The SeaQuest experiment & displaced dark sectors

Stefania Gori

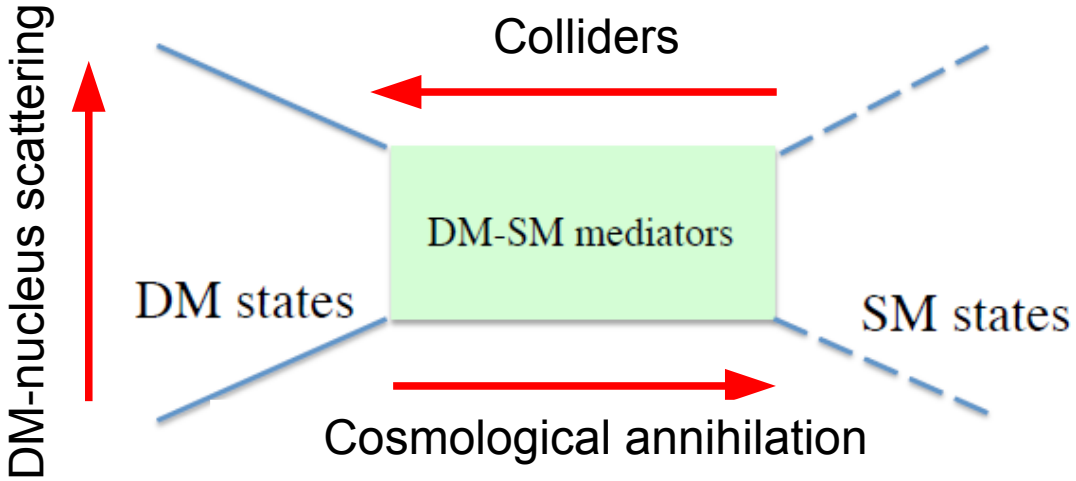
University of Cincinnati

Aspen 2017 winter conference
"From the LHC to dark matter and beyond"

Aspen,
March 21nd 2017

Light dark sectors

What is the Dark Matter energy scale?



- EW mediators lead to the so called Lee-Weinberg window

$$\text{few GeV} \lesssim m_{\text{DM}} \lesssim \text{few TeV}$$

- Light WIMPs are facilitated by light mediators

Dark sectors!

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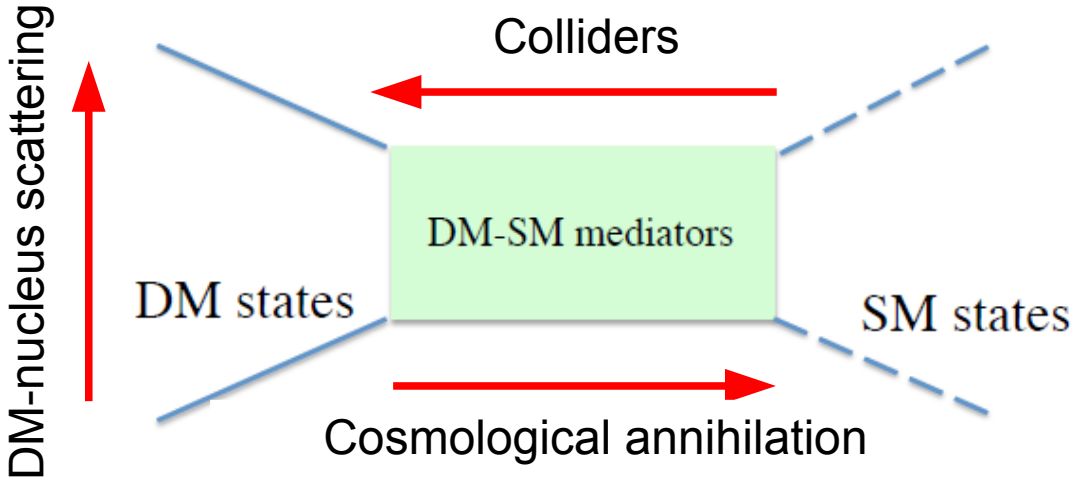
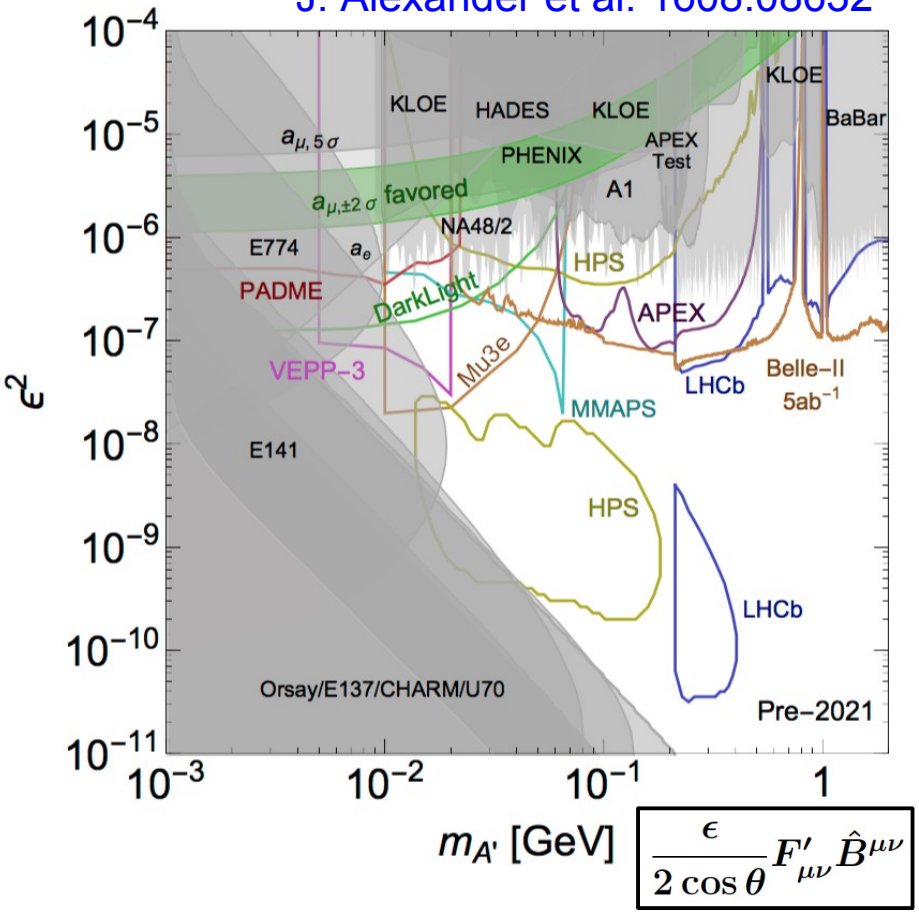


J. Alexander et al. 1608.08632



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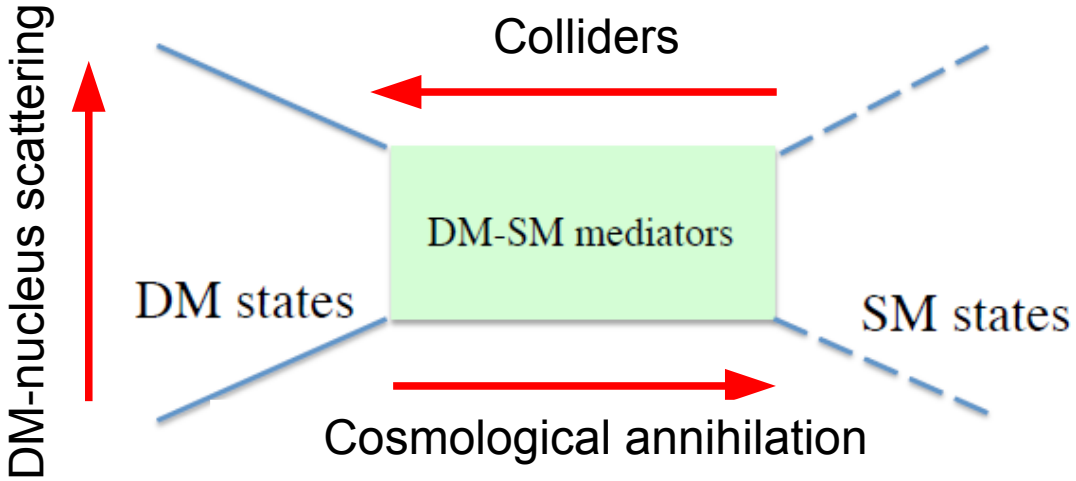

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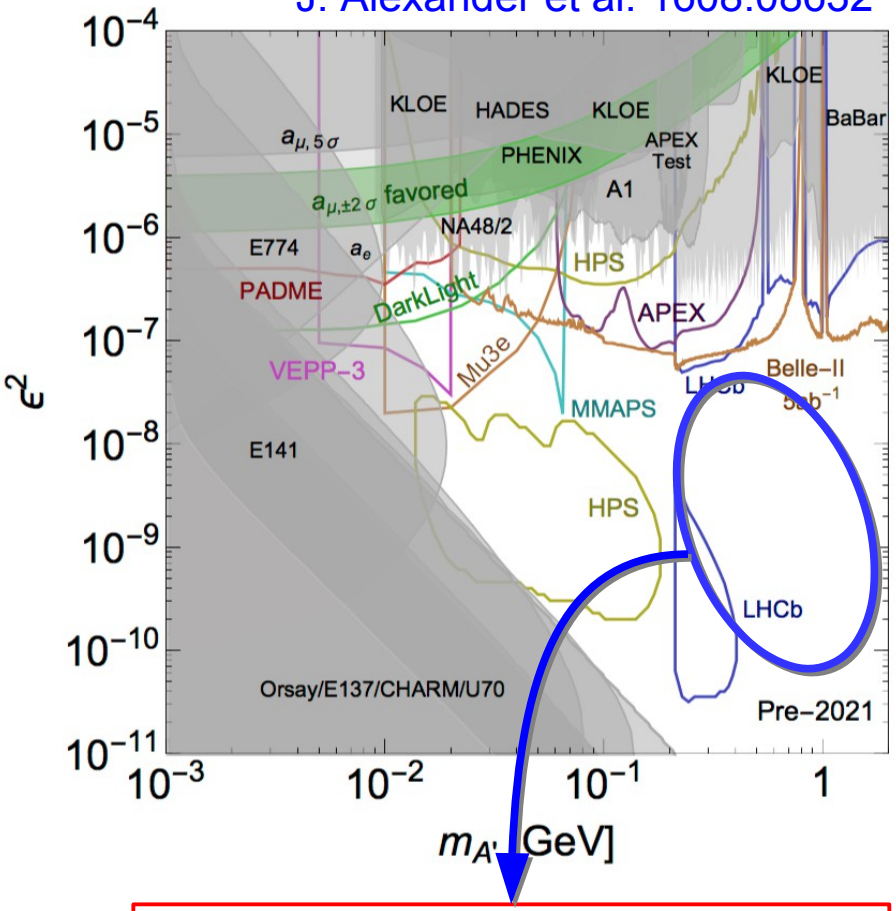

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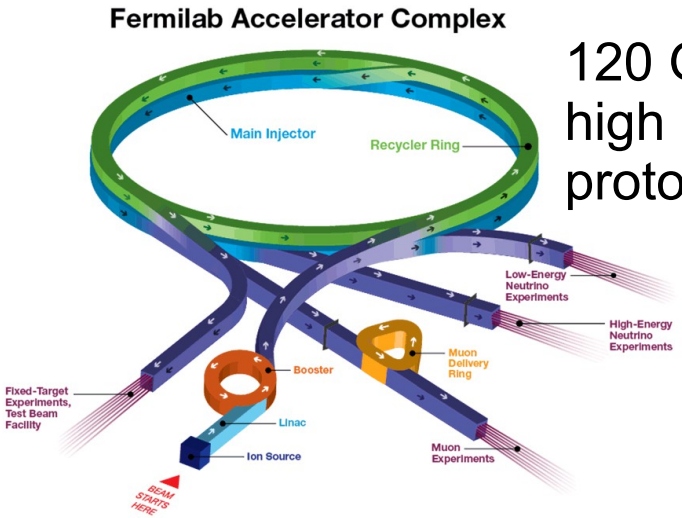
Dark sectors!

How to probe the (100 MeV - few GeV) range?

Fermilab intensity frontier

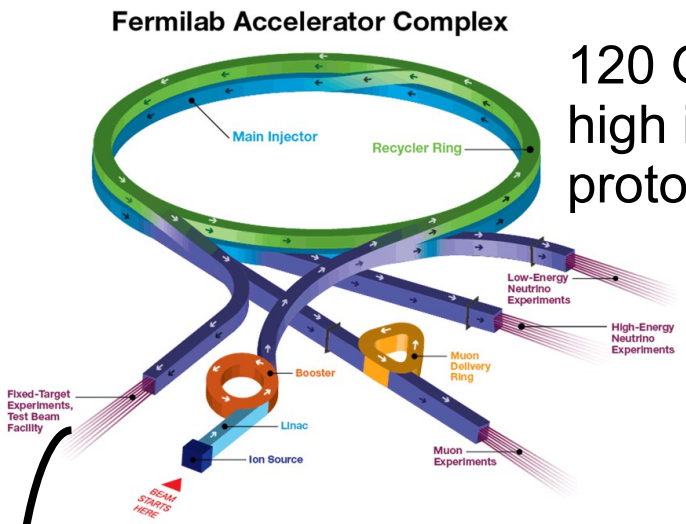


120 GeV high intensity proton beam

Proton Improvement Plan
to get very high intensity (PIP, PIP II)

Final goal: ~2 MW of proton beam power (now ~700 KW)

Fermilab intensity frontier



120 GeV high intensity proton beam

Proton Improvement Plan
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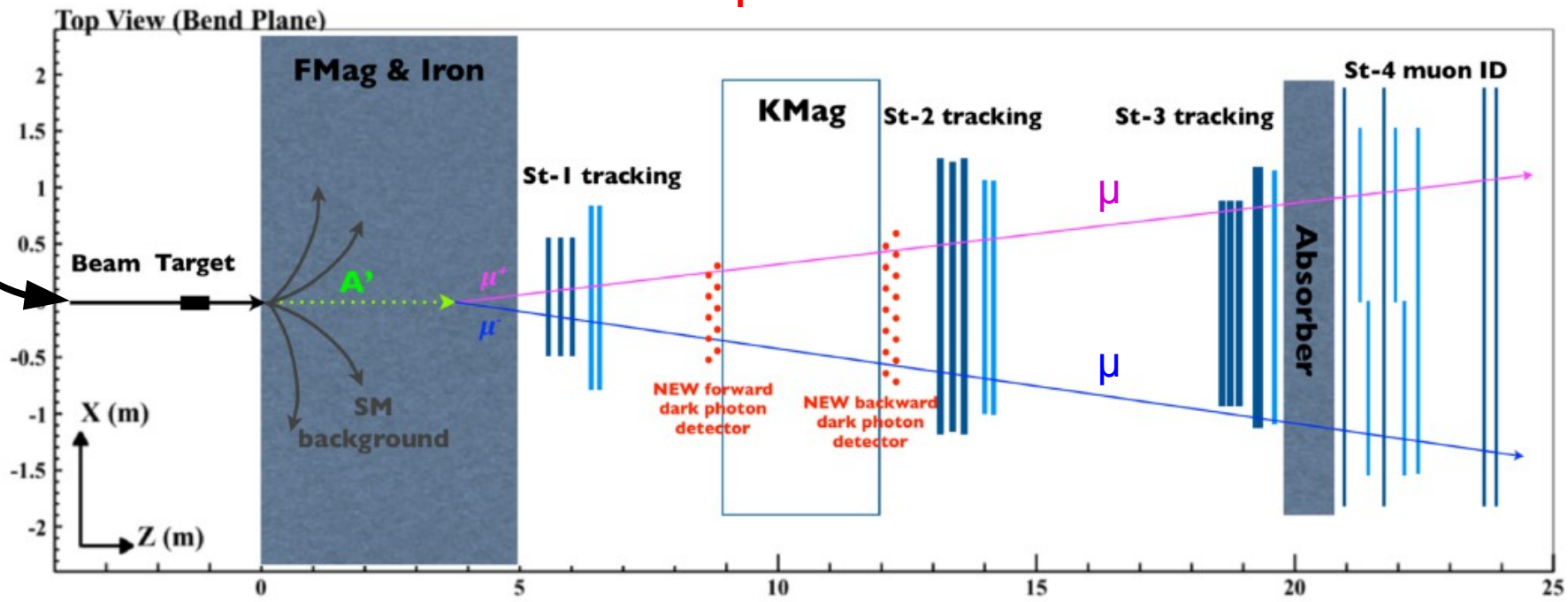
Final goal: ~2 MW of proton beam power (now ~700 KW)

Main task (so far):
measurement of the proton structure functions

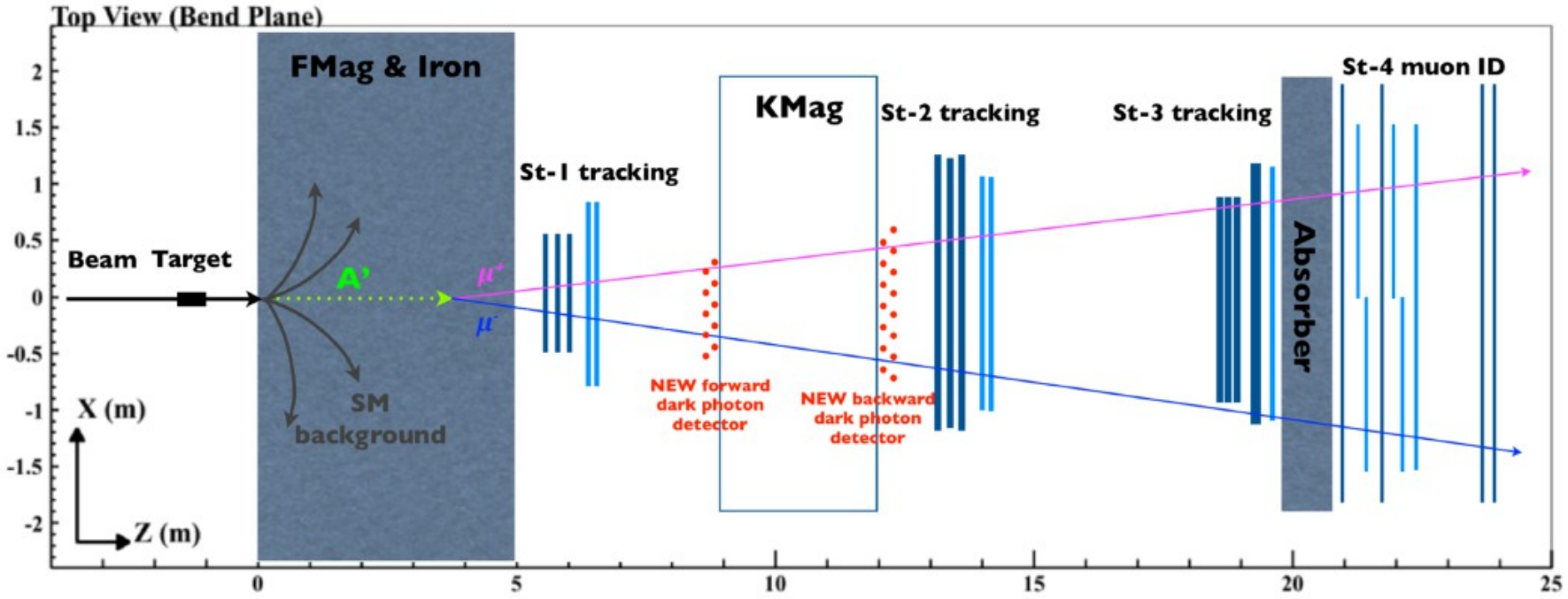
The SeaQuest experiment

5% main injector beam



The SeaQuest fact sheet

5% main injector beam



- Proton beam of 120 GeV, $\sqrt{s} \simeq 15$ GeV
- Recent installation of a displaced trigger

Starting date: April 2!

- Phase I parassitic run: 1.44×10^{18} POT in 200 days
- Possible Phase II: upgrade of the detector + larger luminosity (~ 10^{20} POT?)

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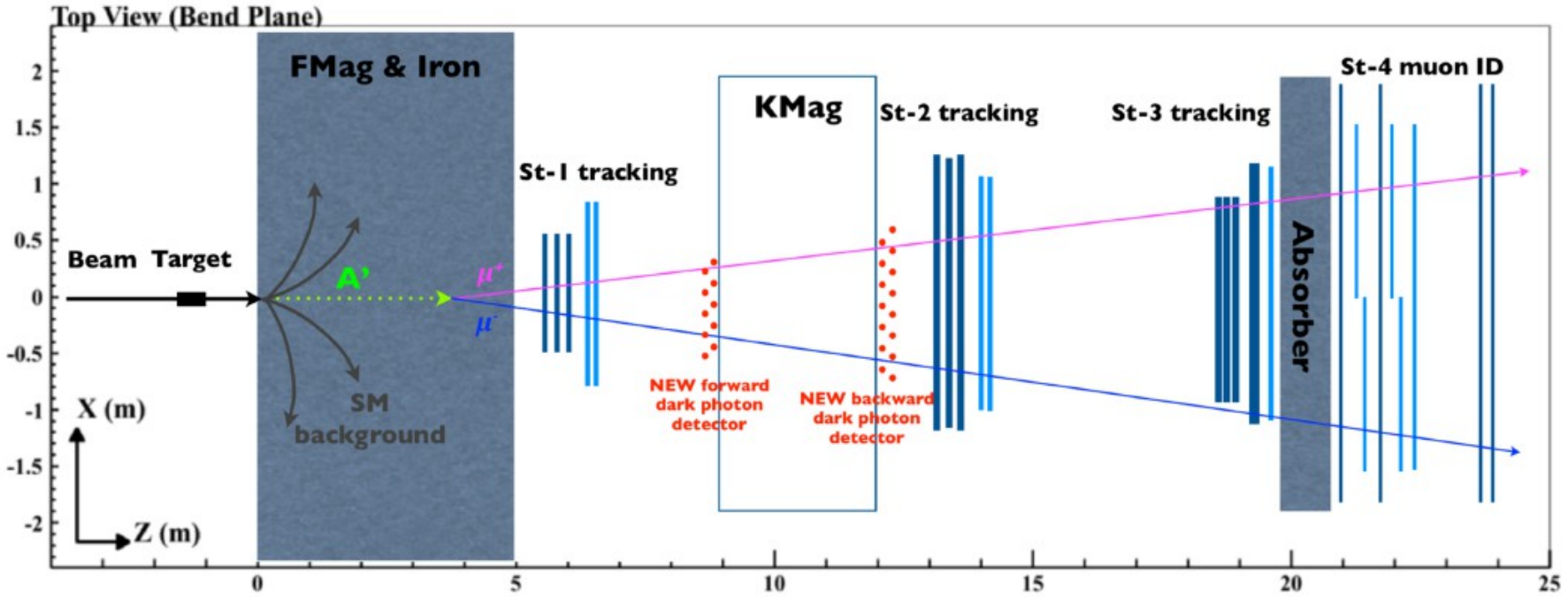

- Proton beam of 120 GeV, $\sqrt{s} \simeq 15$ GeV
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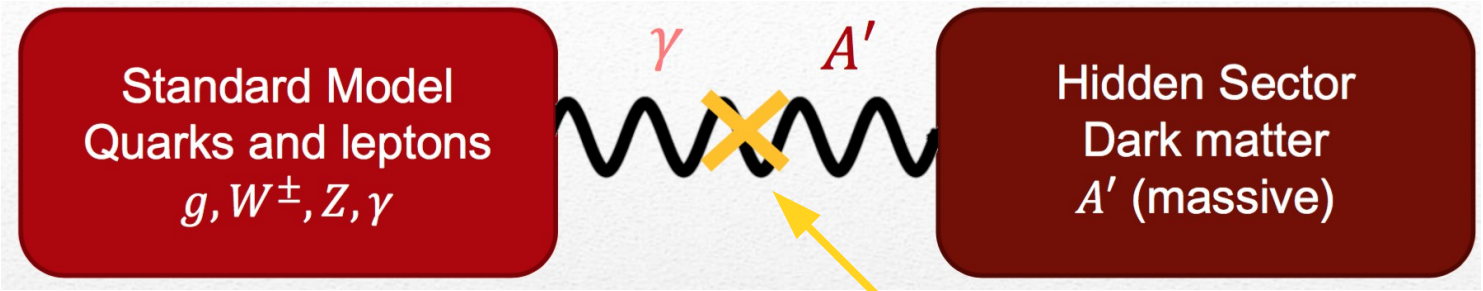
Program for searches for New Physics?

- Phase I parassitic run: 1.44 × 10^{18} POT in 200 days
- Possible Phase II: upgrade of the detector + larger luminosity (~ 10^{20} POT?)

Main features:

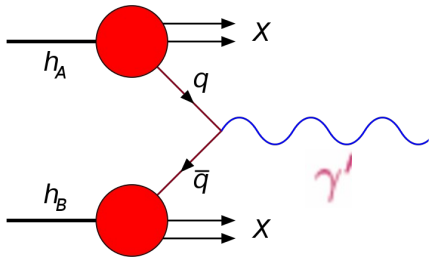
- Higher beam energy (if compared to LSND, MiniBooNE, …)
- Smaller detector-target distance (if compared to CHARM, NOMAD, ...)

A minimal dark photon model

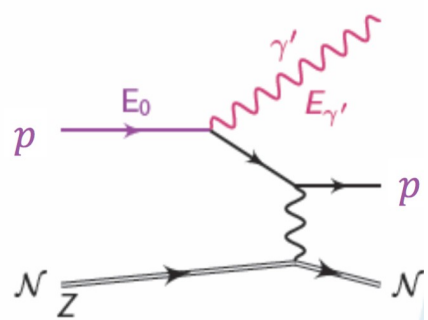


$$\frac{\epsilon}{2\cos\theta} F'_{\mu\nu} \hat{B}^{\mu\nu}$$

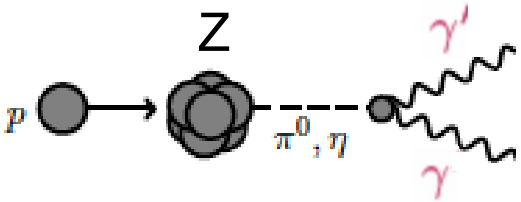
Several production mechanisms
at proton fixed target experiments



Drell-Yan (DY)
production



Bremsstrahlung



Meson decay
(also heavy mesons!)

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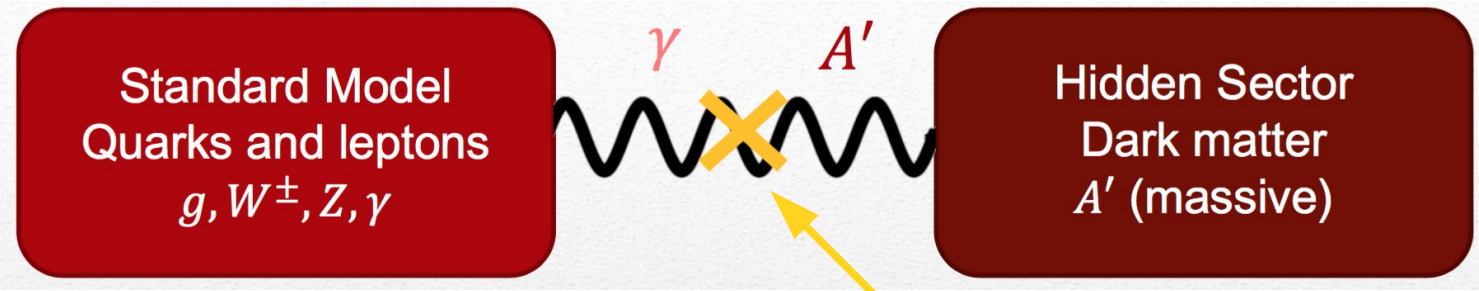

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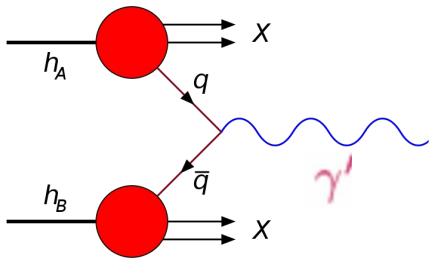

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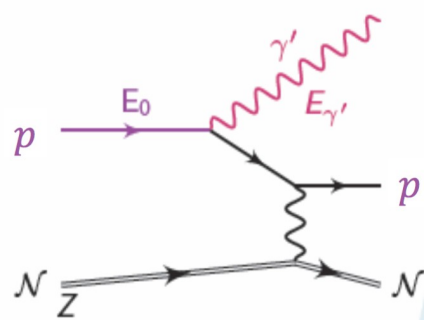

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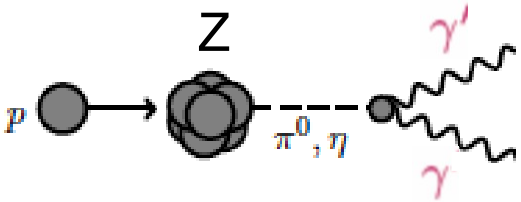

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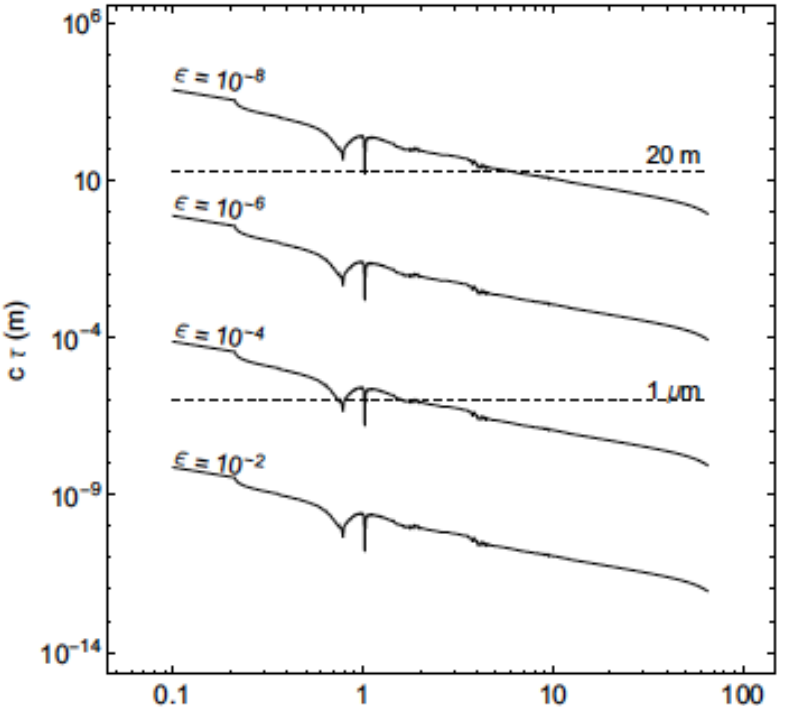
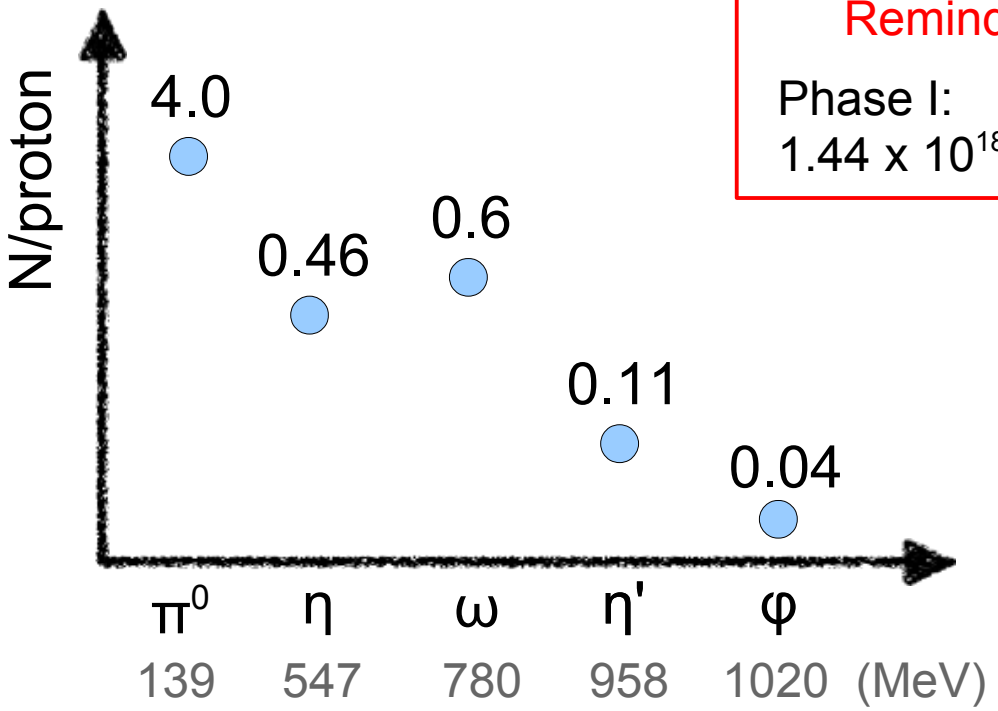
Dark photon life time



Curtin, Essig, SG, Shelton, 1412.0018

Huge meson production at SeaQuest



Reminder

Phase I:
1.44 x 10^{18} POT

Berlin, SG, Schuster, Toro, in progress

$$\begin{aligned}
\mathbf{BR}(\pi^0 \to \gamma\gamma) &= \mathbf{98.8\%} \\
\mathbf{BR}(\omega \to \pi^0\gamma) &= \mathbf{8.28\%} \\
\mathbf{BR}(\eta \to \gamma\gamma) &= \mathbf{39.4\%} \\
\mathbf{BR}(\eta' \to \rho\gamma) &= \mathbf{29.1\%} \\
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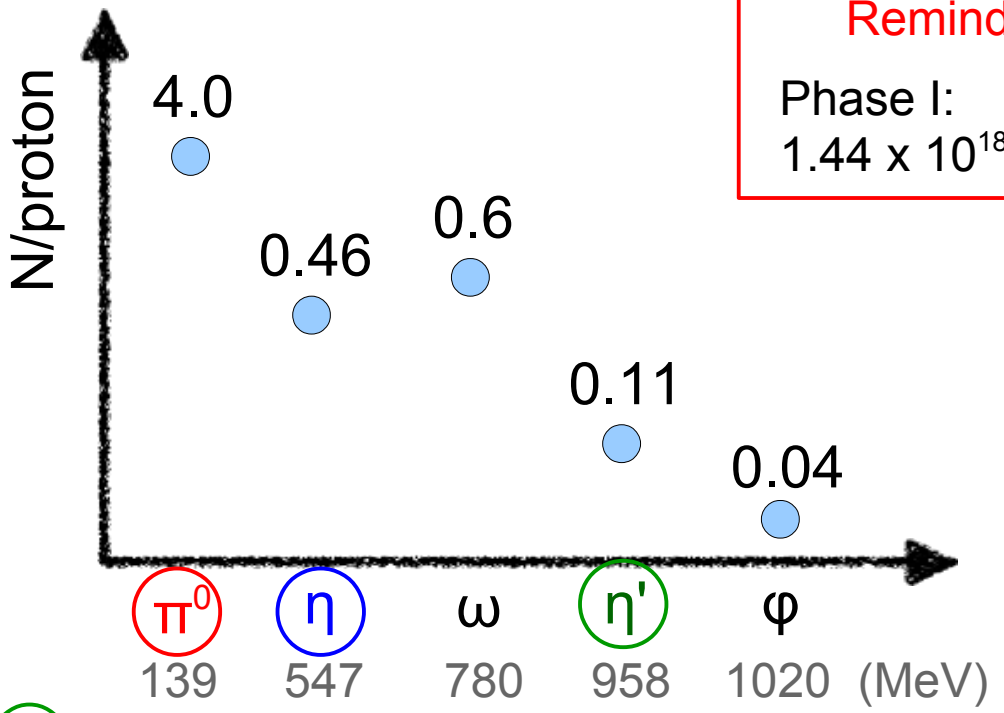

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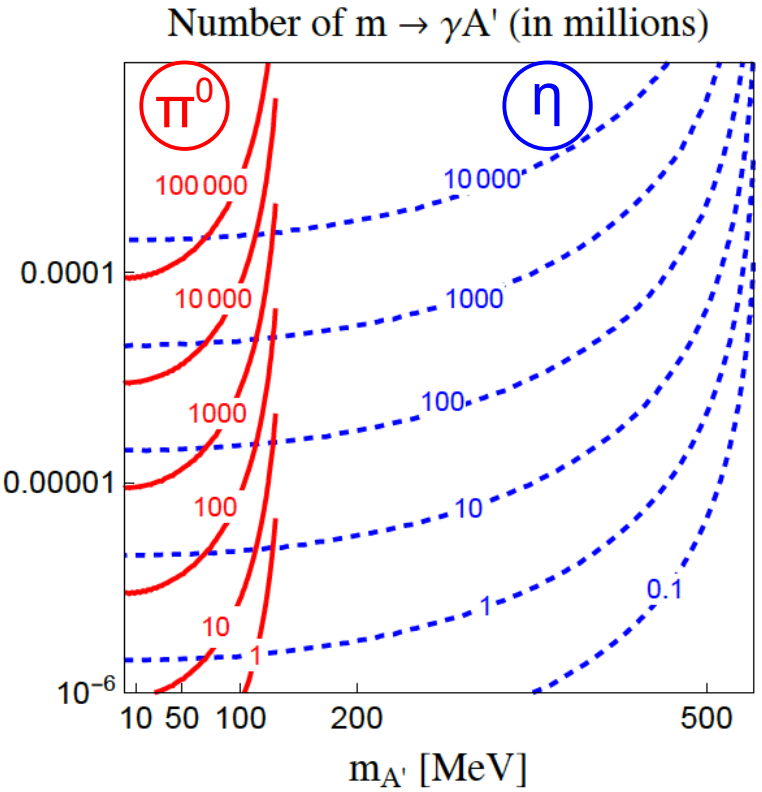


η'

$$\mathrm{BR}(\eta' \to \gamma A') \sim 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\eta'}^2}\right)^3 \times \mathrm{BR}(\eta' \to \gamma\gamma)$$

$$\frac{N}{N_p} \sim 4.8 \times 10^{-3}\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\eta'}^2}\right)^3 \sim 4.9 \times 10^{-4} \times \epsilon^2$$

as opposed to electrons:

$$\frac{N}{N_e} \sim 5\epsilon^2 \left(\frac{m_e^2}{m_{A'}^2}\right) \sim 2.6 \times 10^{-6} \times \epsilon^2$$

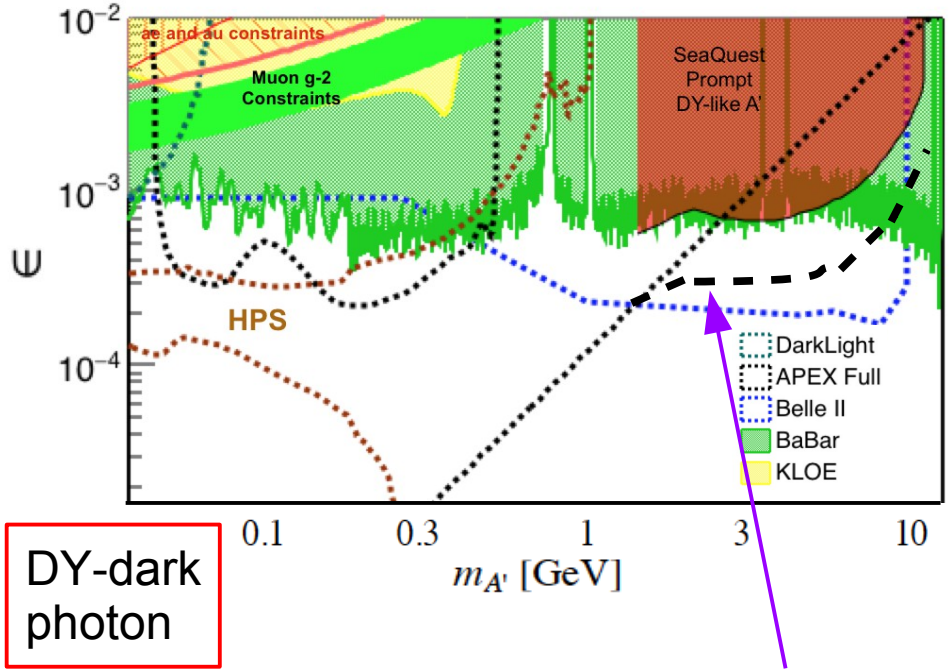
see also Gardner, Holt, Tadepalli, 1509.00050

Prompt vs. displaced dark photons

Before 2017, SeaQuest could only see prompt di-muons

Expected sensitivities for Phase I (solid) & Phase II (dashed)

In collaboration with the SeaQuest collaboration:



DY-dark photon

Systematics limited (S/B ~ few 10^{-5})

Improvement can be achieved with a better mass resolution (6% assumed)

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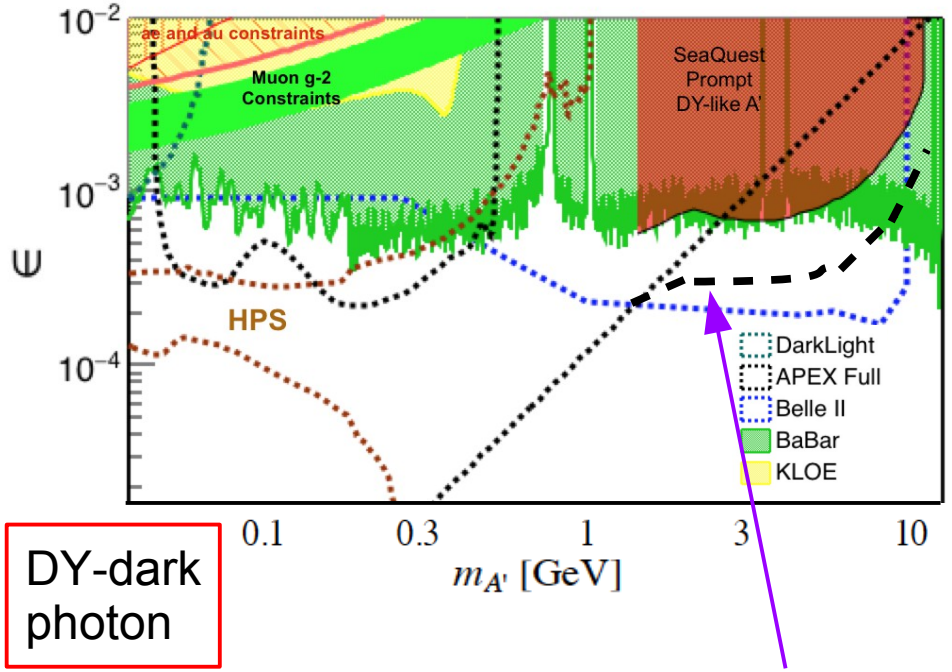

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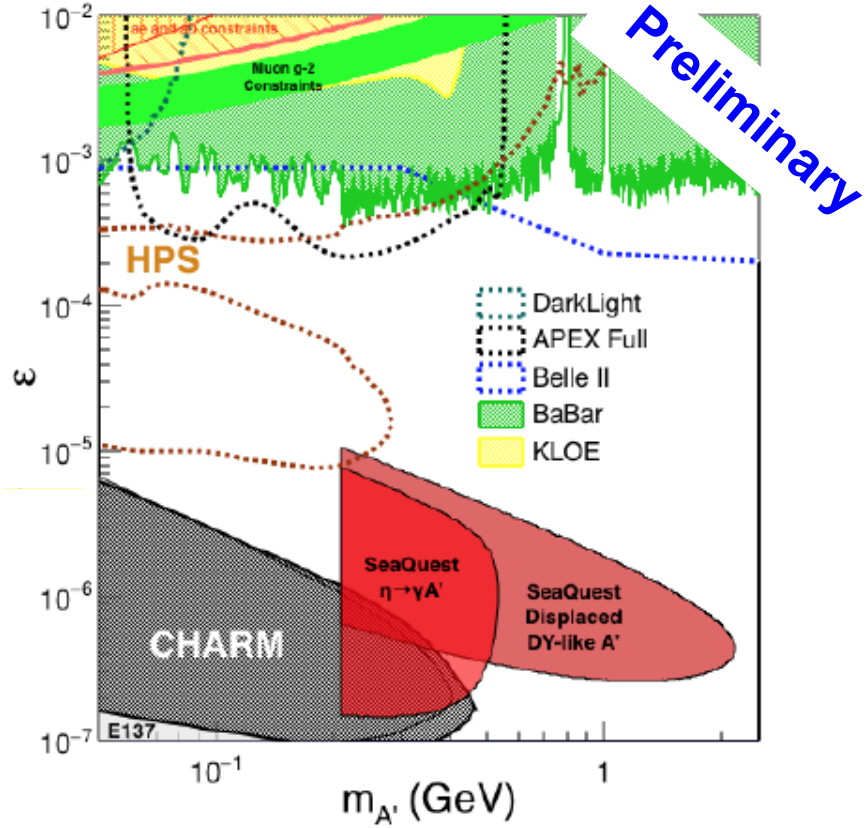

We ask for displaced muons originating after the bump

➡ almost background 0 experiment

Beyond resonance searches: the IDM case

With the installation of the displaced trigger,
the SeaQuest program broadens considerably!

Any dark sector coupled to protons and muons (even very weakly)

What is the physics case we can establish?

Work in progress on SIMP models, inelastic DM models, and right handed neutrinos

Berlin, SG, Schuster,
Toro, in preparation

Beyond resonance searches: the IDM case

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Any dark sector coupled to protons and muons (even very weakly)

Inelastic Dark Matter

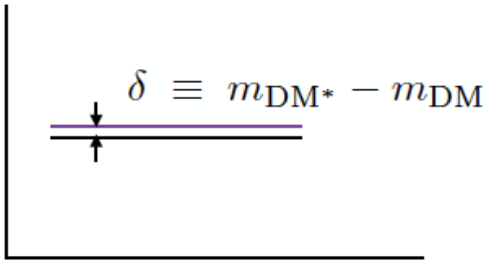
Tucker-Smith, Weiner
0101138, 0402065

In a nutshell:

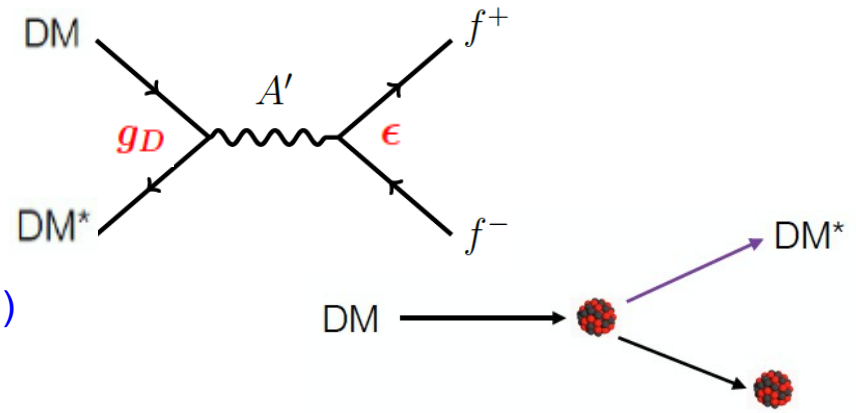
- Dirac spinor charged under a $U(1)_D$ symmetry $\psi = (\eta, \xi^\dagger)$

$$-\mathcal{L} \supset m_D \eta\xi + \frac{m_\eta}{2}\eta\eta + \frac{m_\xi}{2}\xi\xi + h.c.$$

It is natural that m_η, m_ξ << m_D



- Main interactions are inelastic



- leading annihilation process DM DM* → SM
- very suppressed direct detection signals

(see however Bramante et al., 1608.02662)

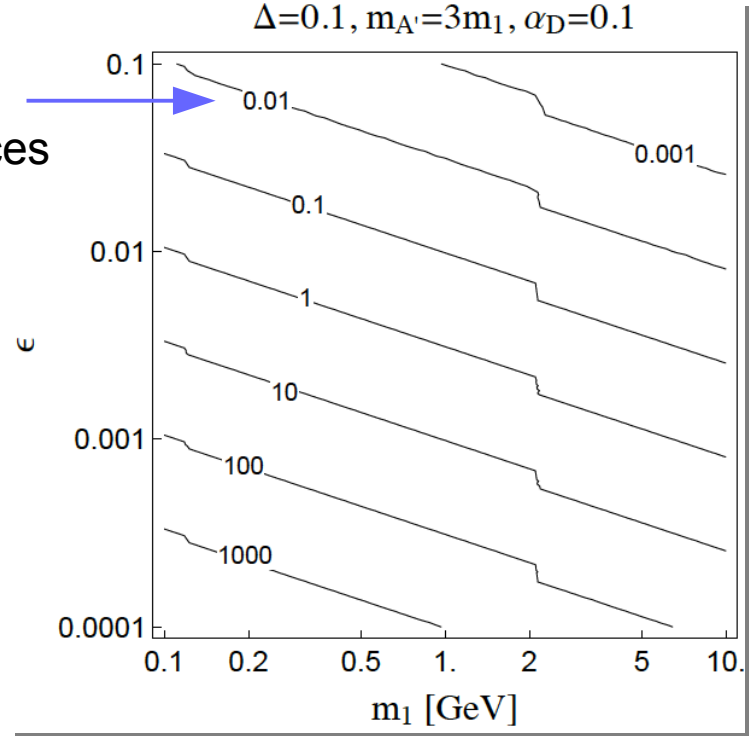
A long lived DM excited state

Berlin, SG, Schuster, Toro, in preparation

Life time of the excited state (in meters)

Also this region typically produces a sizable displacement

(large boost of the system)



$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2 \alpha \alpha_D \Delta^5}{15\pi m_{A'}^4}, \quad \Delta \equiv \frac{m_2 - m_1}{m_1}$$

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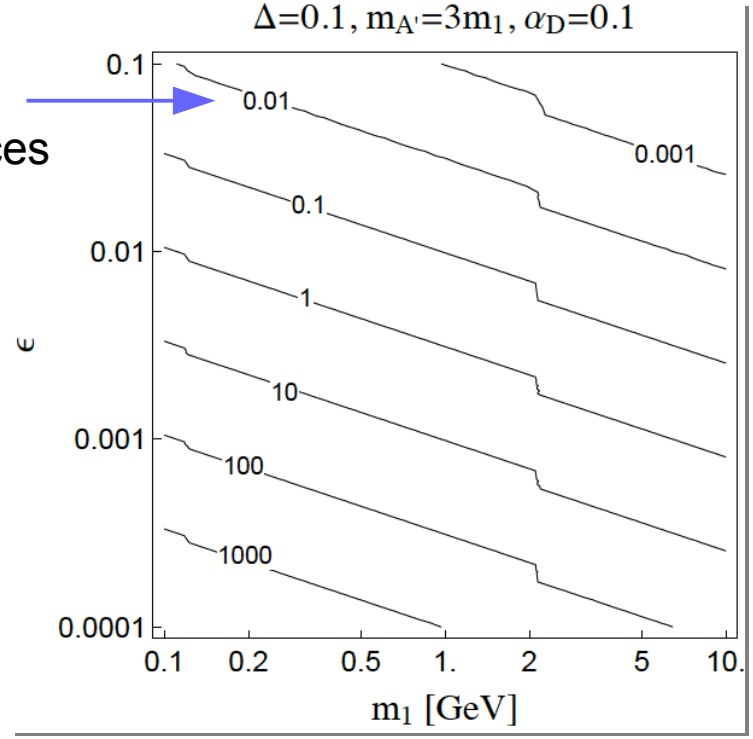

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A variety of search strategies:

Production topologies:

$(\gamma, j) A' \to \chi_2 \chi_1 \to (f \bar{f} \chi_1)\chi_1$

$(\gamma, j) A' \to f \bar{f}$ (suppressed by ε^2)

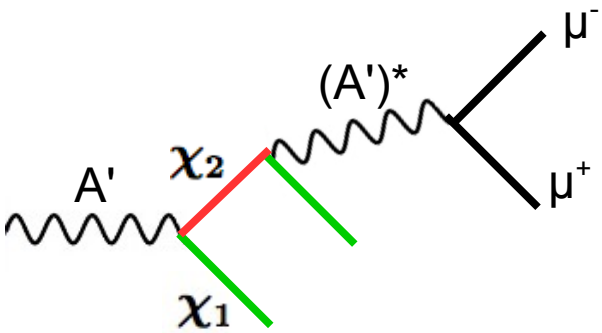
- Babar (and future B-factories)
  - visible (monophoton + 2 electrons/muons)
  - invisible (monophoton + missing)
- LHC
  - monojet
  - proposed search for displaced (soft) muons plus a jet (Izaguirre, Krnjaic, Shuve, 1508.03050)
- (low energy) electron and proton fixed target experiments (BDX, LSND, E137...)
  - electrons
  - missing mass

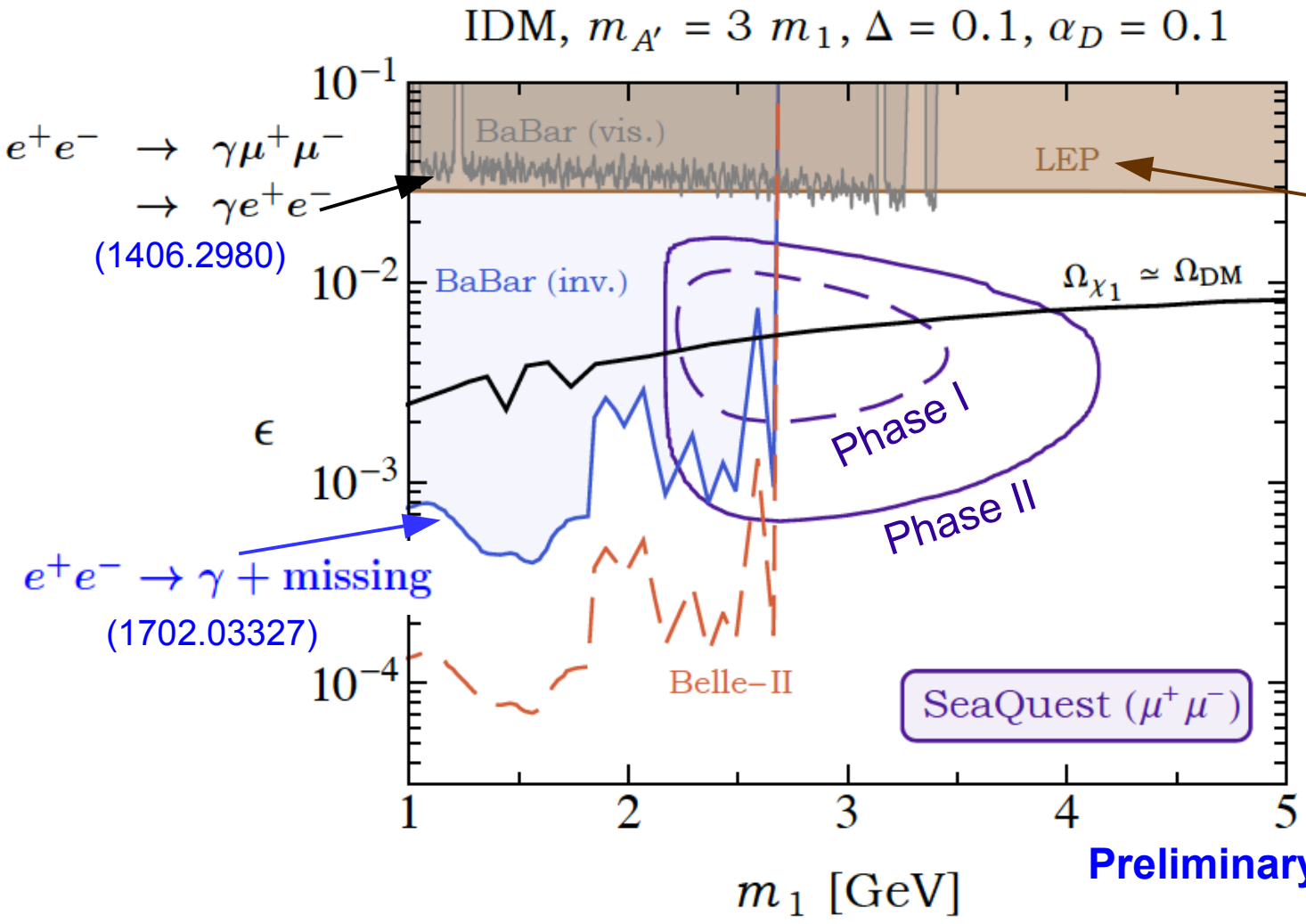
What is the role of SeaQuest?

The SeaQuest reach

$$pp \to A' \to \chi_2\chi_1 \to (\mu^+\mu^-\chi_1)\chi_1$$

Drell-Yan is the main production





Shift in the Z boson mass

Hook, Izaguirre, Wacker, 1006.0973
Curtin, Essig, SG, Shelton, 1412.0030

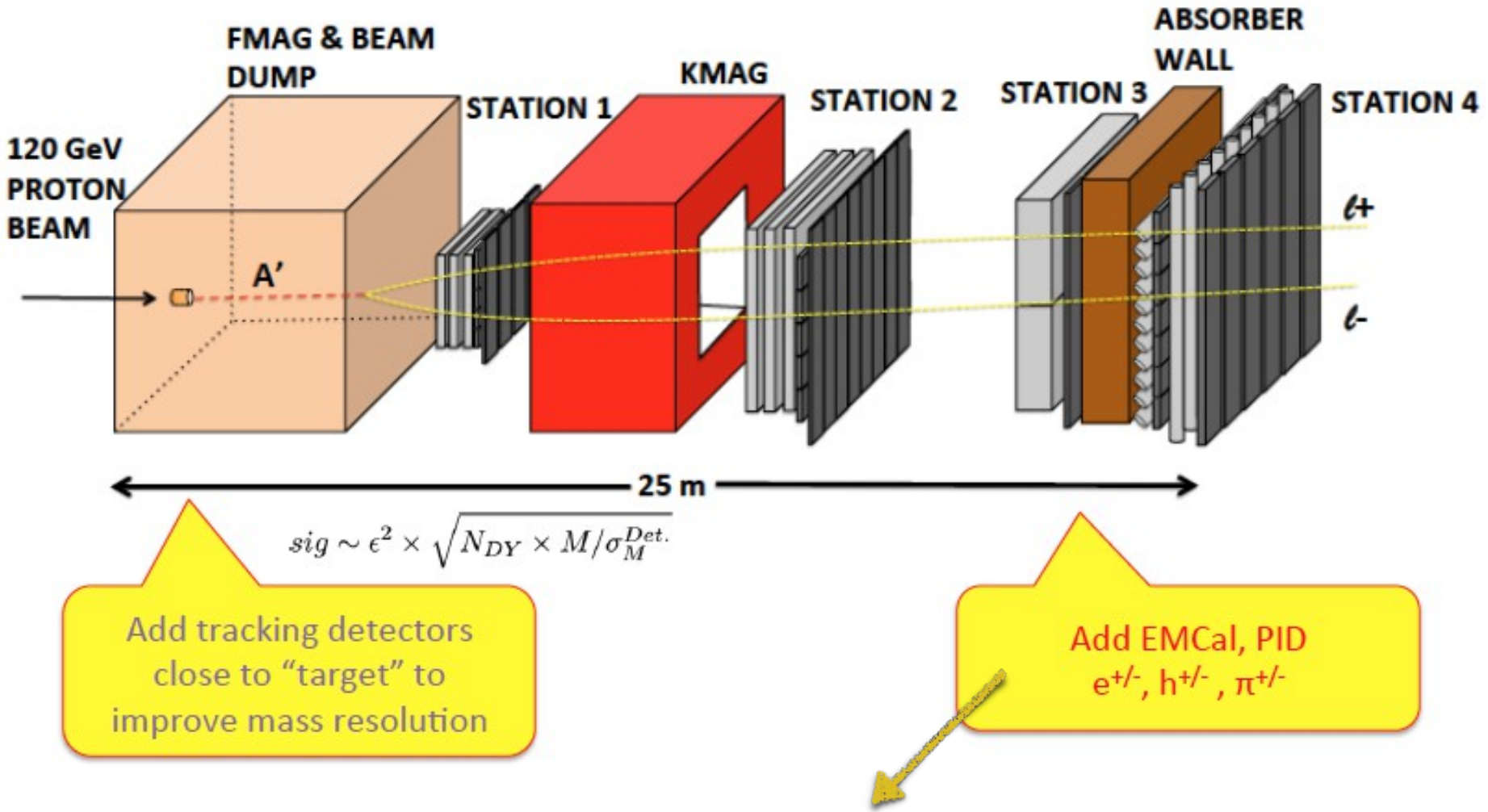
Phase I: $1.44 \cdot 10^{18}$ POT
Phase II: ~10^{20} POT

Preliminary

Berlin, SG, Schuster, Toro

SeaQuest phase II: more lumi & upgrade

Plan for 2020 - 2025

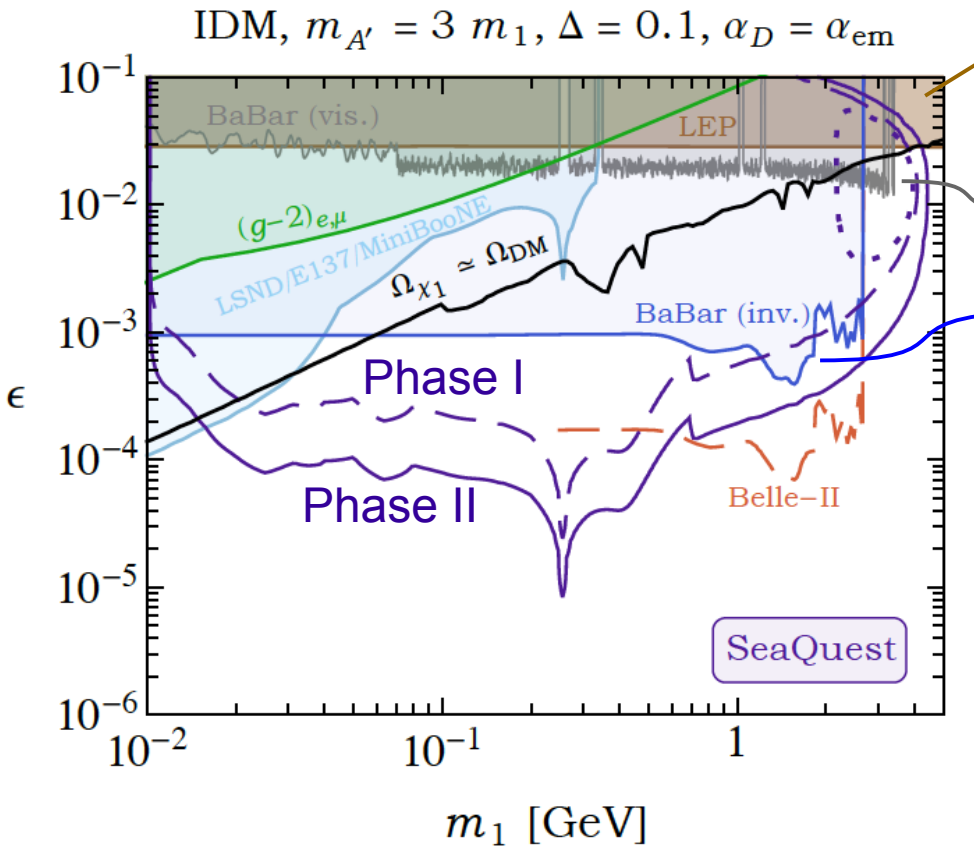


- Lighter dark sectors (decaying to electrons)
- More possibilities for heavier dark sectors (decaying to hadrons)

IDM SeaQuest reach, electron signature

$$pp \to A' \to \chi_2\chi_1 \to (e^+e^-\chi_1)\chi_1$$

Berlin, SG, Schuster, Toro, in preparation



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$e^+e^- \to \gamma\mu^+\mu^-, \gamma e^+e^-$ (1406.2980)

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Preliminary Berlin, SG, Schuster, Toro

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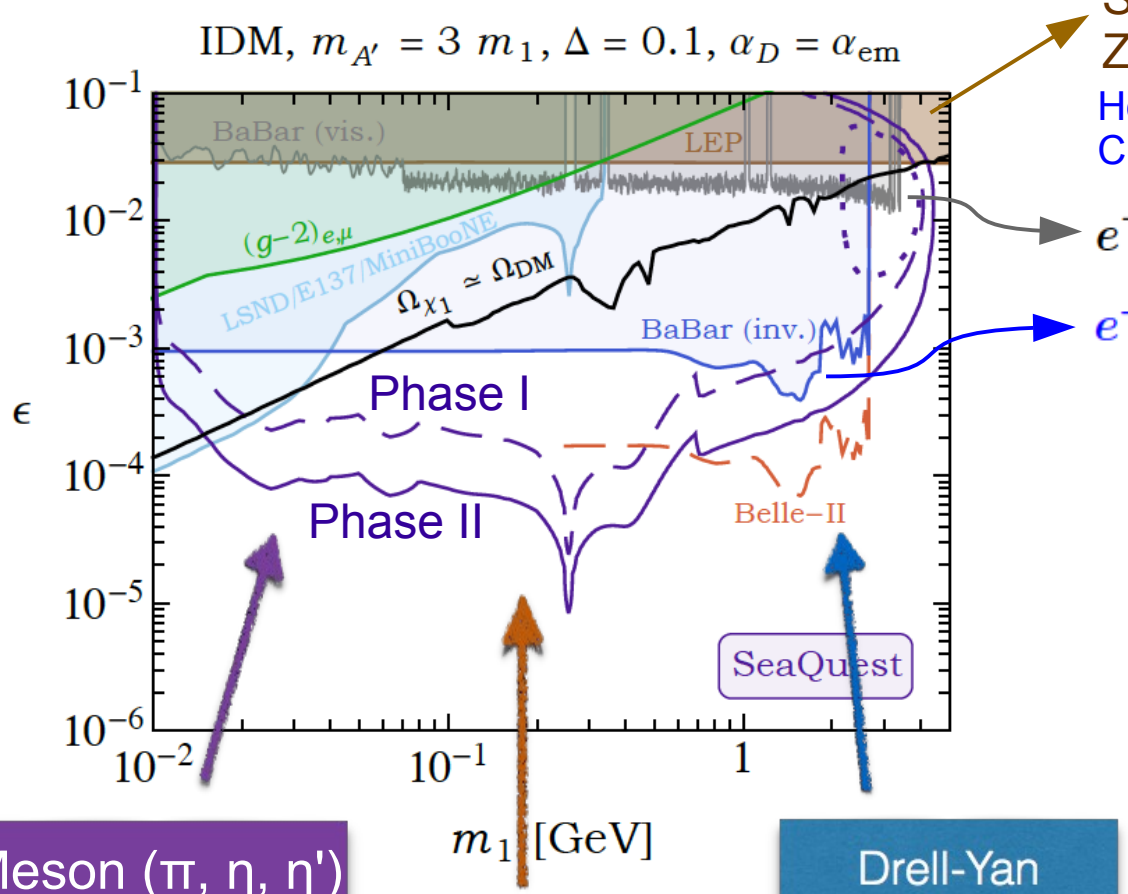

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Meson (π, η, η') production

Bremsstrahlung production

Drell-Yan production

Preliminary Berlin, SG, Schuster, Toro

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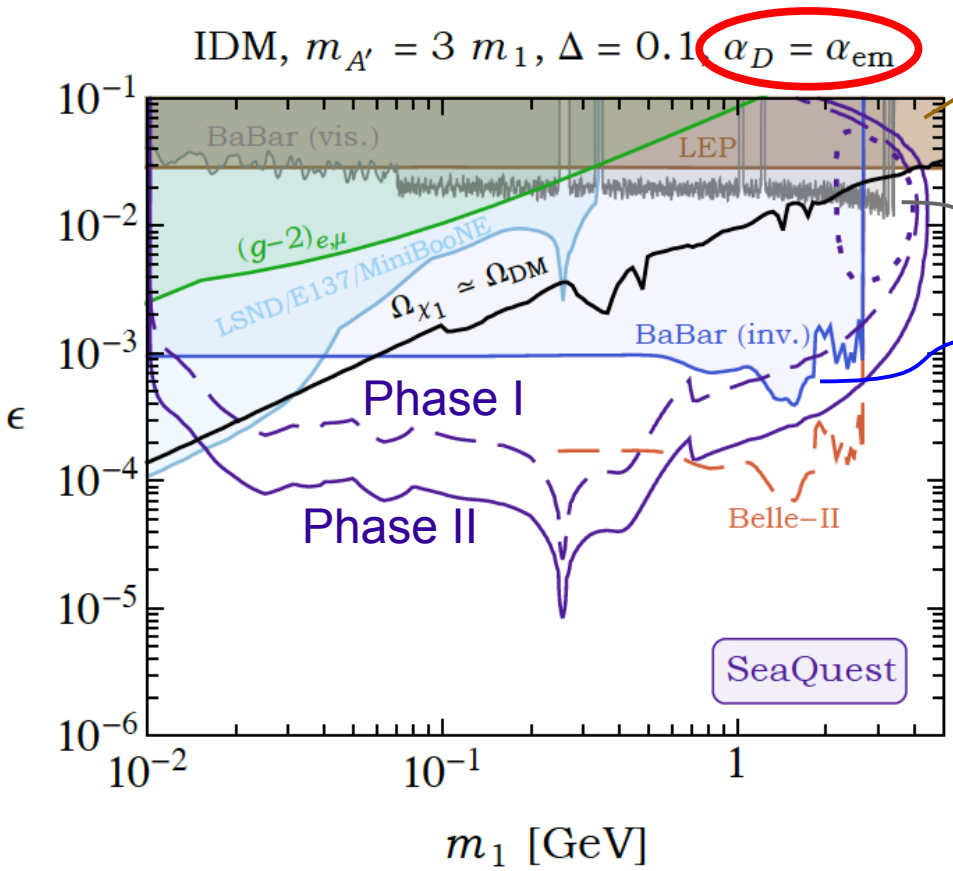

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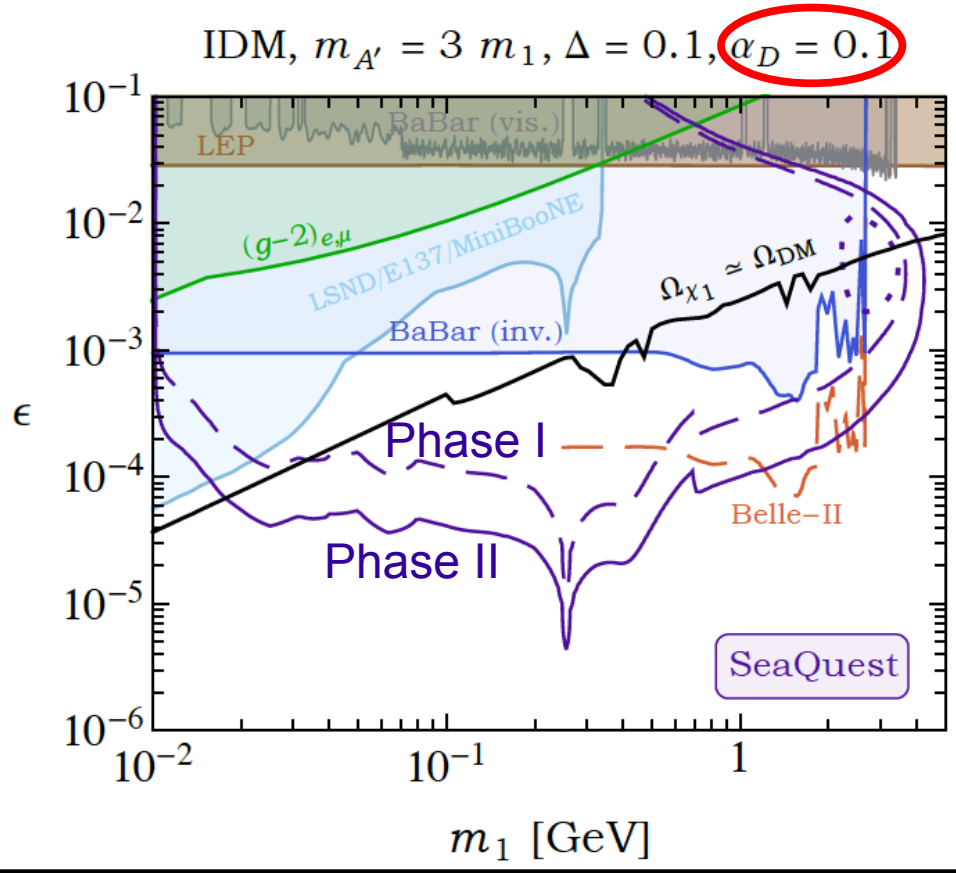
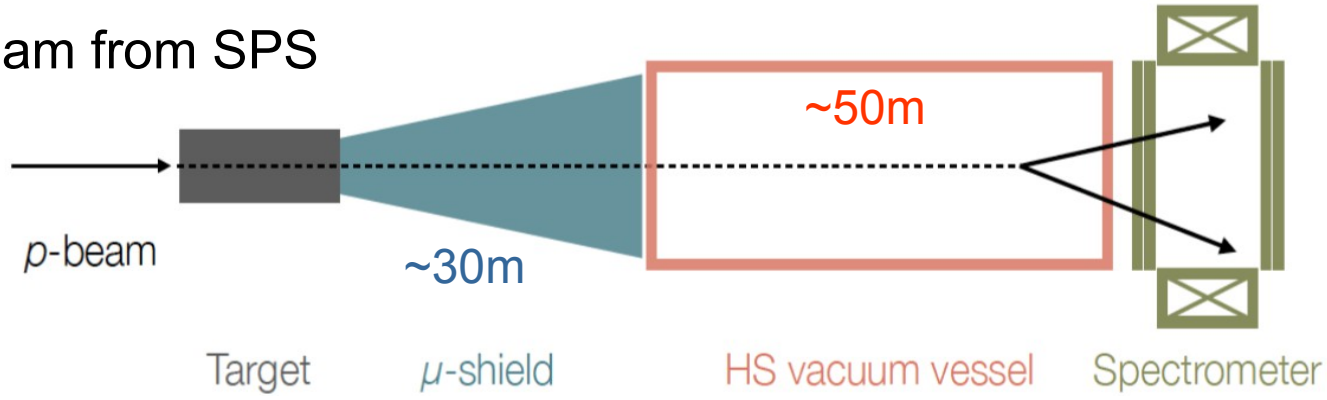


Preliminary Berlin, SG, Schuster, Toro

Future CERN effort

Ongoing proposal for the ShiP experiment

- 400 GeV CERN proton beam from SPS
- 10^{20} POT



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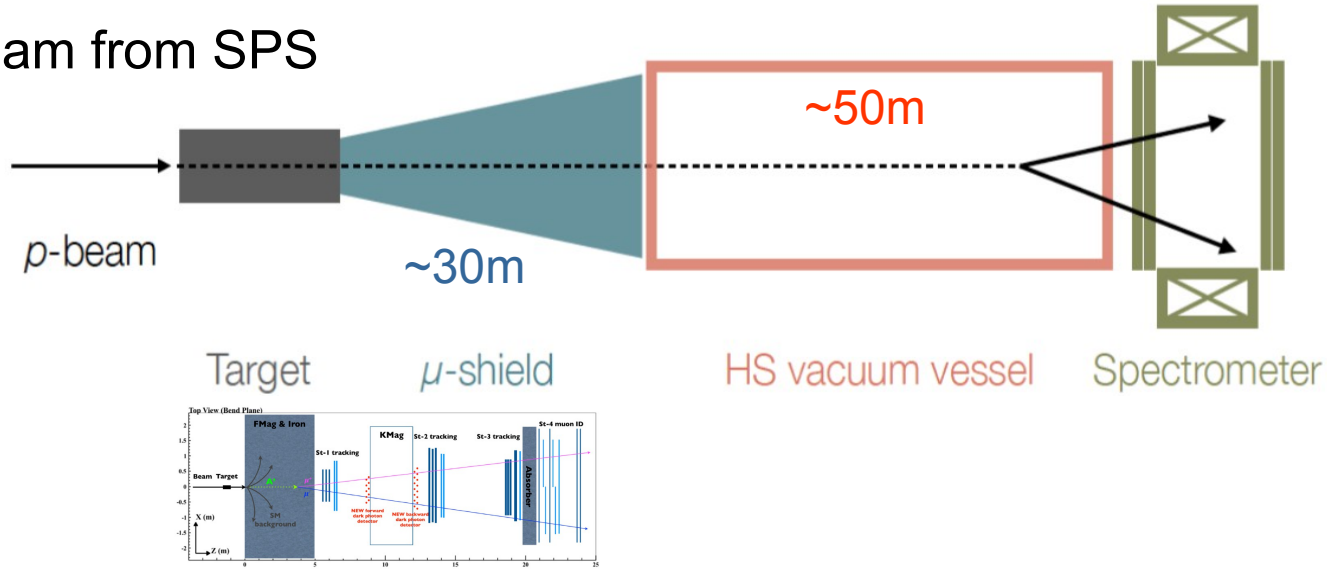
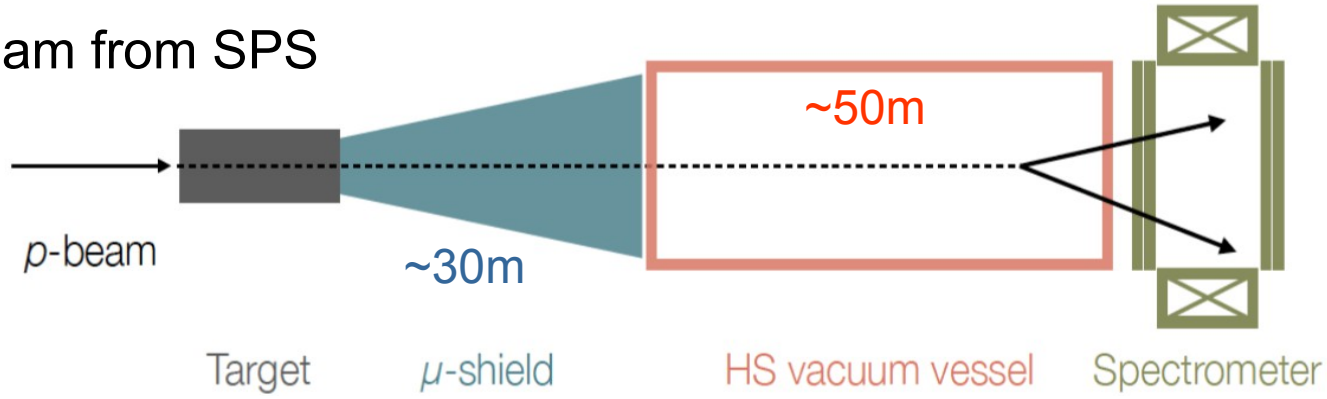


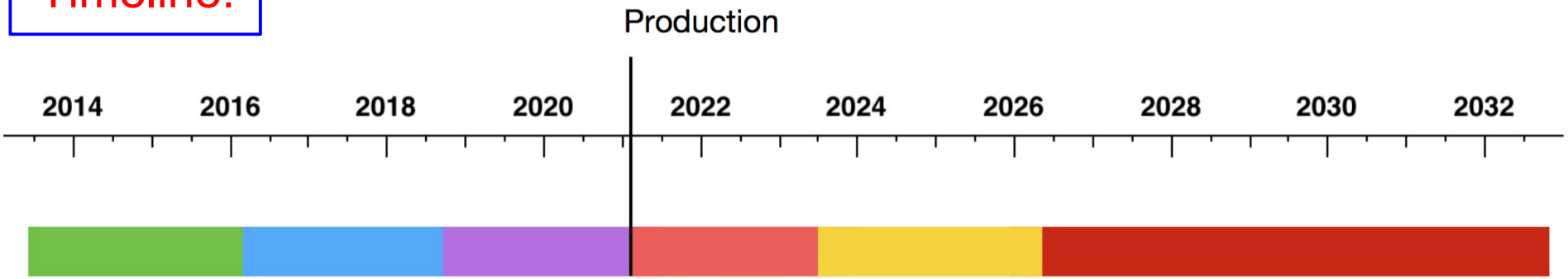
Future CERN effort

Ongoing proposal for the ShiP experiment

- 400 GeV CERN proton beam from SPS
- 10^{20} POT



Timeline:



SeaQuest

Phase I — Phase II - - - - - - - - - - additional upgrades/more lumi?

Future CERN effort

Ongoing proposal for the ShiP experiment

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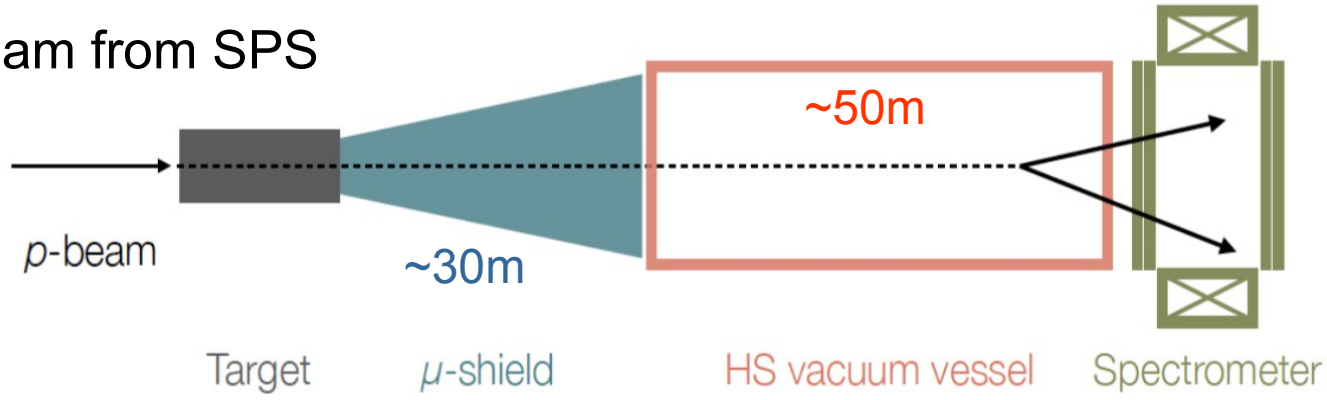
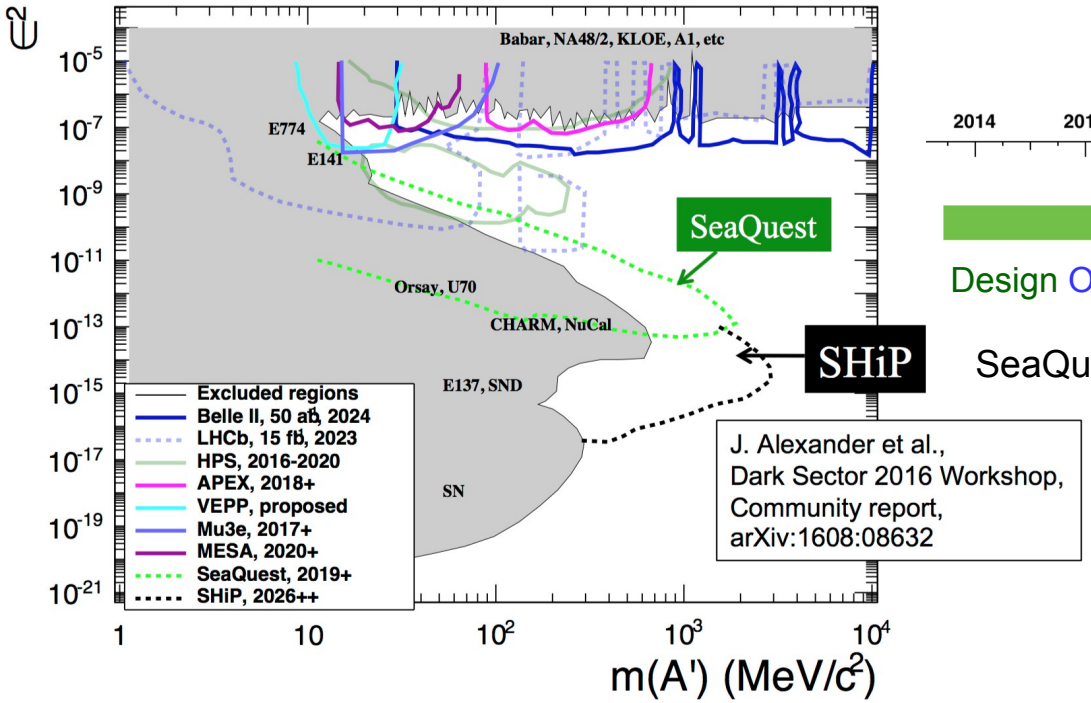
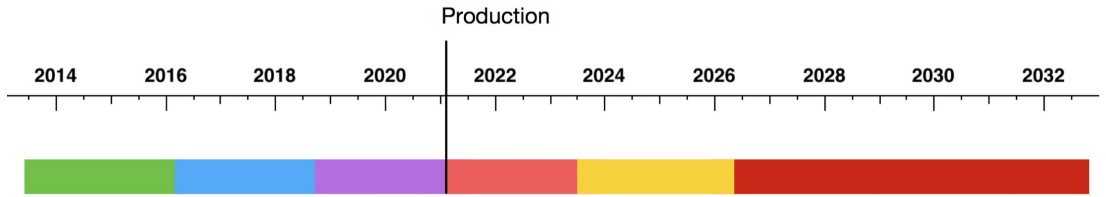




J. Alexander et al., Dark Sector 2016 Workshop, Community report, arXiv:1608:08632



SeaQuest

Phase I — Phase II — additional upgrades/ more lumi?

Interesting complementarity with SeaQuest!

Conclusions

High energy proton beam dump experiments

Interesting setup for looking for Dark particles. Huge rates!
Feasible high intensity program for Fermilab

- Beyond di-muon bump-hunt, Seaquest

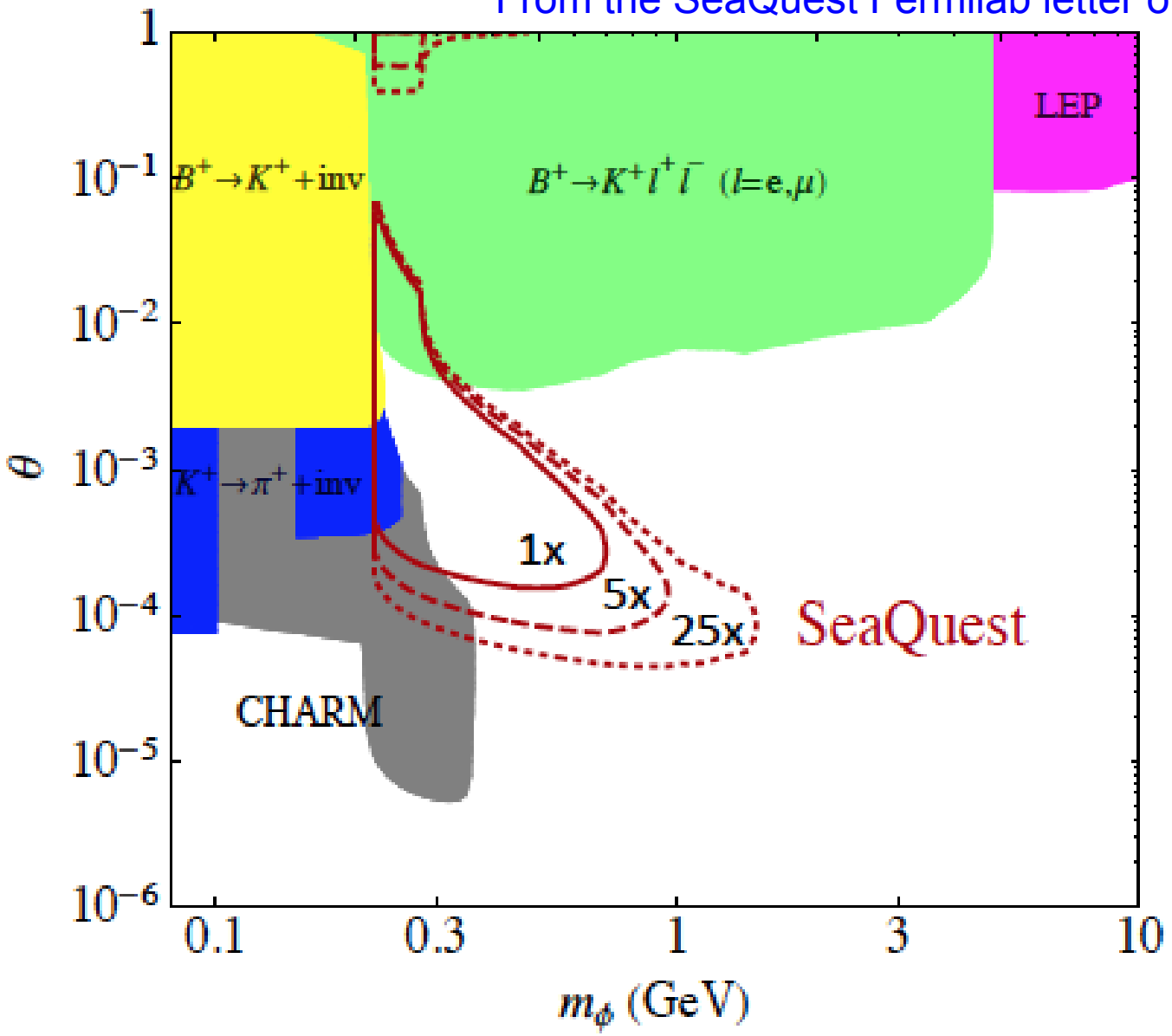
- can efficiently look for displaced signatures
- has a unique opportunity to test large part of the remaining parameter space of Inelastic Dark Matter (IDM) models
- can be upgraded with a EMCal to see electron signatures
- can test additional models: SIMPs, right handed neutrinos, … (in progress)

- Additional "dark signatures" to look for?

- Ultimate program at the ShiP experiment at CERN
(400 GeV proton beam, ~10^{20} POT, starting in ~2026?)

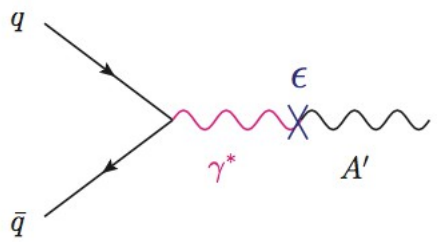
SeaQuest reach for dark scalars

From the SeaQuest Fermilab letter of intent

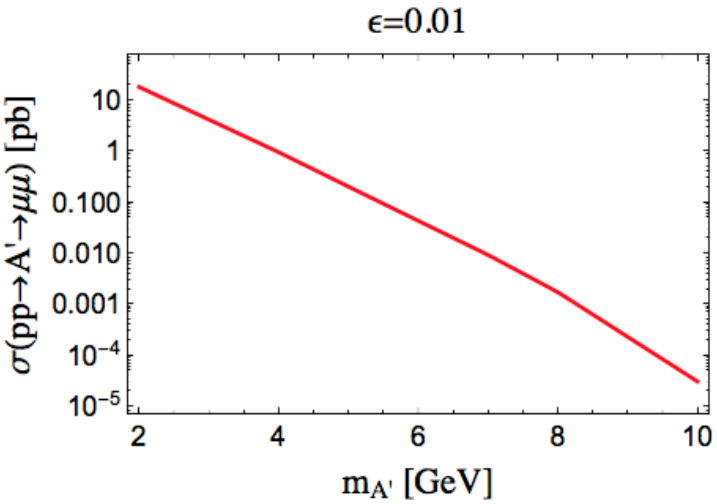


Drell-Yan, prompt

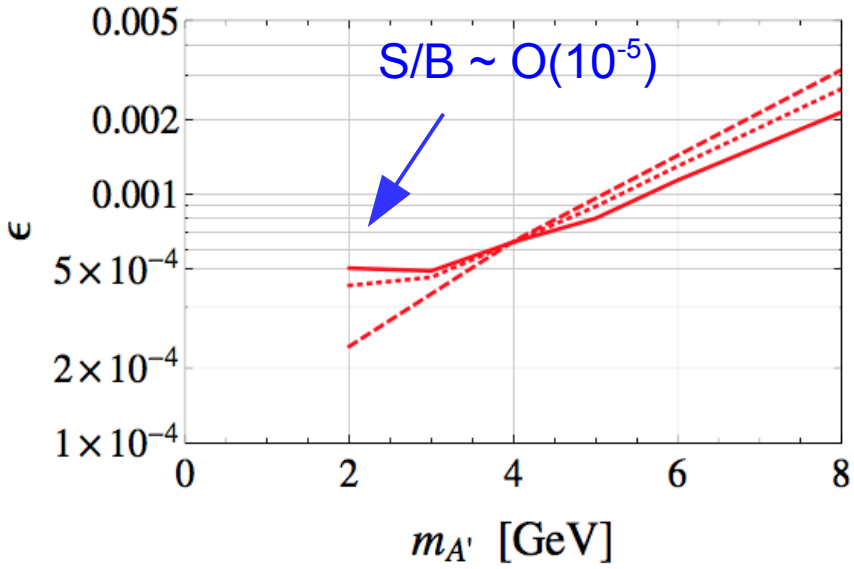
The cross sections for dark photon production are rather sizable



Expected lumi: 35 ab^{-1}



Our preliminary reach:



The exact reach depends sizably on the mass resolution and on the momentum of the two muons

- —— E_μ > 10 GeV, p_x/p_Z>0.05 and dM = 225 MeV
- – – – E_μ > 1.5 GeV and dM = 225 MeV
- ····· E_μ > 10 GeV, p_x/p_Z>0.05 and dM = 6% $m_{A'}$ p_y/p_Z<0.1