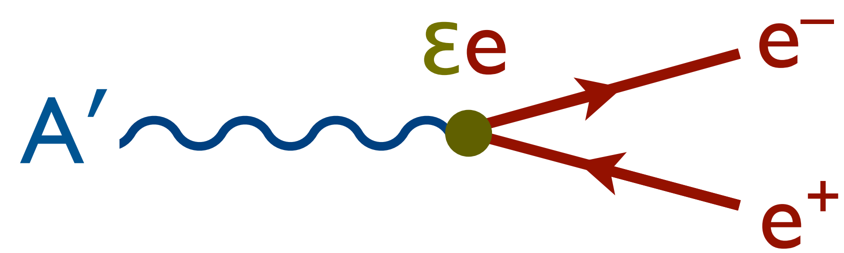
Lessons from DarkLight for Invisible Dark Photon Searches

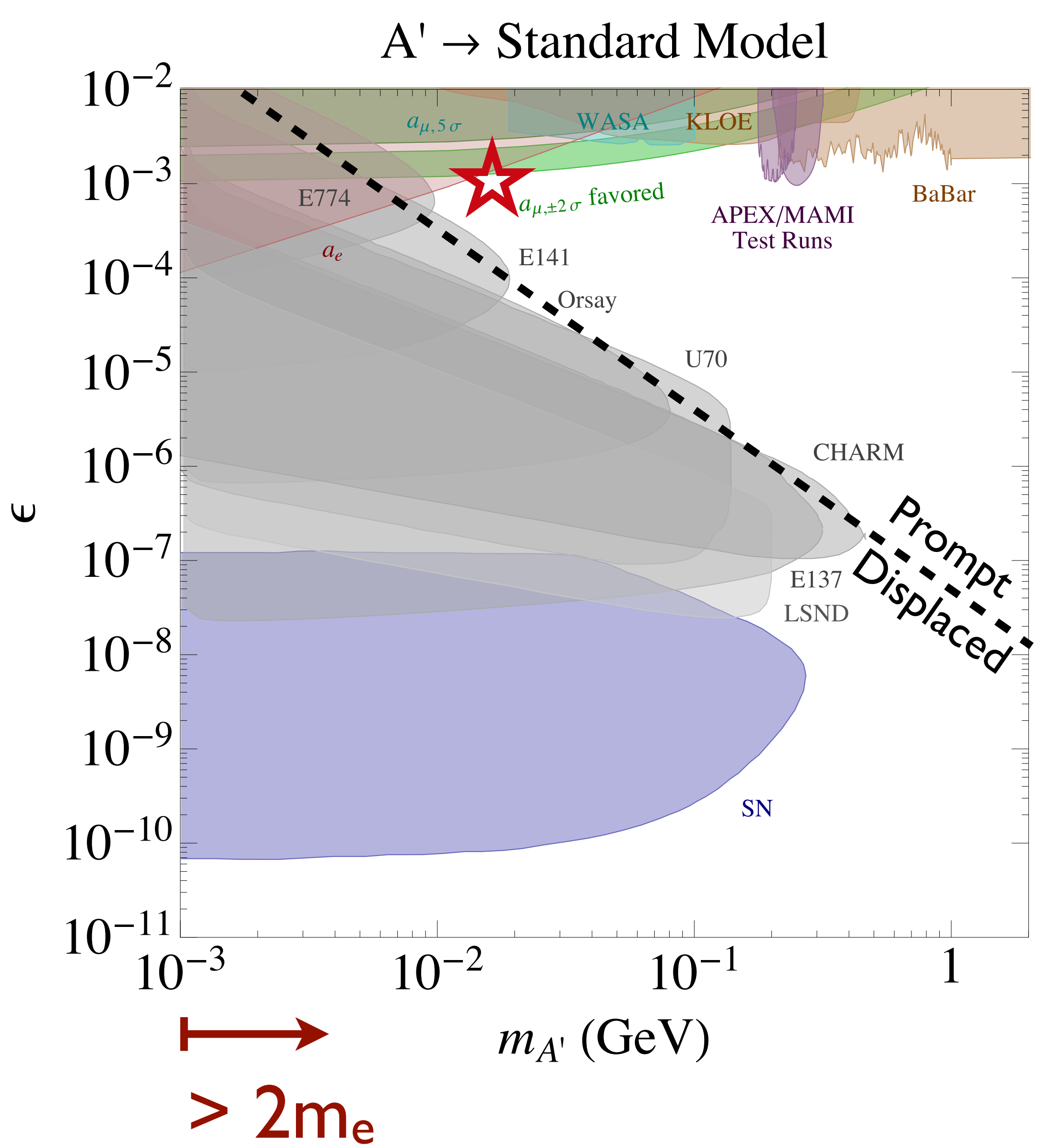
Jesse Thaler

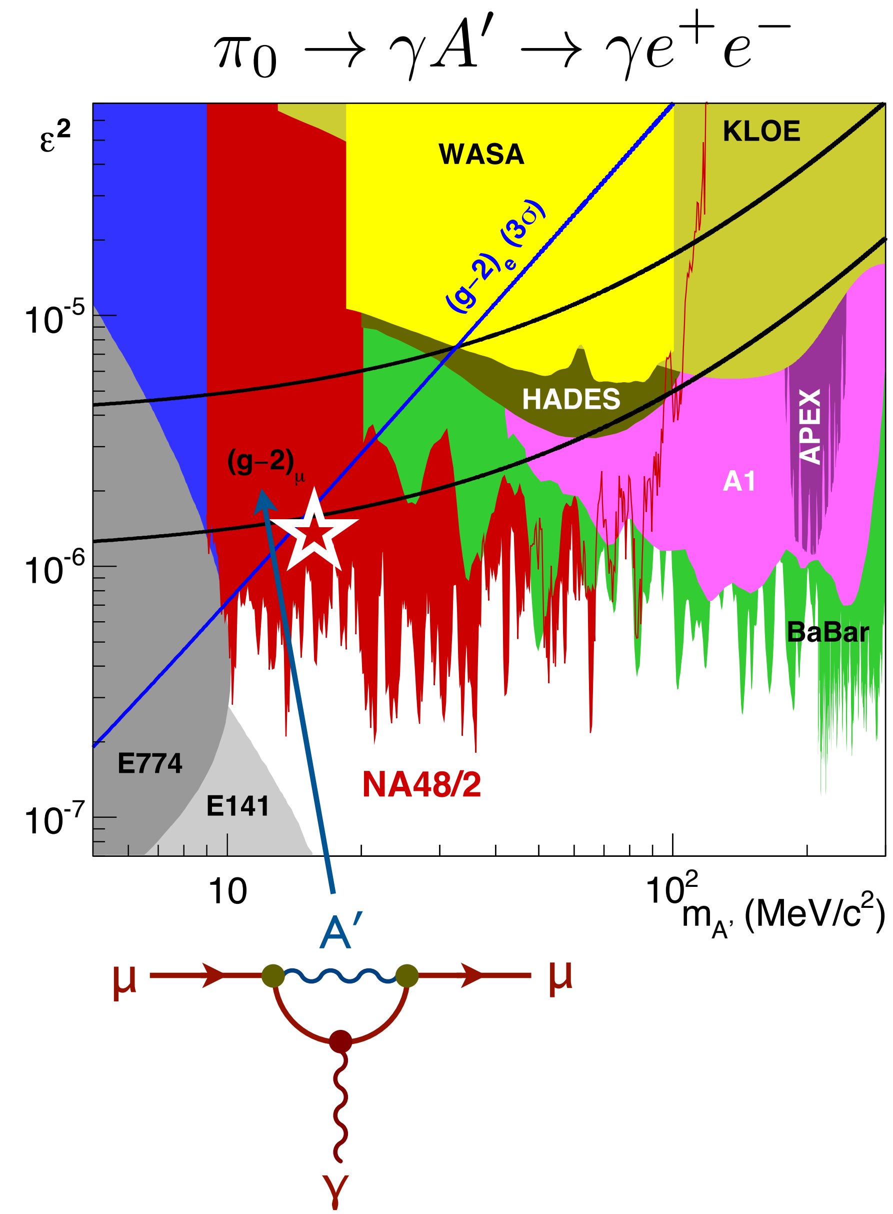
NEXT Collaboration Meeting — December 4, 2015

Dark Force Bounds: $m_{A'}$ vs. ε

Decay Allowed:

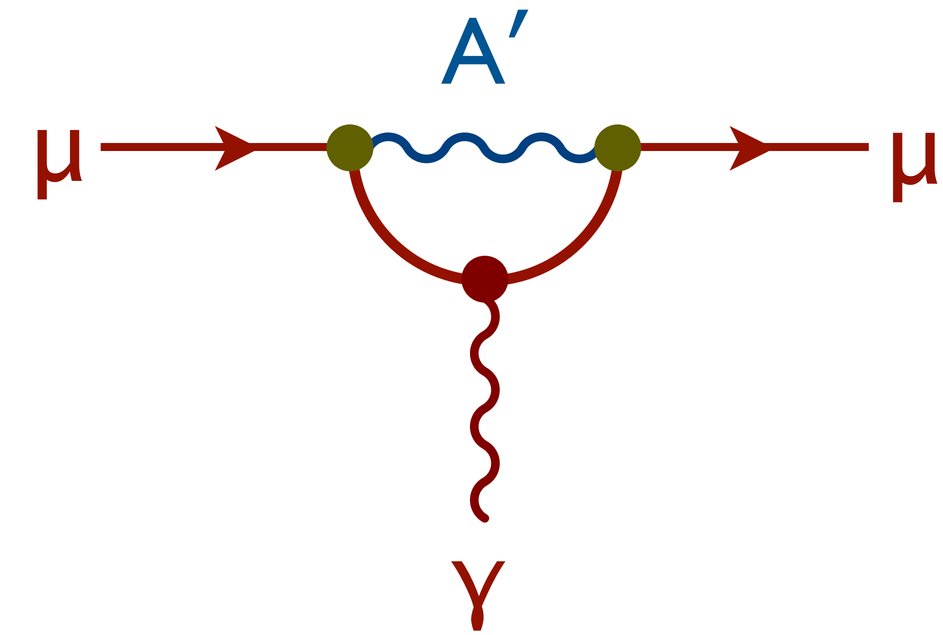






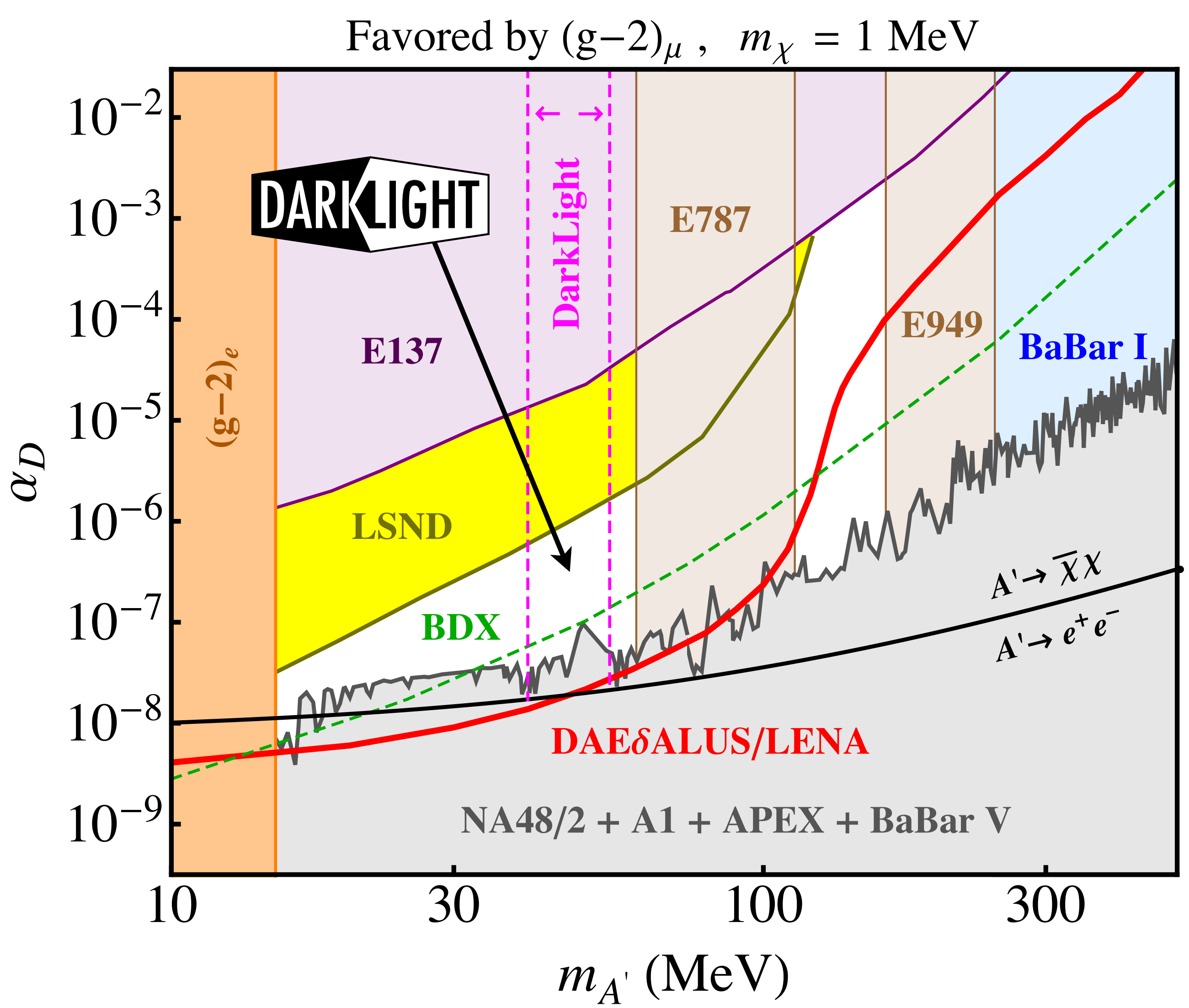
[Snowmass Report, 2013; NA48/2, 2015; see Pospelov, 2008]

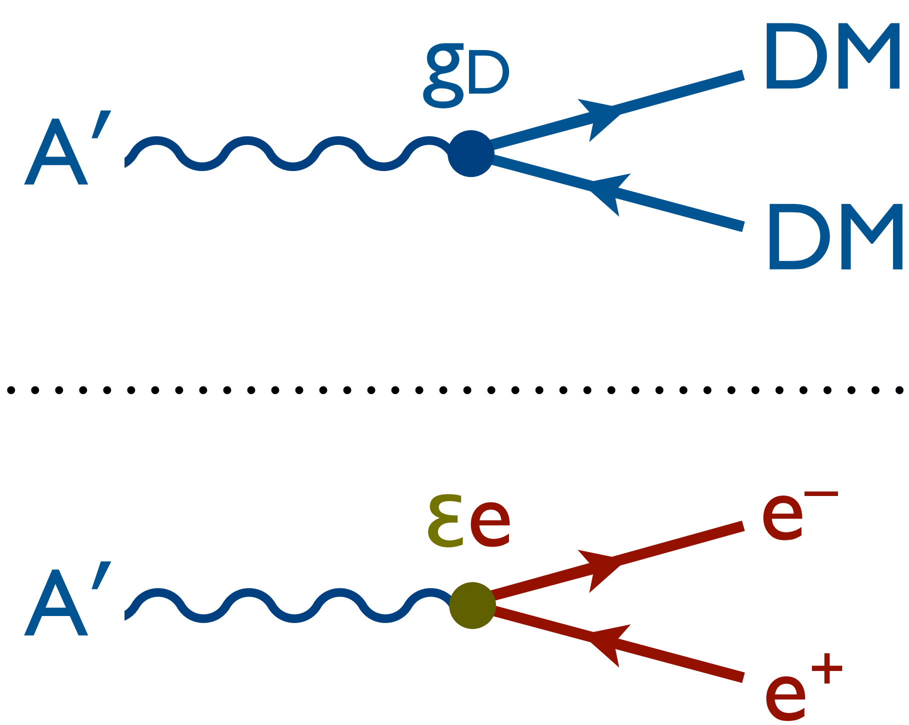
The Invisible Frontier



Set ε to solve anomaly

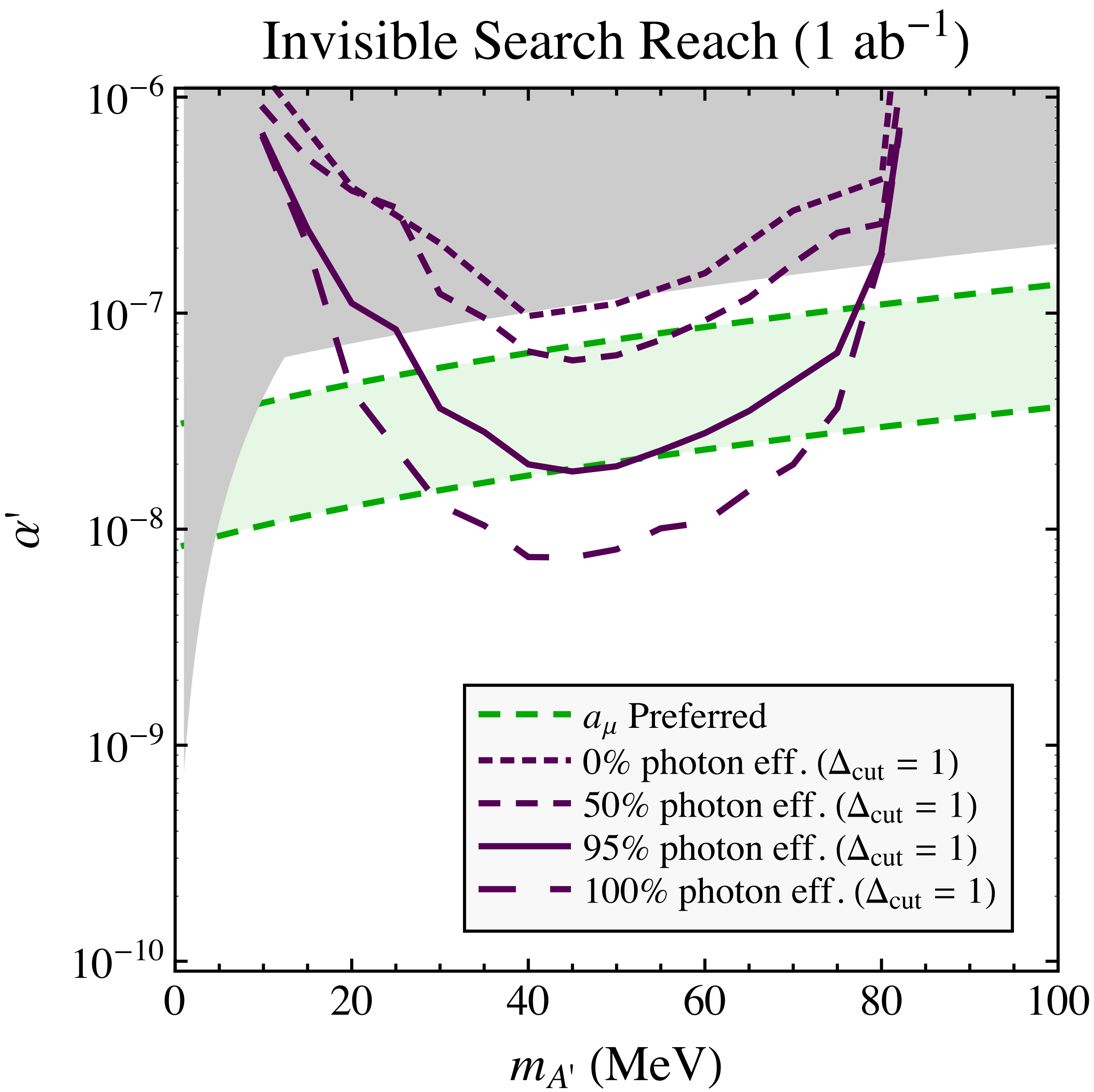
Set $m_{DM} < m_{A'}/2$



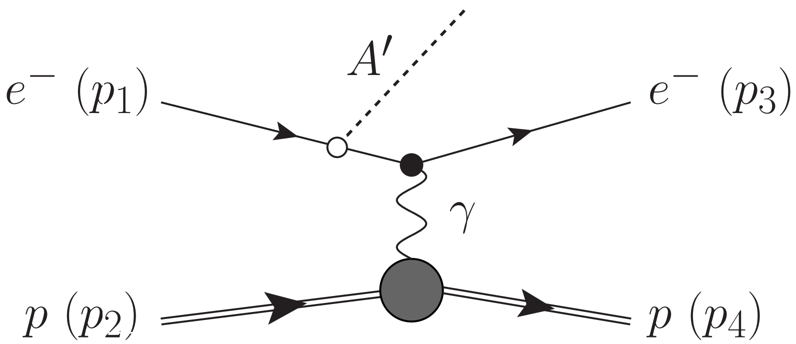


[plot from Kahn, Krnjaic, JDT, Toups, 2014; see Pospelov, 2008]

Today's Goal



Explain physics challenges for invisible searches



"Searching for an Invisible A′ Vector Boson with DarkLight"
Yonatan Kahn, JDT, 1209.0777

Lesson from DarkLight for Invisible A' Searches

Missing mass searches are hard
- Full event reconstruction essential
- Streaming detector output seems necessary

Kinematics are somewhat counterintuitive
- Want missing mass without missing momentum
- Optimal to match beam energy to dark photon mass

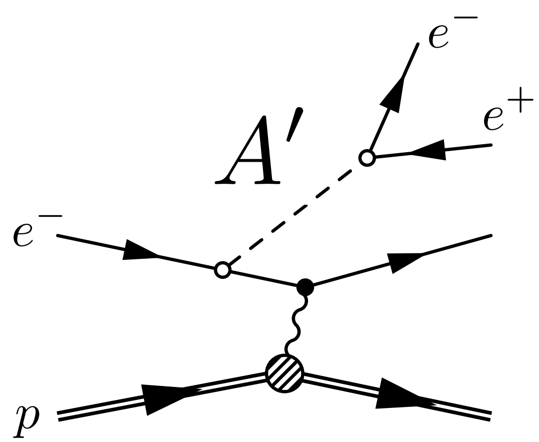
Background sources are somewhat surprising
- Elastic & single photon backgrounds not showstoppers
- Elastic pileup negligible with negative mass-squared cut
- Dominant background is radiative diphoton production
- Therefore need efficient photon detection

Other invisible search strategies also look promising
- Dark matter beam experiments?
- Hermetic beam test setup?

Overview of DarkLight

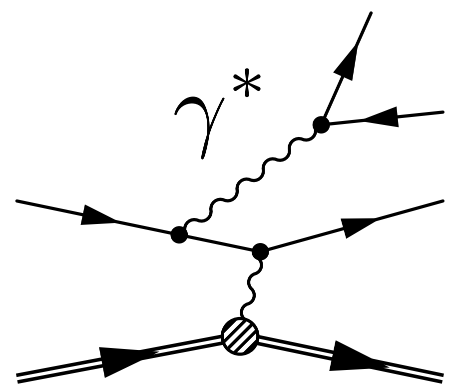
Original DarkLight Concept

Narrow resonance on huge QED background

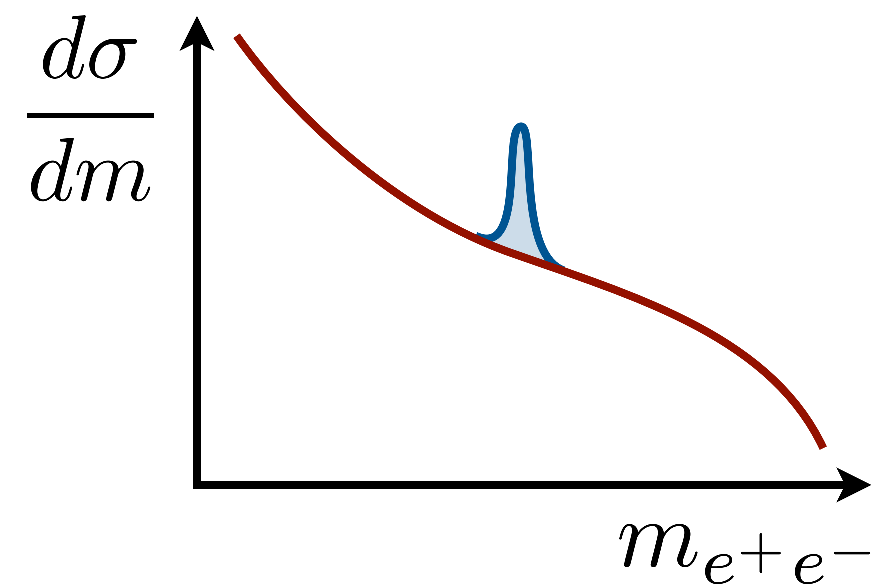


S

vs.



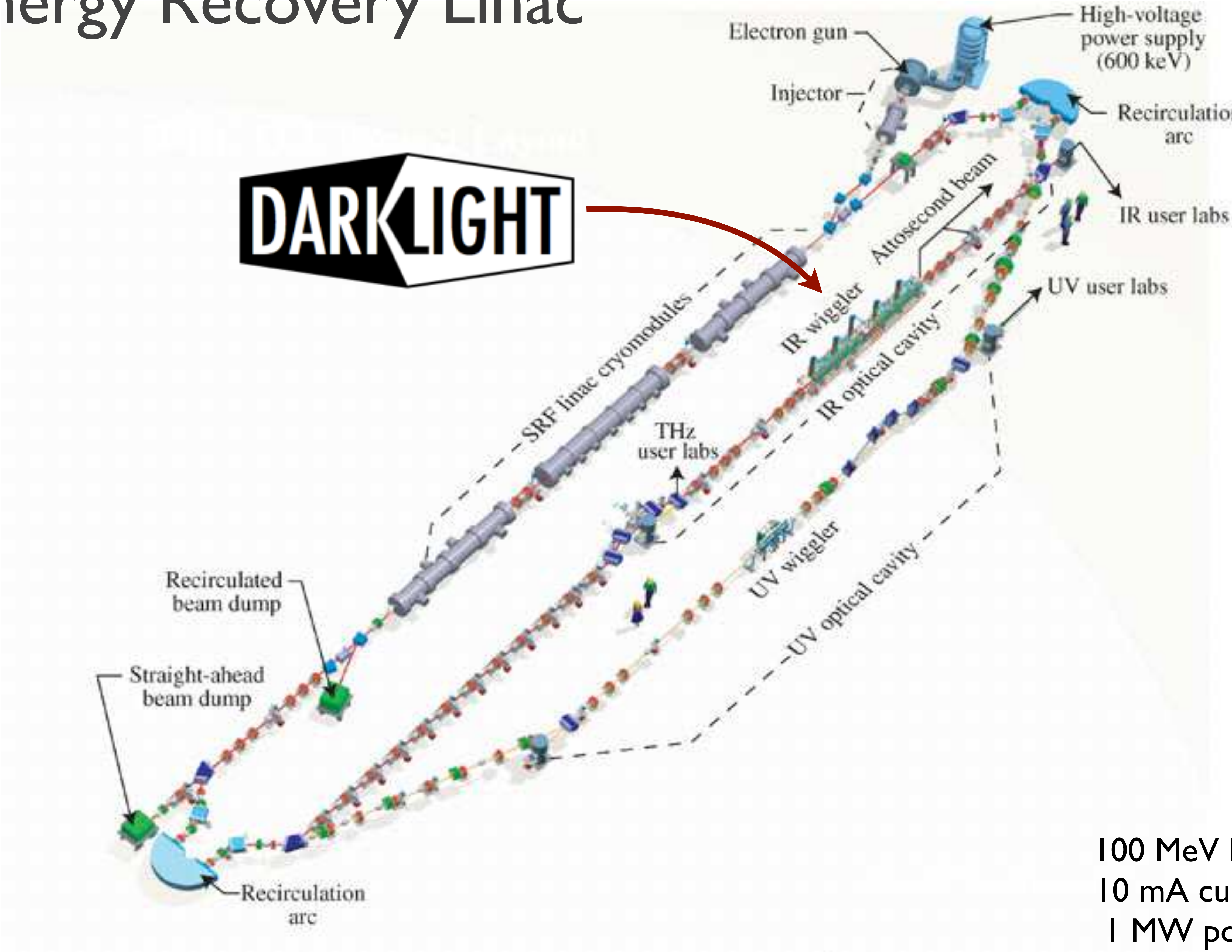
$\sqrt{B}$



Prioritize full reconstruction of final state

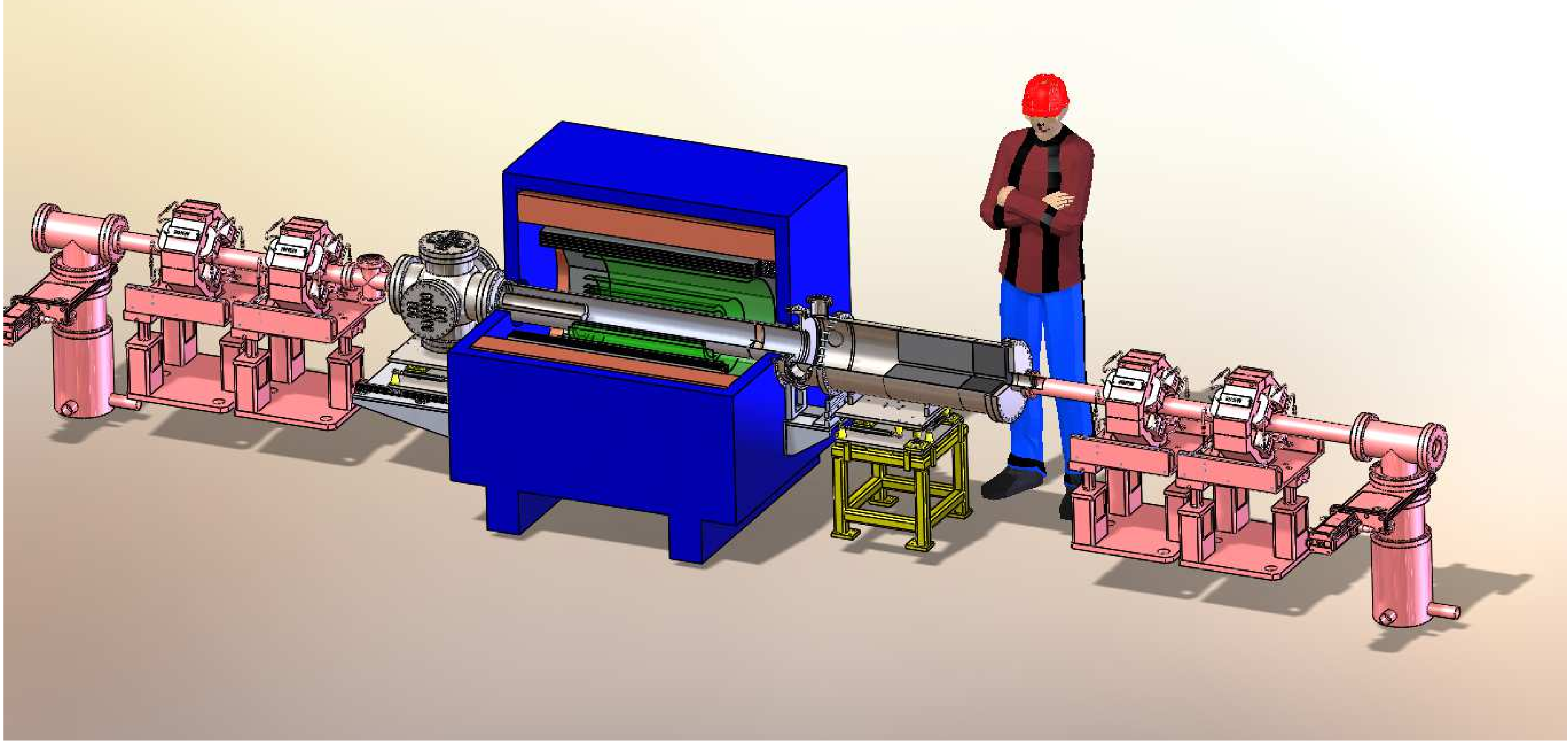
[Freytsis, Ovanesyan, JDT, 2009]

Energy Recovery Linac



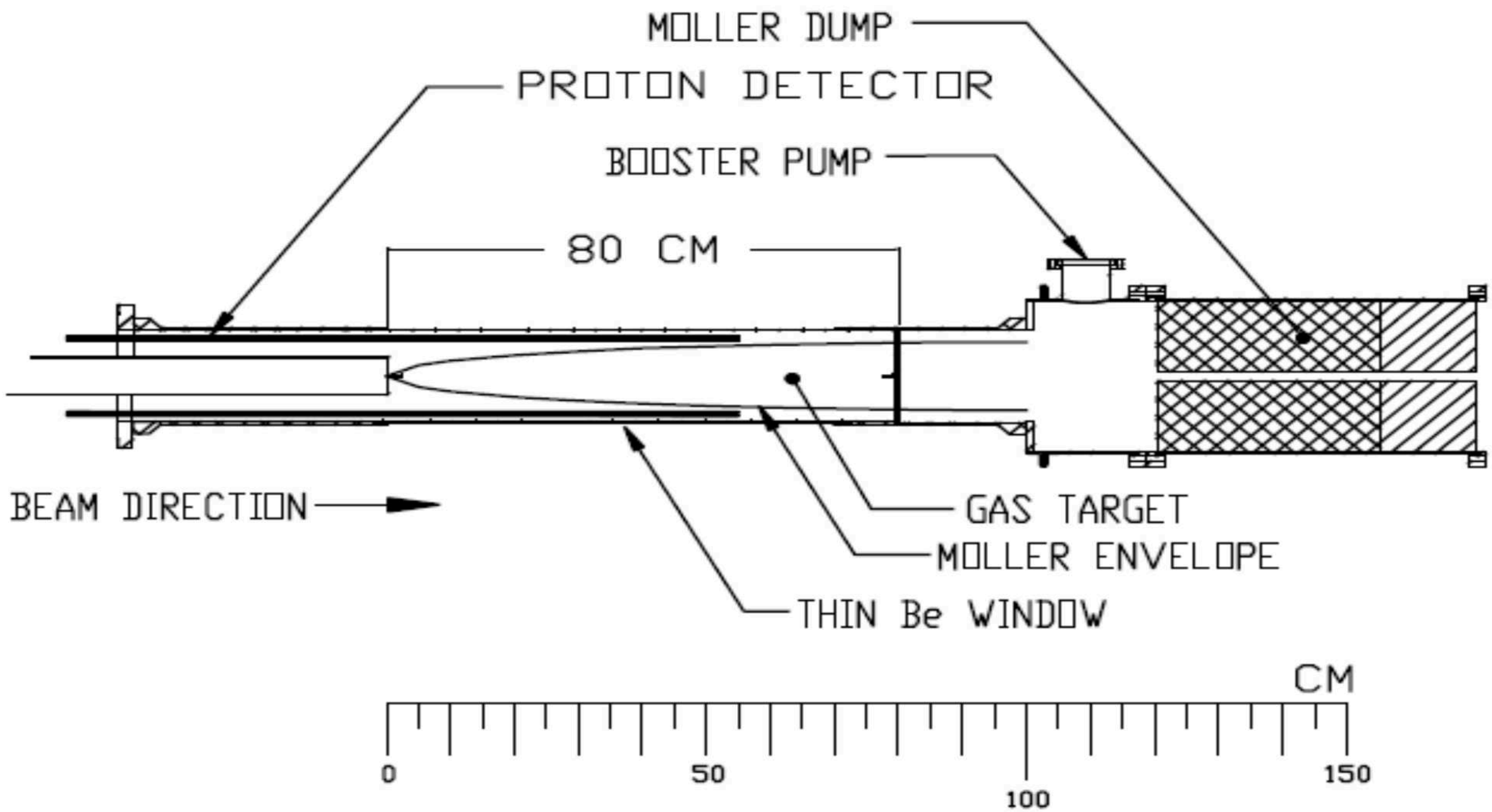
100 MeV beam
10 mA current
1 MW power

DarkLight Geometry



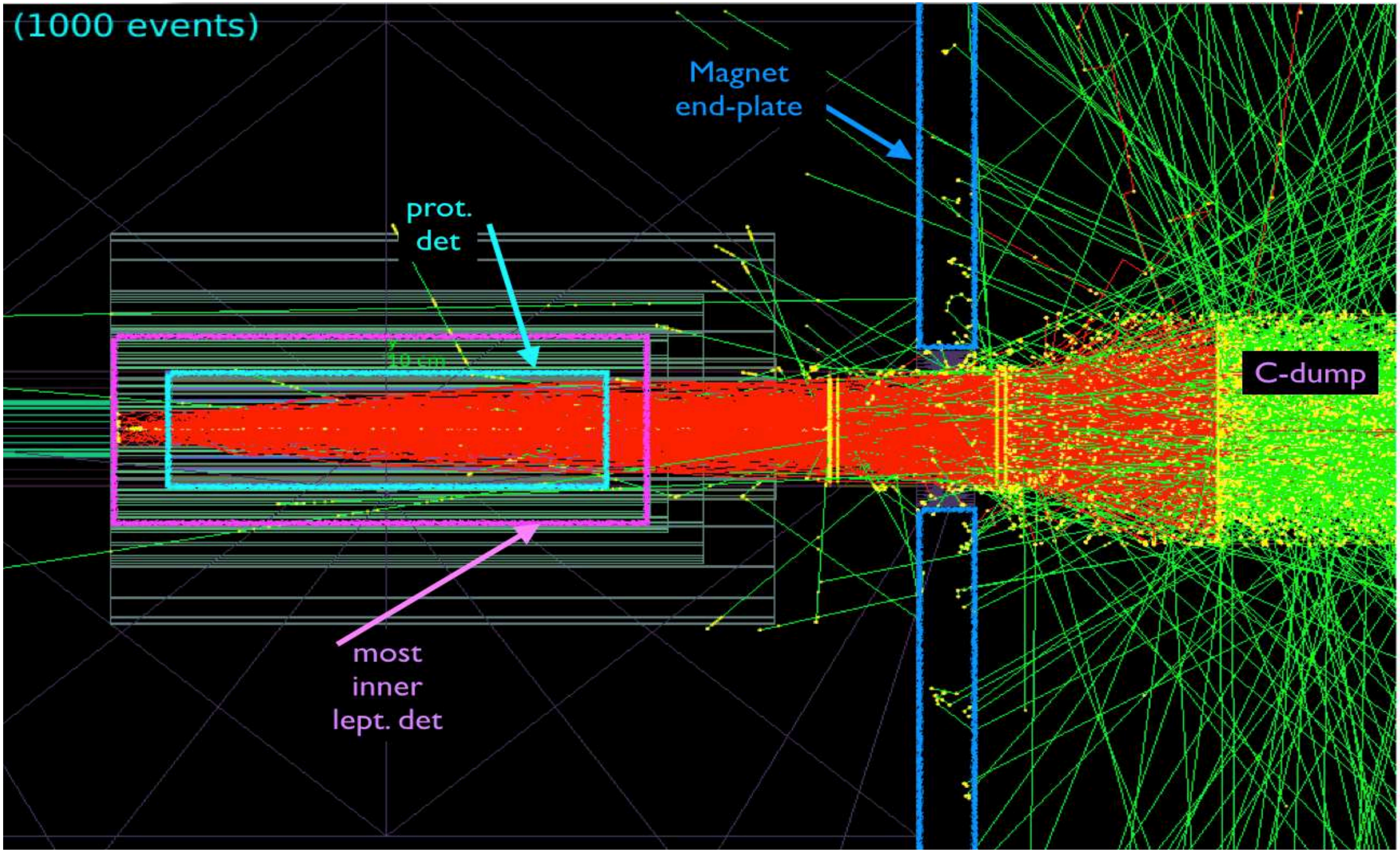
[DarkLight, 1412.4717]

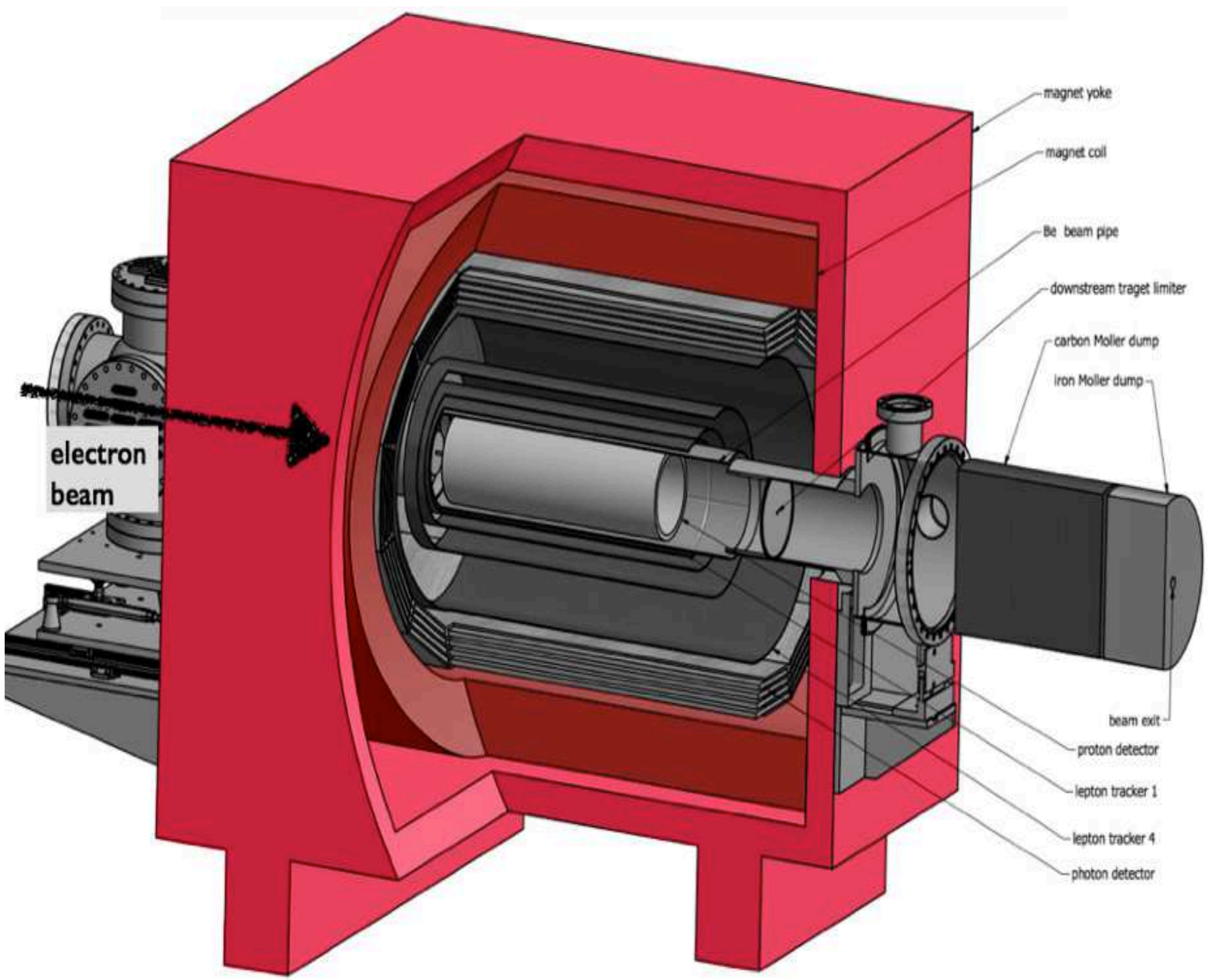
Internal Hydrogen Gas Target



10^{19} cm^{-2} thickness
10 mA of electrons
6 x 10^{-35} cm^{-2} sec^{-1}
$\approx$ 1 ab^{-1} / month

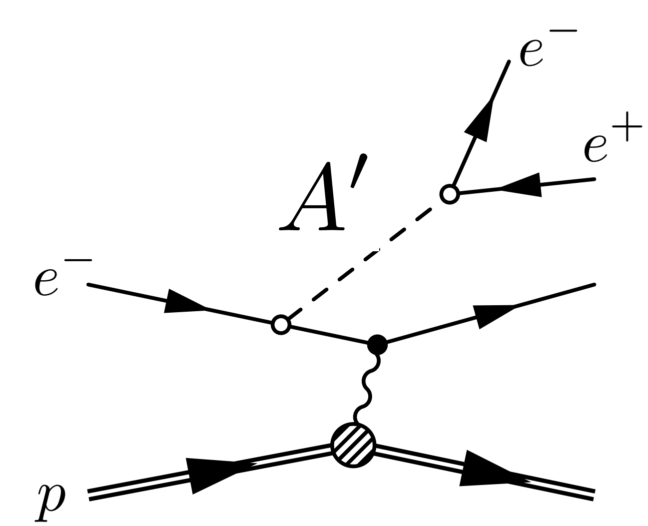
Geant4 simulation of backscattered Mollers

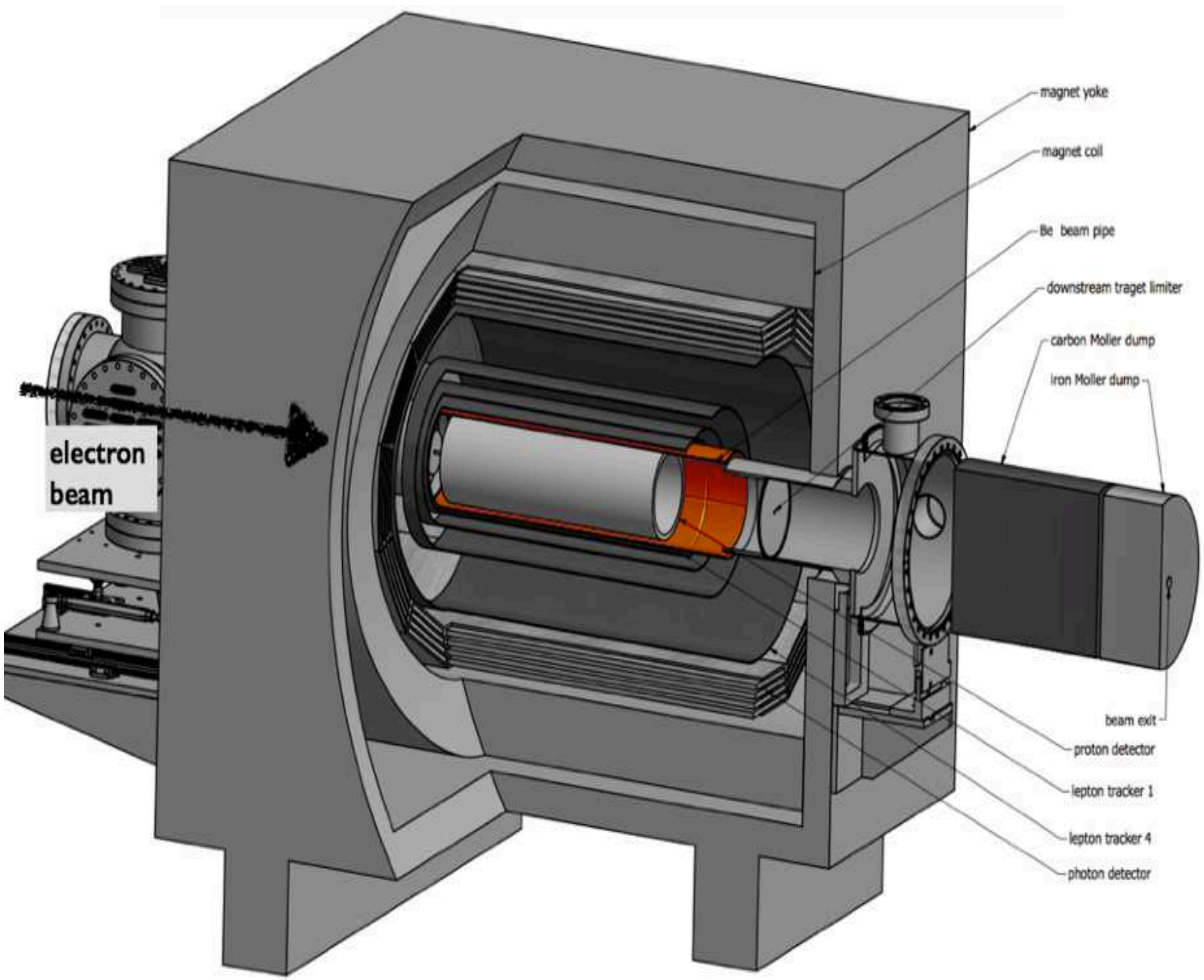




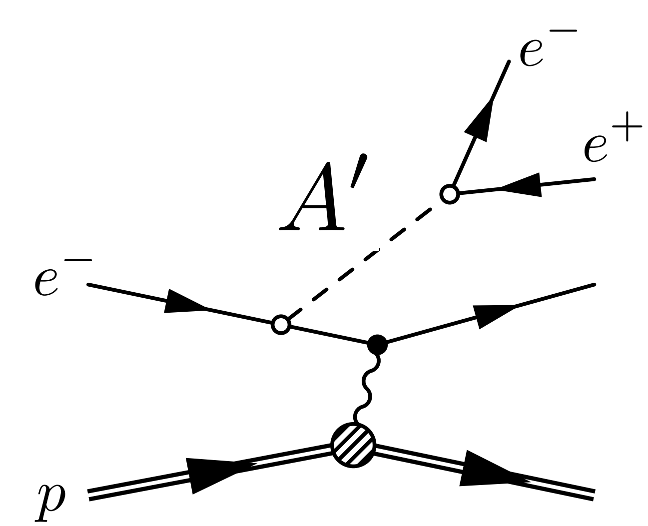
0.5 Tesla

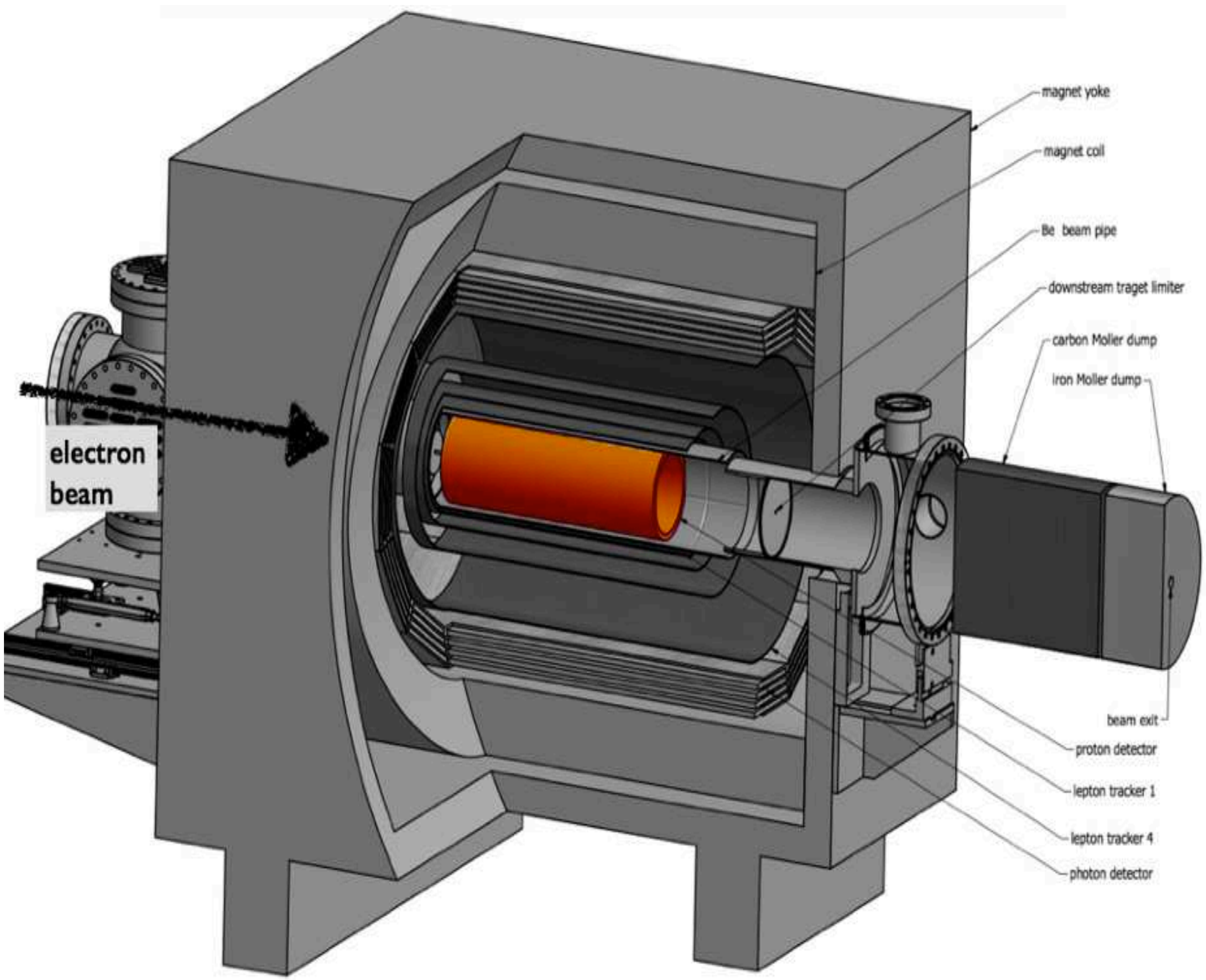
- Solenoidal magnet



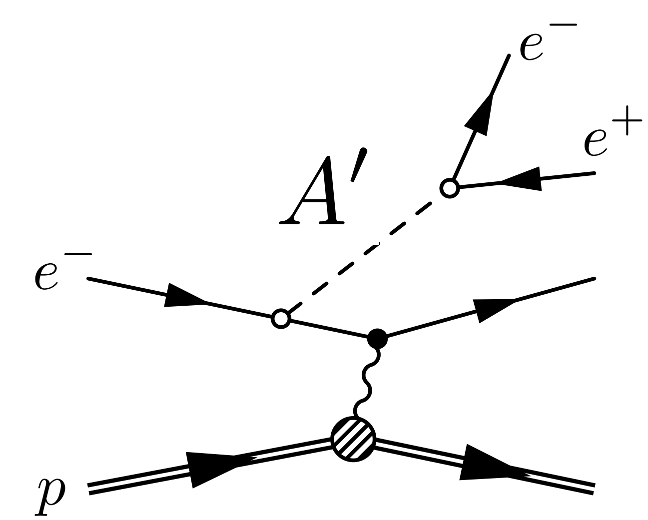


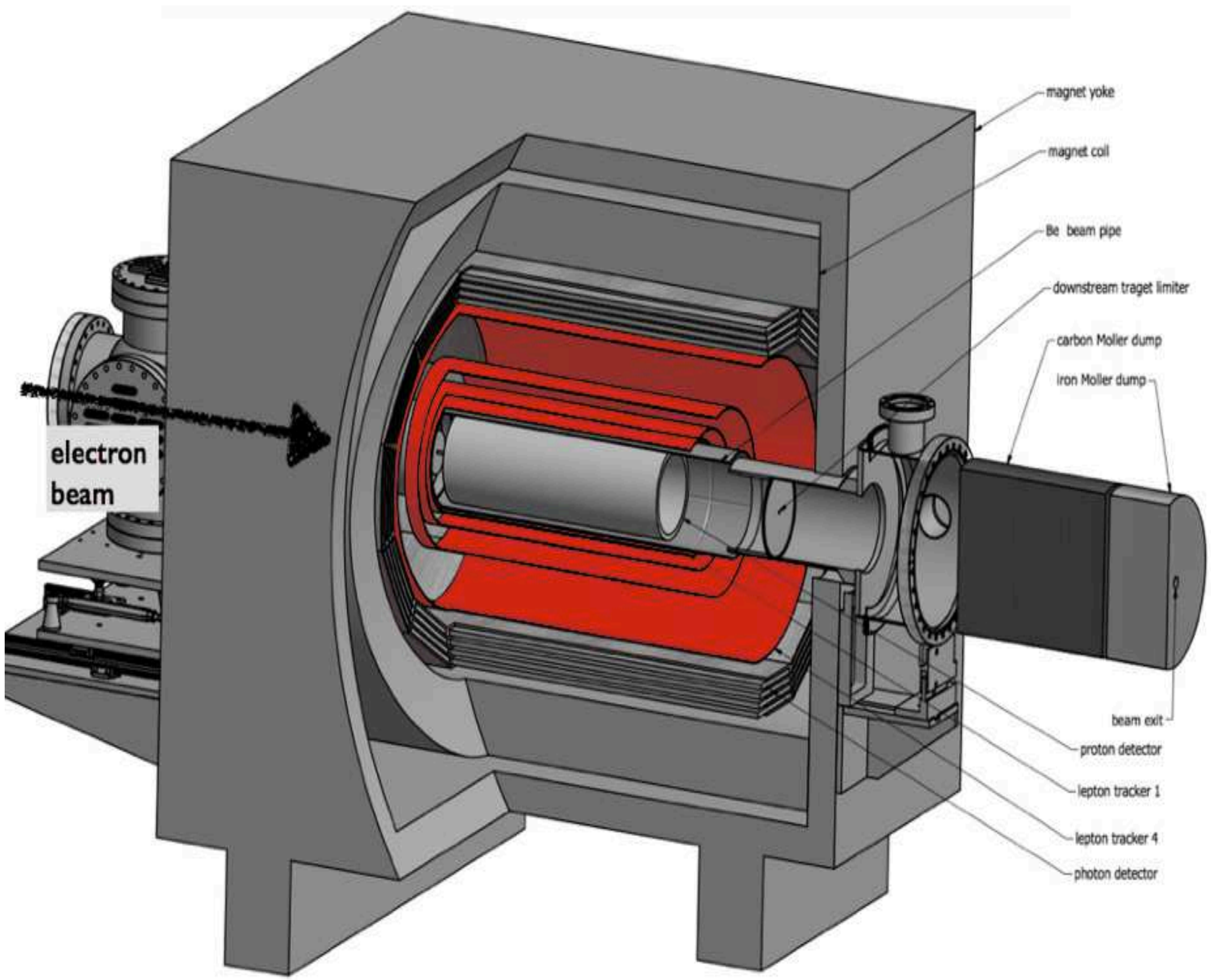
- Solenoidal magnet
- Be beampipe
  1 mm thick



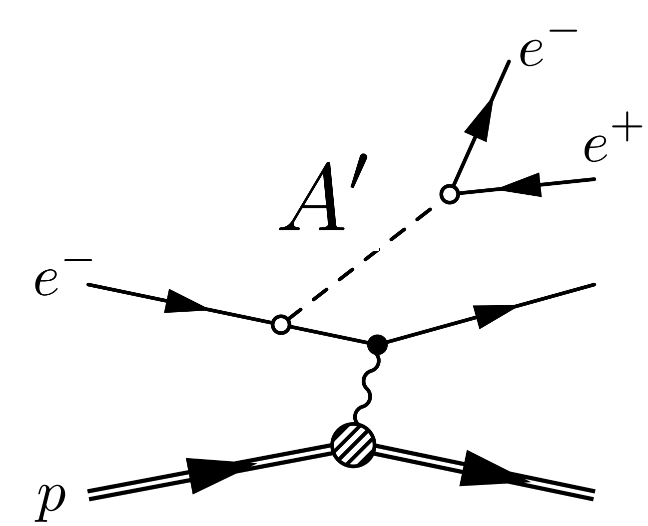


- Solenoidal magnet
- Be beampipe
  1 mm thick
- Proton silicon detector
  300 micron thick

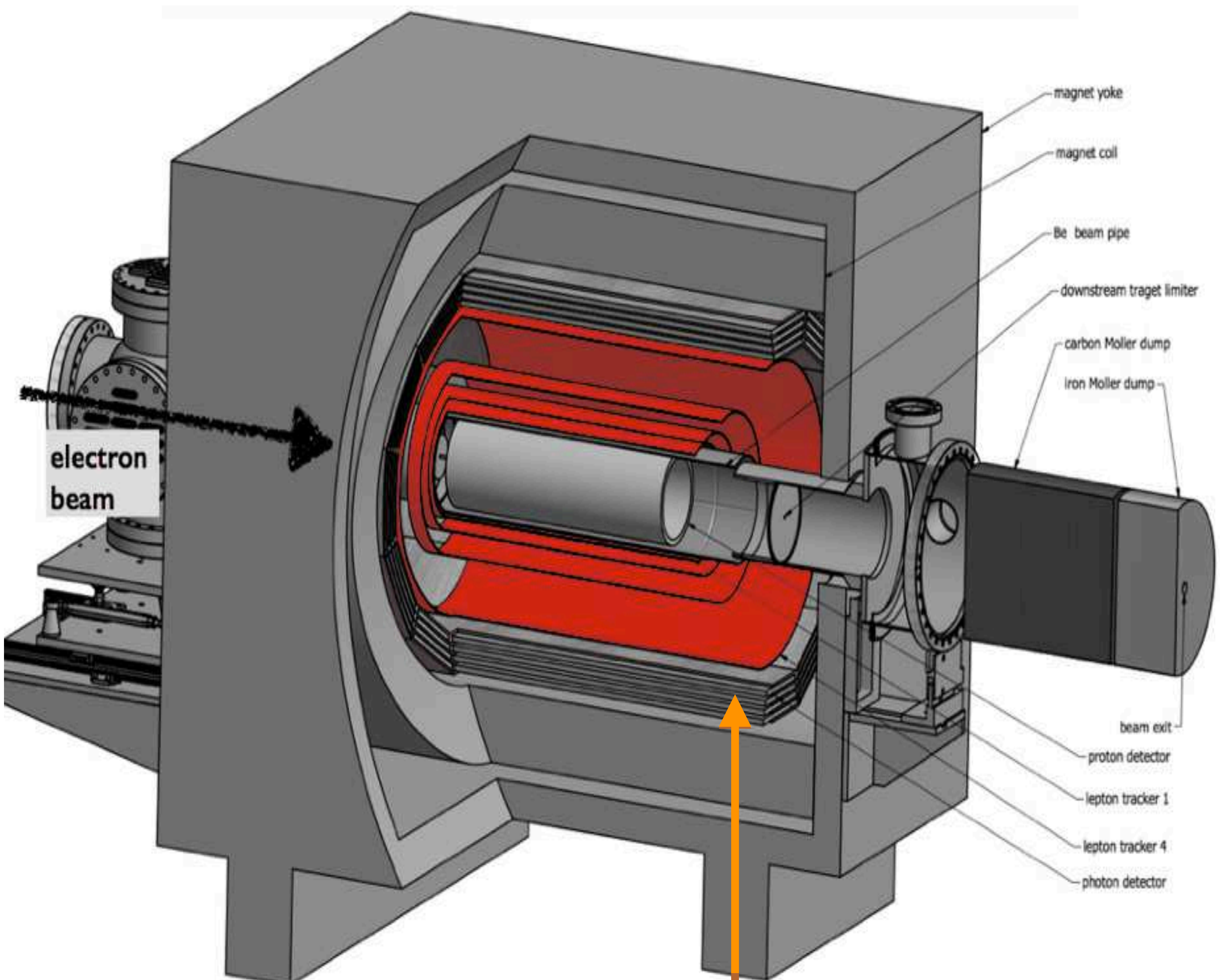




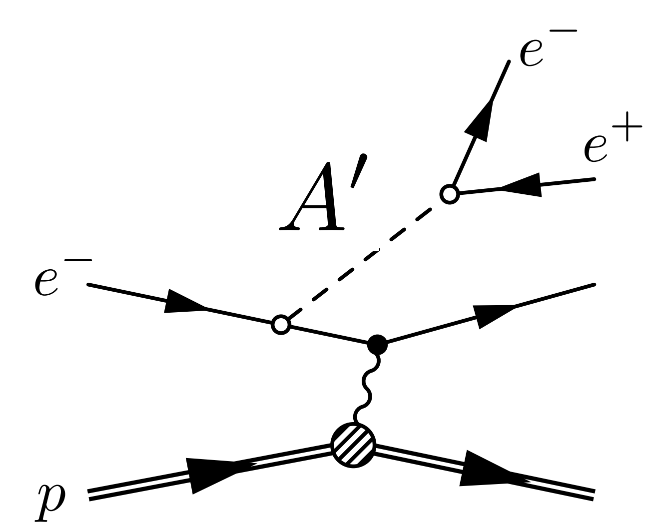
- Solenoidal magnet
- Be beampipe
  1 mm thick
- Proton silicon detector
  300 micron thick
- Lepton tracker
  4 layers
  GEM/Micromegas



1–3 MeV invariant mass resolution



- Solenoidal magnet
- Be beampipe
  1 mm thick
- Proton silicon detector
  300 micron thick
- Lepton tracker
  4 layers
  GEM/Micromegas



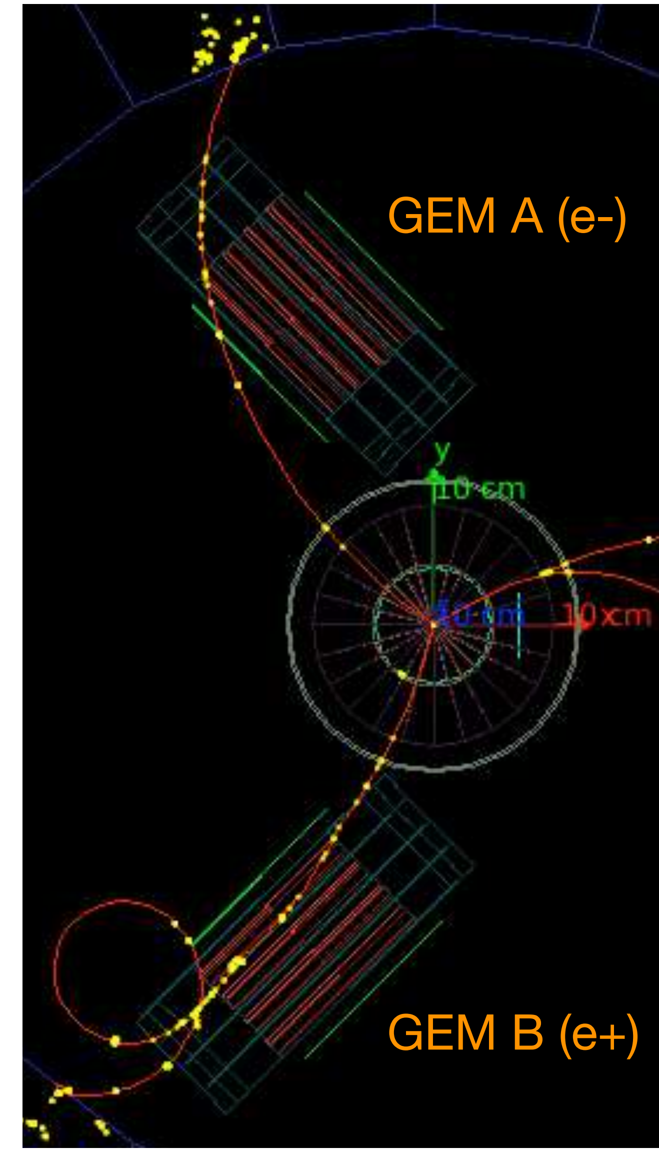
& Photon Detectors

Current Plan (starting 2016)

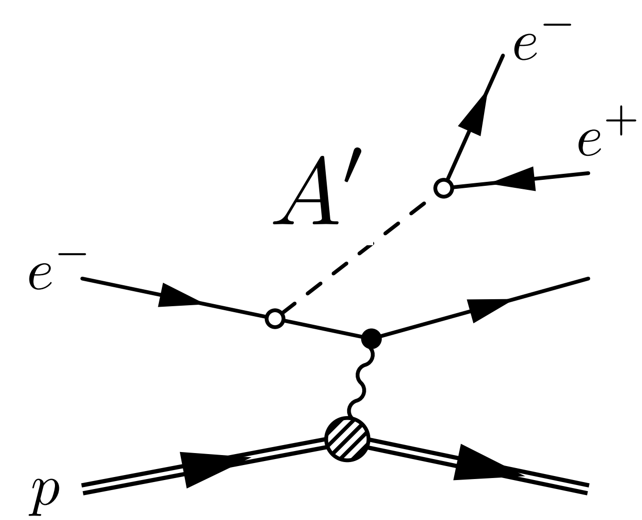
Phase 1a: Test ERL performance
with gas target and solenoid

Phase 1b: Measure radiative Møller
scattering on carbon foil target

Phase 1c: Measure QED background
$e^- p \rightarrow e^- p\, e^+ e^-$ with prototype
GEM tracker and silicon p detector

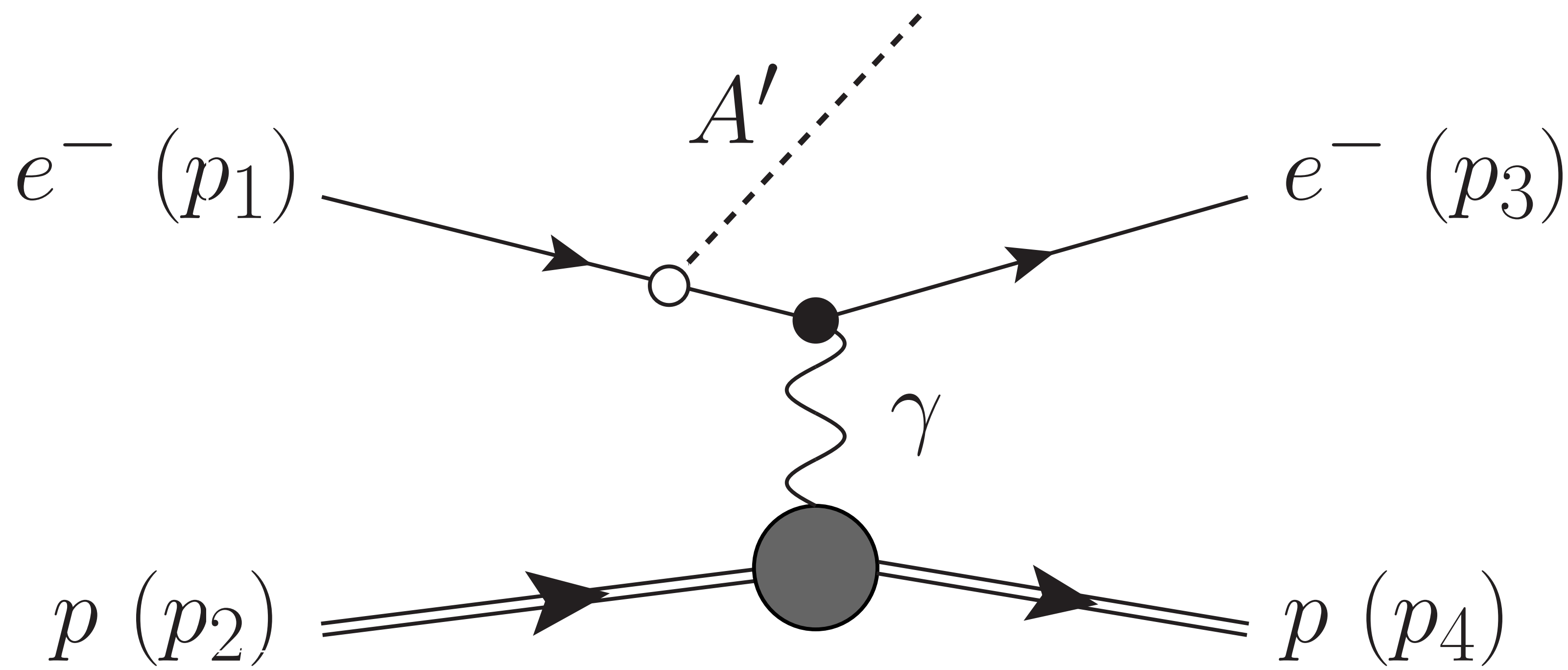


Phase 2: Full visible A′ → e^+e^- search
Attempt invisible A′ search



DarkLight Invisible Search

If you can measure the recoil proton…



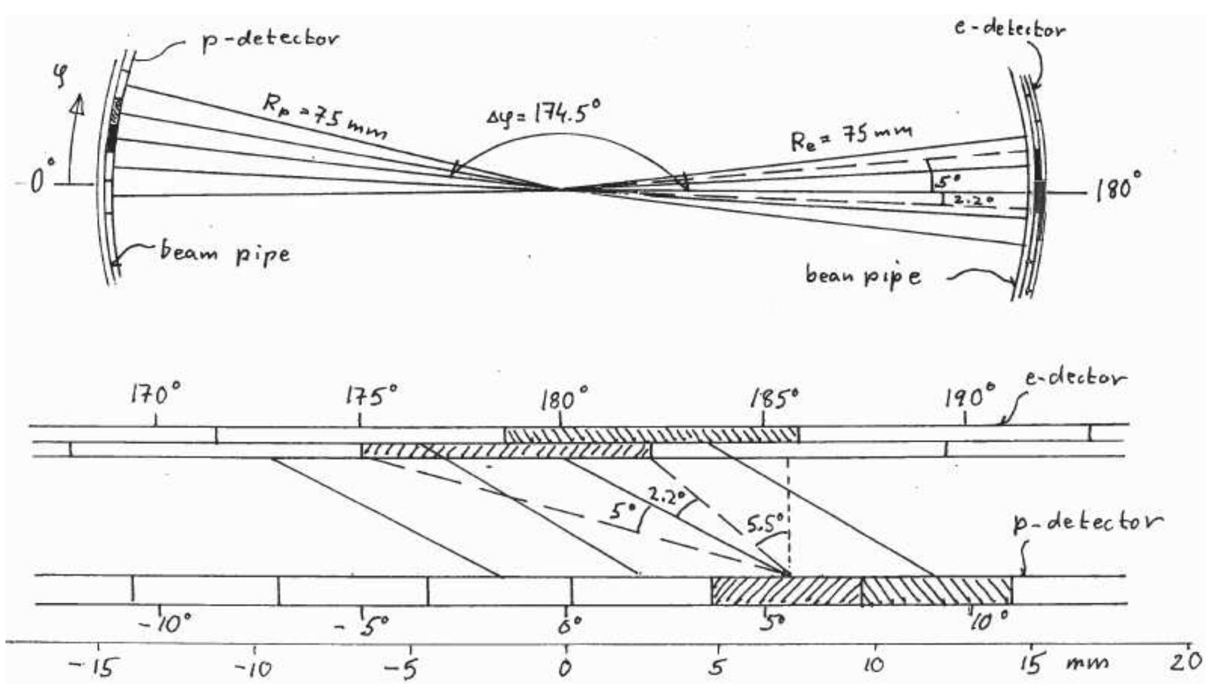
$$m^2_{\rm miss} = (p_1 + p_2 - p_3 - p_4)^2$$

[Kahn, JDT, 2012]

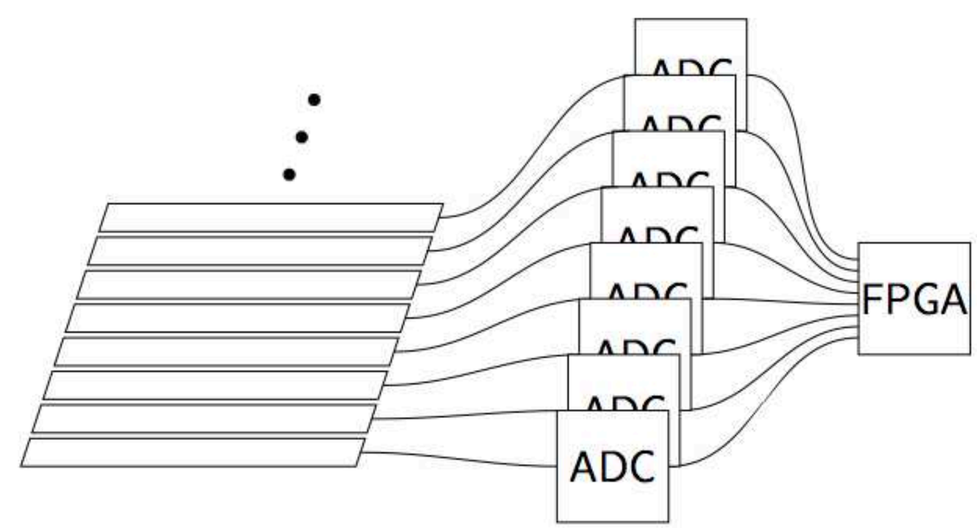
But same ep final state as elastic scattering

$e^- p \to e^- p \approx$ 2 events per bunch @ 75 MHz

Screen with
fast coincidence?

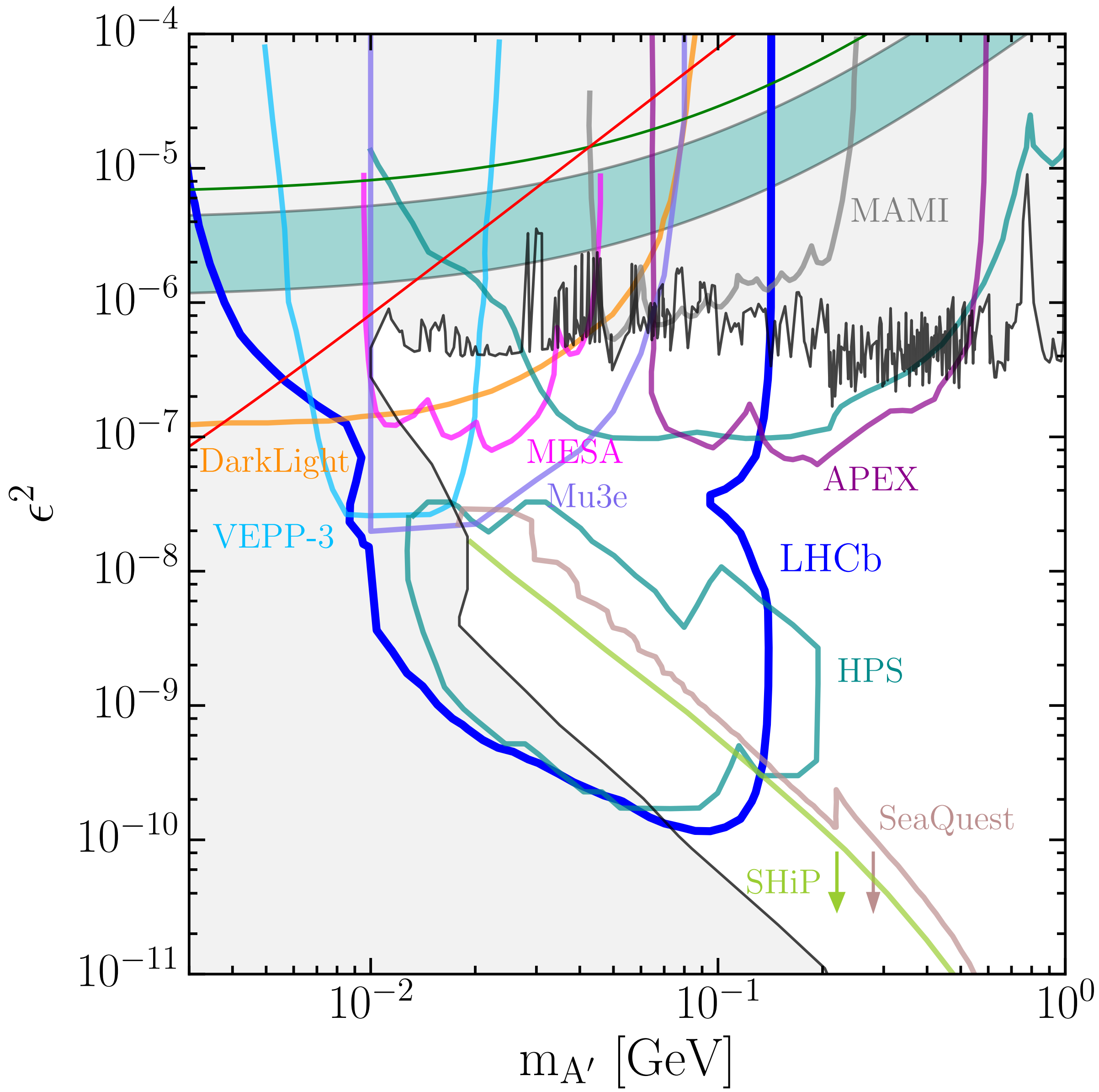


Streaming
detector readout?



The Streaming Revolution?

e.g. Run 3 of LHCb

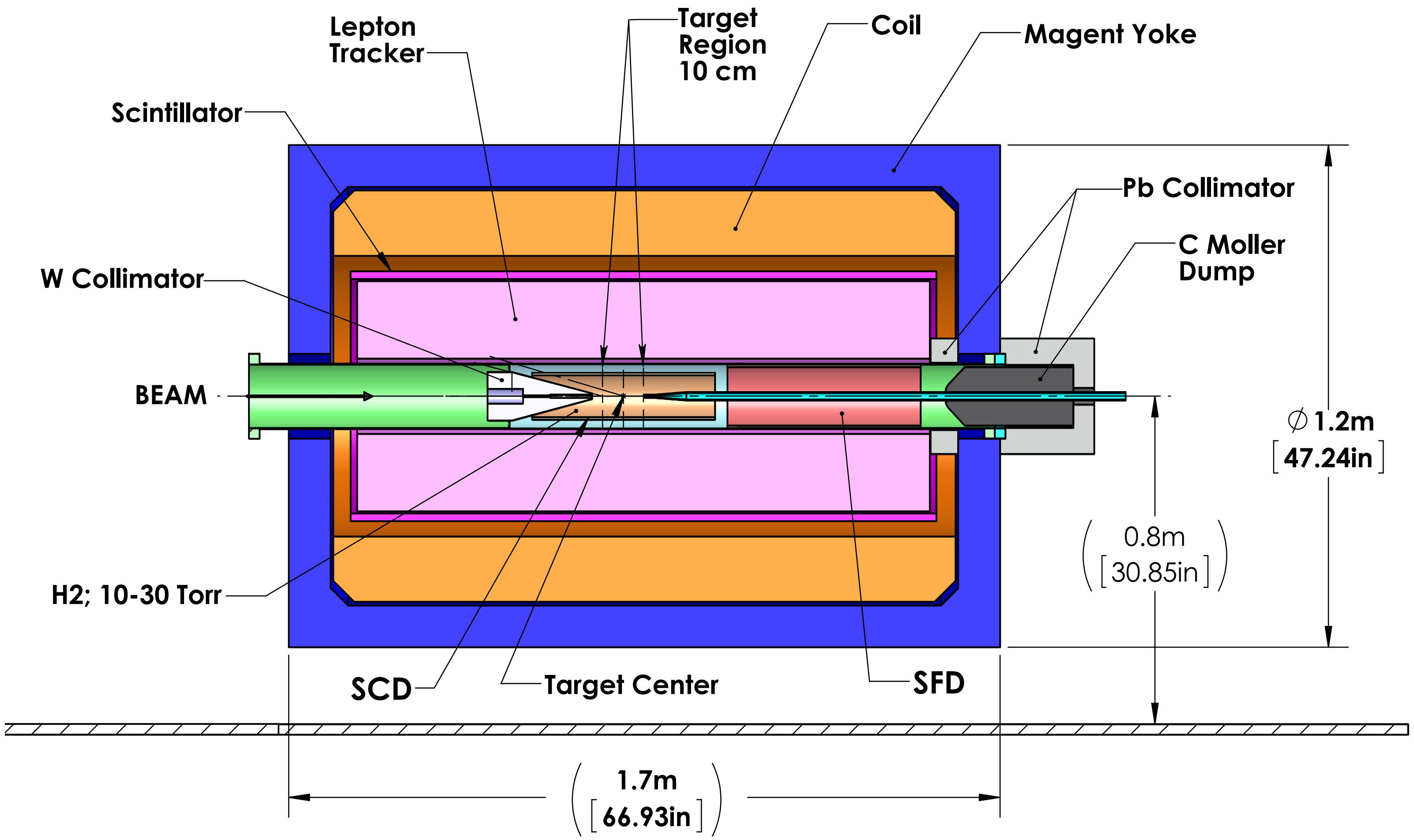


$$D^{*0} \to D^0 A'$$
$$A' \to e^+ e^-$$

What you can do by reconstructing 30 billion $D^{*0} \to D^0 e^+ e^-$ decays

[Ilten, JDT, Williams, Xue, 2015]

Baseline Resolutions (2012 DarkLight Design)



Particle	e^+/e^-	p	γ
Angular acceptance	$25^\circ - 165^\circ$	$5^\circ - 89^\circ$	$25^\circ - 165^\circ$
Angular resolution	$\sigma_\theta = \sigma_\phi = 0.002$ rad	$\sigma_\theta = \sigma_\phi = 0.02$ rad	N/A[a]
Energy/momentum resolution	$\sigma_{p_T}/p_T = 2\% \times (p_T/100\text{ MeV})$	$\sigma_{\text{KE}}/\text{KE} = 0.1\%$	N/A[a]
Detection threshold	$p_T > 10$ MeV	KE > 1 MeV	$E > 5$ MeV
Detection efficiency	100%[b]	99%	95%[c]

(optimistic?)

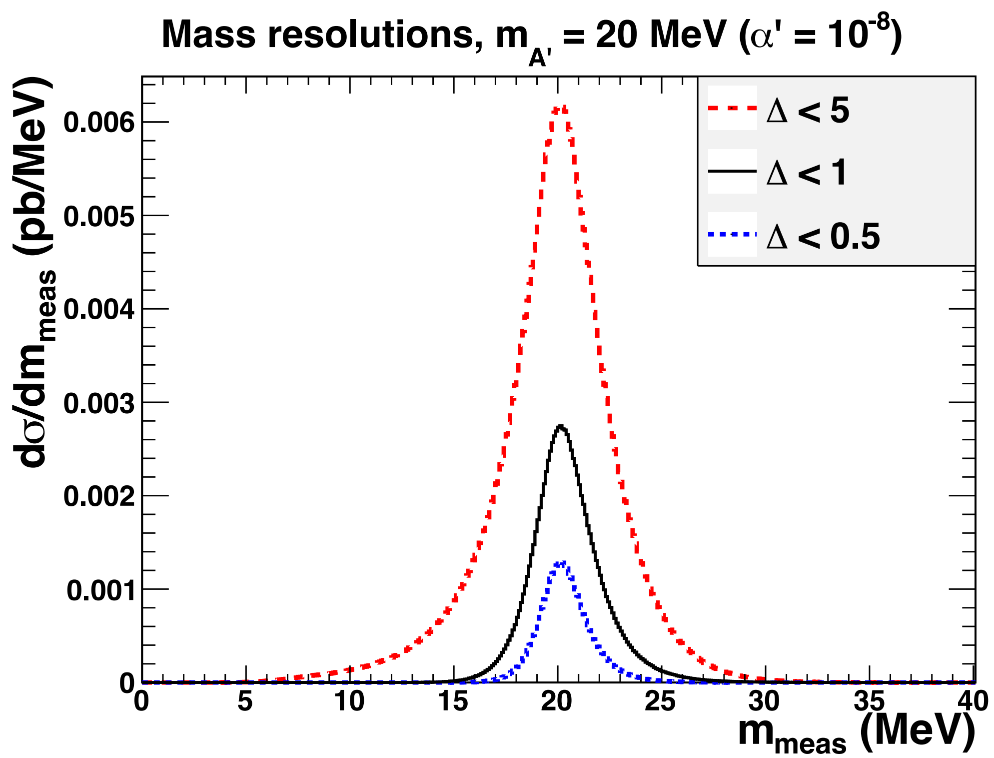
Missing Mass Resolution

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

Want as little missing momentum as possible!

$$E_{\text{miss}}/m_{\text{miss}} \equiv 1 + \Delta$$

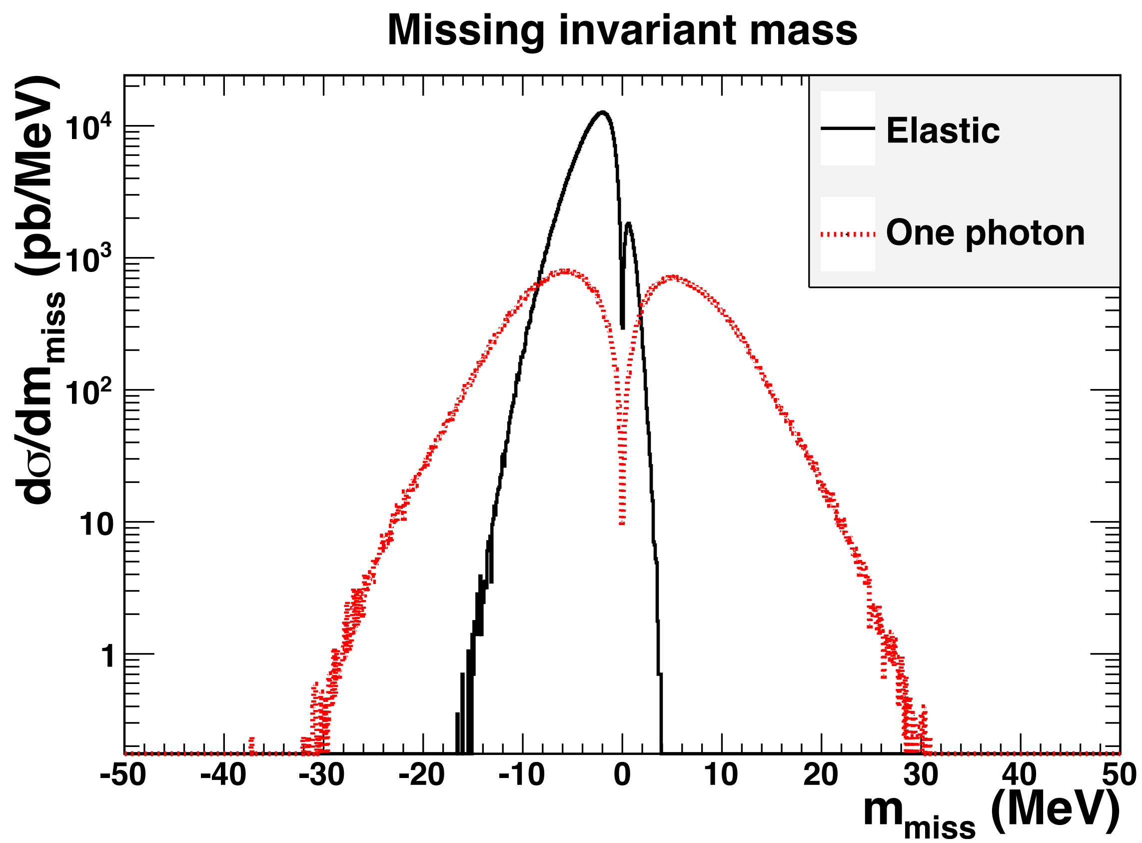
$\mathbf{m_{A'}}$ **(MeV)**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
$\mathbf{\Delta_{\text{cut}} = 10}$	4.0	3.7	2.6	1.8	1.3	0.92	0.66	0.35
$\mathbf{\Delta_{\text{cut}} = 1}$	3.0	2.5	2.1	1.6	1.3	0.92	0.66	0.35
$\mathbf{\Delta_{\text{cut}} = 0.5}$	2.1	1.8	1.5	1.4	1.2	0.92	0.66	0.35



Impact of Elastics and Single Photons

$ep \to ep$ $\qquad m_{miss}^2 = 0$

$ep \to ep + \gamma$ $\qquad m_{miss}^2 = 0$

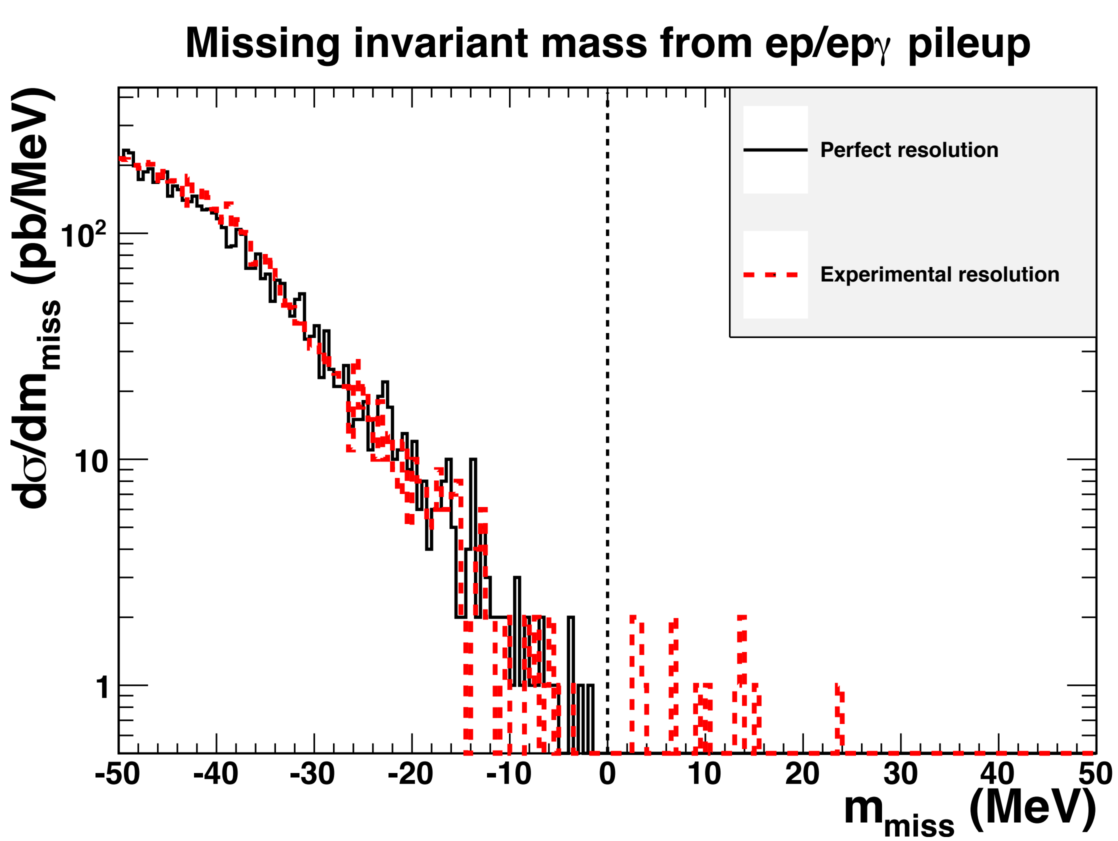


Up to resolution effects, elastic and single radiative backgrounds are controllable

Negative Mass Trick

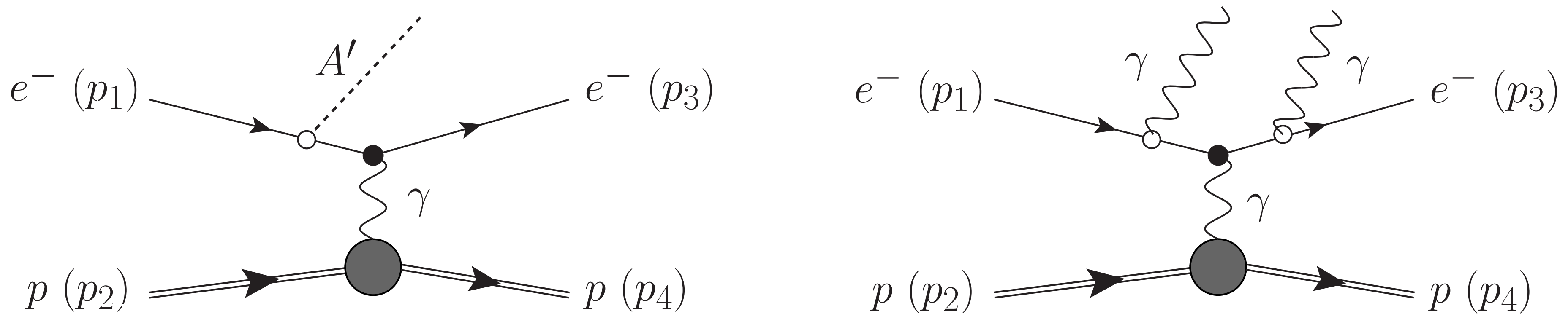
$$\left.\begin{array}{l} ep \to ep \\ ep \to ep \end{array}\right\} \text{wrong pair} \qquad m_{miss}{}^2 \leq 0$$

$$\left.\begin{array}{l} ep \to ep \\ ep \to ep + \text{anything} \end{array}\right\} \text{wrong pair} \qquad m_{miss}{}^2 \leq 0$$

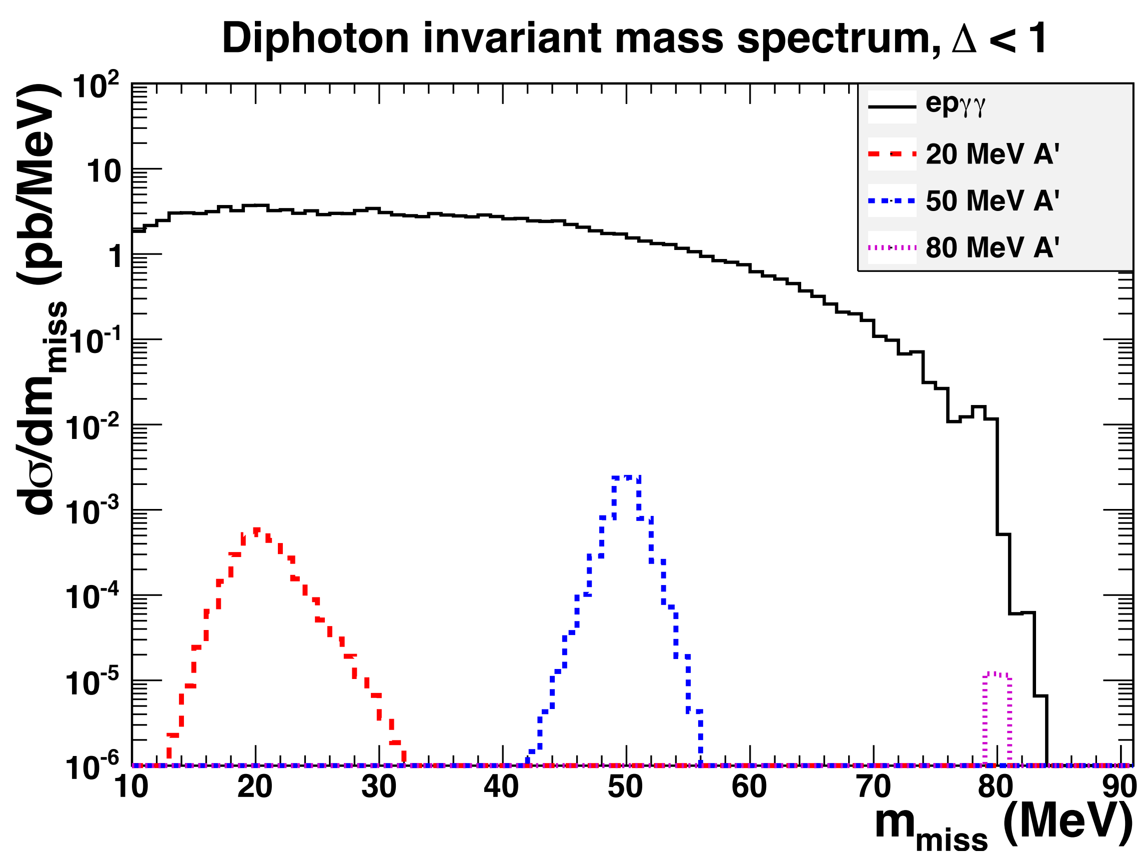


Up to resolution effects, pileup has small impact on invisible search

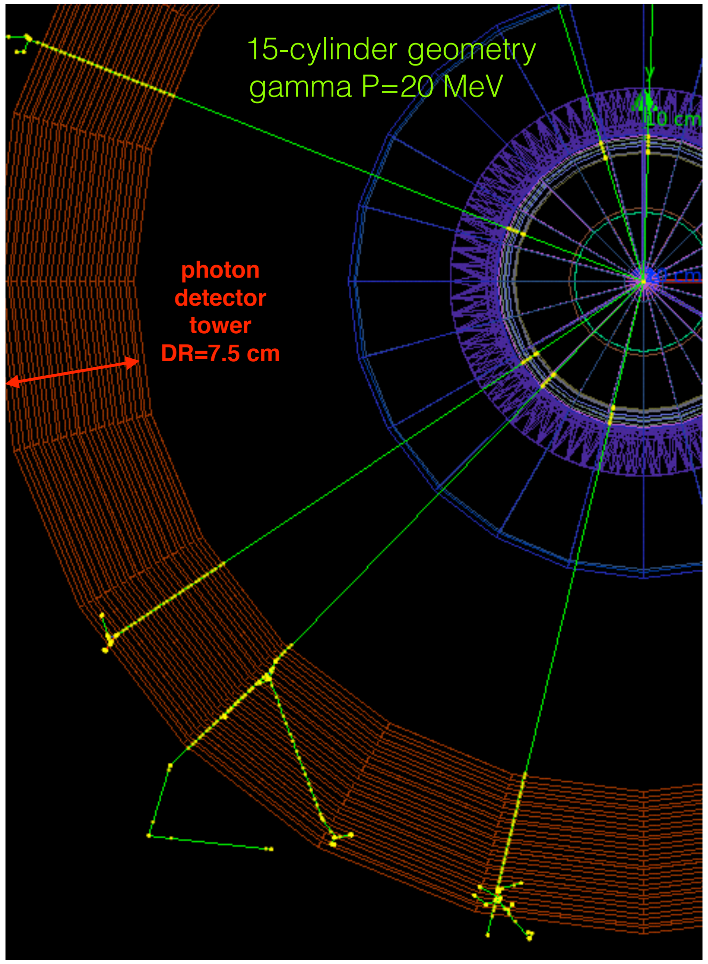
Dominant Background: ep → ep + γ γ

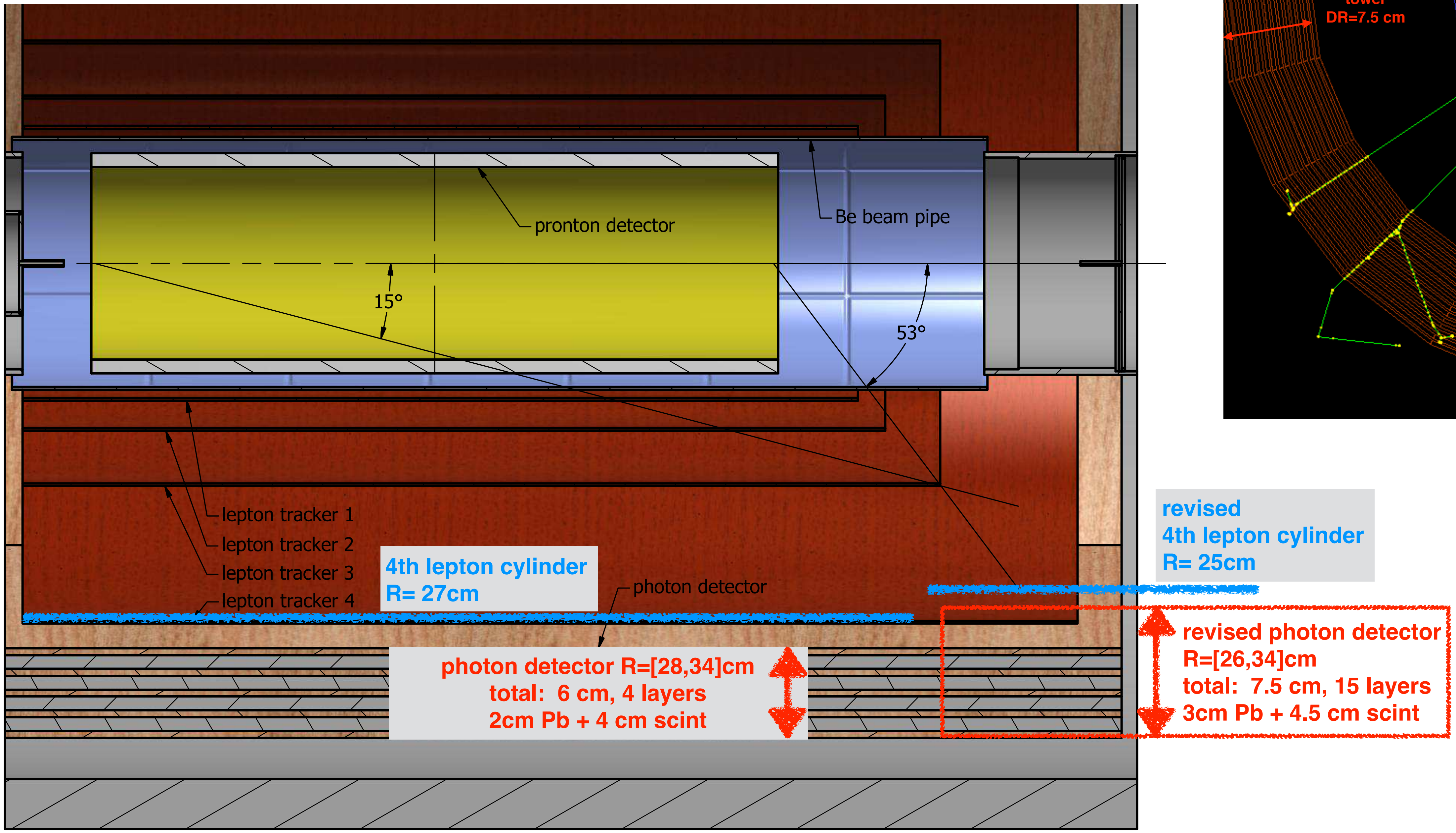


Unless you can veto photons, these are the same final state



Aim: 90–95% Photon Efficiency





Example Search: 50 MeV A′ in (g–2)$_\mu$ band

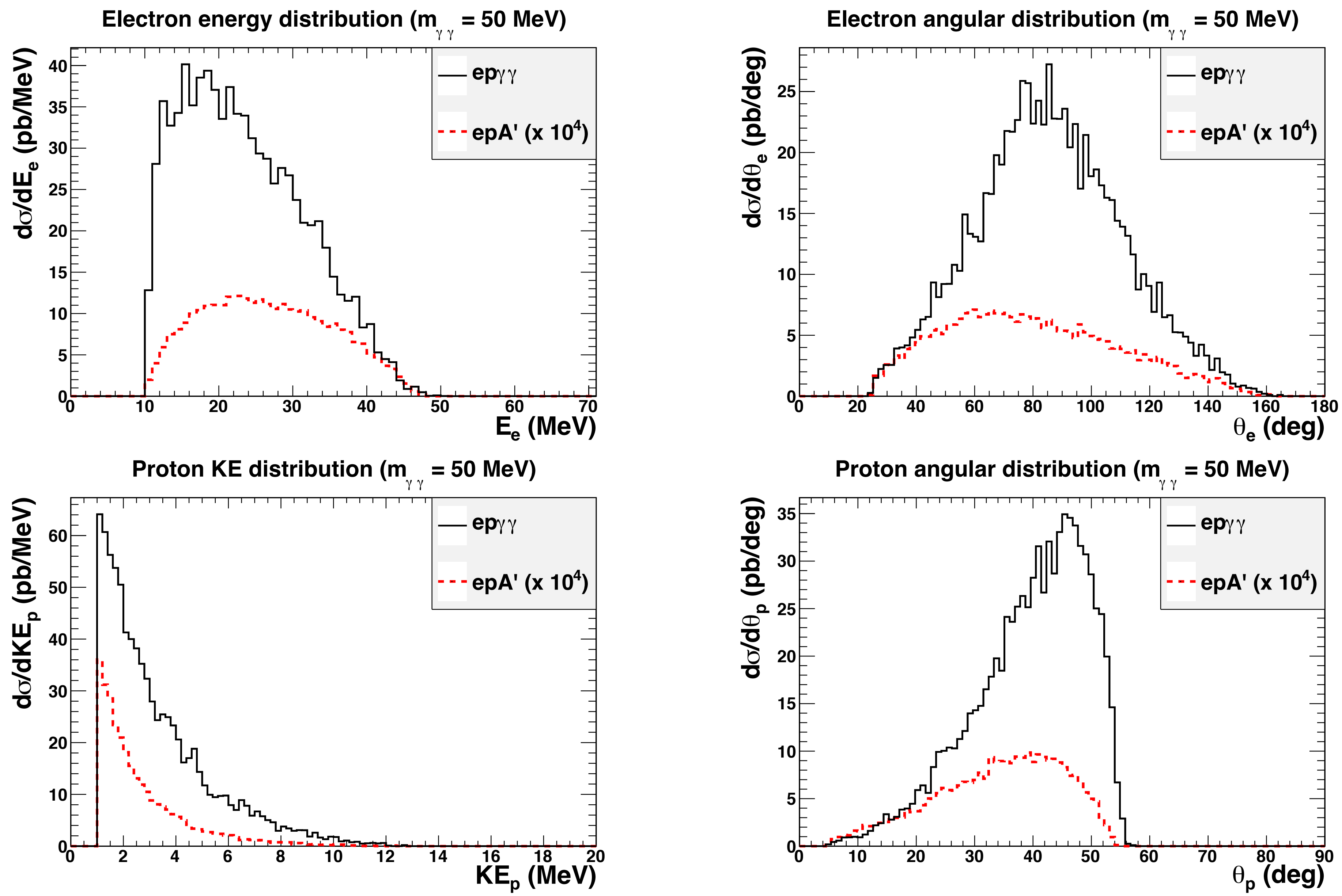
Process	**Raw (Hz)**	**Veto**	**Level 1 (Hz)**	**Level 2 (Hz)**	**50 MeV mass window (Hz)**
$\boldsymbol{ep}$	6.5×10^7	p	< 1	$< 10^{-2}$	$< 10^{-3}$
$\boldsymbol{ep\gamma}$	5.0×10^6	γ	5.0×10^4	2.0×10^2	$< 10^{-3}$
$\boldsymbol{ep\gamma\gamma}$	1.6×10^5	γ	1.7×10^2	77	2.4
$\boldsymbol{epe^+e^-}$	6.6×10^3	e^-, e^+	1.2×10^2	2.3	$< 10^{-2}$
$\boldsymbol{ep/ep}$	3.1×10^7	p, e^-	1.2×10^3	$< 10^{-2}$	$< 10^{-3}$
$\boldsymbol{ep/ep\gamma}$	2.4×10^6	p, γ, e^-	4.1×10^2	$< 10^{-2}$	$< 10^{-3}$
$\boldsymbol{ep\gamma/ep\gamma}$	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}

backward going electron (to limit epγ rate)
veto proton consistent with ep elastics
veto any positron in acceptance
veto photon above threshold
veto nearby electrons (tail of pileup background)

exactly one positive missing mass
reconstruction above 10 GeV

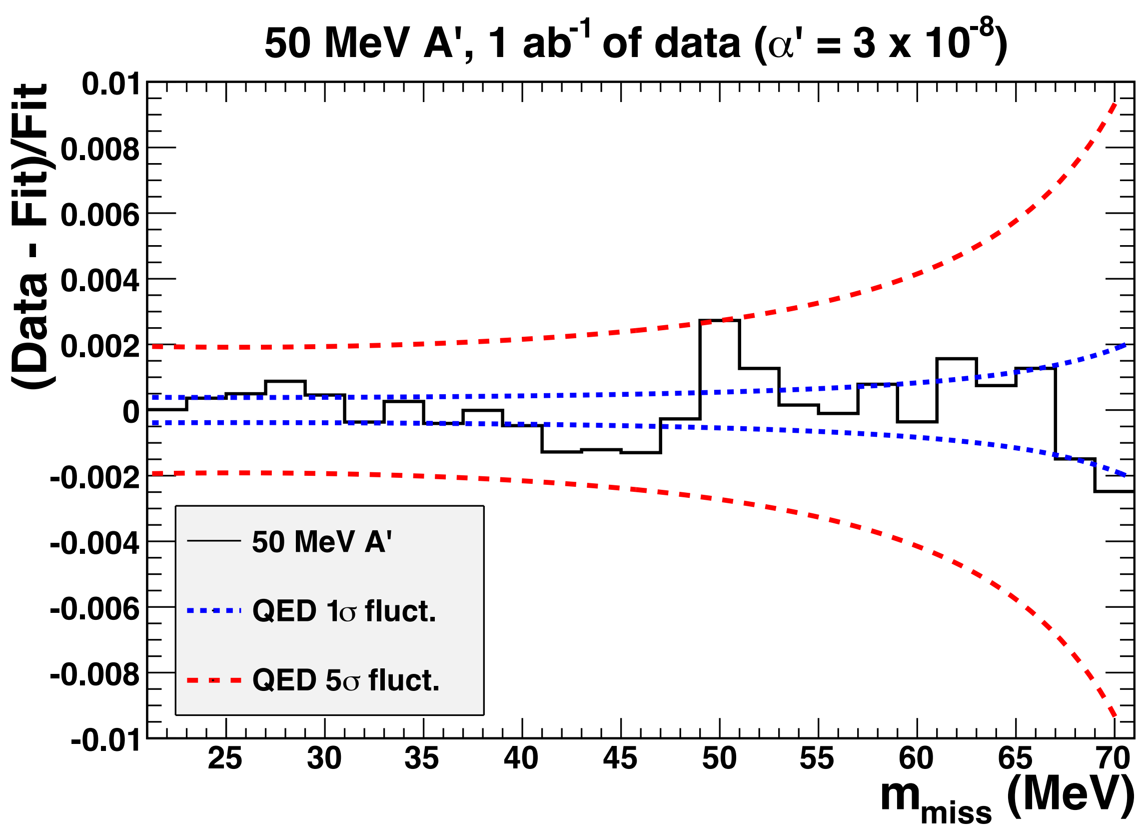
require missing energy to be
not much larger than missing mass

Signal/Background Comparison



Apart from mass bump, no distinguishing features

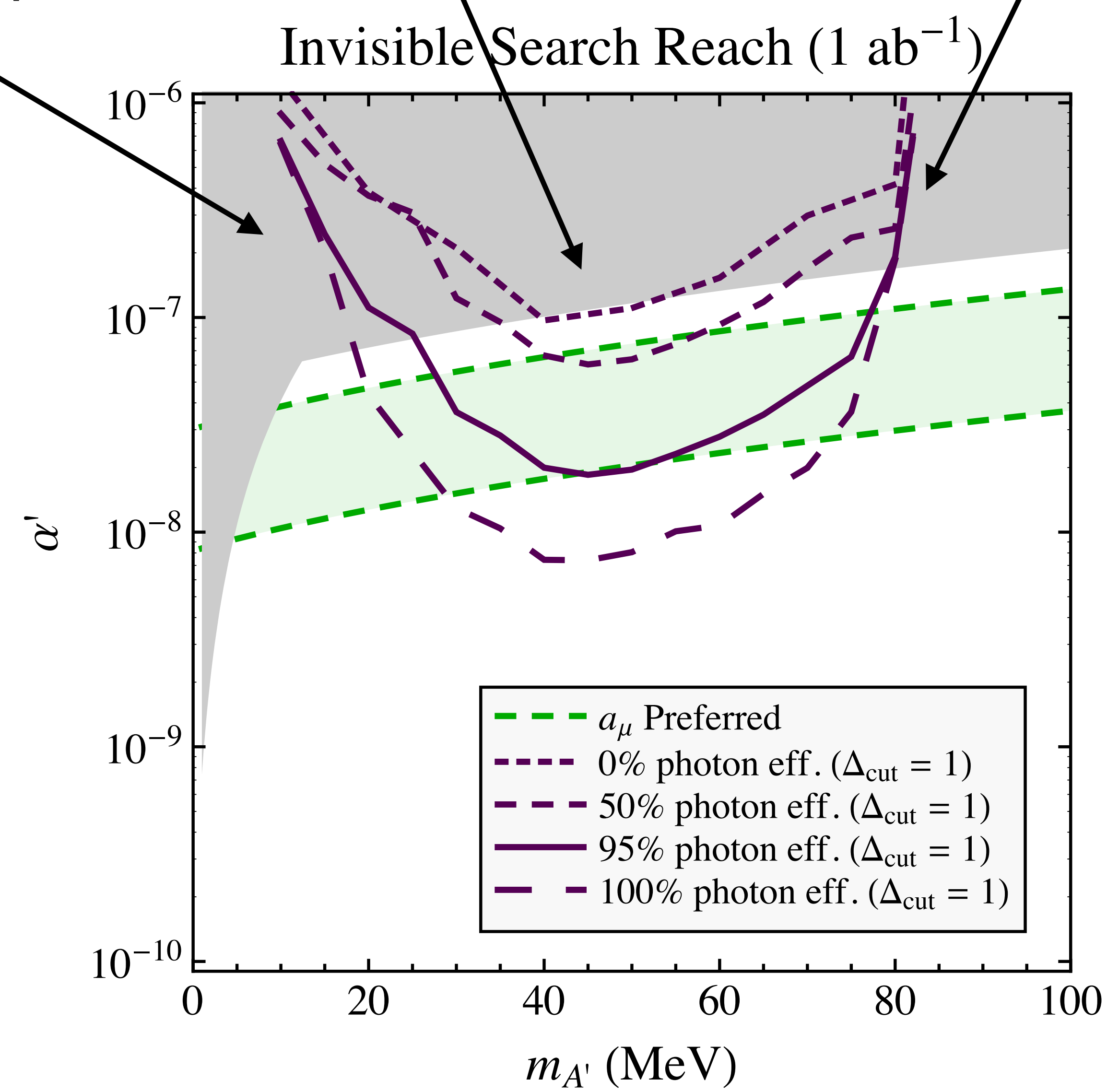
Anticipated Invisible Reach



limited by
missing mass
resolution on epγ

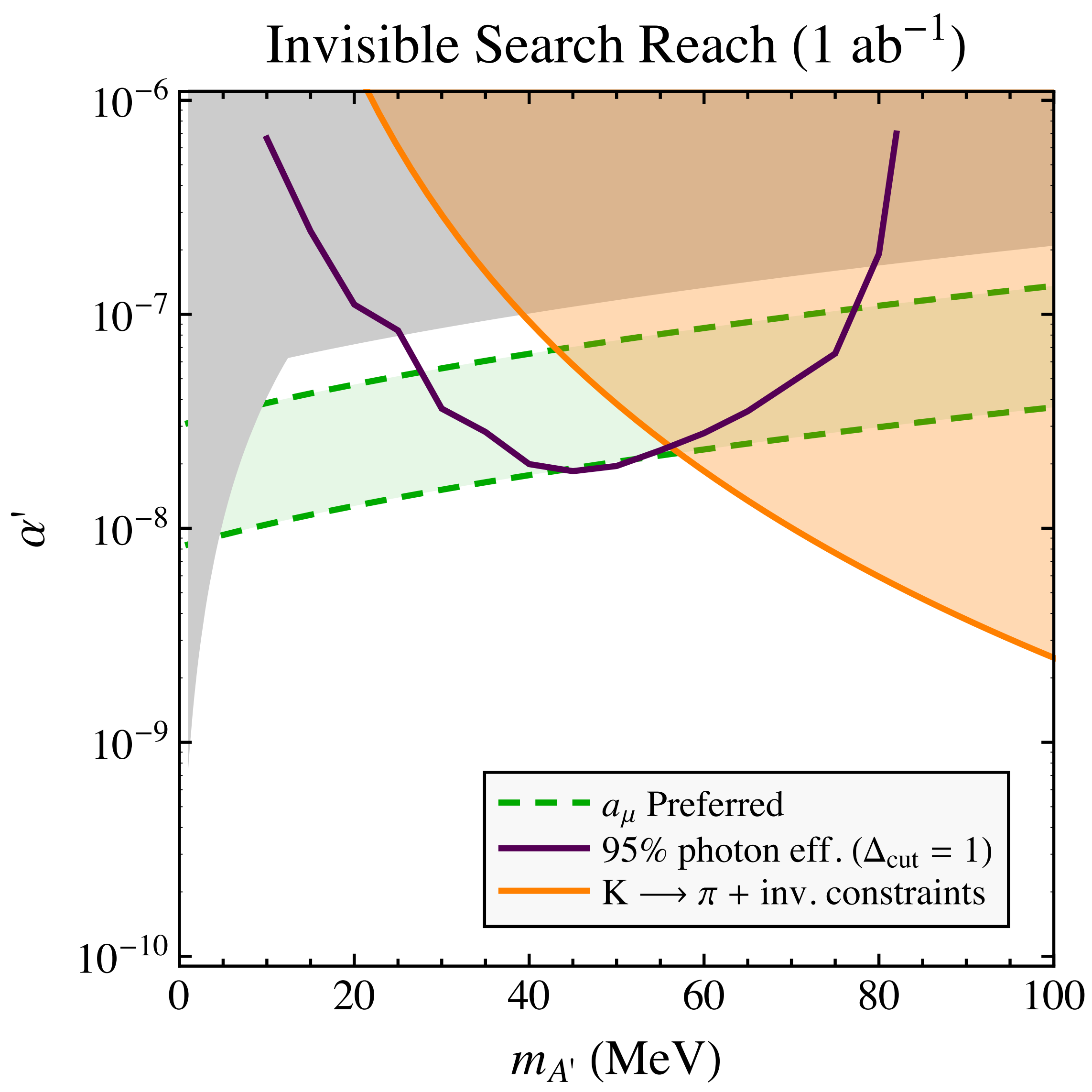
have to reject
epγγ background

limited by
beam energy



Competition to Missing Mass Searches

Rare Kaon Decays

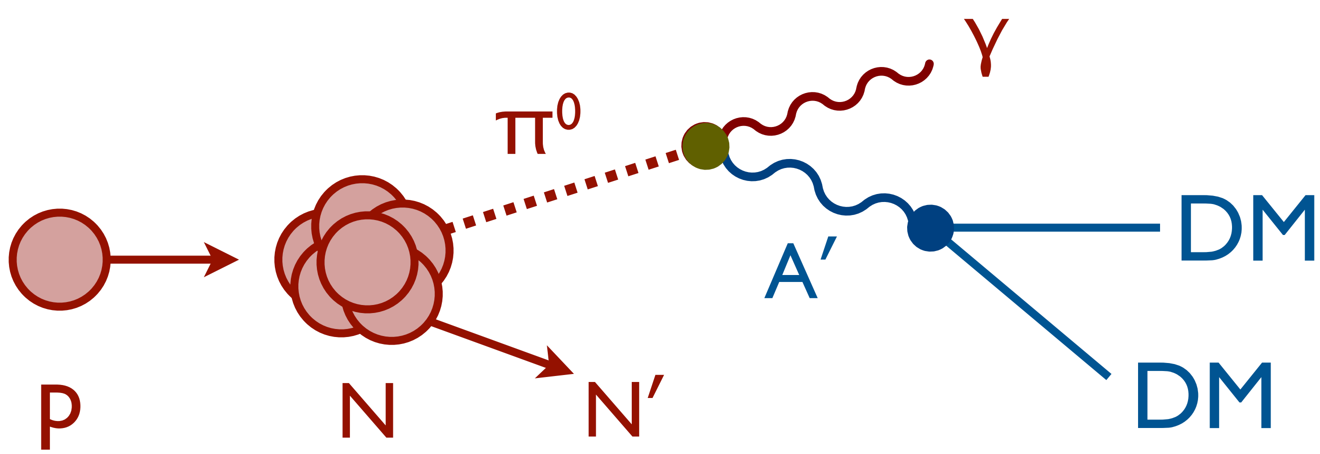


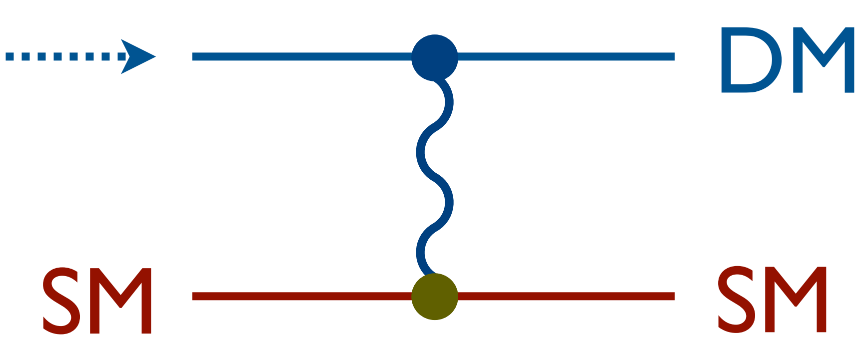
(Might not be present if dark photon only couples to leptons)

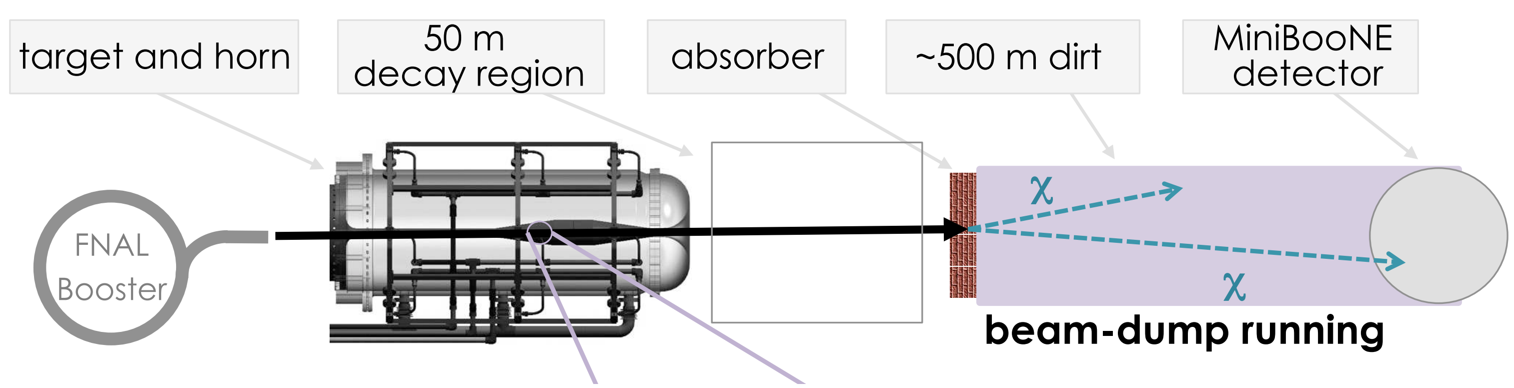
Making Dark Matter Beams

Production in beam dump… …detection downstream

On-shell if $m_{\pi 0} > m_{A'} > 2m_{DM}$





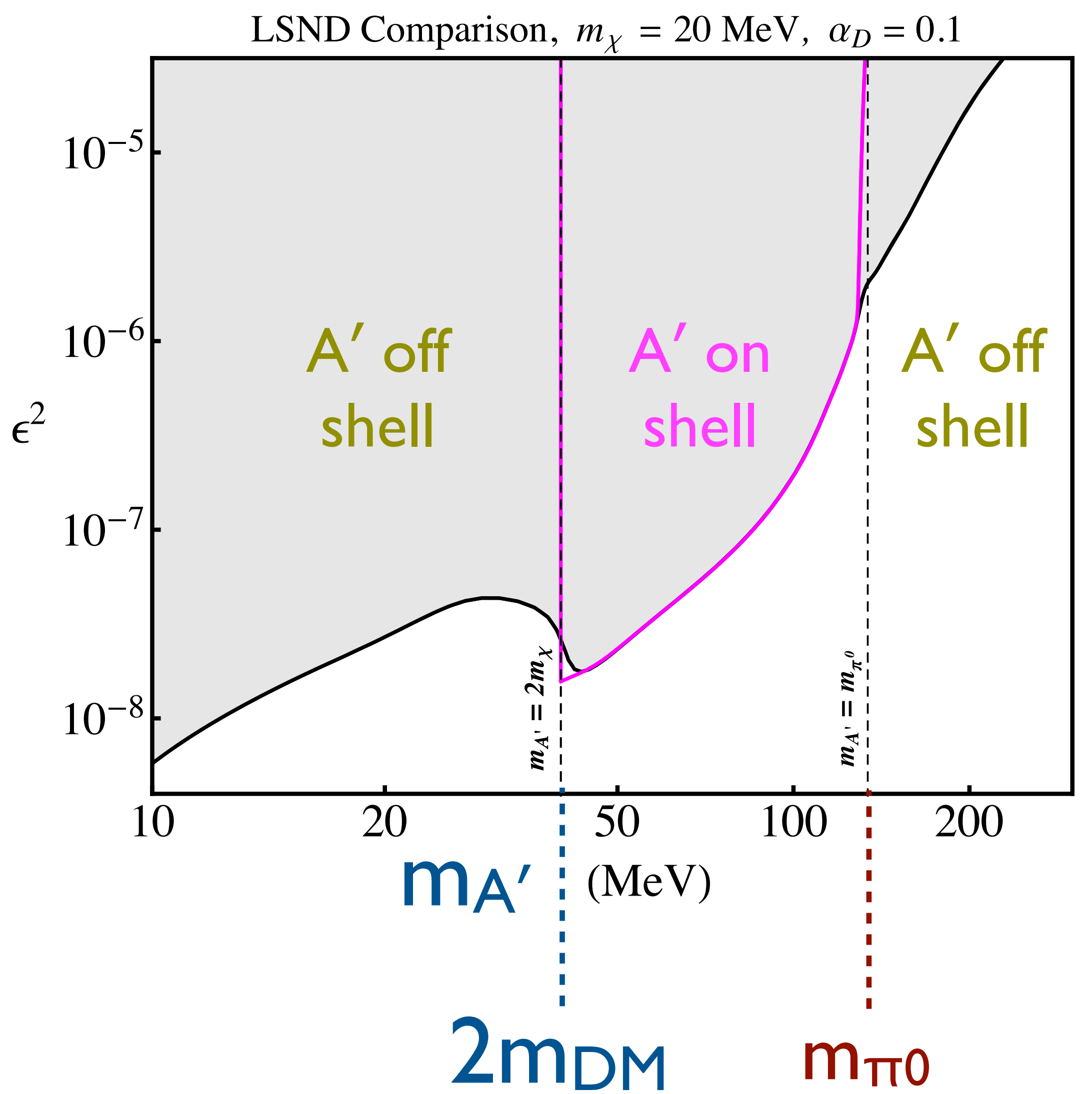


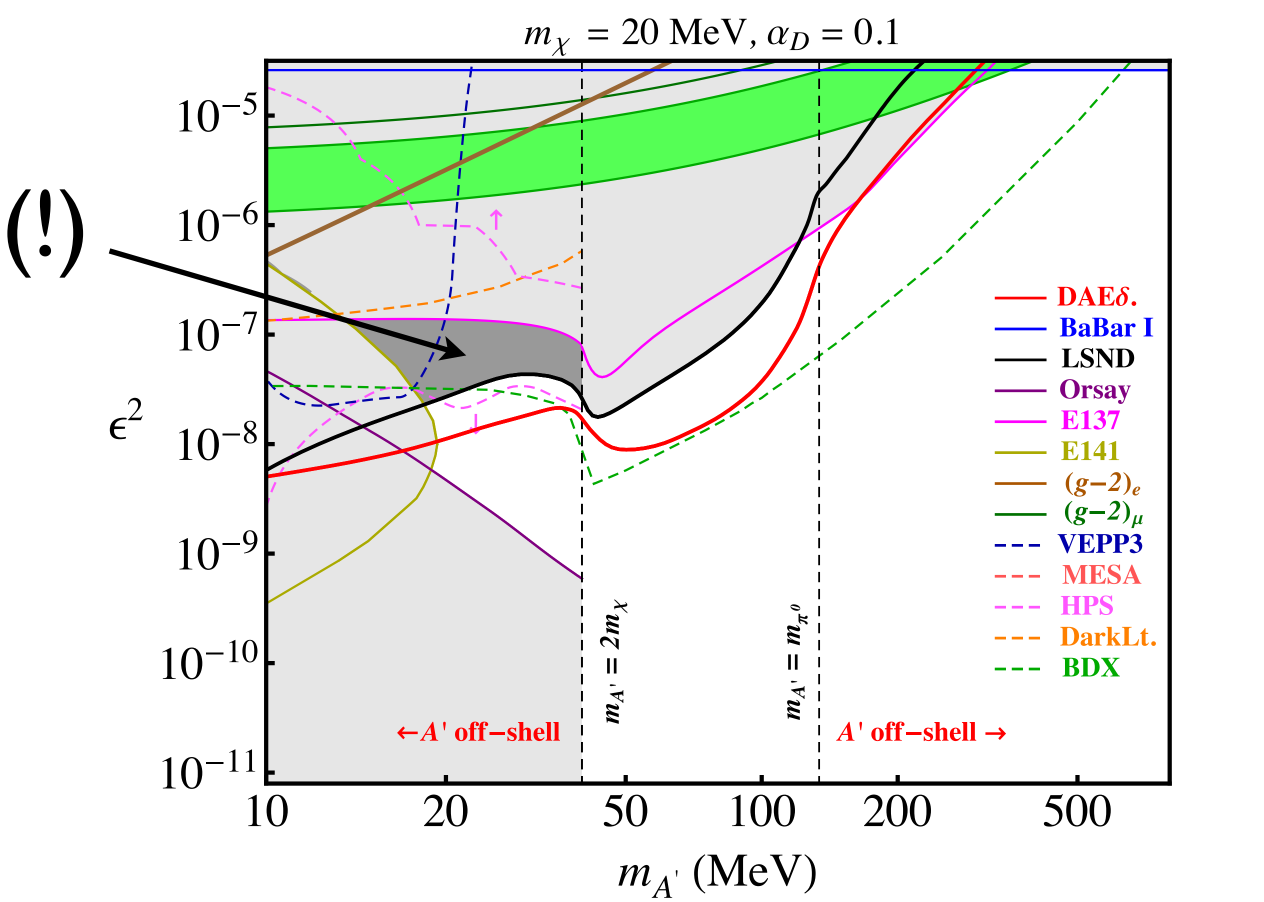
[Batell, Pospelov, Ritz, 2009; + deNiverville, 2011; + McKeen, 2012; Izaguirre, Krnjaic, Schuster, Toro, 2013]

LSND Reinterpretations

$p \rightarrow \pi \rightarrow \mu \rightarrow \nu_e \; . \; . \; . \; . \; . \; . \; \nu_e \, e^- \rightarrow \nu_e \, e^-$

$p \rightarrow \pi^0 \xrightarrow{A'^{(*)}} \gamma \; \mathrm{DM} \; \mathrm{DM} \; . \; . \; . \; . \; . \; . \; \mathrm{DM} \; e^- \rightarrow \mathrm{DM} \; e^-$

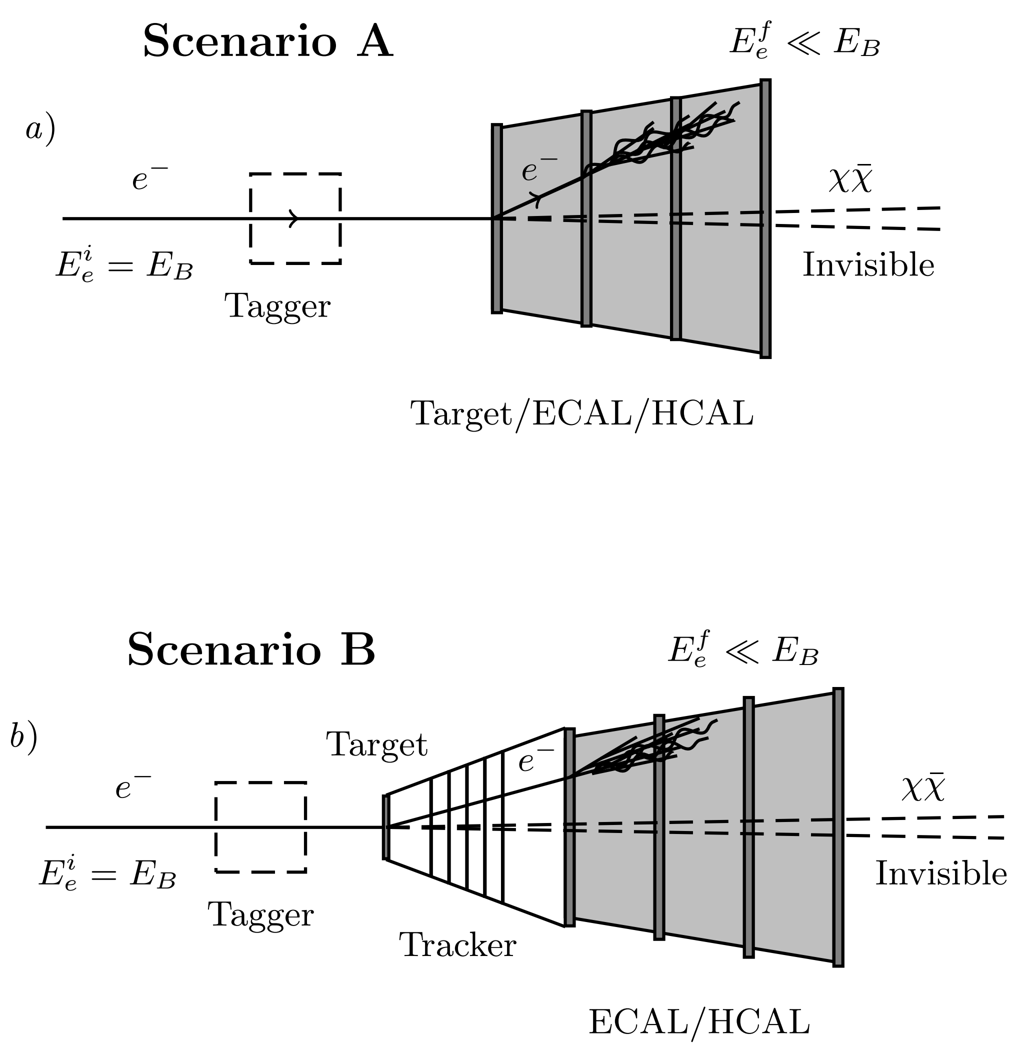




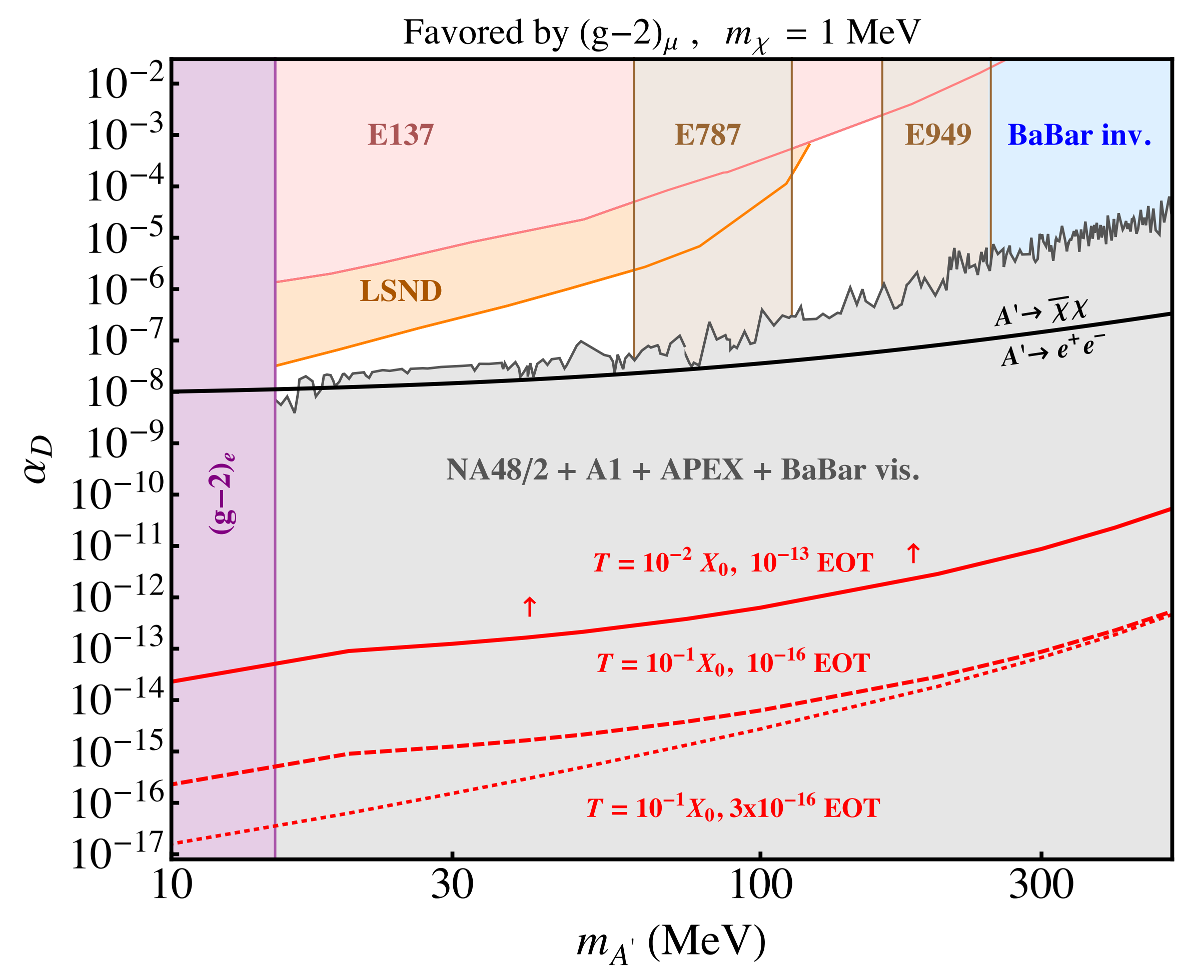
[using LSND, 2001; Kahn, Krnjaic, JDT, Toups, 2014]

Another Approach to Missing Mass?

Extremely hermetic target/detector…



…leaves little doubt about $(g\text{-}2)_\mu$



[Izaguirre, Krnjaic, Schuster, Toro, 2014]

Lesson from DarkLight for Invisible A′ Searches

Missing mass searches are hard
- Full event reconstruction essential
- Streaming detector output seems necessary

Kinematics are somewhat counterintuitive
- Want missing mass without missing momentum
- Optimal to match beam energy to dark photon mass

Background sources are somewhat surprising
- Elastic & single photon backgrounds not showstoppers
- Elastic pileup negligible with negative mass-squared cut
- Dominant background is radiative diphoton production
- Therefore need efficient photon detection

Other invisible search strategies also look promising
- Dark matter beam experiments?
- Hermetic beam test setup?