Searching for an invisible dark photon at DarkLight

Yonatan Kahn
with Jesse Thaler

Phys. Rev. D86:115012

What is a dark photon?

New, massive U(1) gauge boson A' which kinetically mixes with the hypercharge boson Y:

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

Remove kinetic mixing with a field redefinition:

$$\mathcal{L} \supset \epsilon \cos\theta_W g_D A'_\mu J^\mu_{EM}$$

$\Longrightarrow$ A' couples universally to charged matter with strength $\alpha' \propto \epsilon$

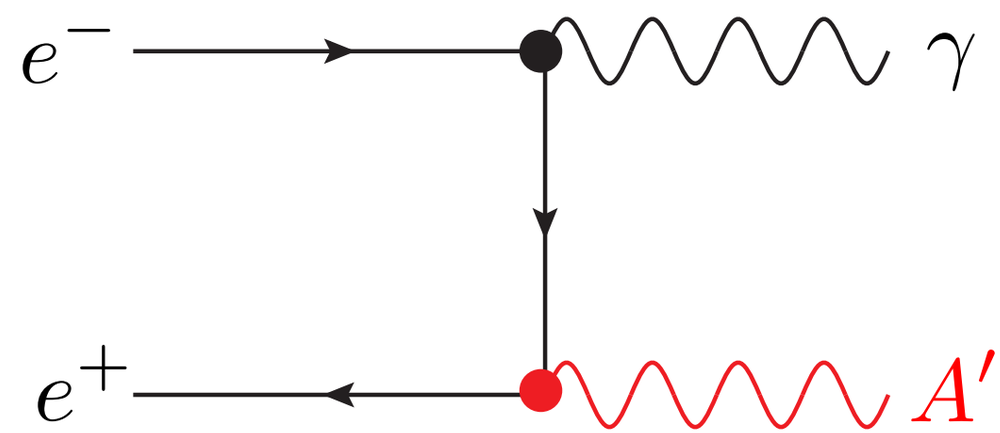
(note asymmetry: photon is massless, so doesn't talk to dark sector)

How can we look for it?

Replace a photon with an A' in any QED process

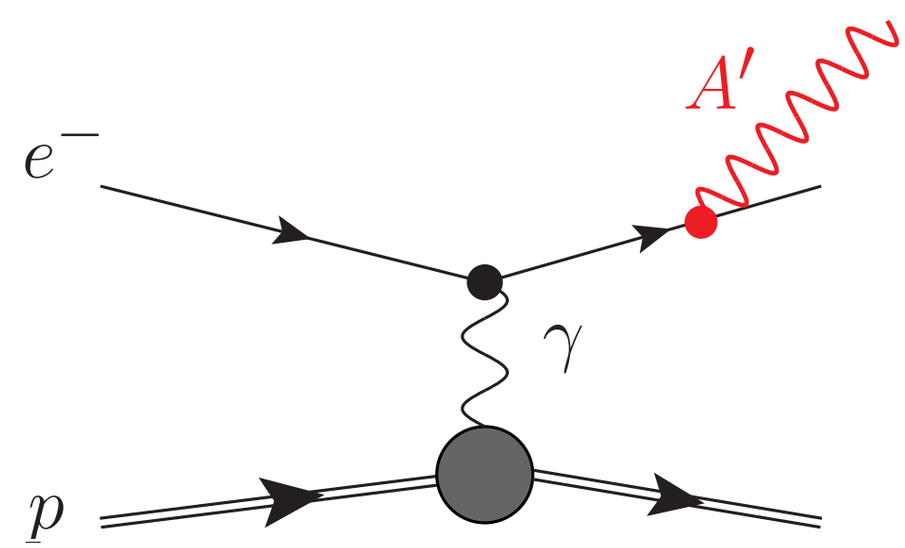
Pair annihilation:

$$e^+e^- \to \gamma A'$$



Bremsstrahlung:

$$e^-p \to e^-pA'$$

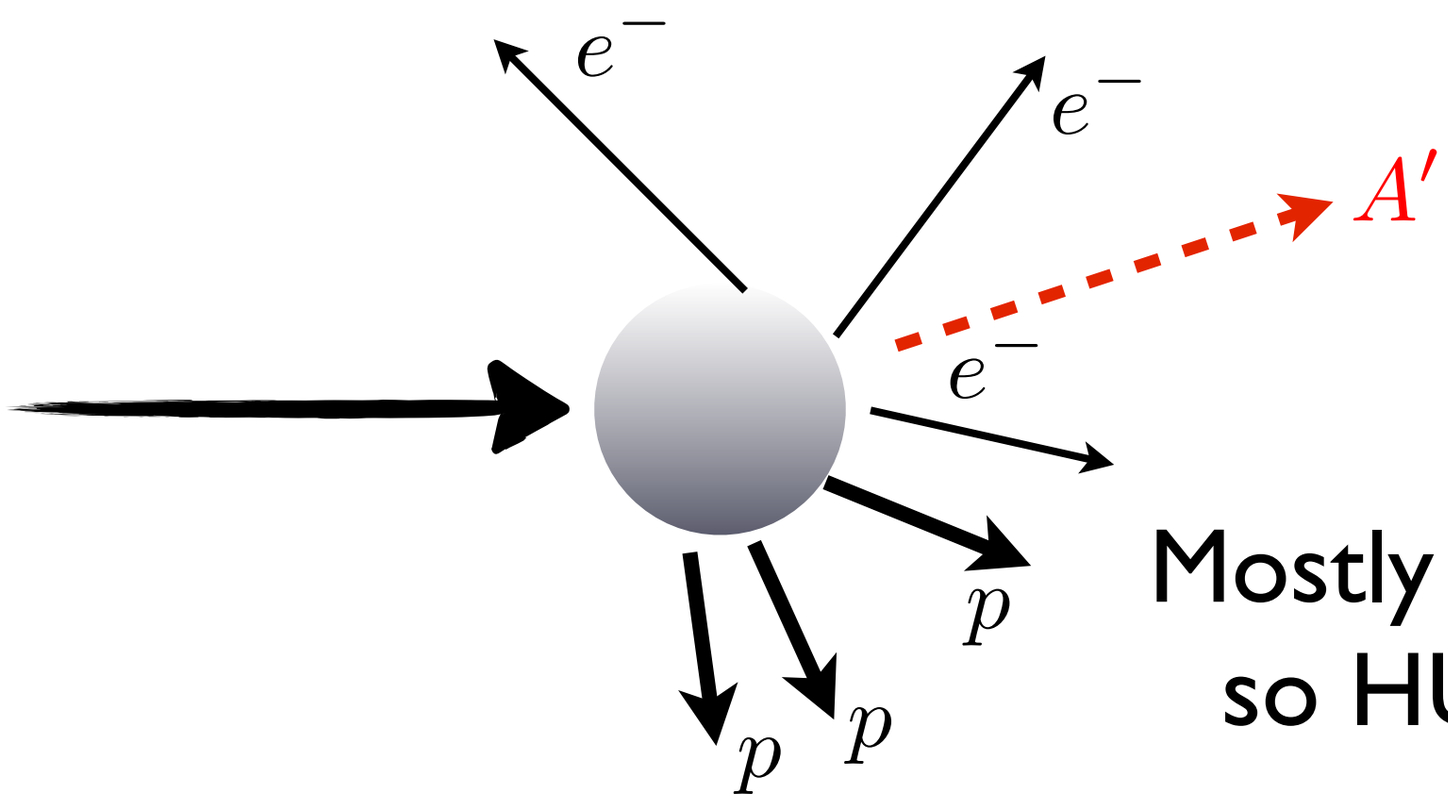


DARKLIGHT

"Detecting a Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target"

Electrons: Jefferson Lab Free Electron Laser drive beam (100 MeV @ 1 MW: compare LHC wall plug 100 MW)

Protons: fixed target of hydrogen gas



Mostly elastic scattering, so HUGE event rate!

DarkLight: visible search

cf Ray Cowan's talk

(Freytsis, Ovanesyan, Thaler, JHEP 2010:111; DarkLight PAC 39 proposal)

Suppose A' decays into an e+/e- pair:

$$e^- p \to e^- p A', \qquad A' \to e^+ e^-$$

If A' is on-shell, see a bump at the 10^{-6} level in the e^+/e^- invt. mass spectrum

Want a high-statistics experiment (1 ab^{-1}!)*
which can reconstruct electron and positron 4-vectors

*entire LHC data set

DarkLight: invisible search

(YK, Thaler, Phys. Rev. D86:115012 (2012))

A' could also decay predominantly into dark matter or some other hidden state:

$$e^- p \to e^- p A', \qquad A' \to \text{inv.}$$

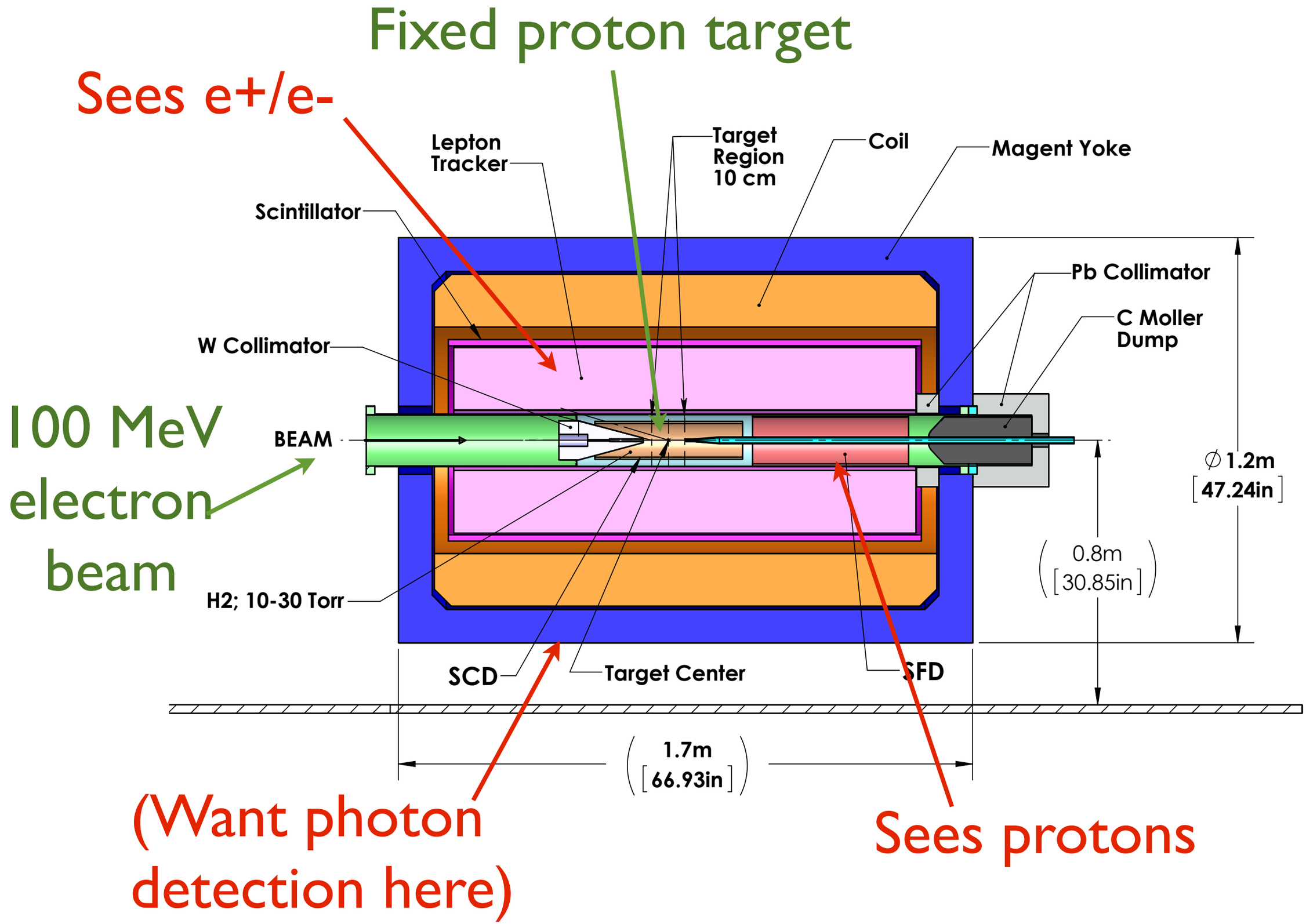
Now proton detection and reconstruction is crucial:

$$m^2_{miss} = (p_1 + p_2 - p_3 - p_4)^2$$

Furthermore, photons can fake invisible final state, so want efficient photon veto

Focus on invisible search here

Detector design



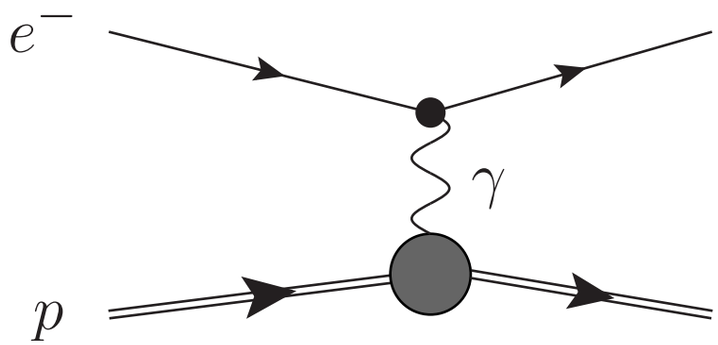
Backgrounds?

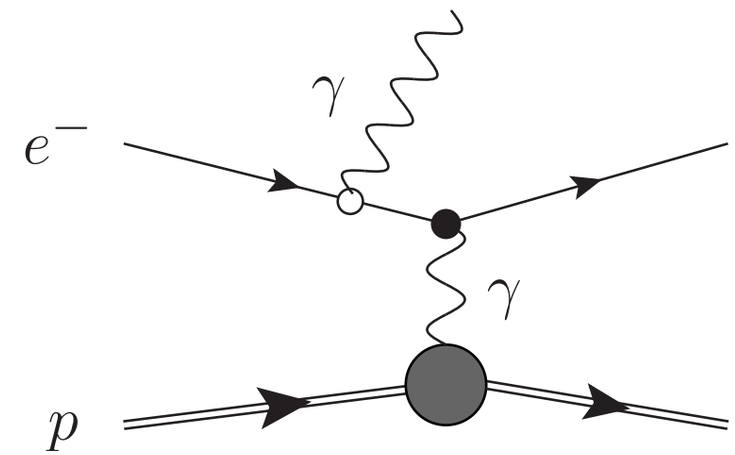
- $ep \to epZ^* \to ep\nu\overline{\nu}$: Z is so far off shell that this is completely negligible
- But nothing else gives missing energy in SM!
- Only have to worry about neutral or lost objects
- 100 MeV < m_π, so no QCD to give pions or neutrons

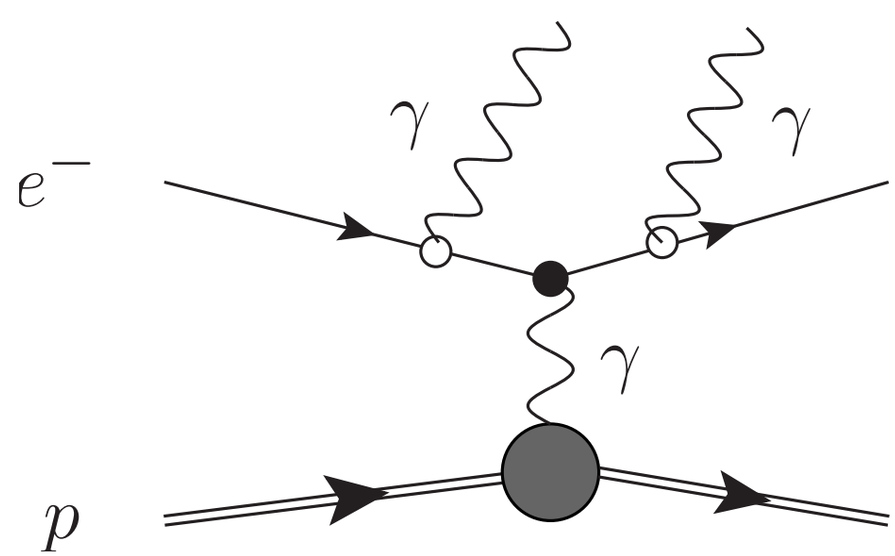
Actual backgrounds

$$m^2_{miss} = 0$$

(with perfect resolution...)







$$m^2_{miss} \neq 0$$

Irreducible without photon detection!

Key things to worry about

- Mis-measurement: easy to fake missing energy by mis-measuring an electron or proton
- Pileup: tons of events being tracked in the detector, what if we mis-reconstruct an event? Huge elastic rates...

Dealing with mis-measurement

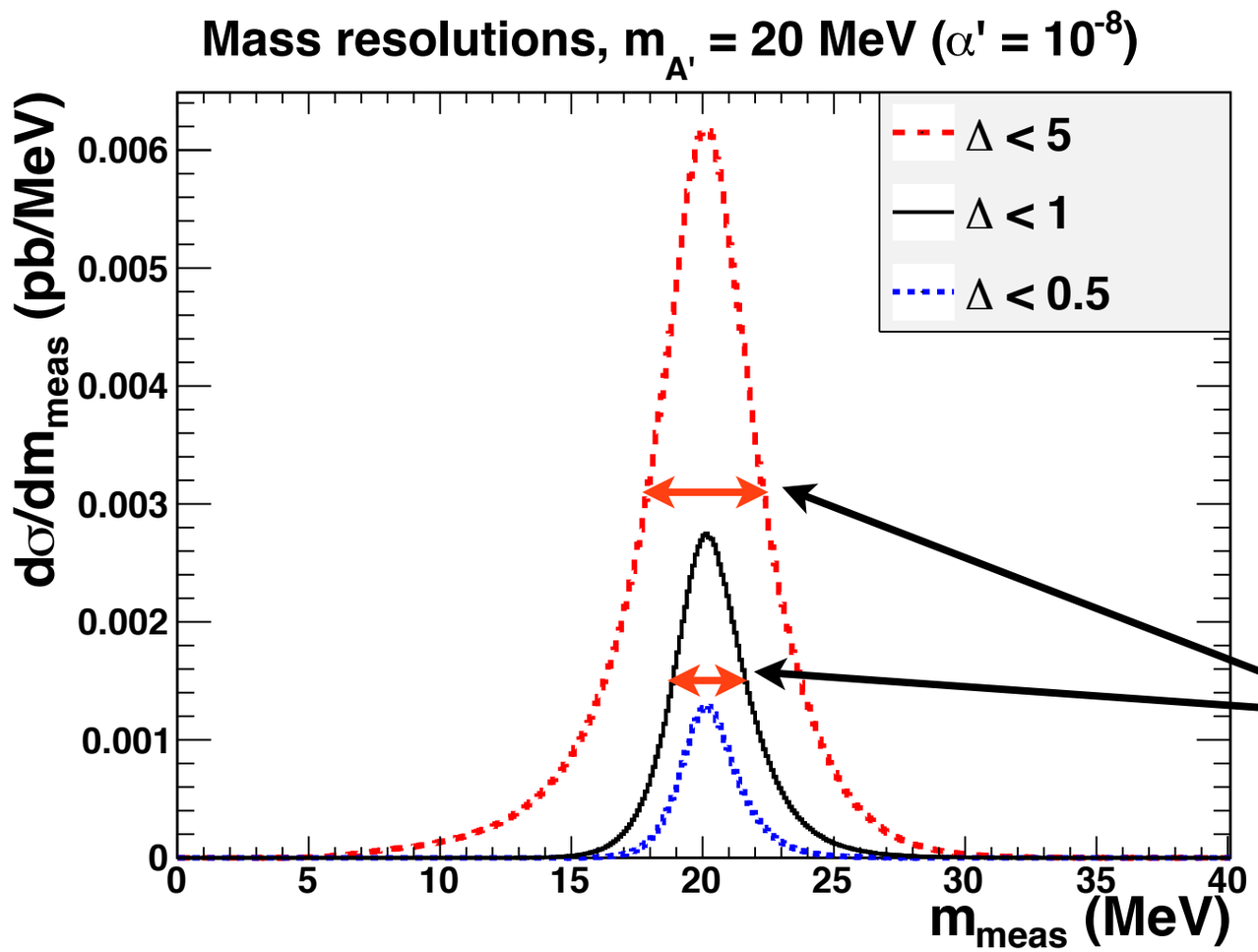
$$\sigma_m^2 = \left(\frac{E}{m}\right)^2 \sigma_E^2 \oplus \left(\frac{p}{m}\right)^2 \sigma_p^2$$

Mass resolution gets worse with increasing A' energy

Unlike LHC, want to minimize missing energy for a given missing mass

$$\frac{E}{m} \equiv 1 + \Delta$$

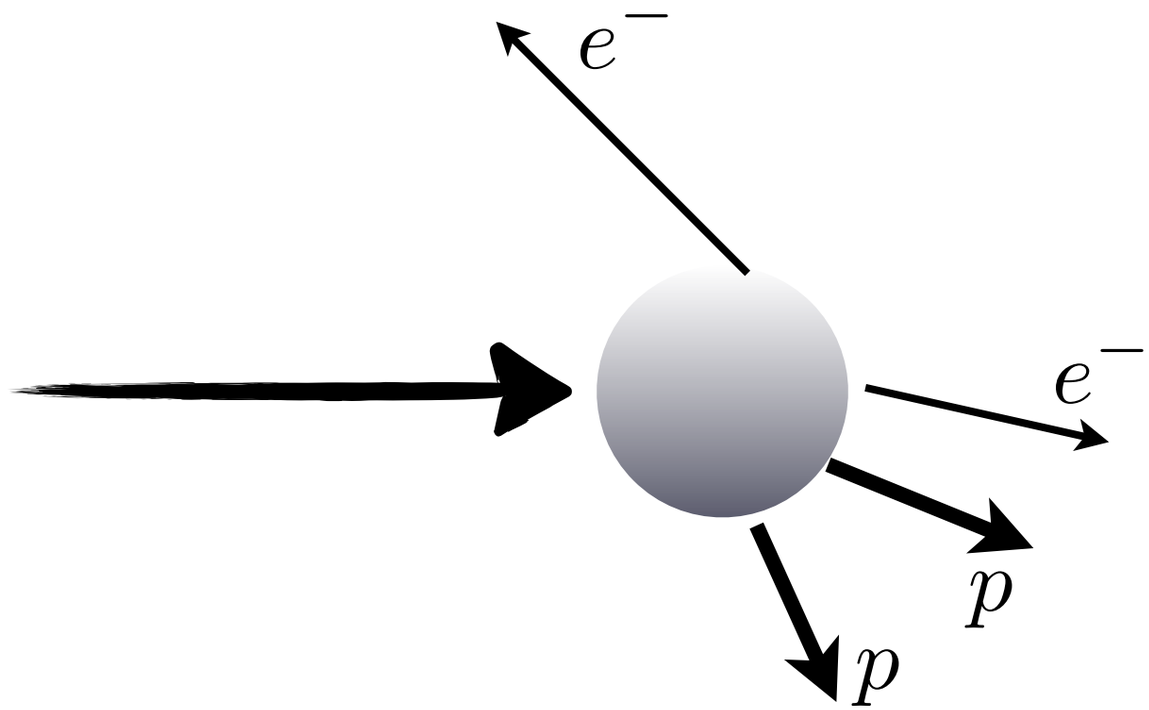
Dealing with mis-measurement



smaller FWHM, but less signal

Dealing with pileup

Huge luminosity means huge event rate.
Can QED pileup fake a large missing invariant mass?



which electron with which proton?

Kinematics of ep with ep+anything:

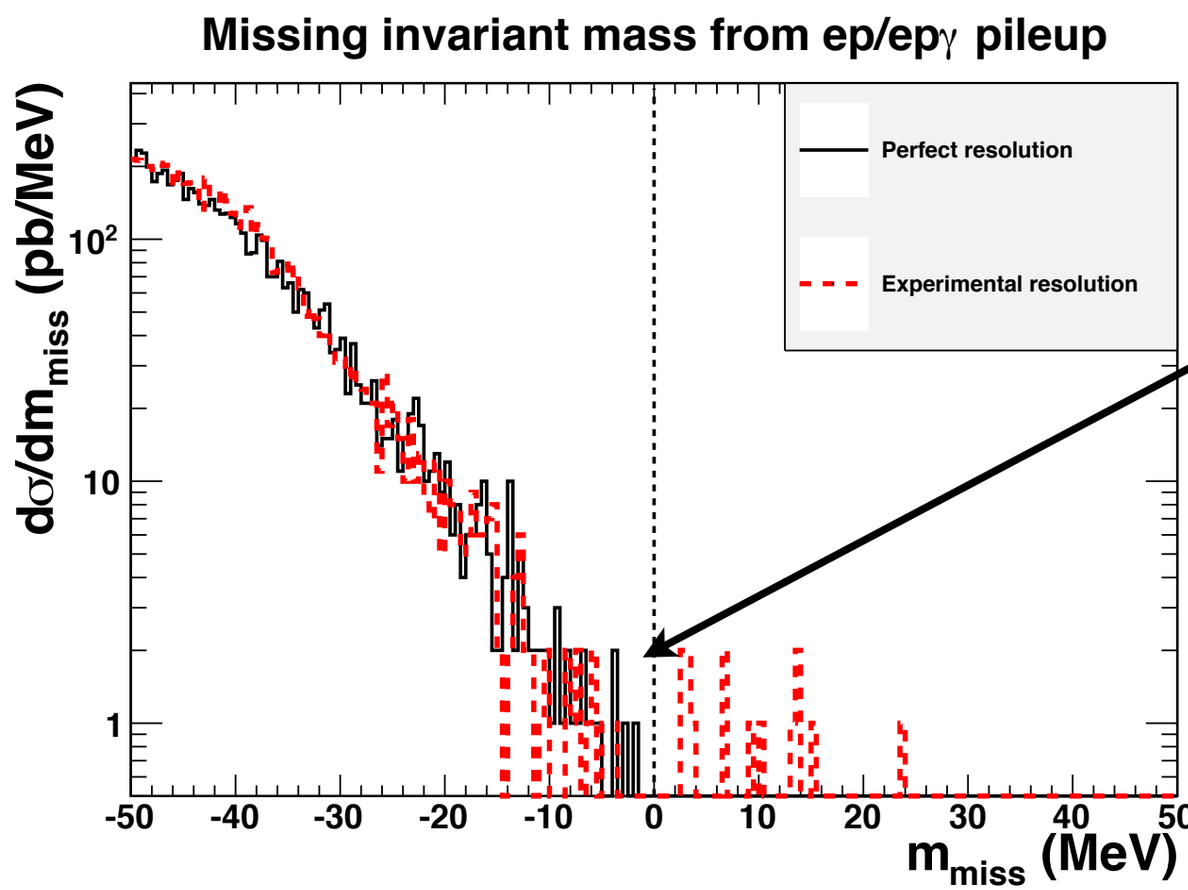
$$p_1 + p_2 \to p_3 + p_4$$

$$p_1 + p_2 \to p_3' + p_4' + q$$

$$(p_3 = e^-, p_4 = p, q = \text{anything})$$

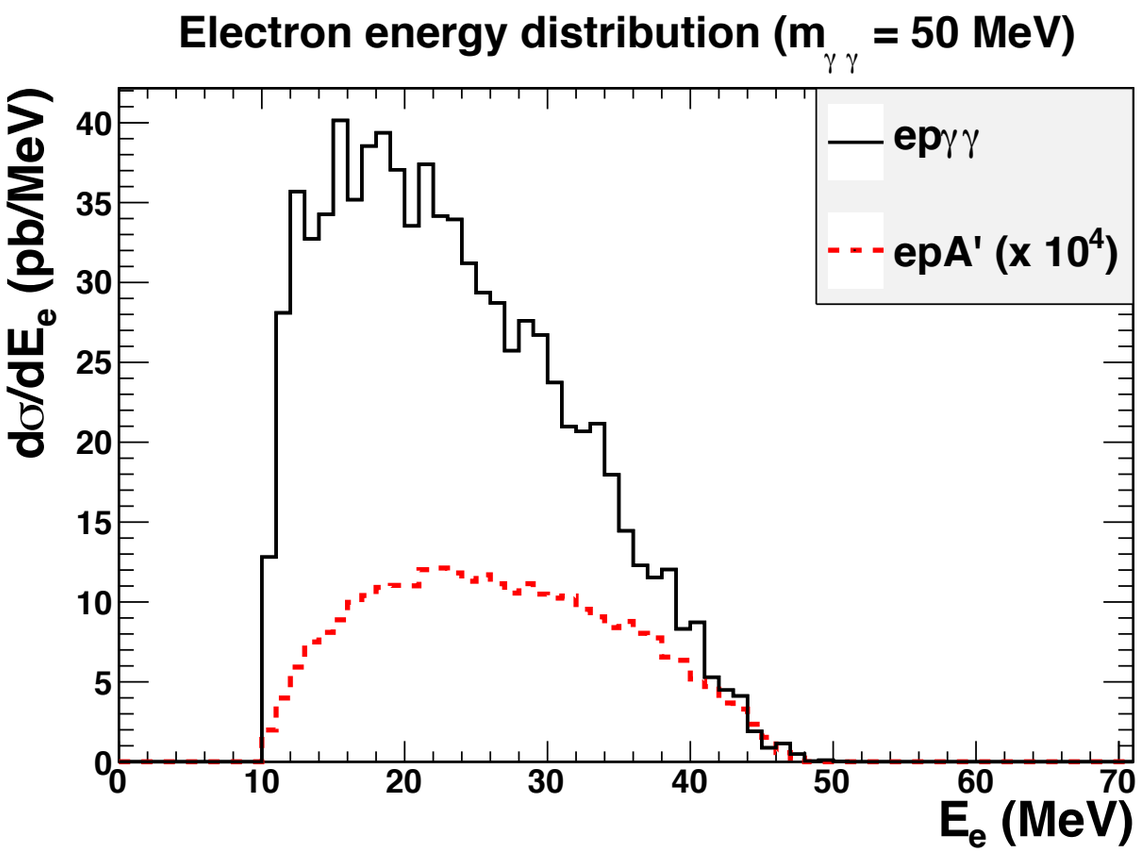
Dealing with pileup

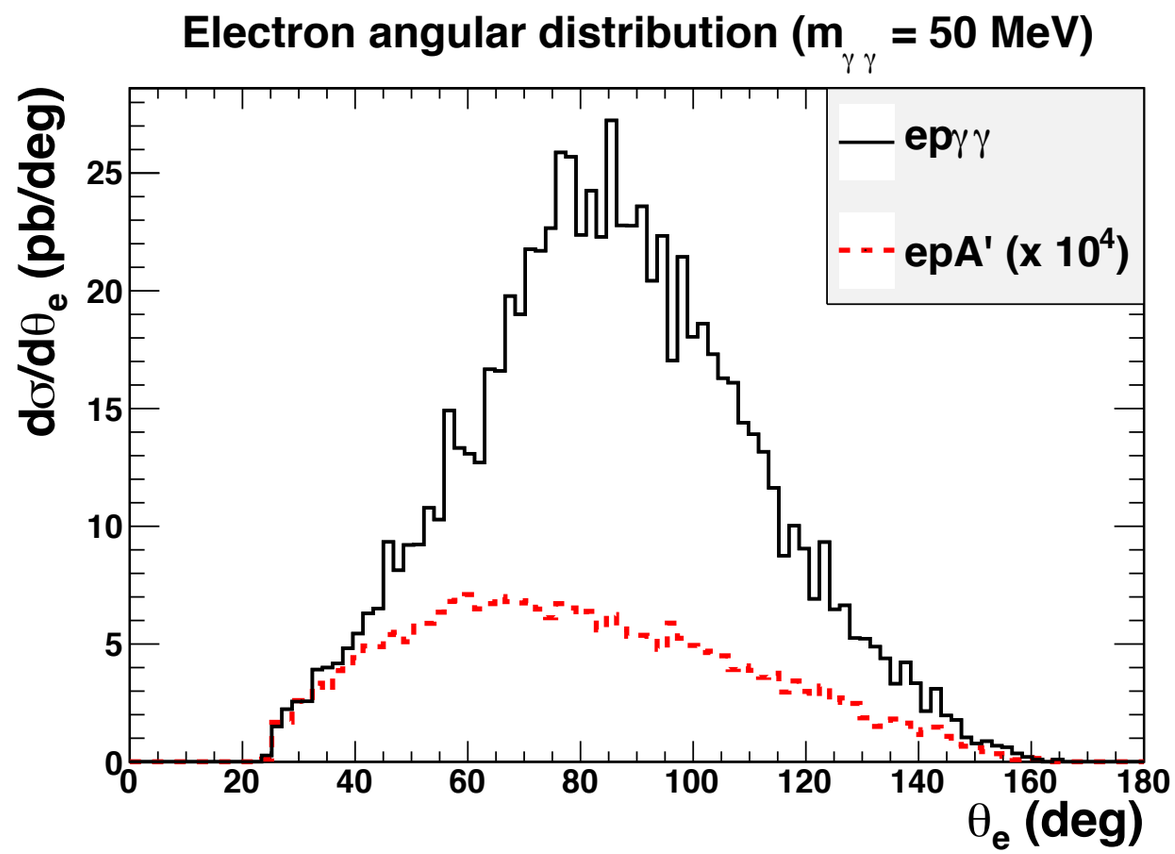
$$
\begin{aligned}
m^2_{miss} &= (p_1 + p_2 - p_3' - p_4)^2 \\
&= (p_3 + \cancel{p_4} - p_3' - \cancel{p_4})^2 \\
&= (p_3 - p_3')^2 \leq 0
\end{aligned}
$$



Strictly nonpositive!

“Irreducible” background: $ep\gamma\gamma$

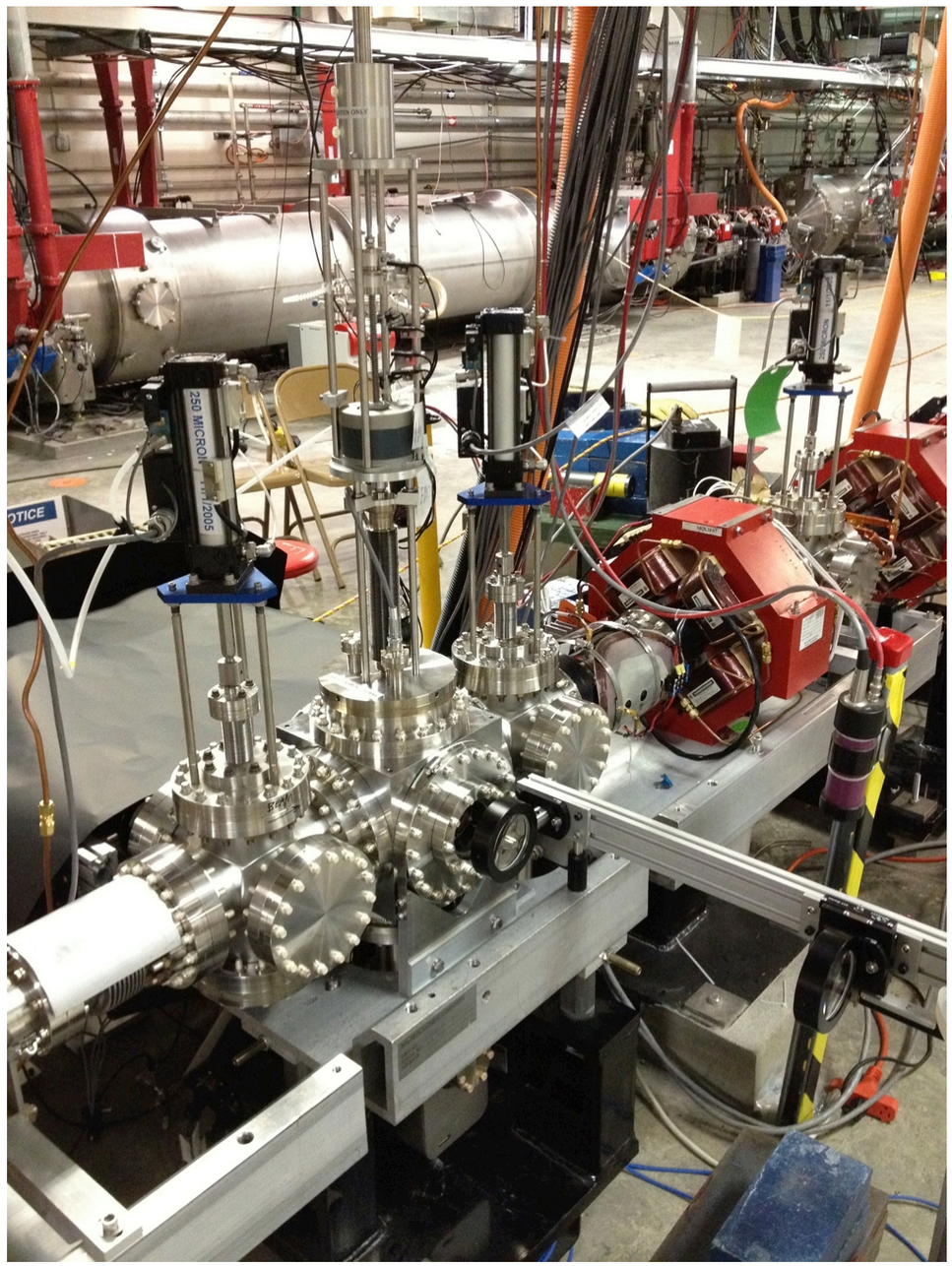




Identical kinematics, four orders of magnitude larger!

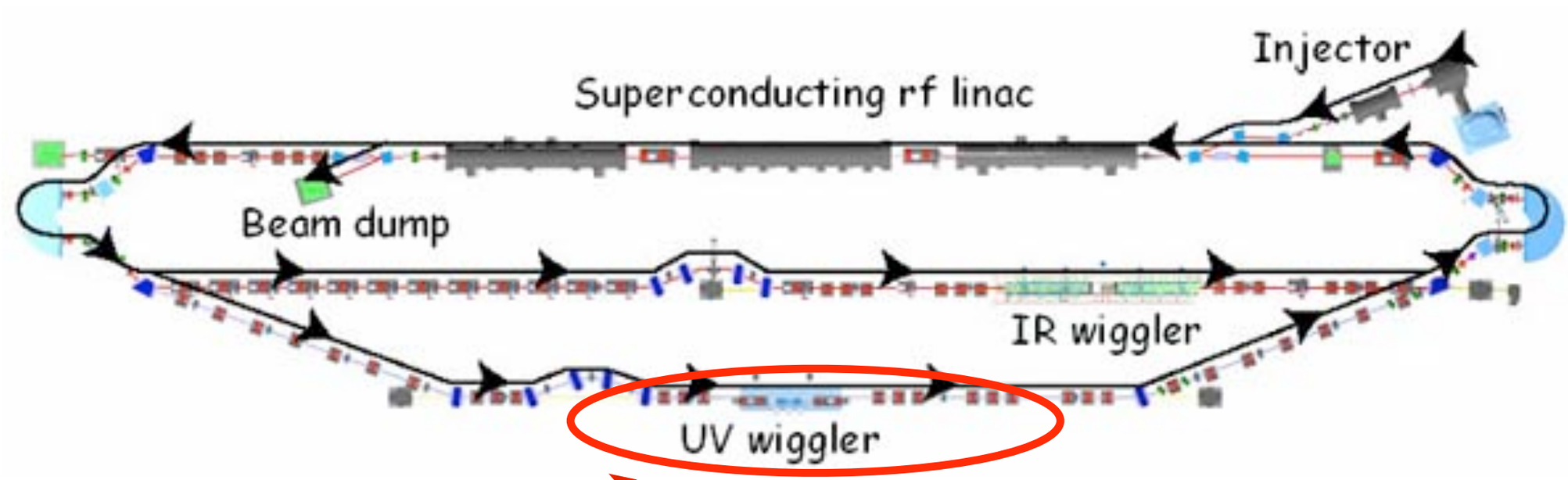
Need photon detection capability

What you can do with a 10 mA electron gun



- Use drive beam from JLab FEL
- Macroscopic current!
- Luminosity: 6×10^{35} $cm^2\ s^{-1}$
- 1 ab^{-1} in only 60 days of running!

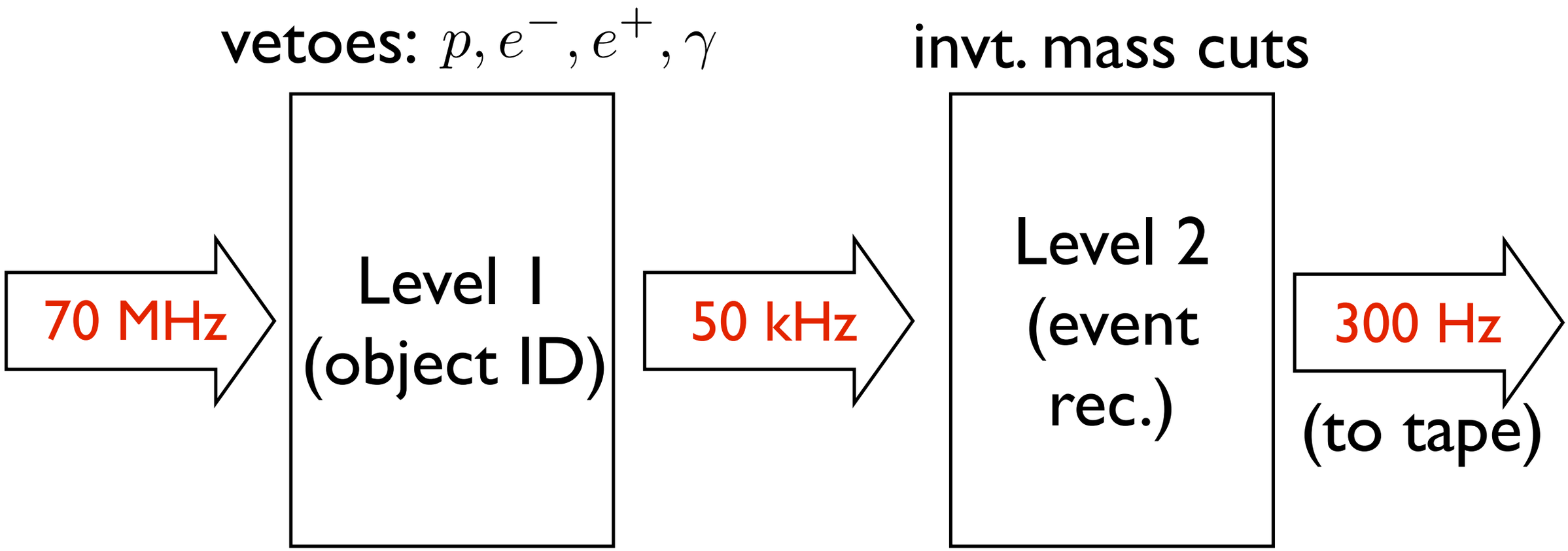
JLab FEL setup



DarkLight goes here

Analysis strategy

Goal: make overall data-taking rate manageable



Total data output comparable to LHC!

Rates

saturates Level 1

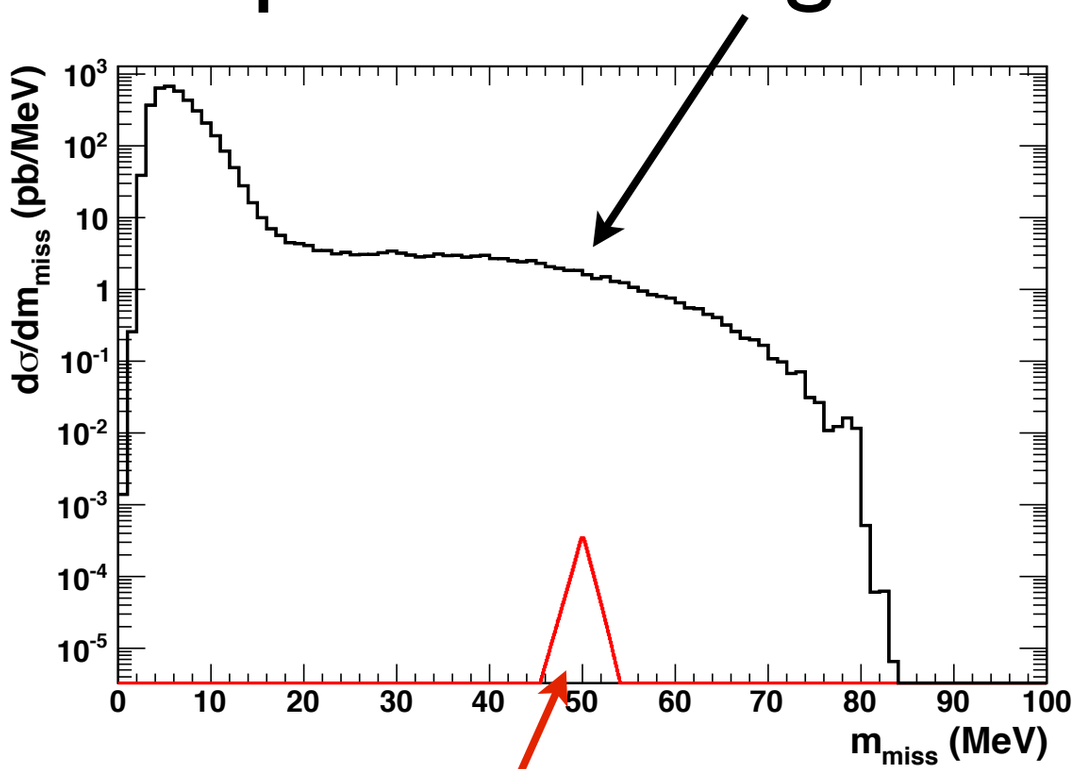
Process	Raw (Hz)	Veto	Level 1 (Hz)	Level 2 (Hz)	50 MeV mass window (Hz)
ep	6.5×10^7	p	< 1	$< 10^{-2}$	$< 10^{-3}$
$ep\gamma$	5.0×10^6	γ	5.0×10^4	2.0×10^2	$< 10^{-3}$
$ep\gamma\gamma$	1.6×10^5	γ	1.7×10^2	77	2.4
epe^+e^-	6.6×10^3	e^-, e^+	1.2×10^2	2.3	$< 10^{-2}$
ep/ep	3.1×10^7	p, e^-	1.2×10^3	$< 10^{-2}$	$< 10^{-3}$
$ep/ep\gamma$	2.4×10^6	p, γ, e^-	4.1×10^2	$< 10^{-2}$	$< 10^{-3}$
$ep\gamma/ep\gamma$	2.4×10^5	γ, e^-	1.3×10^3	7.3	0.27
Total Background	7.1×10^7	–	5.0×10^4	2.8×10^2	2.7
Signal	5.4×10^{-2}	none	1.3×10^{-2}	1.3×10^{-2}	9.8×10^{-3}

$\Longrightarrow$ everything negligible after analysis cuts except diphoton irreducible background

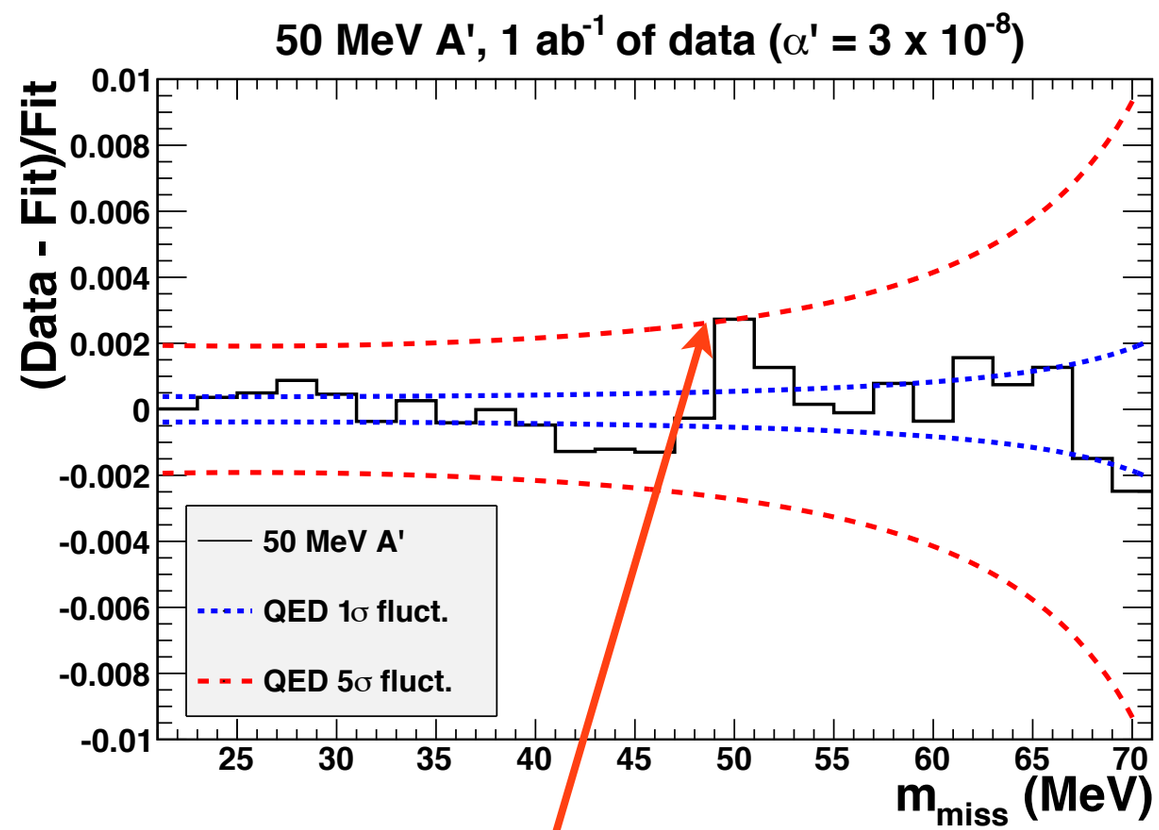
Annoying feature: $ep\gamma$ dominates Level 1, but gets thrown out immediately...

Bump hunting

photon background

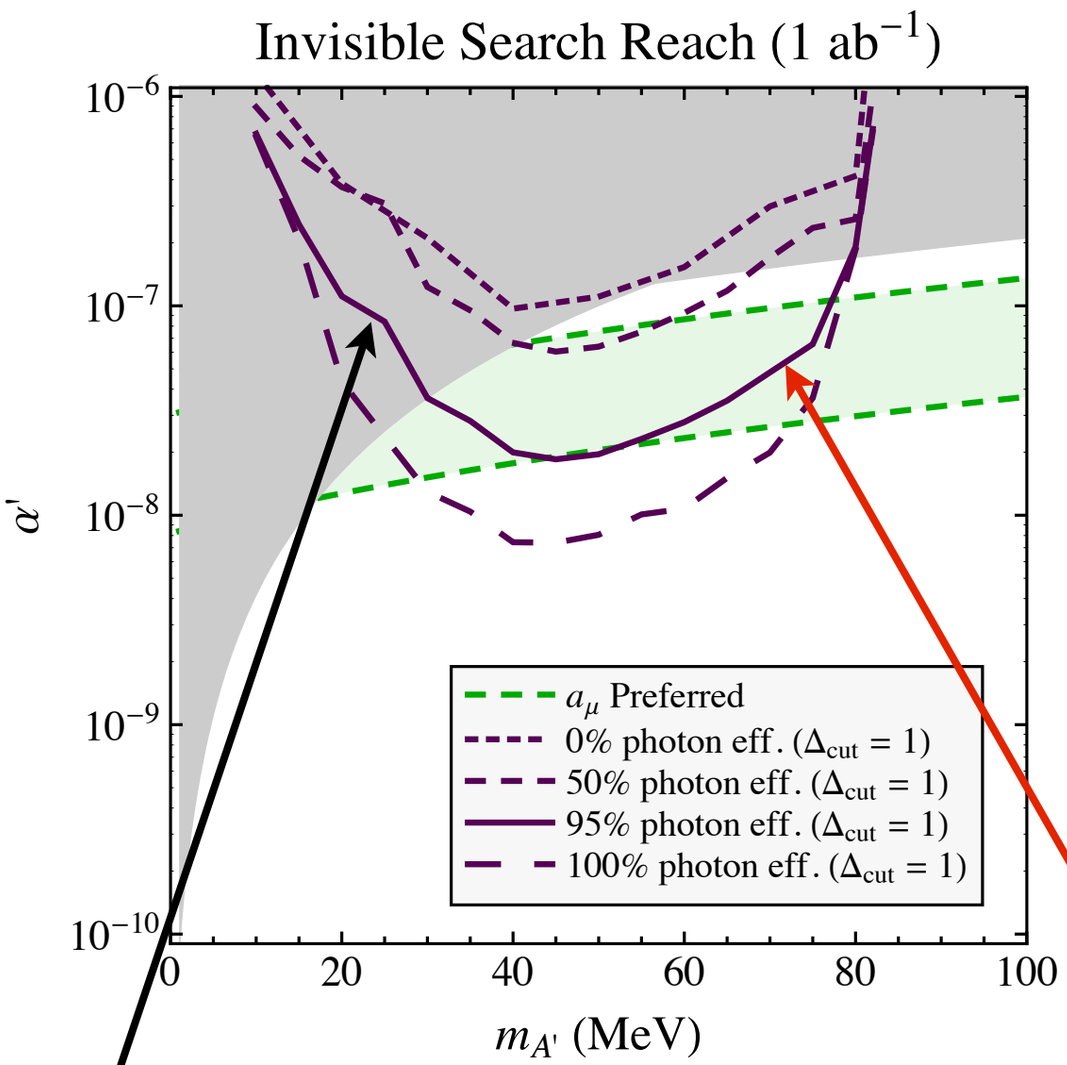


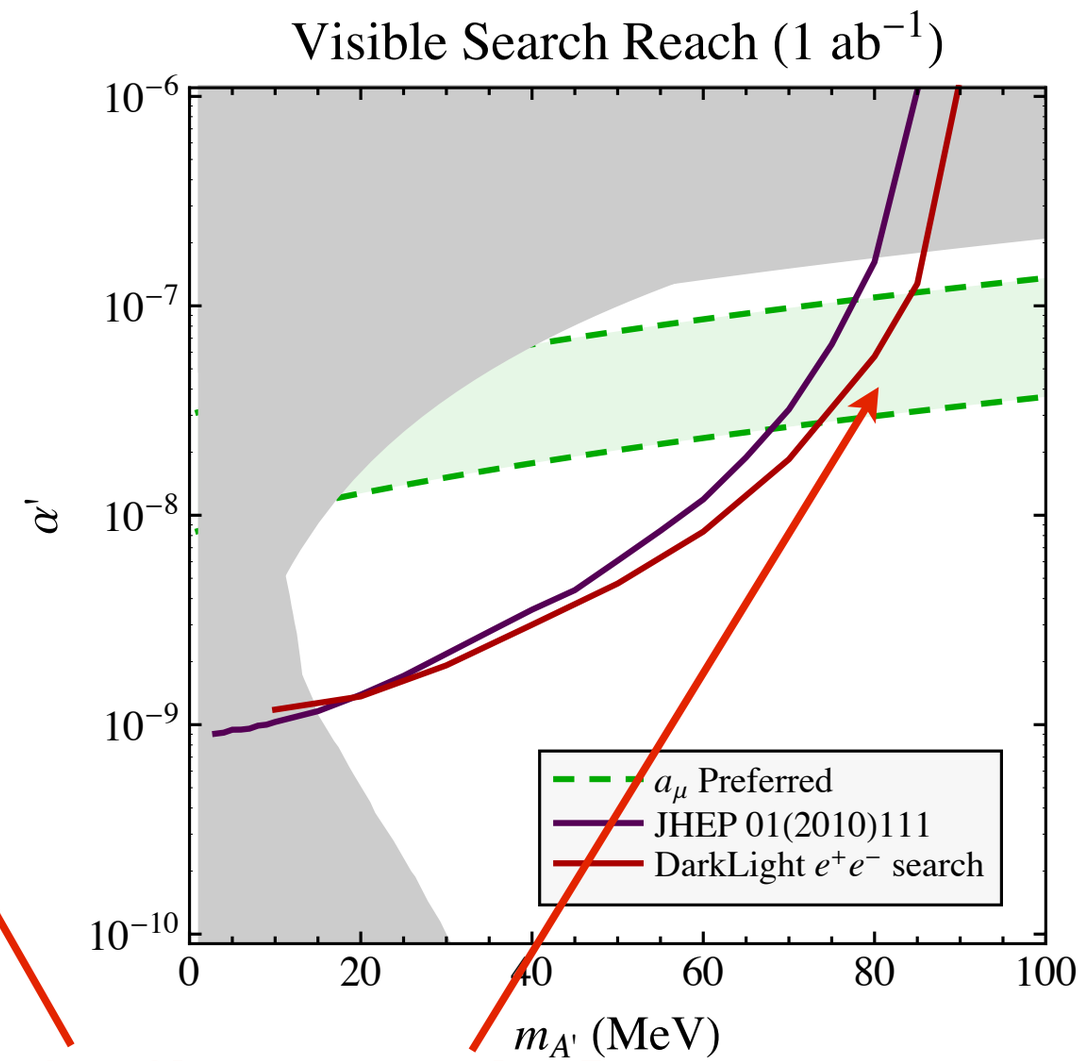
tiny signal



can actually see signal over enormous background, with enough statistics!

Experimental reach





mis-measurement

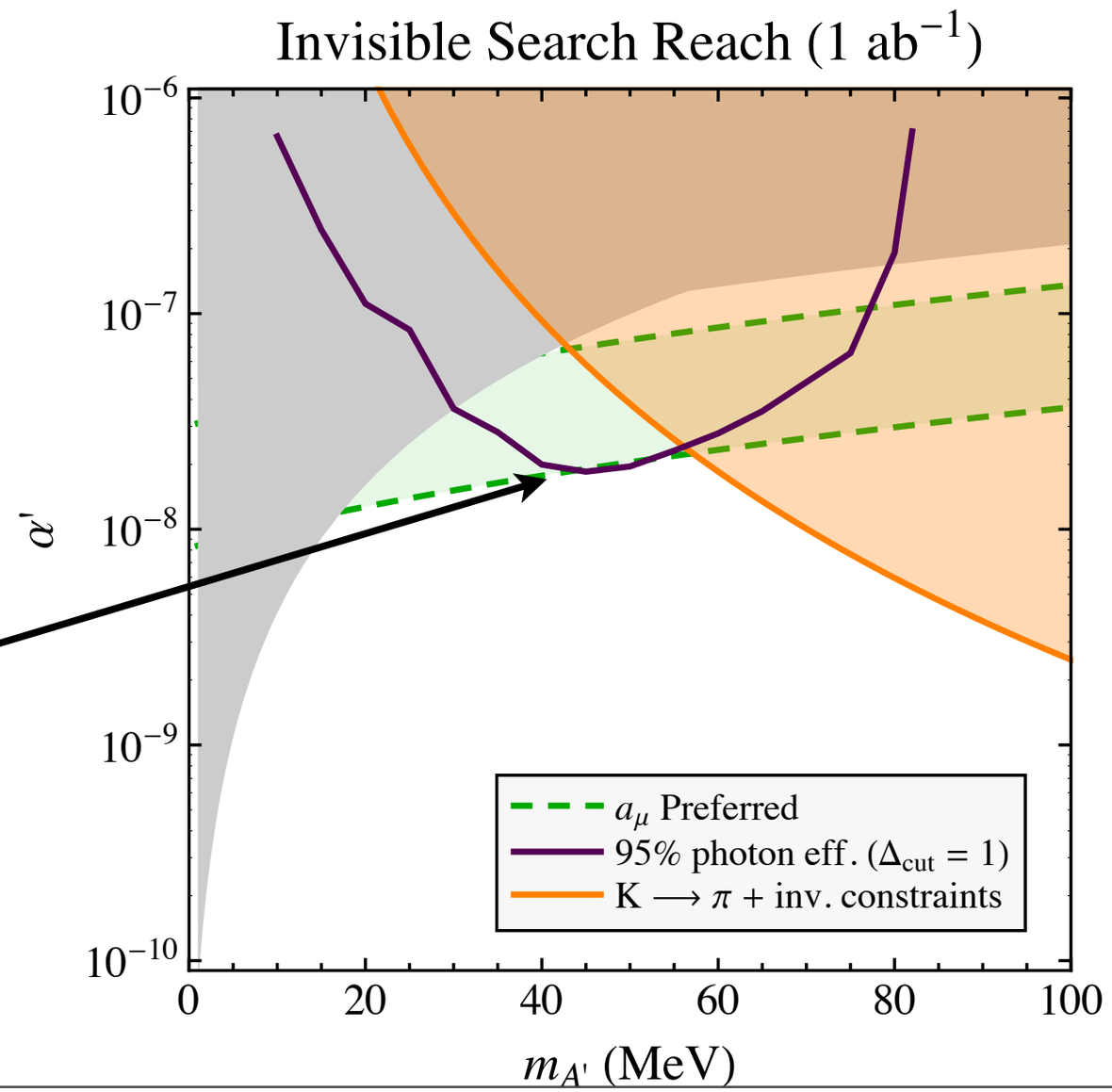
similar reach for large masses (both QED bkgrnd)

Constraints from rare kaon decays

$K^+ \to \pi^+ \gamma^* \implies K^+ \to \pi^+ A'$ (kinetic mixing)

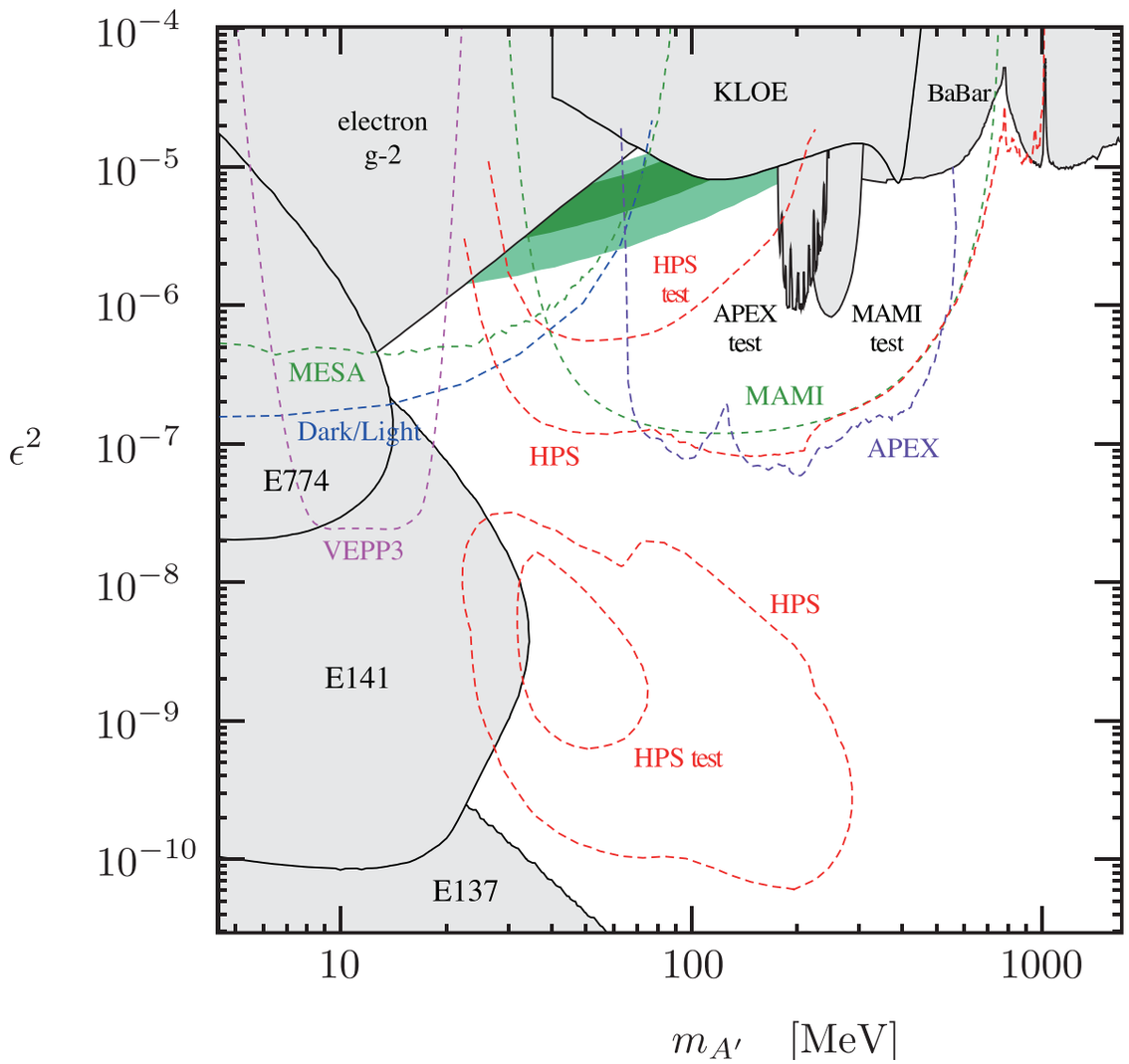
Suppressed at tree-level by absence of FCNC...
but still significant at 1-loop

still not excluded!



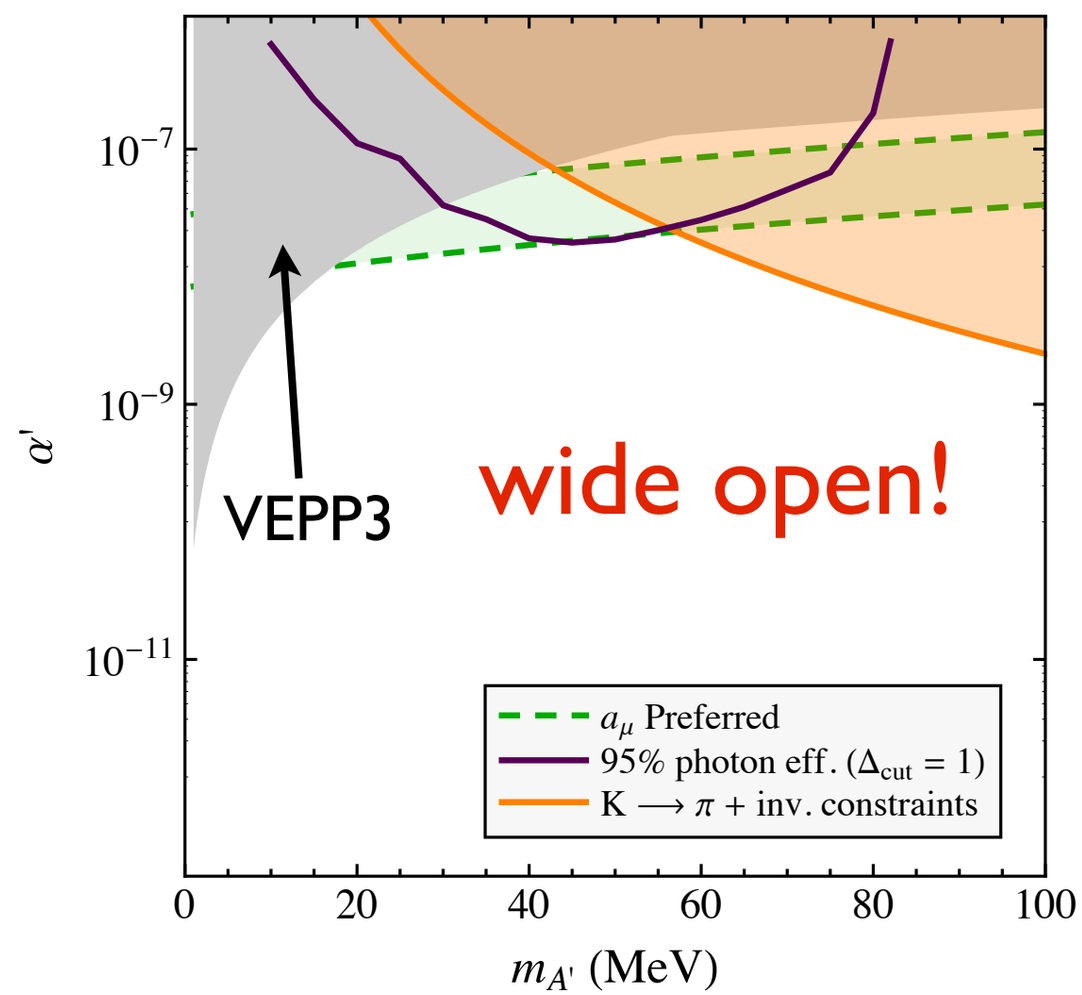
Comparison to other experiments

Visible



(Endo, Hamaguchi, Mishima, Phys. Rev. D86, 095029 (2012))

Invisible

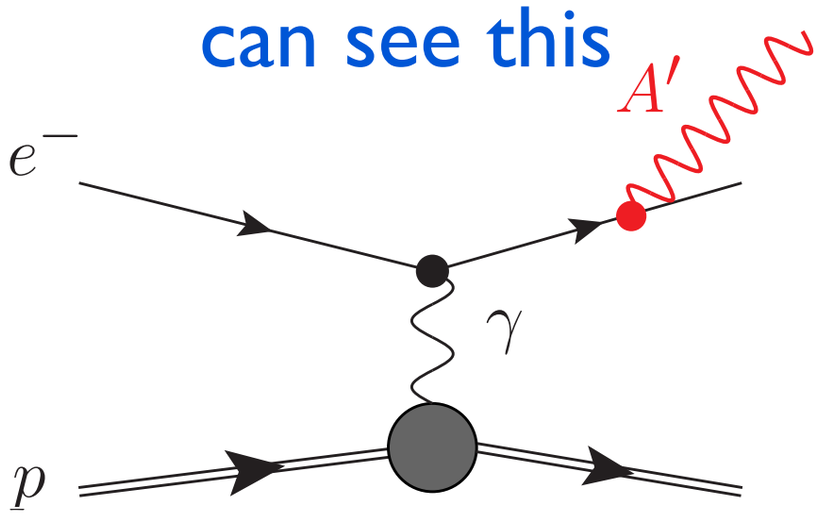


only DarkLight has reach; other invisible searches excluded by g-2

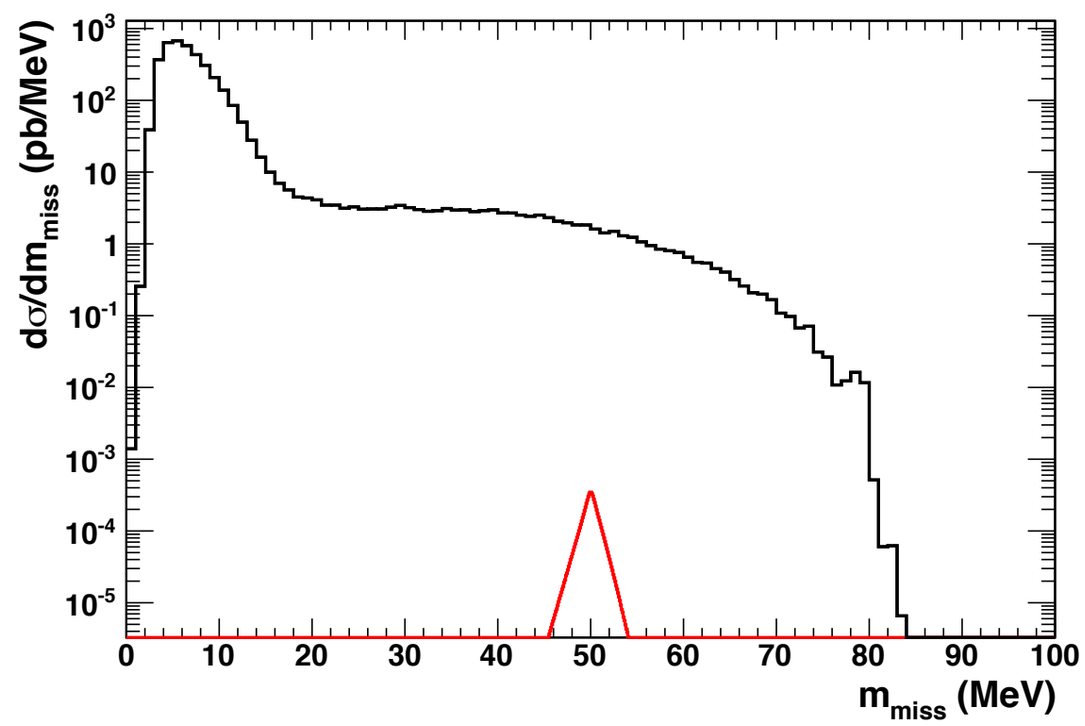
Summary

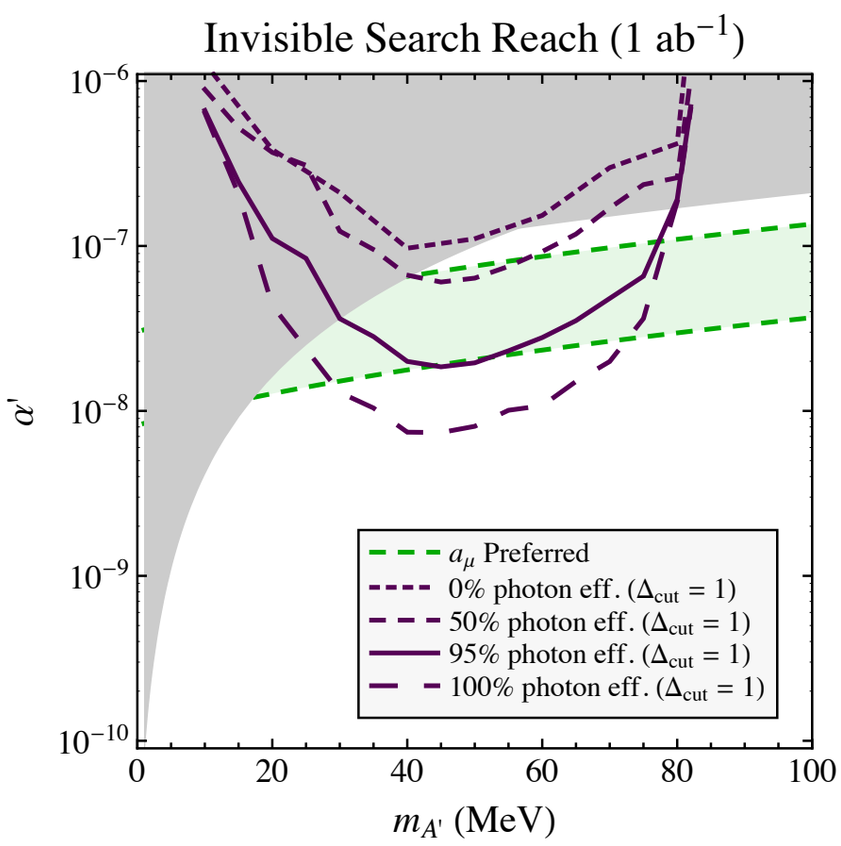
With two months of data,

can see this



over this enormous background

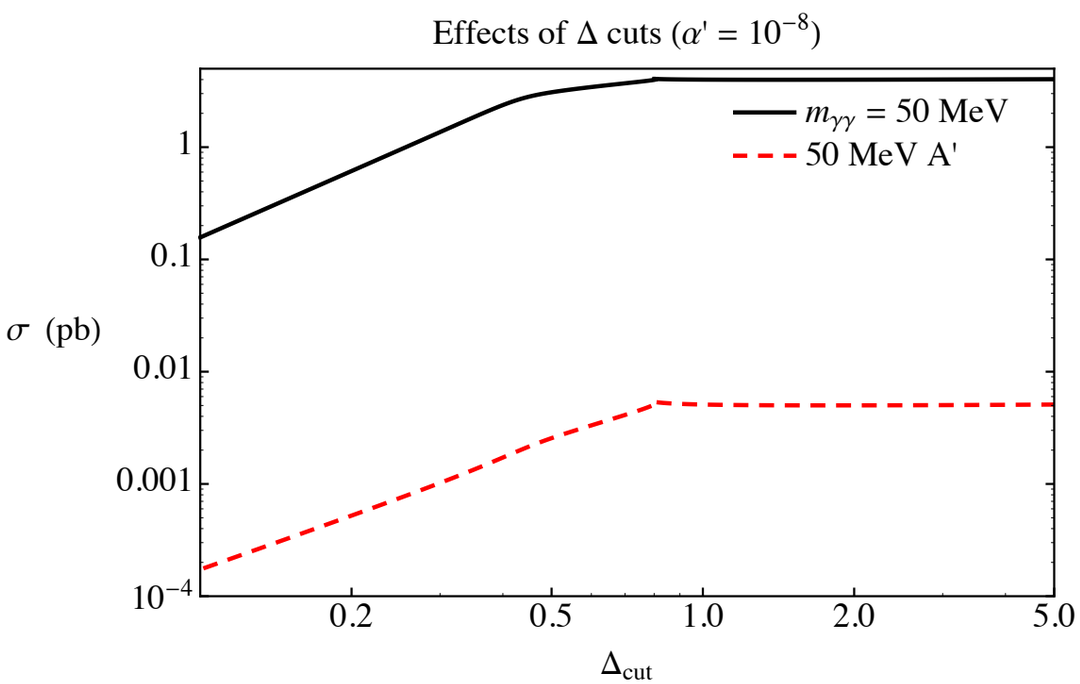


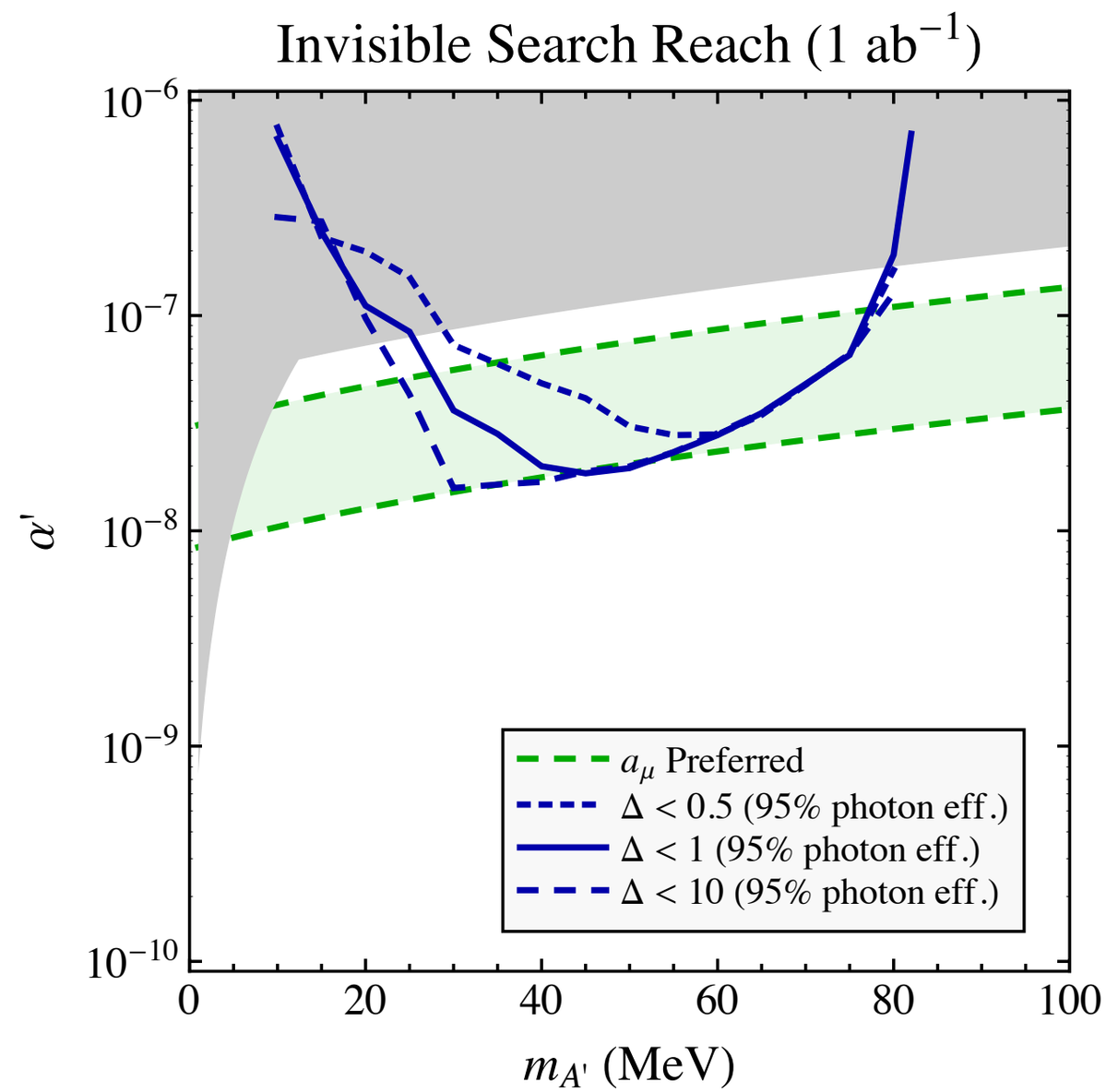


and set these limits on coupling

Backup slides

Effects of Delta cuts





Why haven't we already seen it?

- A' is massive, so no extra long-range force at low energies
- Coupling is very small, so requires extremely high statistics to see deviations from Standard Model

Upshot: new physics could be hiding at the luminosity frontier, not just the energy frontier!

Why a dark photon?

Consider all renormalizable operators coupling new physics to SM:

$(hL)\psi$ sterile neutrinos?

$|h|^2|\phi|^2$ rare Higgs decays?

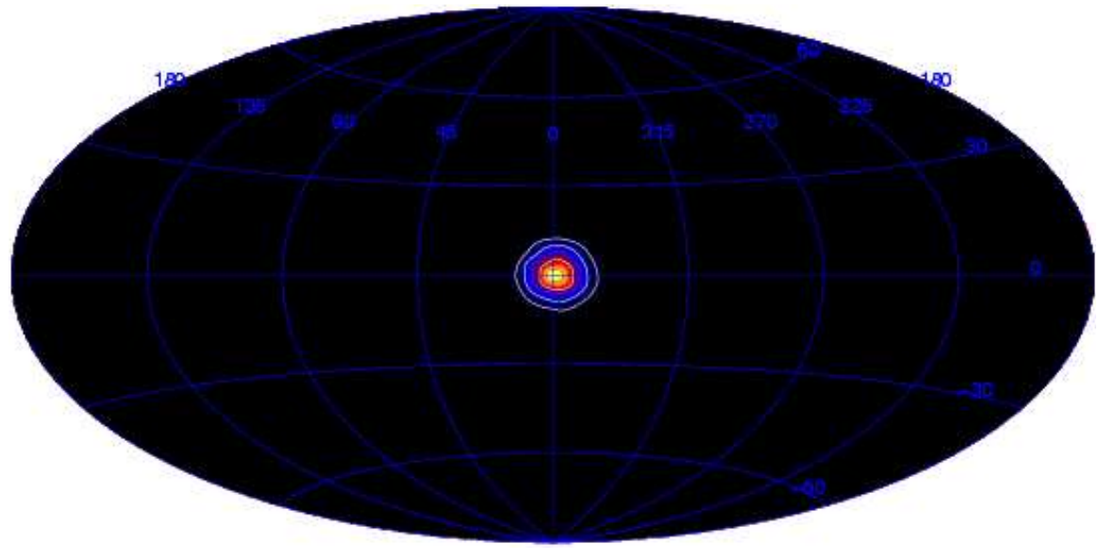
$F^Y_{\mu\nu}F'^{\mu\nu}$ dark photon

only really viable interaction at low energies!

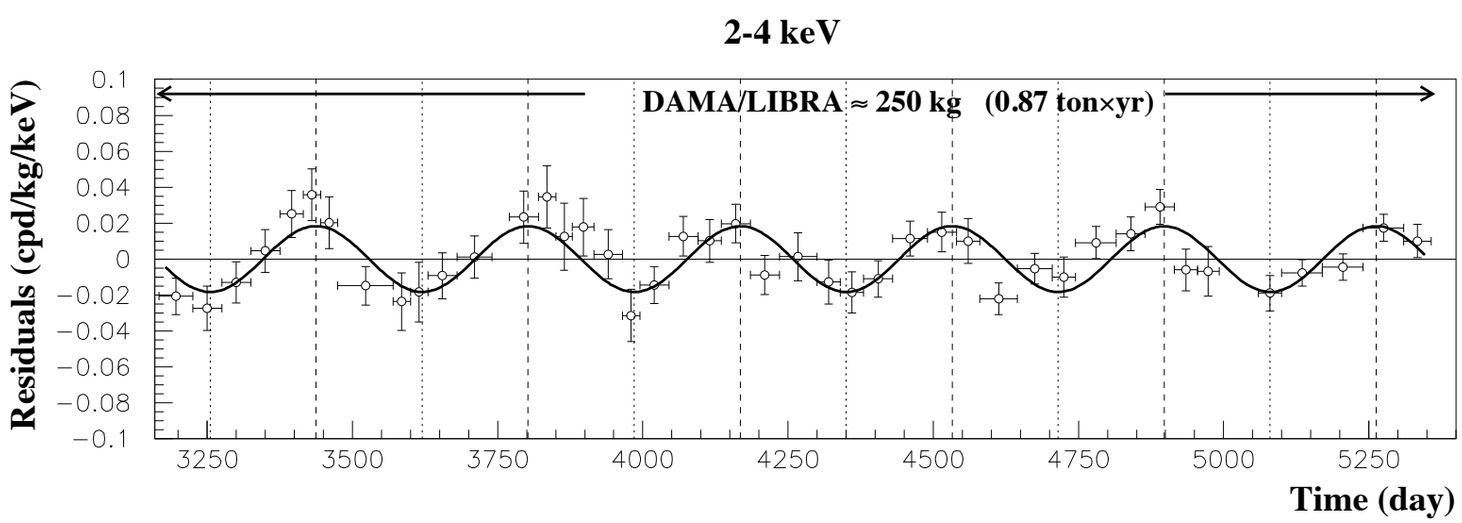
More motivation

- Any enlarged gauge group (think GUT) usually has U(1) subgroups
- Motivation from string phenomenology: SM embedded in Type II has lots of U(1)'s from bulk D-branes not intersecting SM branes

Why MeV-scale?



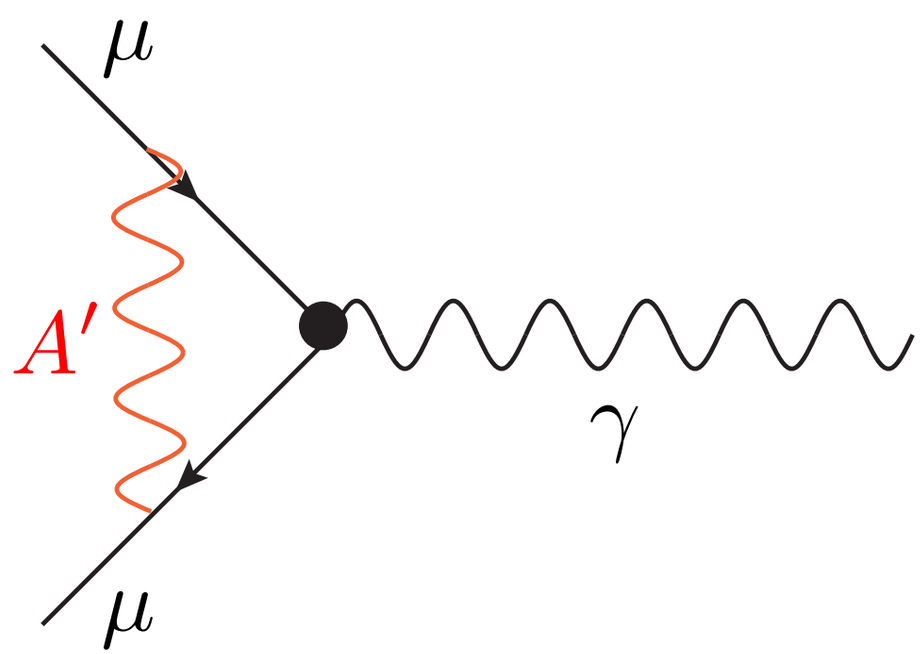
INTEGRAL 511 keV signal (astro-ph/0702621)



DAMA/LIBRA annual modulation (1002.1028)

Why MeV-scale?

Muon anomalous magnetic moment



$$a_\mu^{SM} = 1.16591802(2)(42)(46) \times 10^{-3}$$
$$a_\mu^{exp} = 1.16582089(5.4)(3.3) \times 10^{-3}$$

3.6-sigma discrepancy!

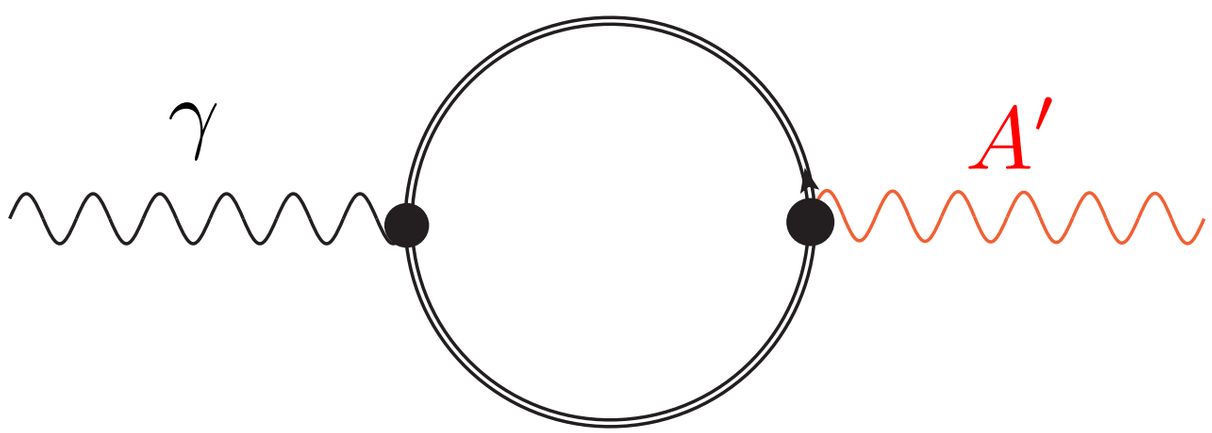
Why is the coupling so small?

Kinetic mixing operator not SU(5) gauge-invariant.
However, can generate this operator with Planck-suppressed GUT-breaking operators

GUT Higgs, gets vev

$$\frac{1}{M_{Pl}} \mathrm{Tr}[\Phi F^5_{\mu\nu}] F_D^{\mu\nu}$$

One loop: kinetic mixing through heavy particles



Constraints

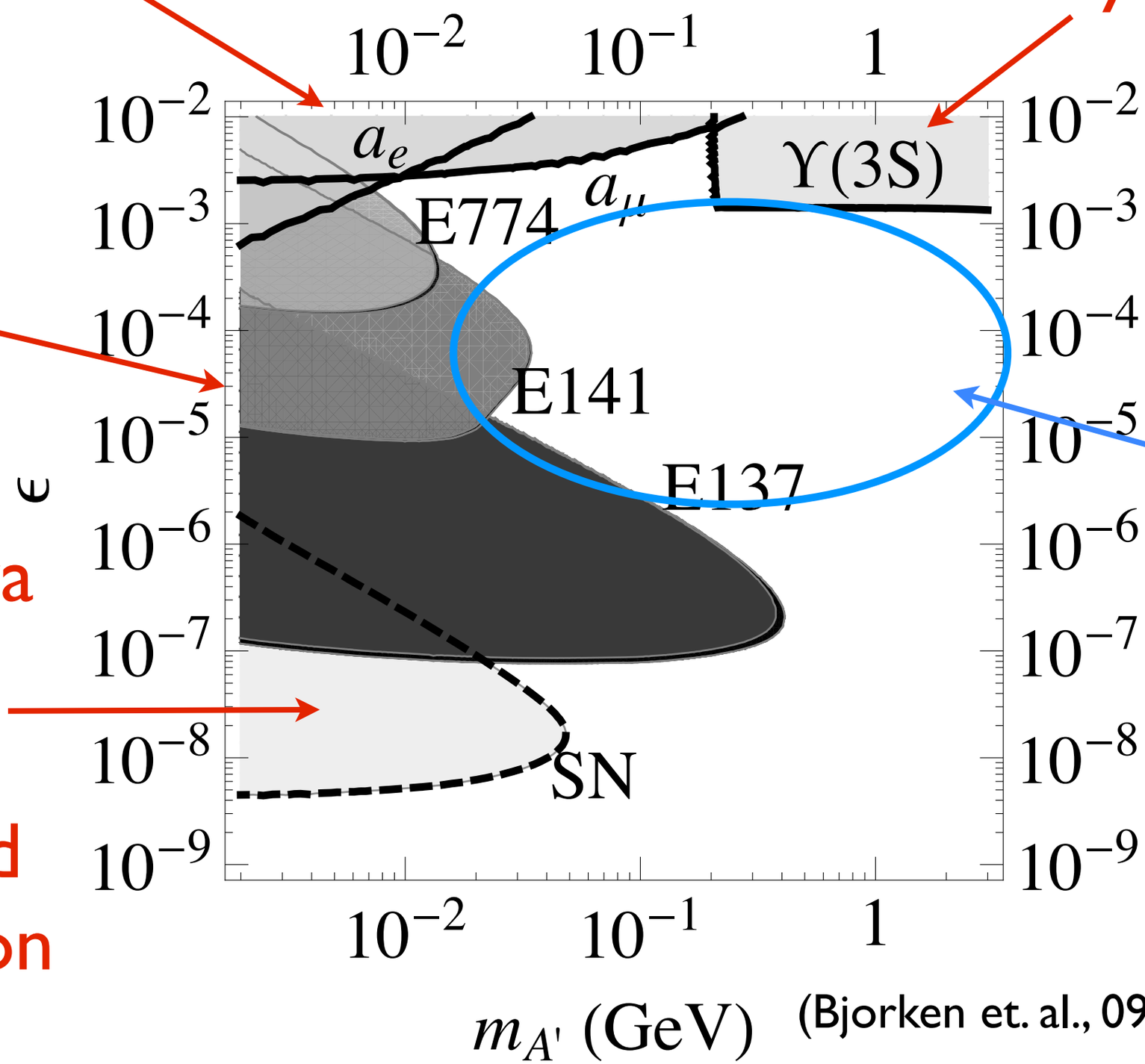
anomalous mag. moments

heavy meson decays to muons

beam dump

supernova cooling through long-lived A' emission

lots of room to explore!



(Bjorken et. al., 0906.0580)

DarkLight timeline

- July 2012: successful beam tests
- Summer 2013: technical review
- Fall 2013: detector construction begins
- Fall 2015: detector commissioning
- 2016: data-taking