Accelerator based Dark Matter searches

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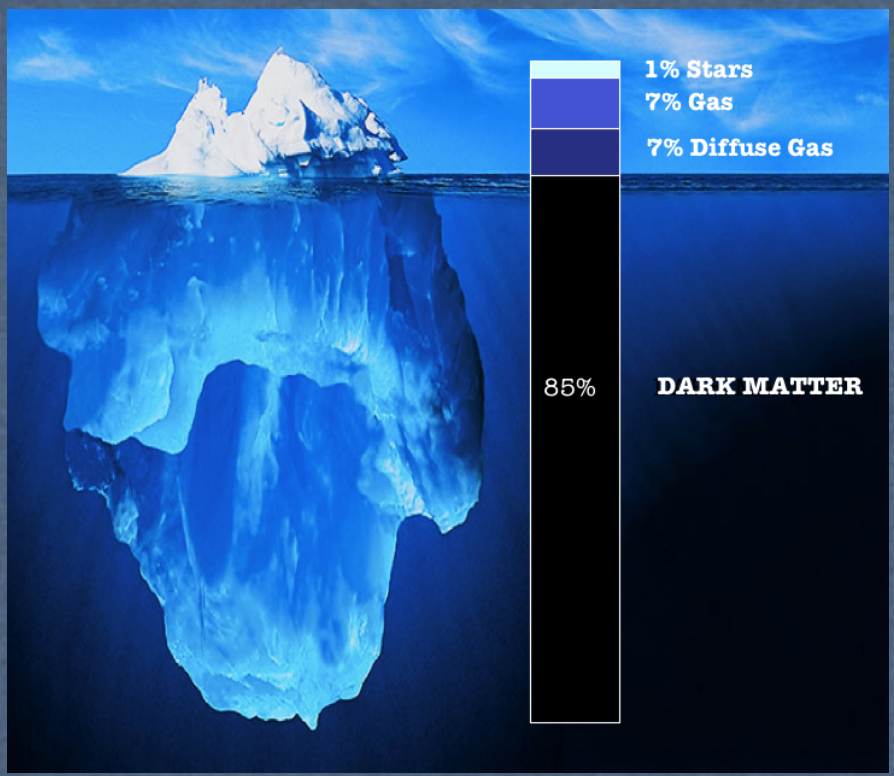
Dark Matter (DM) vs Baryonic Matter (BM)

Compelling astrophysical indications about DM existence

★ How much DM w.r.t. BM?



★ Does DM participate to non-gravitational interactions?
★ Is DM a new particle?

★ Constraint on DM mass and interactions

- should be '*dark*' (no em interaction)
- should weakly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

… assuming that the gravity is not modified and DM undergoes to other interactions

★ We can use what we know about standard model particles to build a DM theory

Use the SM as an example: $SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

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

Two options:

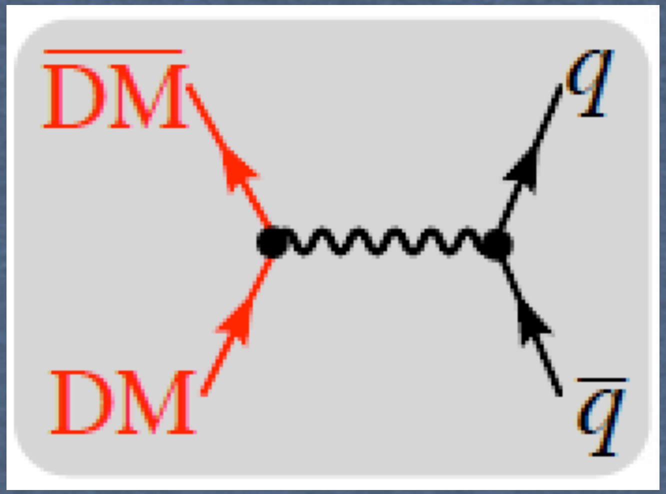
★ New matter interacting trough the same forces
★ New matter interacting through new forces

Any guess about the DM mass and interaction?

Yes, if we do a couple of assumptions:

★ DM thermal origin

in the early Universe DM was in thermal equilibrium with regular matter (via annihilation)



★ DM as thermal relic from the hot early Universe

Minimal DM abundance is left over to the present day

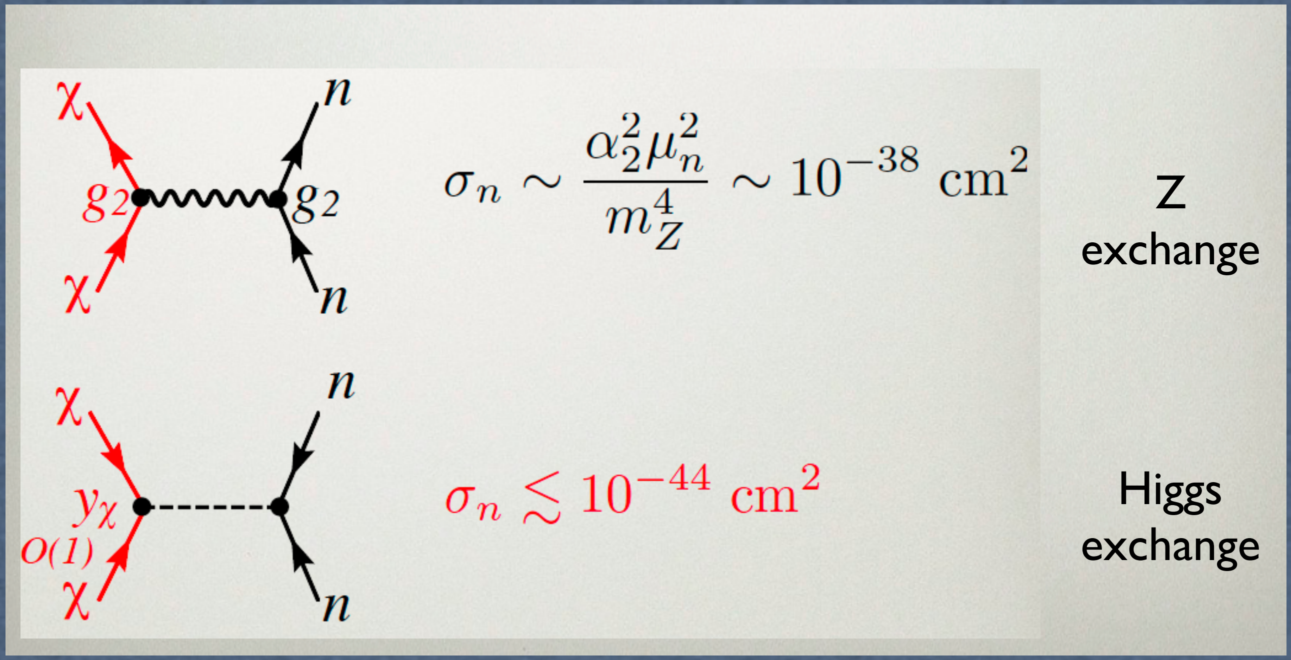
Correct DM density for an annihilation xsec:

$\langle \sigma v \rangle \sim 3\mathrm{x}10^{-26}\ \mathrm{cm}^3/\mathrm{s} \sim 1/(20\ \mathrm{TeV})^2$

$\langle \sigma v \rangle \sim M^2_{DM}/M^4_{mediator}$

WIMPs (Weakly Interacting Massive Particles)

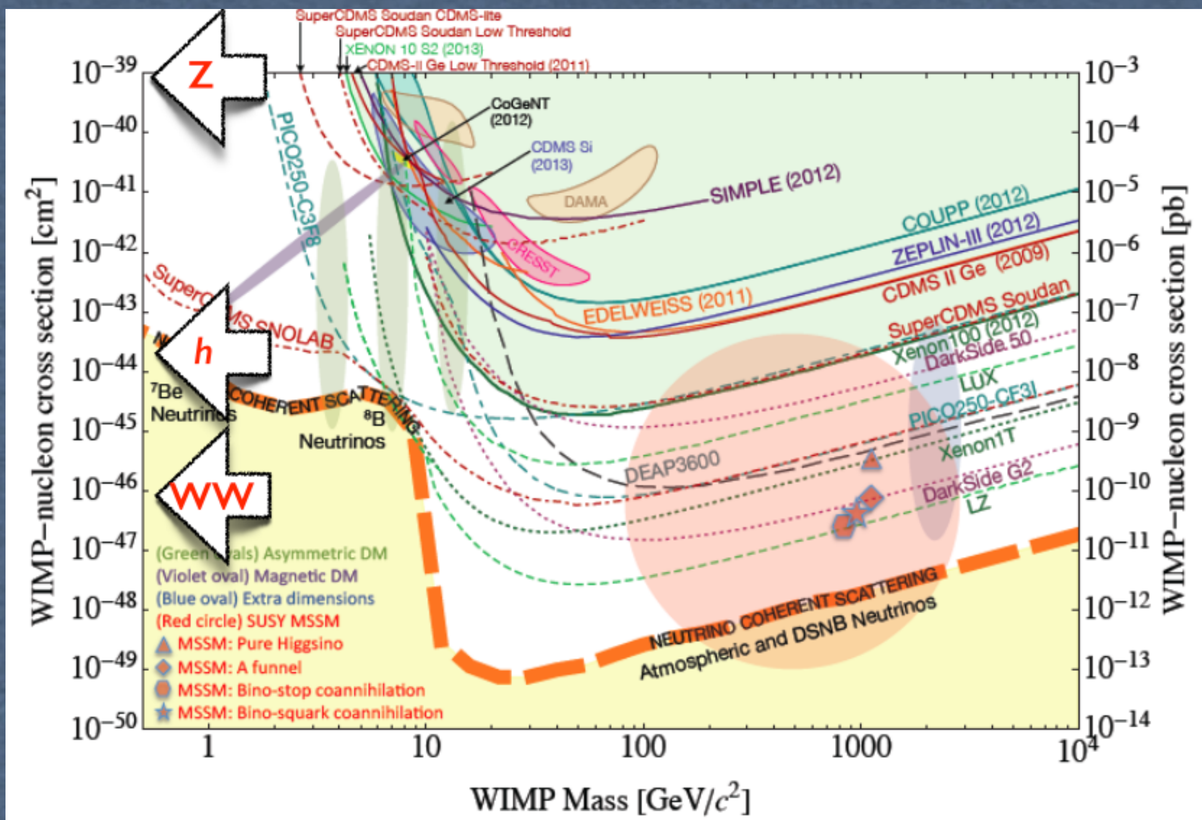
- Massive DM with massive mediator
- For ~100 GeV DM mass, weak-scale mediators provide reasonable annihilation rate and range of DM-scattering rates



Thermal origin suggests DM interactions and mass in the vicinity of the weak-scale

Exploring the WIMP's option

★ Experimental limits



Slow-moving cosmological weakly interacting massive particles

- DM detection by measuring the (heavy) nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits
  - Scattering through Z boson ($\sigma \sim 10^{-39}$cm^2): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45}$cm^2)
  - Close to irreducible neutrino background

Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

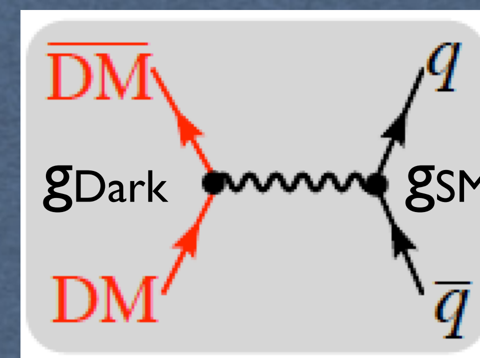
✳ No signal in direct detection

✳ Experiments have (almost) no sensitivity to (light) DM (<1 GeV)

Any guess about the DM mass and interaction?

★ (Obvious) first guess: DM interaction in the range of the weak force scale (WIMPS) with DM mass in the range of TeV

WIMPs paradigm is not the only option (keeping the DM thermal origin)



$\langle \sigma v \rangle \sim g^2_{Dark}\, g^2_{SM}\, M^2_{DM}/M^4_{mediator}$

Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

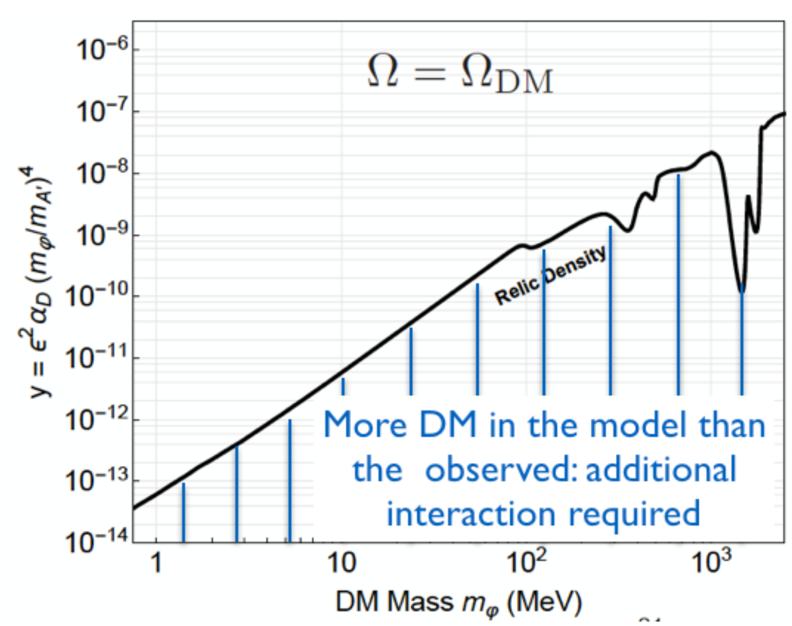
New interaction

★ Definition of [adimensional] variable $y \sim g^2_{Dark}\, g^2_{SM}\, (M_{DM}/M_{mediator})^4 \sim \langle \sigma v \rangle\, M^2_{DM}$

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D \frac{m_\varphi^2}{m_{A'}^4} = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}^4} \frac{1}{m_\varphi^2} = \frac{y}{m_\varphi^2}$$

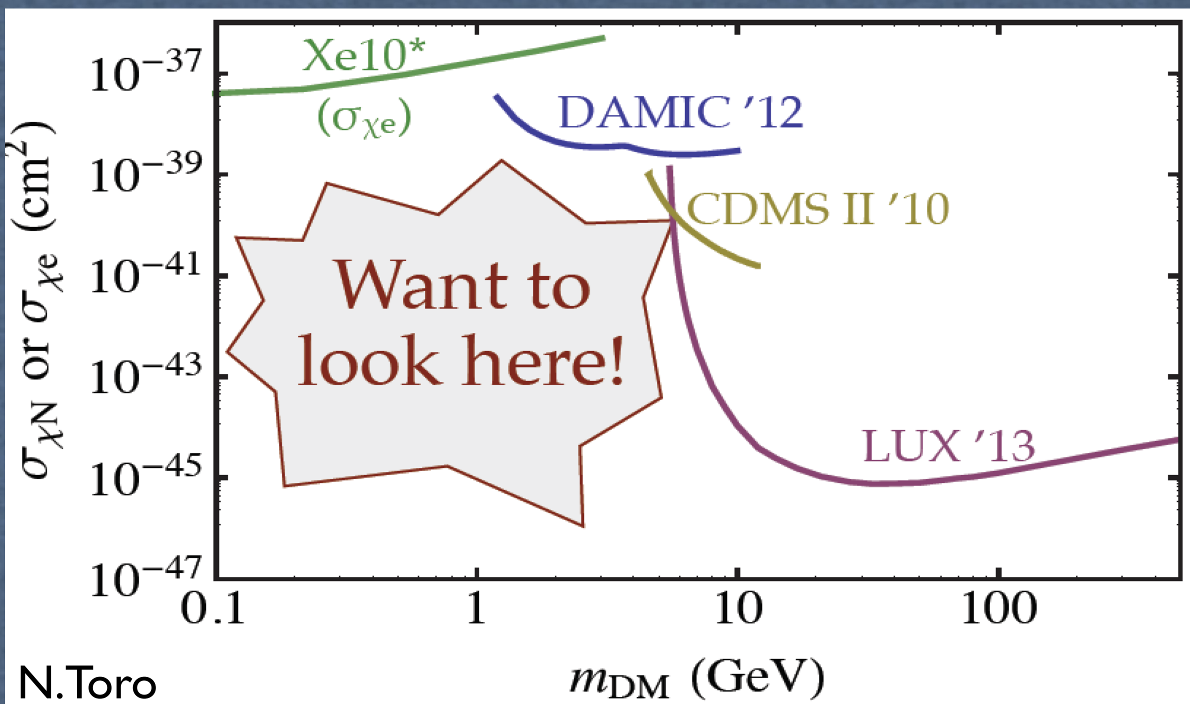
Computed for $m_{A'}/m_{\varphi/\chi} = 3$

But thermal target largely insensitive to this ratio



Light Dark Matter

★ Experimental limits



Light Dark Matter with a (almost) weak interaction (new force!)

- Direct Detection is (almost) impossible
  - Low mass elastic scattering on heavy nuclei produces small recoil
  - eV-range recoil requires a different detection technology
  - Directionality may help to go behind existing limits at large masses

Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- **High intensity**
- **Moderate energy**

Light Dark Matter | Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

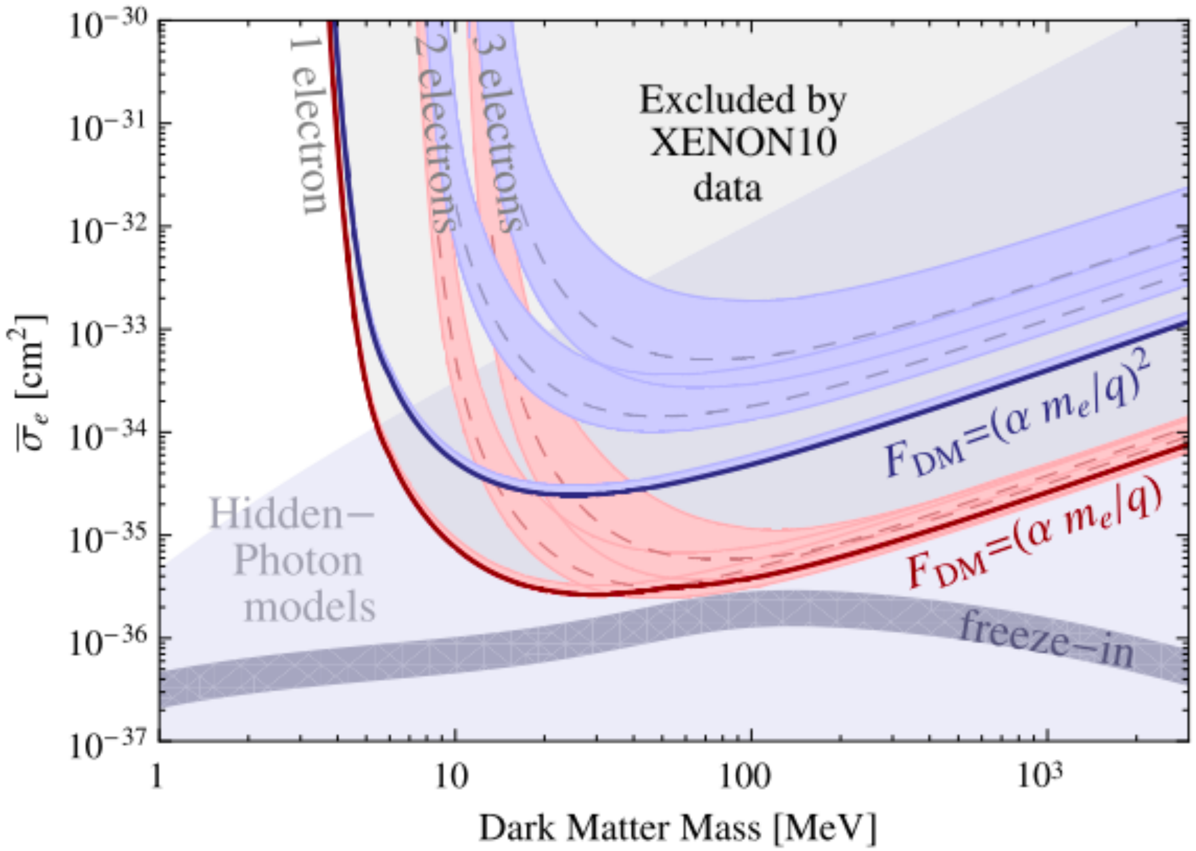
WIMPs

Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

Can be explored at accelerators!

LDM - Direct Detection limits

Limits from XENON10



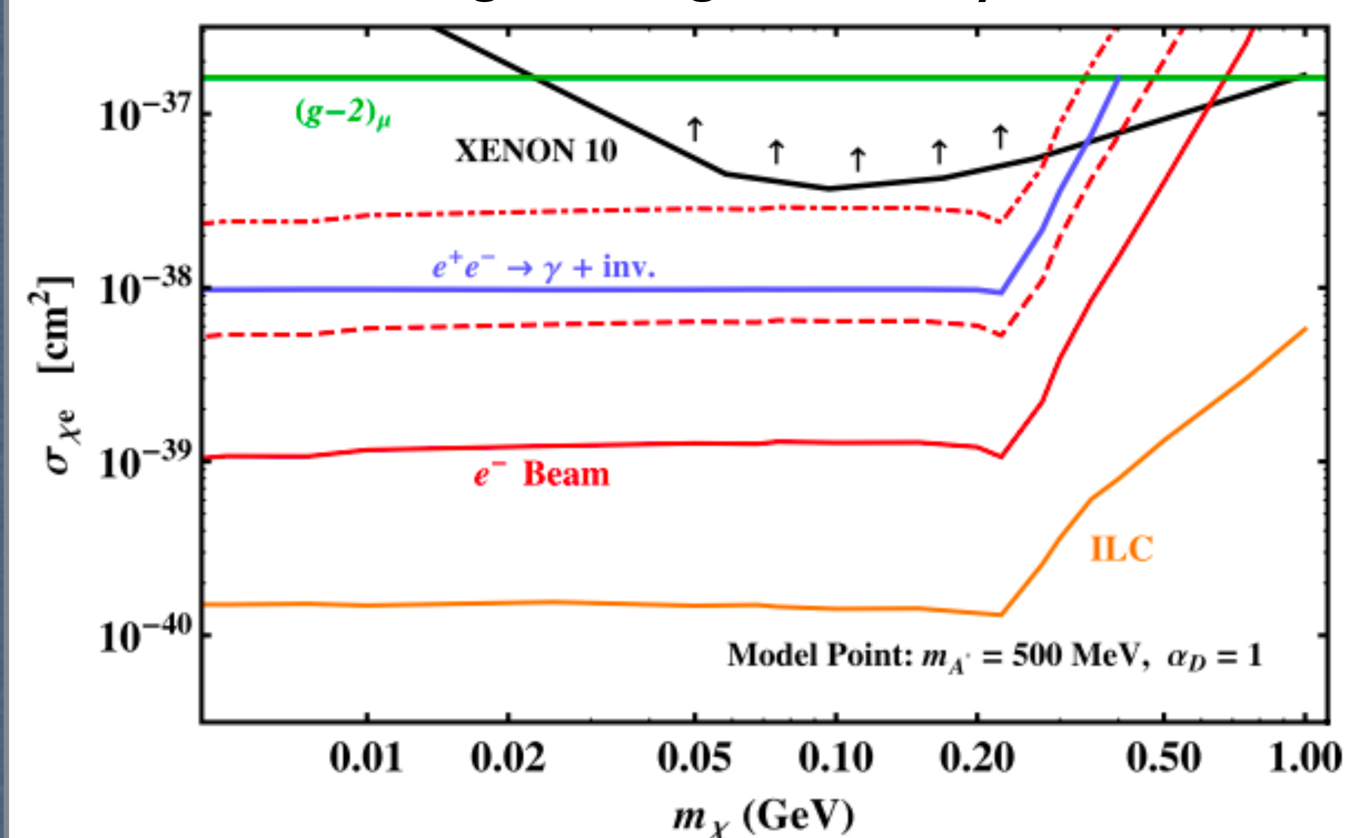
PhysRevLett. 109.021301 R.Essig, A.Manalaysay, J.Mardon, P.Sorensen, T.Volansky,

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

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

- No experiments were designed to measure LDM (all limits come from reinterpretation of old experiments)

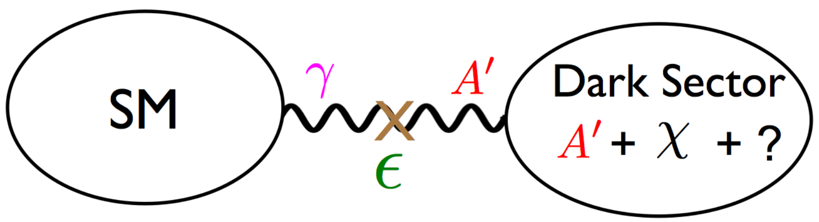
Fixed target & high intensity e⁻ beam

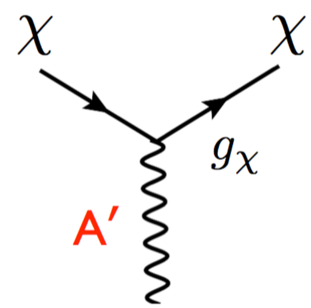


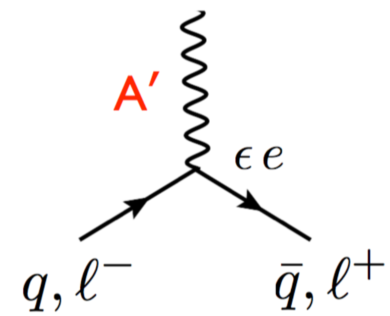
PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, Gordan, P.Schuster, N.Toro

Dark forces and dark matter

(Light WIMPs - light mediators)



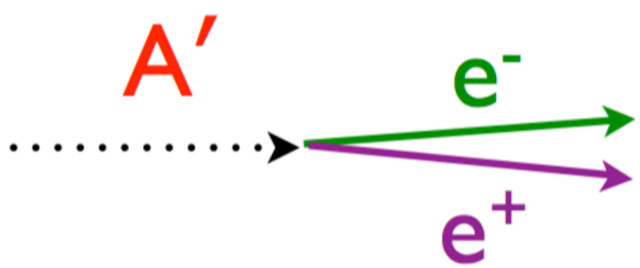




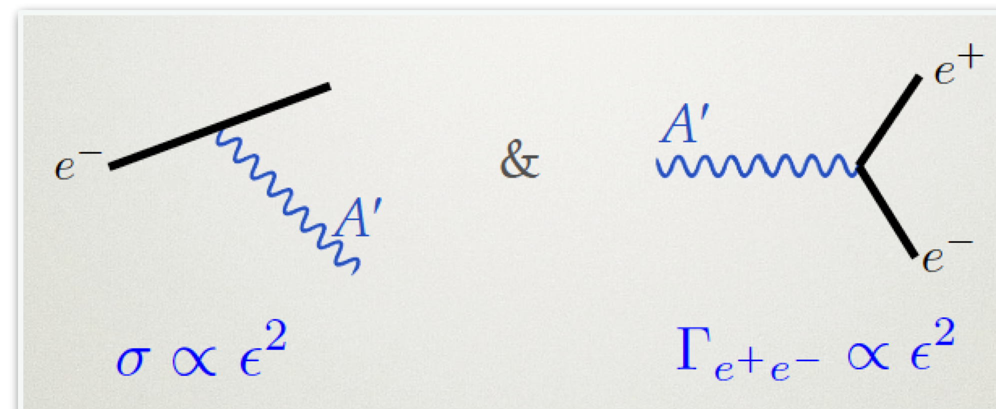
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

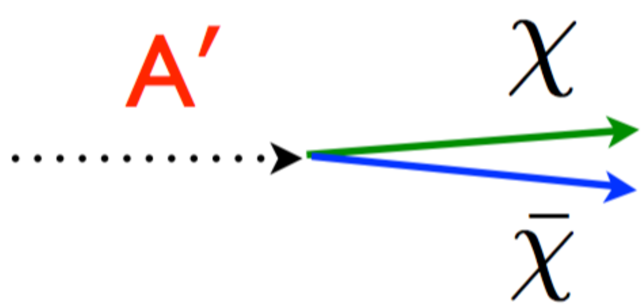
Visible



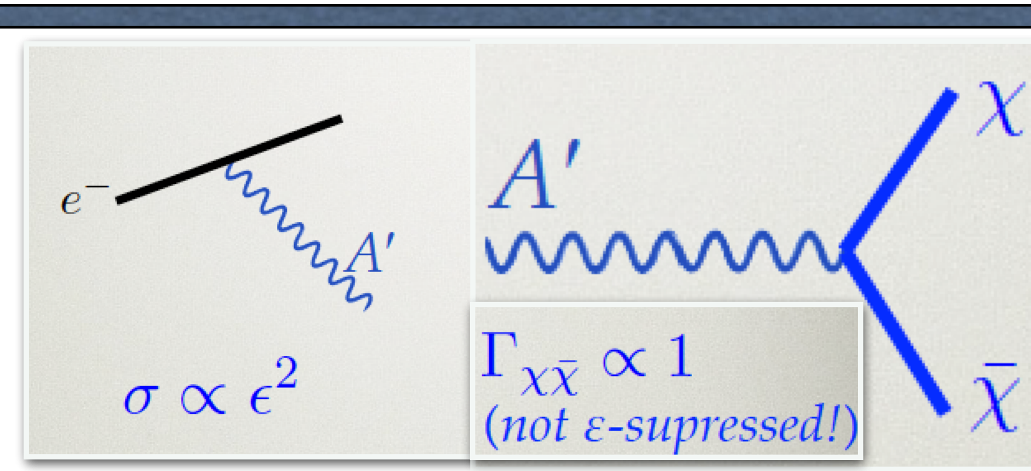
- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$



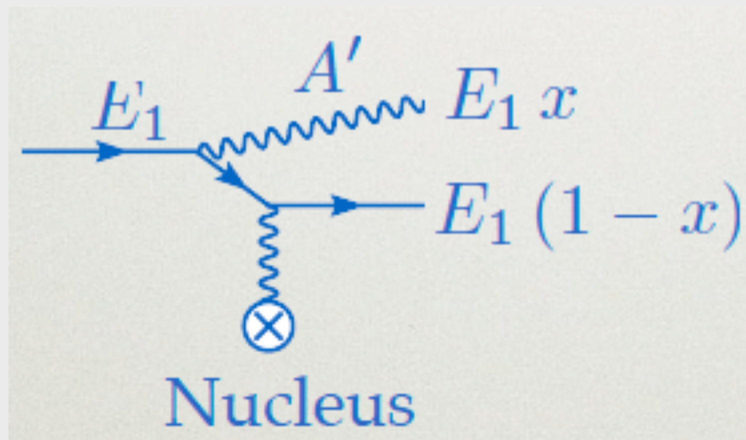
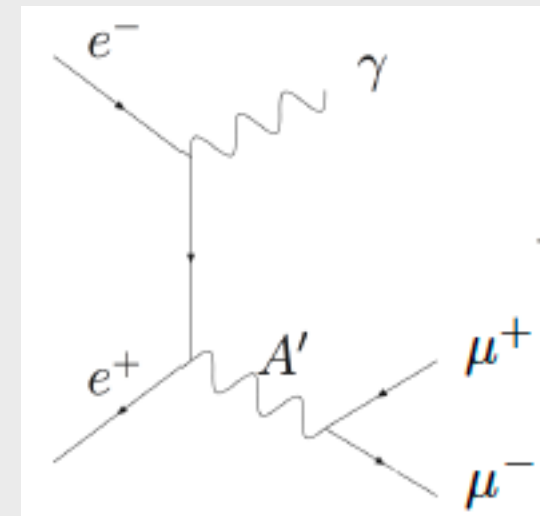
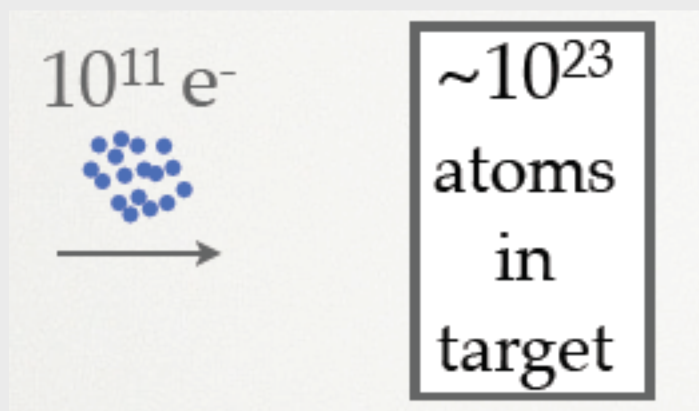
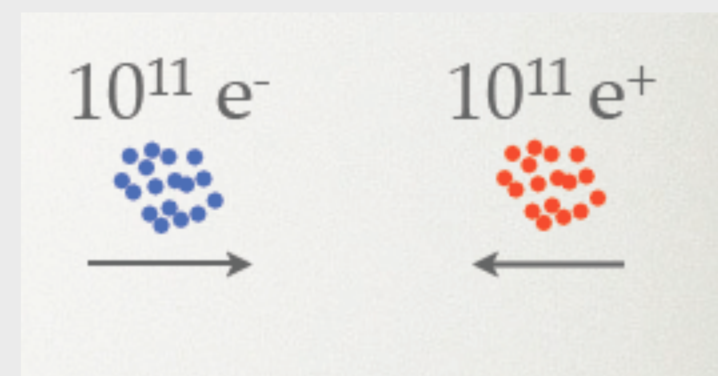
Invisible



- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g^2_\chi/4\pi \gg \varepsilon^2\alpha_{EM}$



Fixed target vs. collider

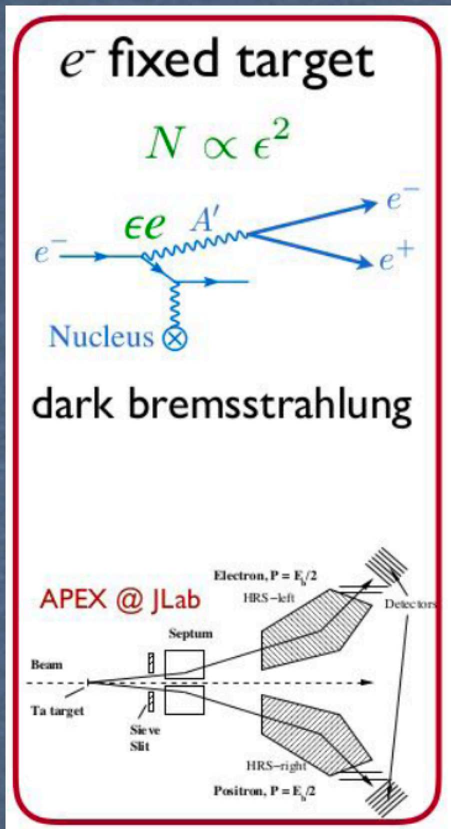
	Fixed Target	e+e- colliders
Process		
Luminosity		
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

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

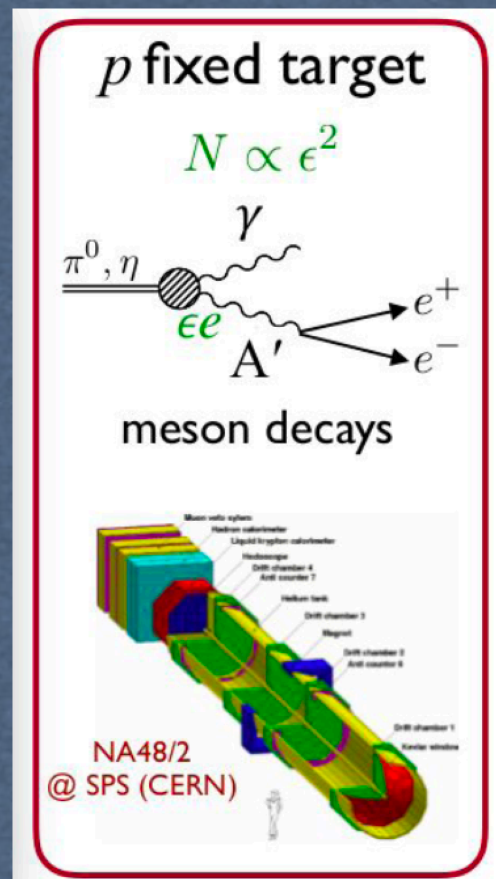
Fixed Target:
- high backgrounds
- limited A' mass

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

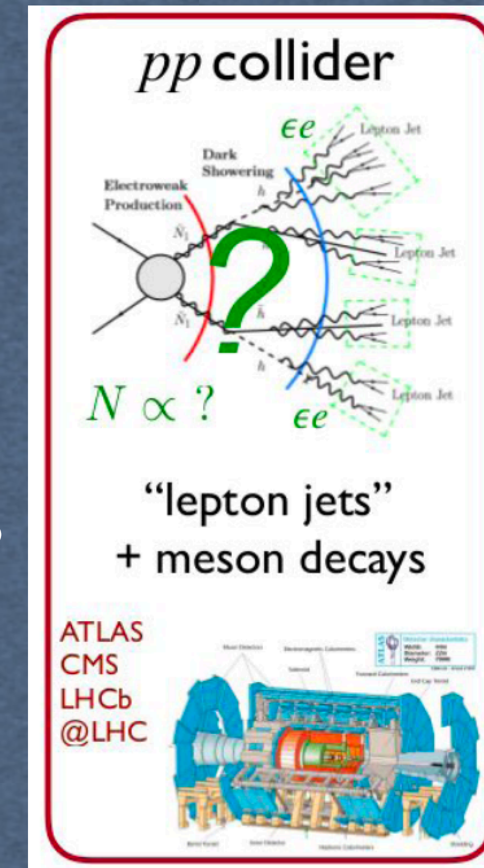
A' visible and invisible decay at accelerators



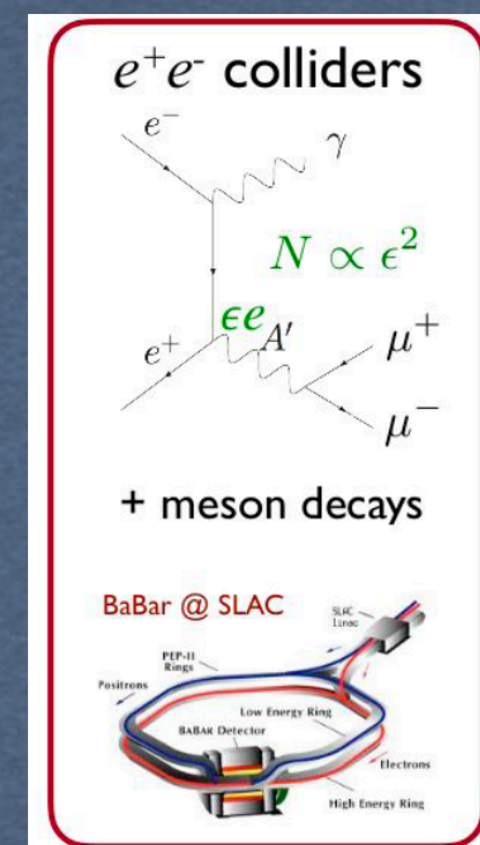
Fixed target:
e N →N γ'→ N Lepton Lepton+
➜ JLAB, MAINZ



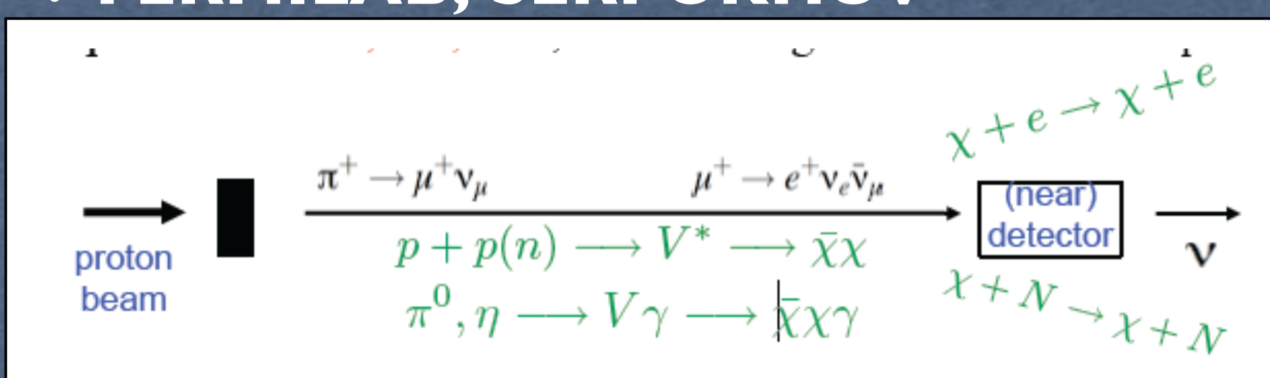
High Energy
Hadron Colliders:
pp → lepton jets
➜ ATLAS, CMS, CDF&D0



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



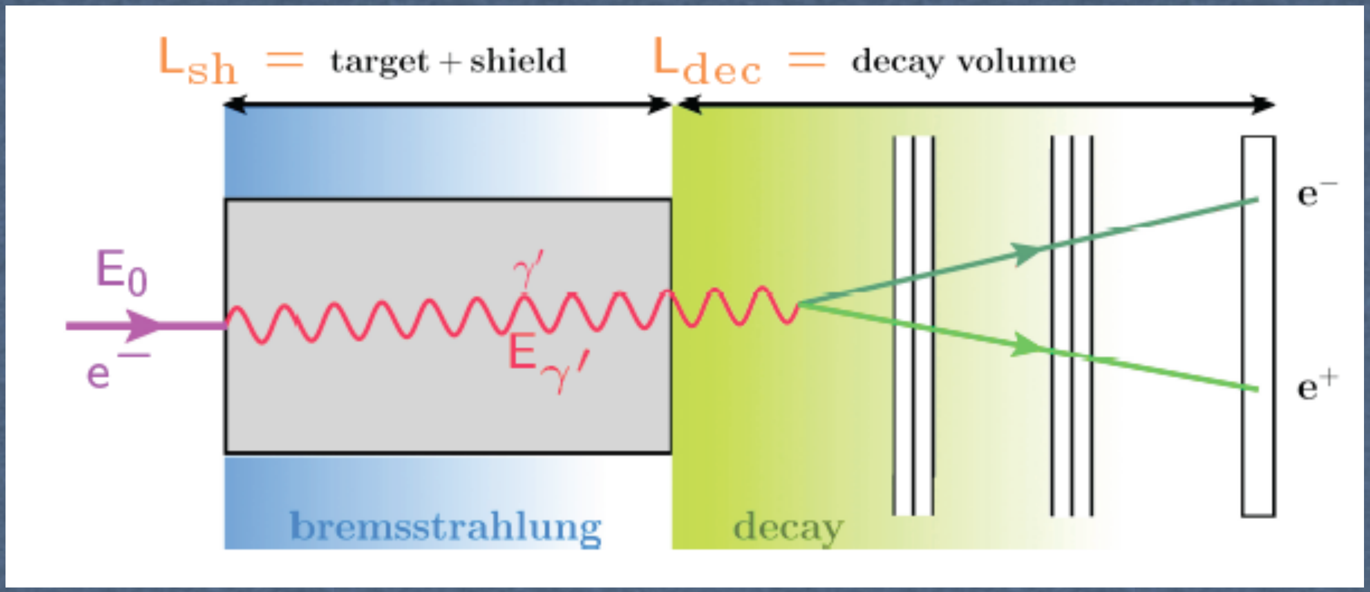
Fixed target:
p N →N γ'→ p Lepton Lepton+
➜ FERMILAB, SERPUKHOV



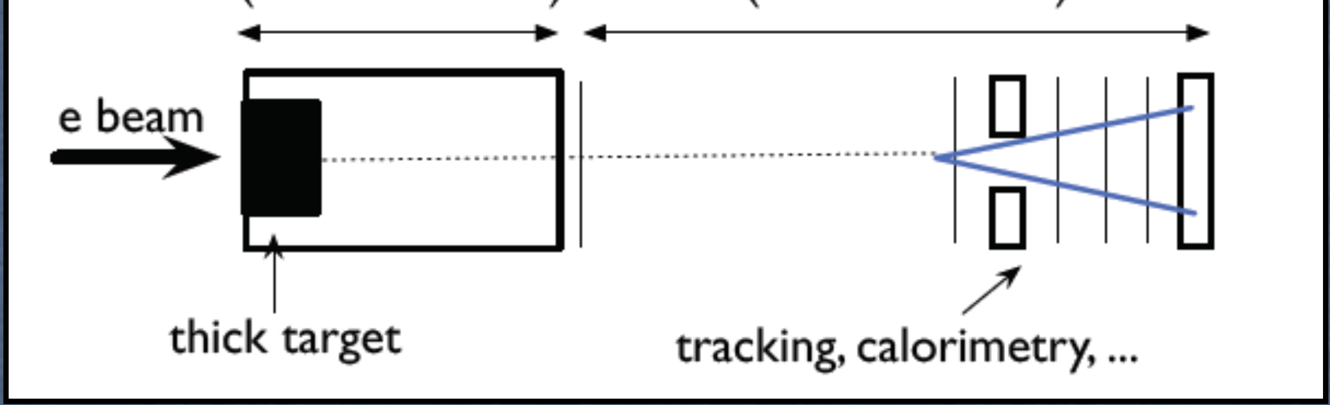
Annihilation:
e+e- → γ' γ → $\mu\mu$ γ
➜ BABAR, BELLE, KLOE, CLEO

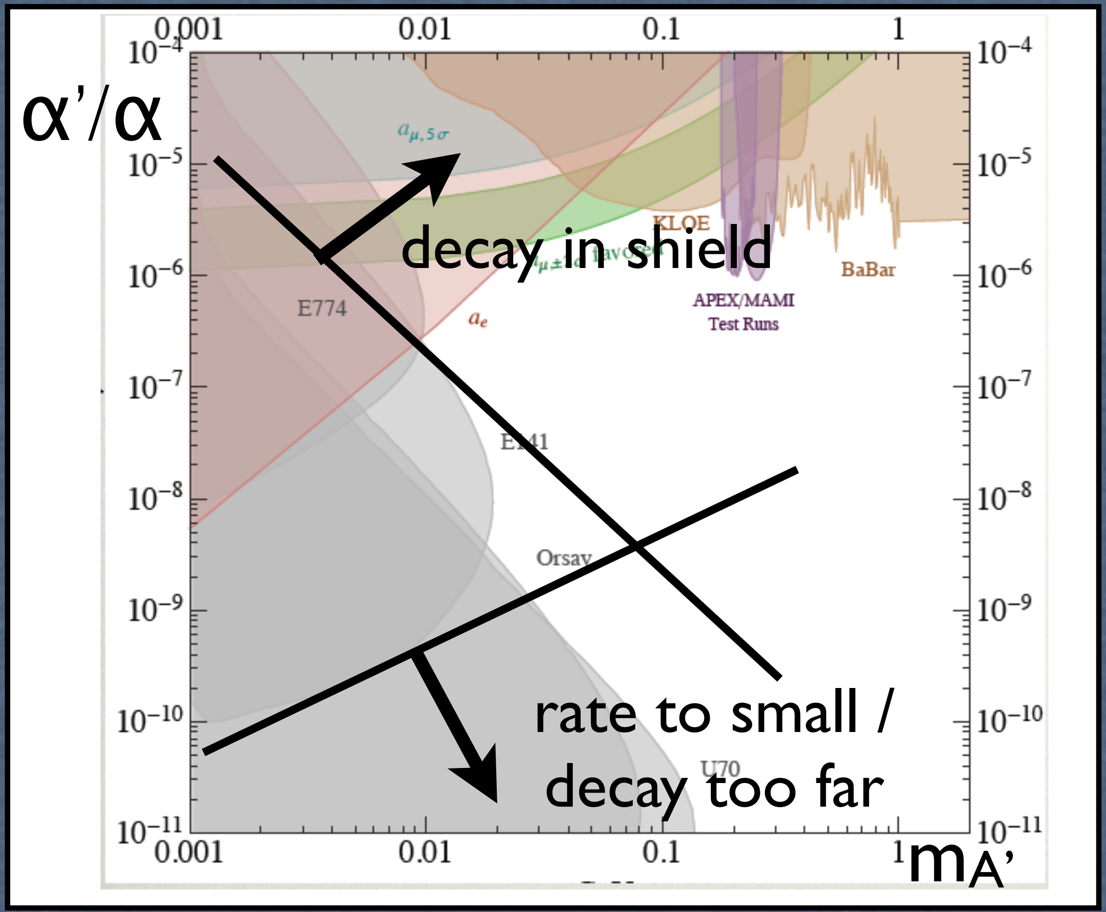
Beam-dump experiments - visible -

- 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

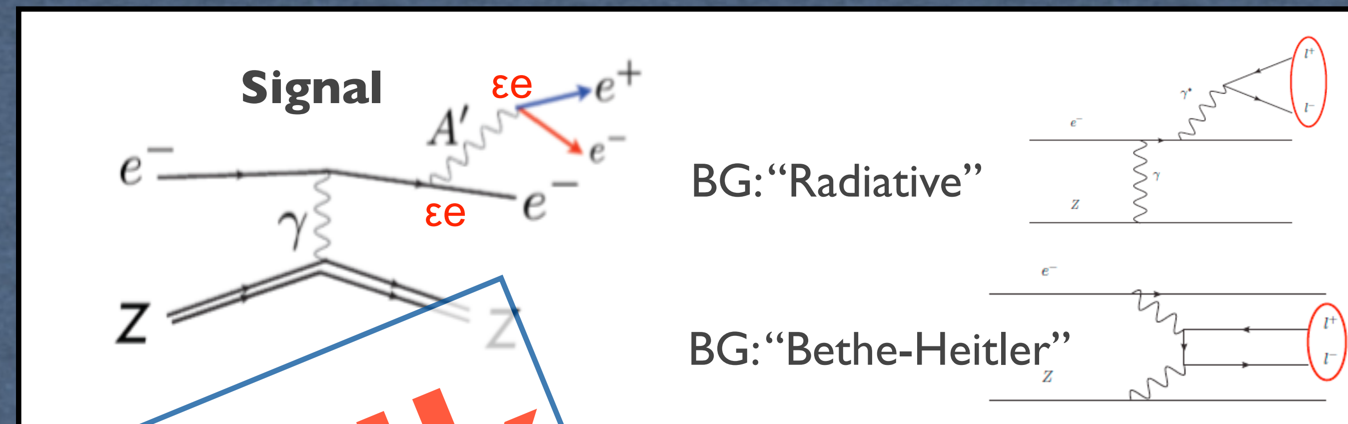


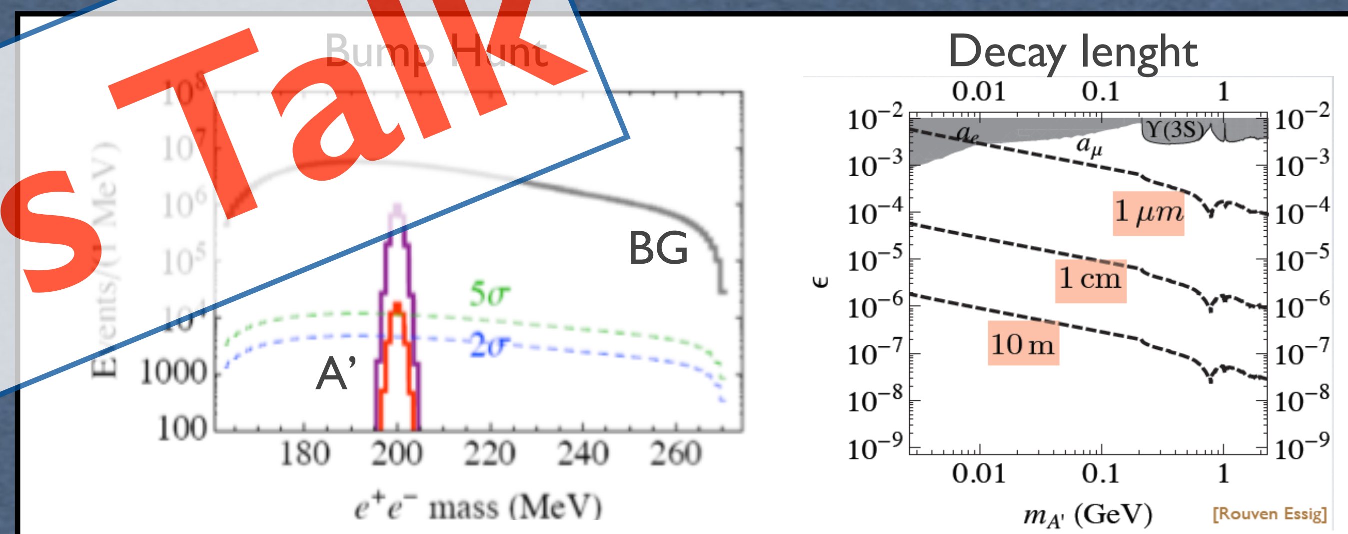
$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\,(10^{-8}\alpha/\alpha')$$
$$\times\,(100\ \mathrm{MeV}/m_{A'})$$





HPS@JLab
Heavy Photon Search





Rafo's Talk

Heavy photon signatures in HPS

1) Bump Hunting (BH)

Narrow e+e-resonance over a QED background

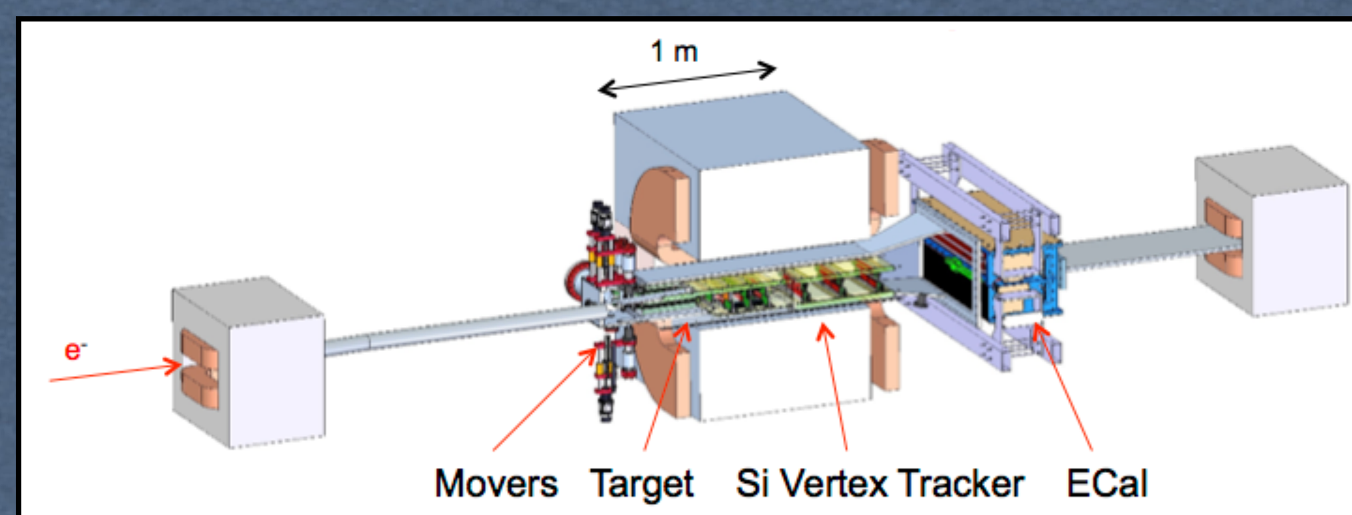
➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

2) Secondary decay vertex (vertexing)

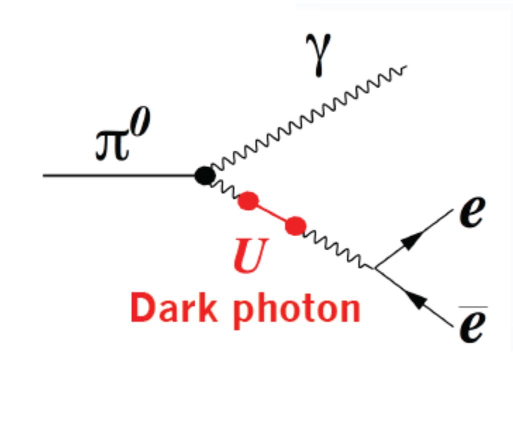
Detached vertex from few mm to tens cm

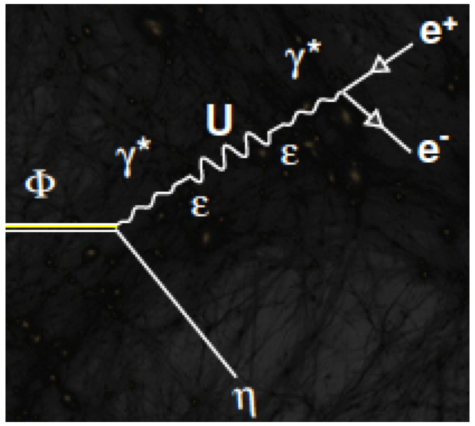
➥ good spacial resolution: σ_{vertex}~1mm

BH + Vertexing = enhanced experimental reach

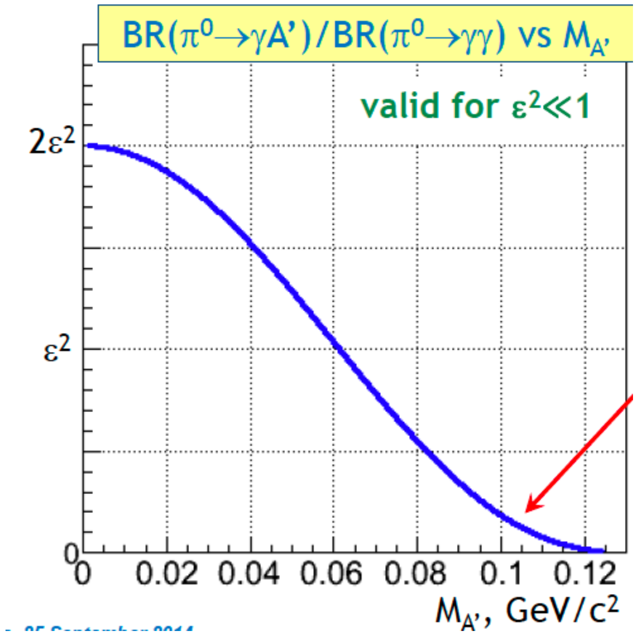


Meson Decay - The latest Results

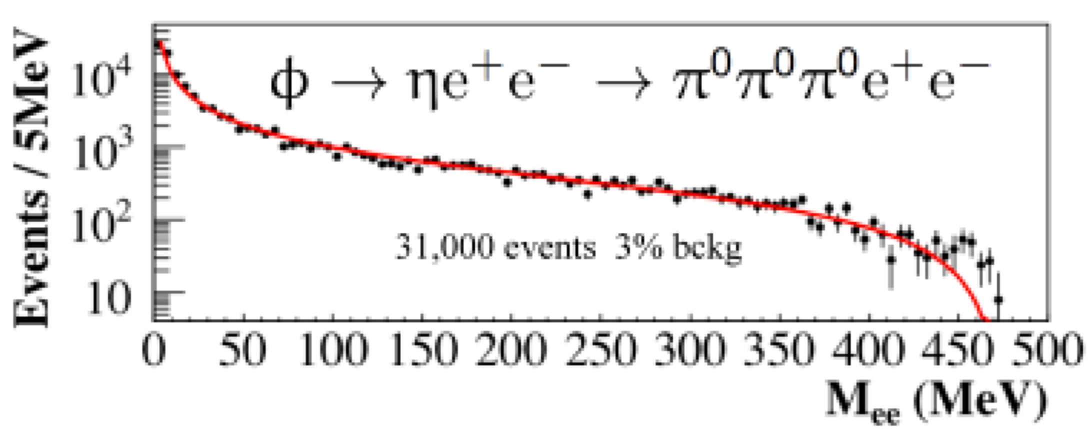


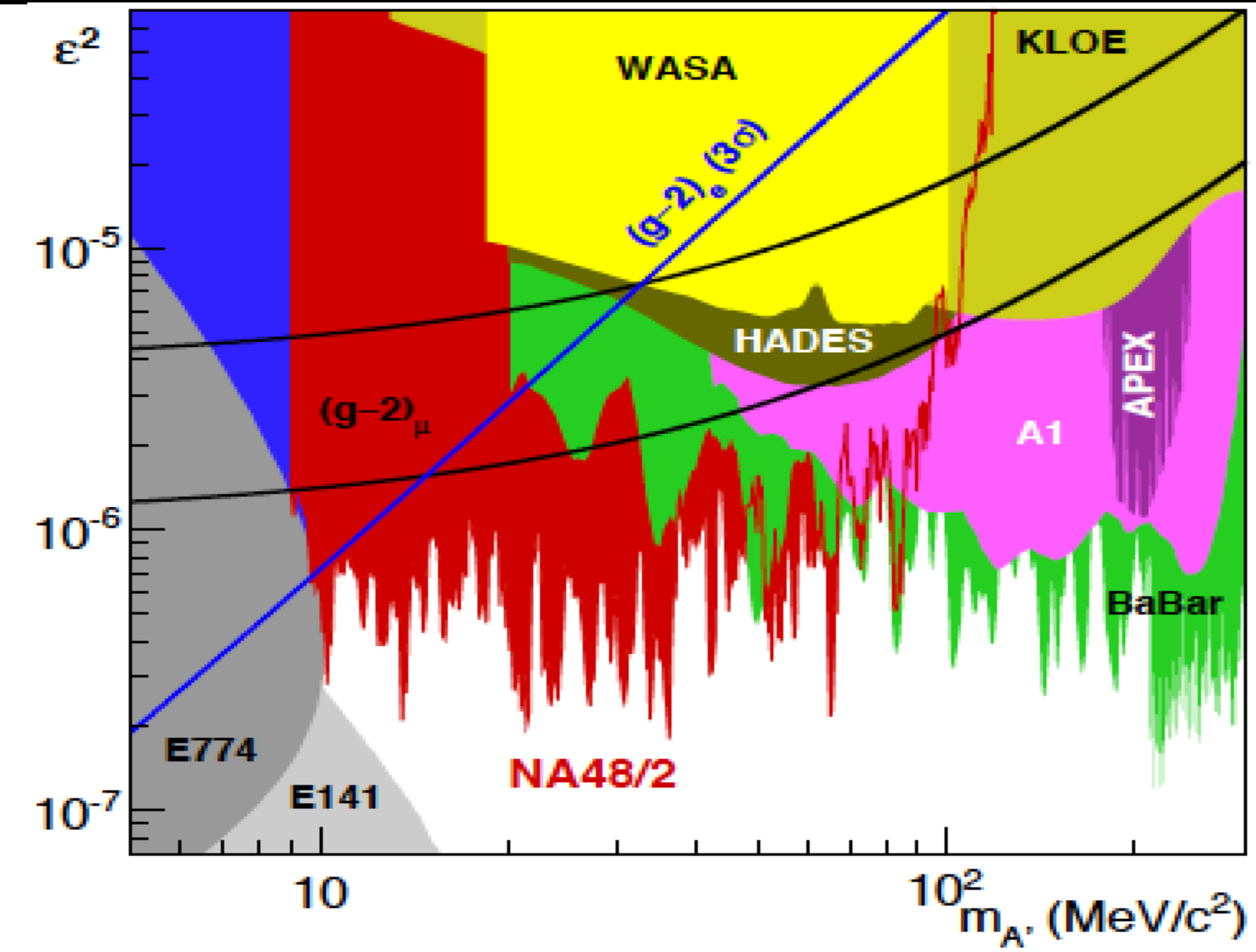


$K^\pm \to \pi^\pm \pi^0$, $\pi^0 \to \gamma A'$, $A' \to e^+e^-$



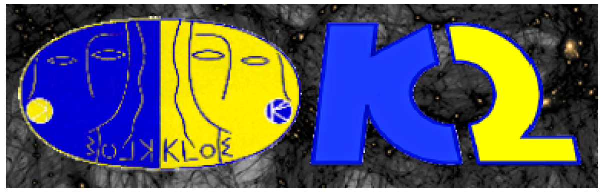
- 4×10^{10} π^0
- Acceptance ~ 2.5%
- δM ~ 1% Mee



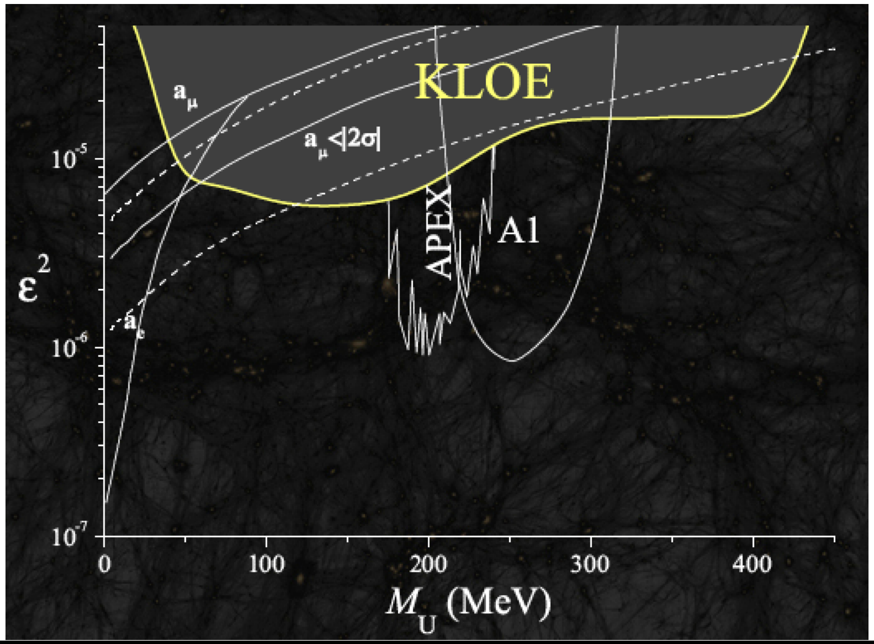


NA48/2

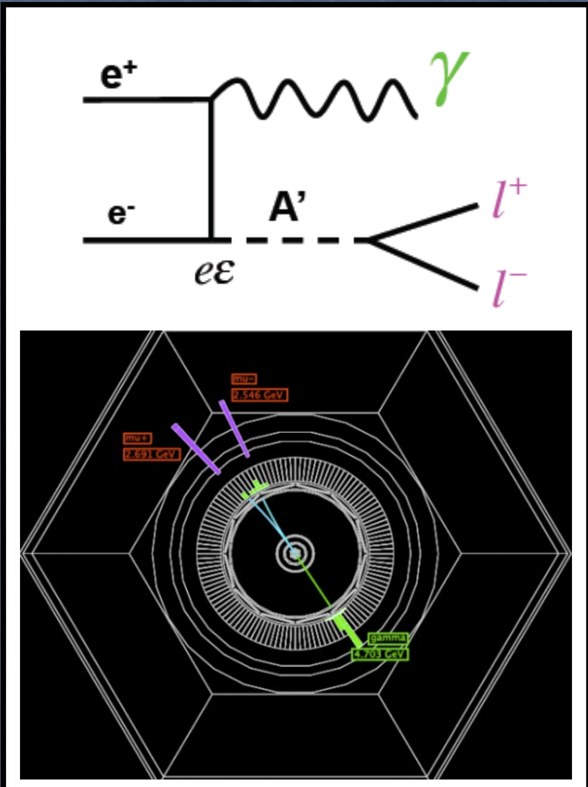
J.R.Batley et al.
Arxiv: 1504.00607



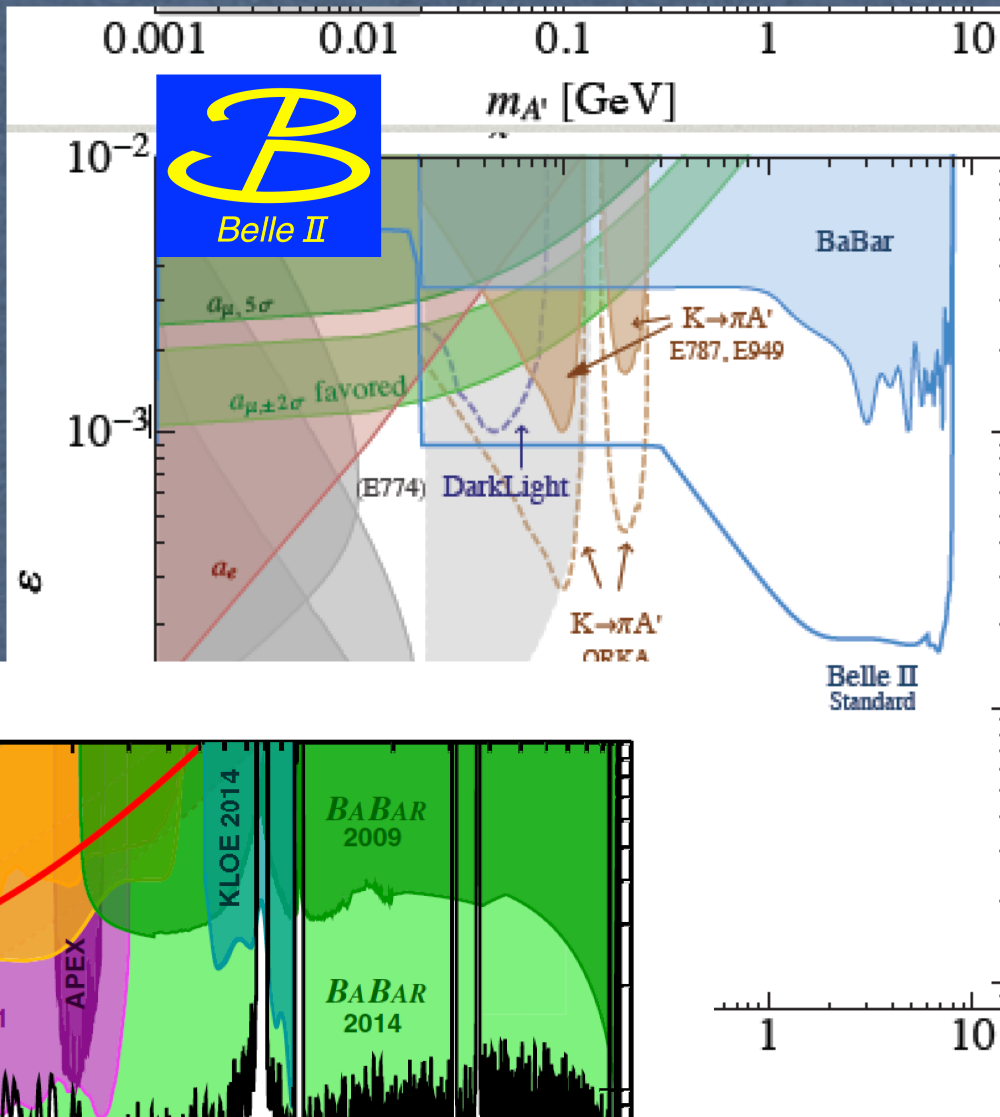
Phys. Lett. B 706 (2012) 251
Phys. Lett. B720 (2013) 111



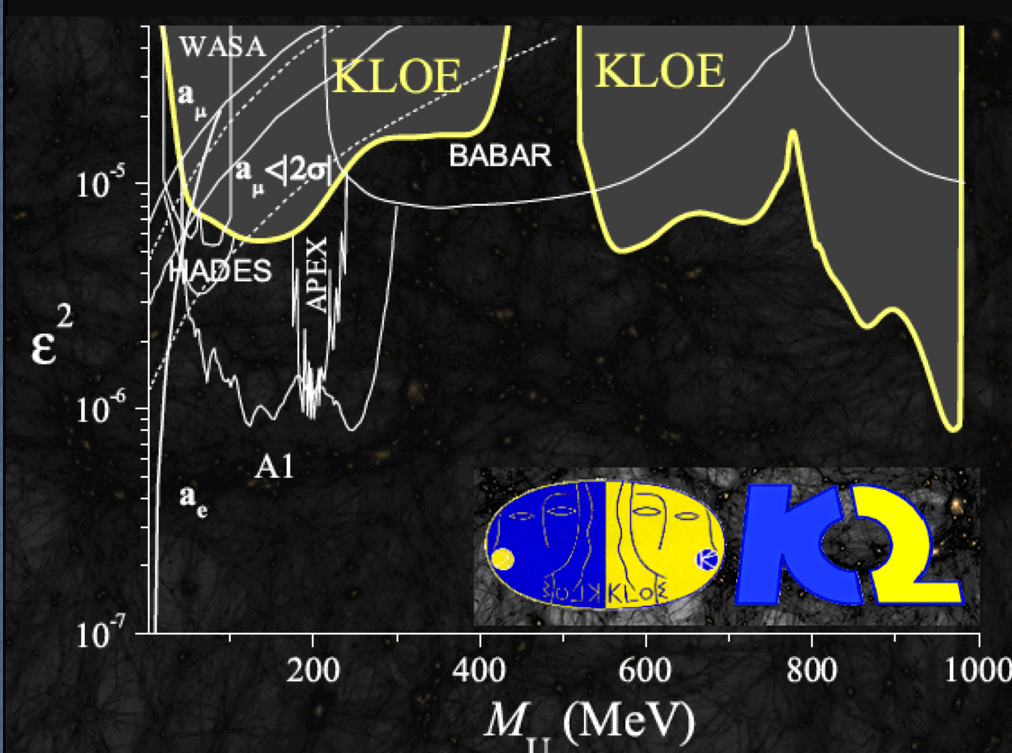
e+e- Colliders Recent & future results - visible -



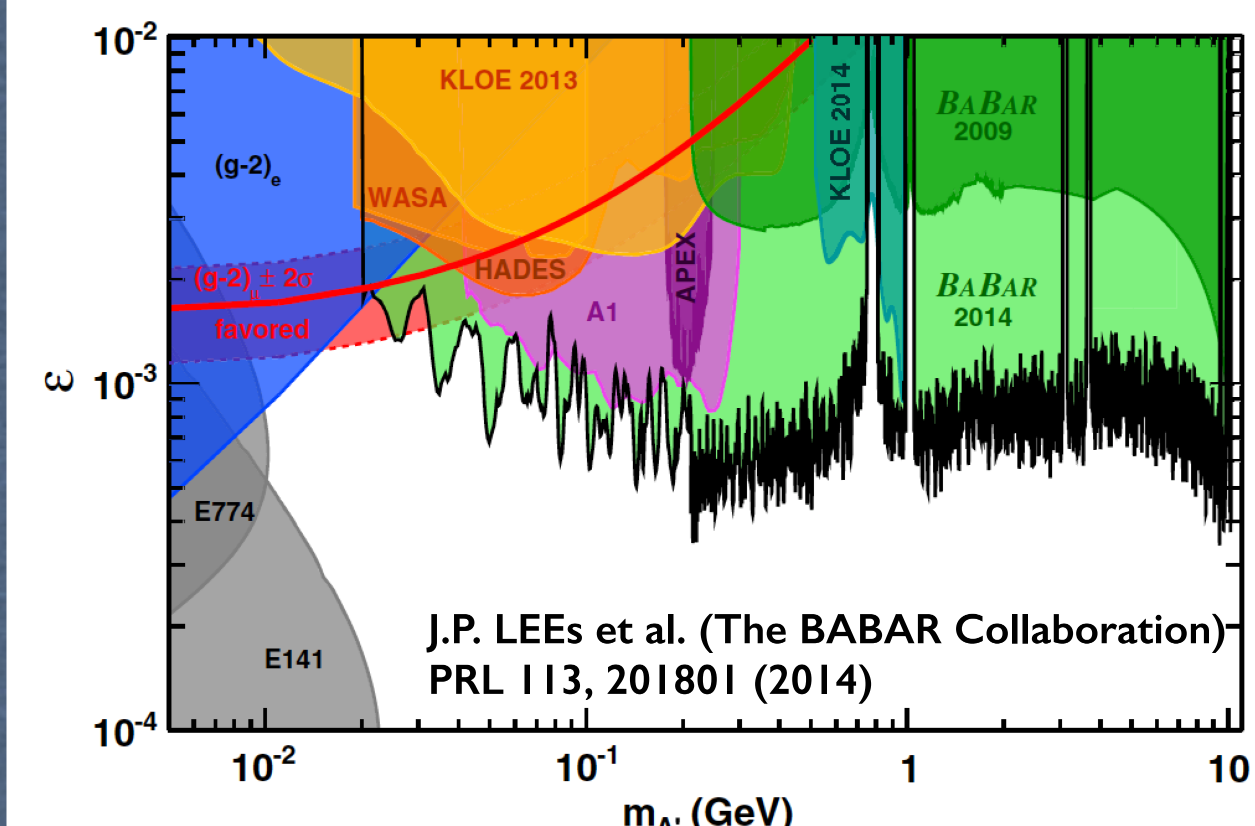
- 1gamma + 2 opposite leptons
- Di-lepton mass fit to a bg
- Mass resolution: 1.5 MeV - 8 MeV
- Int (L) = 514 fb^{-1}



Phys. Lett. B 736 (2014) 459



- Events with μ+μ- detected
- L~ 240 pb^{-1}



J.P. LEEs et al. (The BABAR Collaboration) PRL 113, 201801 (2014)

Hunting for A' at accelerators

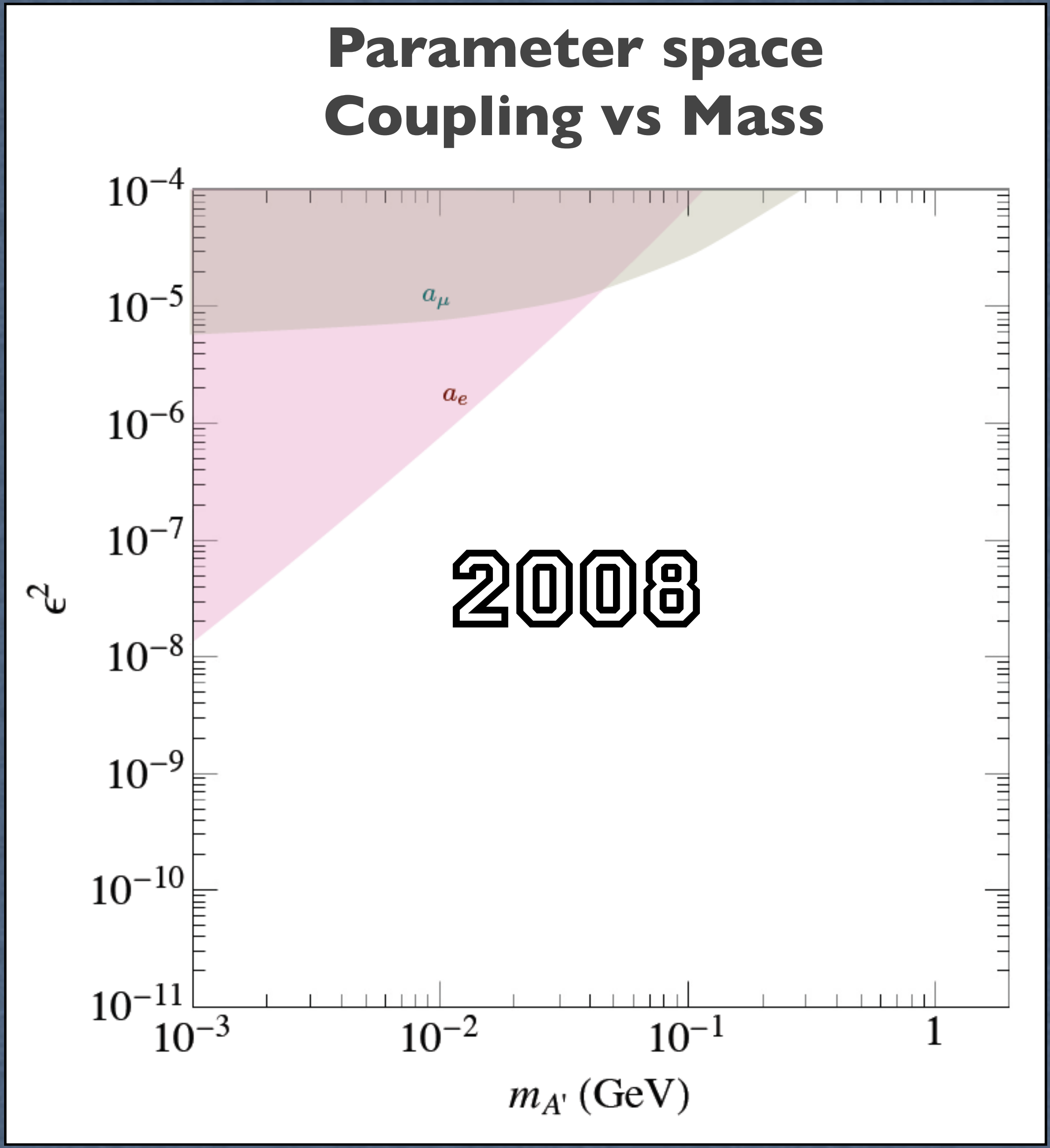
Fixed target: e N →N γ'→ N Lepton- Lepton+
  → **JLAB, MAINZ**

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, NA48, HC**

coupling vs mass



Hunting for A' at accelerators

Fixed target: e N →N γ'→ N Lepton⁻ Lepton⁺
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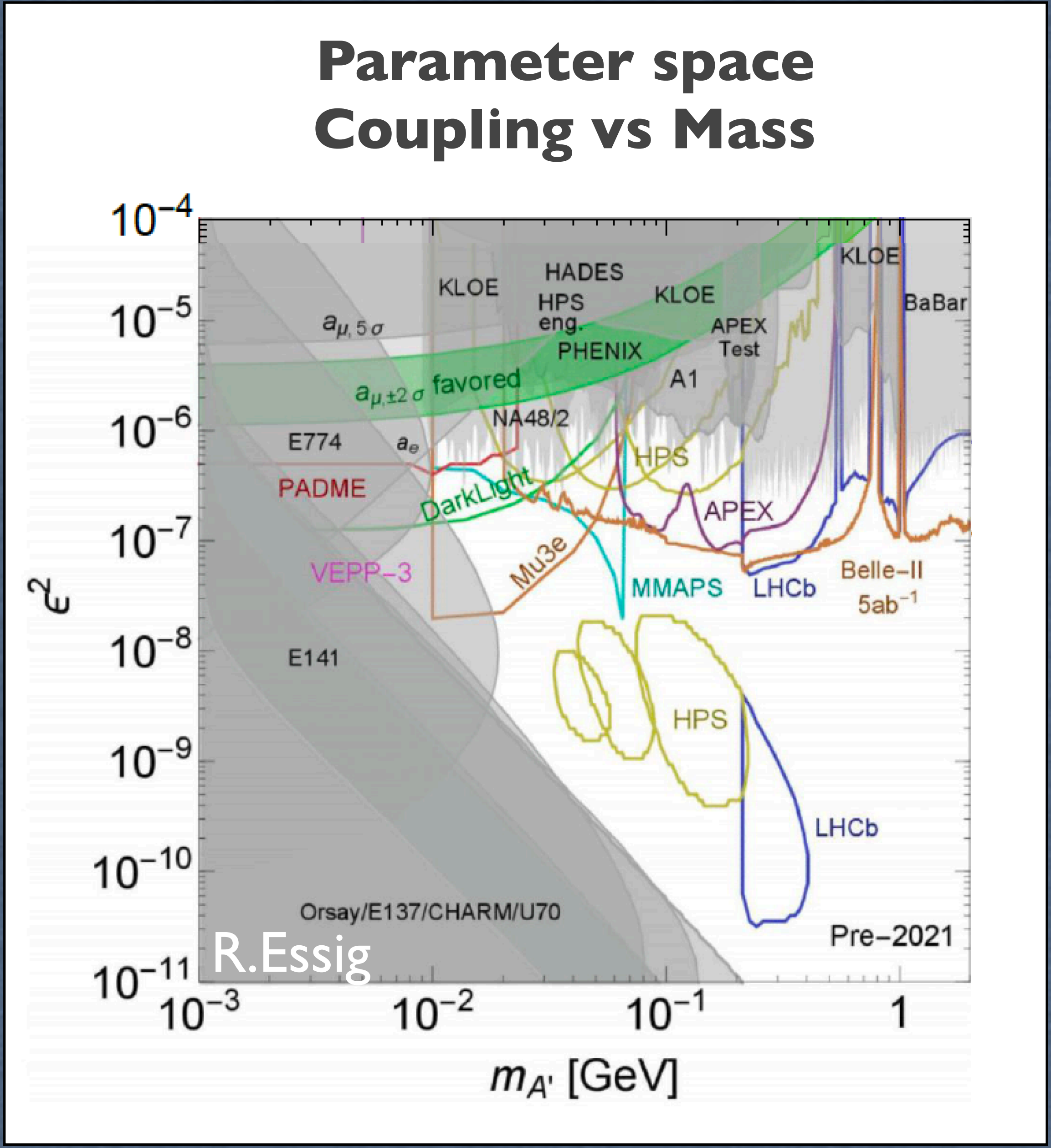
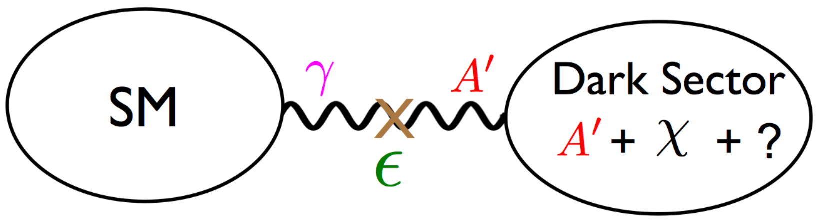
Annihilation: e+e- → γ' γ → $\mu\mu$ γ
→ **BABAR,BELLE,KLOE**

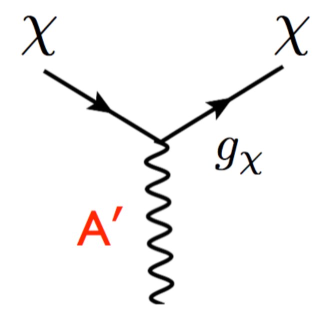
Meson decays: π^0, η, η', ω,' → γ' γ → Lepton⁻ Lepton⁺ γ
→ **KLOE, BES3, NA48, HC**

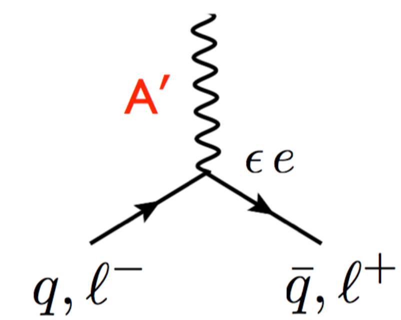
No positive signal (so far) but limits in parameter space coupling vs mass



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



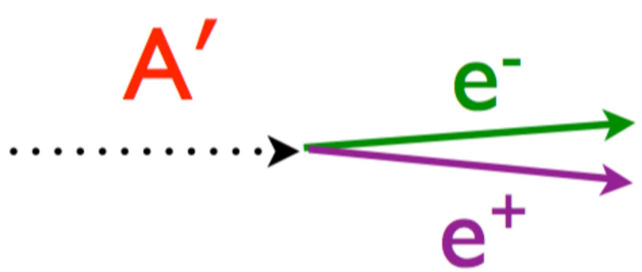




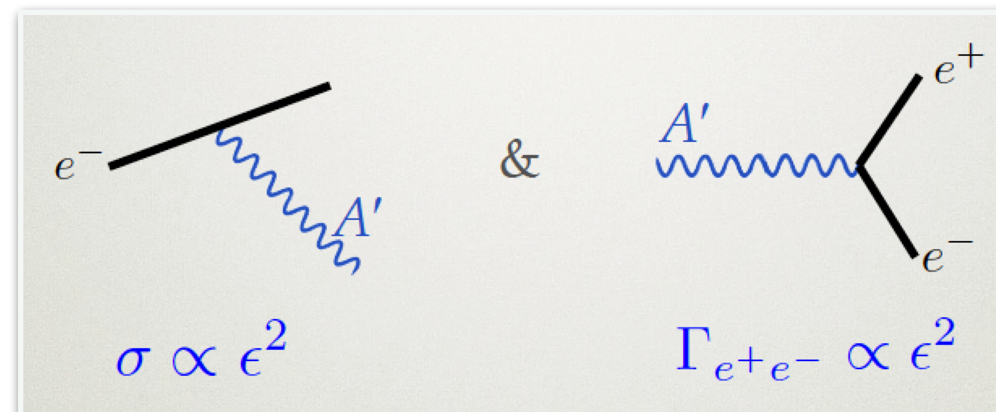
4 parameters: m_χ, $m_{A'}$, ε, α_D

m_χ, ~ $m_{A'}$: MeV - GeV

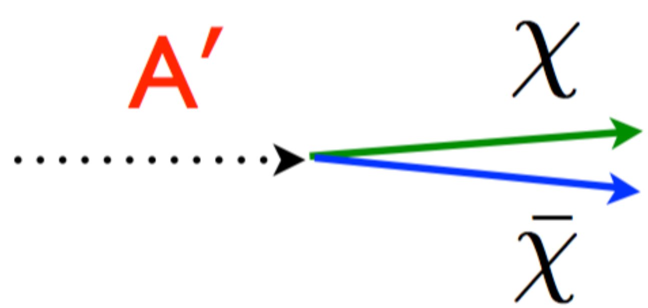
Visible



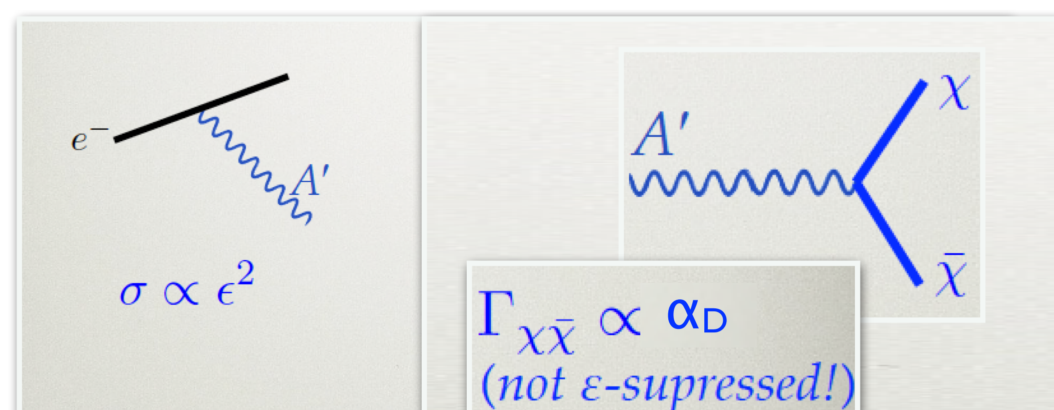
- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'}<2m_\chi$ (on-shell)



Invisible



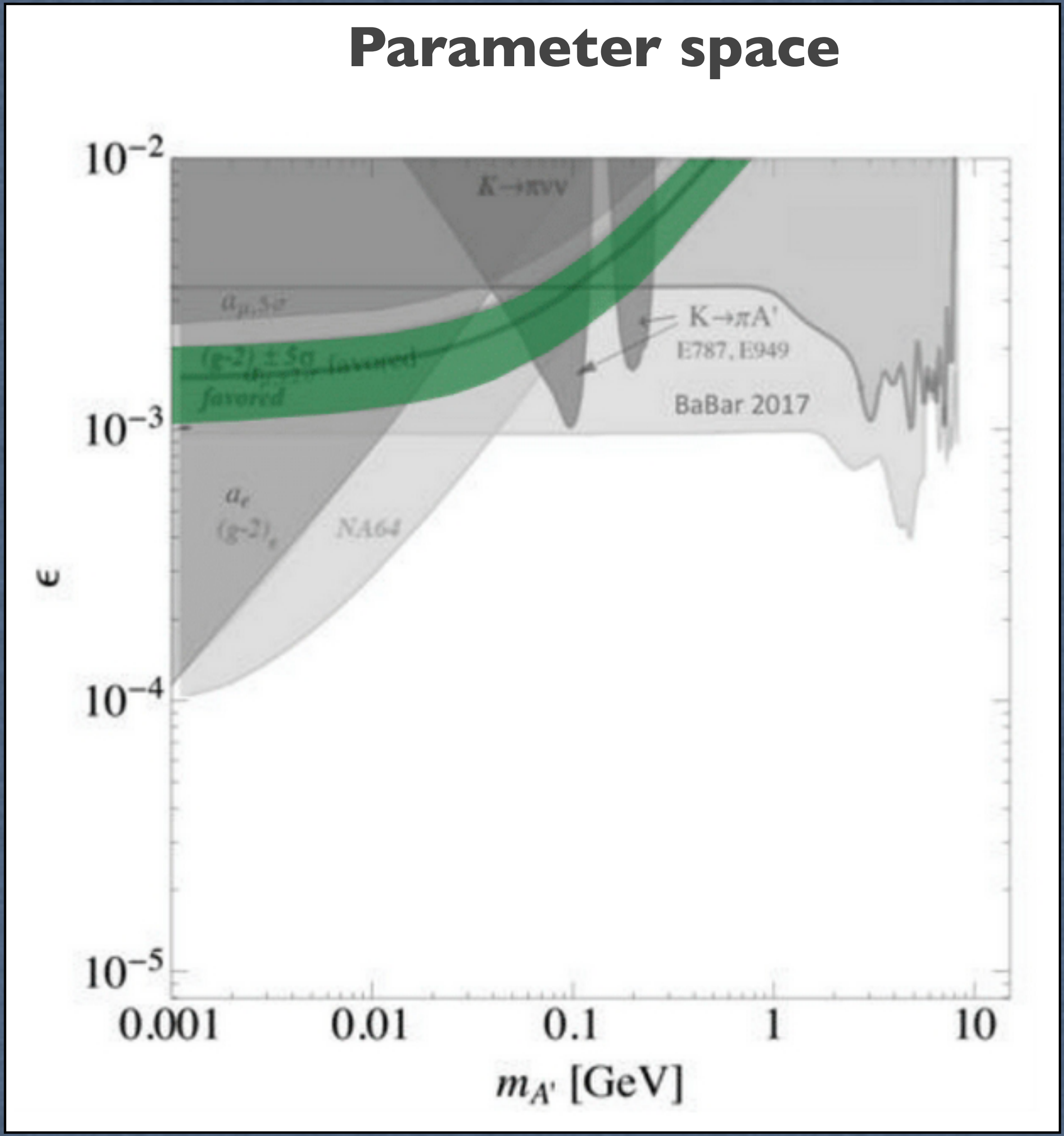
- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D= g^2_\chi/4\pi >> \varepsilon^2\alpha_{EM}$



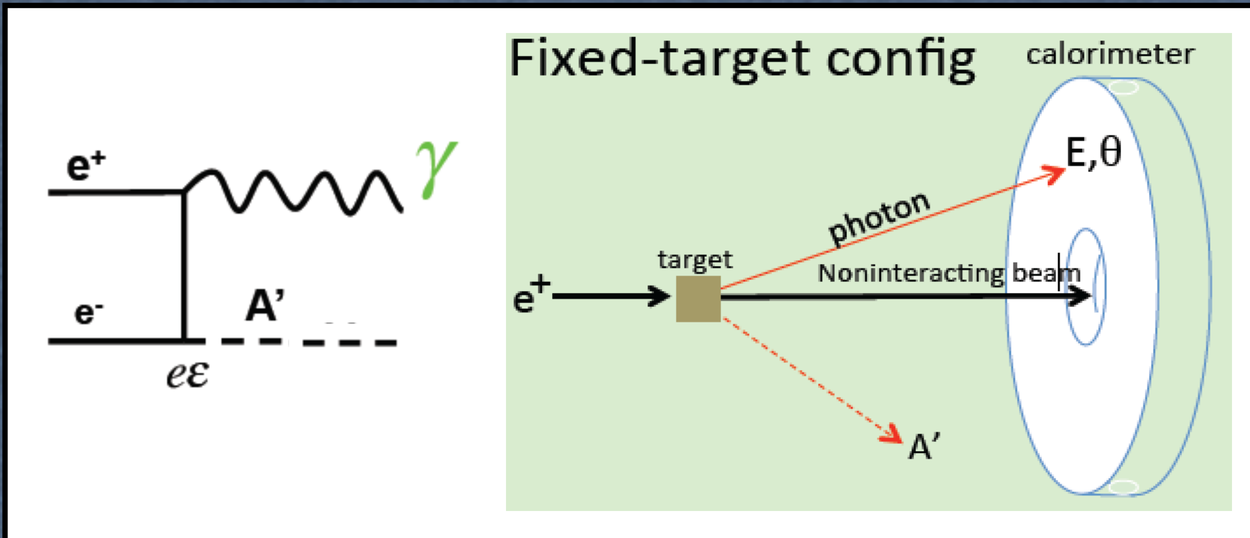
Particle physics search of A'
- invisible -

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, NA48, HC**

No positive signal (so far) but limits in parameter space coupling vs mass



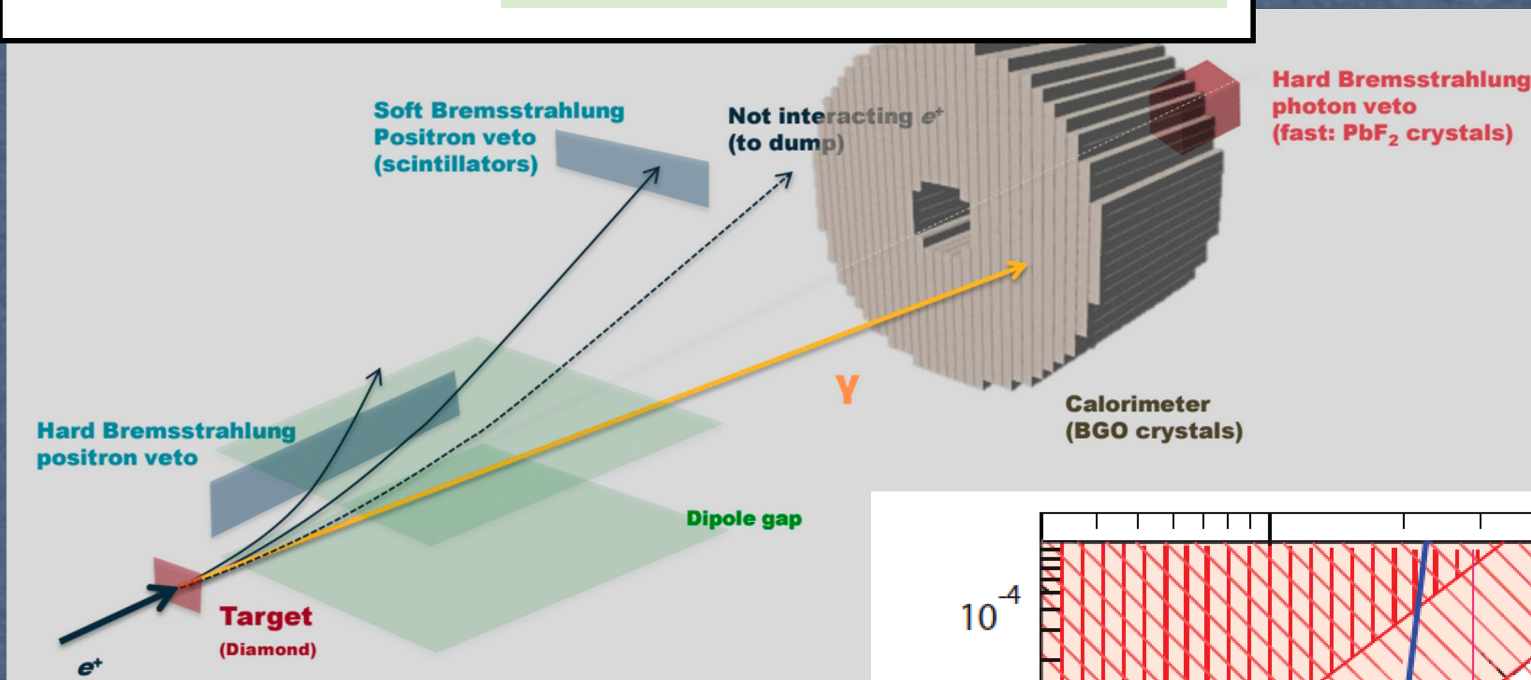
e^+ annihilation on fixed (thin) target - invisible -



Missing mass search:
- Independent of A' decay mechanism
- Bump hunt (monophoton@collider)

- Need a positron beam
- Limited $M_{A'}$ accessible
  - 1 GeV beam: MA' < 31 MeV
  - 5 GeV beam: MA' < 71 MeV

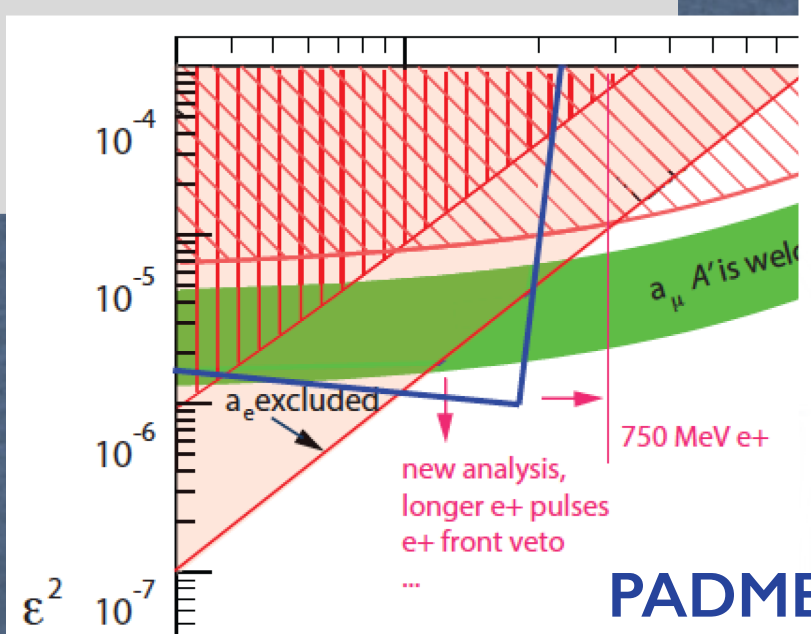
- **Novosibirsk**
- **LNF**
- **Cornell**

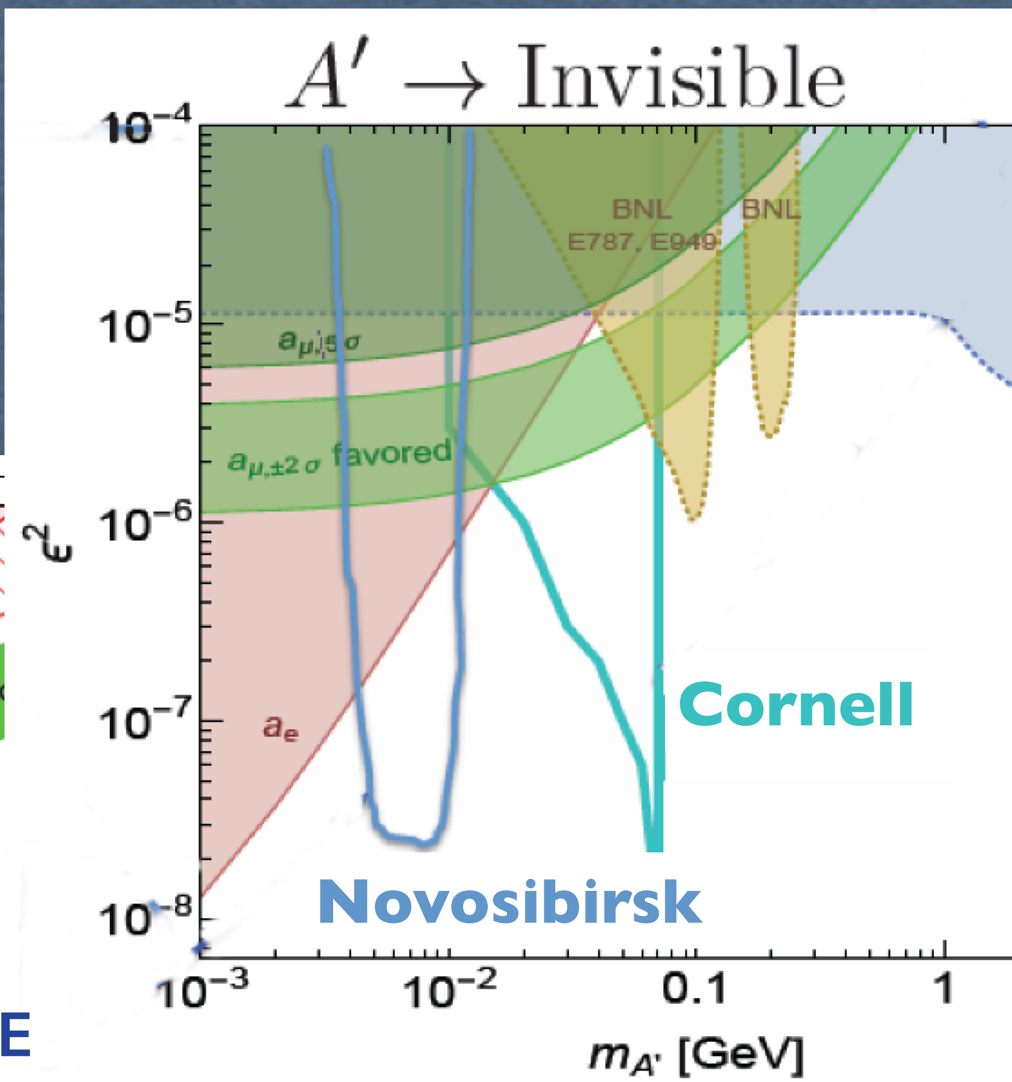


VEPP3
- E_{e+} = 500 MeV
- EOT ~ 10^{15} - 10^{16} year^{-1}

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

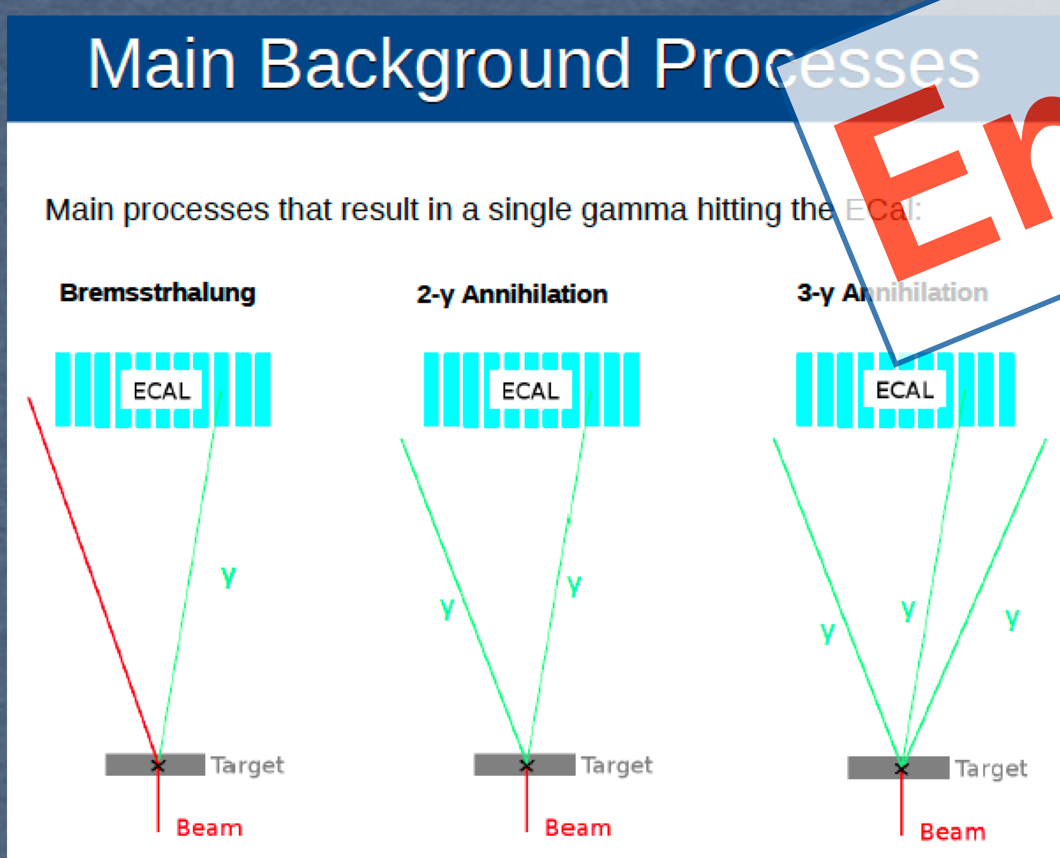
Cornell
- E_{e-} = 5.3 GeV
- EOT ~ 10^{17} - 10^{18} year^{-1}

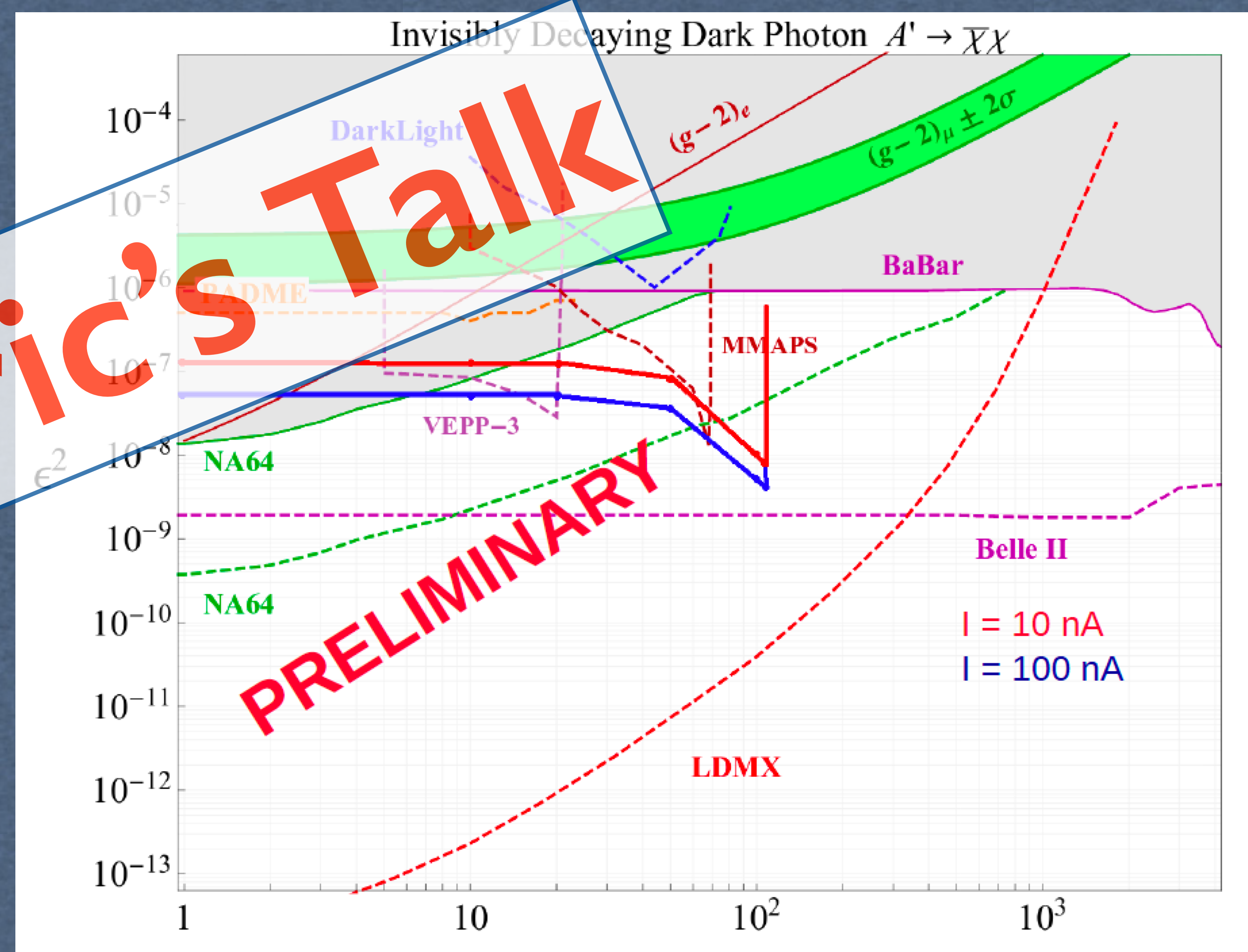




e^+ annihilation on fixed (thin) target

- Main limitation: limited energy in the CM ~ sqrt(E_{beam})
- High energy positron beams are not (yet) available
- The highest energy at JLab (~11 GeV) Max $m_{A'}$ ~ 106 MeV



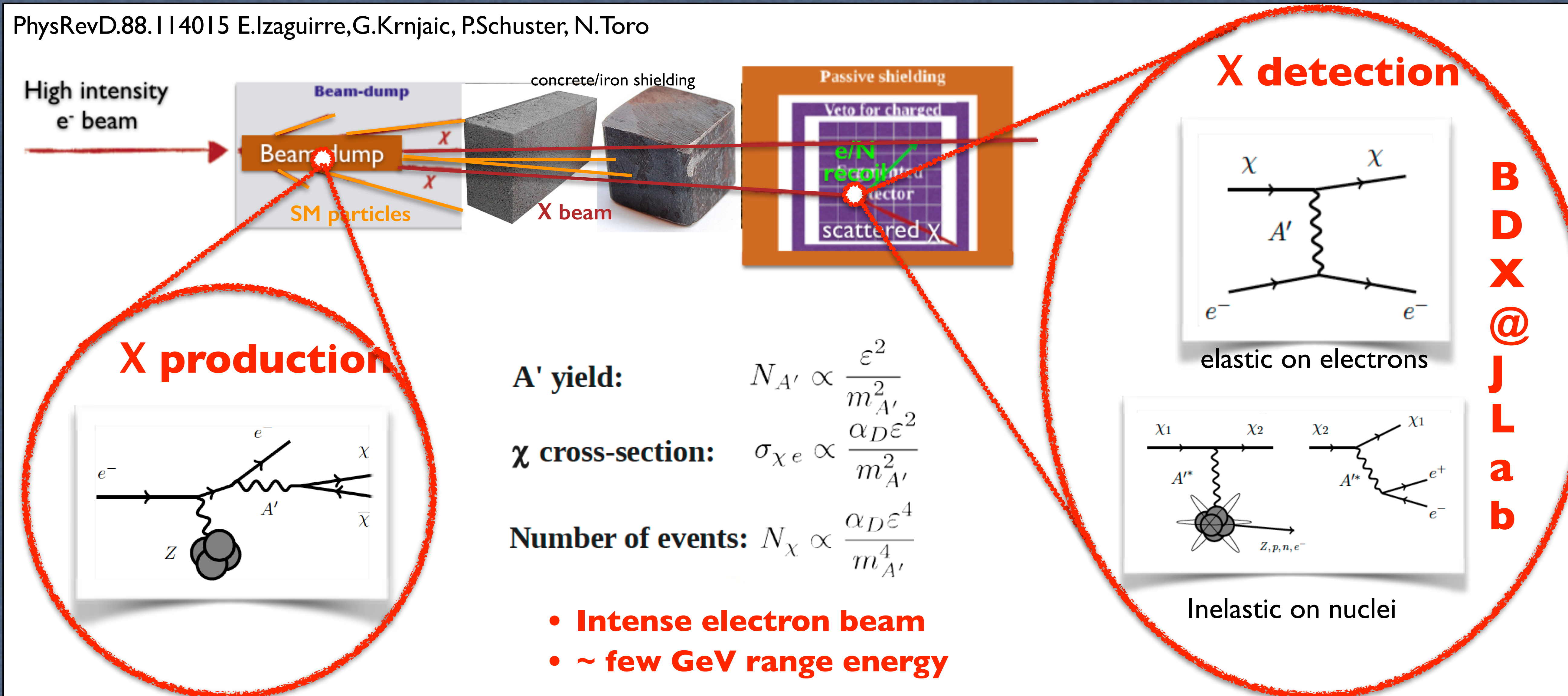


The BDX experiment

Two step process

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

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



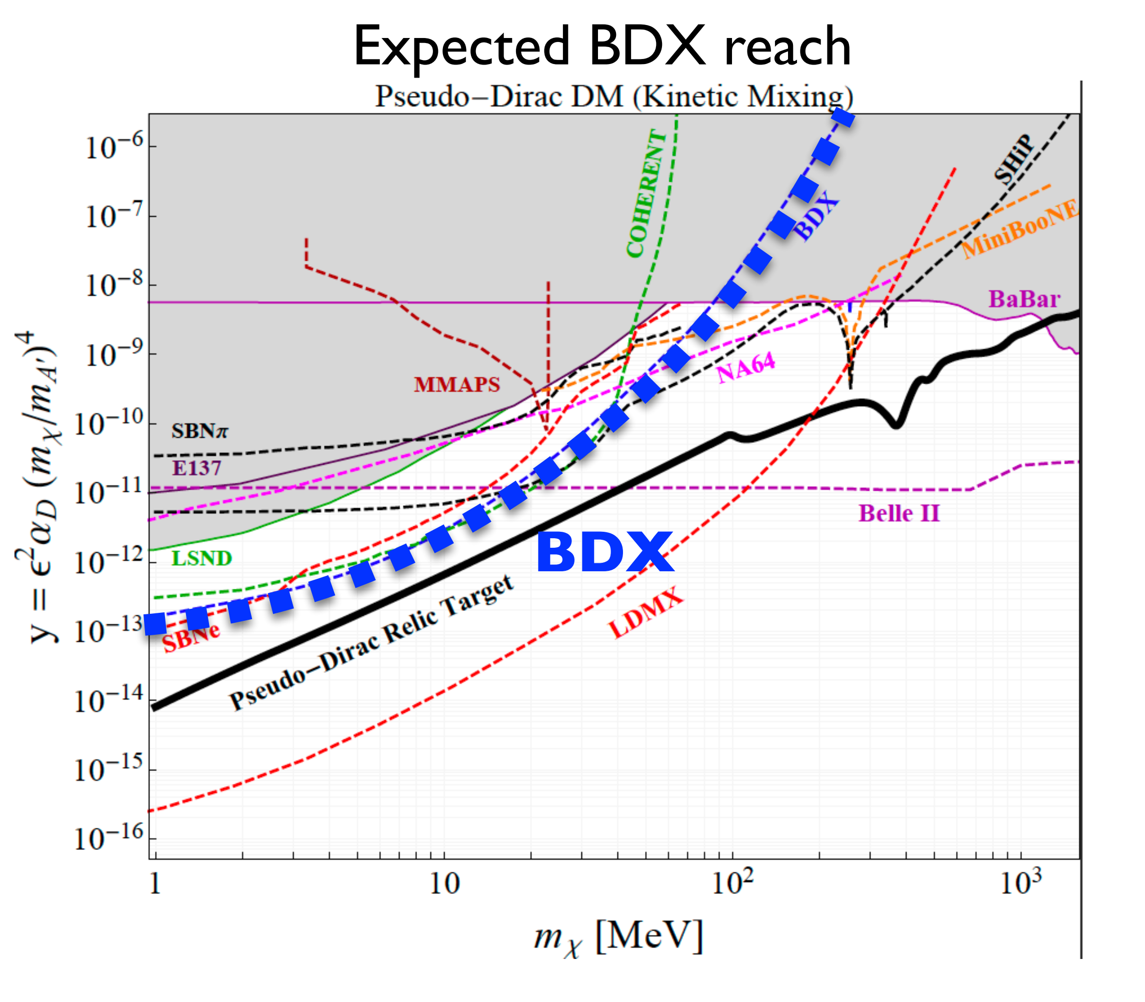
Experimental signature in the detector:

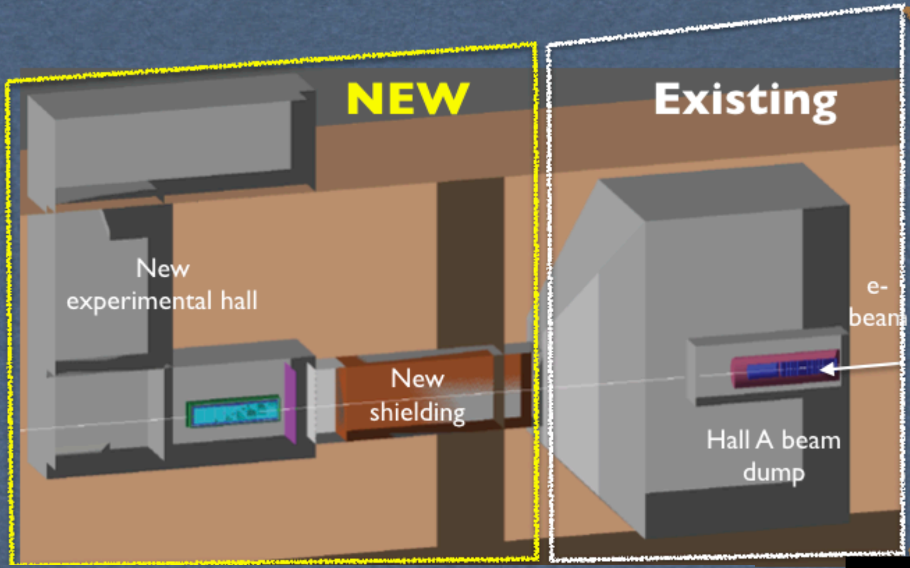
X-electron → EM shower ~GeV energy

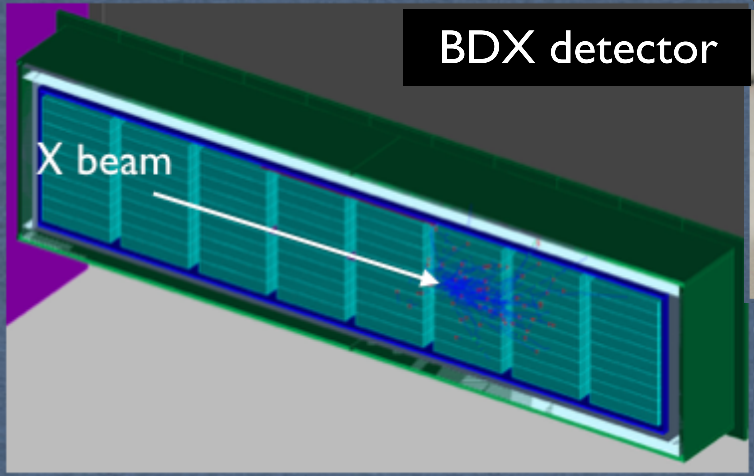
BDX @ JLab

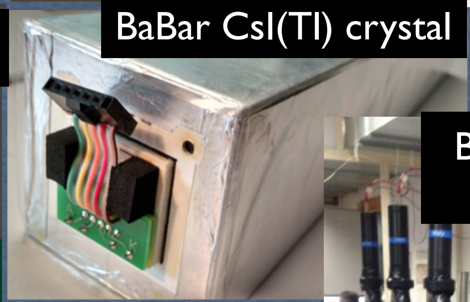
approved by JLab 2018 PAC with max rate (A)

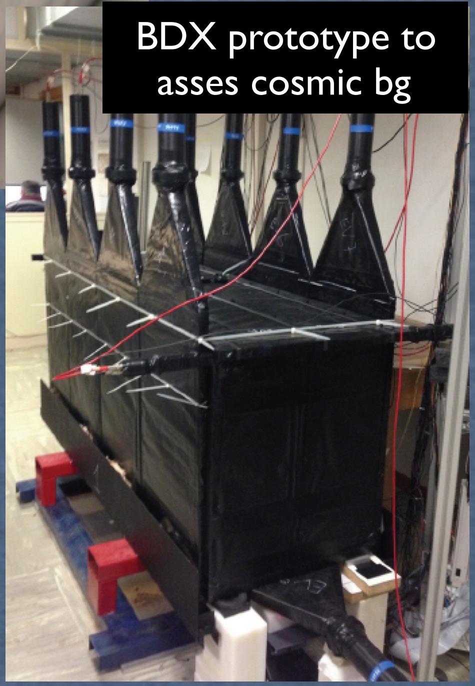
- ★ High energy beam available: 11 GeV
- ★ The highest available electron beam current: ~65 uA
- ★ The highest integrated charge: 10^{22} EOT (41 weeks)
- ★ New experimental hall (~2$M) at JLab
- ★ BDX detector (recycling BaBar CsI crystals) ~$1M
- ★ Expected to run in ~2y











Accumulating 10^{22} EOT in ~1y BDX sensitivity is 10-100 times better than existing limits on LDM

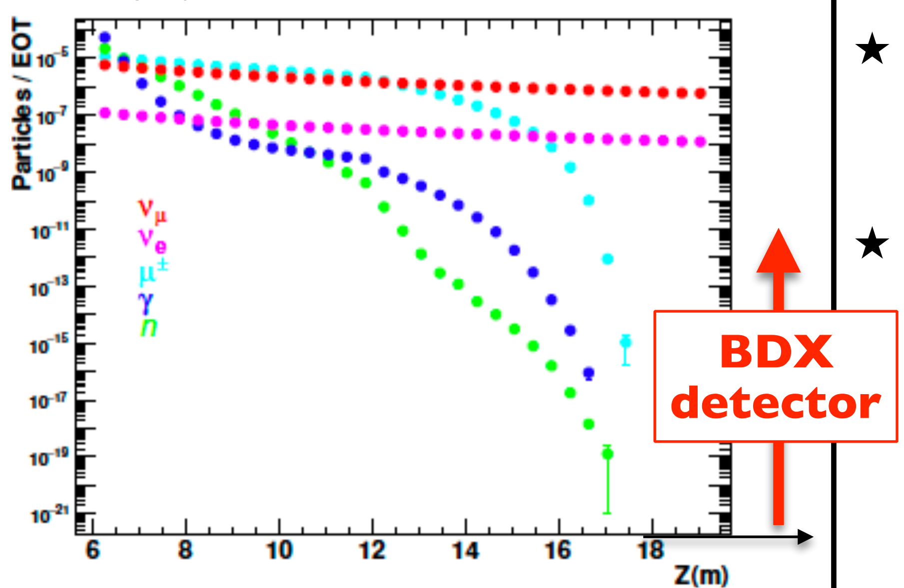
BDX detector: E.M. Calorimeter + Veto

- 8 modules 10x10 crystals each
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 6x6 mm^2 Hamamatsu SiPM readout
- Plastic scintillator + WLS fibres, sips RO

BDX background assessment

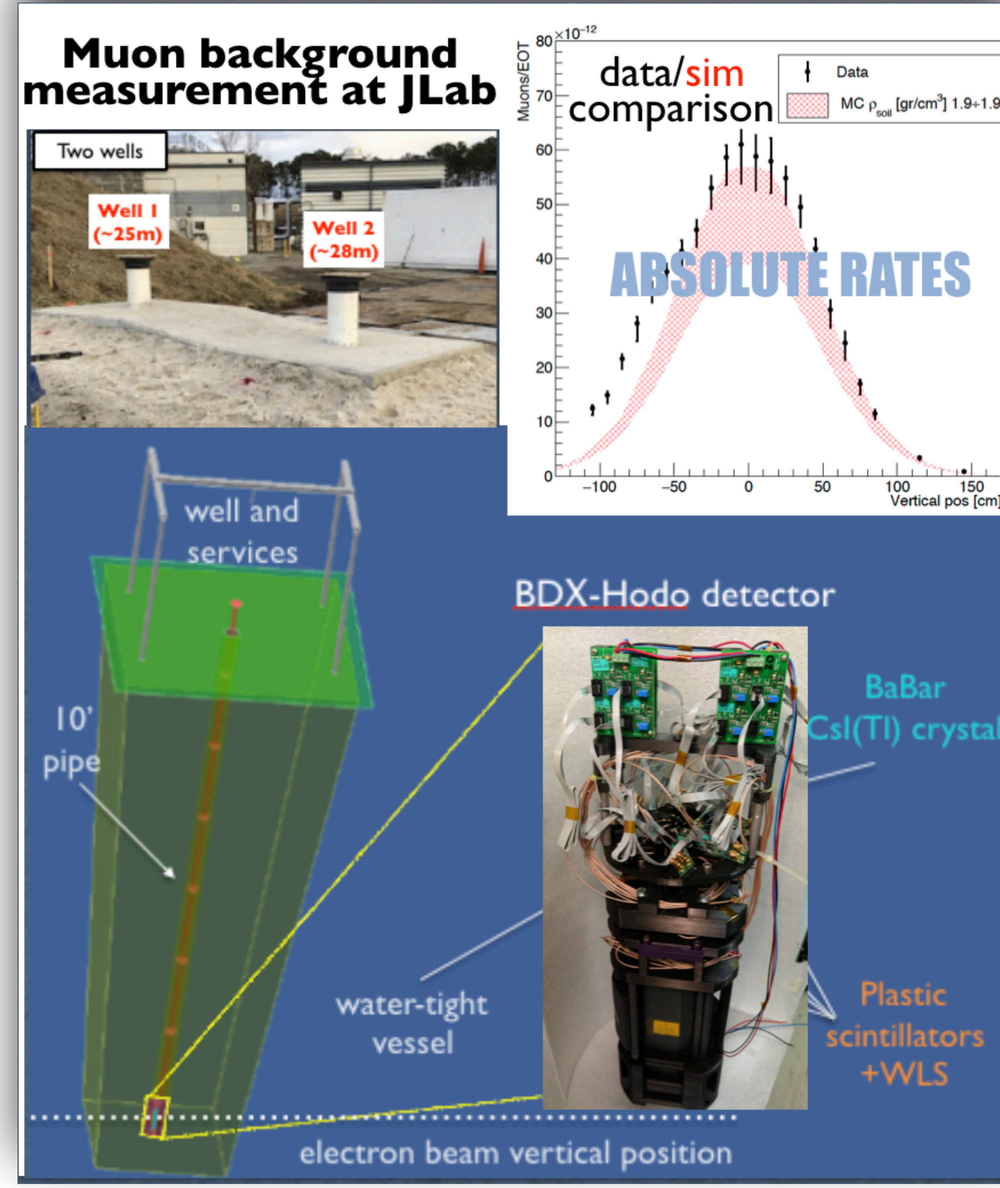
Expected bg (FLUKA and GEANT4) for particles with E>E$_{Thr}$

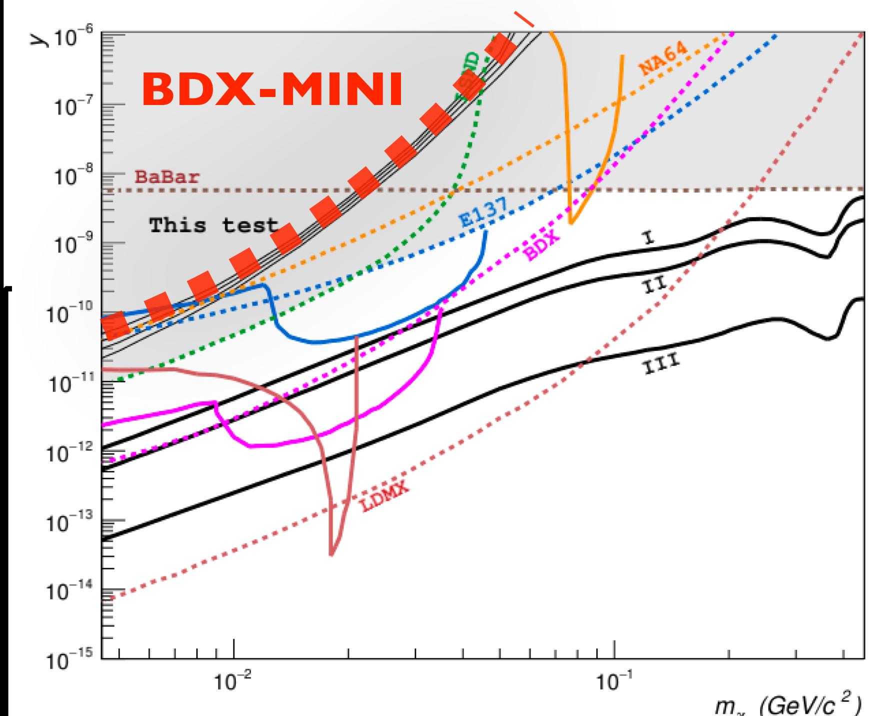
$T_{\mu,n,\gamma}$ > 100 MeV - T_{ν} > 10MeV



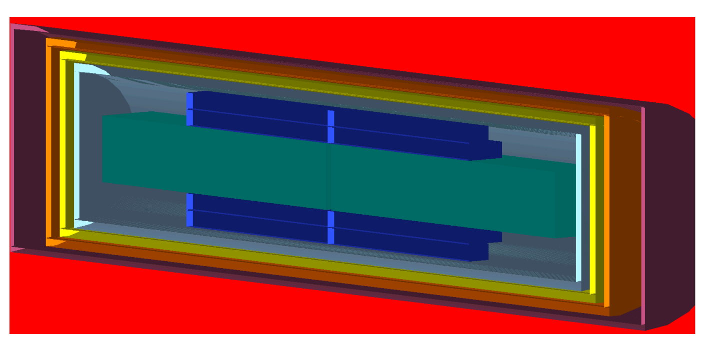
- ★ Cosmic background measured with the BDX detector prototype in CT
- ★ Muon bg: assessed by a dedicated measurement at JLab in spring '18
- ★ Neutrino bg: massive, high stat, FLUKA/GEANT simulations

Good agreement between data and simulations!





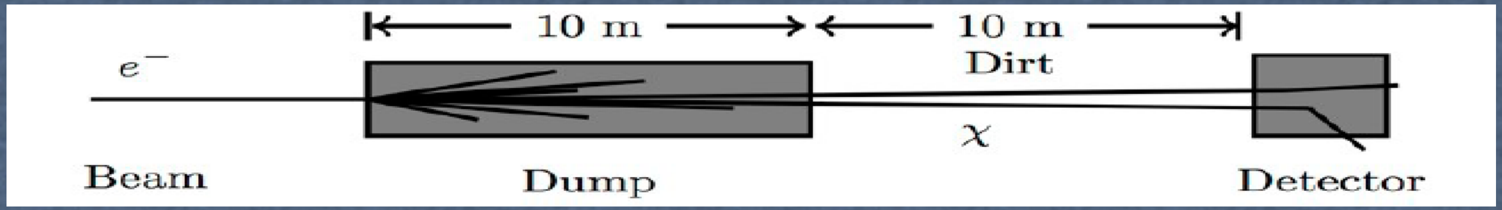
BDX-MINI in 2019

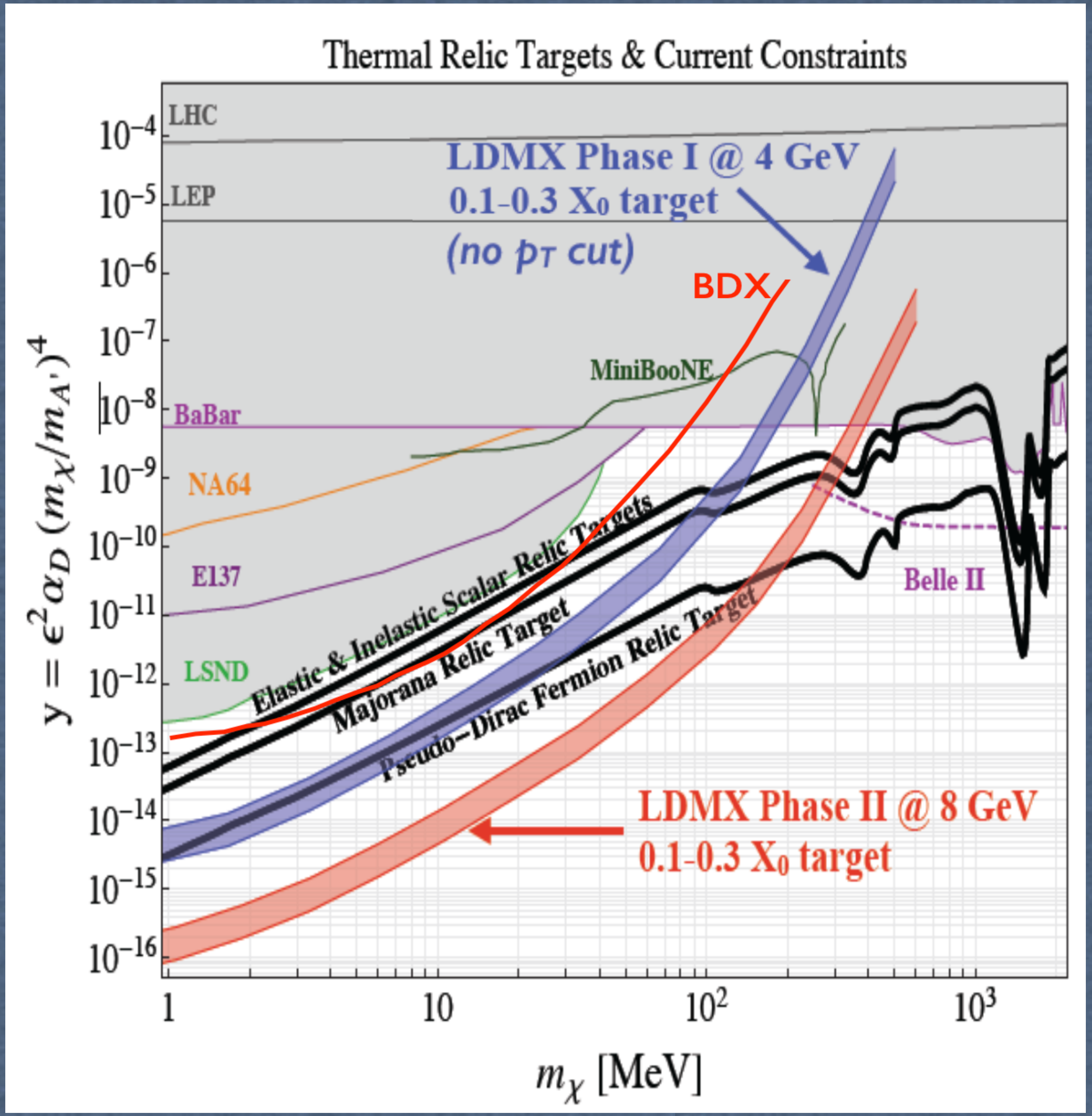


- BDX-MINI fits in BDX-HODO vessel
- 28 PbWO4 PANDA ECal crystals (higher ρ)
- Active vetos (same as BDX), passive W shielding

- take advantage of two wells dug for muon tests
- E_{beam}=2.2 GeV, 5^{20} EOT expected for 2019, no muons at well locations
- **BDX first physics result!**

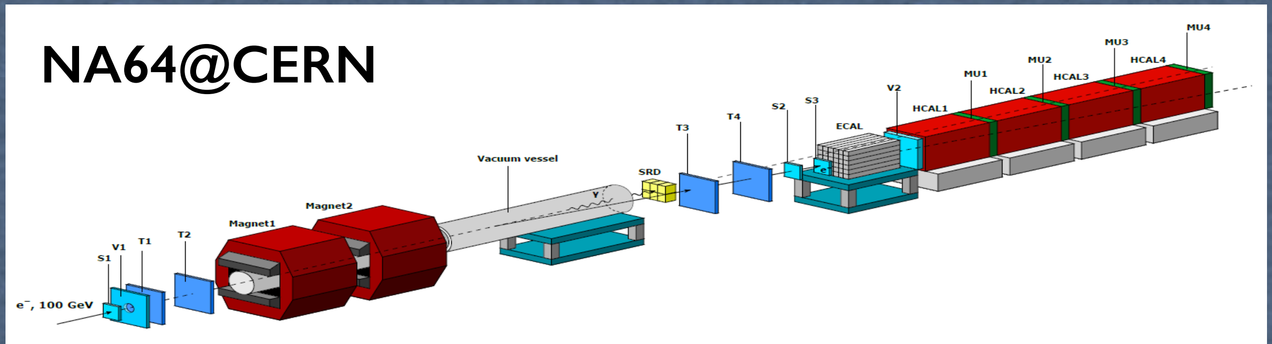
Missing energy/momentum BD experiments





Present …

- E137 and NA64: null results interpreted as invisible decay search
- No showering effects included

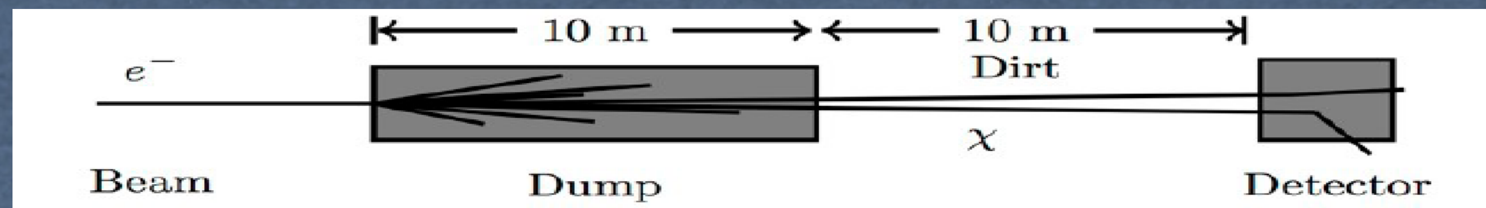


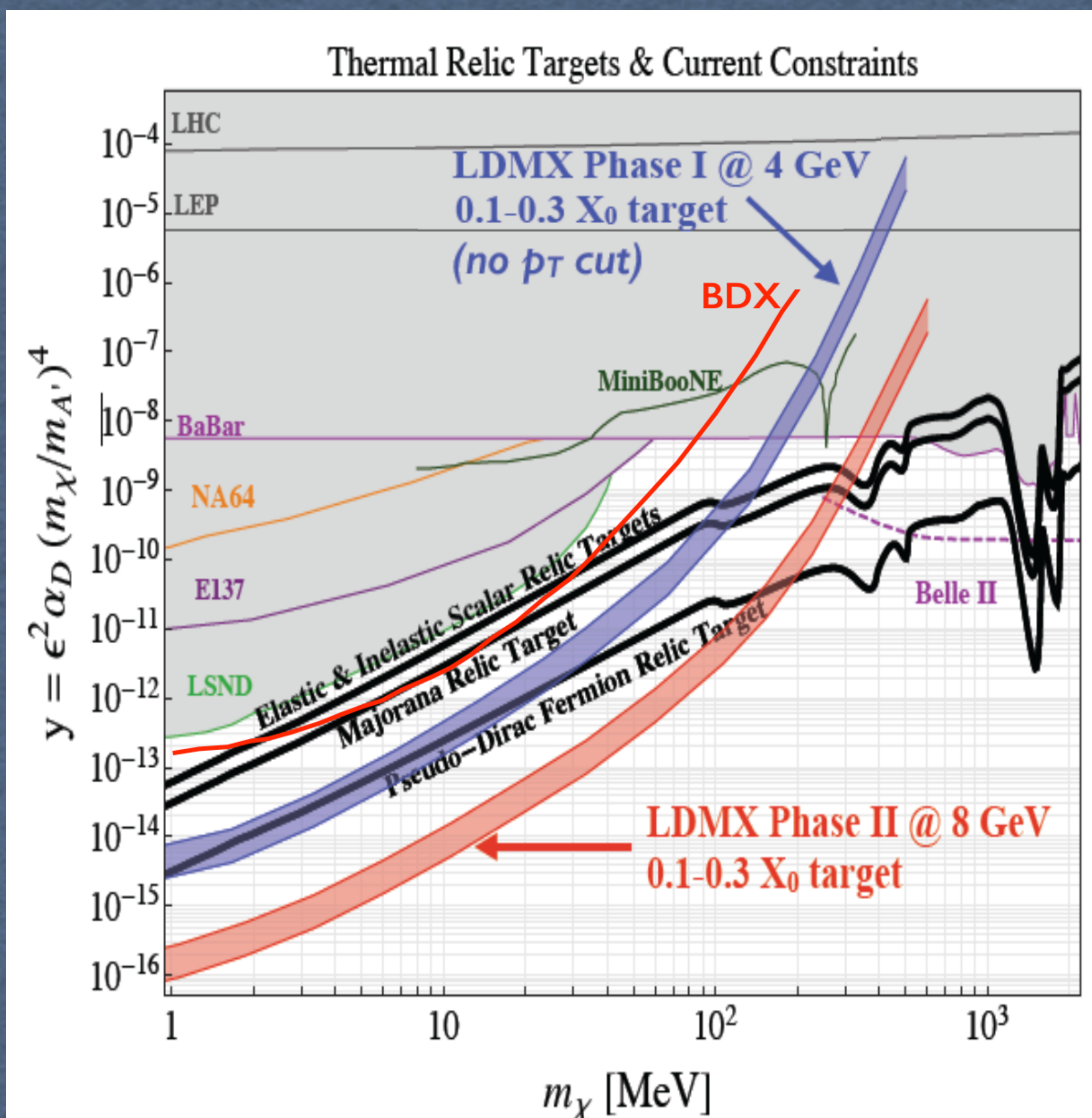
- *Active* beam-dump experiment
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3×10^9 EOT

… and future BD experiments

- LDMX: missing momentum exp proposed at SLAC-LCLS-II 4 GeV e- beam, (*Active* beam-dump)
- BDX: beam-dump exp proposed at JLAB 11 GeV e- beam with 10^{22} EOT in 1y run

Missing endergy/momentum BD experiments





… but

MissingMomentum vs BeamDump
(*disappearance* vs *appearance*)

… **more sensitive** in the exclusion plots but **less reliable/convincing** in case of positive finding!

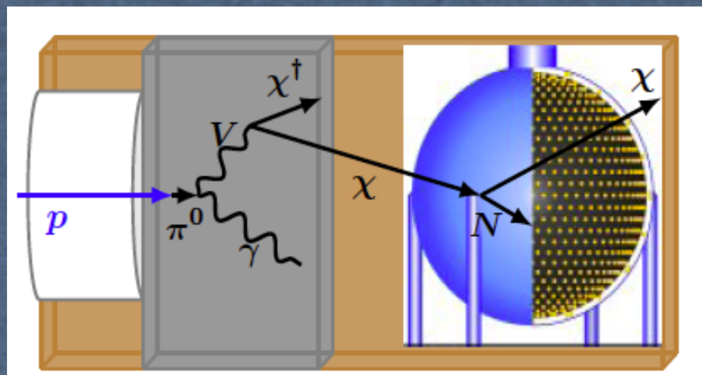
The two experimental approaches are complementary

★BDX will reach the ultimate sensitivity of beam dump experiments hitting the irreducible ν bg with a consolidated technology ready-to-go

★LDMX presents challenges that if/when overcome will lead the 2nd generation LDM searches experiments

Recent results

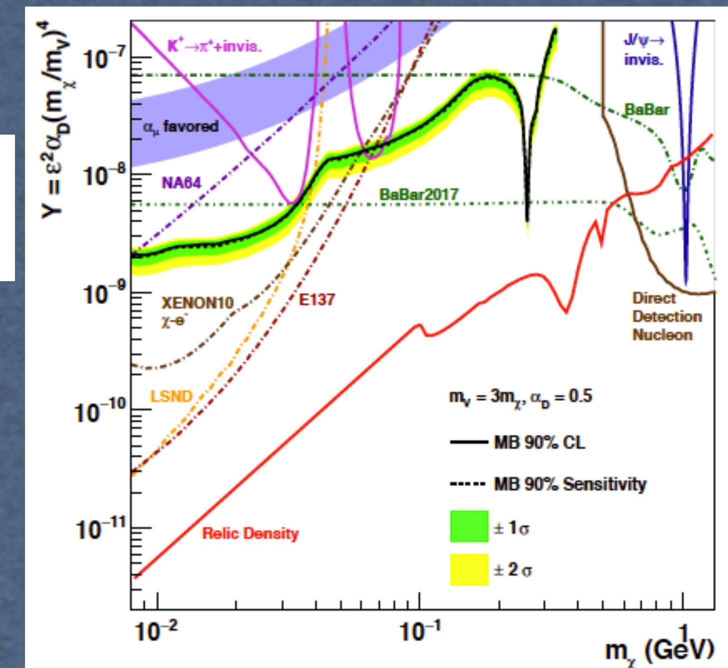
MiniBooNE@FERMILAB (Beam-Dump)



PRL **118,** 221803 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

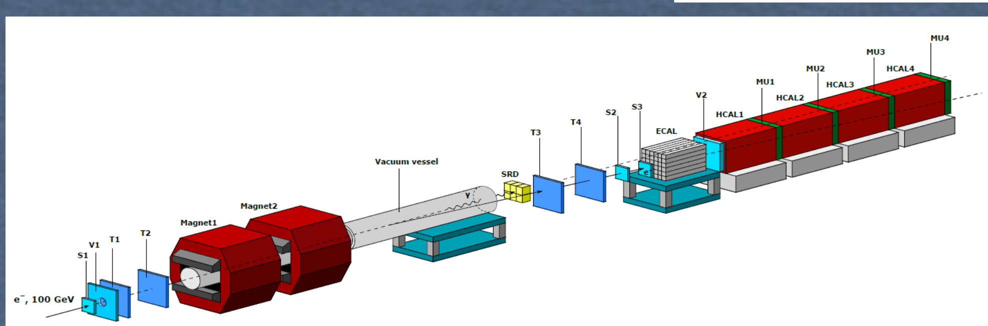
- BDX-like with an 8 GeV proton beam
- Cherenkov response of 12 m spherical detector with 800 tons mineral oil (CH2)
- Typical operation: 2x10[20] protons on target (POT) per year



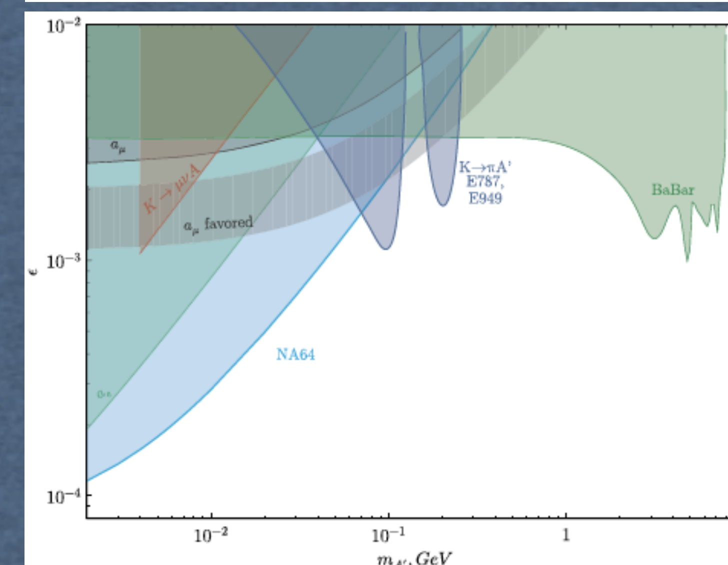
NA64@CERN Missing Energy

PRL **118,** 011802 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

Search for Invisible Decays of Sub-GeV Dark Photons in Missing-Energy Events at the CERN SPS



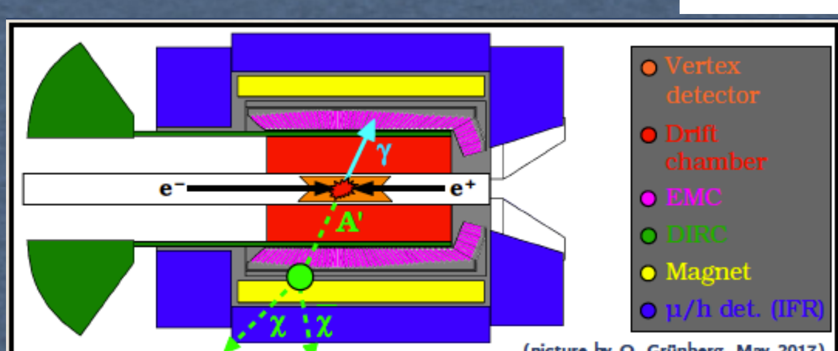
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3x10[9] EOT



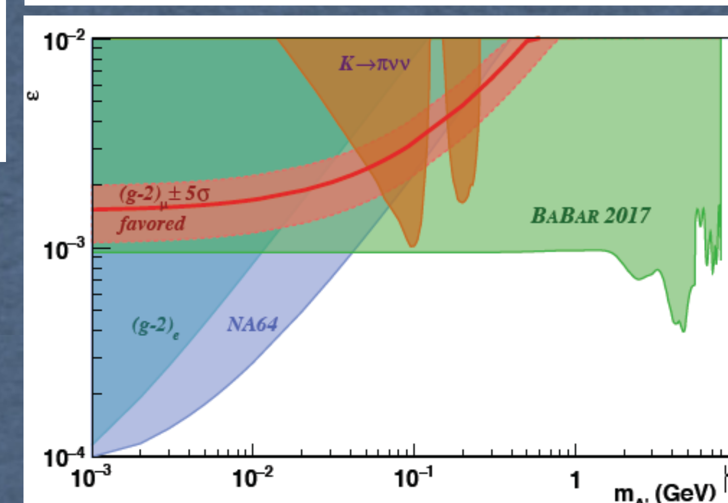
BaBar@SLAC e+e- collider

BABAR-PUB-17/001
SLAC-PUB-16923
arXiv:1702.03327v1 [hep-ex] 10 Feb 2017

Search for invisible decays of a dark photon produced in e^+e^- collisions at BABAR



- Missing mass exp (e- e+ → γ A' with A' → invisible)
- Mono-photon trigger
- Exclusion plots based on ~50 fb[-1]



Status and perspectives

Experiment	Lab	Production	Detection	Vertex	Mass(MeV)	Mass Res. (MeV)	Beam	Ebeam (GeV)	Ibeam or Lumi	Machine	1st Run	Next Run
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65-600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40-300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20-200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10-60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1-50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4-8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5-22$	1	e^+	0.500	$10^{33}\,\mathrm{cm^{-2}s^{-1}}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\leq 10^{14}\,e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	$10^{34}\,\mathrm{cm^{-2}s^{-1}}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	$2\times10^{32}\,\mathrm{cm^{-2}s^{-1}}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1-5$	e^+e^-	4×7	$1\sim10\,\mathrm{ab^{-1}}$/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10$ GeV	$3-6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10$ GeV	$1-2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40$ GeV	~ 4	pp	6500	$\sim 10\,\mathrm{fb^{-1}}$/y	LHC	2010	2015

Dark Sectors 2016 Workshop arXiv:1608.08632

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 unique feature of distinguish DM signal from any other cosmic anomalies or effects

✳ Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz, SLAC (+ p beam at FNAL and CERN)

✳ A new generation of dedicated and optimised experiments at high intensity frontier will test the relic (light) dark matter scenario

✳ Jefferson Lab is the world-leader facility for present and near-future LDM searches: APEX, HPS, DarkLight, BDX (and possibly e+ annihilation and LDMX)

✳ Significant interests from funding agencies (DOE/NSF) and labs (CERN and JLab) to run small scale experiments with a great discovery potential

✳ Discovery or decisive tests of simplest scenarios will possible in the next ~5-8 years!