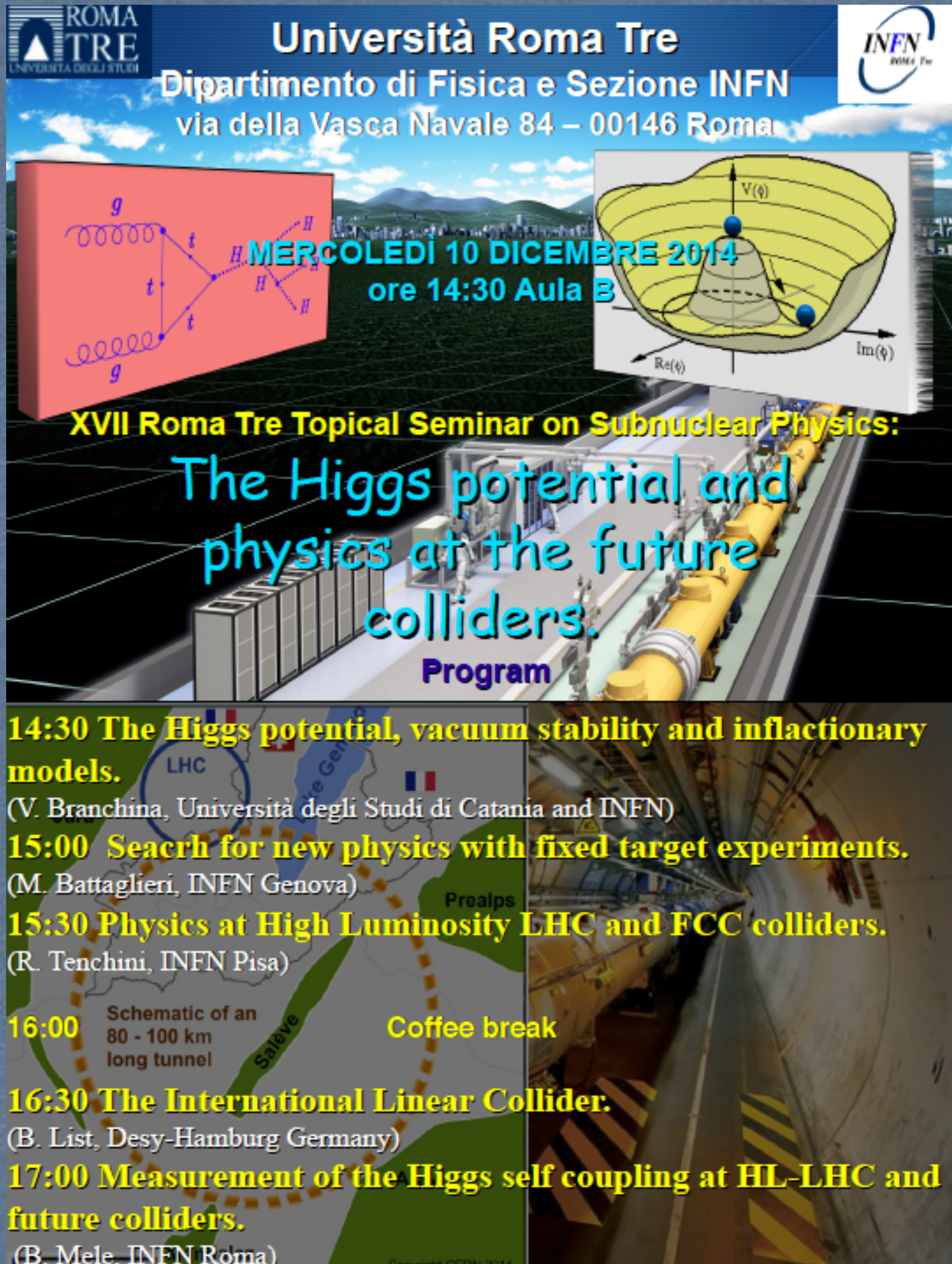
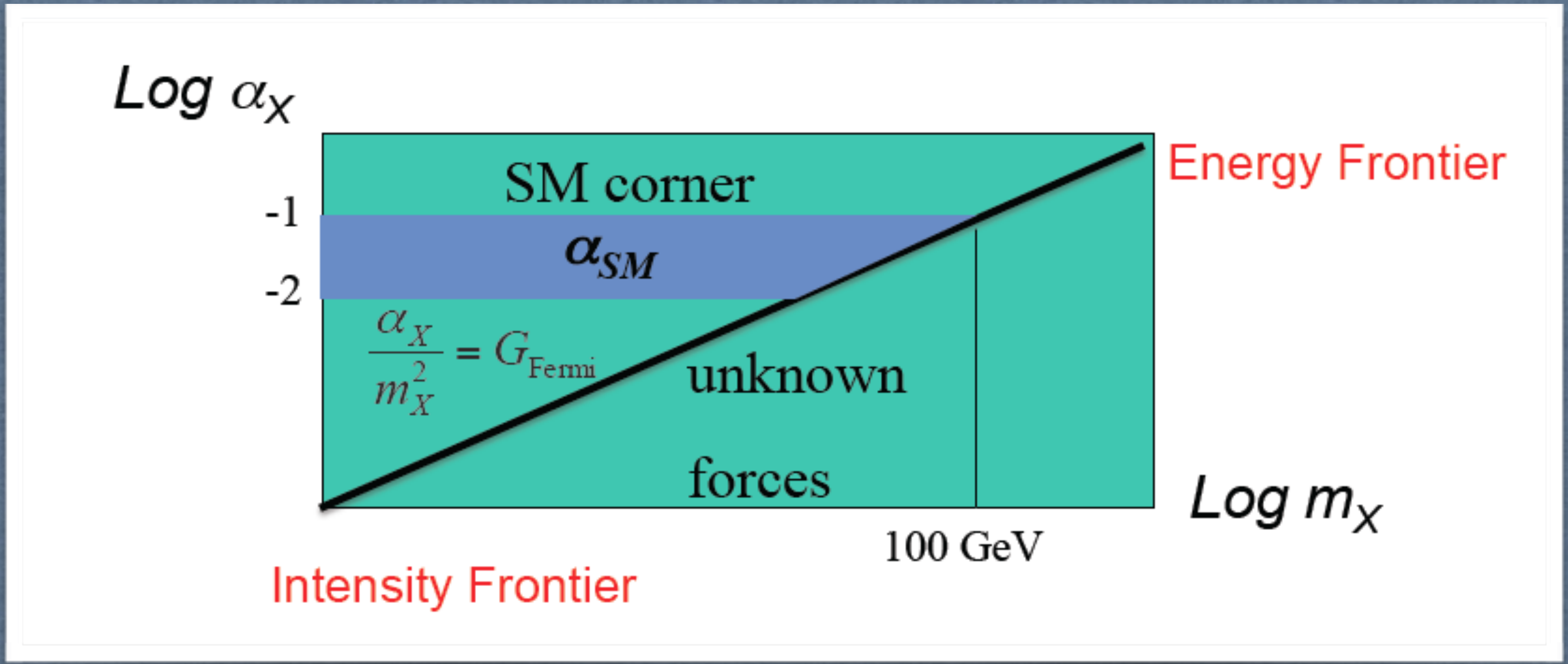


Search for new physics with fixed target experiments

M.Battaglieri
INFN-GE, Italy

- ✳New forces and the vector portal
- ✳Fixed target experiments
- ✳Visible and invisible decays (Light Dark Matter)

How to look for new physics



LHC range: m_x~1TeV, $\alpha_x \sim \alpha_{SM}$

First results show no hints of new strongly-interacting states or new heavy EW bosons (other than Higgs)

What about if: m_x~1GeV, $\alpha_x < 10^{-6}$?

Important progress in neutrino physics, dark matter sensitivity, precise frontier measurements

Precise experiments at low/moderate energy!

New fundamental forces?

4 fundamental interactions known so far:
strong, electromagnetic, weak and gravitational

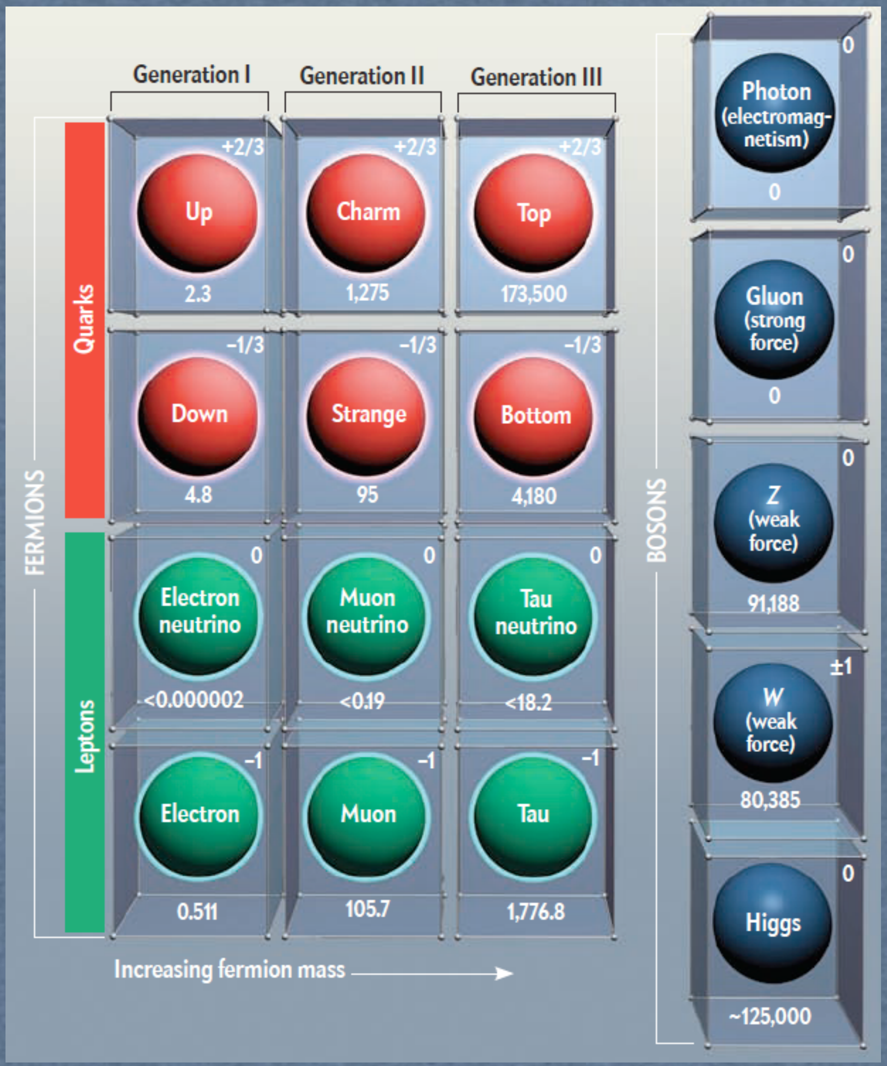
Are there other interactions? how could we know about?
what could be their properties?

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

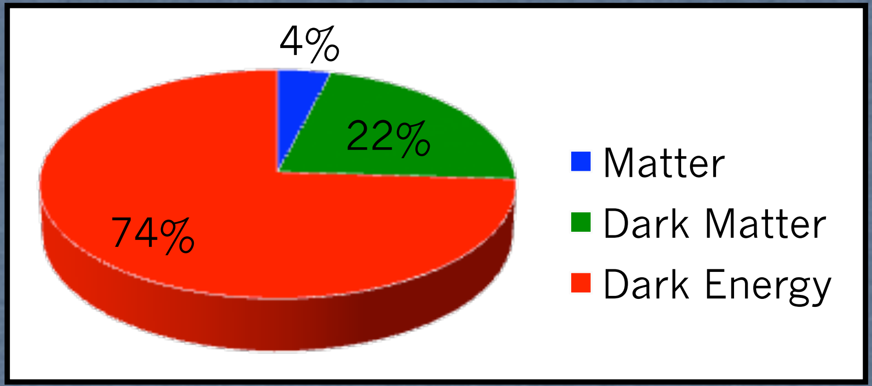
Force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, ...



New particles & new force-carriers

Dark Matter

Spin-1: U bosons ('hidden' or 'dark' photons)
Spin-0: Axions (or axion-like particles)
Spin-0 (scalars): Higgs-like



Neutral doors (Portals) to include DM in the SM

Forces / Matter	EM	Weak	Strong	New force?
Electron	✓	✓	—	—
Neutrino	—	✓	—	—
Quarks	✓	✓	✓	—
Dark Matter?	—	—	—	✓

★ The new force should be weak

★ Different combination of DM and mediator masses are possible:

- heavy WIMPs / heavy mediators
- light WIMPs / light mediators
- heavy WIMPs /light mediators
- light WIMPs / heavy mediators

★ Small number of interactions allowed by Standard Model symmetries with dimensionless couplings

★ Some of them can be tested directly (e.g. rare B-decay)

Vector Portal	$\frac{1}{2}\epsilon_Y\, F^Y_{\mu\nu}F'^{\mu\nu}$	kinetic mixing?
Higgs Portal	$\epsilon_h\,\|h\|^2\|\phi\|^2$	exotic rare Higgs decays?
Neutrino Portal	$\epsilon_\nu\,(hL)\psi$	not-so-sterile neutrinos?
Axion Portal	$\frac{1}{f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	axion-like particles?

New bosons are expected to mediate new interactions

Neutral doors (Portals) to include DM in the SM

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Electron	✓	✓	—	—
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Dark Matter?	—	—	—	✓

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focus of this talk!

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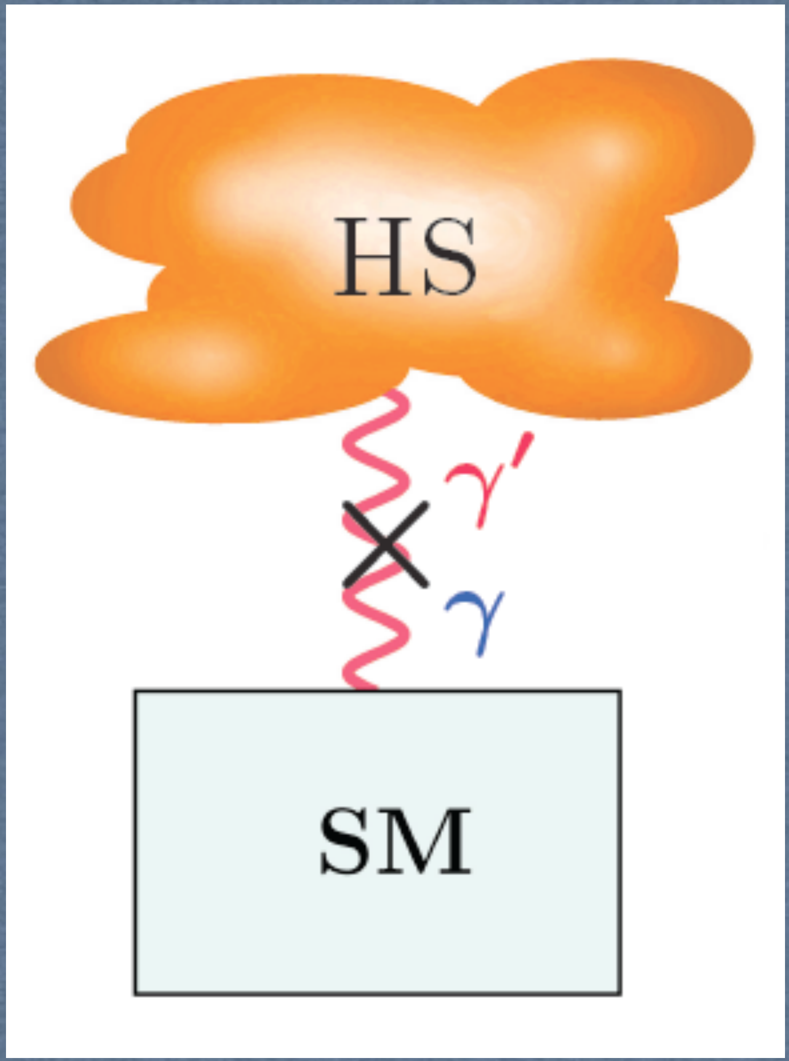
New bosons are expected to mediate new interactions

The vector portal
(Heavy WIMPs - light mediators)

✳Hidden sector (HS)
present in string theory and super-symmetries

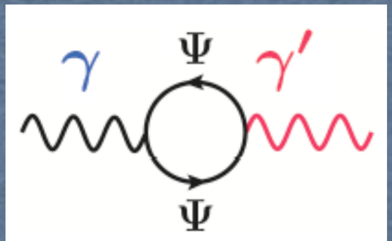
✳HS not charged under SM gauge groups (and v.v.)
no direct interaction between HS and SM
HS-SM connection via messenger particles



A simple way to go beyond the SM (not yet excluded!):

$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ **x extra U(1)**
Color Electroweak Hypercharge Hidden sector

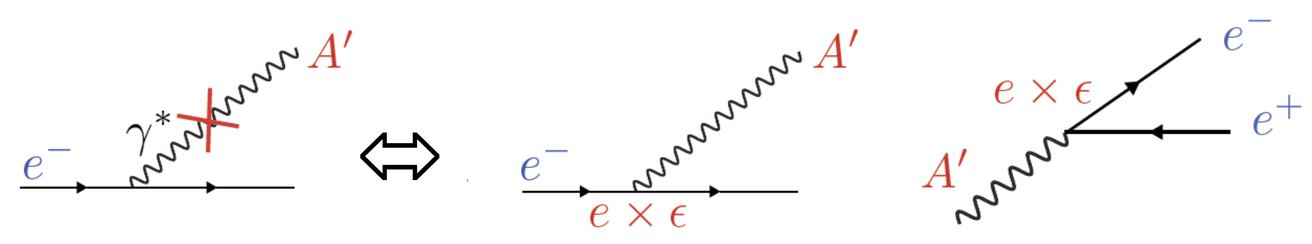
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}\underbrace{X_{\mu\nu}}_{\text{Hidden}}\underbrace{F^{\mu\nu}}_{\text{Visible}} + \frac{m^2_{\gamma'}}{2}X_\mu X^\mu$$



Ψ can be a huge mass scale particle (M_Ψ~1EeV) coupling to both SM and HS

γ'/A' couples to SM via electromagnetic current (kinetic mixing)

→ $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$ $\chi=\varepsilon \sim 10^{-6}$-$10^{-2}$ ($\alpha^{\rm DarkPhoton} = \varepsilon^2 \alpha_{\rm em}$)



The vector portal
(Heavy WIMPs - light mediators)

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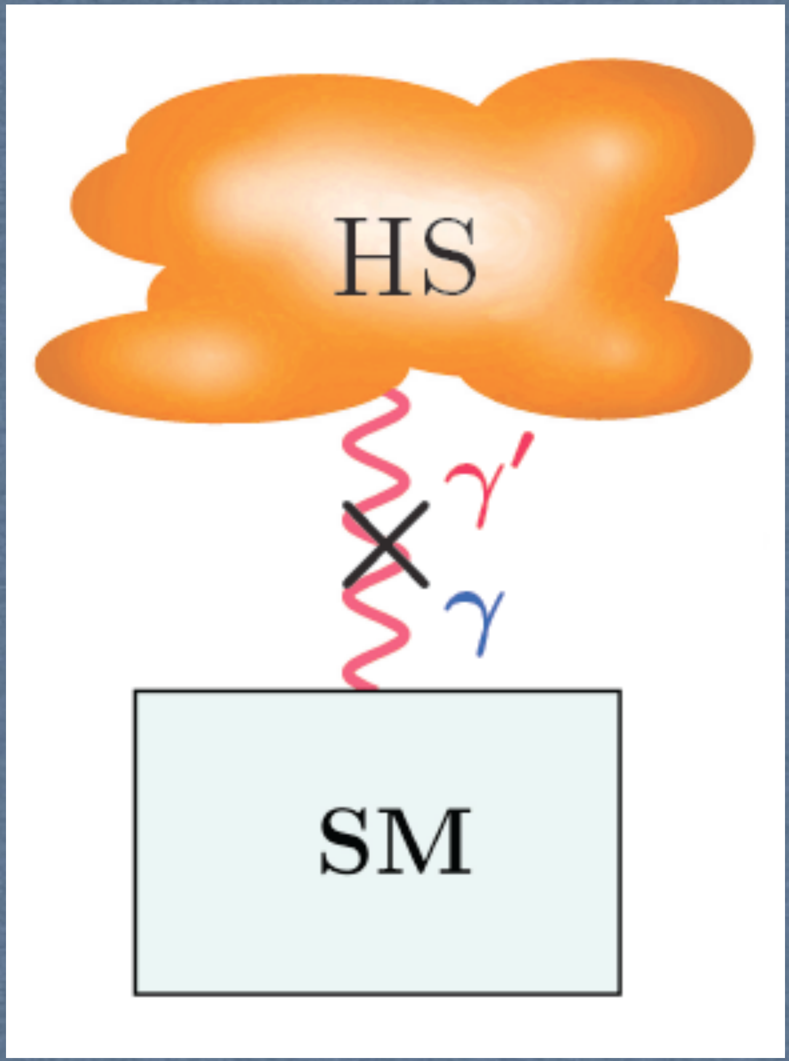

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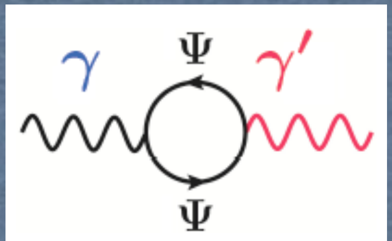
Color | Electroweak | Hypercharge | Hidden sector

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\chi}{2} X^{\text{Hidden}}_{\mu\nu} F^{\mu\nu}_{\text{Visible}} + \frac{m^2_{\gamma'}}{2} X_\mu X^\mu$$



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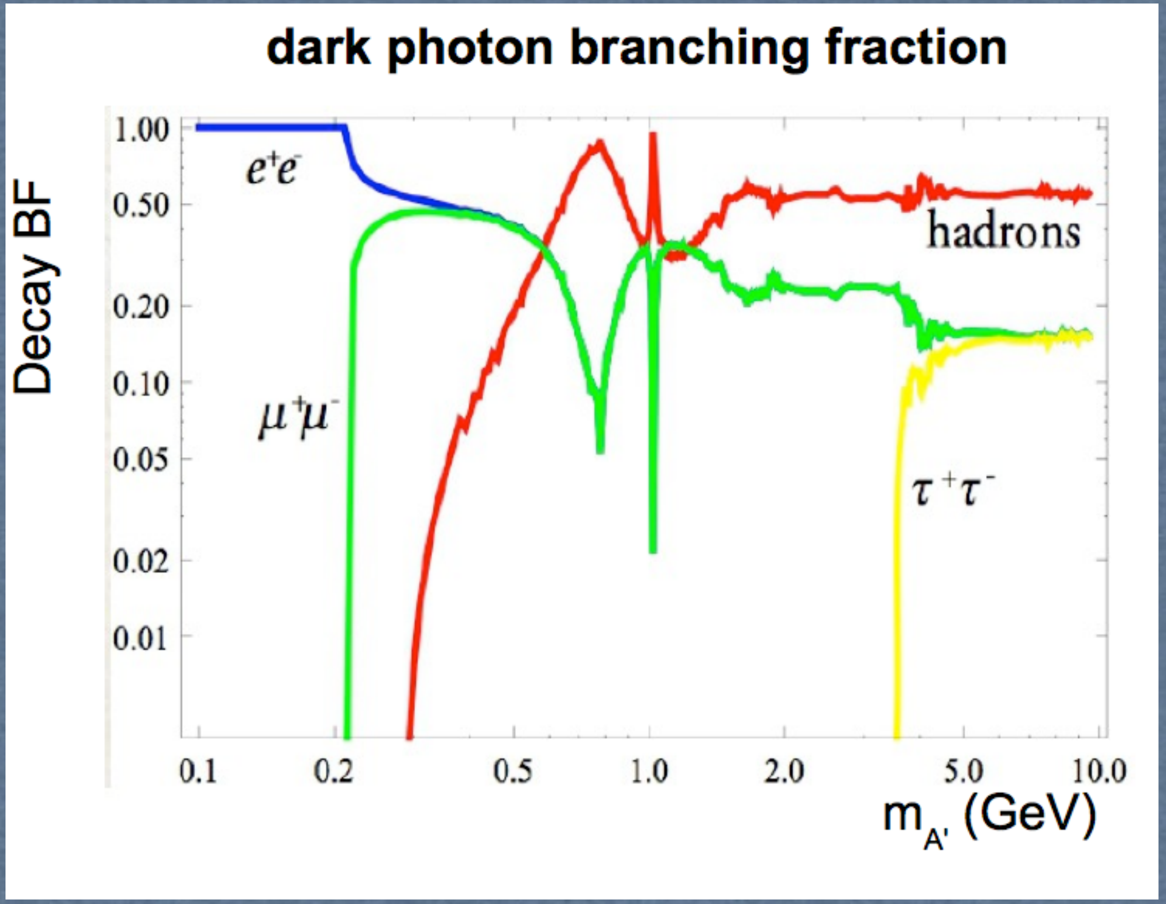
γ'/A' mass depends on the model

→ $\mathbf{m^2_{\gamma'}} \sim \chi M^2_{EW}$ (M_Z or TeV) ~ **MeV - GeV scale**

Consequences
(Heavy WIMPs - light mediators)



Assumptions:
$M_{A'}$>1 MeV and no light dark fermions
- γ'/A' decay back to SM particles
- Prompt decay
- BF (A'→hadrons/A'→leptons) ~ M^2(A')

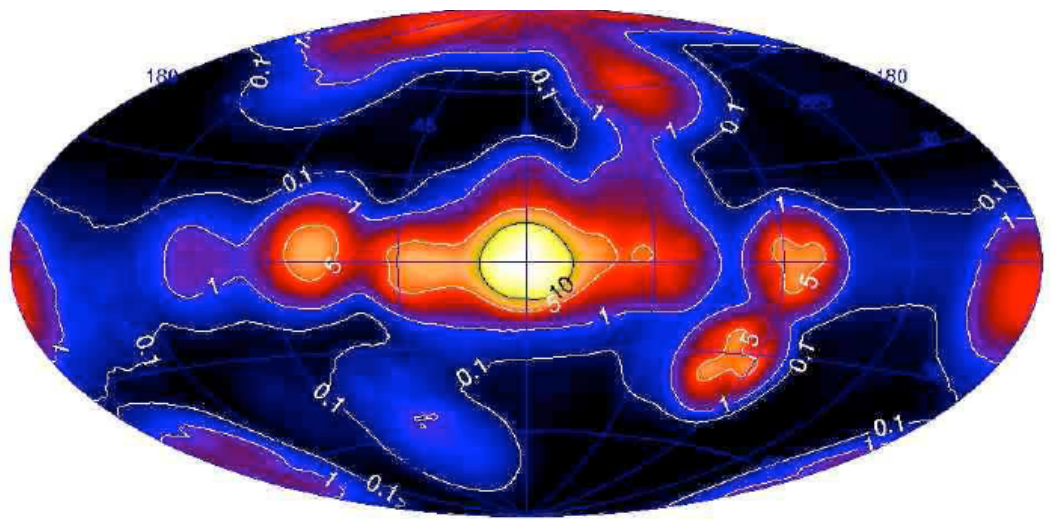
Above 1.2 GeV hadronic decays dominate

γ'/A' decays in leptons
→ **abundance of e^+e^- in Universe**

γ'/A' couples to SM via electromagnetic current (kinetic mixing)
→ **short range modification of EM interaction**

γ'/A' couples weakly to SM particles
→ **long lived states**

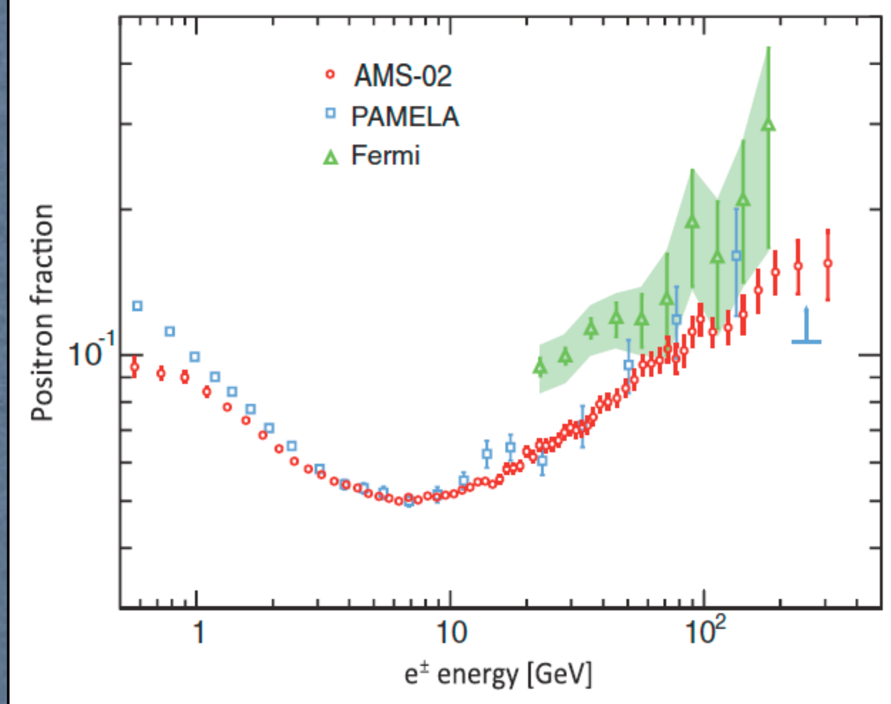
Astrophysical motivation: the 511γ keV line

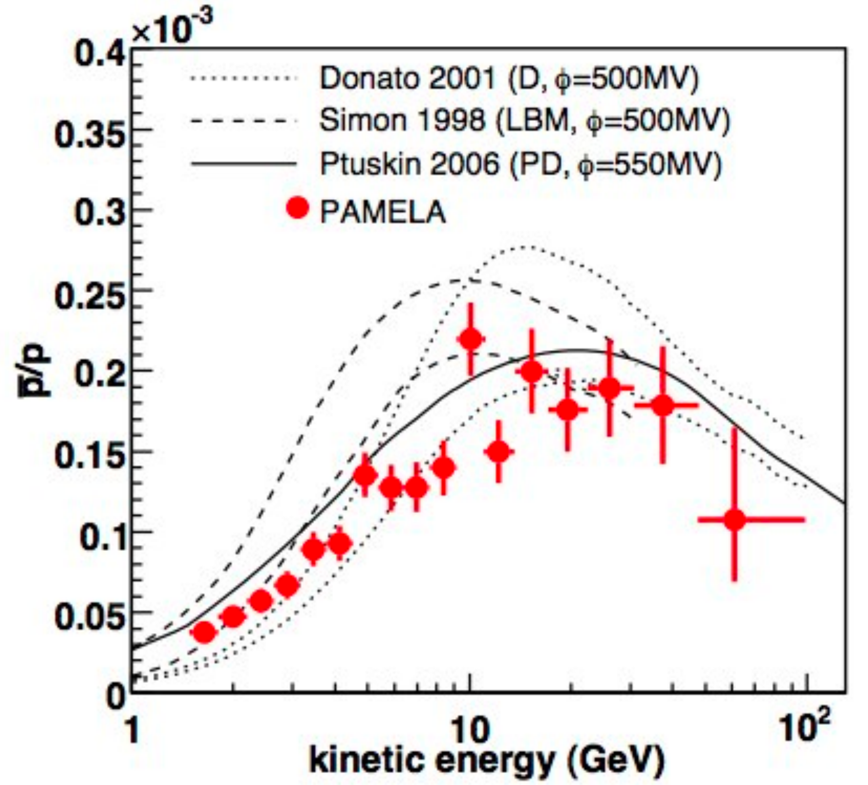


511 keV line map from GRAL/SPI data

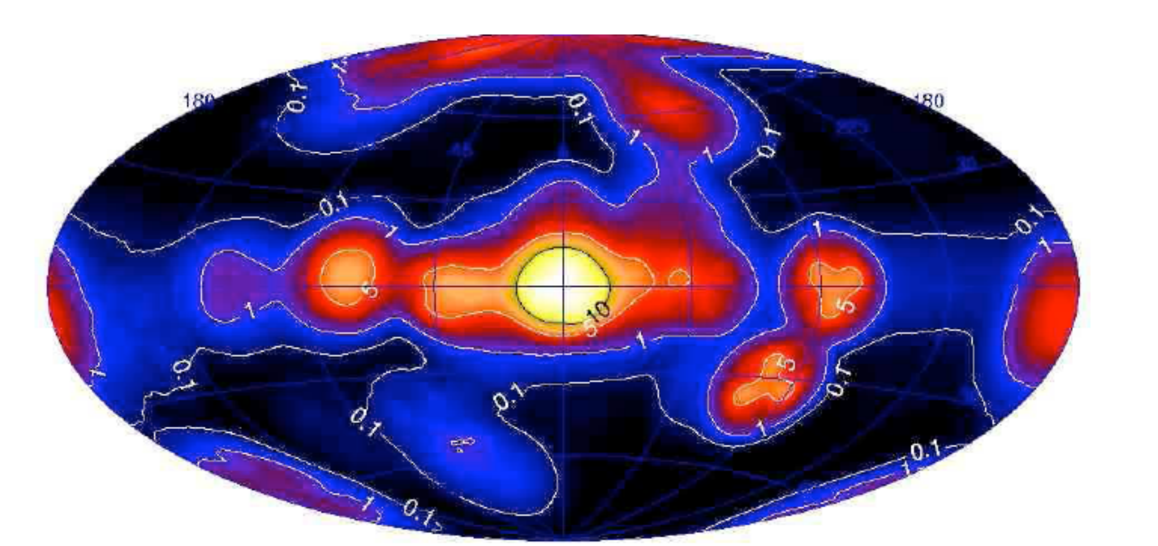
✳ Unexplained concentration of 511 keV line from the galactic center
✳ Diffuse emission of e+ e- annihilation (?)
✳ Increasing fraction of e+/e- measured by PAMELA
✳ No surprise with antiprotons (sub GeV mass gauge boson?)
✳ It is very difficult to explain PAMELA results with standard DM (WIMPs): needs a boost of 100-1000

Positron and antiproton abundance from PAMELA/AMS



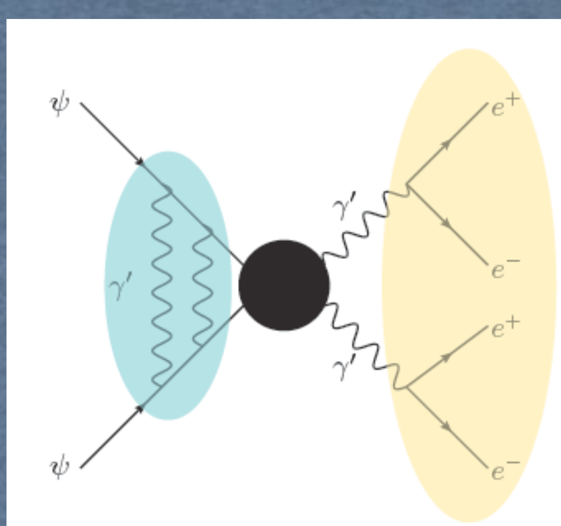


Astrophysical motivation: the 511γ keV line



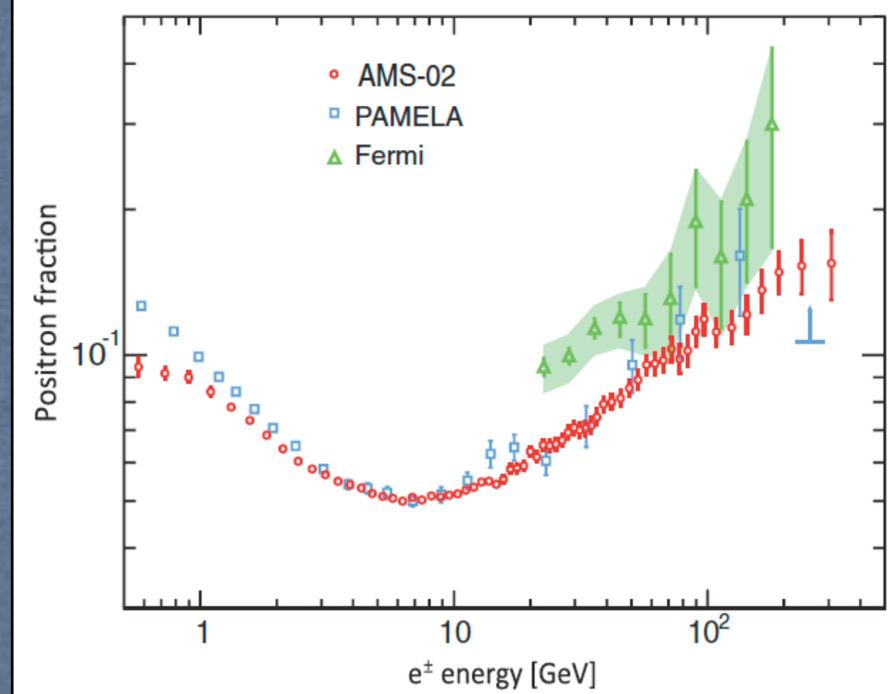
511 keV line map from GRAL/SPI data

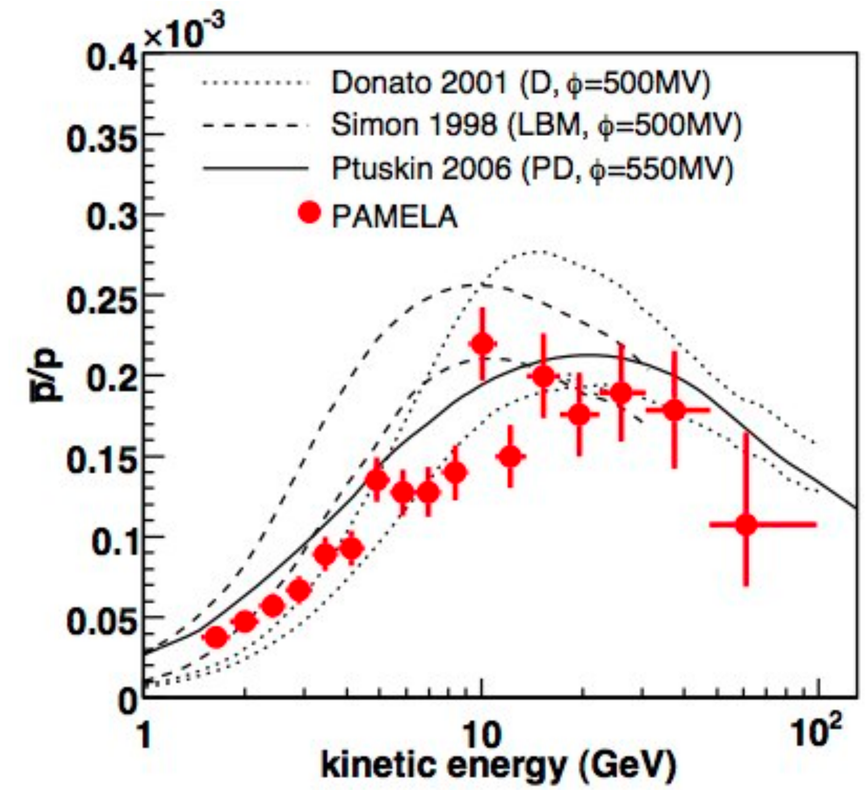
Dark forces may explain it by
DM annihilation in A' ➜ decay to e+e-



1) enhancement in e+ yield
2) hard e+ spectrum
3) no anti-p excess if $M_{A'} < 2\ M_p$

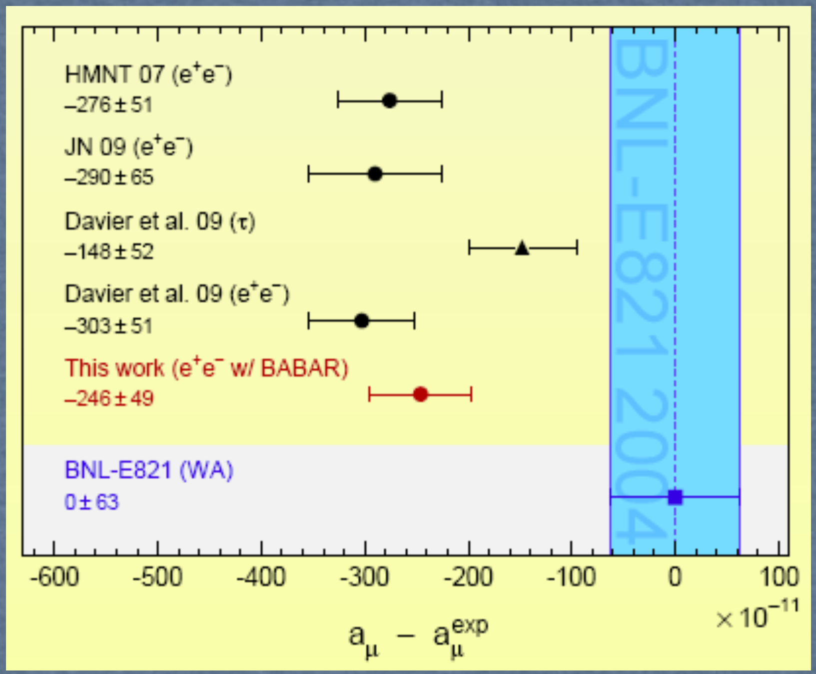
Positron and antiproton abundance from PAMELA/AMS





Modification of EM

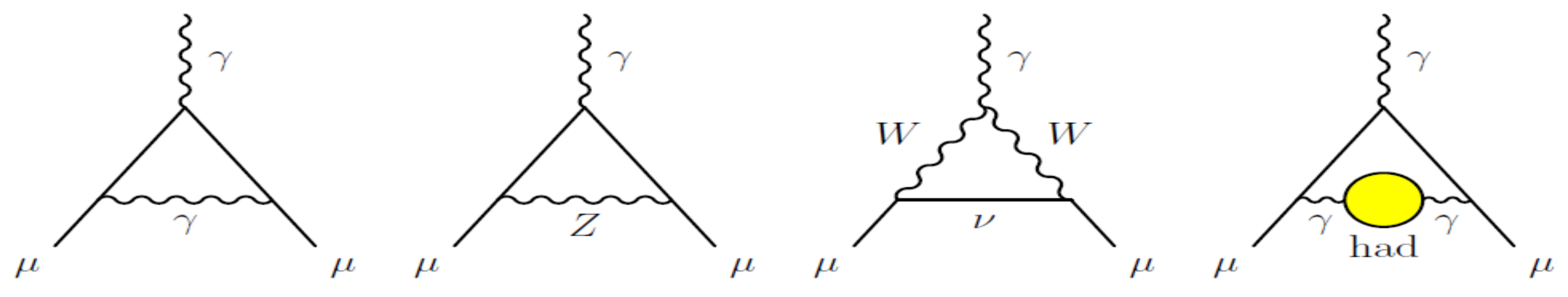
g-2 of muon



- g-2 is expected to be 0
- Discrepancy >3σ
- Some (complicated) strong interaction dynamic?
- New physics?

Standard Model Prediction

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$$



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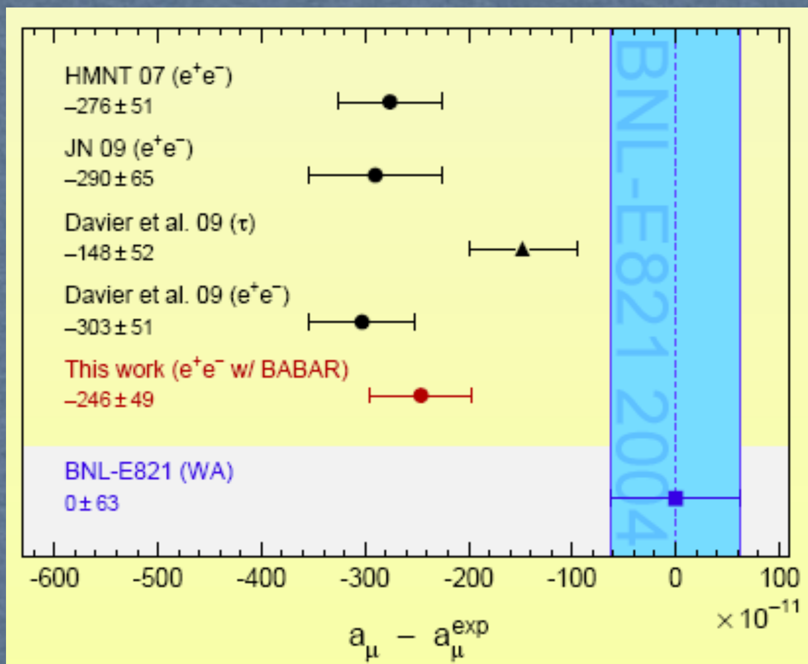
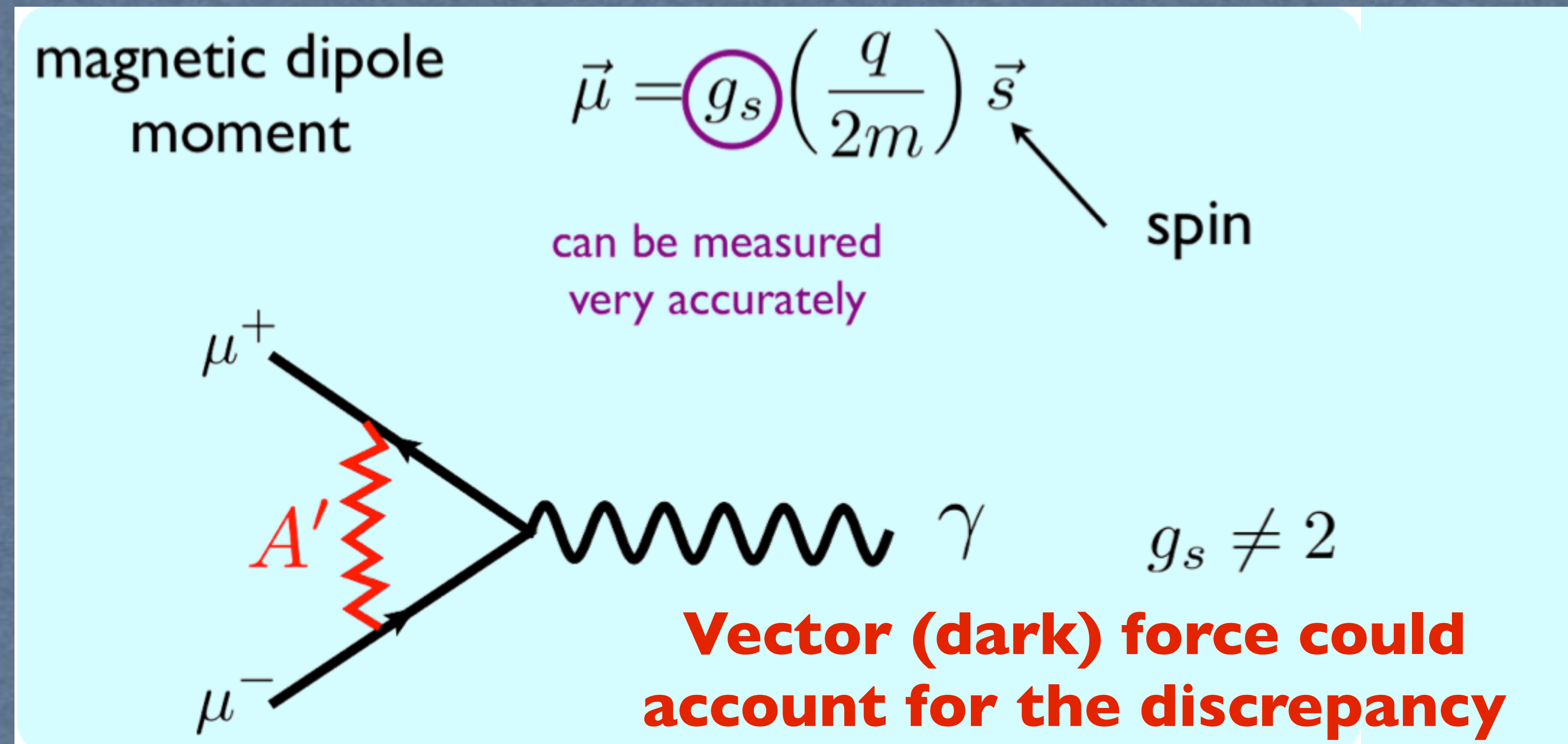




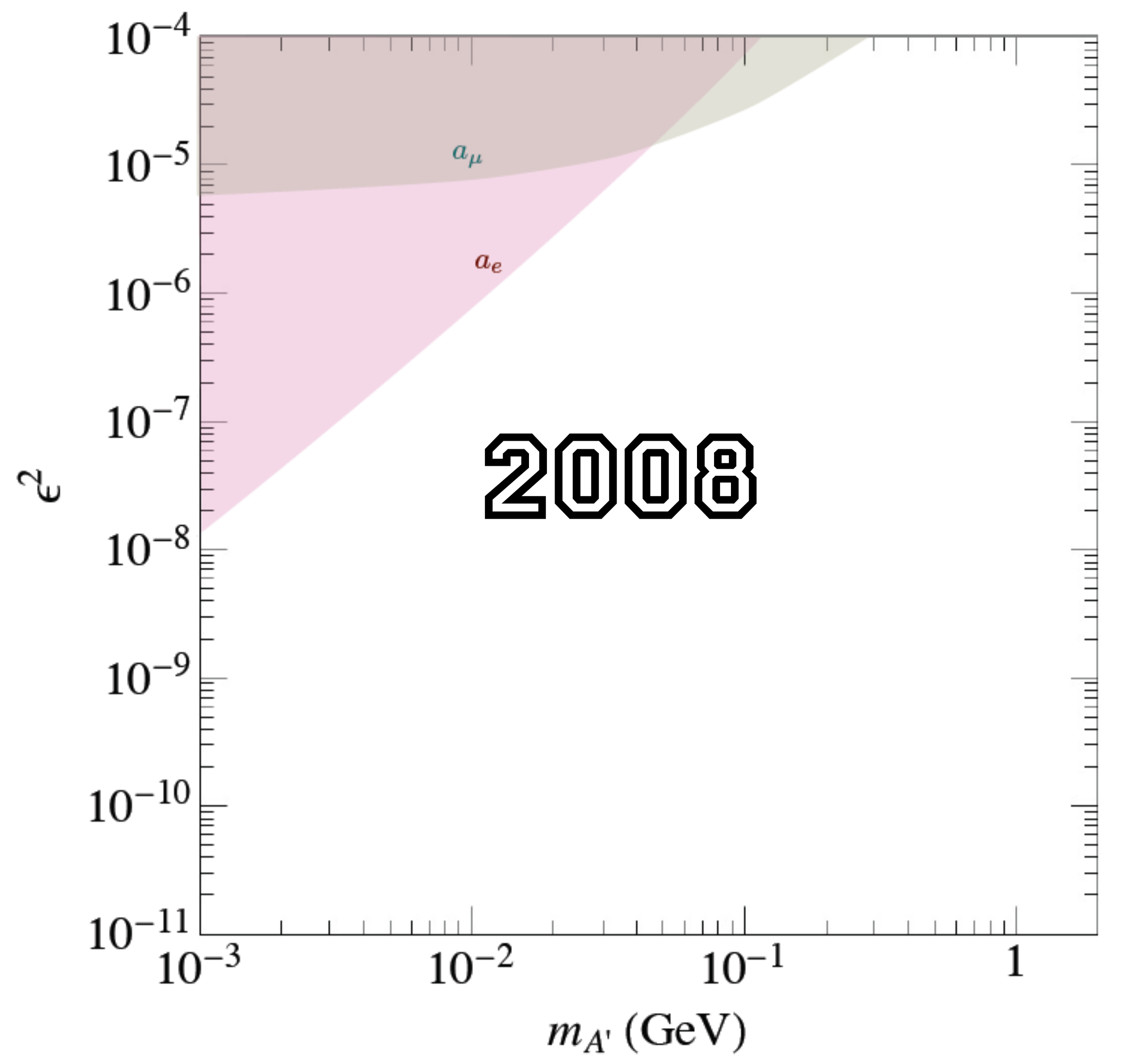
Contribution to g-2 from dark photon

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \tag{17}$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1\text{–}2 \cdot 10^{-3}$ and $m_V \sim 10\text{–}100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

Particle physics search of A'/γ' (visible decay)

Parameter space
Coupling vs Mass



- From 2008: reanalysis of existing data
- New (test) runs
- Full runs expected in 2015-2017

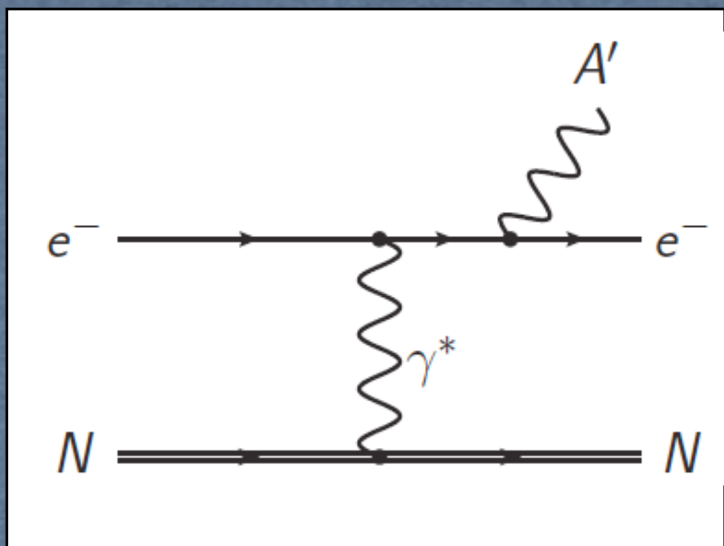
Fixed target: e N →N γ'→ N Lepton⁻ Lepton⁺
→ **JLAB, MAINZ**

Fixed target: p N →N γ'→ p Lepton⁻ Lepton⁺
→ **FERMILAB, SERPUKHOV**

Annihilation: e+e- → γ' γ → μμ γ
→ **BABAR,BELLE,KLOE**

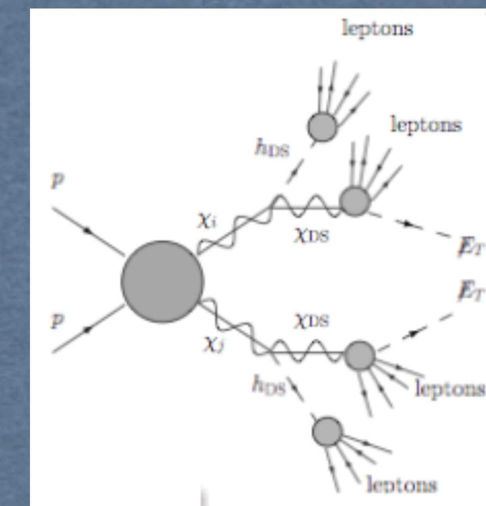
Meson decays: π^0, η, η', ω,' → γ' γ → Lepton⁻ Lepton⁺ γ
→ **KLOE, BES3, WASA-COSY**

Particle physics search of A'/γ' (hidden photon)

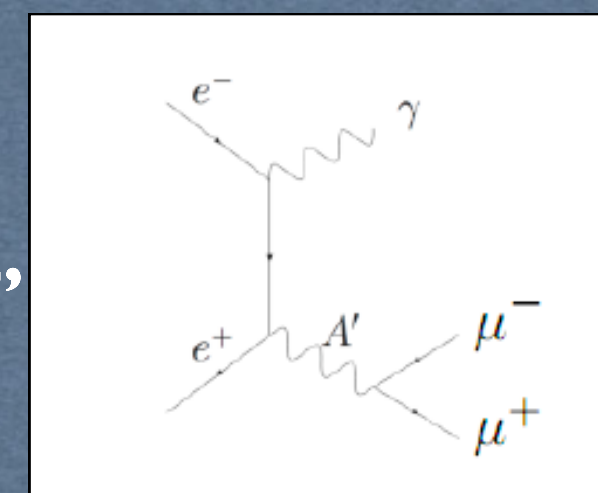


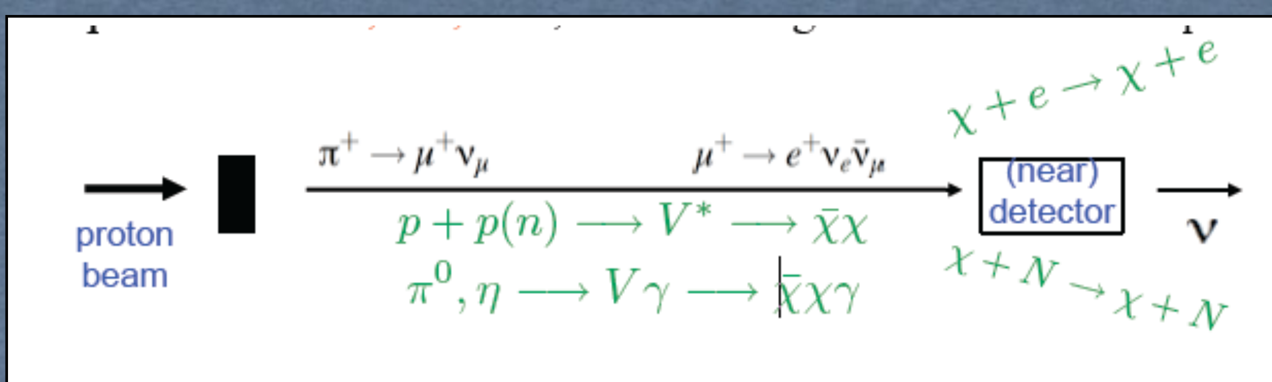
Fixed target:
e N →N γ'→ N Lepton Lepton+
→ **JLAB, MAINZ**

High Energy
Hadron Colliders:
pp → lepton jets
→ **ATLAS, CMS, CDF&D0**



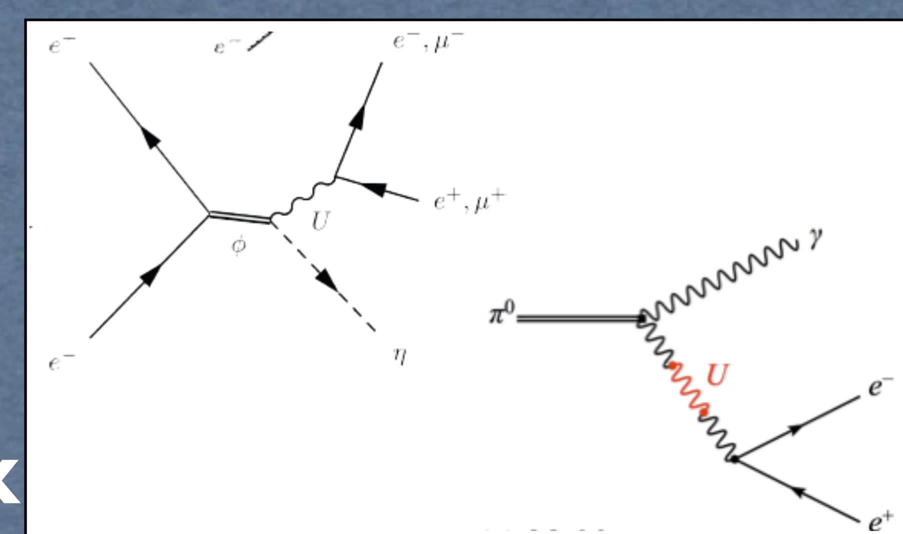
Annihilation:
e+e- → γ' γ → μμ γ
→ **BABAR, BELLE, KLOE, CLEO**



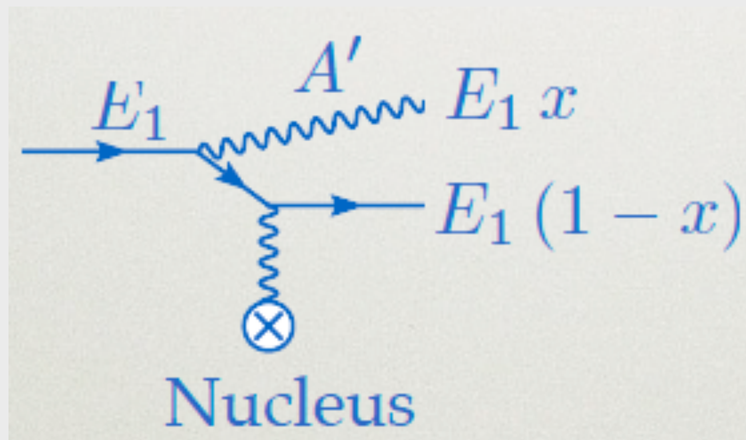
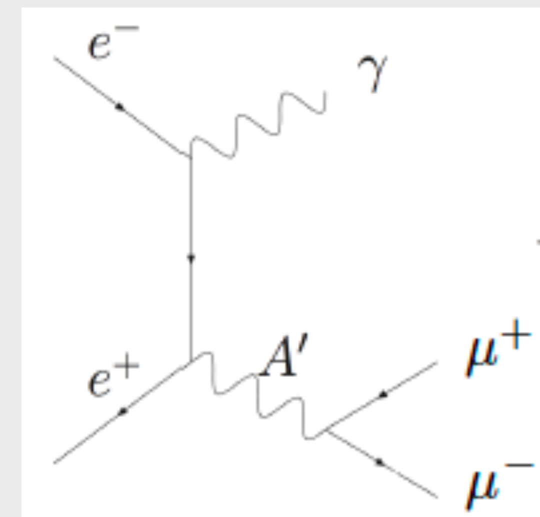
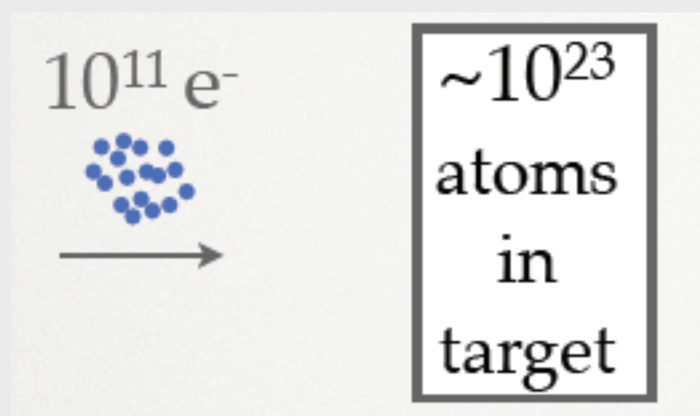
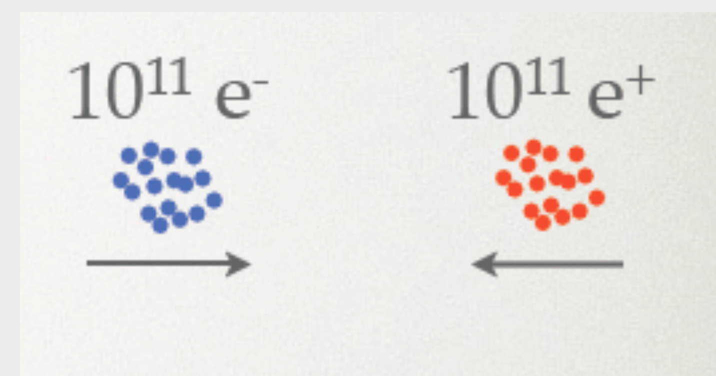


Fixed target:
p N →N γ'→ p Lepton Lepton+
→ **FERMILAB, SERPUKHOV**

Meson decays:
π^0, η, η', ω,' → γ' γ (M)
→Lepton Lepton + γ (M)
→ **KLOE, BES3, WASA-COSY, PHENIX**



A’ production: fixed target vs. collider

	Fixed Target	e+e- colliders
Process		
Luminosity		
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

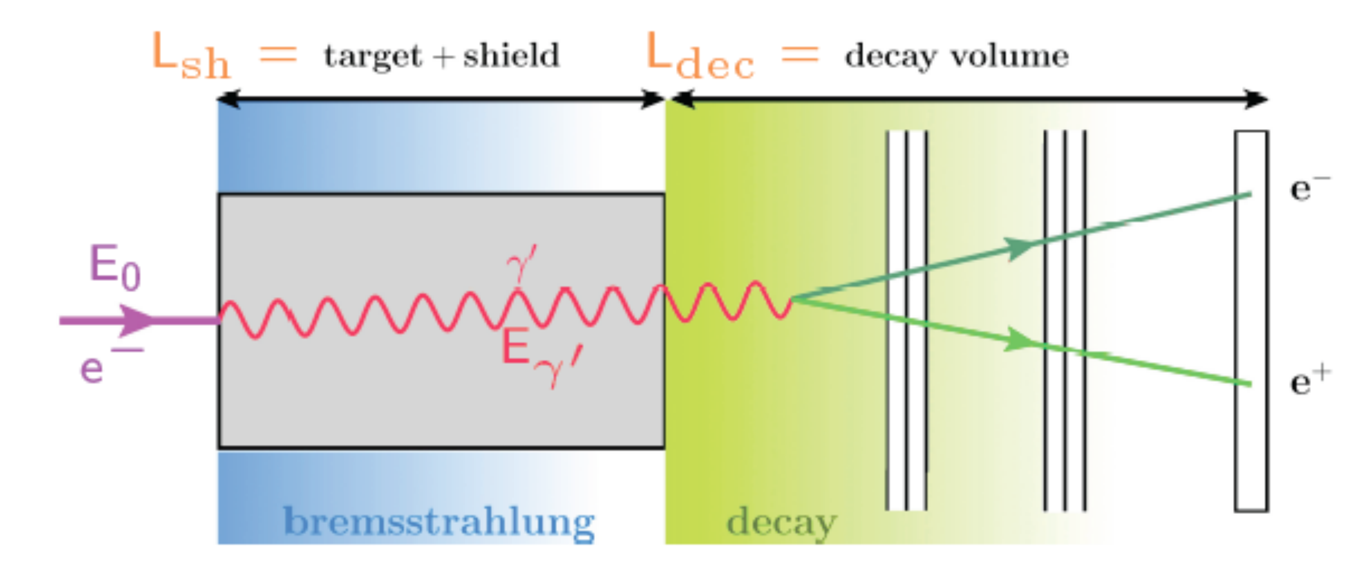
✴1/$M_{A'}$ .vs.1/E_{beam}
✴Coherent scattering from Nucleus (~Z^2)

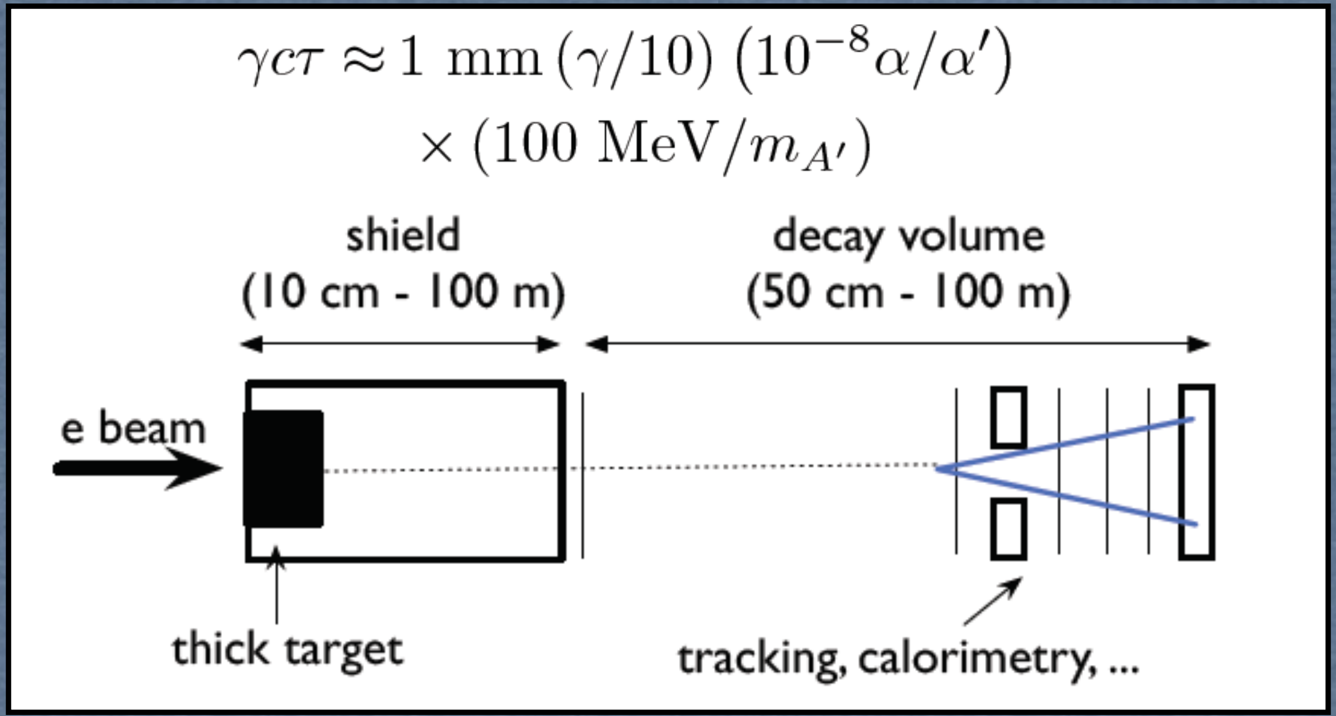
Fixed Target:
- high backgrounds
- limited A’ mass

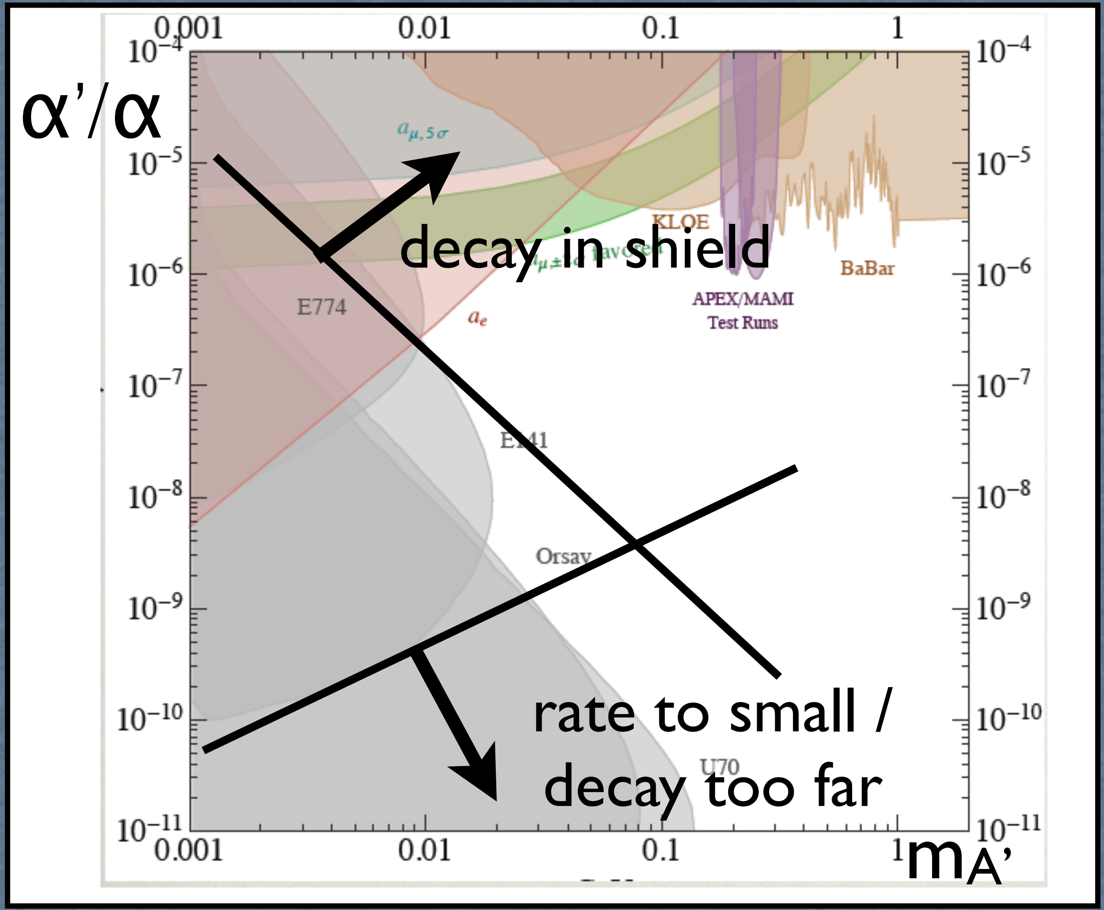
e+e- colliders:
- low backgrounds
- higher A’ mass

Ist generation fixed target exp: beam dump

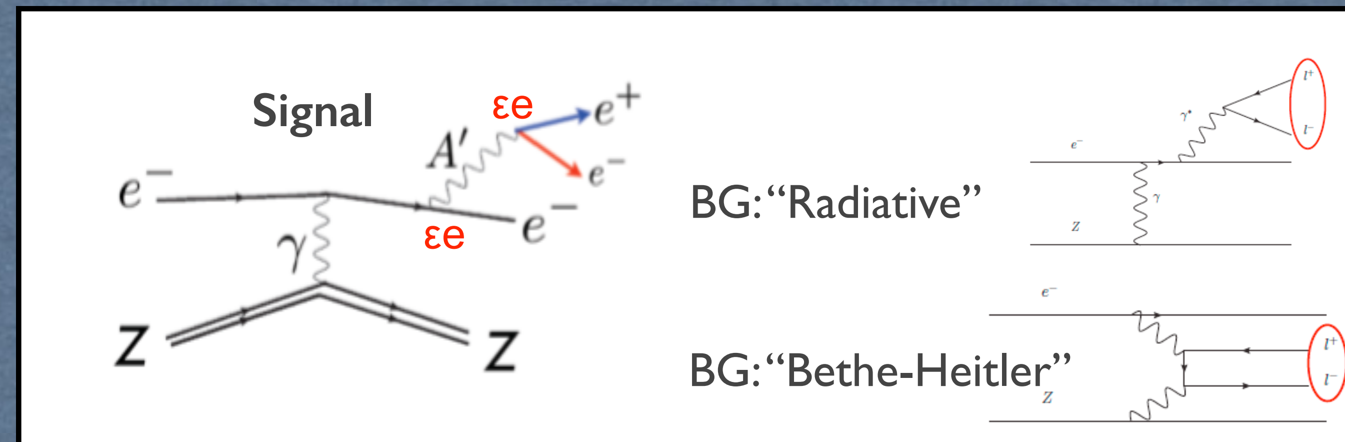
- ✳ e- beam incident on thick target
- ✳ A' is produce in a process similar to ordinary Bremsstrahlung
- ✳ A' carries most of the beam energy
- ✳ A' emitted forward at small angle
- ✳ A' decays before the detector







HPS@JLab
Heavy Photon Search



Heavy photon signatures in HPS

1) Bump Hunting (BH)

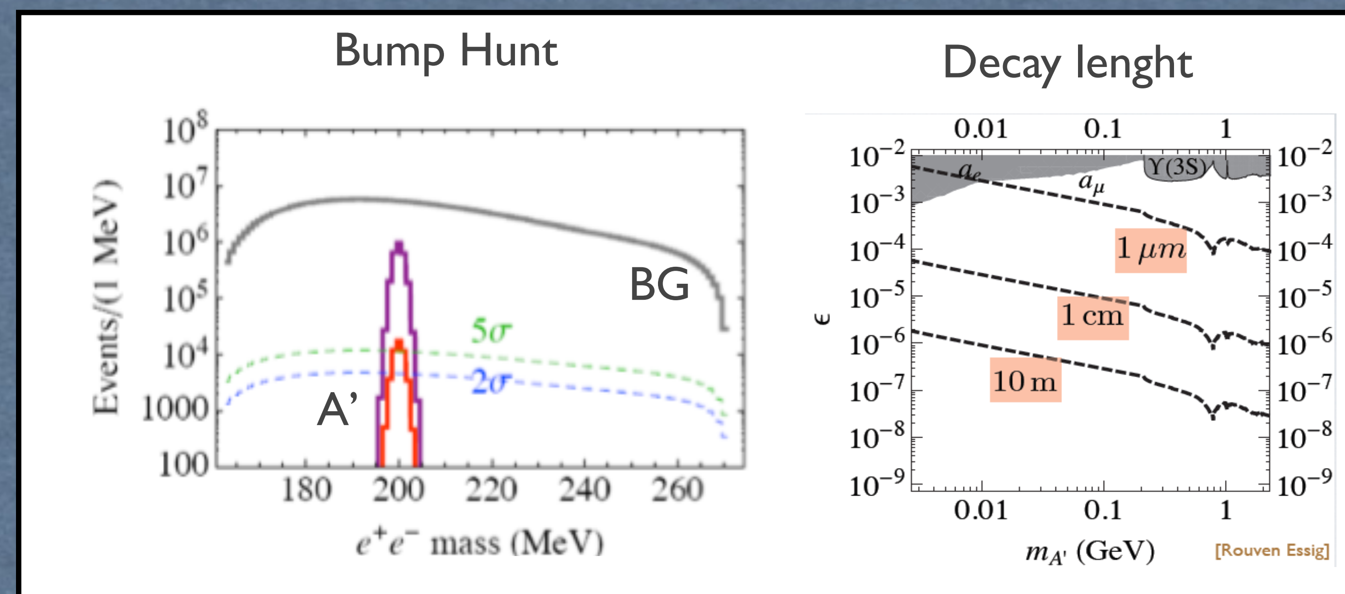
Narrow e+e-resonance over a QED background

➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

2) Secondary decay vertex (vertexing)

Detached vertex from few mm to tens cm

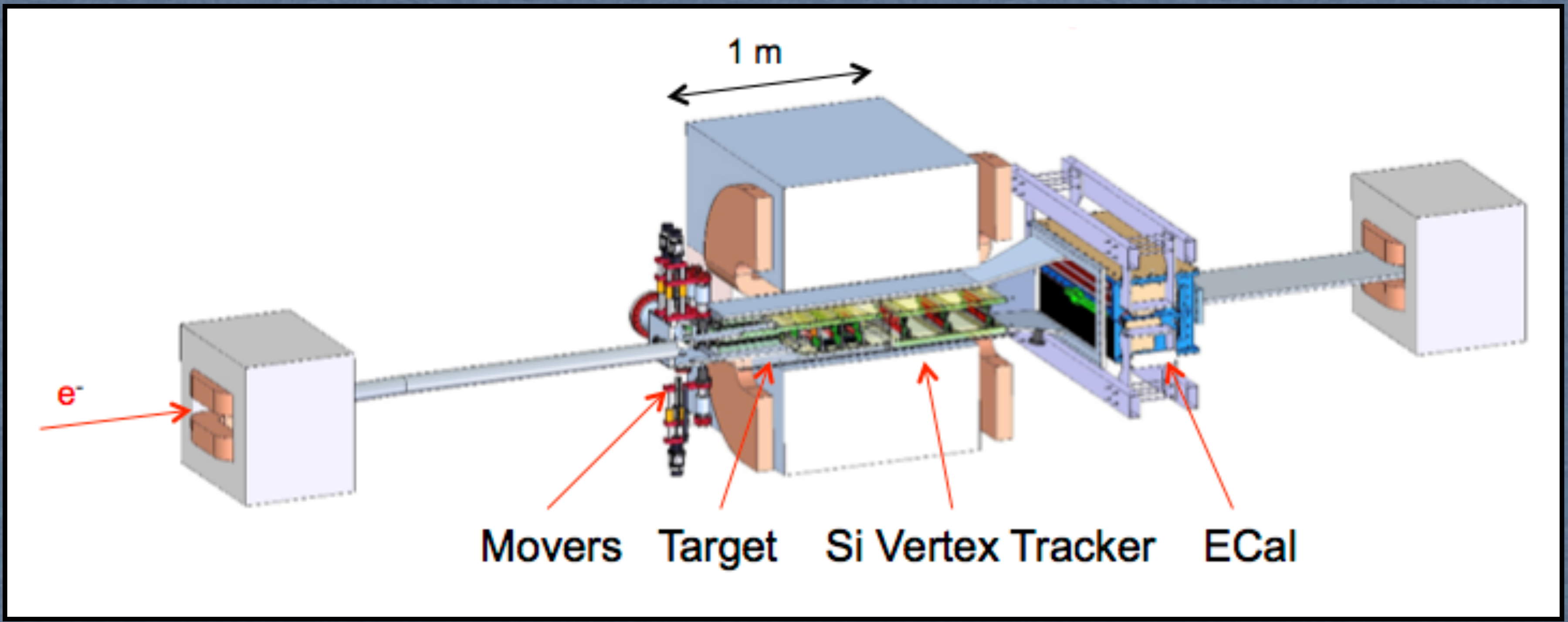
➥ good spacial resolution: σ_{vertex}~1mm



BH + Vertexing = enhanced experimental reach

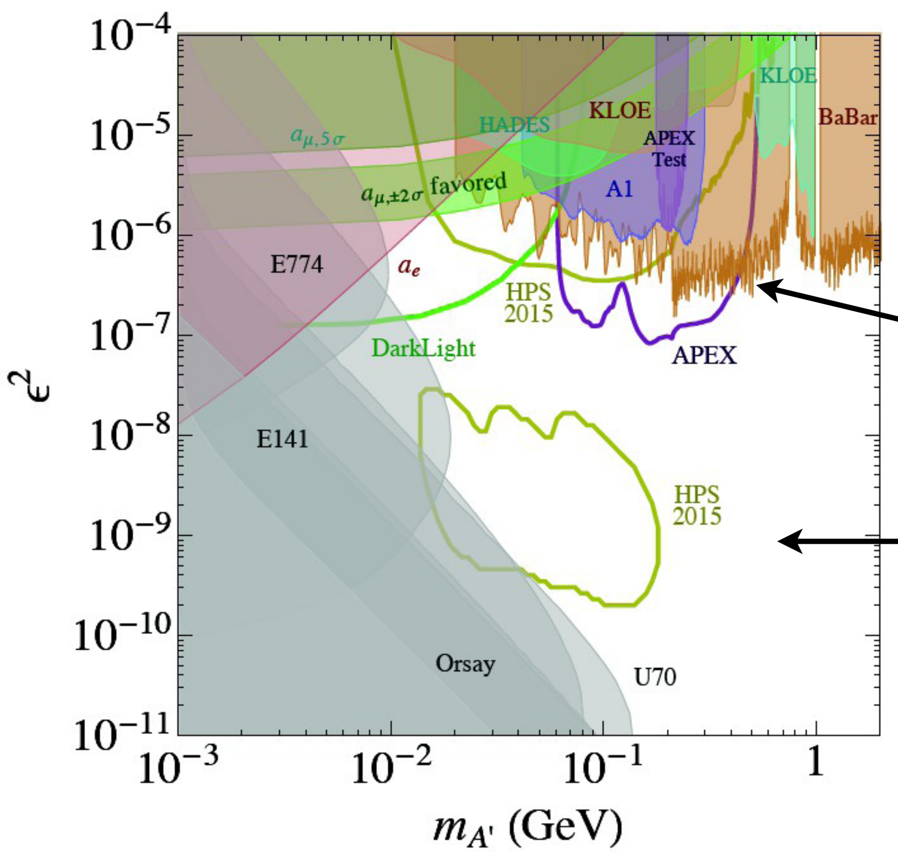
$$l_{\gamma'} \sim \frac{E_{\gamma'}}{\alpha\chi^2 m_{\gamma'}^2} \sim 10\text{cm}\,\frac{E_{\gamma'}}{1\text{GeV}}\left(\frac{10^{-4}}{\chi}\right)^2\left(\frac{10\text{MeV}}{m_{\gamma'}}\right)^2 \sim \mathcal{O}(\text{mm}-\text{km})$$

The HPS Experiment



Requirements:
- forward angles coverage
- good spacial resolution:
  σ_{vertex}~1mm (vertexing)
- good mass resolution:
  $\sigma_{A'mass}$~1 MeV (bump hunting)

Experimental set-up
- B field to bend e+/e- pairs
- Si TRCK for vertexing
- EM cal for triggering



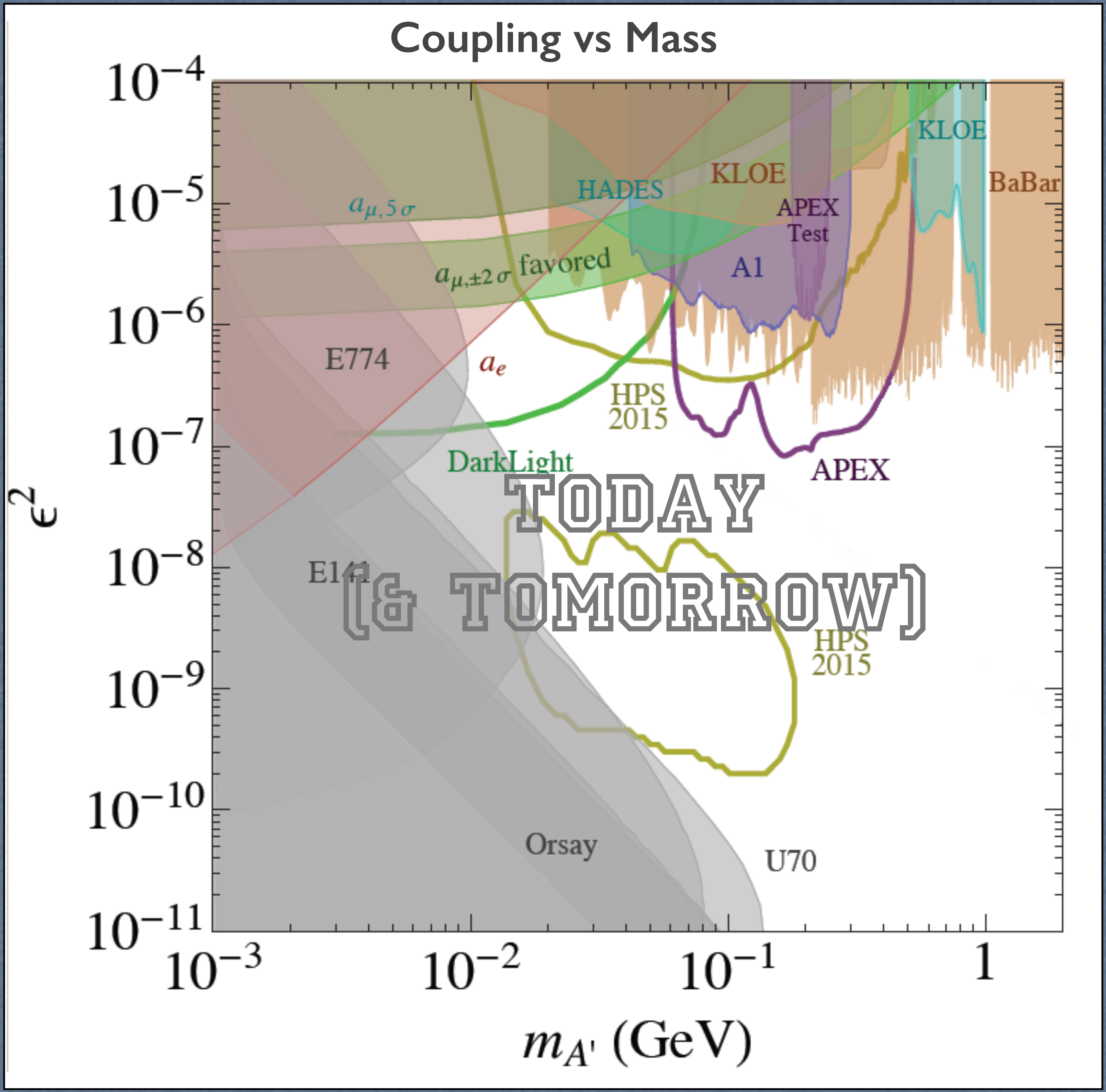
Projected results

Bump hunting	1 week 1.1 GeV 1 week 2.2 GeV 2 weeks 4.4 GeV	Phase I 2014/15
Bump hunting + vertexing	few months 2.2 GeV few months 4.4 GeV few months 6.6 GeV	Phase II 2017 -2019

HPS is running!

JLab - PAC41 High impact rate

Particle physics search of A'/γ' (visible decay)

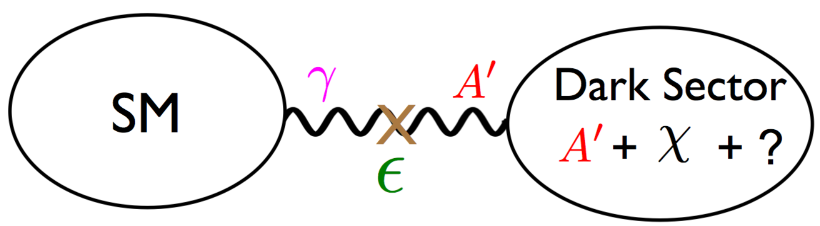


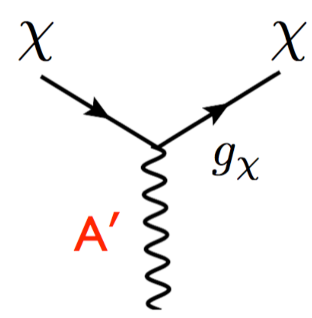
Visible decay:
no positive signal (so far) but strong limits in parameter

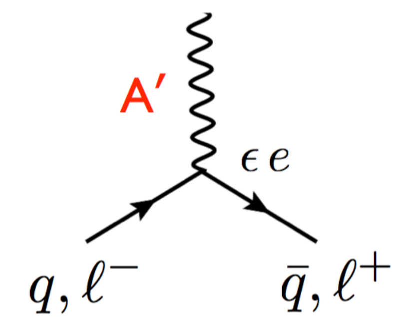
A broad experimental program will explore a significant territory in the next few year

What about the 'invisible decay'?

Dark forces and dark matter
(Light WIMPs - light mediators)



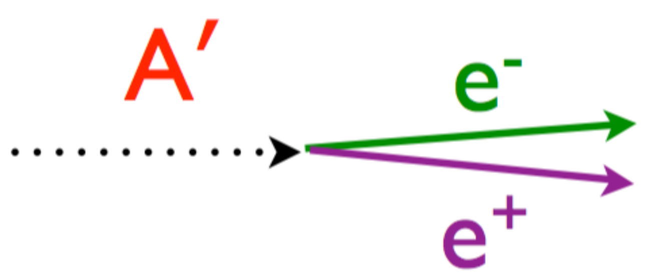




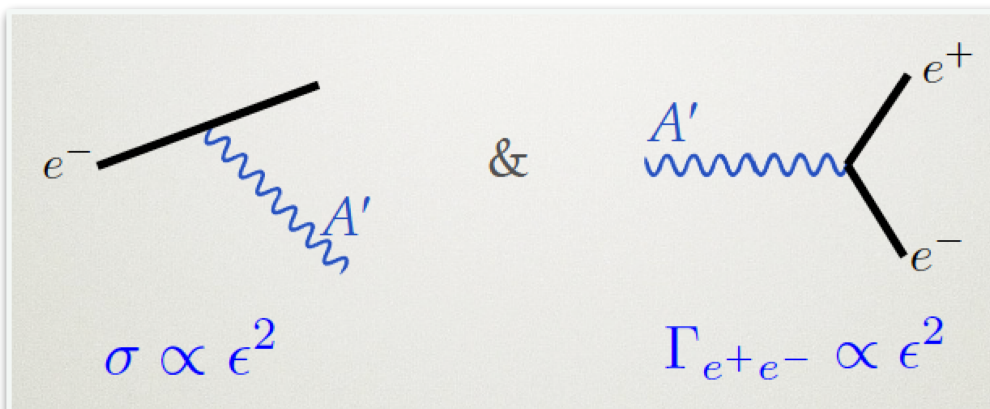
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$m_\chi \sim m_{A'} \sim \mathrm{MeV} - 5\ \mathrm{GeV}$

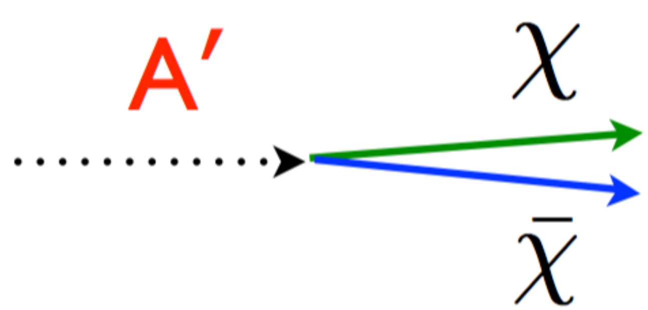
Visible



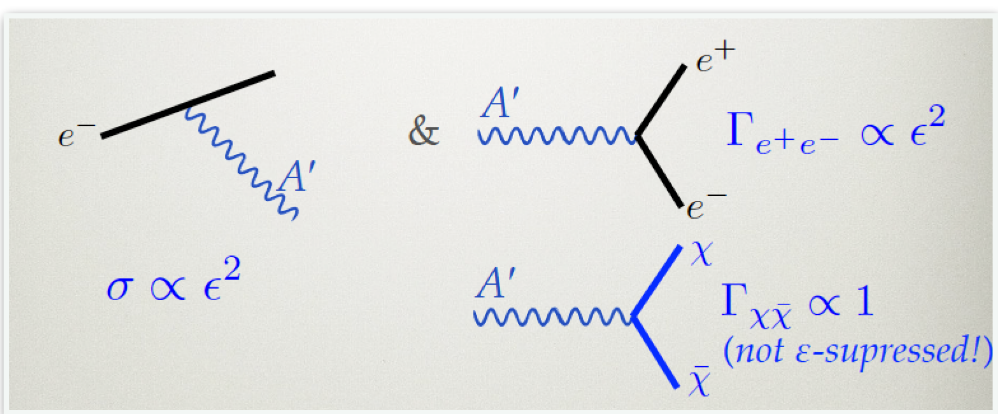
- *Minimal* decay
- Decay regulated by ε^2
- Independent on m_χ
- Requires $m_{A'} < 2m_\chi$



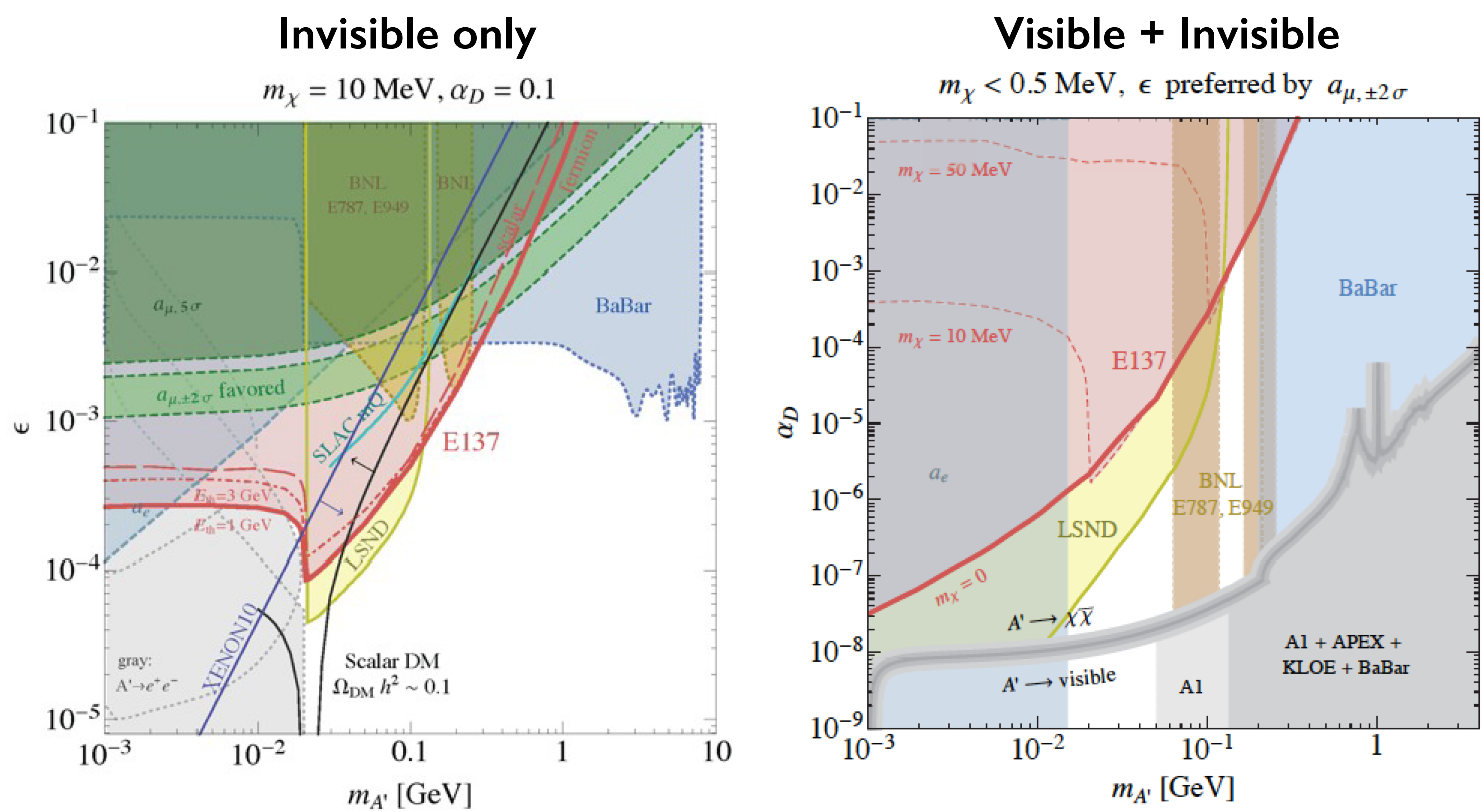
Invisible



- $m_\chi < 2m_{A'}$
- i) stable and invisible
- ii) decays to SM particles
- Independent on ε



Visible vs Invisible: complementarity $(g-2)_\mu$



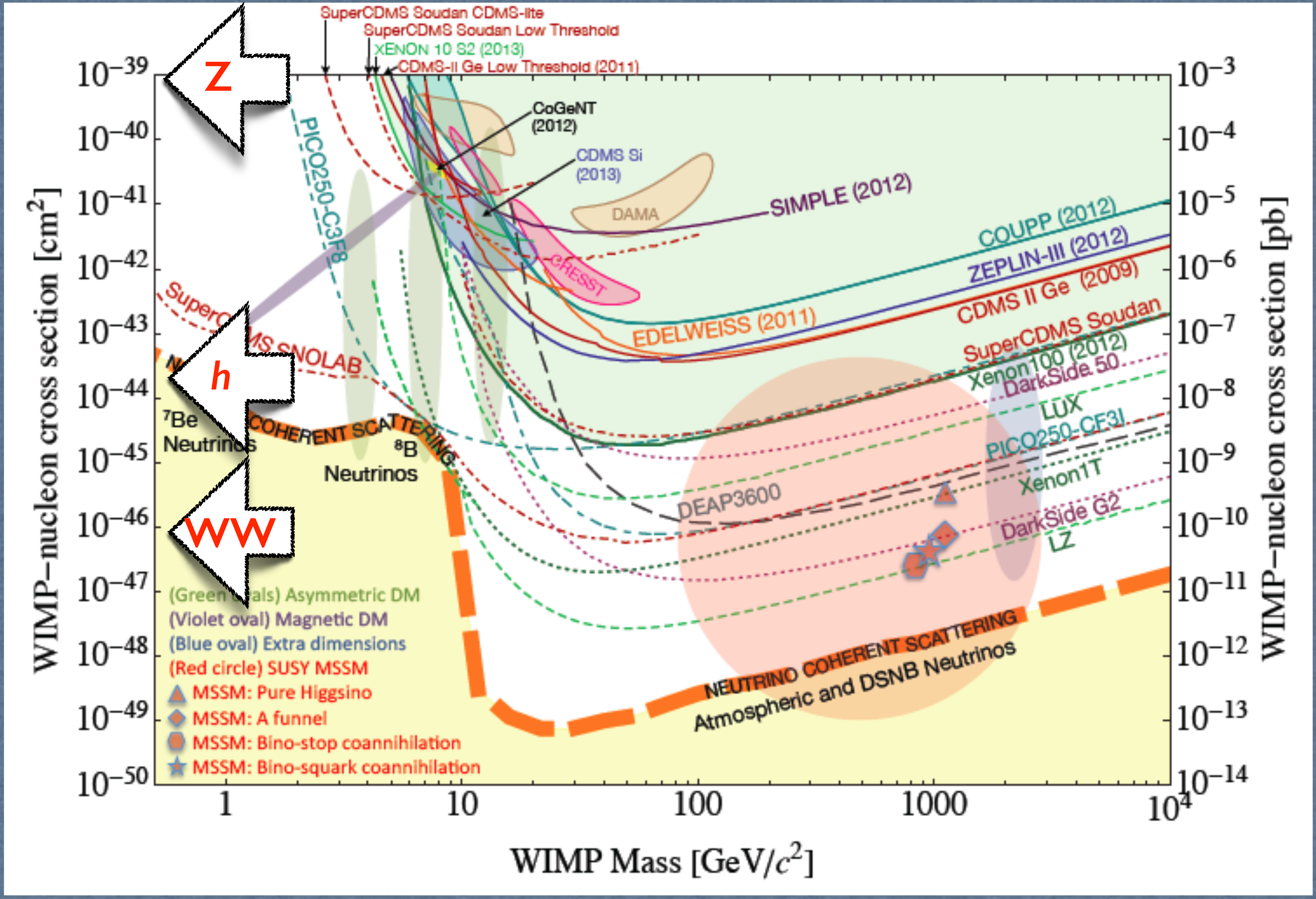
Strong Constraints on Sub-GeV Dark Matter from SLAC Beam Dump E137
http://arxiv.org/abs/1406.2698 Brian Batell, Rouven Essig, Ze'ev Surujon

- Reinterpretation of existing data are ruling out *(g-2)*$_\mu$ favoured region
- Exclusion limits are model dependent: if invisible decay is included limits do not hold!

Dark Matter search - Direct measurements

Dark matter (DM) direct search mainly focused in the mass region 10 GeV -10 TeV

- WIMP: weakly interacting massive particles with weak scale mass provides the correct DM relic abundance
- No signal in direct detection



DM detection by measuring the (heavy) nucleus recoil of slow moving cosmological DM

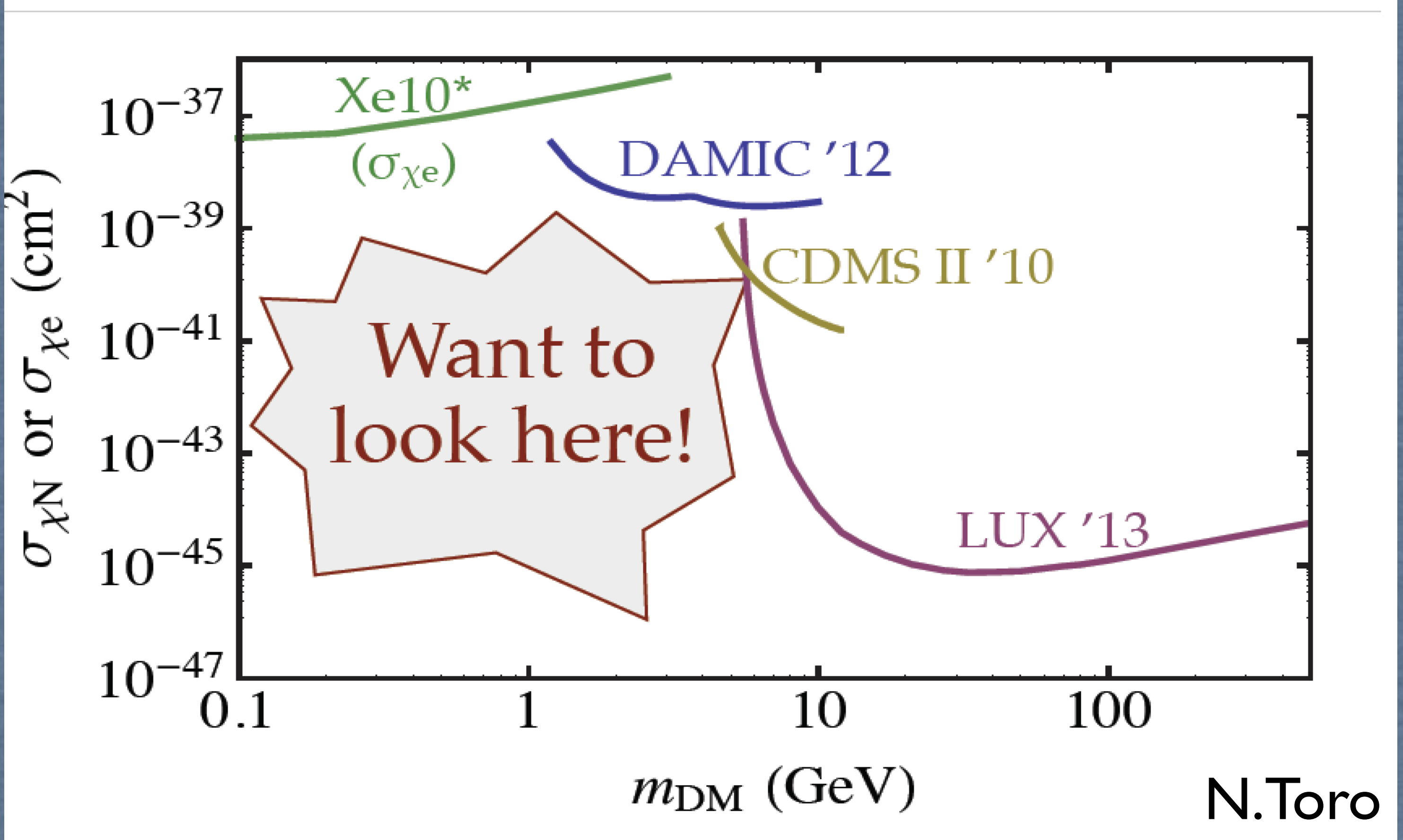
→ no experimental sensitivity to light DM (<1 GeV)

Accelerators-based DM search

Accelerators-based DM search is covering a similar mass region but can extend the reach outside the classical DM hunting territory

Many theoretical suggestions and experimental attempts to extend the search region to:

- **Higher mass (> 10 TeV)**
  LHC, Rare decays, …
- **Lower Mass (<10 GeV)**
  MiniBoone@FNAL, SPS@CERN, BDX@JLab, PADME@LNF, MAINZ, Cornell



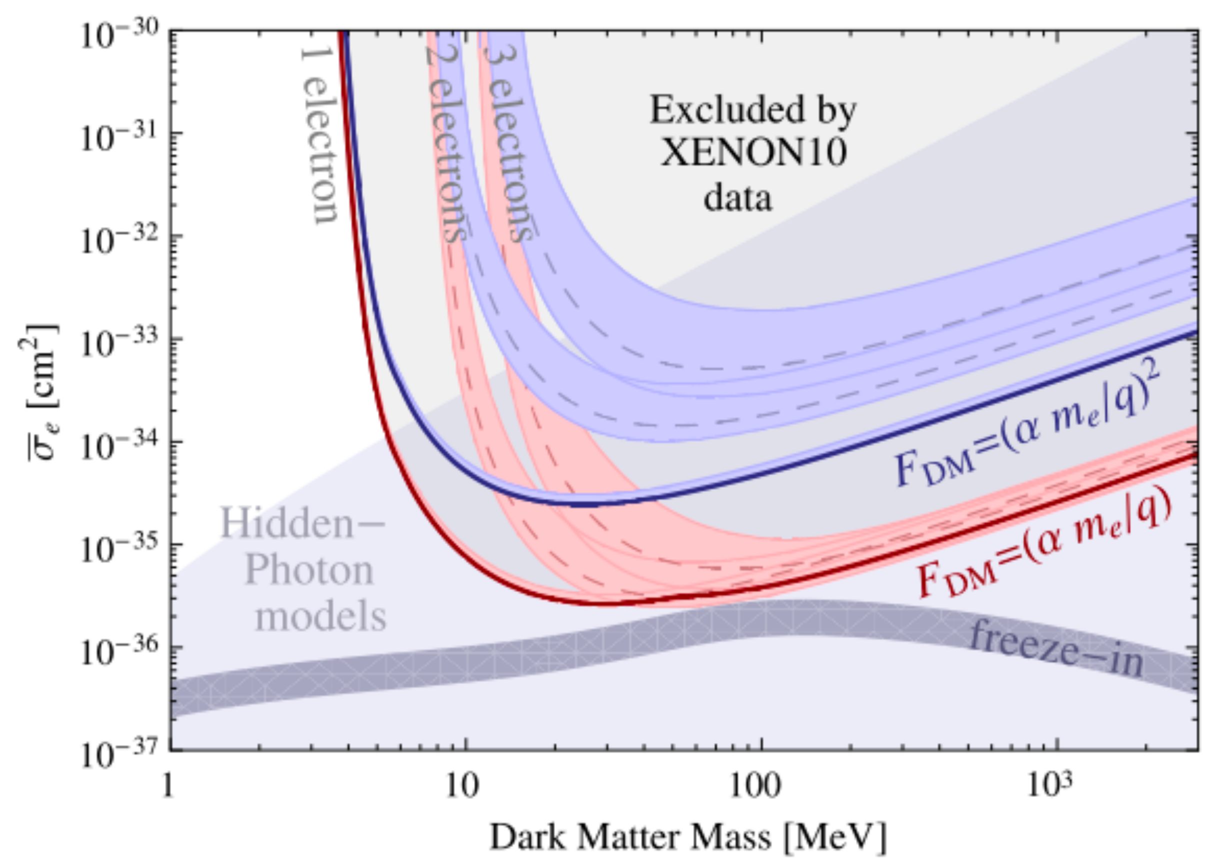
N.Toro

Unique features of accelerator-based (L)DM search:

- ✳Tagging wrt cosmic anomalies
- ✳Clear way of distinguish DM from other effects
- ✳Unprecedented sensitivity in the keep-out zone for direct DM search
- ✳High intensity electron beam can play a significant role in LDM search

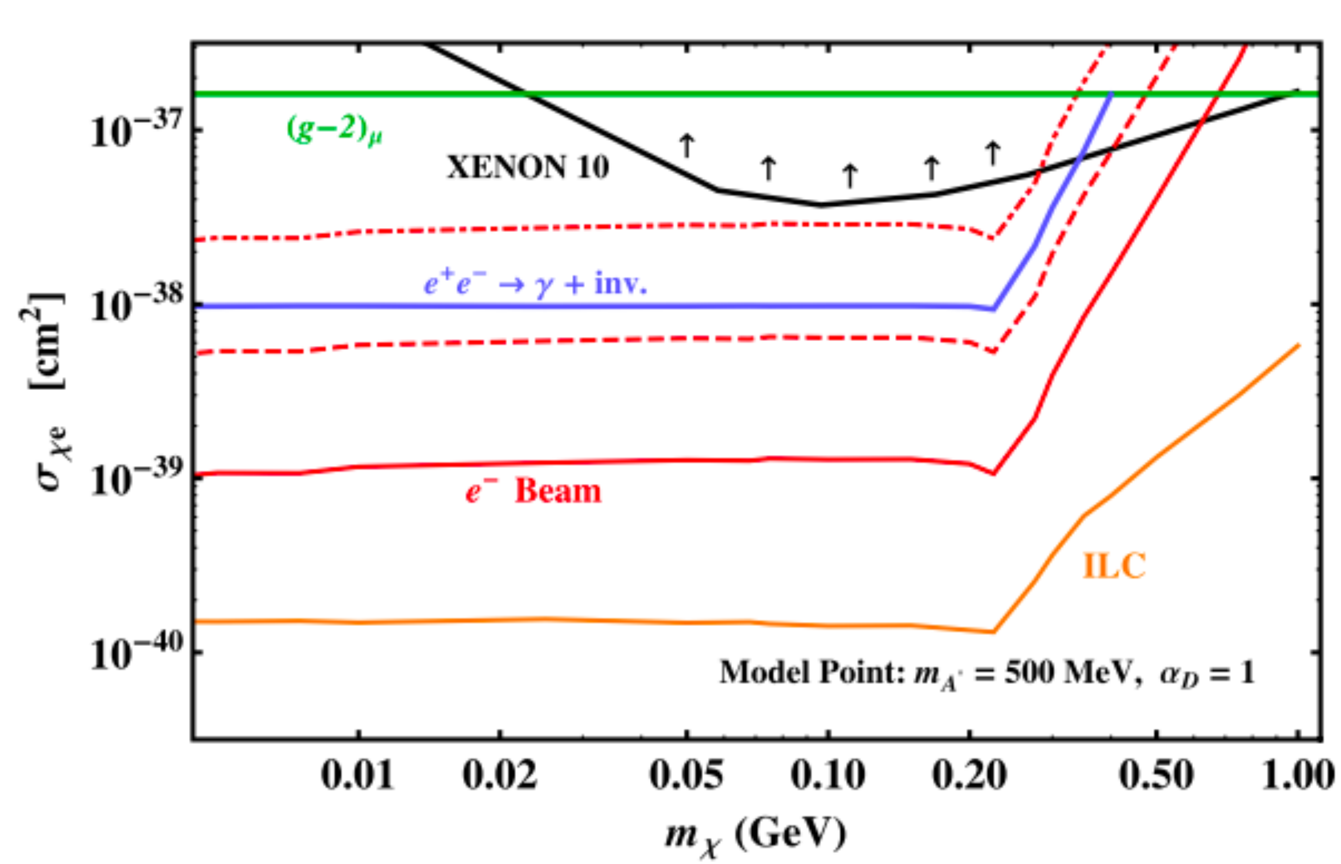
Light Dark Matter limits from direct detection

Limits from XENON10



- Best limits on LDM interaction cross section obtained by direct DM detection (XENON10)
  - χ_{cosmic}-e scattering
  - 1-electron ionization sensitivity
  - No FF for the scattering

Fixed target & high intensity e$^-$ beam



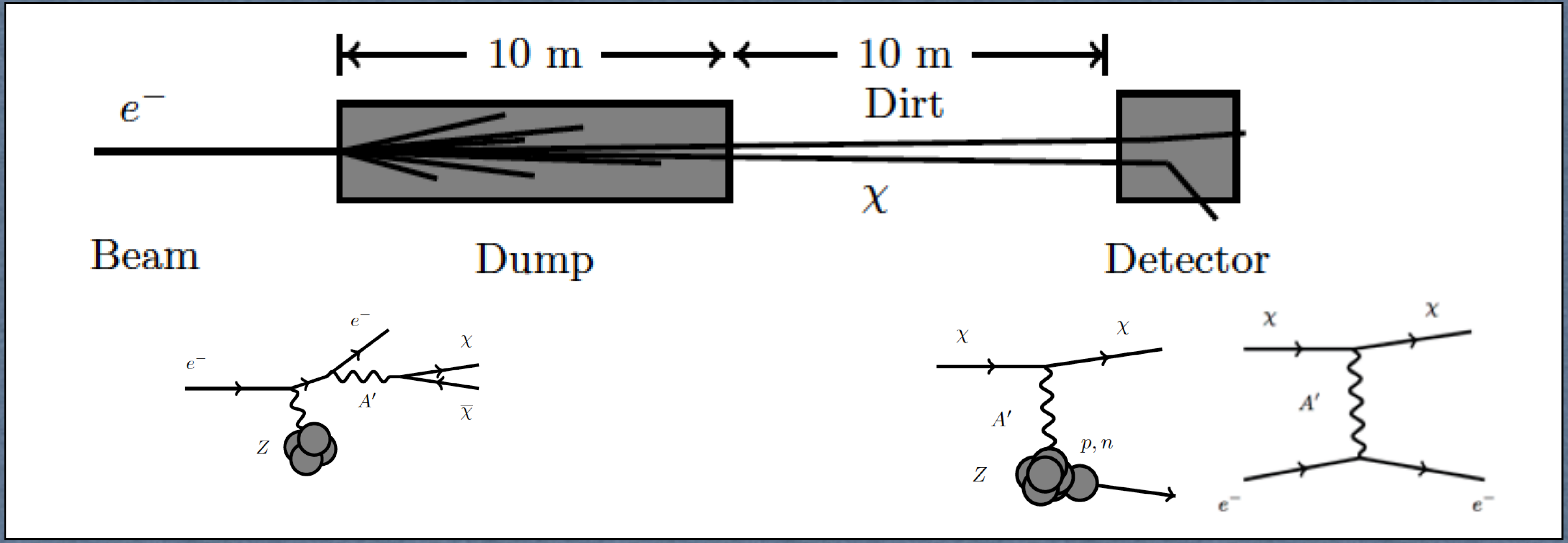
- Fixed target electron beam experiments can be 10^3 - 10^4 more sensitive in the 1 MeV - 1 GeV mass range

Fixed target DM production

Two steps process:

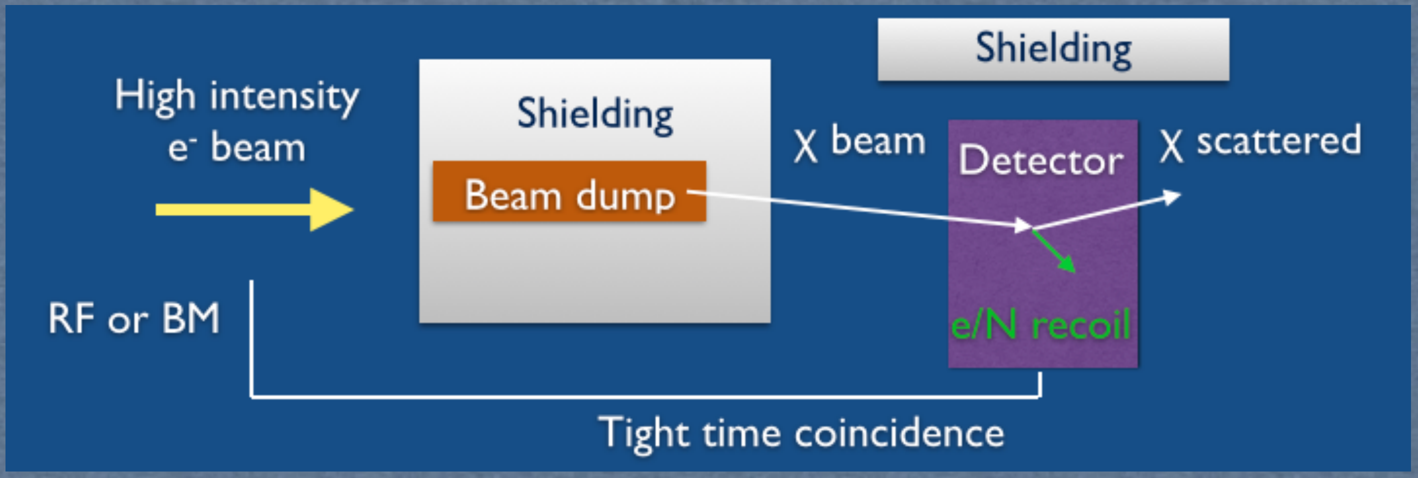
I) An electron irradiates an A' and the A' promptly decays to a χ (DM) pair

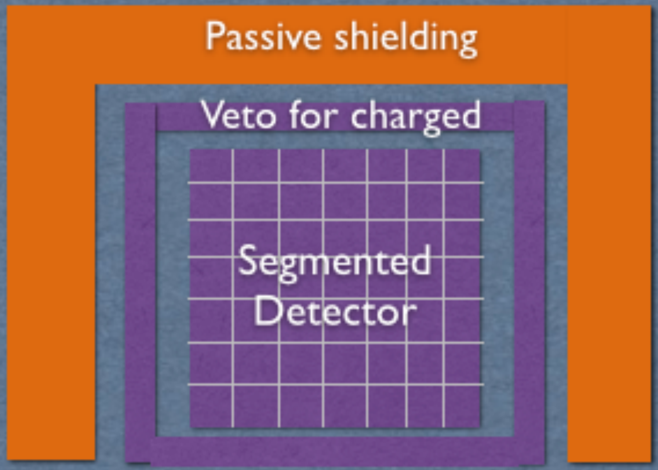
II) The χ elastically scatters on a e⁻/nucleon in the detector producing a visible recoil (GeV/MeV)



Experimental signature:

- proton (MeV)
- electron (GeV)

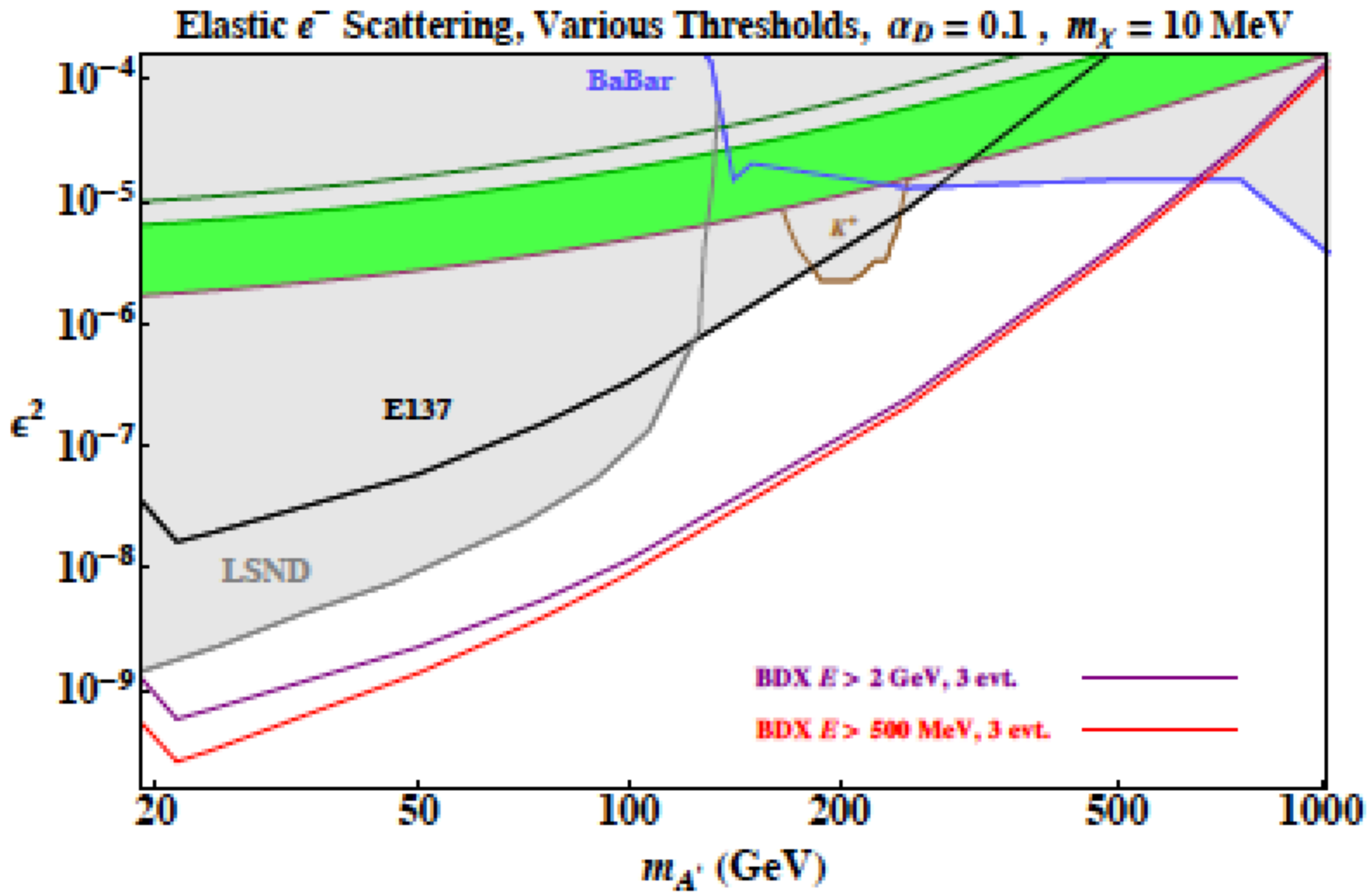


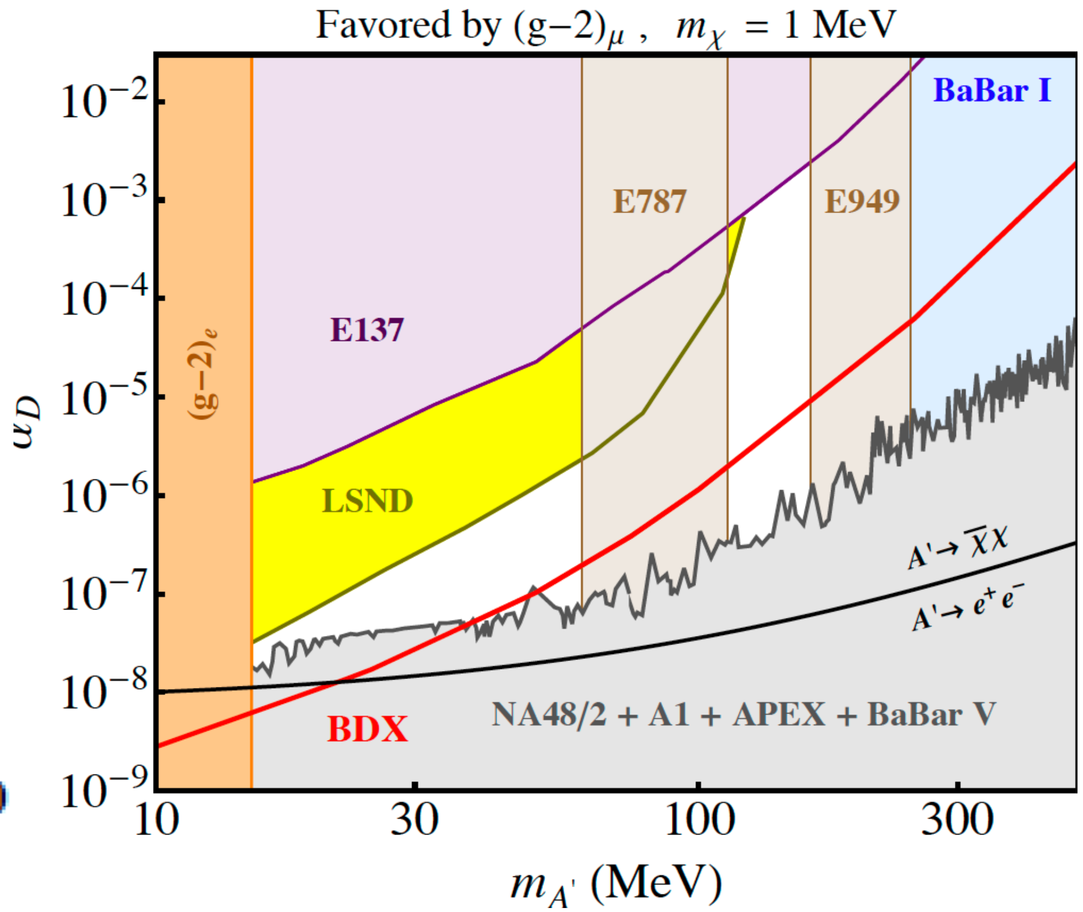


The simultaneous measurement of both provides a strong evidence of LDM existence

BDX - Dark matter search in a Beam Dump eXperiment at JLab >2017(?)

- More than two orders of magnitudes better than any previous experiments
- Unique capability of measuring both electron and nucleon scattering simultaneously



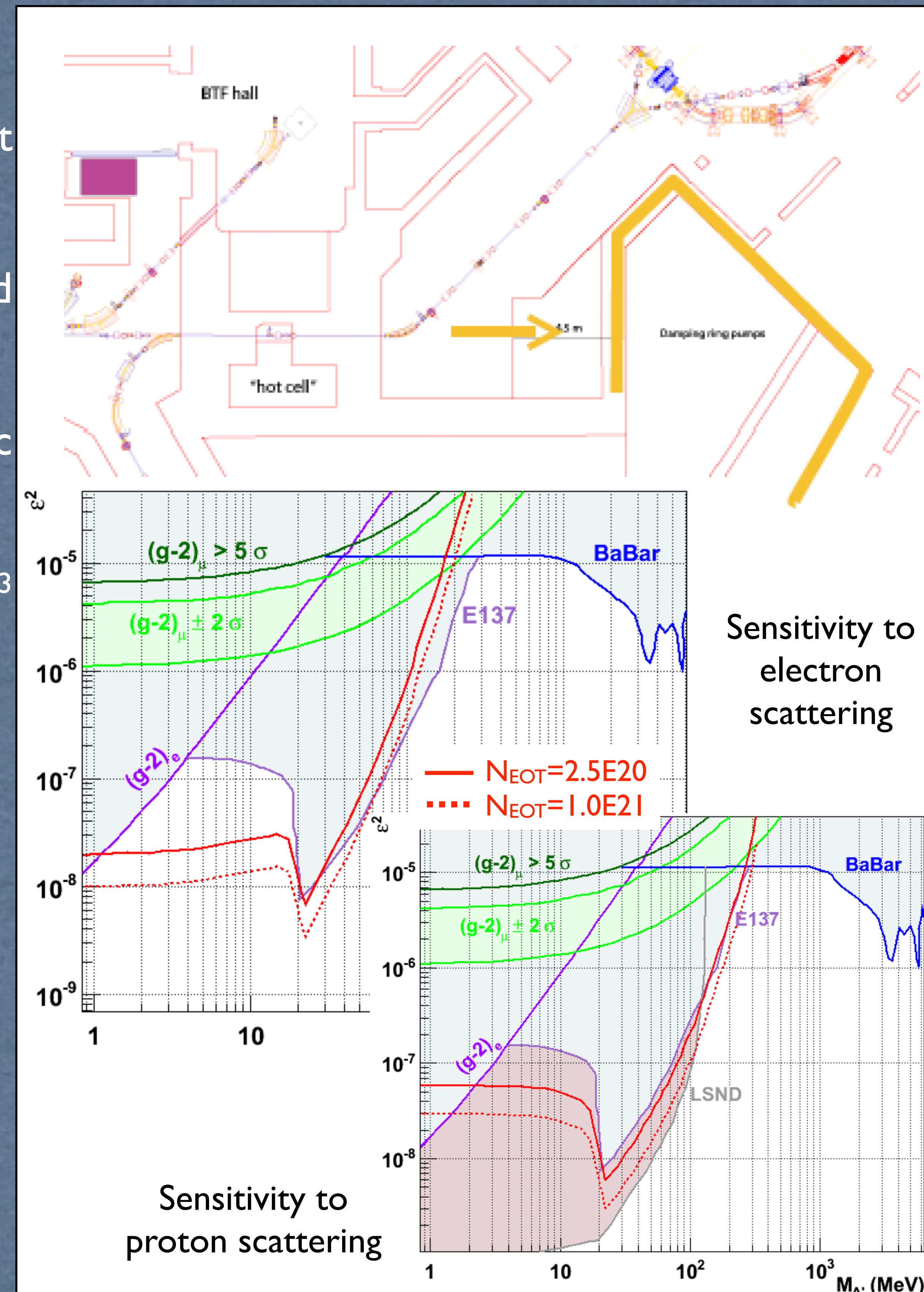


BDX together with the visible decay results will close the $(g\text{-}2)_\mu$ favoured region

Beam dump (e^-) experiments can provide unprecedented sensitivity to light dark matter Jefferson Lab will play a significant role in light DM search

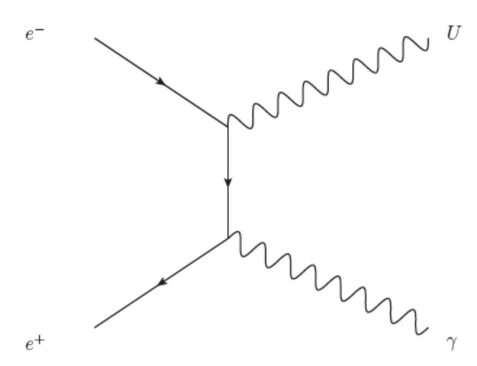
BDX @ LNF ~2016(?)

- E_{beam}~1GeV, 10^{21} EOT enough to explore a significant region of parameter space
- 50 Hz pulsed beam helps in reducing cosmic background (rejection~10^{-5})
- Detector: homogen. em calorimeter based on inorganic scintillator + 2x active veto + passive shield
- Reuse of BaBar CsI(Tl) crystals (6580 ~5x5x30 cm^3 available and ready-to-use)
- Service-Hall downstream of the linac injector
- Limited costs and simplified logistics makes BDX@LNF a cheap option ready in 1-2 years
- Project presented in CSNI as part of the PADME
- A major upgrade of the machine (E_{beam}~10 GeV, 10^{23} EOT) and an optimised detector would make LNF the leading facility for LDM search in next 10 years

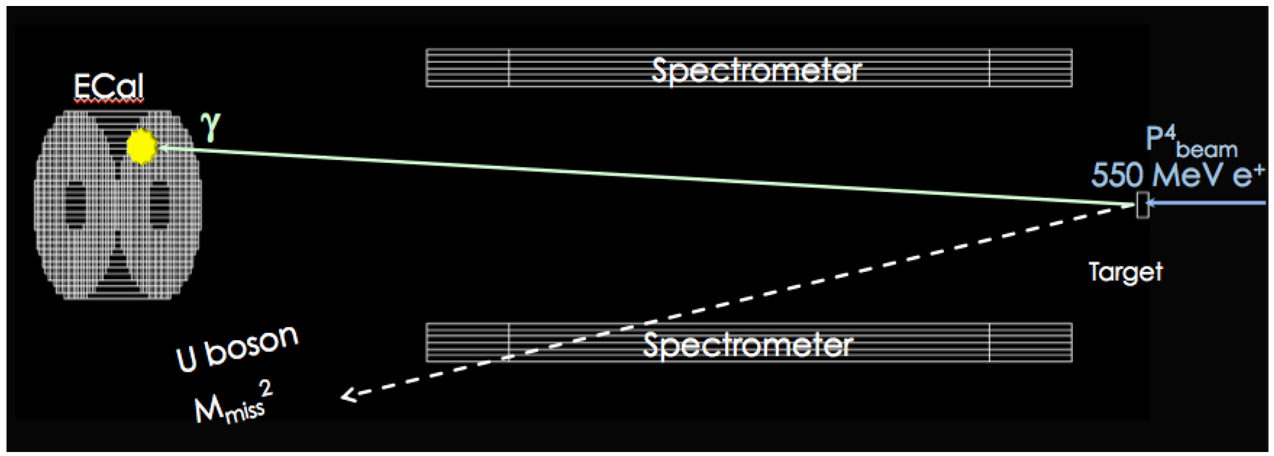


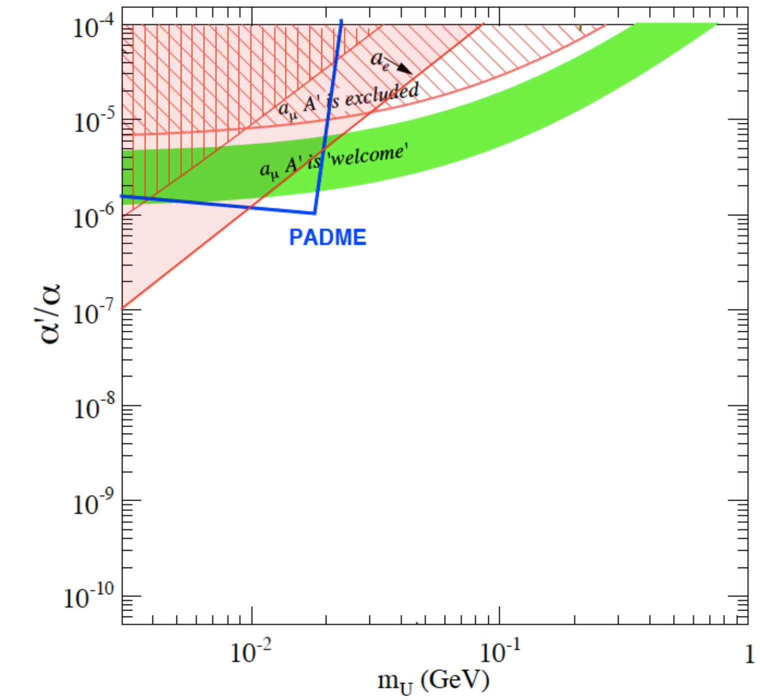
PADME at LNF >2015(?)

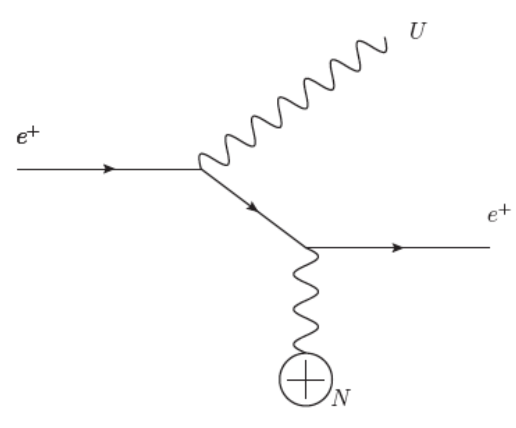
M. Raggi, V. Kozhuharov Advances in High Energy Physics Vol. 2014 ID 959802



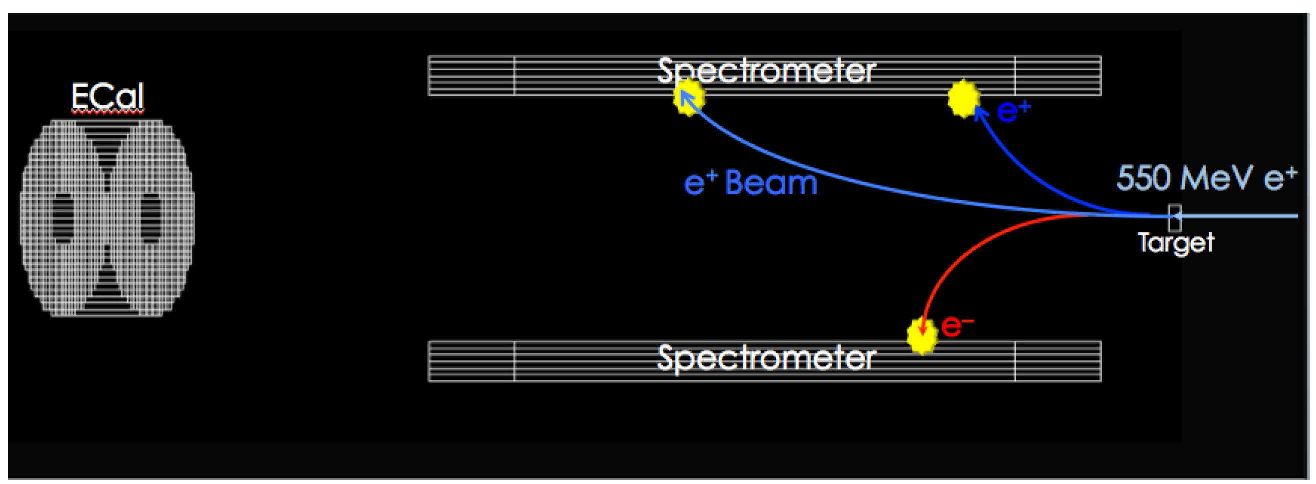
Annihilation

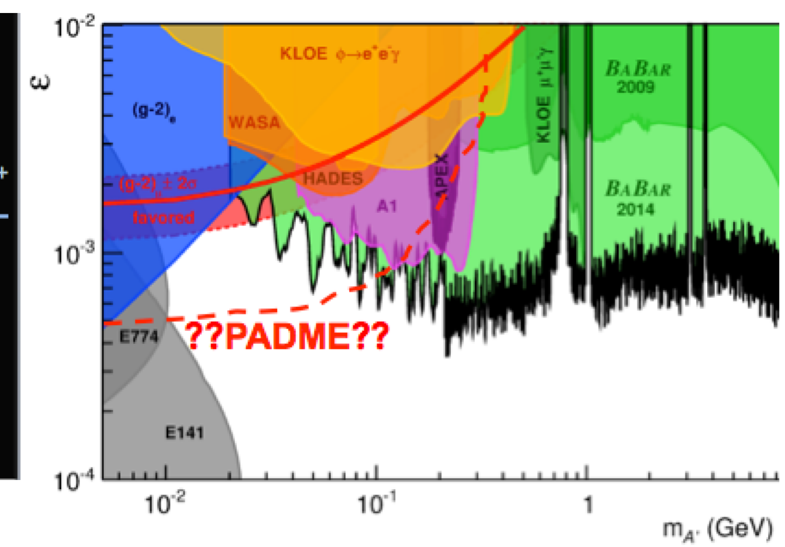






Bremsstrahlung





Present BTF

- E_{e+} = 550 MeV
- EOT ~ 10^{13} - 10^{14} year^{-1}
- 1 year experiment

Future Upgrade

- E_{e-} = 1.250 GeV
- EOT ~ 10^{19} - 10^{20} year^{-1}
- LINAC + BTF beam-dump

Pro's

- no decay hyp needed
- Simple and feasible

Con's

- limited $M_{A'}$ accessible

$$M_{A'}^{\max} = \sqrt{s} = \sqrt{2m_e(m_e + E_+)} \approx \sqrt{2m_e E_+}$$

- sizeable background

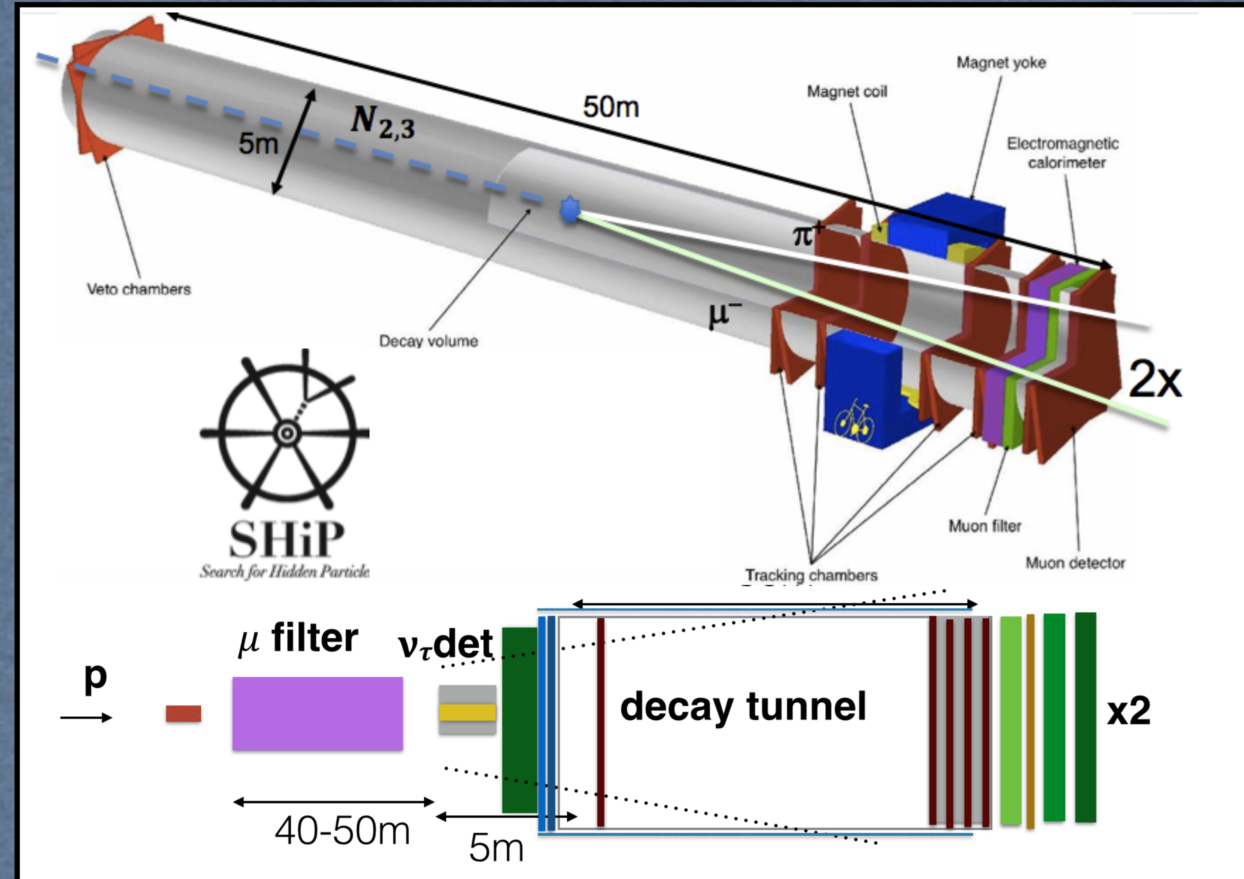
SHIP@CERN (20XX)

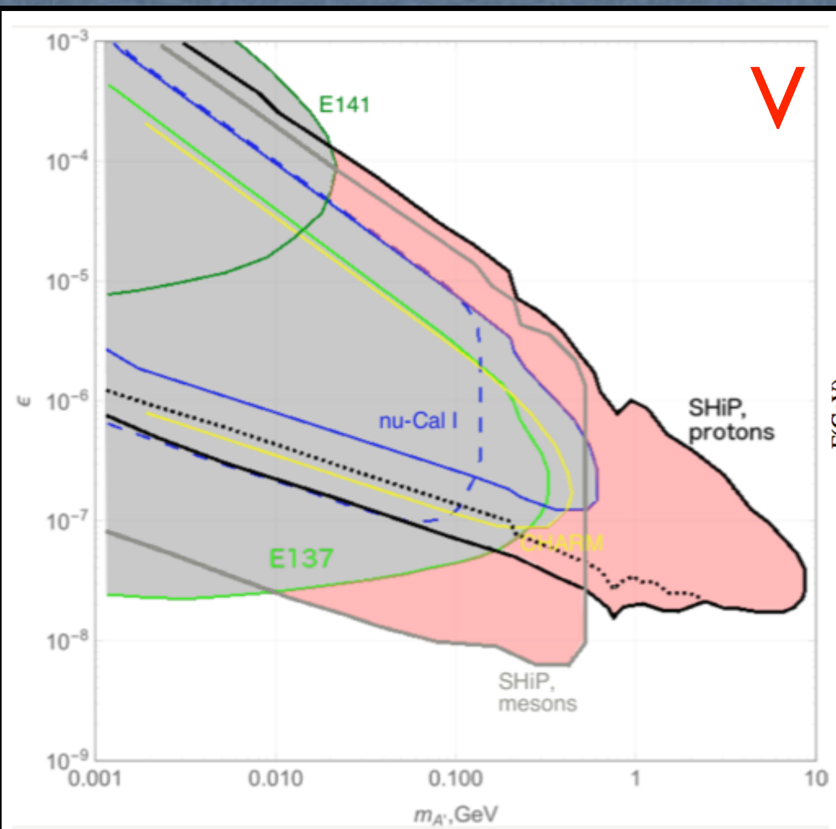
Proposal for a beam dump experiment at CERN/SPS using 400GeV proton beam

★ detection of long lived particles, very weakly interacting or sterile with x10k better stat sensitivity

★ study of ν_τ interactions with x200 better stat sensitivity

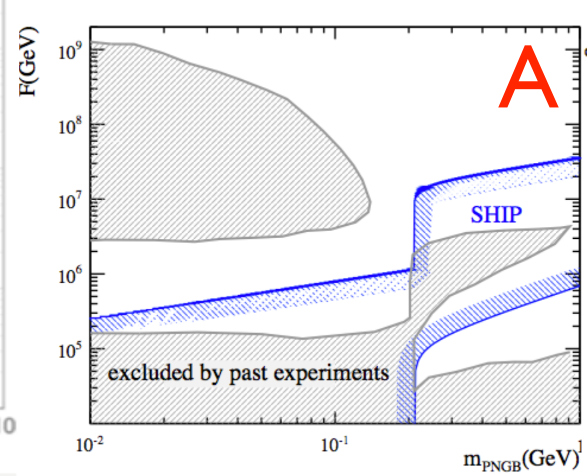
- EOI presented to SPS/CERN in 2014
- Experimental layout concept
- Cost and tech evaluation from CERN-Acc
- Extended physics case
- SHIP in CSN1 form 2015
- Full Technical Proposal for spring 2015

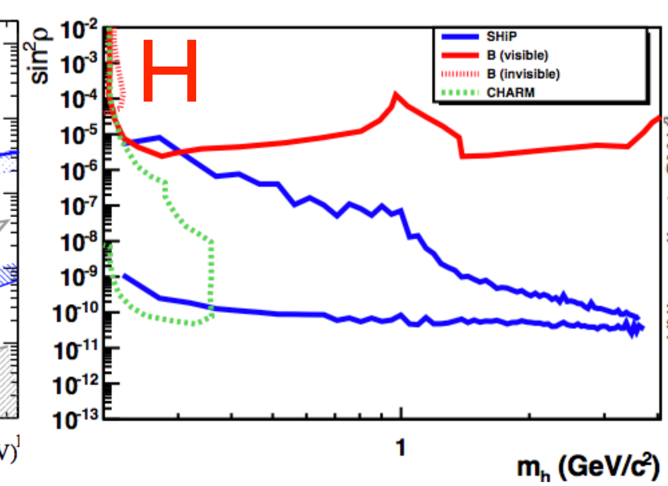


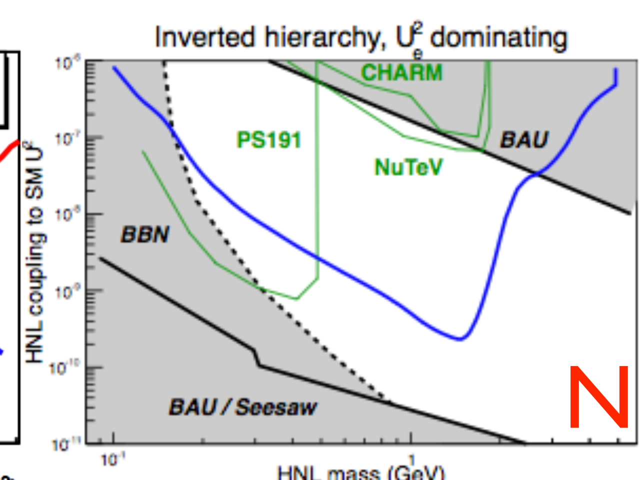


- Sensitivity to different portals
- 2x10^{20} POT

	Portal	Particles	Operator(s)
V	"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
A	"Axion"	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\widetilde{G}^{\mu\nu}_i$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
H	"Higgs"	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
N	"Neutrino"	Sterile neutrinos	$y_N LHN$







Conclusions

- ✳Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass
- ✳Accelerator-based (Light)DM search provides that unique feature of distinguish DM signal from any other cosmic anomalies or effects
- ✳Searches for Dark Photon **visible** decay are excluding a significant part of parameters space
- ✳Light Dark Matter (coupled to Dark Photon **invisible** decay) could explain null results resetting experimental limits
- ✳Many opportunities for experimental exploration and discovery with fixed target exps searching for LDM with orders of magnitude more sensitivity
- ✳Discovery or decisive tests of simplest scenarios possible in the next ~5-8 years!