Searching for Dark Forces

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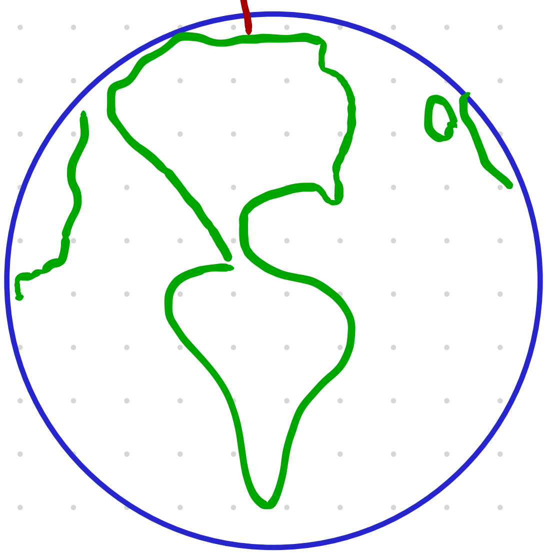
Aug 20, 2014

Lessons of 20th Century

1) Complexity/excess of natural laws:



$e, p, n \longrightarrow$

$U(1) \times SU(2) \times SU(3)$

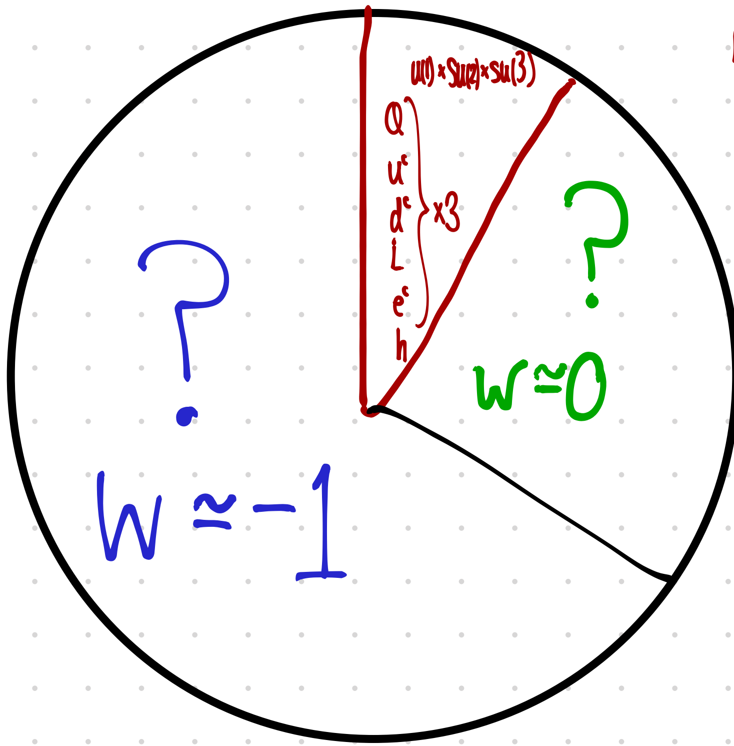
$$\left.\begin{array}{l} Q \\ u^c \\ d^c \\ L \\ e^c \end{array}\right\} \times 3$$

h

Lessons of 20th Century

1) Complexity/excess of natural laws

2) Terrible model of Nature!!



Lessons of 20th Century

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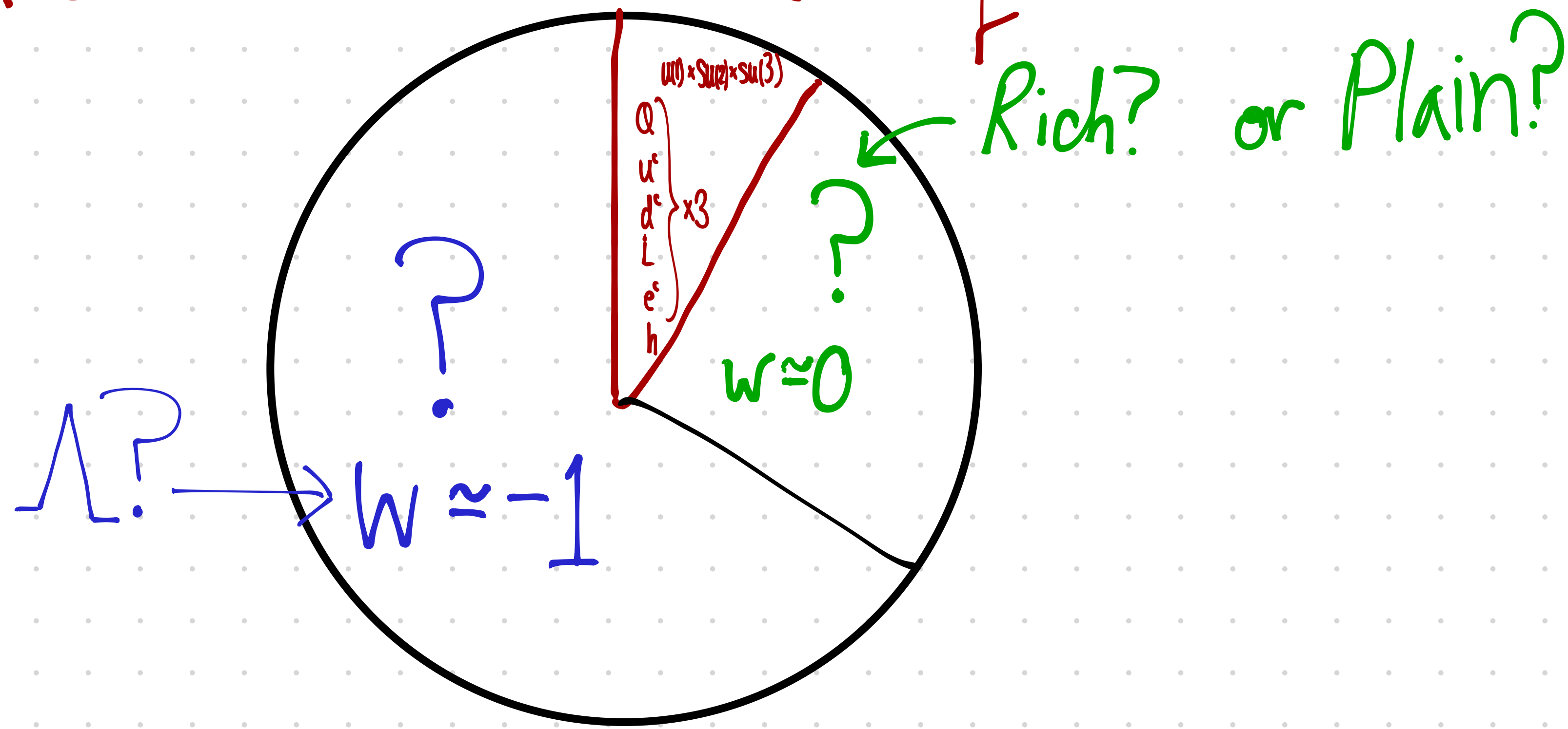

Is Dark Matter

Rich or Plain?

"Collisionless"

Doesn't clump

Occam's Razor

We'd have seen it already!

Is Dark Matter

Rich	or	Plain?
$\sigma/m \lesssim \mathrm{cm}^2/\mathrm{g} \sim 10^3/\mathrm{GeV}$		"Collisionless"
Needs massless γ, $m_e \ll m_p$		Doesn't clump
Experience		Occam's Razor
Symmetry protection ← Key to experimental tests		We'd have seen it already!

Outline

Theory of New "Dark Sectors" and their forces

- Symmetry protection
- Kinetic mixing param. space
- Dark-sector decays
- Applications to DM

References

- Dark forces workshop, SLAC Sept. 2009:
  http://www-conf.slac.stanford.edu/darkforces2009/
- Searching for a New Gauge Boson at JLab, Sept. 2010:
  http://conferences.jlab.org/boson2010/program.html
- Intensity Frontier Workshop:
  http://www.intensityfrontier.org
  Summary document — arXiv:1205.2671
- Dark 2012
  http://www.lnf.infn.it/conference/dark/index.php
- Snowmass 2013
  http://www.snowmass2013.org/
  Major summary document — arXiv:1311.0029
- New Perspectives on Dark Matter, FNAL April 2014:
  http://theory.fnal.gov/people/fox.html/New_Perspectives_on_Dark_Matter
- Dark Interactions, Brookhaven June 2014:
  http://www.bnl.gov/di2014/

Organizing our thinking

∞ possibilities but just a few relevant operators

e.g. suppose χ is fermion charged under $G \neq G_{SM}$.
Leading couplings to SM matter will be 4-fermi

$$\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi J_\mu$$

No renormalizable interactions $\Rightarrow$ high scale Λ suffices to decouple us from χ "dark sector"

$$\Lambda \sim m_{Link} \text{ or } m_{Z'} \gtrsim \text{TeV}$$

Organizing our thinking

Totally generic dark sectors can have only 4 marginal/relevant couplings consistent with SM symmetries!

	$\mathcal{O}^{SM}$
dim-2	$\|h\|^2$
dim-5/2	hL
dim-2	$F_Y^{\mu\nu}$
dim-3	$J^\mu_{B-L,\, e-\tau,\, etc.}$

Organizing our thinking

Totally generic dark sectors can have only 4 marginal/relevant couplings consistent with SM symmetries!

	$\mathcal{O}^{SM}$	$\mathcal{O}^{Dark}$		
dim-2	$\lvert h \rvert^2$	Φ	neutral scalar	Higgs portal
		$\lvert \phi \rvert^2$	charged scalar	Higgs portal
dim-5/2	hL	Ψ	neutral fermion	← ν portal
dim-2	$F_Y^{\mu\nu}$	$F'_{\mu\nu}$	U(1) gauge group	← Vector portal / Kinetic Mixing
dim-3	$J^{\mu}_{B-L,\, e-\tau,\, etc.}$	V_μ	gauging of SM global symmetry	

Organizing our thinking

Below weak scale:

	$\mathcal{O}^{SM}$	$\mathcal{O}^{Dark}$		
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		$\lvert \phi \rvert^2$	charged scalar	Higgs portal
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dim-2	$F_Y^{\mu\nu}$	$F'_{\mu\nu}$	$U(1)$ gauge group	← Vector portal / Kinetic Mixing
dim-3	$J^{\mu}_{B-L,\, e-\tau,\, etc.}$	V_μ	gauging of SM global symmetry	

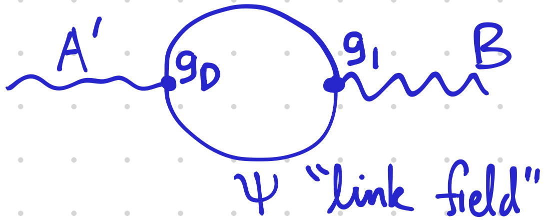
Organizing our thinking

Below weak scale:

	$\mathcal{O}^{SM}$	$\mathcal{O}^{Dark}$		
dim-2	$\lvert h\rvert^2 \to v^2$	Φ	neutral scalar	tadpole
		$\lvert\phi\rvert^2$	charged scalar	mass term
dim-5/2	$hL \to v\,\nu_L$	Ψ	neutral fermion	mass mixing
dim-2	$F_Y^{\mu\nu} \to F_{EM}^{\mu\nu}$	$F'_{\mu\nu}$	U(1) gauge group	kinetic mixing
dim-3	$J^\mu_{B-L,\, e-\tau,\, etc.}$	V_μ	gauging of SM global symmetry	

How Big is Kinetic Mixing? [Holdom '86]

- Could be $\mathcal{O}(1)$ param. @ cutoff scale $\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$
- If absent, can be generated by heavy-particle loops:

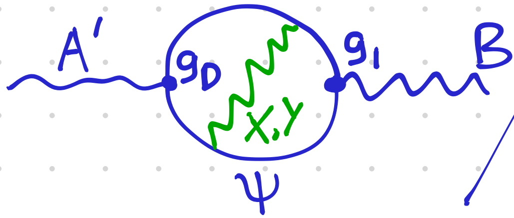


$\rightarrow \epsilon_Y \sim \frac{g_1 g_D}{16\pi^2} \log(M_\Psi/\Lambda)$

$\sim 10^{-3} \times \mathcal{O}(1-10)$

- In unbroken GUT, must vanish!
  $F^a_{\mu\nu}$ not gauge-invariant!
  (Above: linear in hypercharge of $\Psi \Rightarrow$ GUT multiplet of Ψ's cancel out)

- GUT-breaking corrections $\sim \frac{g_1 g_D}{16\pi^2} \log(M_3/M_2) \sim 10^{-6} - 10^{-3}$



/ Similar range from $\frac{1}{M_P} \mathrm{Tr}[F^a_{\mu\nu} \Phi^a] F'^{\mu\nu}$

- Even smaller ϵ_Y if both U(1)'s unify or from non-perturbative effects.

Effects of Kinetic Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_Y^2 - \frac{1}{4}F'^2 + \frac{\epsilon_Y}{2} F_Y^{\mu\nu} F'_{\mu\nu} - g_1 B_\mu J_Y - g_D A'_\mu J_D^\mu$$

$F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$ (dark gauge group)

$F^Y_{\mu\nu} = \partial_{[\mu} B_{\nu]}$ (hyper-charge)

Effects of Kinetic Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_Y^2 - \frac{1}{4}F'^2 + \frac{\epsilon_Y}{2}F_Y^{\mu\nu}F'_{\mu\nu}$$
$$- g_1 B_\mu J_Y - g_D A'_\mu J_D^\mu$$

$$\left[\begin{array}{l} F'_{\mu\nu} = \partial_{[\mu}A'_{\nu]} \quad \text{(dark gauge group)} \\ F^Y_{\mu\nu} = \partial_{[\mu}B_{\nu]} \quad \text{(hyper-charge)} \end{array}\right.$$

Can rewrite action in terms of fields $\begin{pmatrix}\hat{A}' \\ \hat{B}\end{pmatrix} = M\begin{pmatrix}A' \\ B\end{pmatrix}$

Effects of Kinetic Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_Y^2 - \frac{1}{4}F'^2 + \frac{\epsilon_Y}{2}F_Y^{\mu\nu}F'_{\mu\nu} + m_{A'}^2 A'^2$$

$$- g_1 B_\mu J_Y - g_D A'_\mu J_D^\mu$$

Must avoid field re-defs that induce **mass mixing**

To diagonalize kin. + mass terms, take $\hat{B}^\mu = B^\mu - \epsilon_Y A'^\mu$

Effects of Kinetic Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_Y^2 - \frac{1}{4}F'^2 + \frac{\epsilon_Y}{2}F_Y^{\mu\nu}F'_{\mu\nu} + m_{A'}^2 A'^2$$

$$-g_1 B_\mu J_Y - g_D A'_\mu J_D^\mu$$

Must avoid field re-defs that induce **mass mixing**

To diagonalize kin. + mass terms, take $\hat{B}^\mu = B^\mu - \epsilon_Y A'^\mu$, $\hat{A}' = A^\mu$

$$\mathcal{L} \supset -\frac{1}{4}\hat{F}_Y^2 - \frac{1}{4}F'^2 + m_{A'}^2 A'^2 - g_D A'_\mu J_D^\mu - g_1(\hat{B}_\mu - \epsilon_Y A'_\mu) J_Y$$

Redefine light field, its charged matter gets ϵ-millicharge under heavy field's gauge group.

Exercise: convince yourself that in $m_{A'} \to 0$ limit, redefining A' instead of B would give the same results for matter-matter interactions

Effects of Kinetic Mixing

After EWSB:

$$\mathcal{L} \supset \mathcal{L}_{kin} + m_{A'}^2 A'^2 + m_Z^2 Z^2 + \epsilon_Y \left(F_{EM}^{\mu\nu} \cos\theta_W + Z^{\mu\nu} \sin\theta_W \right) F'_{\mu\nu}$$

$+ \text{currents}$

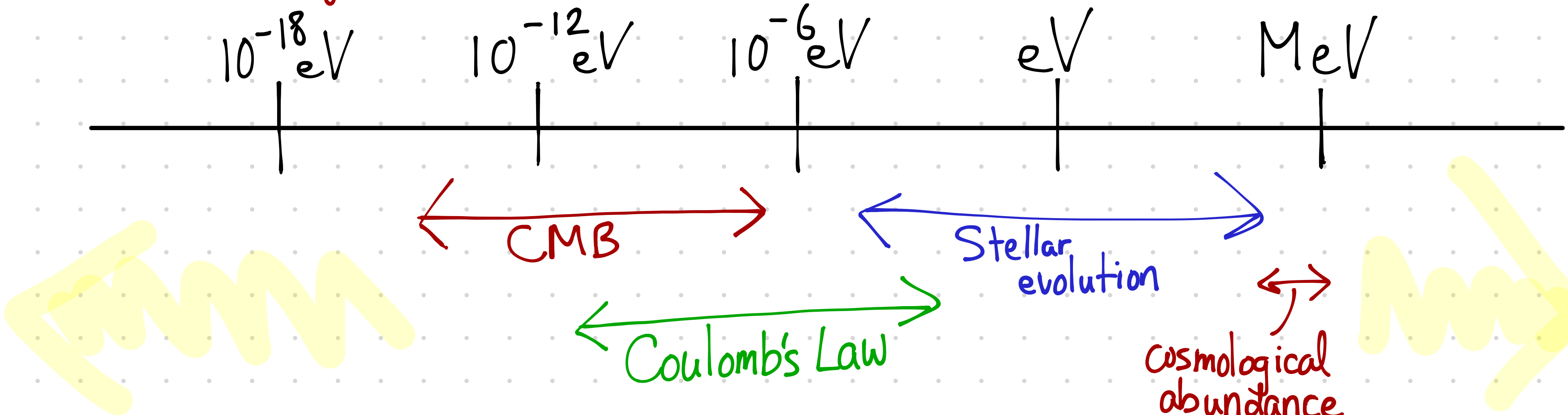
Redefine light field, its charged matter gets ϵ-millicharge under heavy field's gauge group.

$\Rightarrow$ EM charges acquire $\epsilon \equiv \epsilon_Y \cos\theta_W$-suppressed A'-coupling
Dark charges acquire $\epsilon_Y \sin\theta_W$-suppressed Z-coupling

Notation aside: $A' \simeq U \simeq A_D \simeq V$, $\epsilon \simeq \chi \simeq \kappa$

(Where) are couplings in perturbative range allowed? $(\epsilon \sim 10^{-3} - 10^{-6})$

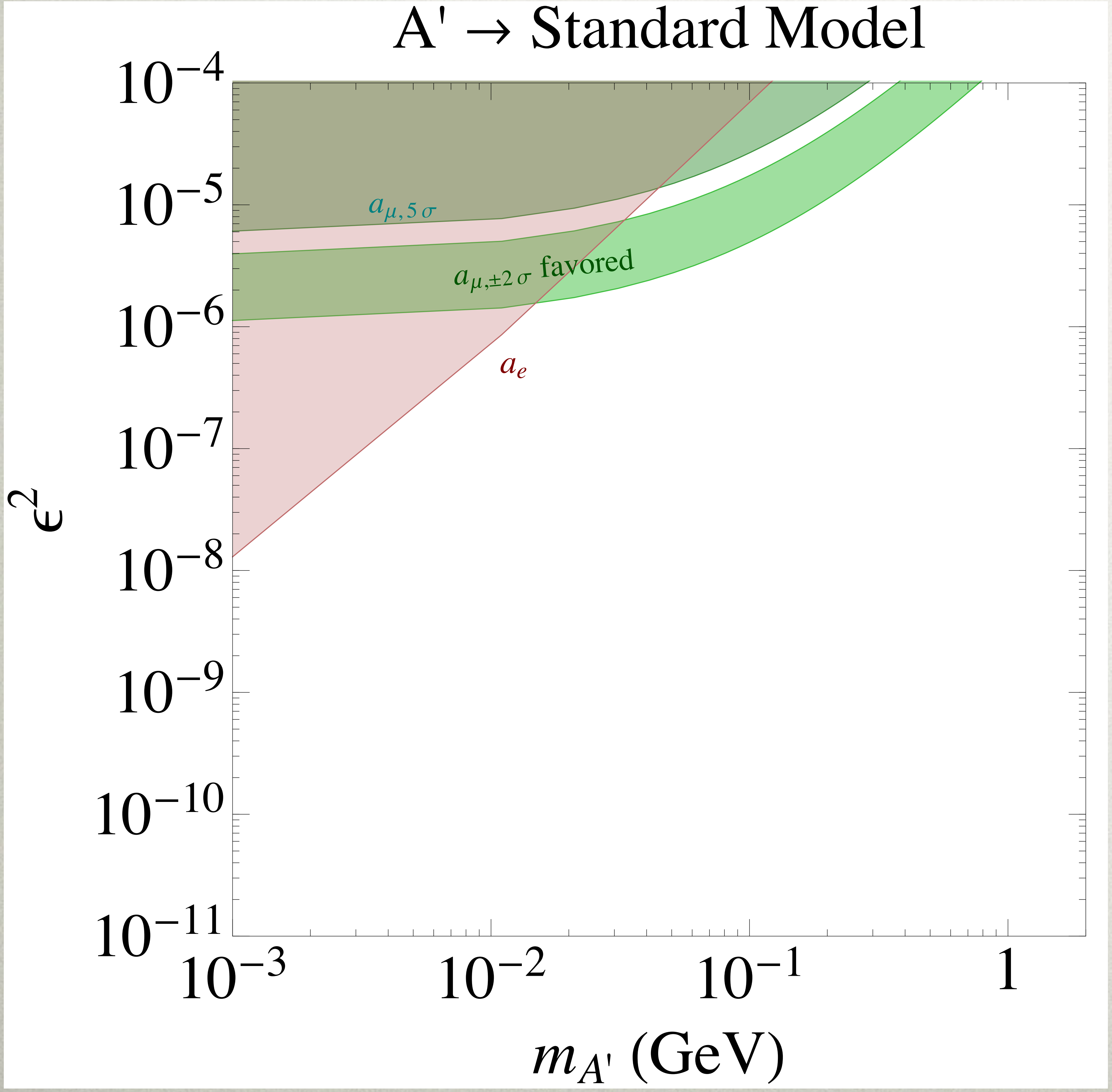
3 overwhelming constraints



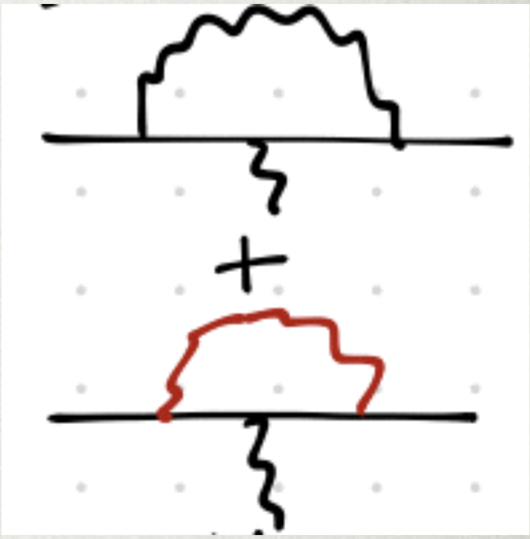
Opportunity zones: $m_{A'} > 2m_e$ or $\lesssim 10^{-14}$ eV (and lower couplings)

(is there theoretical motivation?)

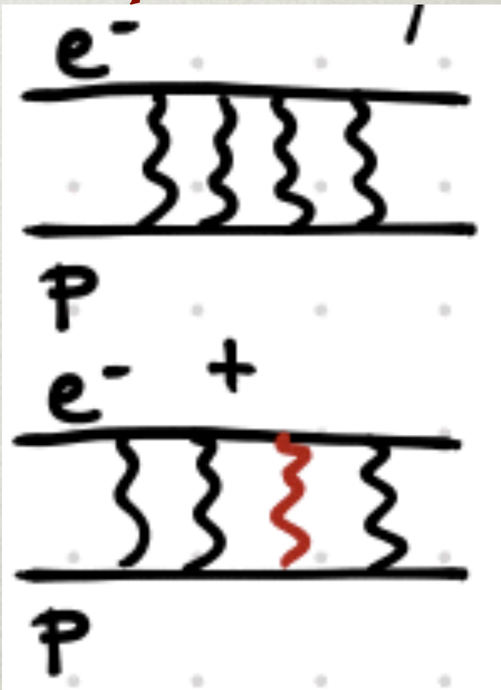
Decay-Independent Constraints



$q{\sim}m_\mu$ (m_e)



$q{\sim}\alpha m_e$



Motivation for MeV-to-GeV A′

"$m_{A'}$ related to M_Z, but parametrically smaller"

e.g. less contact w/ ~~SUSY~~ than SM

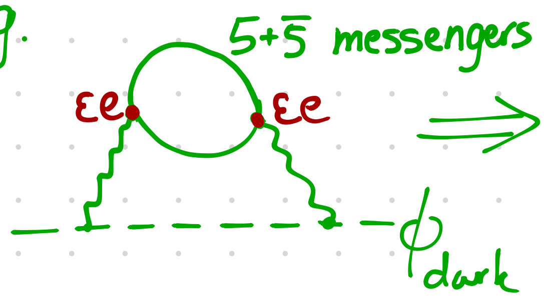
1) SUSY + $\epsilon F F' \Rightarrow \epsilon D D'$ [Cheung et al 0902.3246]
Dienes, Kolda, March-Russell '96

$D \rightarrow |h_u|^2 - |h_d|^2$, $D' \rightarrow |\phi_u|^2 - |\phi_d|^2$

EWSB drives dark Higgs mechanism $\longrightarrow m_{A'} \sim \sqrt{\varepsilon}\, m_W \sim 100$ MeV–1 GeV
for $\varepsilon \sim 10^{-3} - 10^{-6}$

2) ~~SUSY~~ masses for dark Higgses

e.g.



$\Longrightarrow m_{A'}^2 \sim m_\phi^2 \sim \varepsilon^2 M_{\not{SUSY}}^2$

$m_{A'} \sim (10^{-6} - 10^{-3}) \times (1 - 100\ \text{TeV})$
$\sim$ MeV to 10s of GeV

We've narrowed our focus

to marginal "portal" operators

↳ potentially important even for high "link" scale

to kinetic mixing among all portals

↳ Important at energies $\ll M_W$

↳ Involves states similar to those in SM

↳ Generic mechanisms give $\varepsilon \propto$ (1 or 2 loop factors)

to MeV-to-GeV scale mediator

↳ Plausible origin from EWSB/SUSY & ε

↳ Allowed @ $\varepsilon \sim 10^{-6} - 10^{-3}$ motivated by perturbative mechanisms

↳ Experimentally accessible

↳ Interesting consequences for DM

Heading into the Dark Sector and Back

- A' production and decay in minimal dark sector

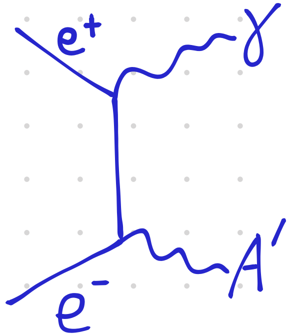
- Dark-Photon Searches

- New Forces & Dark Matter

Making Dark Photons

A'-coupling $\propto$ electric charge $\Rightarrow$ wherever there's a γ, there's an A'

e^+e^- $(q\bar{q})$

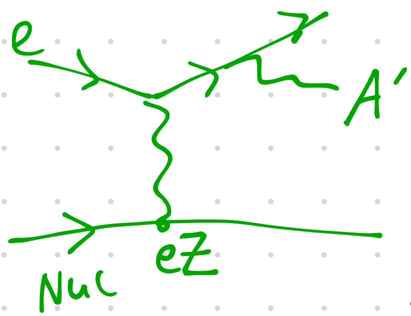


$\sigma \sim \frac{2\pi\alpha^2\varepsilon^2}{E_{cm}^2}\left(1-\frac{m_{A'}^2}{E_{cm}^2}\right)\times\log$ ← t-channel singularity

[Essig, Schuster, NT 0903.3941]

Note $1/E_{cm}^2 \Rightarrow fb^{-1}$ @ 1 GeV (KLOE) competes w/ ab^{-1} @ 10 GeV (B-factories) $\gg$ LEP

e^+e^- or eNuc



$\sigma \sim \frac{Z^2\alpha^3\varepsilon^2}{m_{A'}^2}\times\log_{t\text{-}chan}\times\log_x$

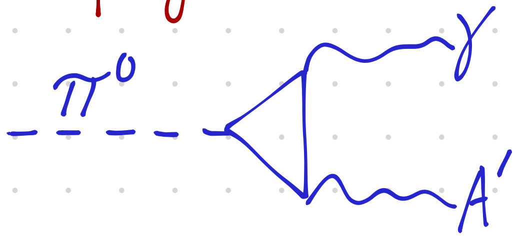
[Bjorken, Essig, Schuster, NT 0906.0580]

Fixed-target: $N_{A'} \approx N_e \times \varepsilon^2 \times \frac{m_e^2}{m_{A'}^2}$ one rad. length

for $m_{A'}^2 \lesssim E_{beam}/(\text{nuclear size})$

Making Dark Photons

A′-coupling ∝ electric charge ⇒ wherever there's a γ, there's an A′



$$\Gamma_{A'\gamma}/\Gamma_{\gamma\gamma} = 2\varepsilon^2 \times (1 - m_{A'}^2/m_\pi^2)$$

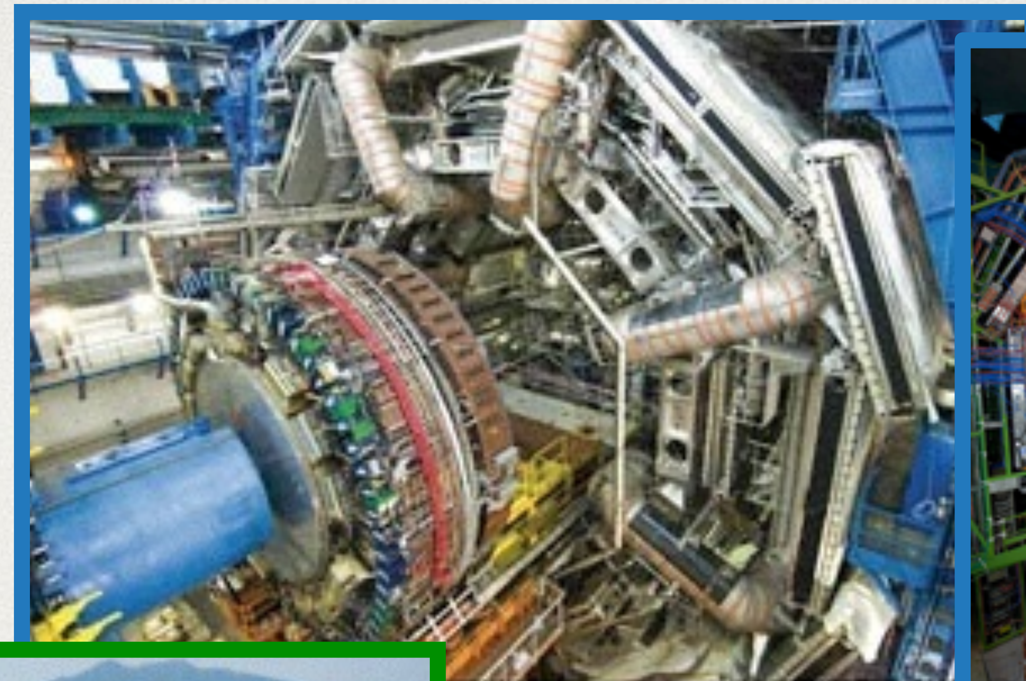
$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR$(X \to Y + \gamma)$	BR$(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8}[a]	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

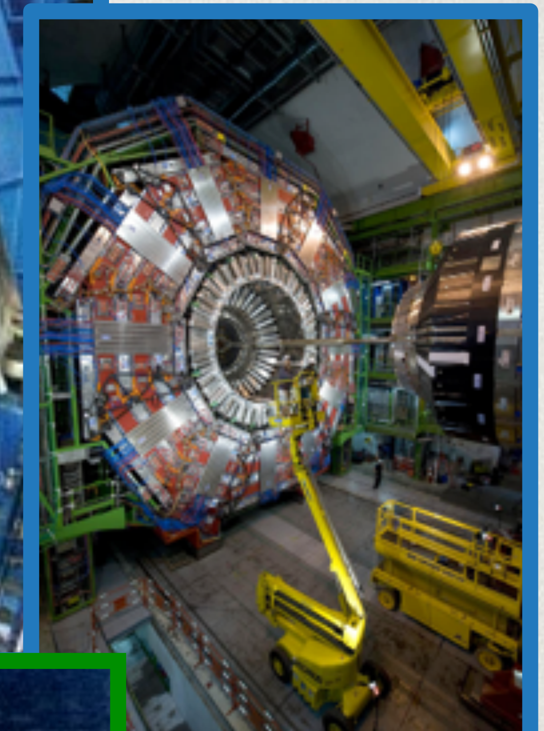
[a]Branching ratio BR$(K^+ \to \mu^+ \nu e^+ e^-)$ for $m_{e^+e^-} > 145$ MeV [39]

[Reece+Wang 0904.1743]

An Array of Opportunities for Discovery!

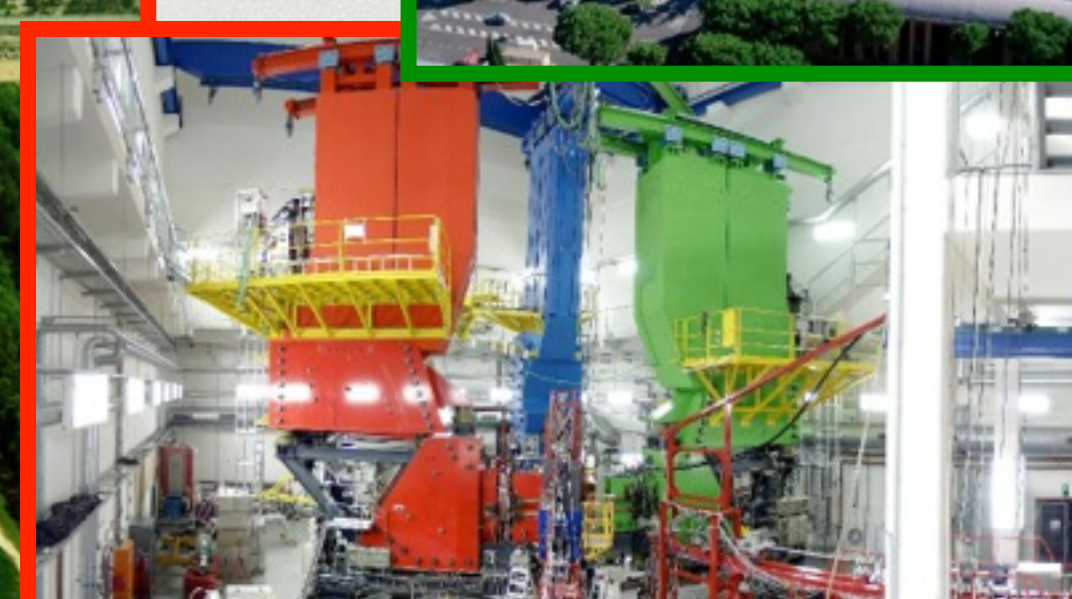
High-energy colliders





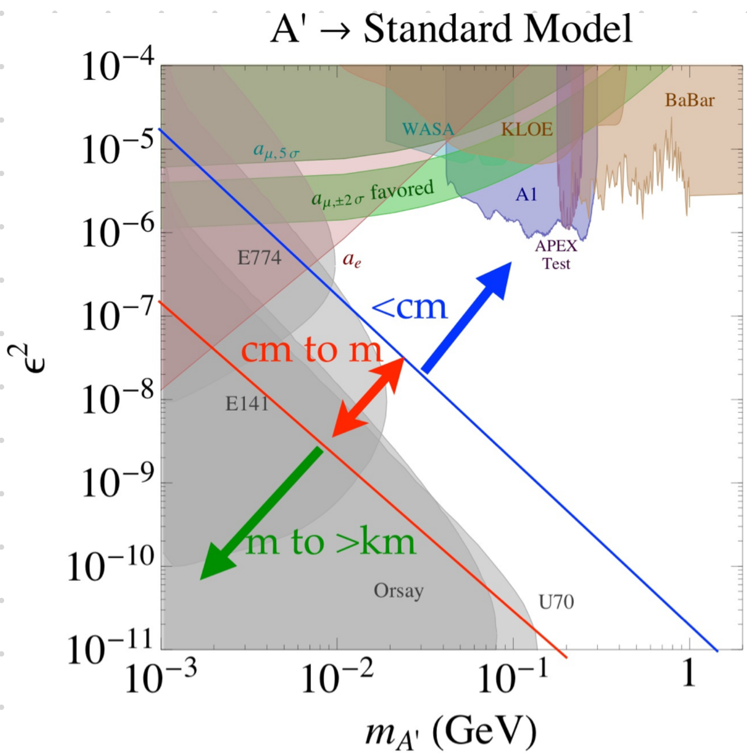
High *intensity* colliders

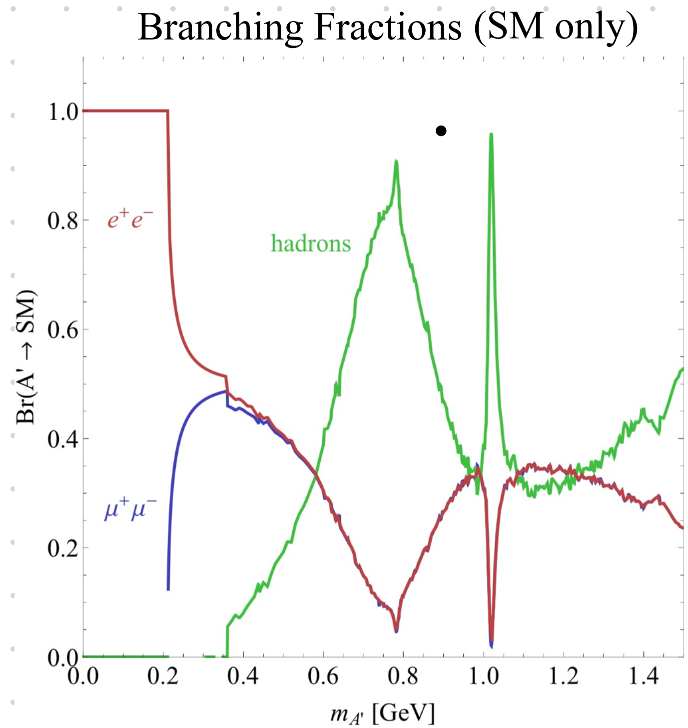
Fixed Target



Dark Photon Decays

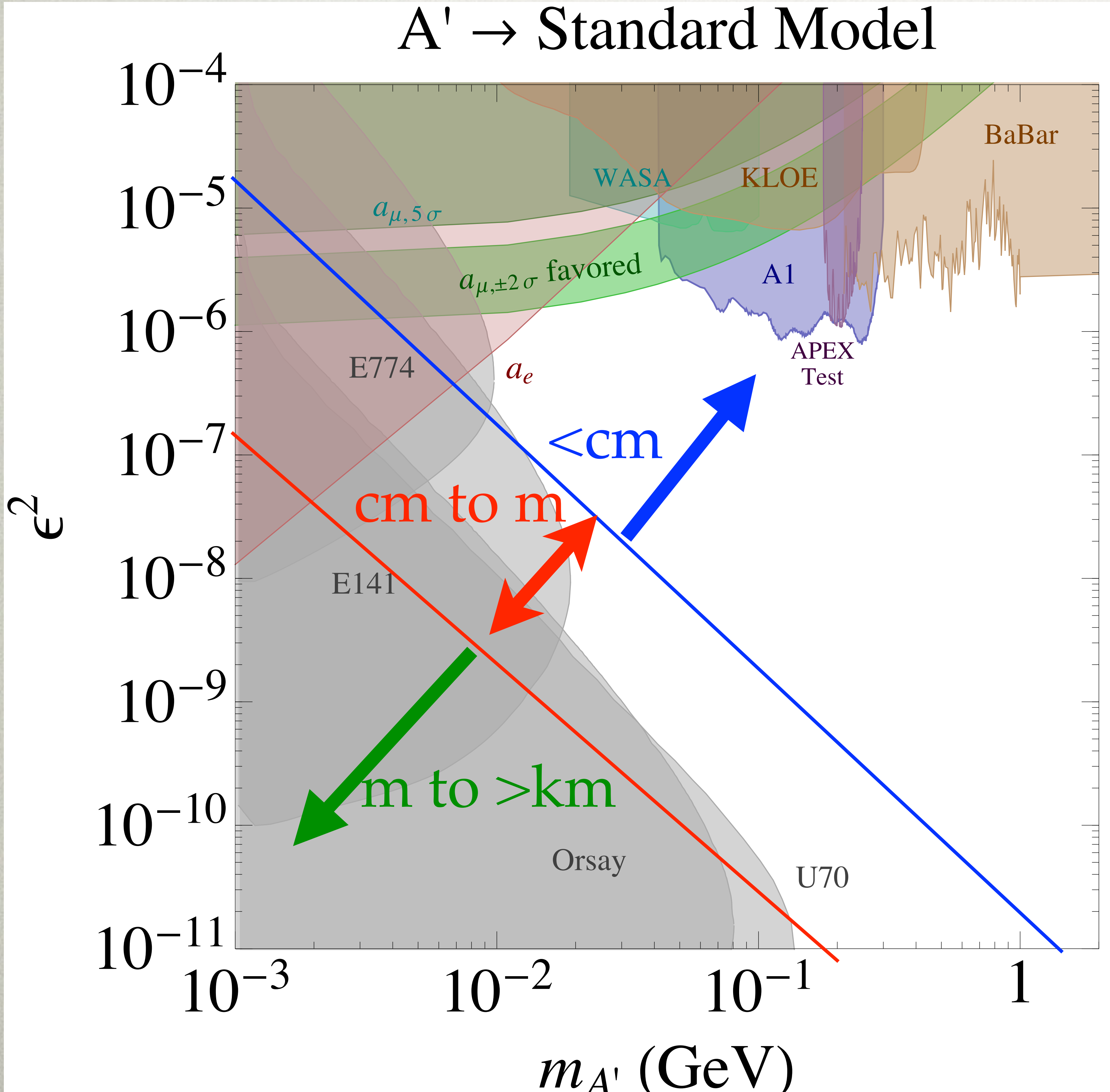
$\Gamma_{e^+e^-} = \frac{1}{3}\alpha\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_e^2}{m_{A'}^2}}$ $\qquad \Gamma_{\mu^+\mu^-}$ similar





Small width $\Gamma_{A'\to SM}$ $\Rightarrow$ <u>any</u> other decays with ε-indep width will dominate.

Status ~Today (published results)

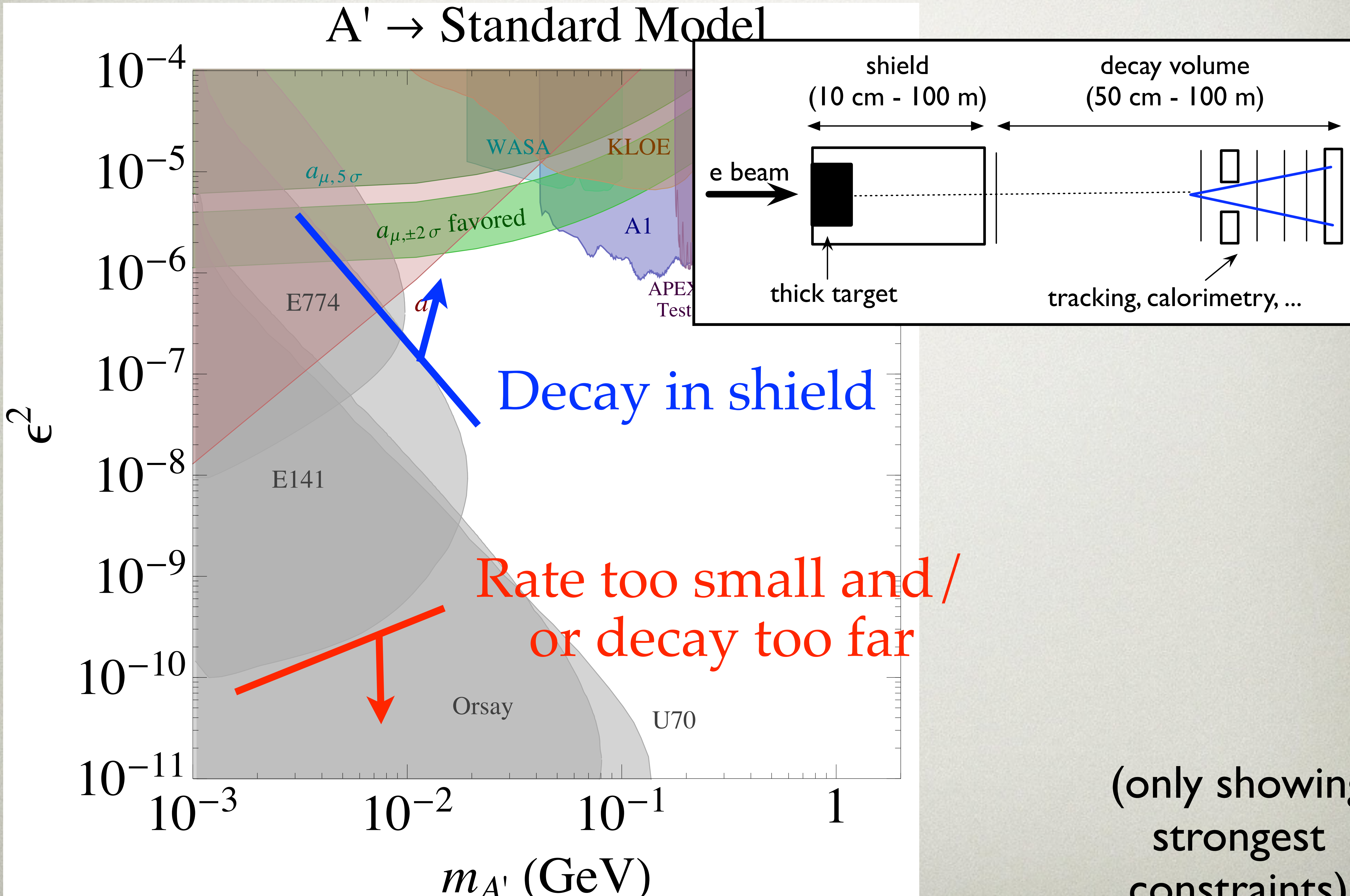


one-loop

two-loop (GUT)

(only showing strongest constraints)

Status ~Today (published results)

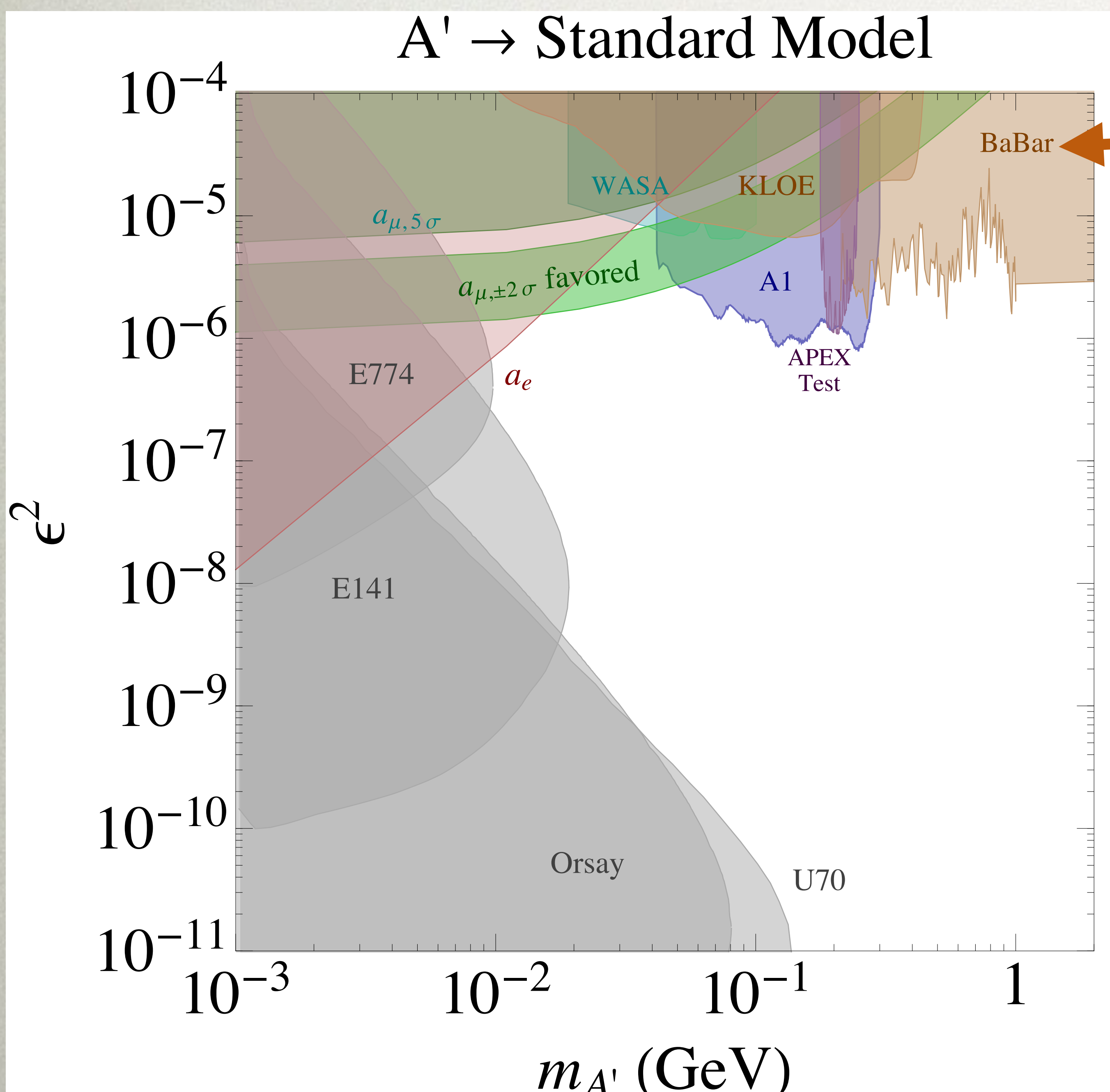


(only showing strongest constraints)

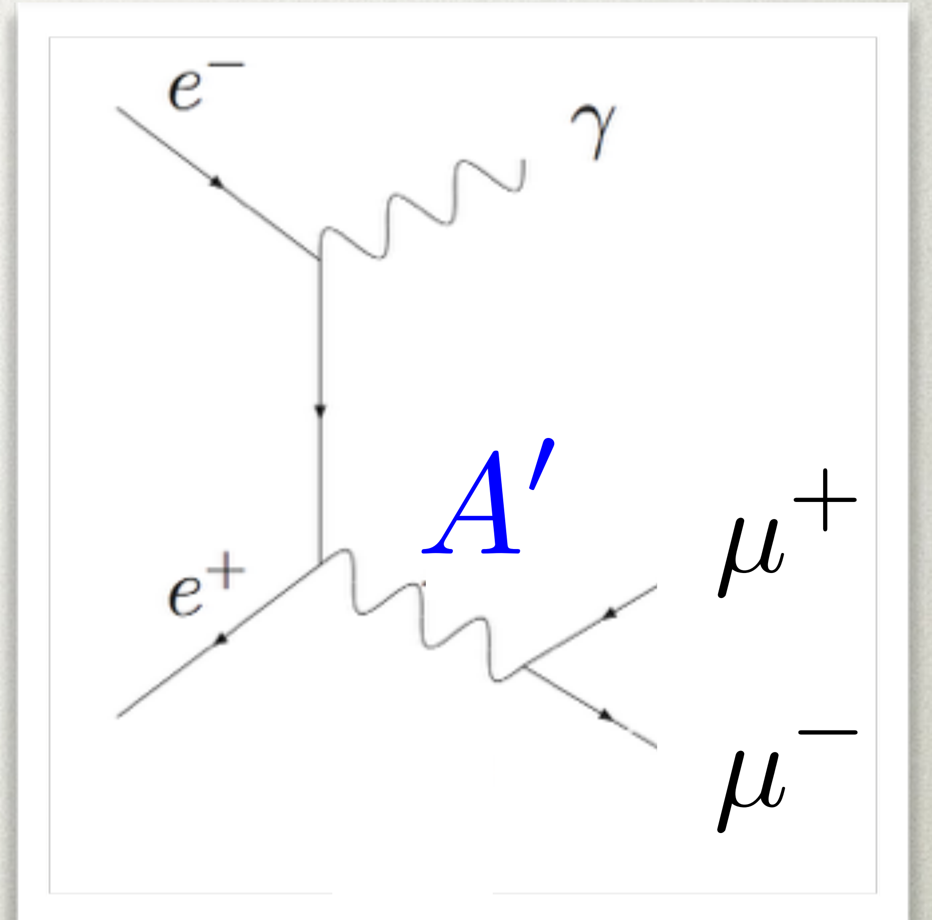
BaBar

2008

Re-interpretation by theorists of a BaBar analysis looking for pseudo-scalar decaying to $\mu^+\mu^-$

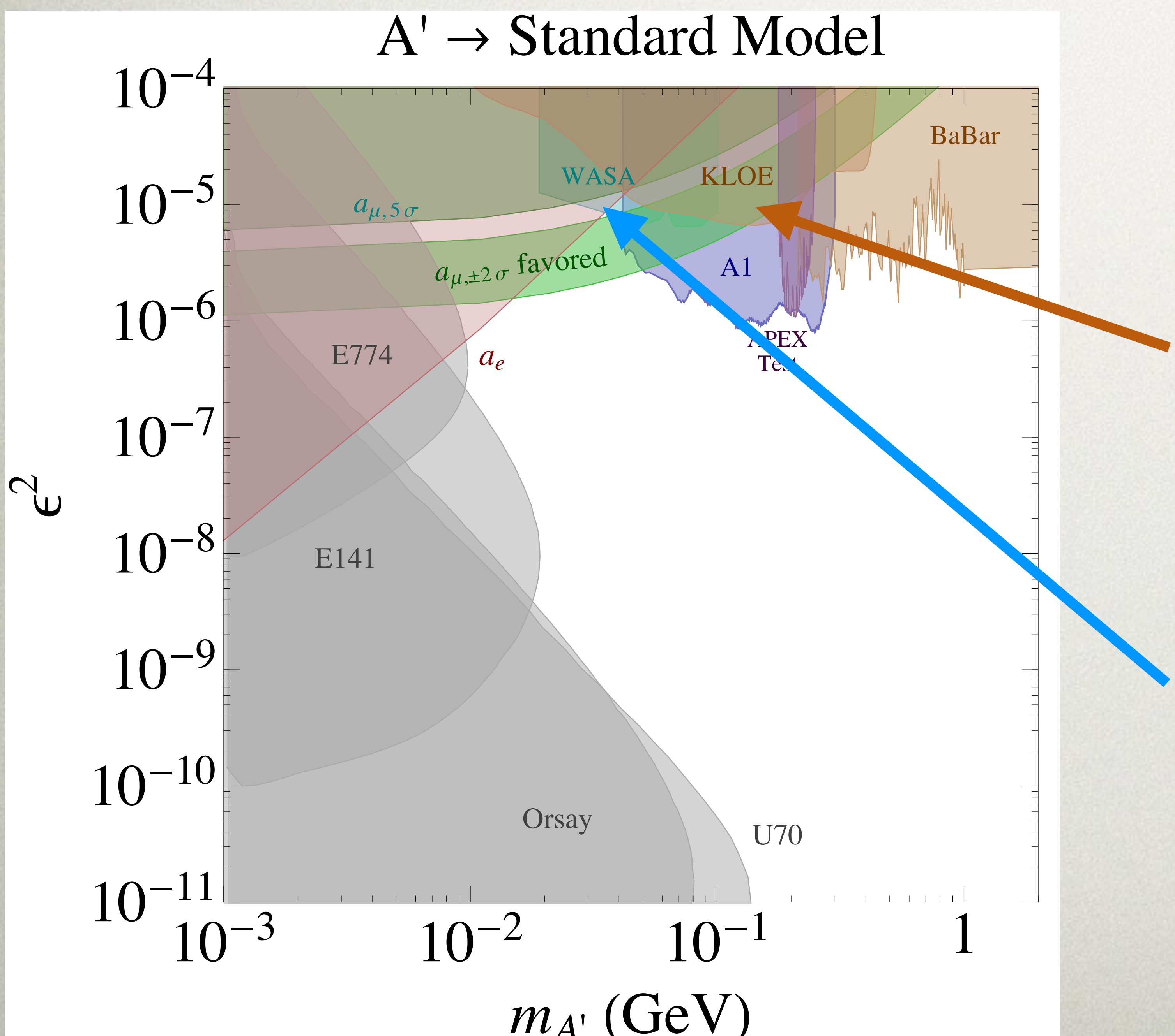


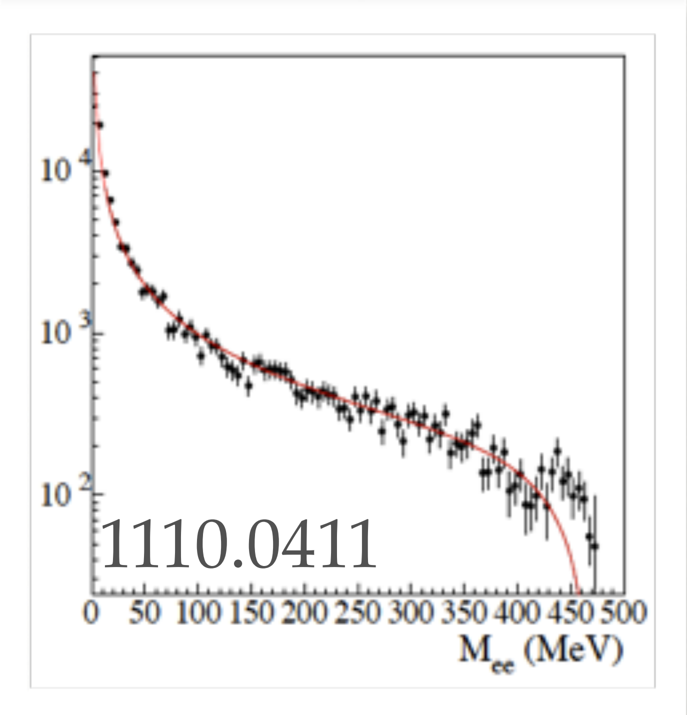
BaBar



KLOE & WASA@COSY 2011-13

Use rare meson decays





KLOE

$$\phi \to \eta A'$$
$$A' \to e^+ e^-$$

WASA

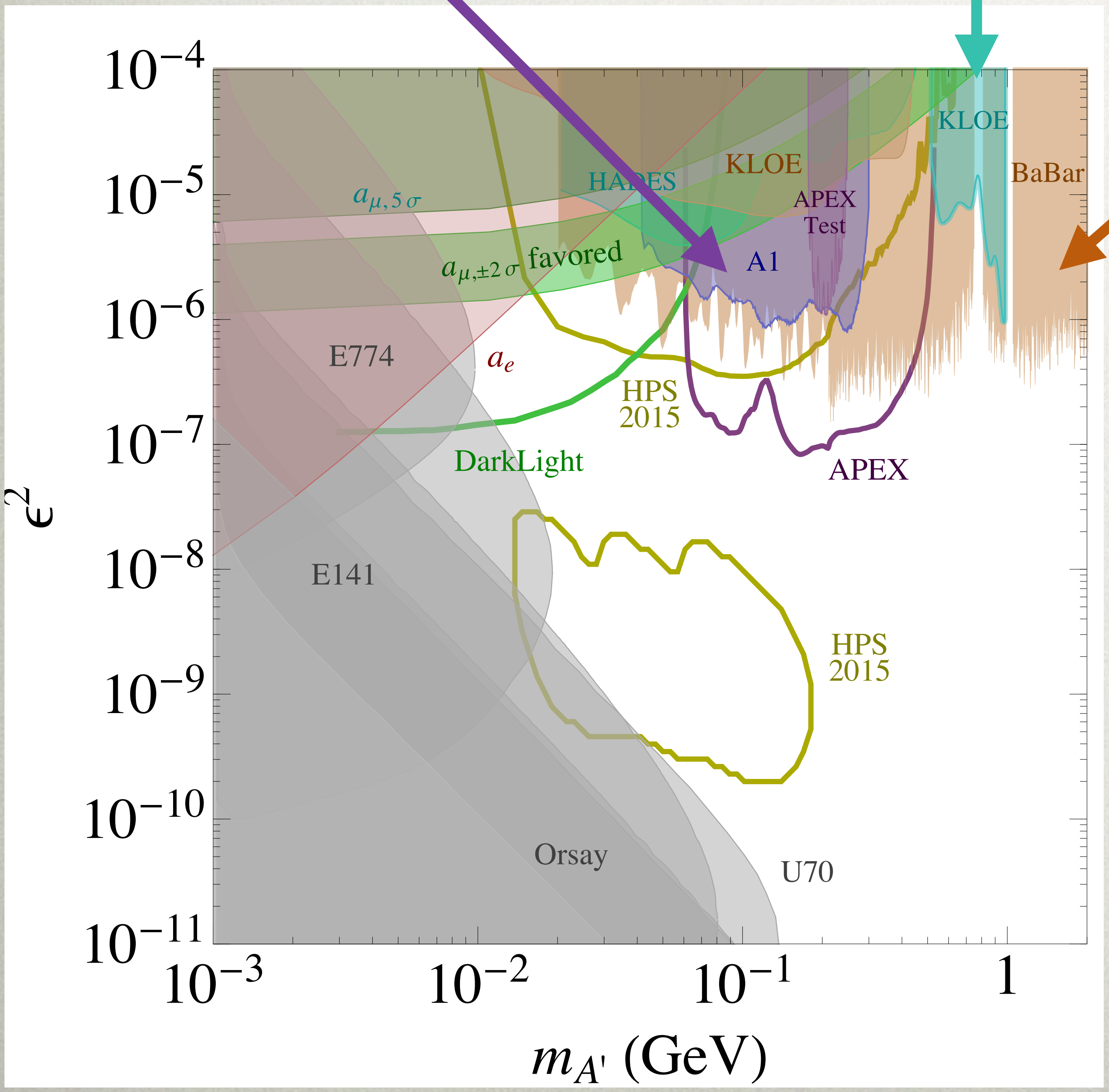
$$\pi^0 \to \gamma A'$$
$$A' \to e^+ e^-$$

MAMI KLOE BaBar 2014

fixed-target in Mainz
Many new data runs

A' ISR

New analysis in full dataset, using e^+e^- and $\mu^+\mu^-$ channels



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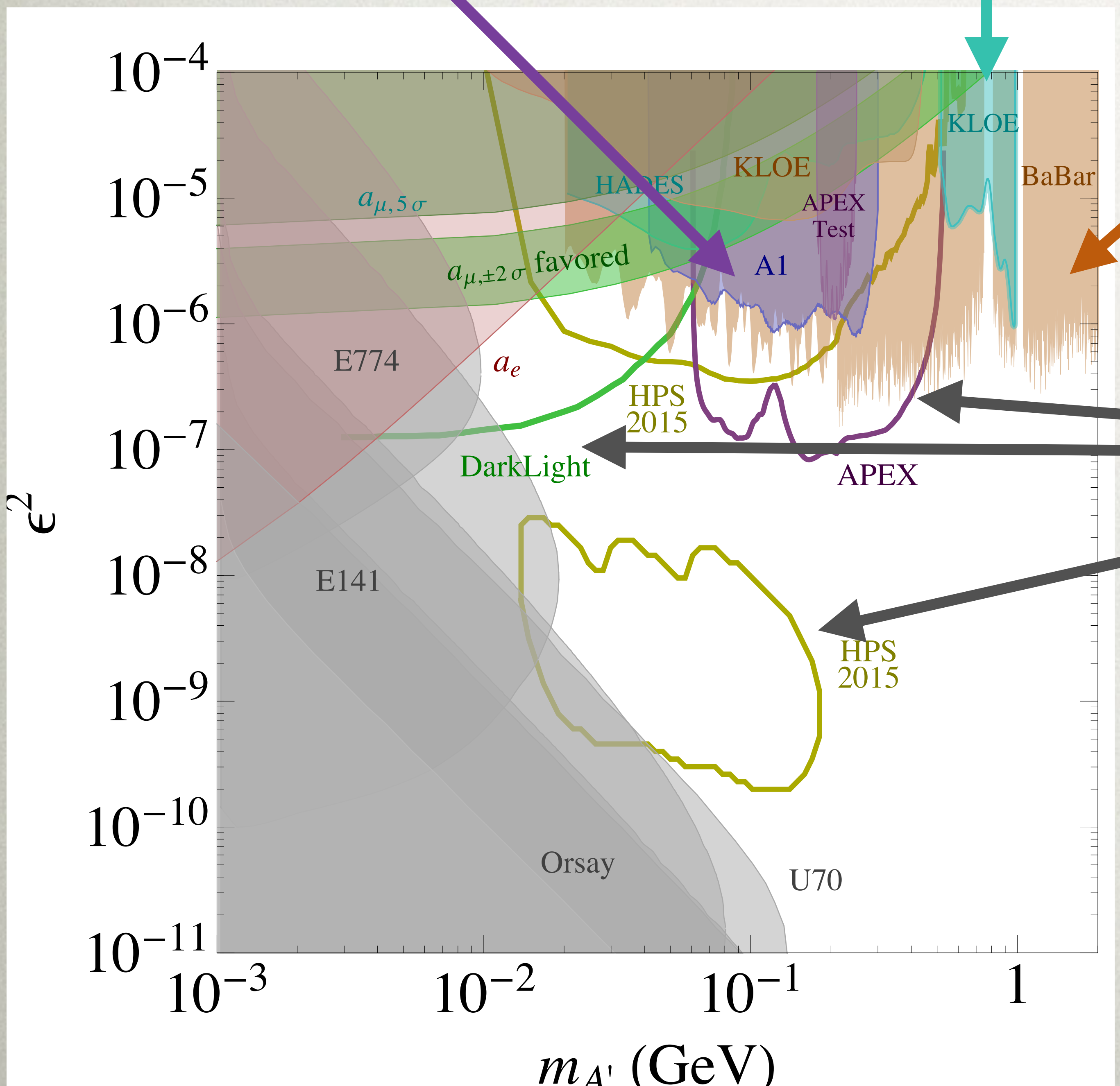
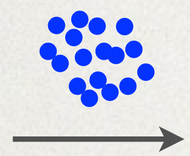
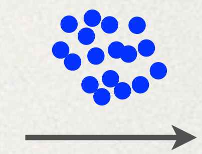


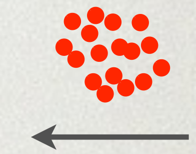
Fixed-target proposals for 2015-17

Fixed-Target Advantages

	Fixed-Target	e^+e^-
Luminosity	10^{11} e^- → ; $\sim 10^{23}$ atoms in target	10^{11} e^- → ; ← 10^{11} e^+
	N(hard scatter) ~ 0.01 – 1 *per electron*	N(hard scatter) ~ 1 *per crossing*
	O(few) ab^{-1} per day	O(few) ab^{-1} per decade

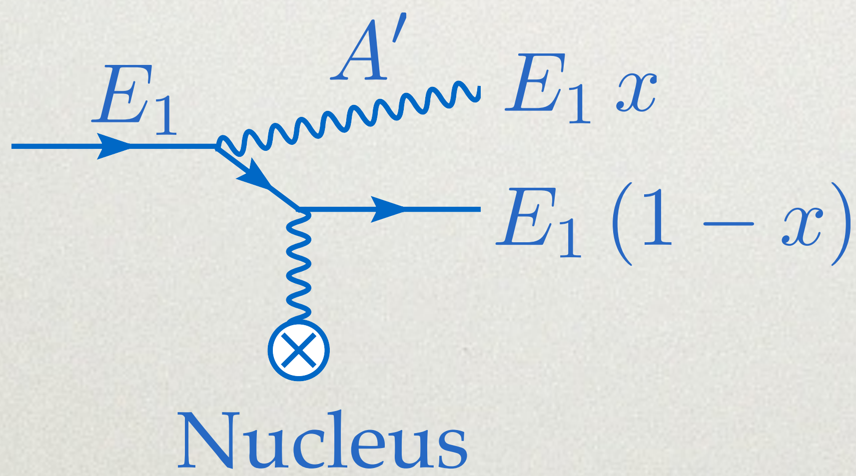




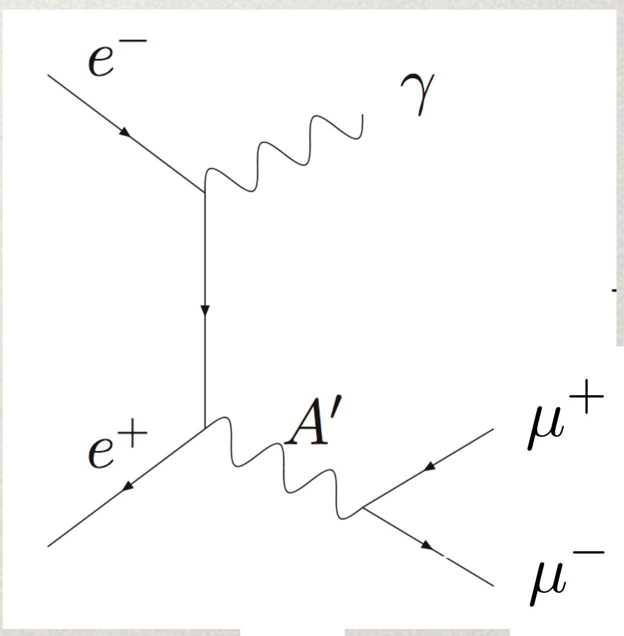


Cross-Section

- Scales as A′ mass, not beam energy
- Coherent scattering from nucleus



$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$



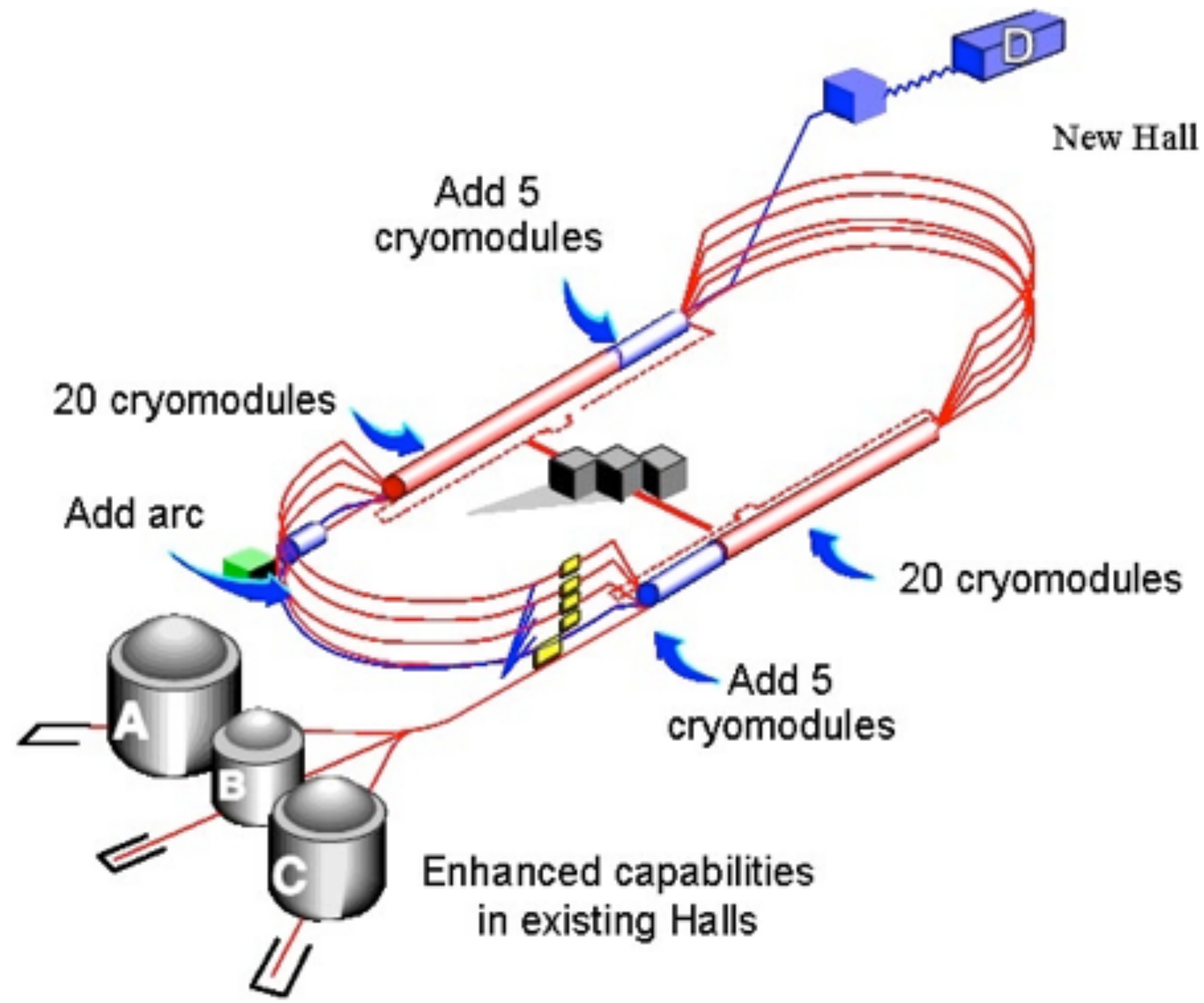
$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

Continuous Electron Beam Accelerator Facility

- Delivers beam up to 6 GeV to 3 experimental halls

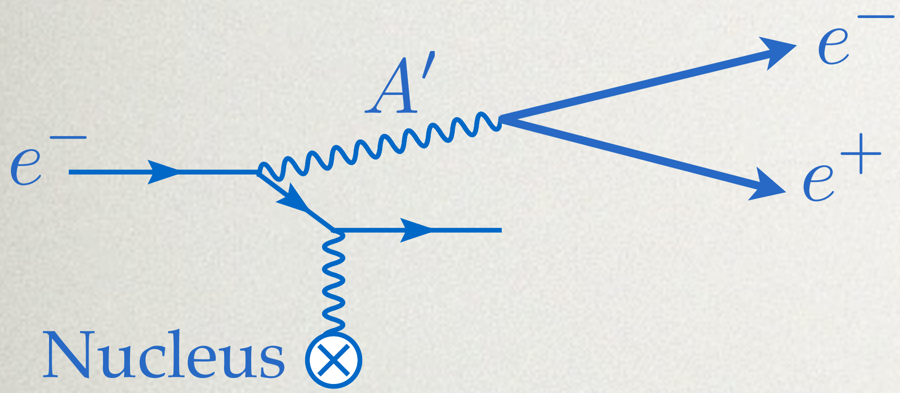
Halls A,C up to 100 μA
Hall B: 1 μA

- 1.5 GHz RF ⇒ each hall gets bunch every 2ns
- 12 GeV upgrade by 2014



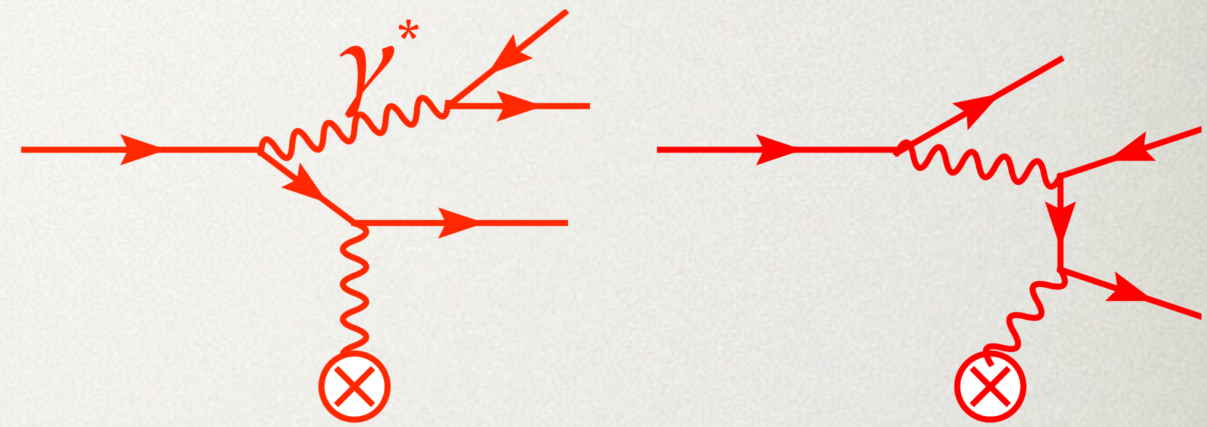
Where Do the Dark Photons Go?

A′ Production

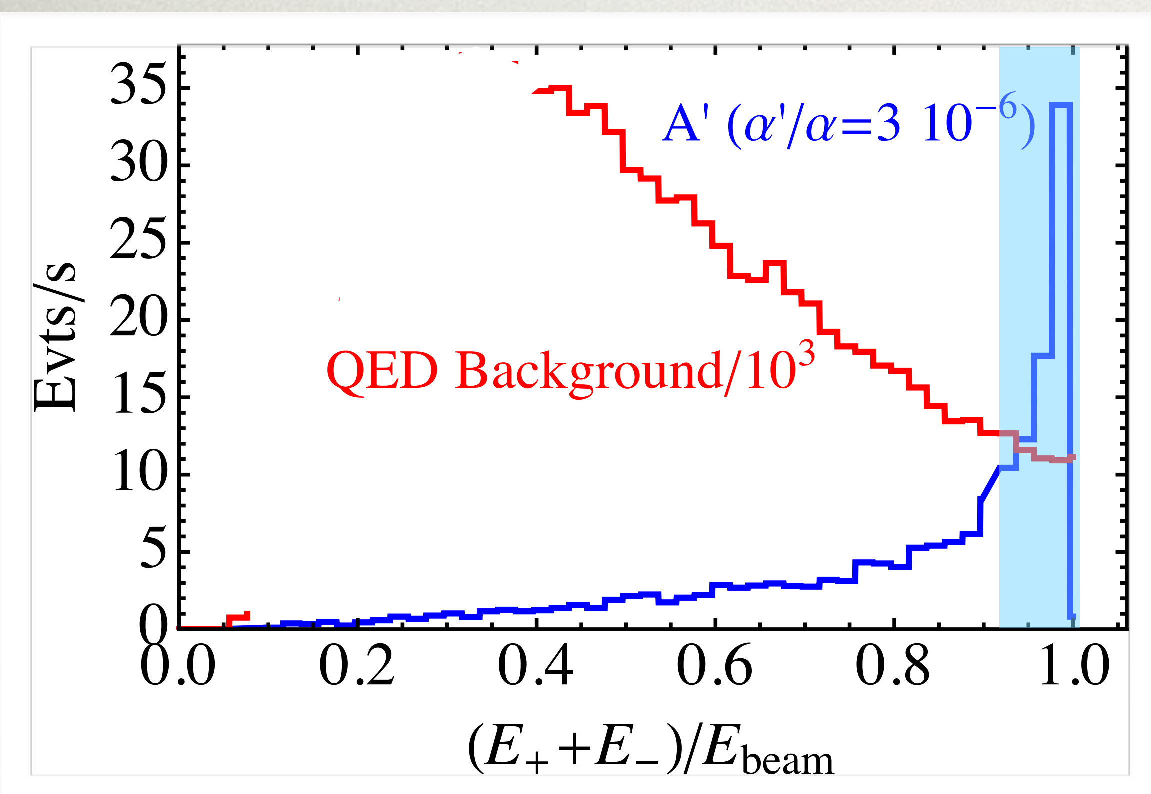


$$\sigma \sim \alpha'/m^2 = \varepsilon^2\alpha/m^2$$

QED Backgrounds



$$d\sigma \sim \alpha^2/m^3\, dm$$



(rates after loose angular cuts)

Match spectrometer acceptance to distinctive kinematics:

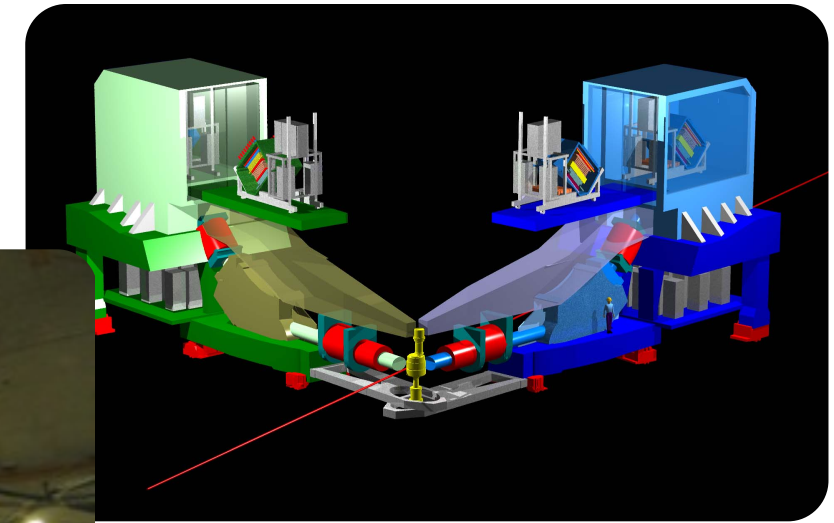
A′ carries (almost) full beam energy

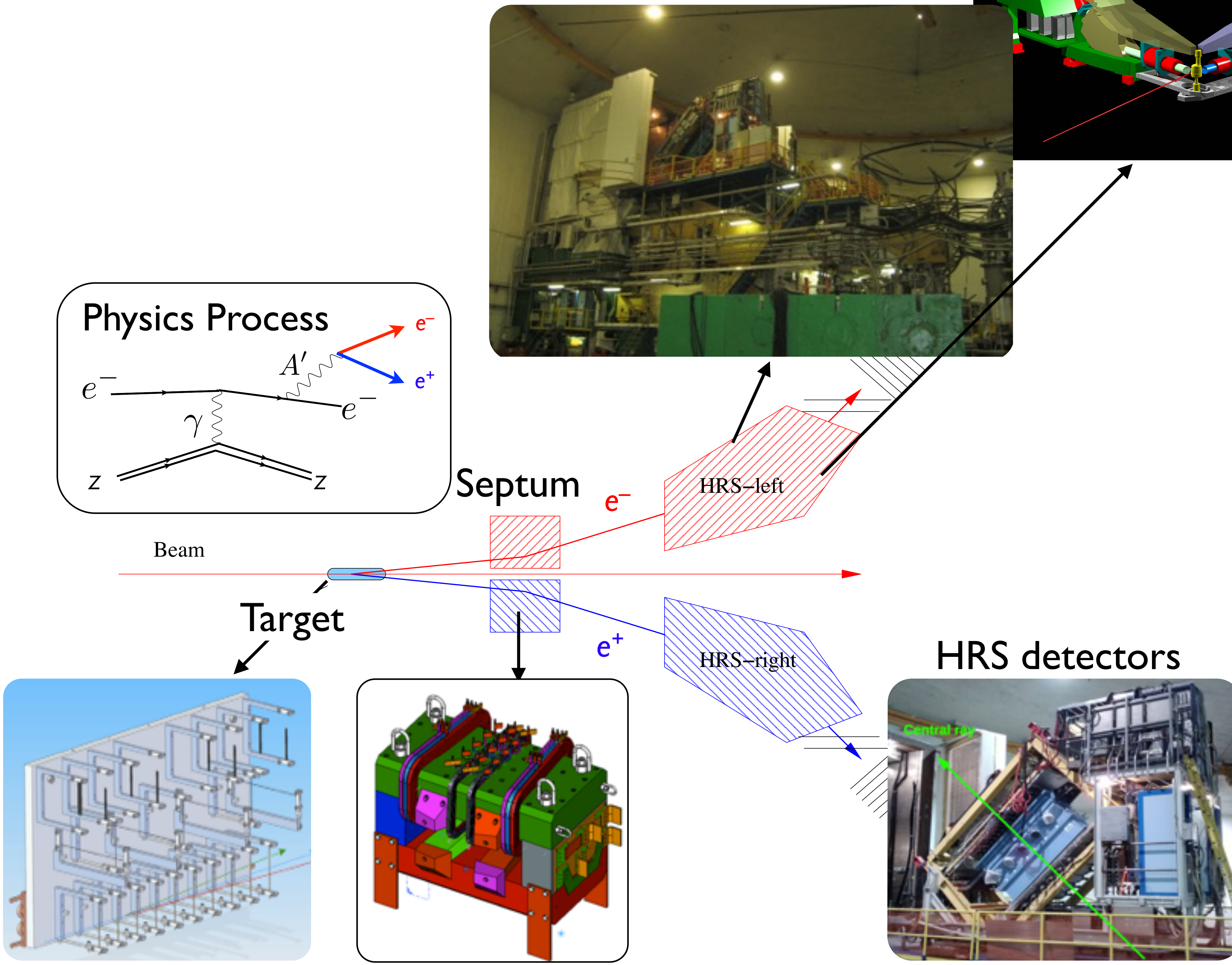
…and at very forward angle

Many large backgrounds are removed by this kinematic selection

(QED still >>> A′ production)

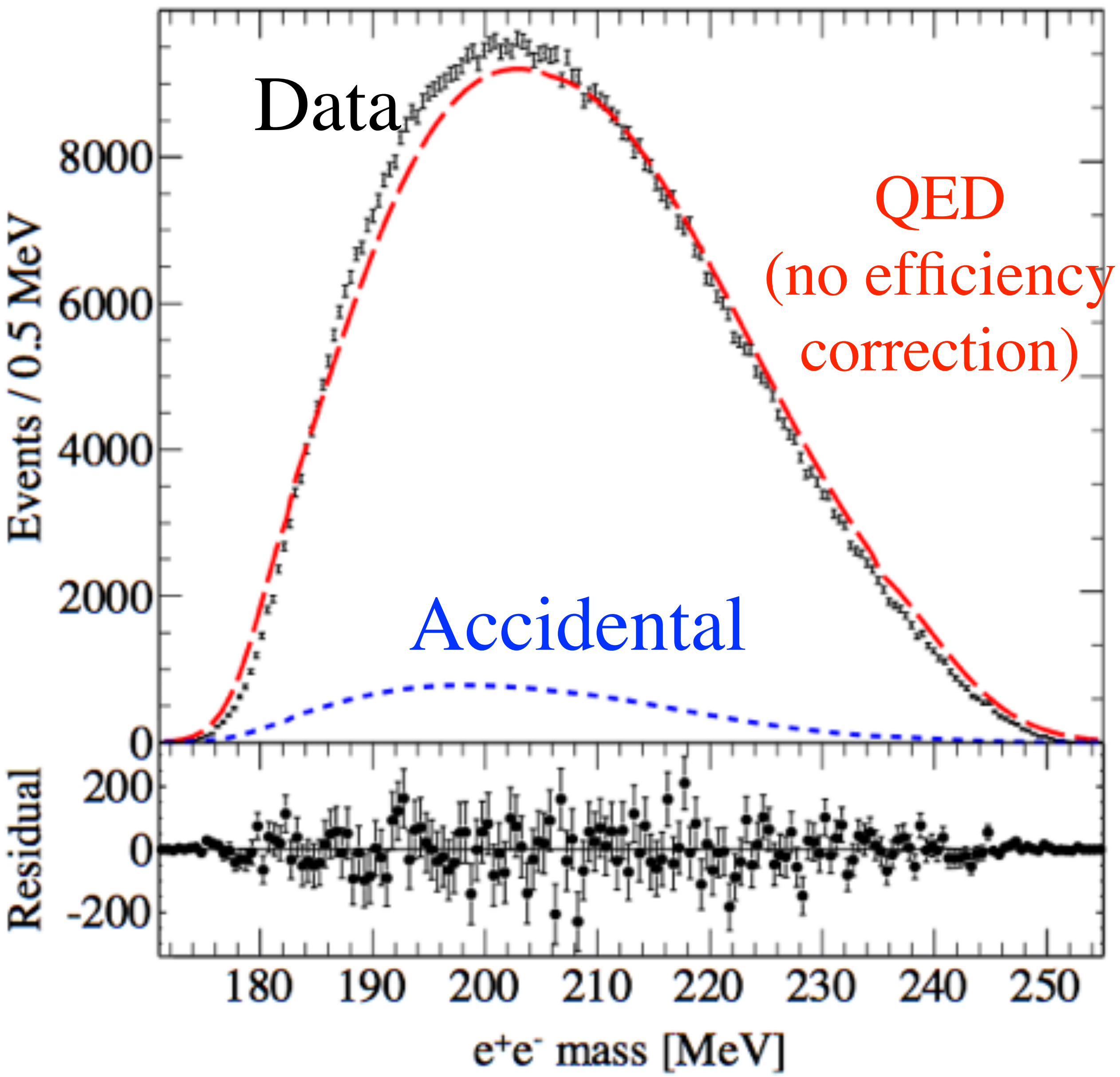
APEX

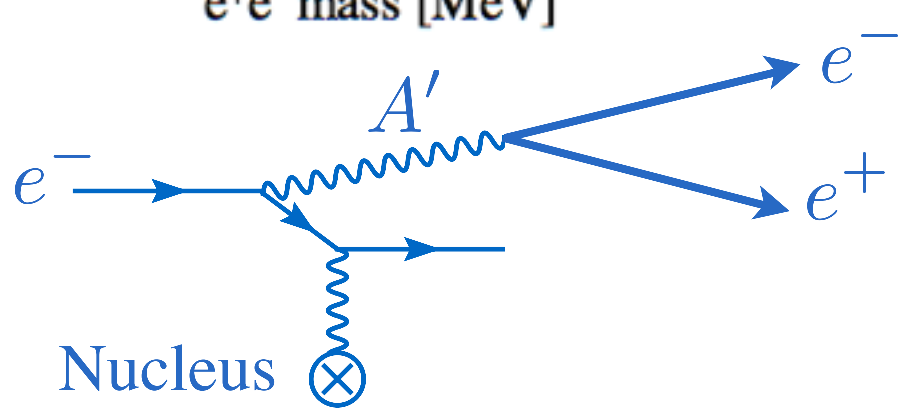


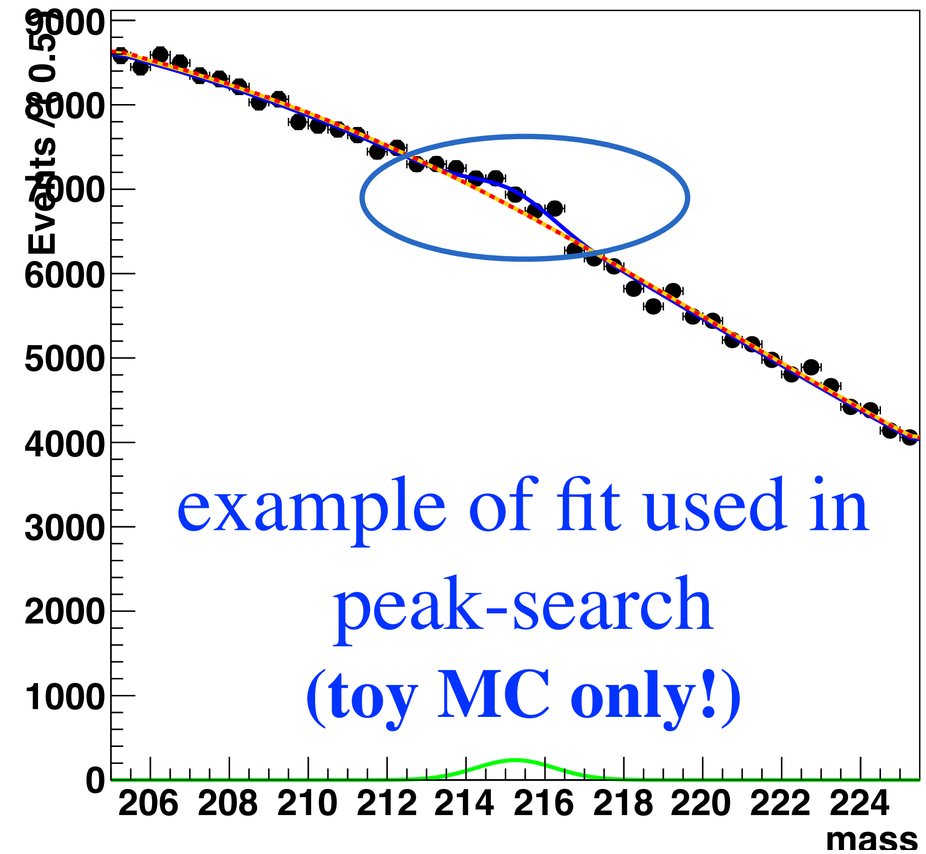


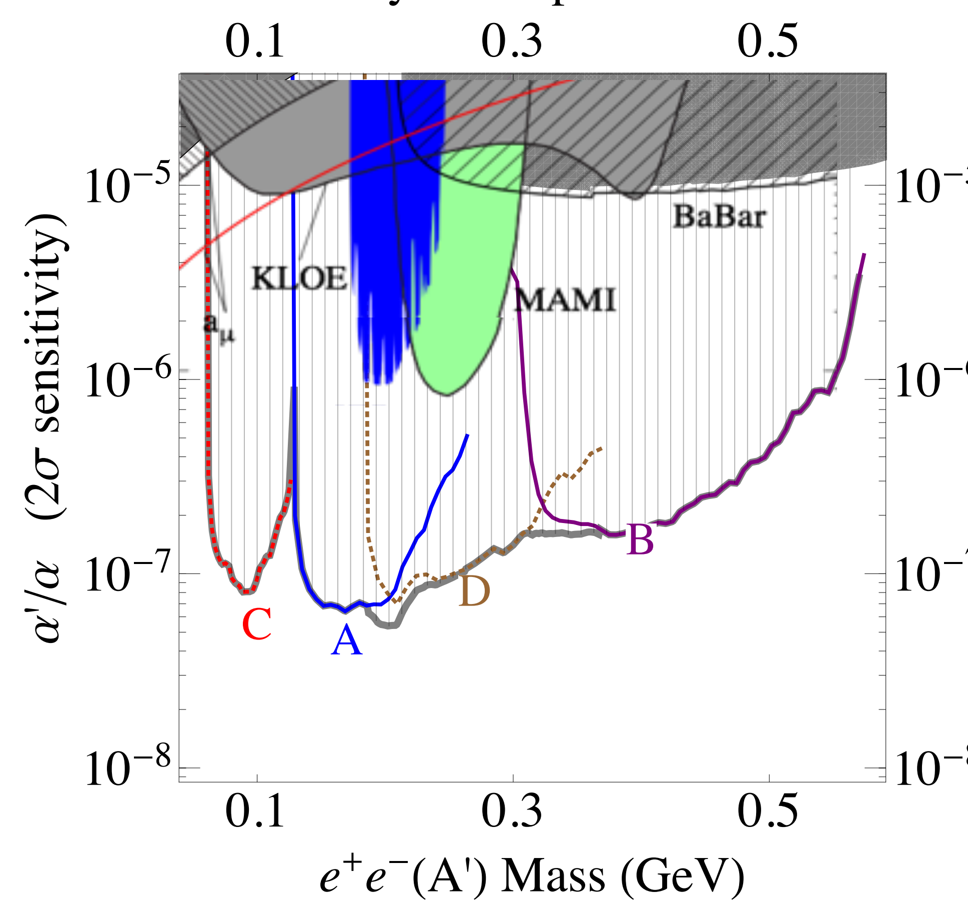
Physics Process
e^-
A'
γ
e^-
e^+
Z
Z
Septum
Beam
Target
e^-
e^+
HRS−left
HRS−right
HRS detectors
Central ray

Test-Run Science Data and Resonance Search





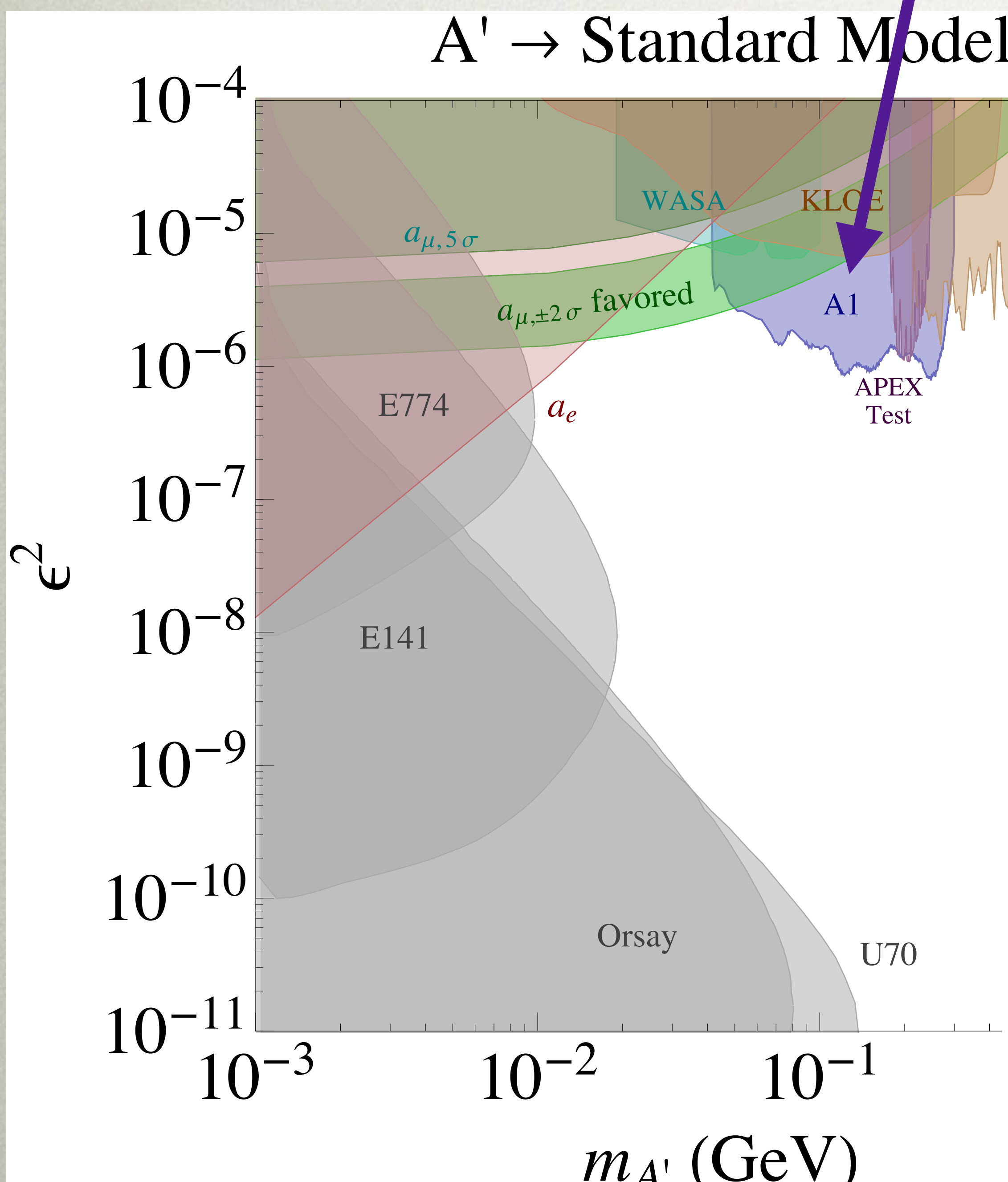


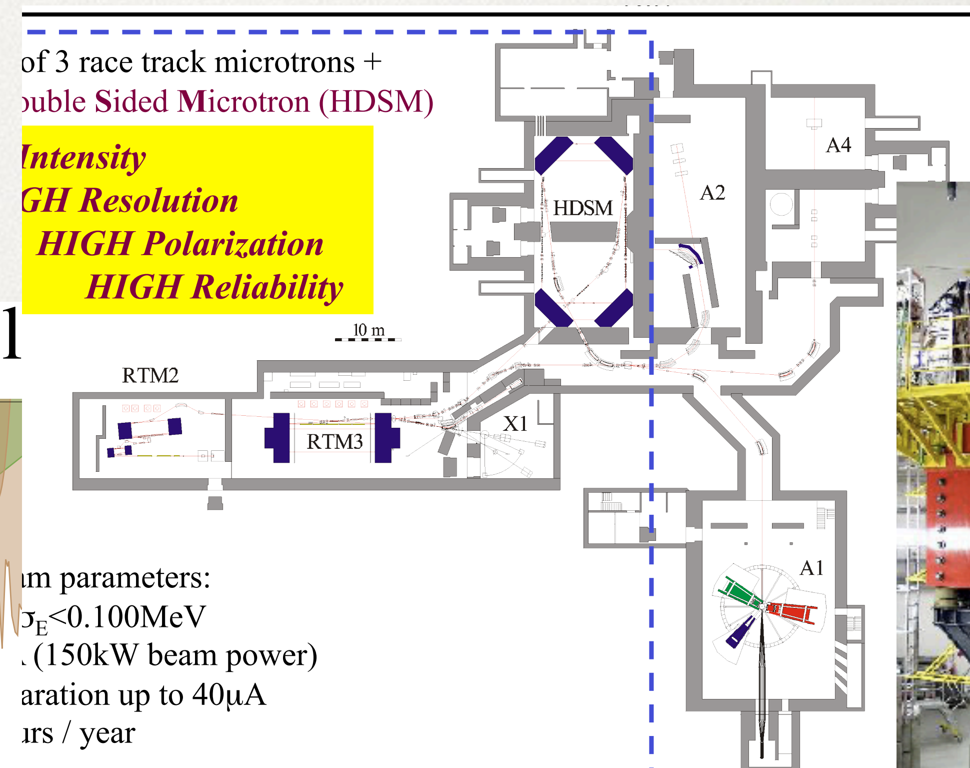


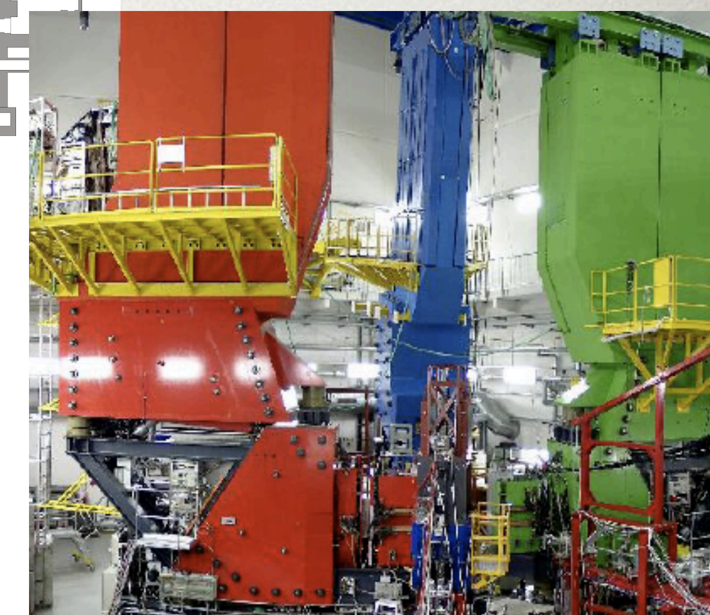
APEX PRL 107 191804, arxiv:1108.2750

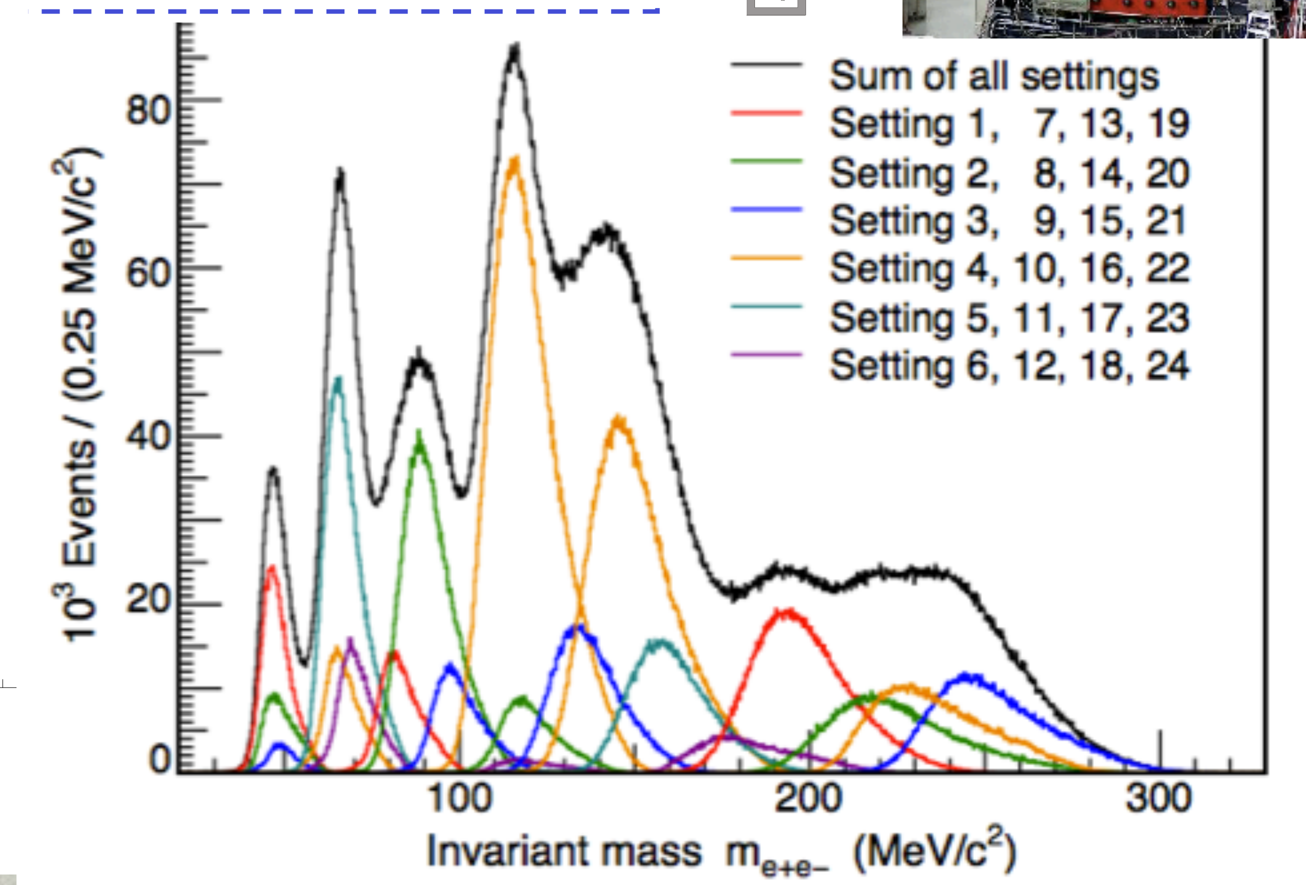
MAMI A1 Full Run

April 2014
arXiv:1404.5502

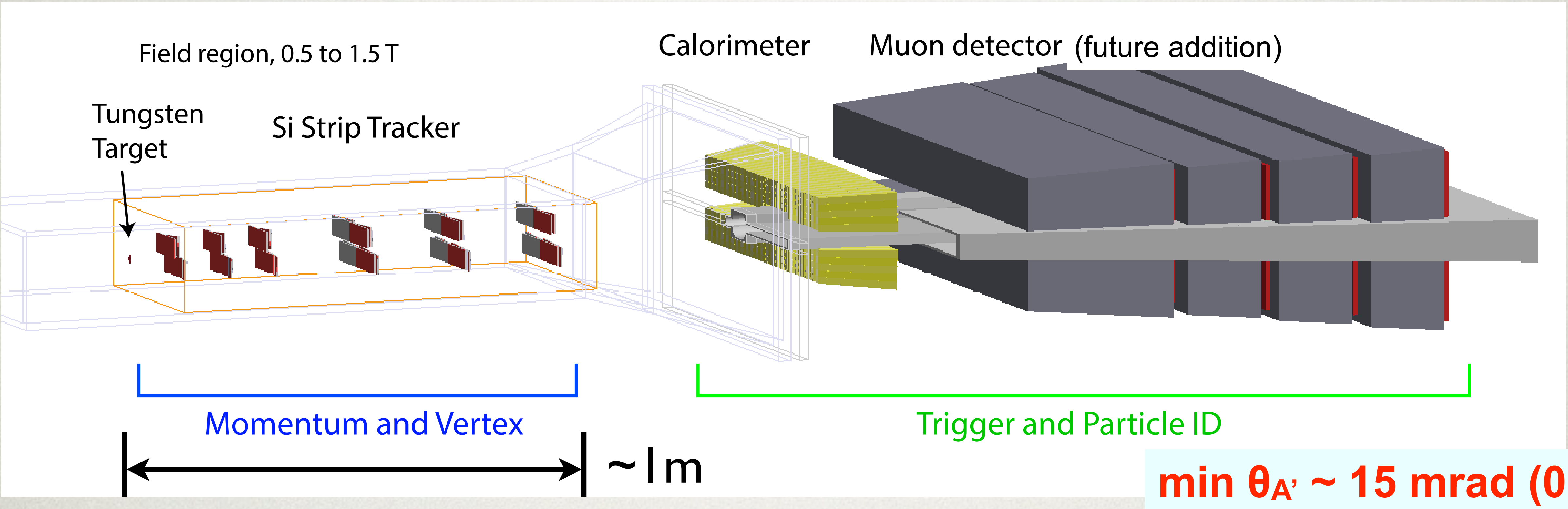






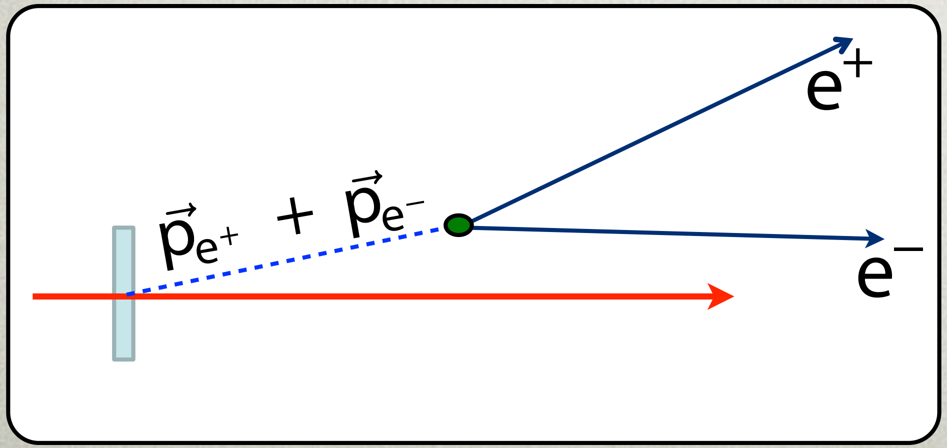


HPS: Resonance + Vertex Searches

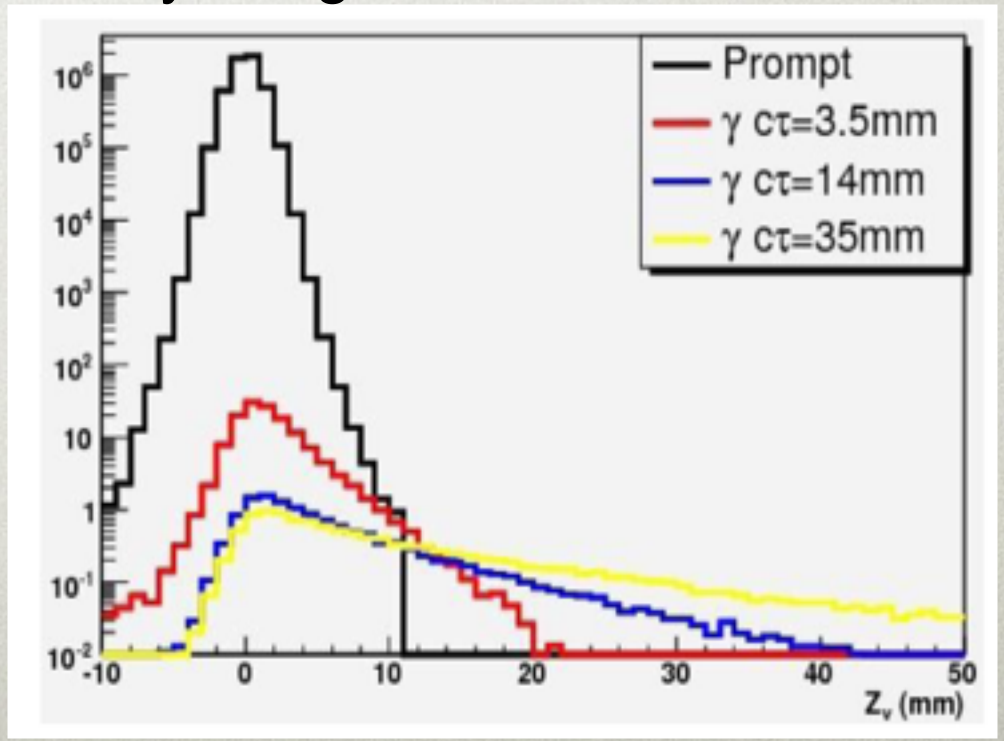


min $\theta_{A'}$ ~ 15 mrad (0.85°)
$\Delta m/m$ ~ 1% (bump hunt)
Δz ~ 1mm (vertexing)

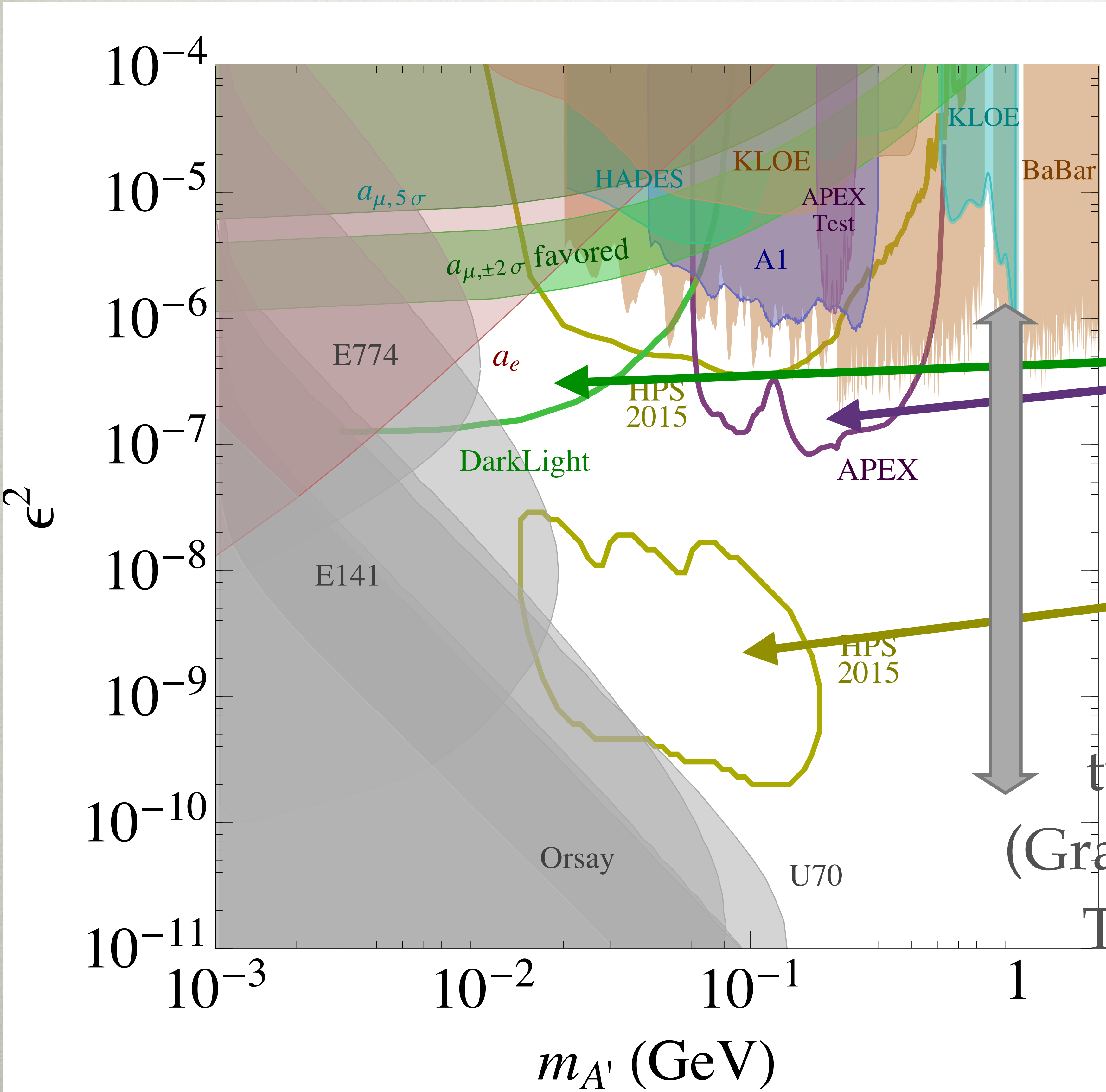
Vertexing allows sensitivity to weakly coupled A′ that produce only ~25 events!



Decay Length Distribution



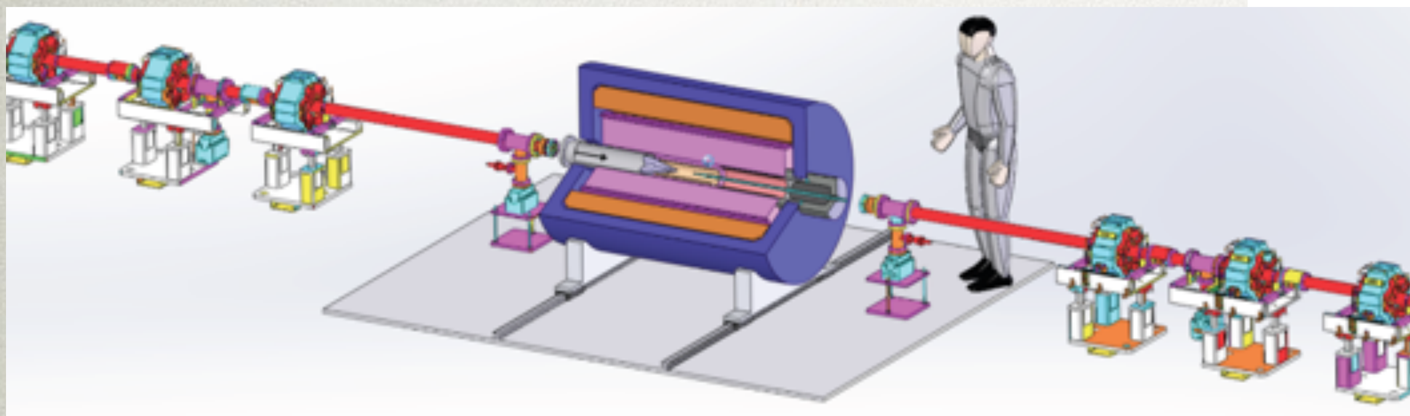
Projections for 2015-17

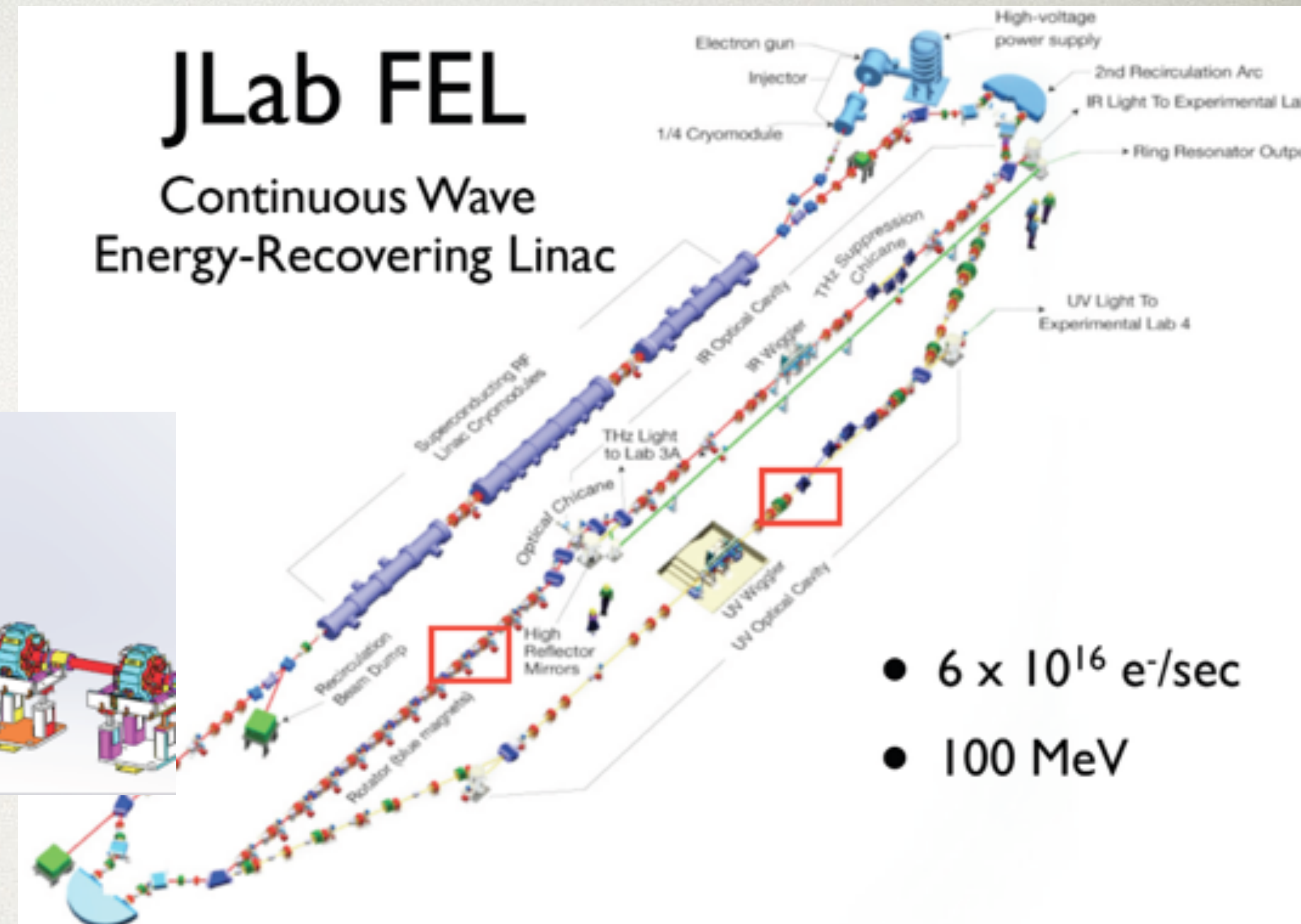


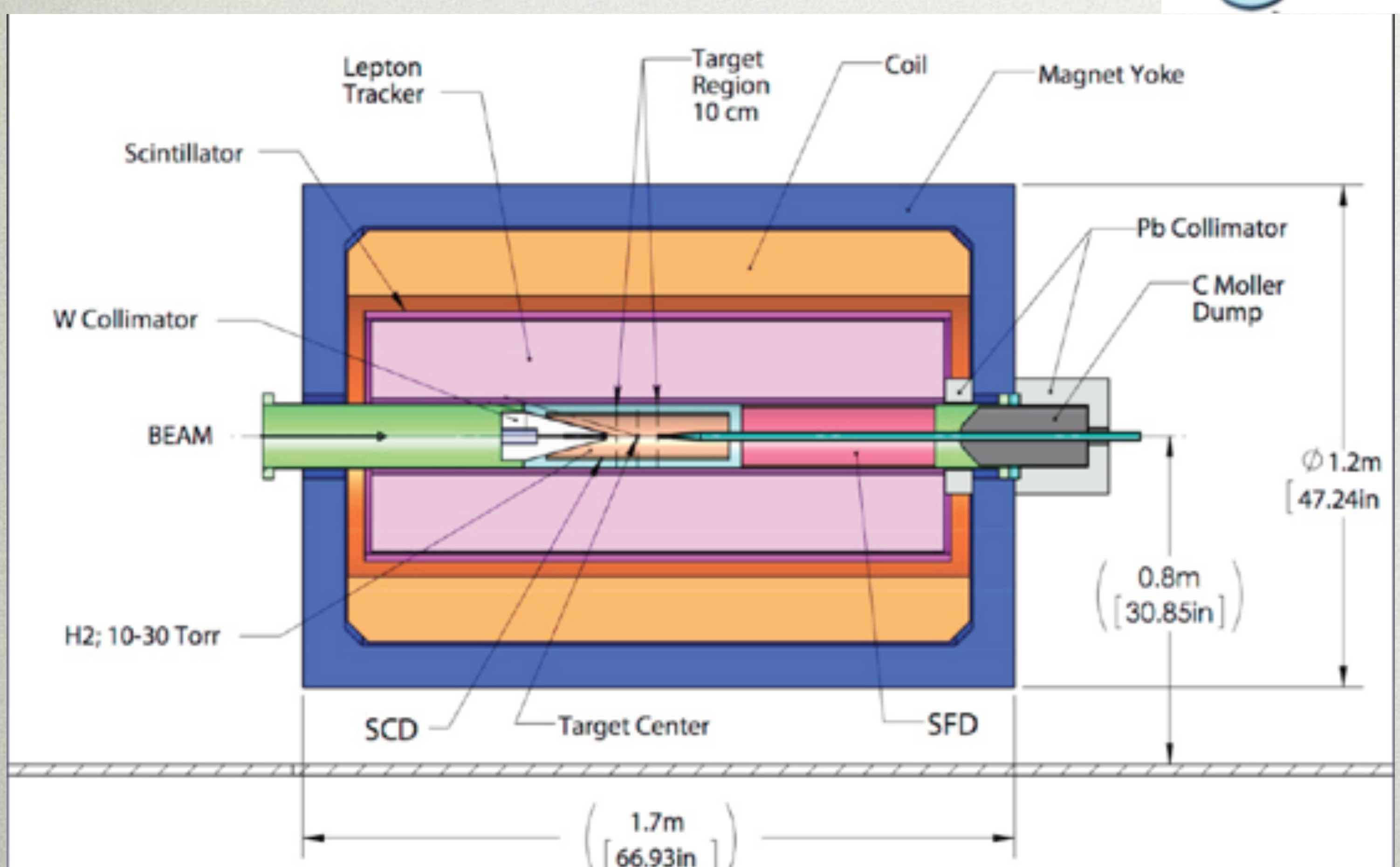
APEX & DarkLight uniquely explore GUT region from above, HPS from below

two-loop (Grand Unified Theories)

DARKLIGHT



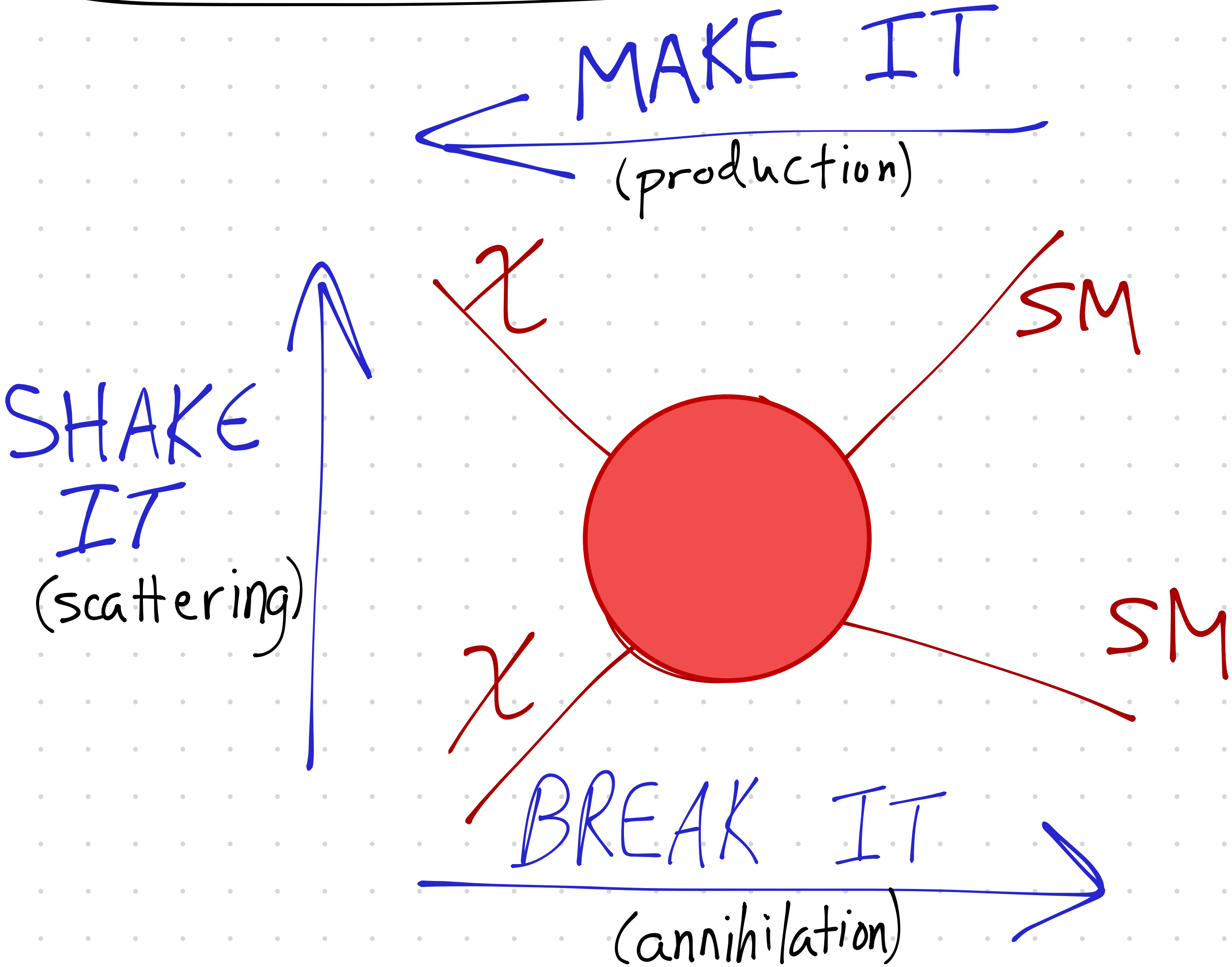




~10^{19}cm^{-2} gas target, 10mA beam

Searches for visible and invisible A′ decay

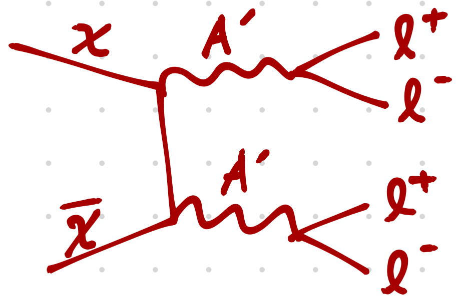
Dark Matter in the Dark Sector



Dark Matter in the Dark Sector

Complementary but often not simply related

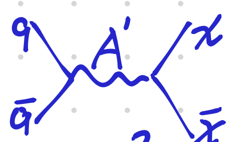
e.g. for $m_{A'} < m_\chi$, annihilation



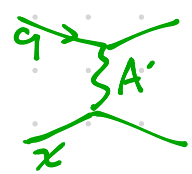
$\sigma \propto \varepsilon^0$

is IRRELEVANT for production & scattering.

Kinematics of production vs. scattering ⇒ very different cross-sections



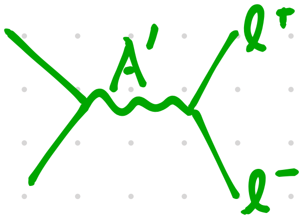
$s \gg m_{A'}^2$



$-t \ll m_{A'}^2$

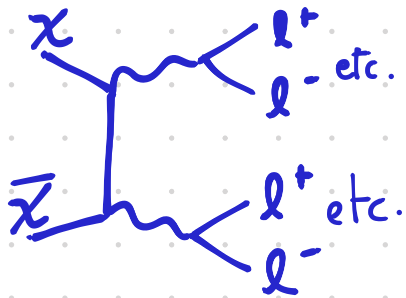
DM Annihilation

$m_\chi < m_{A'}$



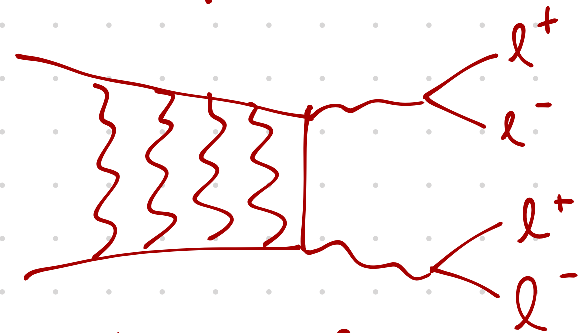
$$\langle \sigma v \rangle \sim \frac{m_\chi^2}{m_{A'}^4} \alpha \alpha_D \varepsilon^2$$

$m_\chi > m_{A'}$



$$\langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2}$$

$m_\chi \gg m_{A'}$



$$\langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2} \times S$$

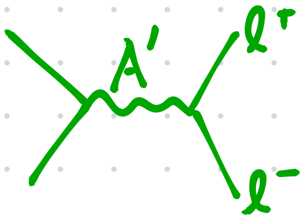
$$S \sim \min\left(\frac{\alpha_D m_\chi}{m_{A'}}, \frac{1}{v}\right)$$

Sommerfeld-enhanced & leptophilic annihilation an early motivation for dark-sector DM*

[Arkani-Hamed et al, Pospelov & Ritz]

DM Annihilation

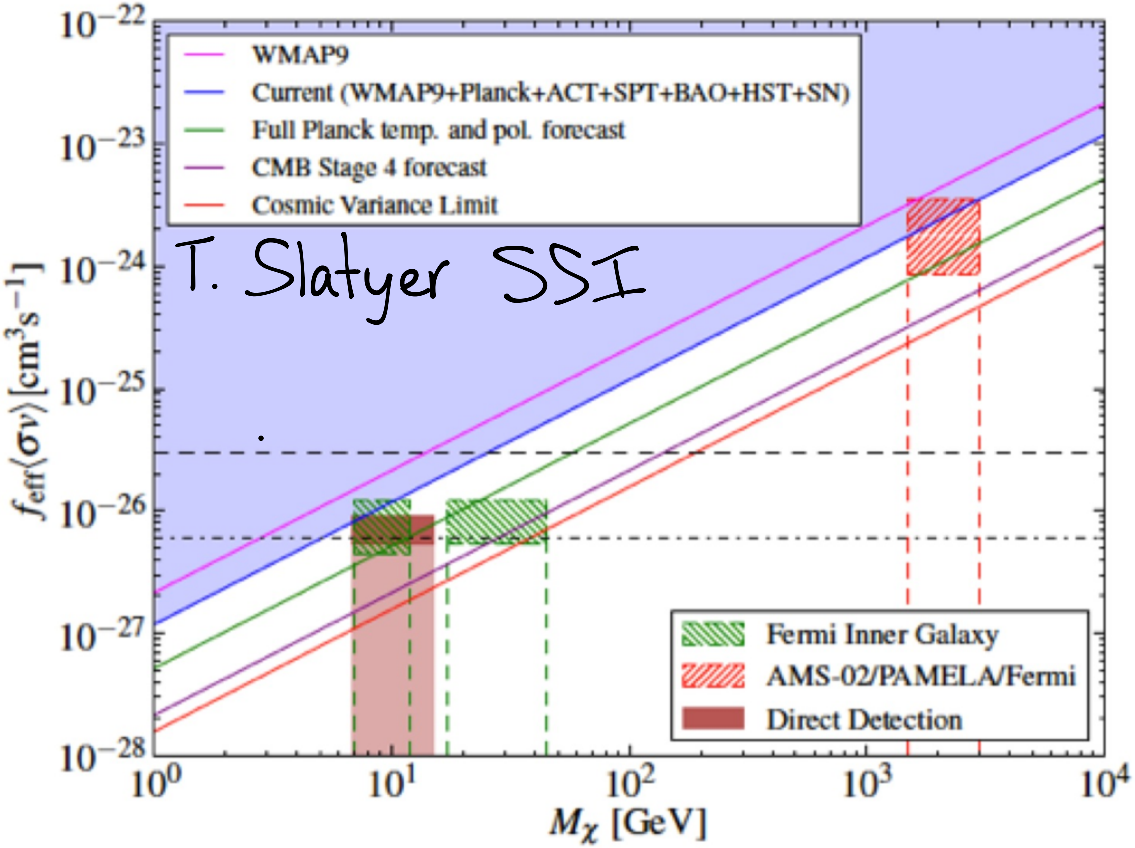
$m_\chi < m_{A'}$ $\qquad$ $m_\chi > m_{A'}$ $\qquad$ $m_\chi \gg m_{A'}$



$\langle \sigma v \rangle \sim \frac{m_\chi^2}{m_{A'}^4} \alpha \alpha_D \varepsilon^2$ (× p-wave suppression for scalar DM)

To avoid over-production of light ($\lesssim$ GeV) DM, MUST have a light mediator (~Lee-Weinberg bound) or interactions so weak that it never thermalizes

Annihilation & the CMB



T. Slatyer SSI

Caveats

① p-wave for light scalar DM ⇒ suppressed @ low v

② If DM is split by a Majorana mass term

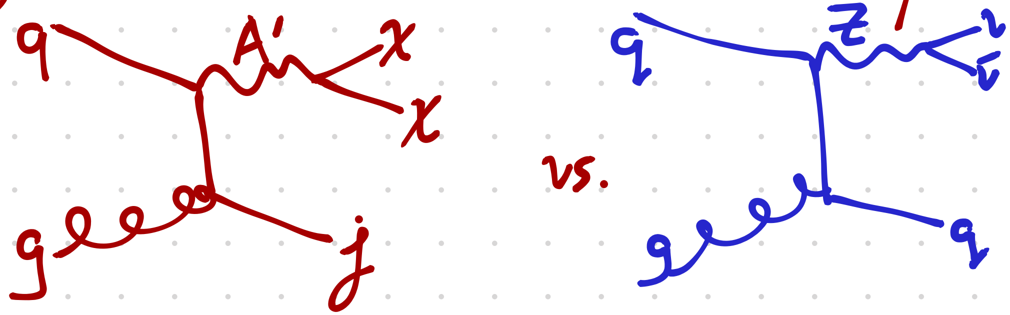
- Dark Higgs coupling
- Radiative correction in non-Abelian dark sector

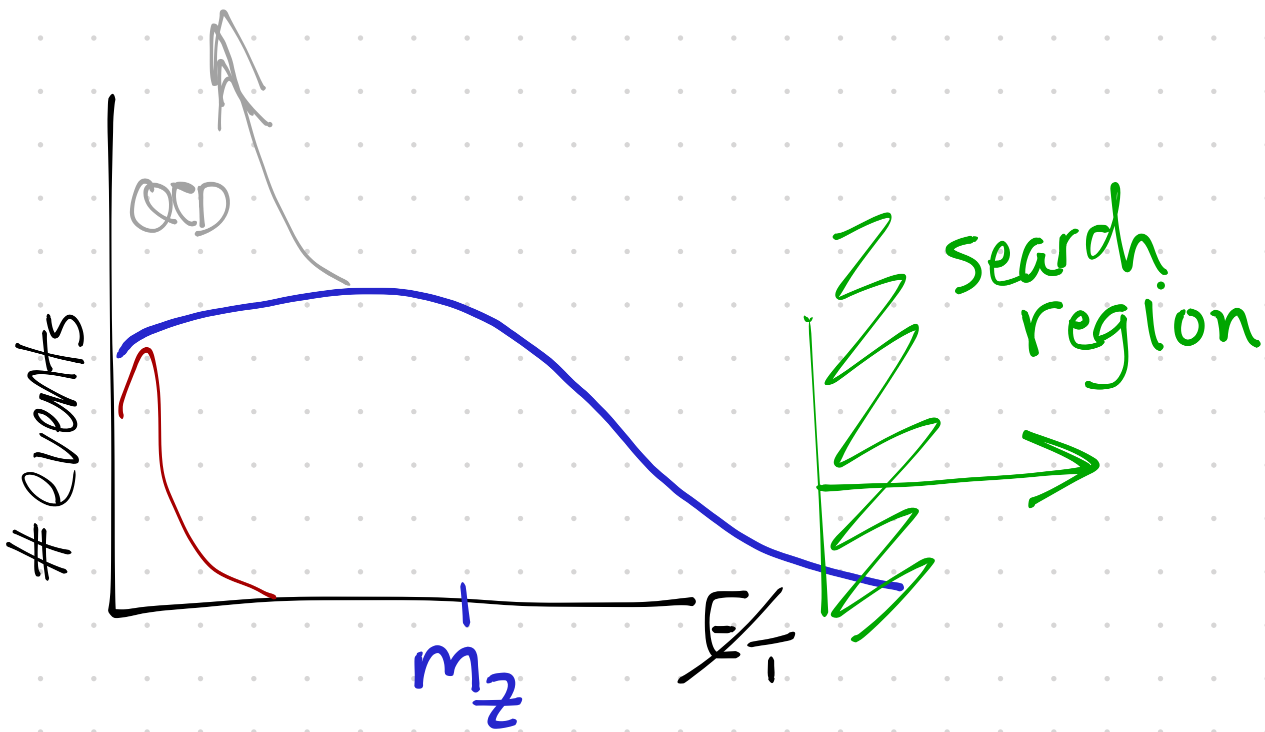
then $\chi\,\chi^* \to$ SM SM inelastic

⇒ irrelevant at high z if $n_{\chi^*} \ll n_\chi$

DM Production

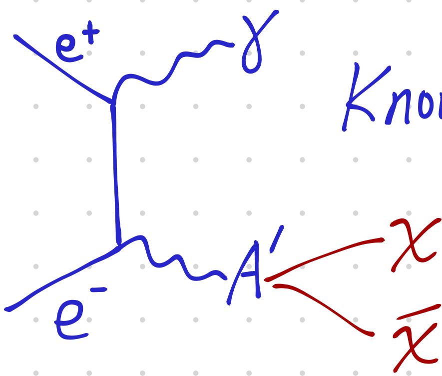
Light A′ ⇒ far from contact-operator regime in collider



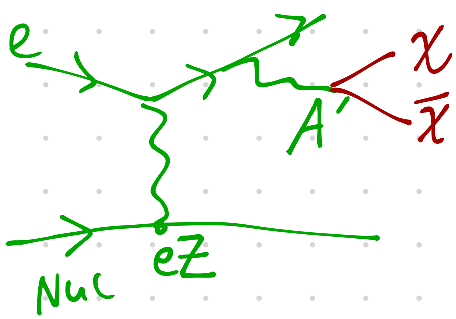


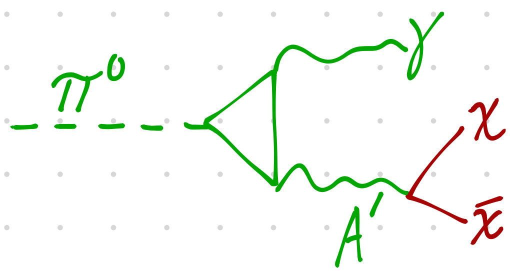
DM Production

Low-energy collider production still viable:



Known $E_{cm} \Rightarrow$ can reconstruct $m_{\chi\bar{\chi}}$ from p_γ^μ



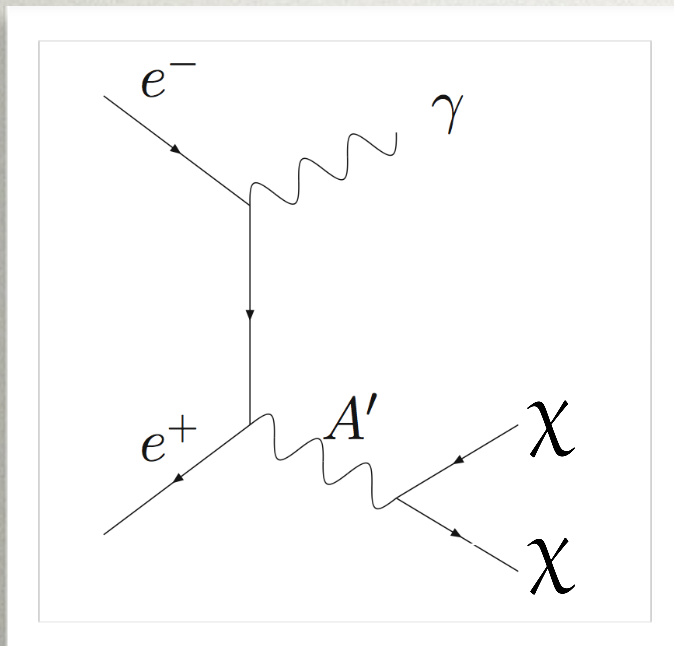


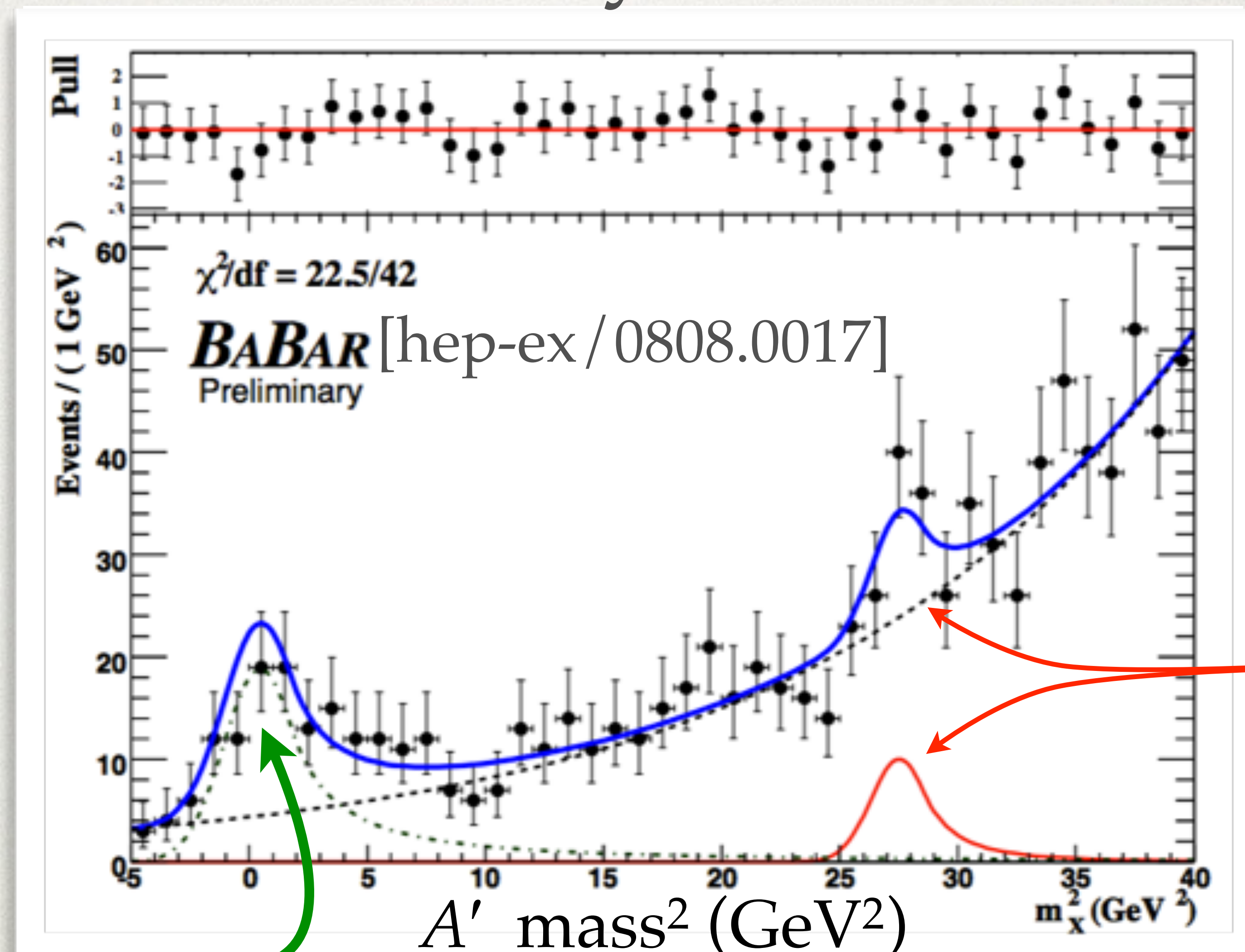
Fixed-target exp's can produce light DM, but usually can't reconstruct full final state to infer $m_{\chi\bar{\chi}}$.

(Direct production of heavy dark-sector DM essentially impossible.)

DM Production at Lower Energies

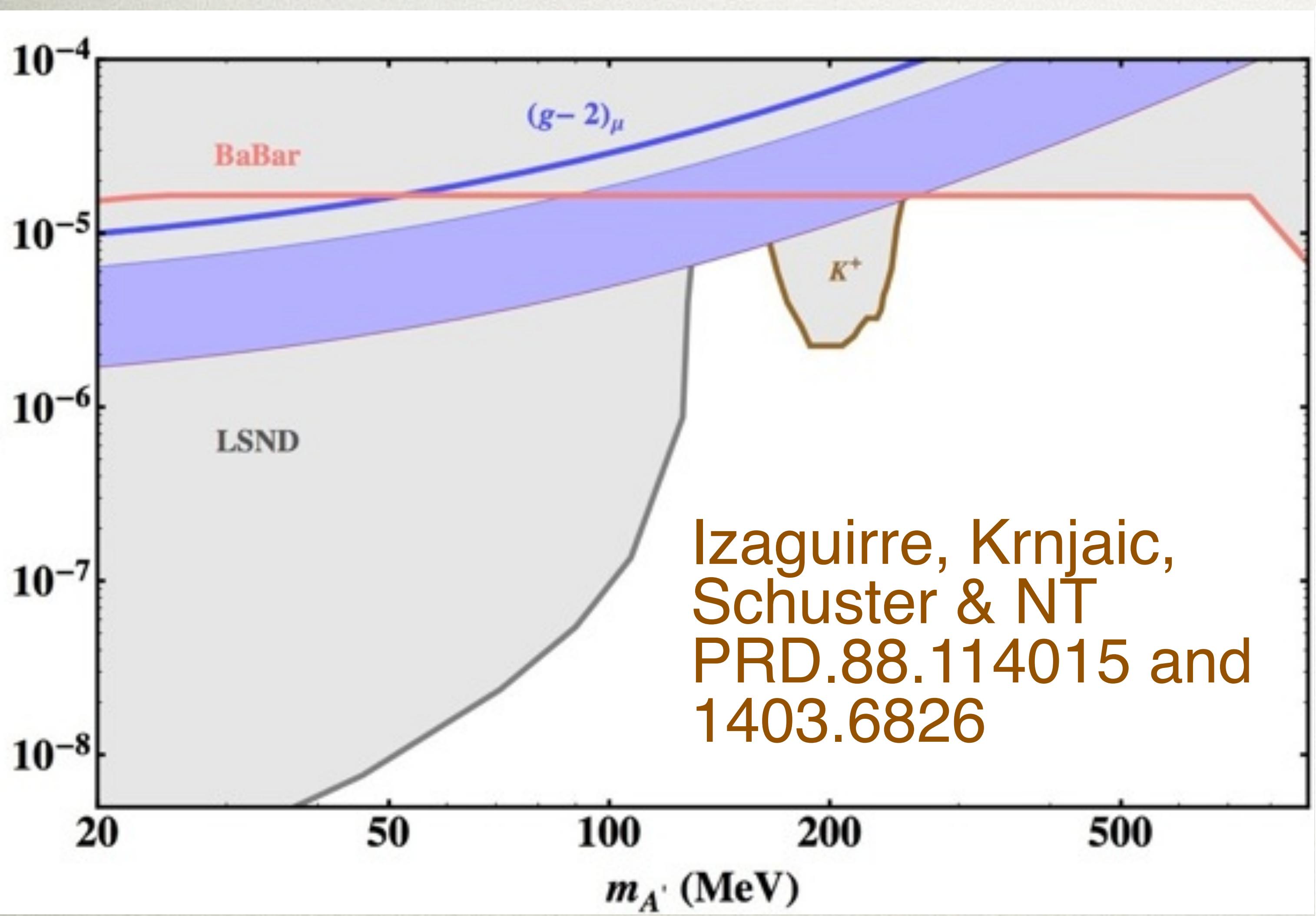
$A' \to \chi\,\chi$ decay constrained by BaBar search

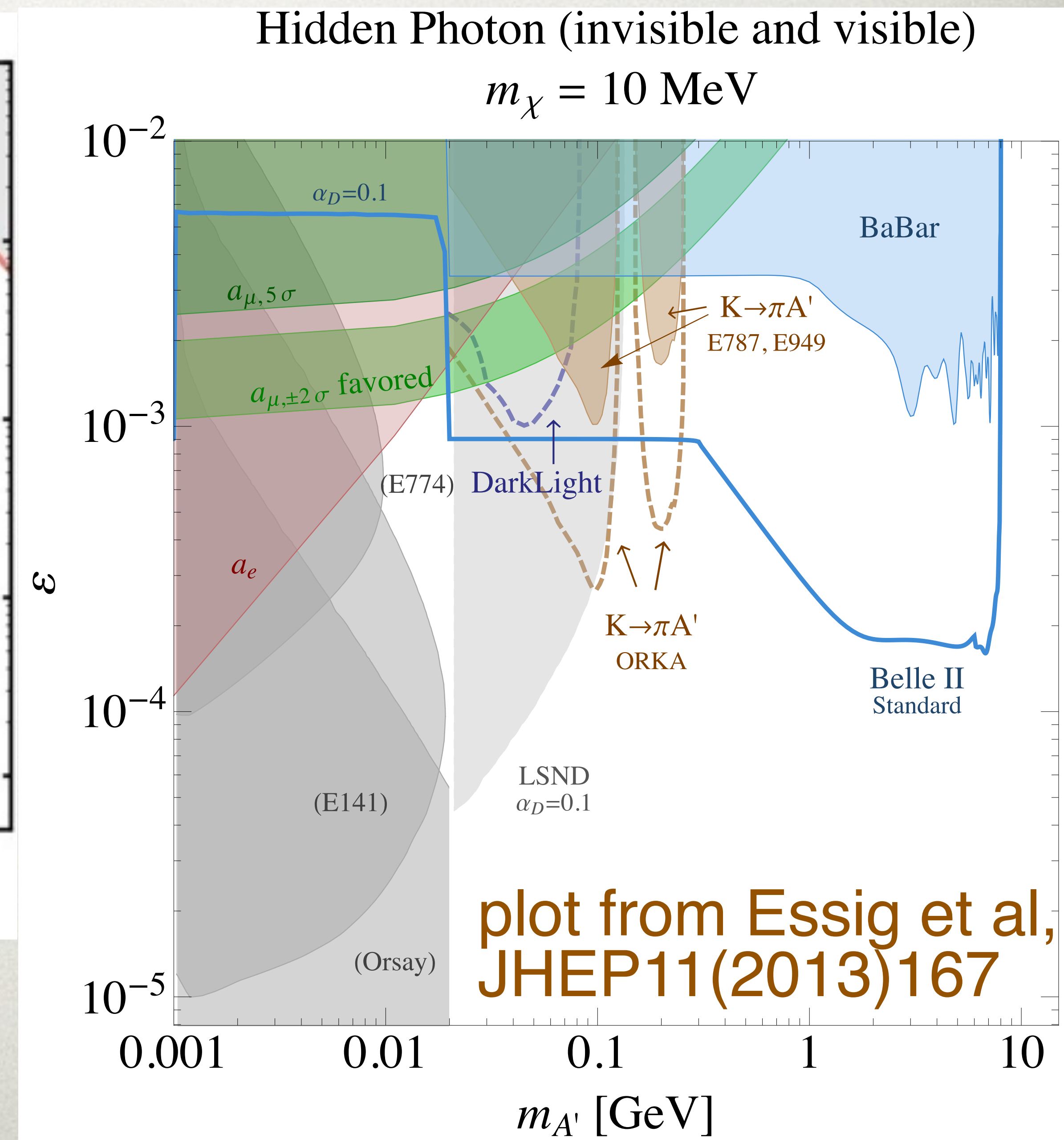




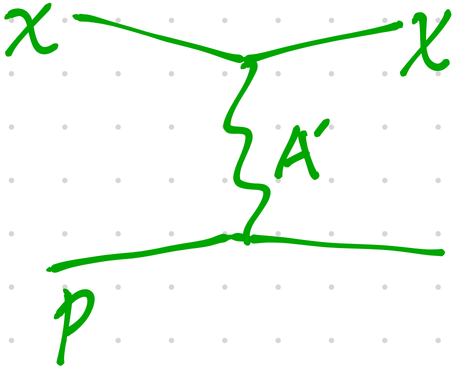
2γ background (signal-faking)

DM Production at Lower Energies





Light DM Scattering

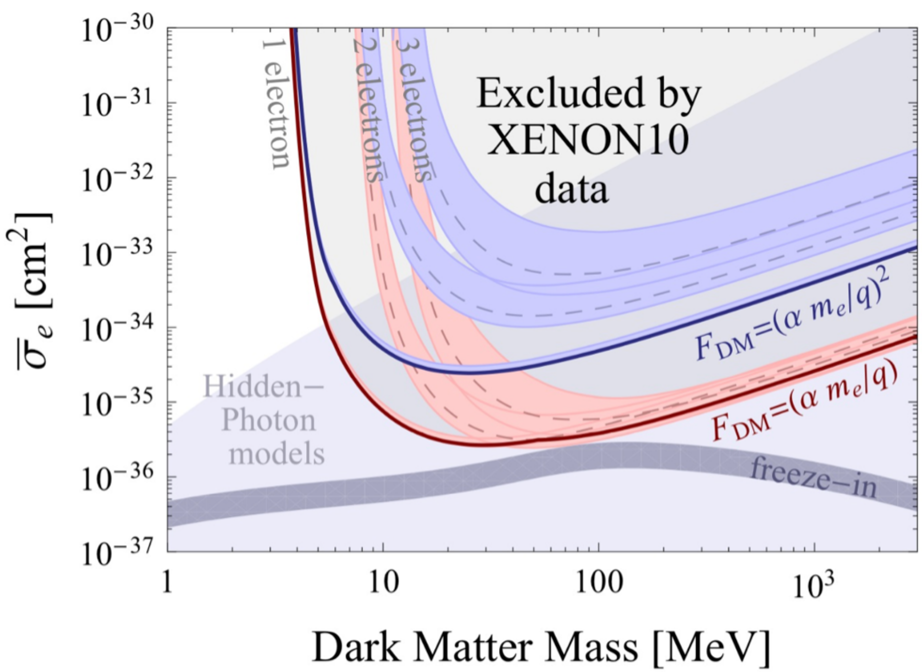


$$\sigma \sim \frac{\alpha \alpha_D \varepsilon^2 \cdot \mu^2}{m_{A'}^4}$$

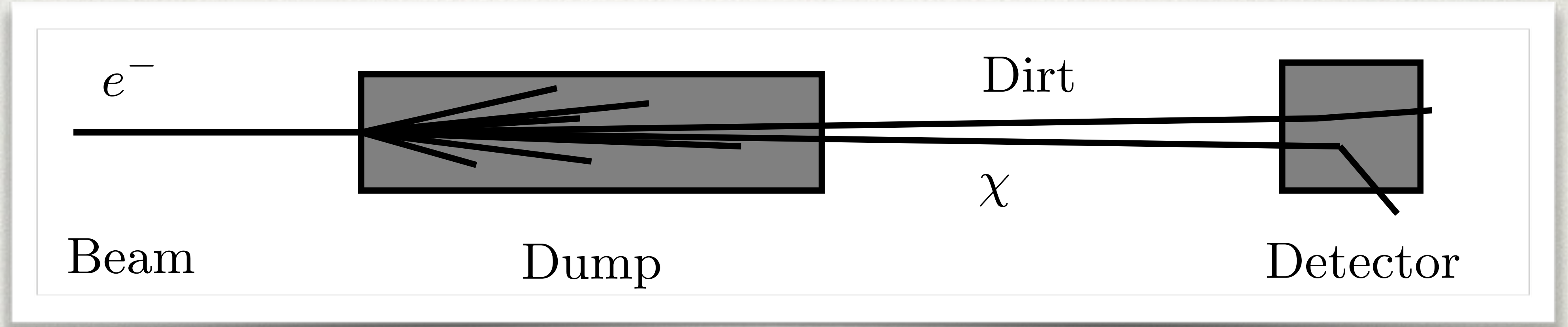
$$E_R^{nuc} \sim \frac{(m_\chi v)^2}{m_{Nuc}} \ll \text{keV}$$ for $m_\chi \lesssim$ GeV] NOT VISIBLE!

— Somewhat visible in e^- recoils
[Essig, Mardon, Volansky]
+ Manalaysay, Sorensen

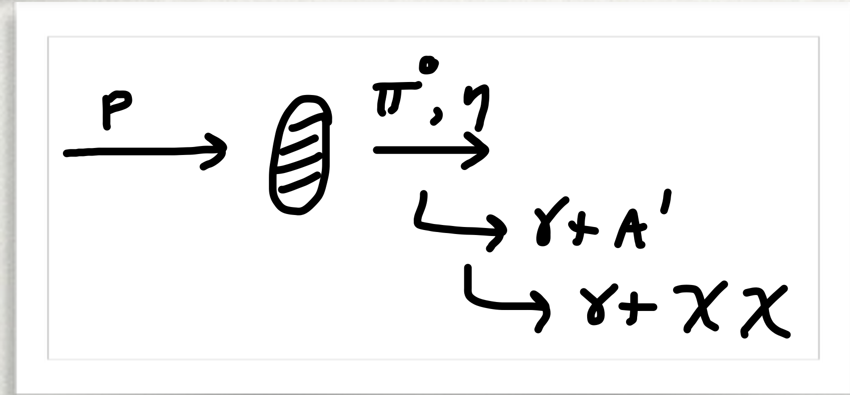
— Near GeV mass:
Super-CDMS SNOLAB
Silicon detector



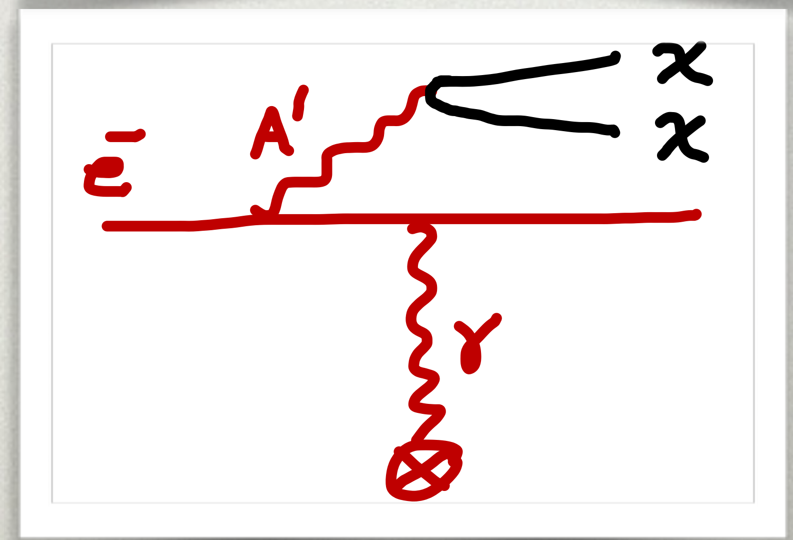
DM Production… and Detection

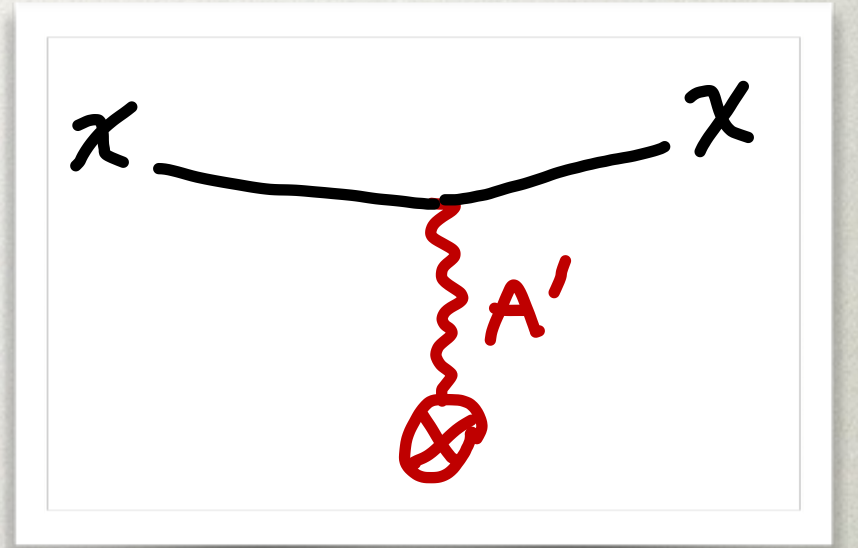


0906.5614,
1107.4580,1205.3499
Batell,DeNiverville,
McKeen, Pospelov, Ritz



Izaguirre, Krnjaic,
Schuster & NT
PRD.88.114015 and
1403.6826





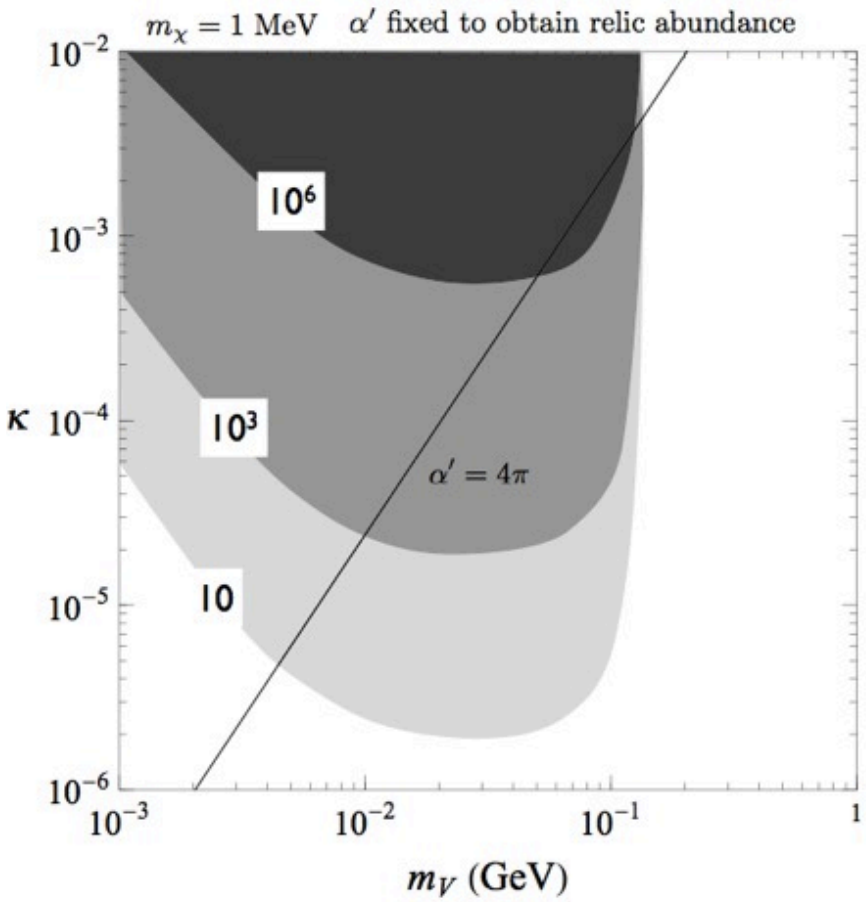
nuclear dissociation;
nucleon, nucleus, or
electron recoil

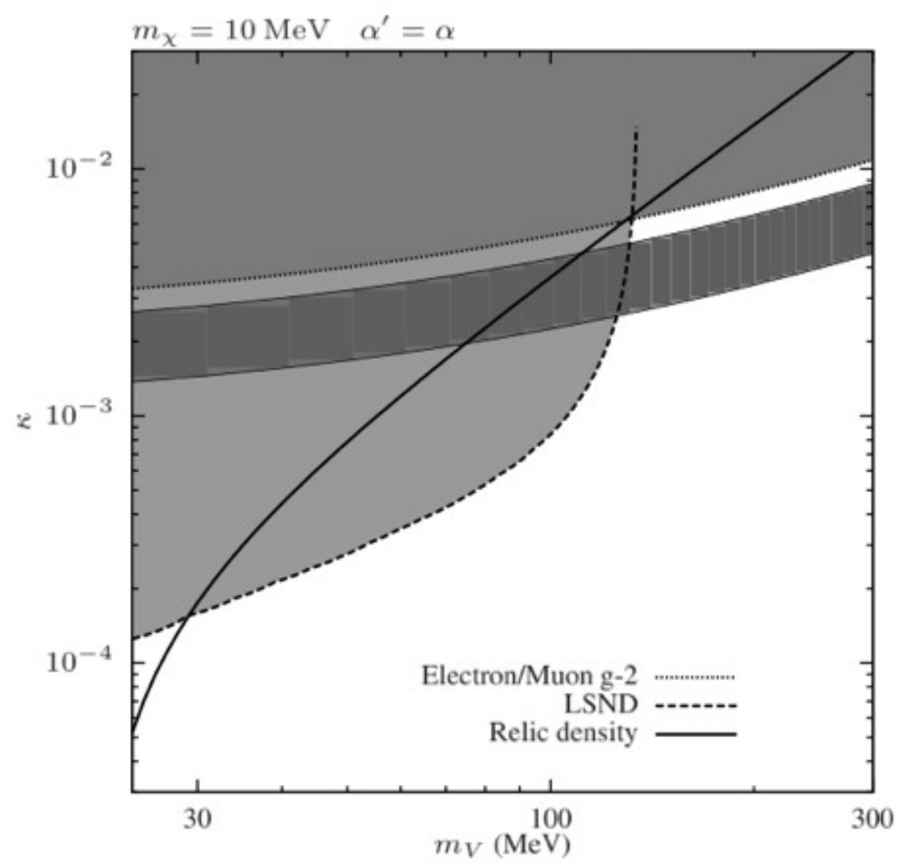
PAST, PRESENT AND FUTURE DM SEARCHES AT PROTON BEAMS

Other Experiments

LSND
800 MeV p, 10^{23} POT

DM prod. through π^0 decay
NC scattering on electrons
170 T mineral oil detector
30 m off-axis





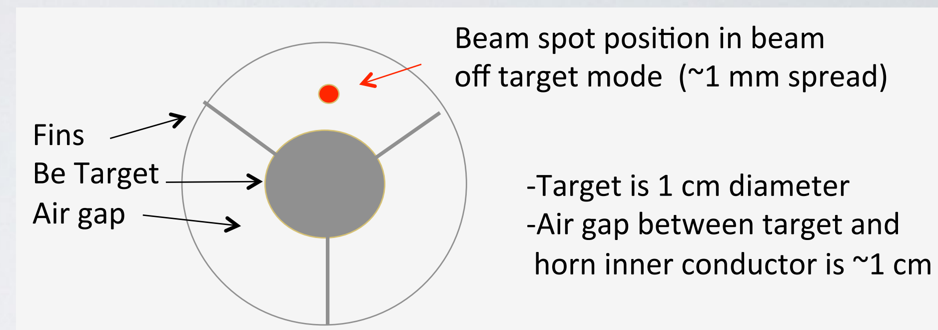
[Batell, Pospelov, Ritz '09] [deNiverville, Pospelov, Ritz '11]

slide from Dave McKeen, FNAL New Perspectives on Dark Matter

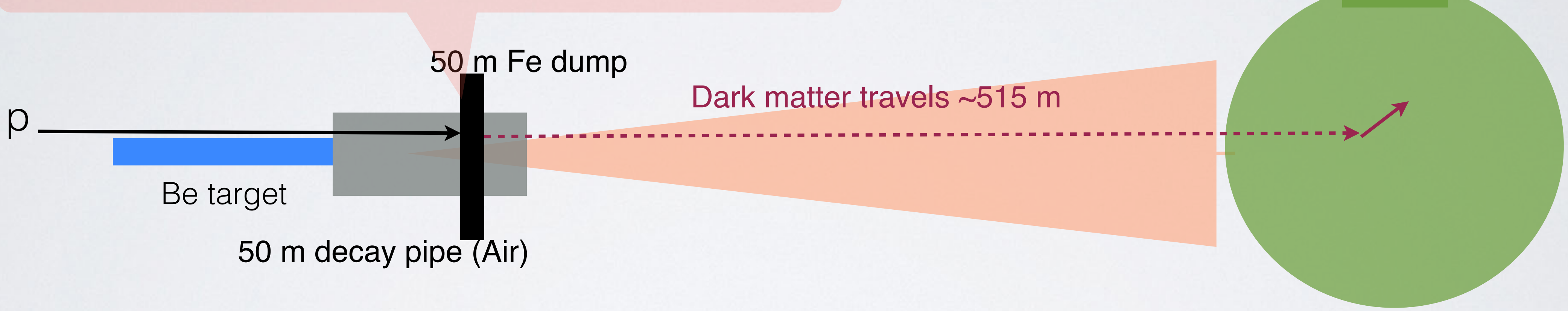
Past, Present and Future DM Searches at Proton Beams

MiniBooNE Beam-dump mode: Setup

Running now!



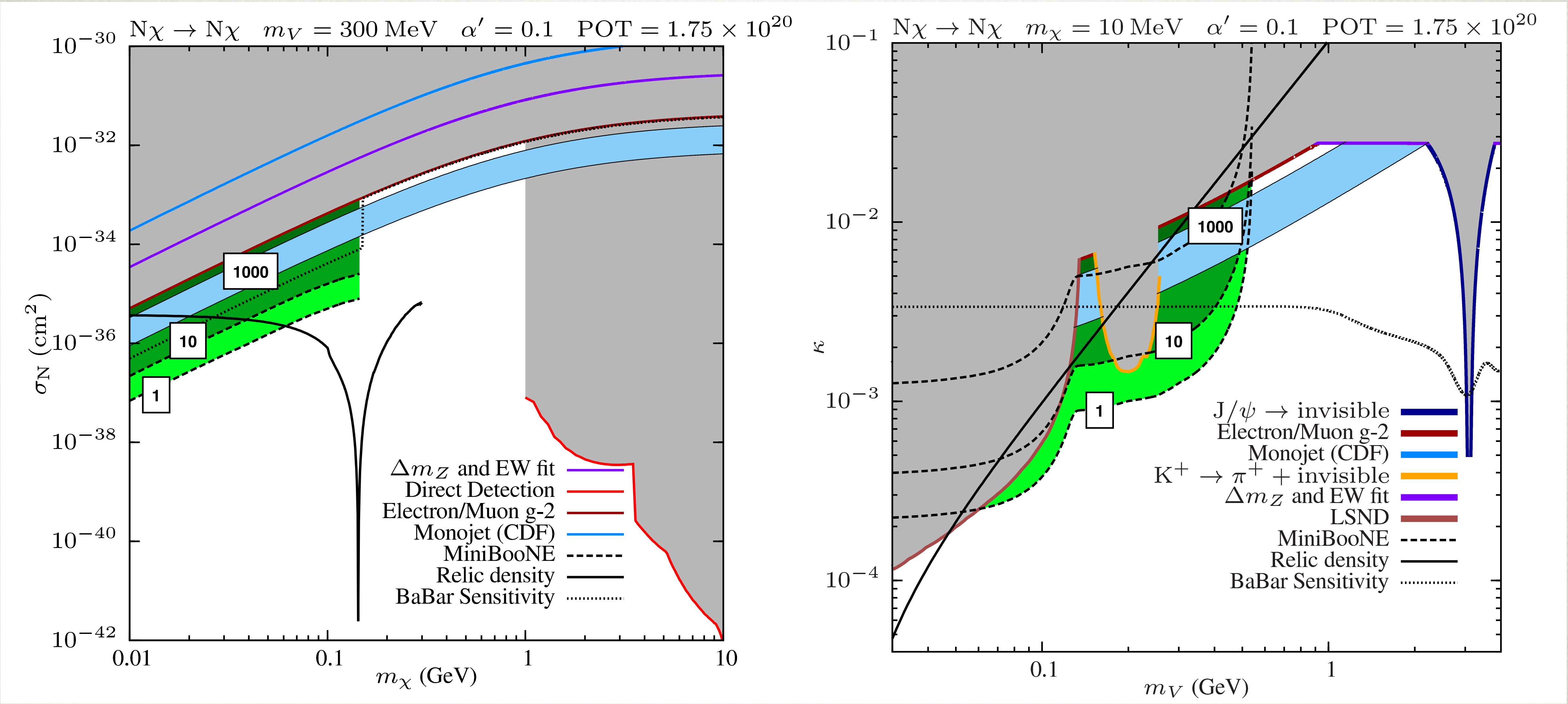
- π^0 and η decay quickly (to new vector bosons and subsequently dark matter)
- The charged mesons are absorbed before decaying.



Beam off-target mode reduces the neutrino background by a factor of ~40.

slide from Ranjan Dharmapalan, FNAL New Perspectives...

Past, Present and Future DM Searches at Proton Beams



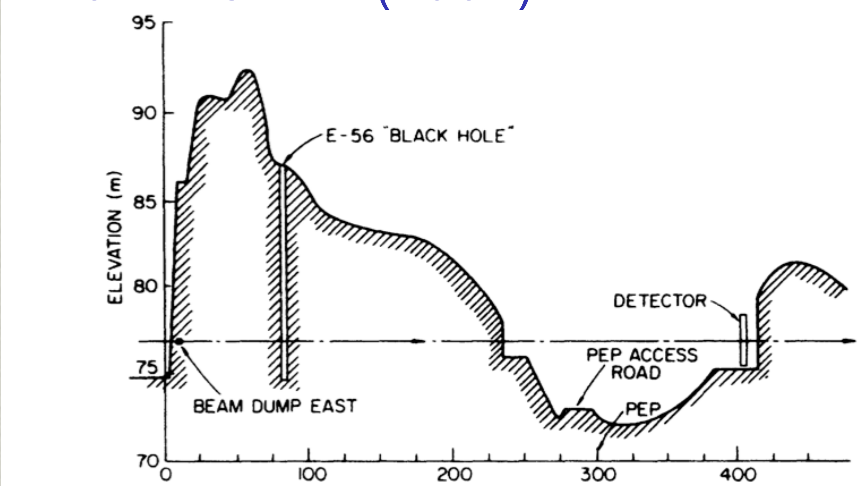
Plots by P. deNiverville

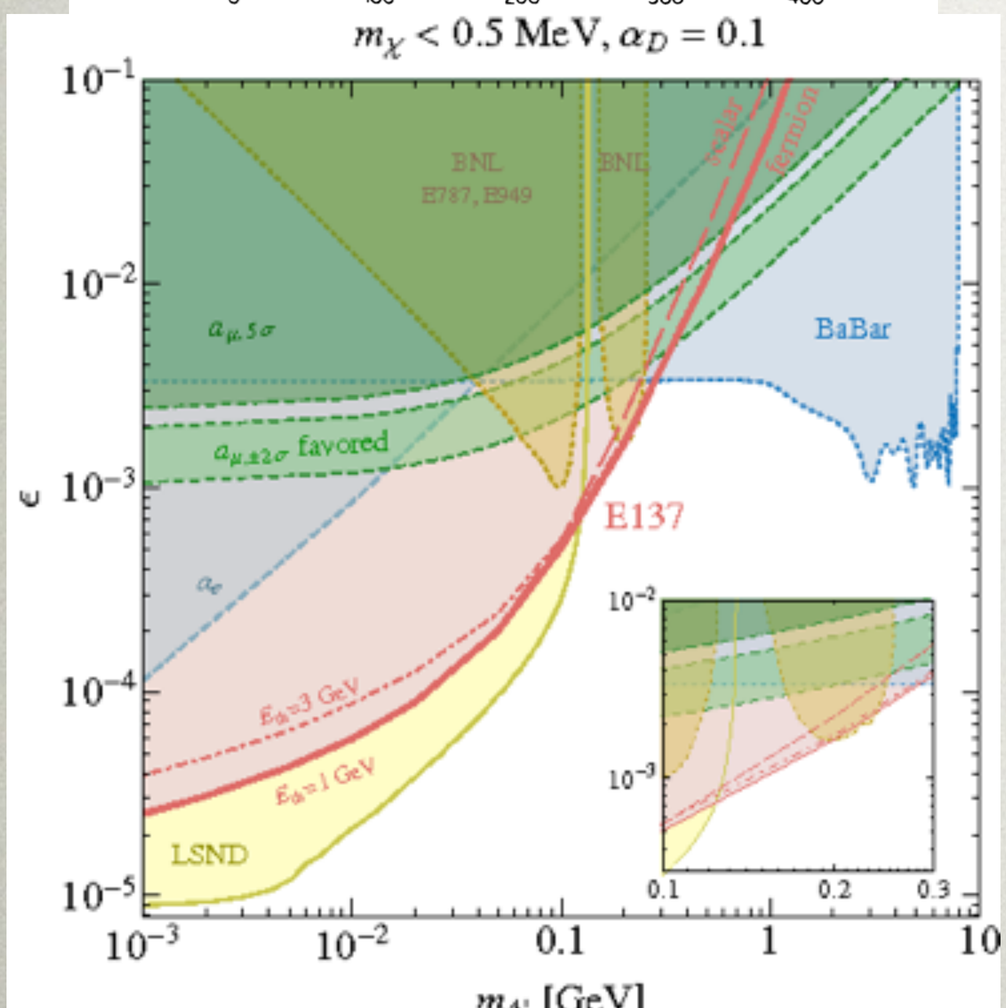
Searches are being developed for T2K, MicroBoone, LBNE, …

Electron Beam Dumps in Action

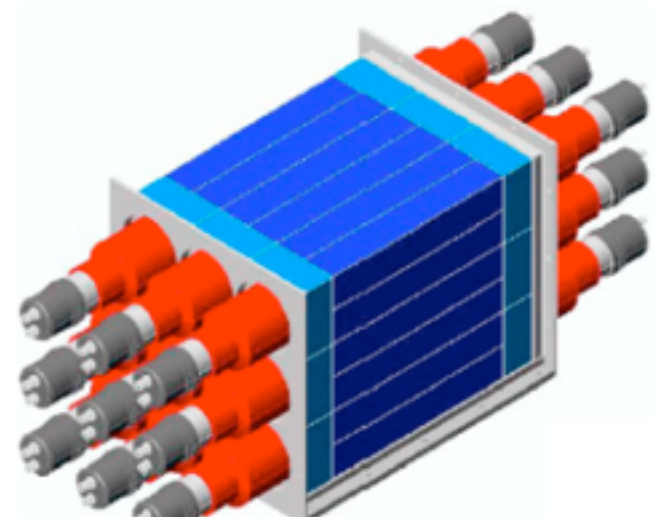
[BDX Collaboration arXiv:1406.3028]

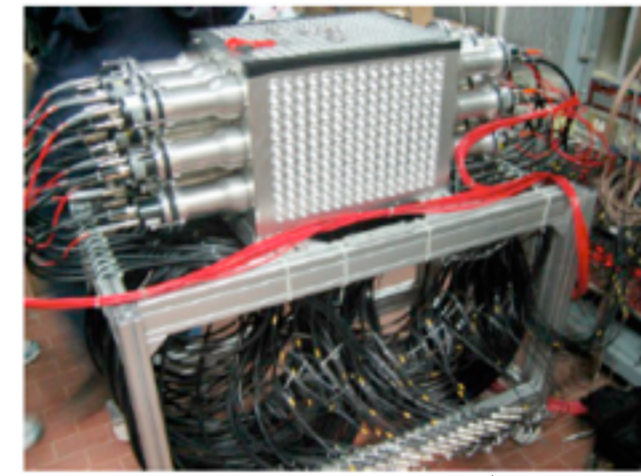
E137 @ SLAC (1982)



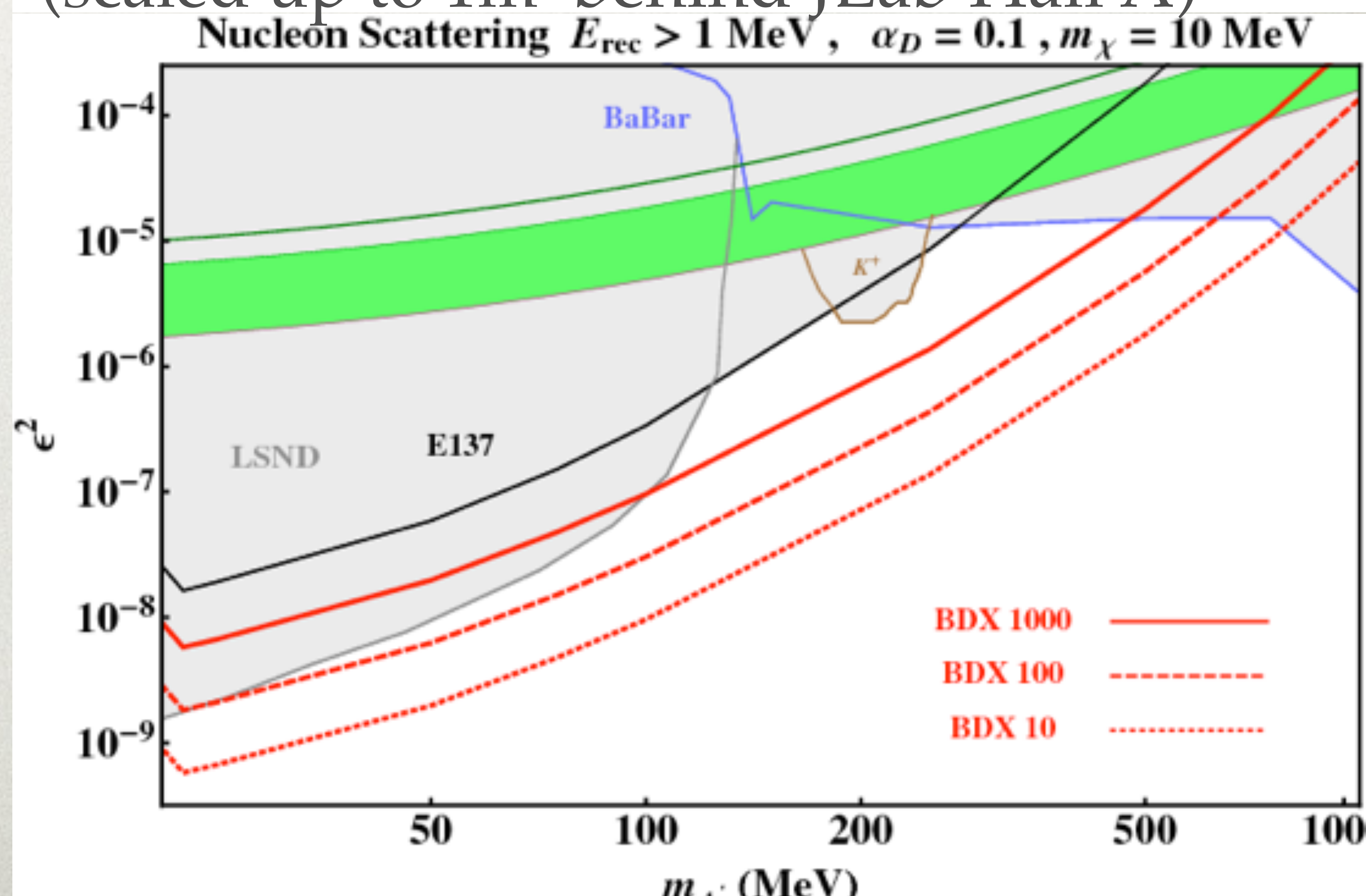


[Batell, Essig, Surujon 1406.2698]





(scaled up to $1m^3$ behind JLab Hall A)



Next Steps

- First generation of searches for **visibly** decaying dark photons ~2015-17
  - Future experiments may close the gaps in coupling & reach higher masses
- Proton- and electron-beam-dump searches for dark photons decaying **invisibly** running & under development
- Realistic near-term goal: test g-2 “preferred” region for **any** branching ratio between visible & invisible decays

Summary

Nature is more intricate than it "needs" to be —
— came as surprise in exploring high energies.

Similar opportunity today to discover new gauge groups/sectors by looking at HIGH PRECISION

Focusing on marginal couplings turns the infinity of possible sectors into a tractable problem

MeV-to-GeV scale, kinetic mixing w/ photon $\sim 10^{-3} - 10^{-6}$ is a well-motivated place to look!

Suggests a rich experimental program & broad range of DM possibilities