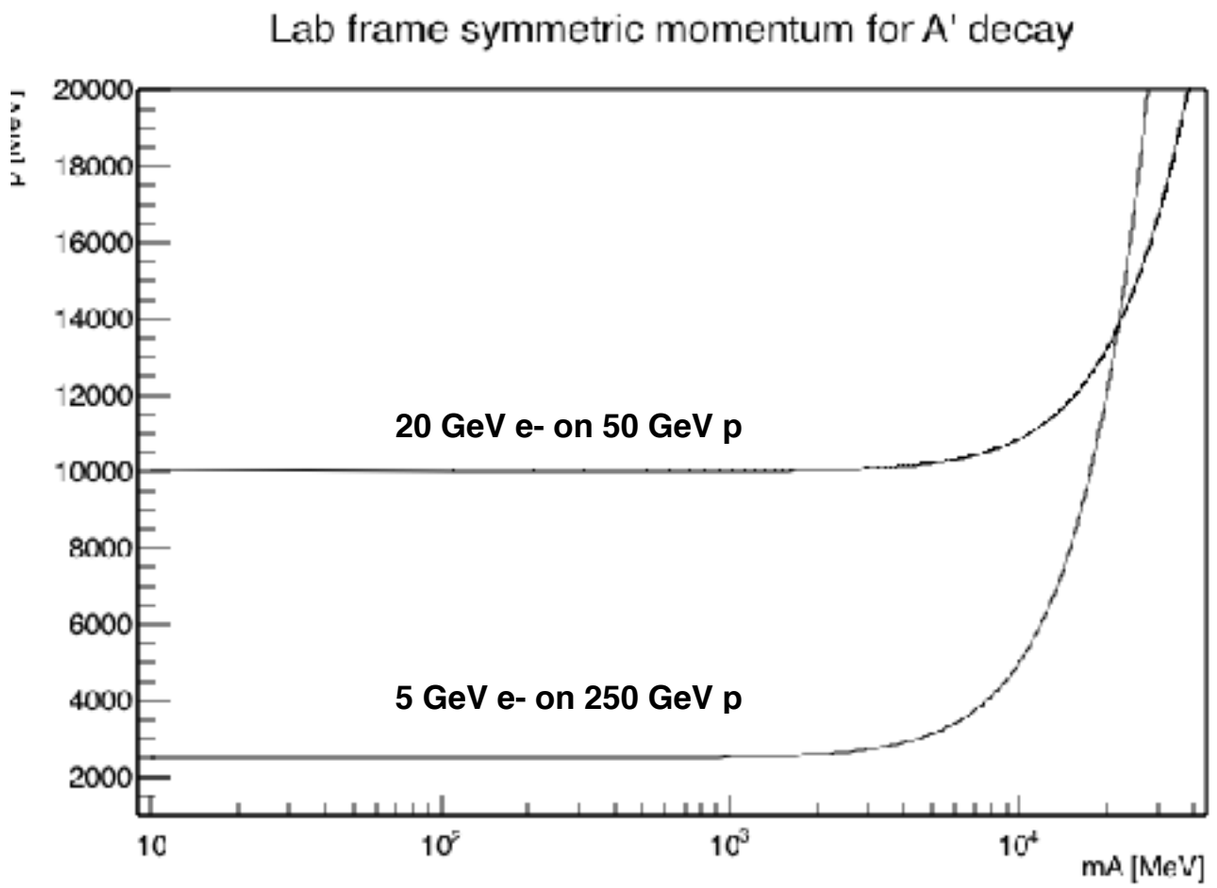
Lab frame symmetric θ for A' decay



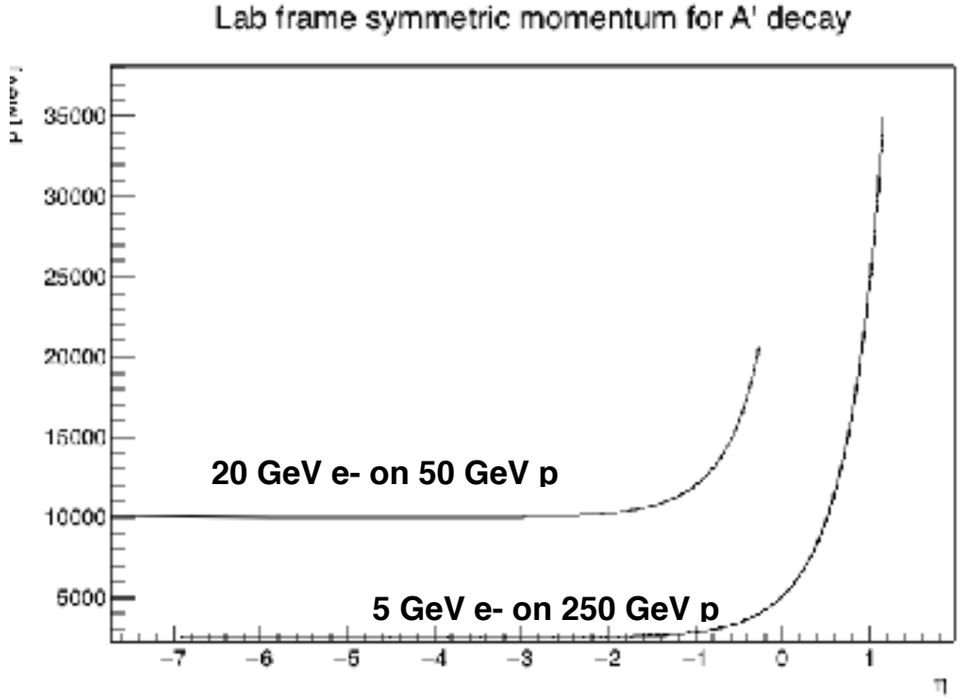


EIC Kinematics





- For ep, handbook detector reaches to O(100MeV)

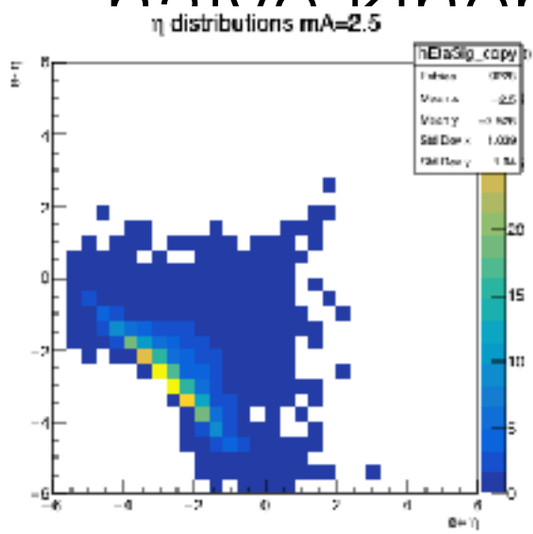


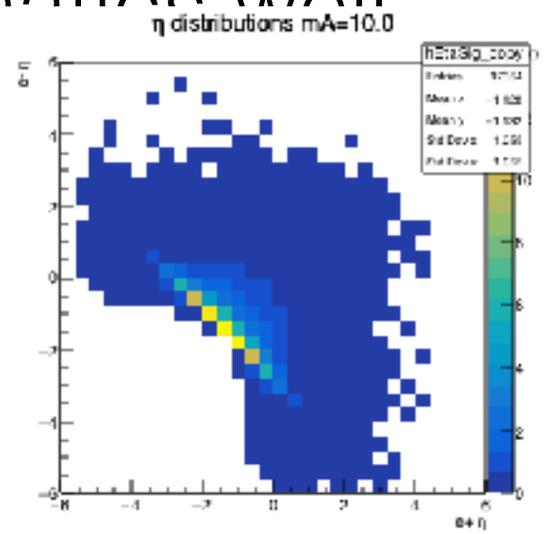
Generating Events

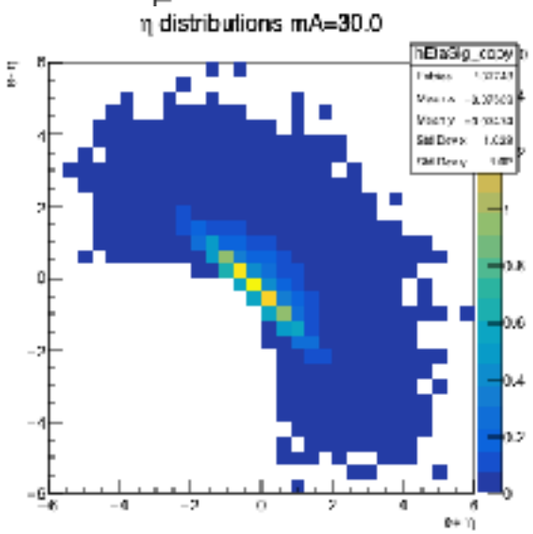
- Madgraph4.4 configuration:
  - custom (A',e,e) vertex
  - *ignores proton structure*
  - ~10TeV e- on fixed proton target, boost to lab frame after generation (20x250 setting)
  - Gen-level cut at $1° < \theta_e < 179°$ wrt e- direction in lab ($0.001° < \theta_e < 30°$ wrt e- beam in p-rest)
  - generate leading order:
    Signal: ep->epA'->epee for various m_A
    Irred. Bg: ep->epγ*->epee

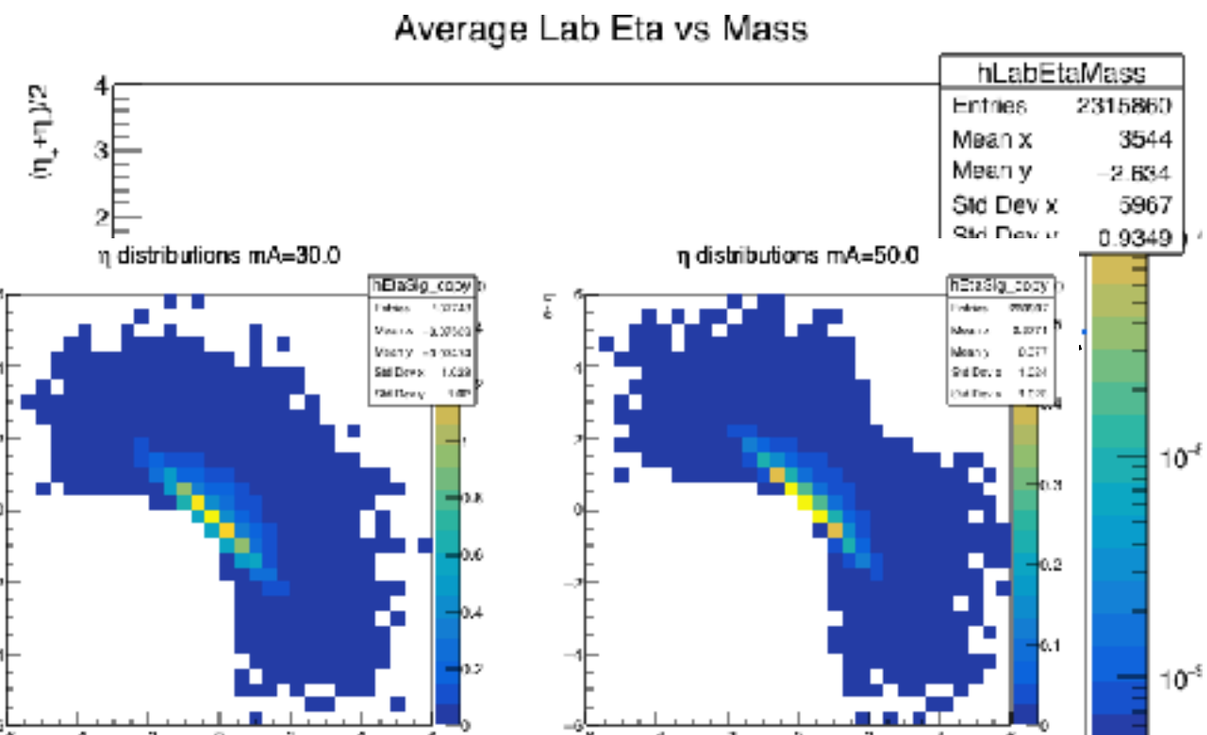
MC Kinematics

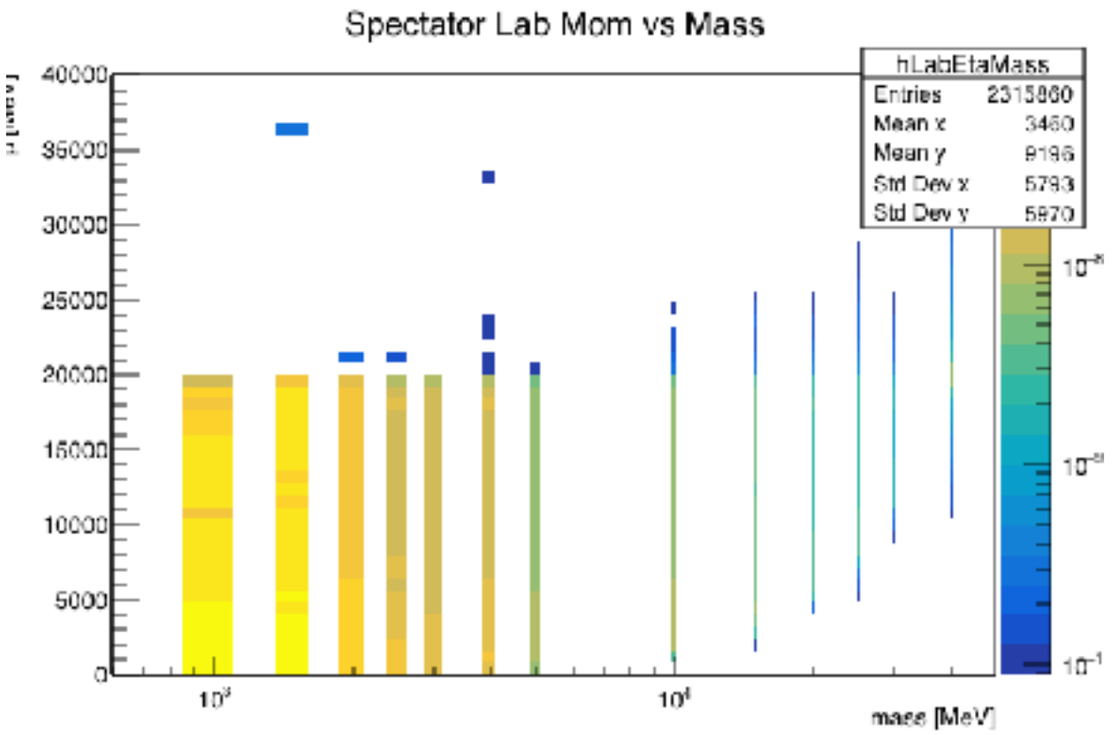
- Signal e+e- pairs track naive kinematics well

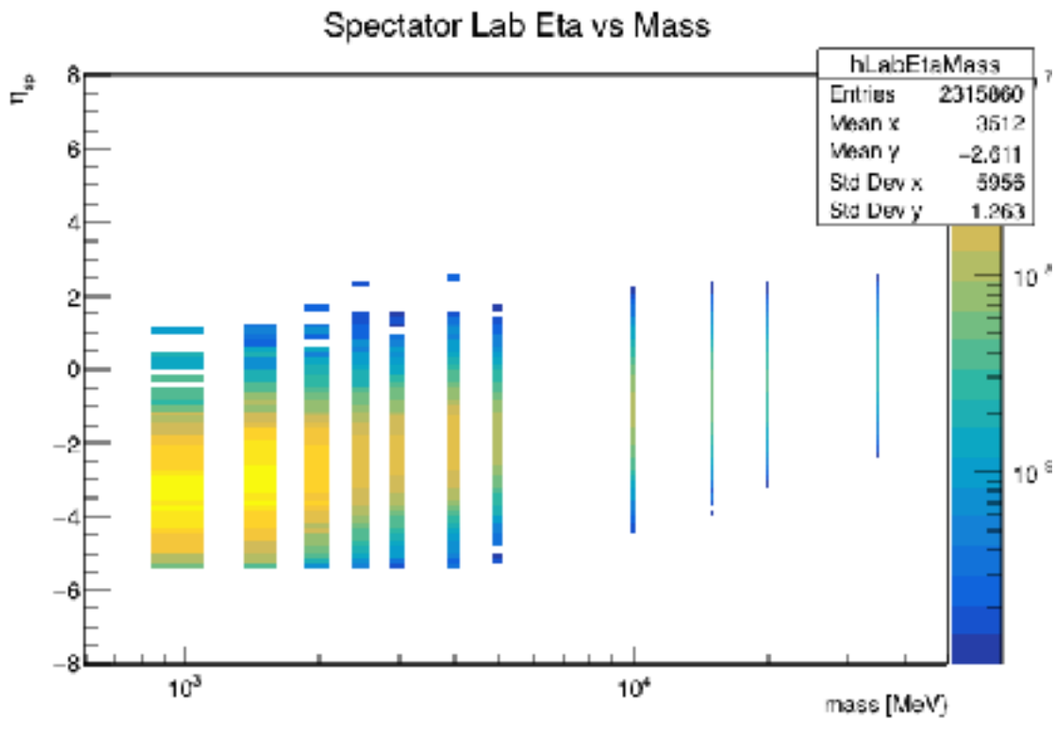












Reach Calculation

- Significance is signal size compared to fluctuation in irreducible background:

$$S = \frac{\sigma_A L}{\sqrt{\sigma_{QED} L}}$$

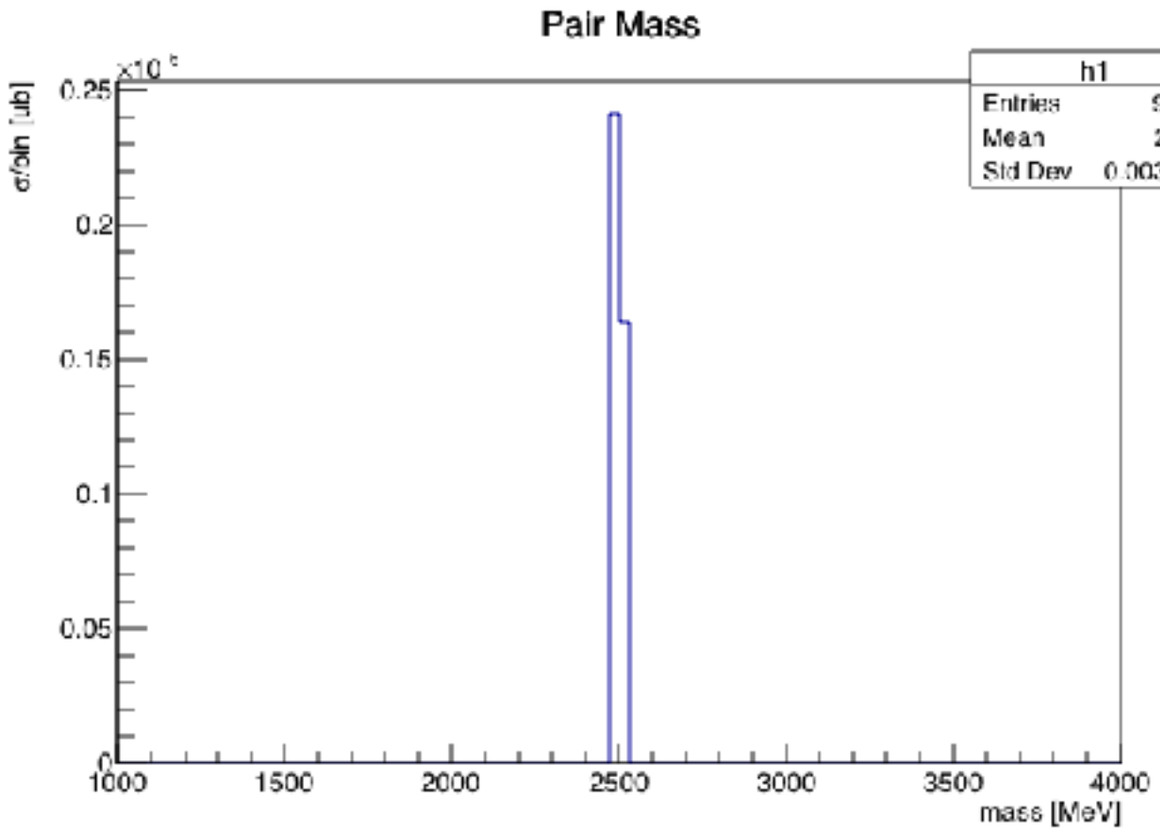
- Signal xs scales with coupling (ε^2):

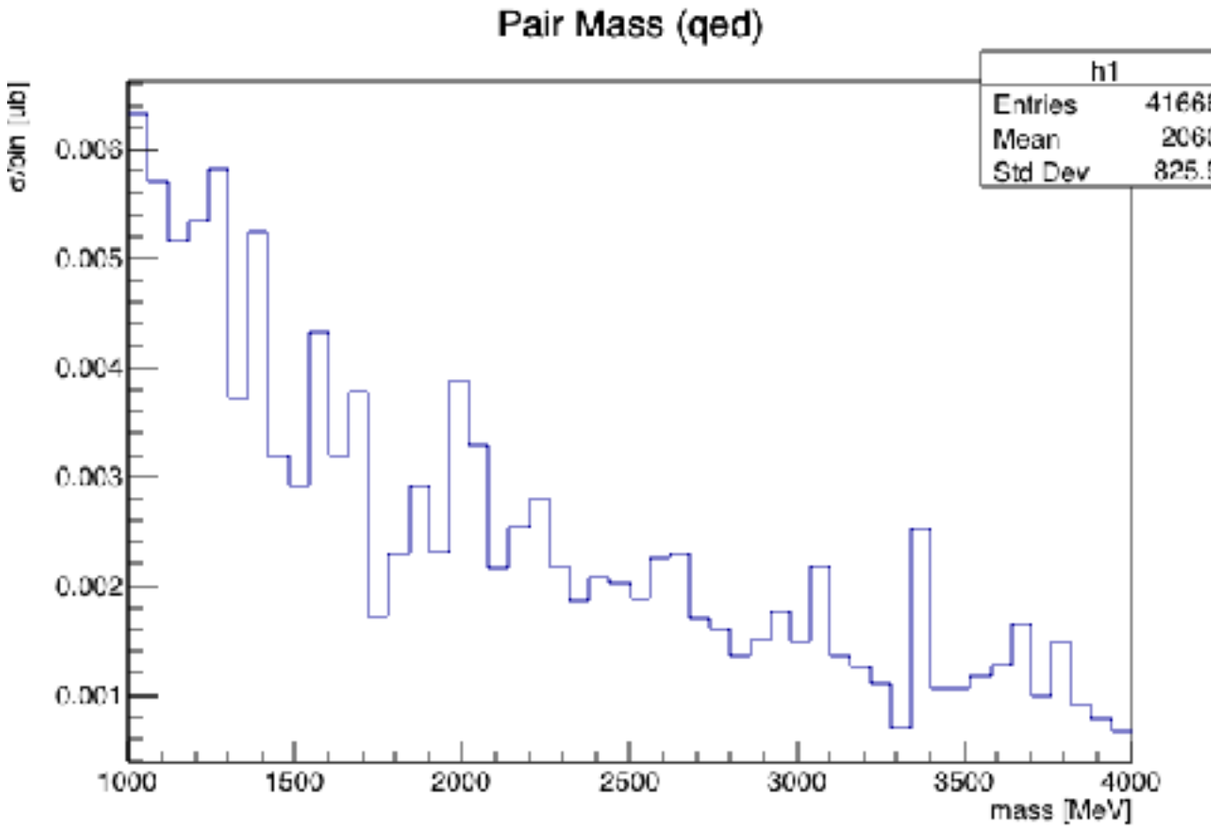
$$S = \sigma_{A0} \frac{\alpha_D}{\alpha_{D0}} \sqrt{\frac{L}{\sigma_{QED}}}$$

Reach defined by extrinsic factors and Sig/√Bg:

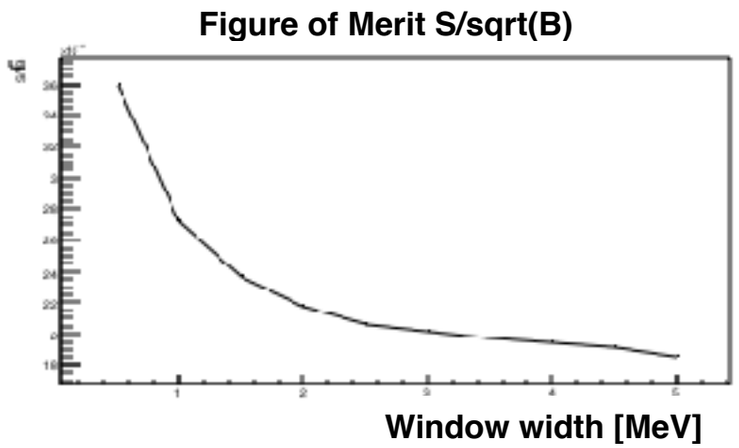
$$\alpha_D = S \frac{\alpha_{D0}}{\sqrt{L}} \frac{\sqrt{\sigma_{QED}}}{\sigma_{A0}}$$

Optimizing mass window



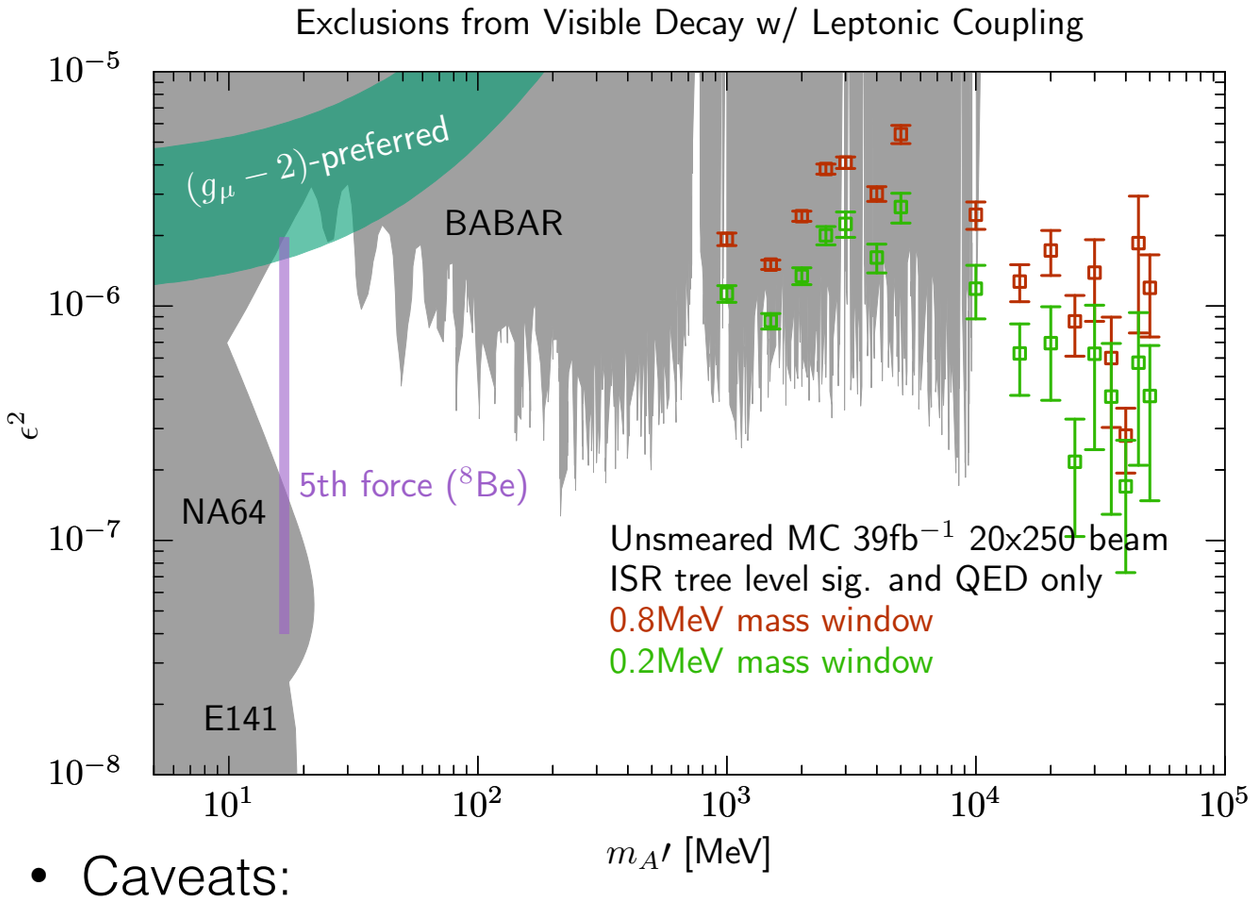


- Integrate yield in Signal and Bg samples in window of varying size, find local maximum (trivial for unsmeared MC)
- Inv Mass from e+ and spectator e- does not have a peak



MC Reach

- Repeat FOM calculation for every sample, propagate finite statistics uncertainties
- Arbitrary settings:
  Significance = 5σ
  L=39fb^{-1} (6 months of running at 25x250 design lumi)



$$\alpha_D = S\frac{\alpha_{D0}}{\sqrt{L}}\frac{\sqrt{\sigma_{QED}}}{\sigma_{A0}}$$

- Caveats:
  - Ignores resonances (gaps in BaBar reach)
  - Above muon threshold, decay to muons will halve yield to electrons
  - Hadronic modes also accessible (depending on model)
  - No cuts/smearing have been applied other than detector PID bounds

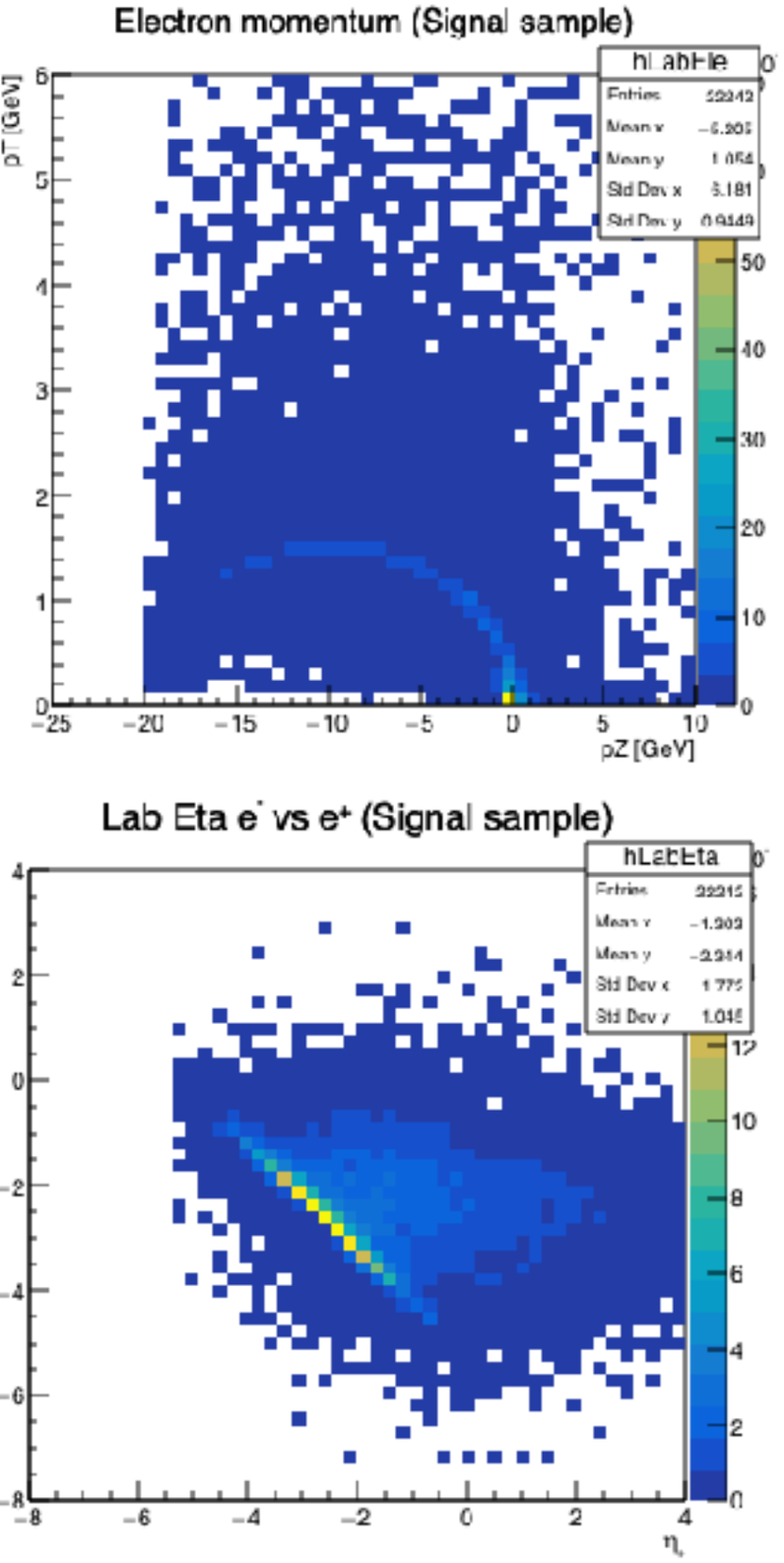
Detector Needs

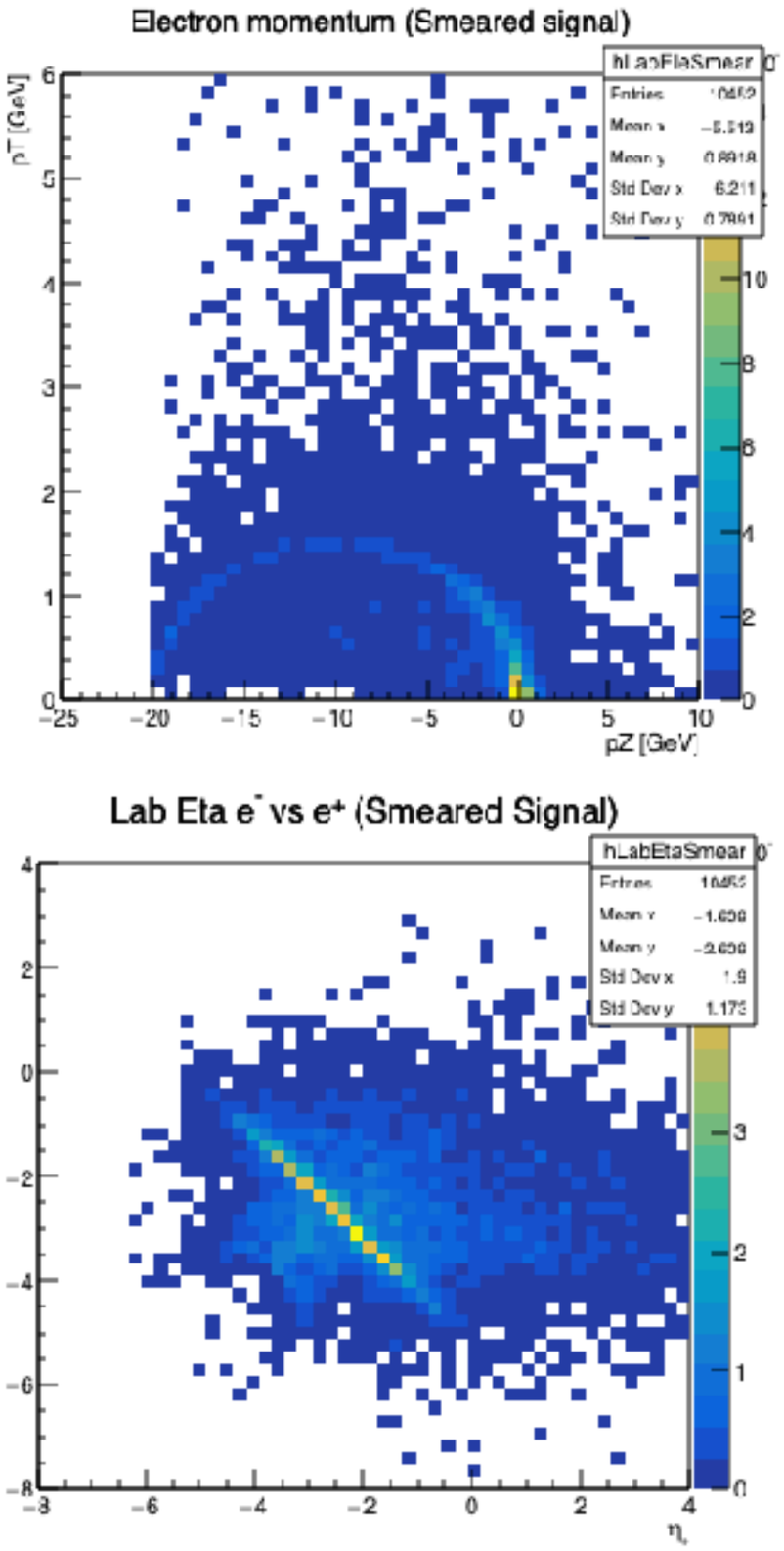
- Mass resolution -- maximize FOM. Intrinsic width very narrow, so window dominated by detector.
- Charge sign reco/PID -- reduce combinatorics, fewer wrong-pairs to deal with
- Coverage -- higher (-) eta accesses lower masses

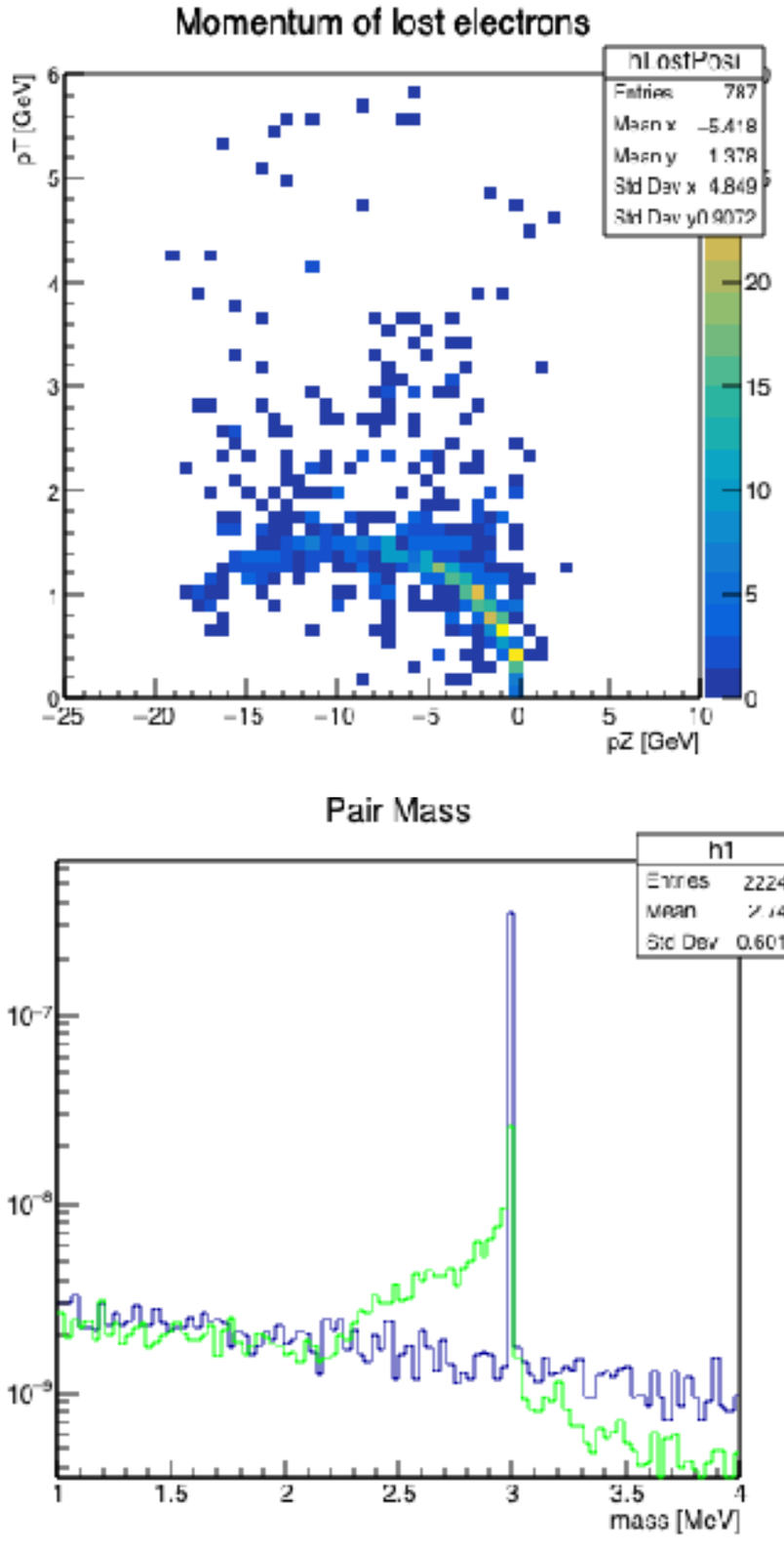
Converting Events

- Parse MadGraph trees into DJANGOH-like text files
- Patch missing variables with synchronized tree
- Convert back into MG tree for parallel analysis

Signal in Handbook Detector



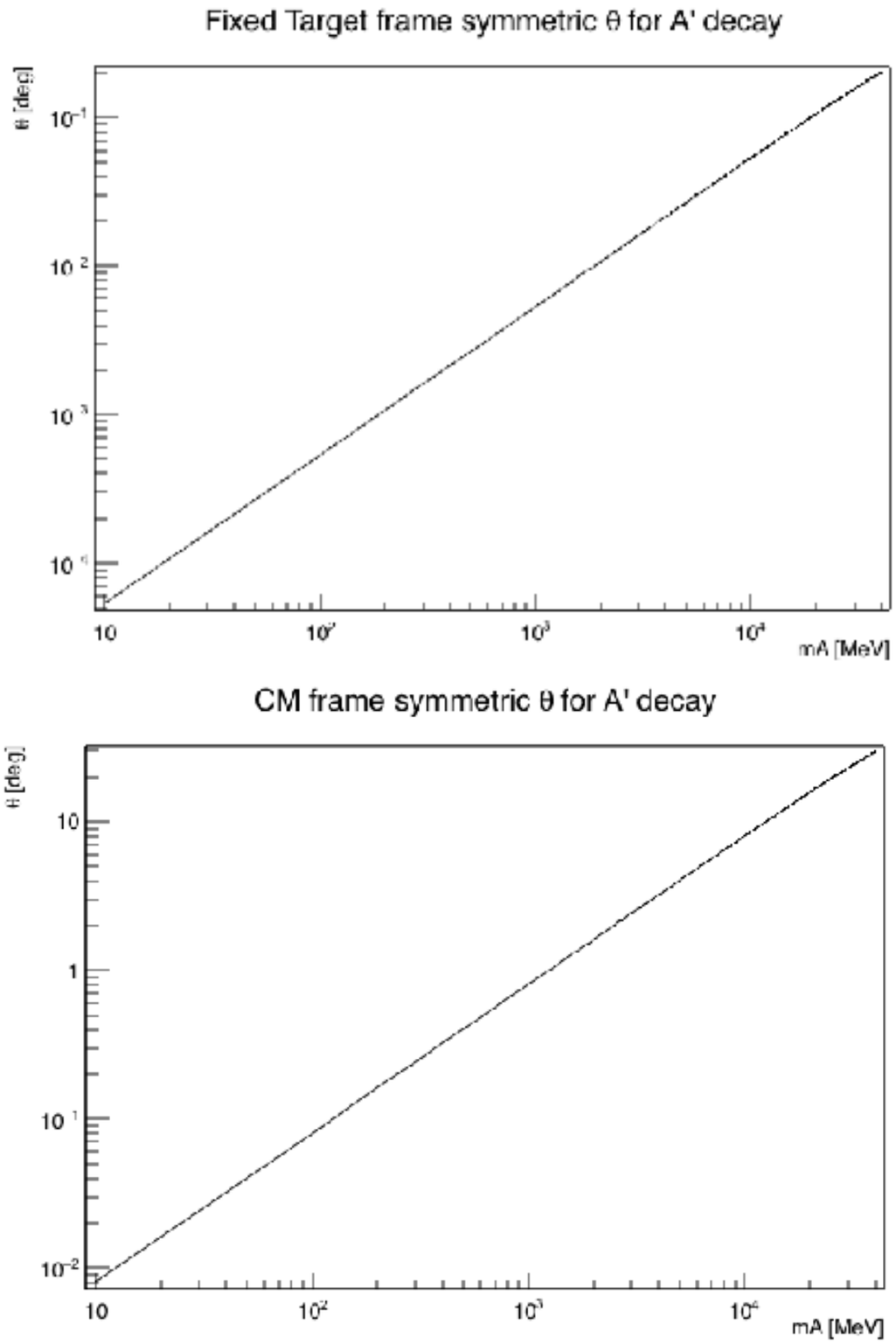
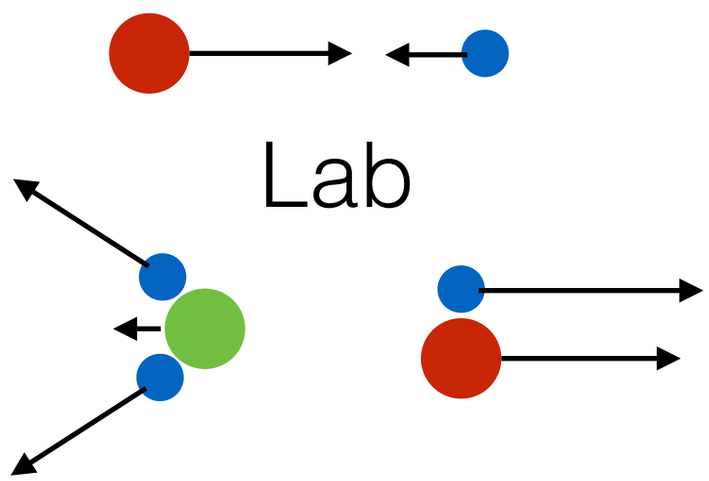
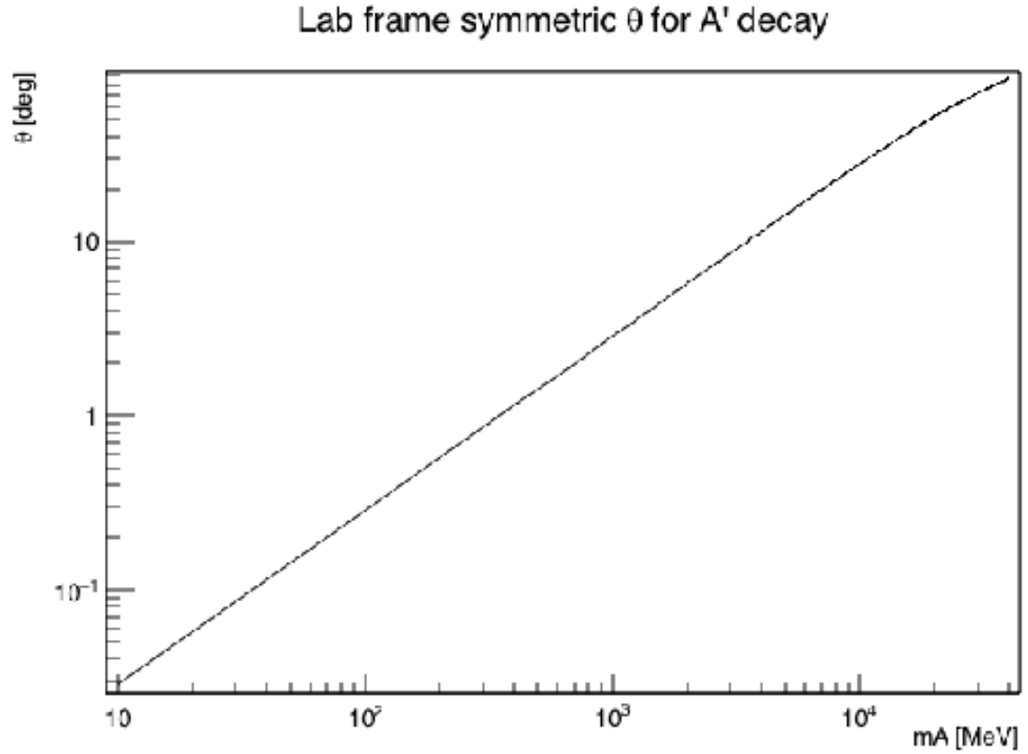




Next Steps

- Upgrade MC generator:
  - muons, more efficient cuts, heavier ion beam
  - hadronic couplings, proton structure
- (Gently) Improve algorithm
  - shape-fitting and cut optimization
    - same-sign pairs for in-situ background
    - displaced vertices?
- Improve handling of more realistic detector
  - tracing lost pid and systematic shifts
  - combinatoric/mis-ID'd backgrounds

Summary

- Multiple probes desired to explore A' generalized parameter space
- Multiple approaches available at EIC:
  - ISR leptons - ~500MeV<mA<~50GeV from kinematics
  - Dalitz decays - mA<parent
  - hadronic decays?
- Boosted CM helps in ISR scenario
- Benefits from pid, charge, and resolution -- especially in electron-going direction

EIC Kinematics