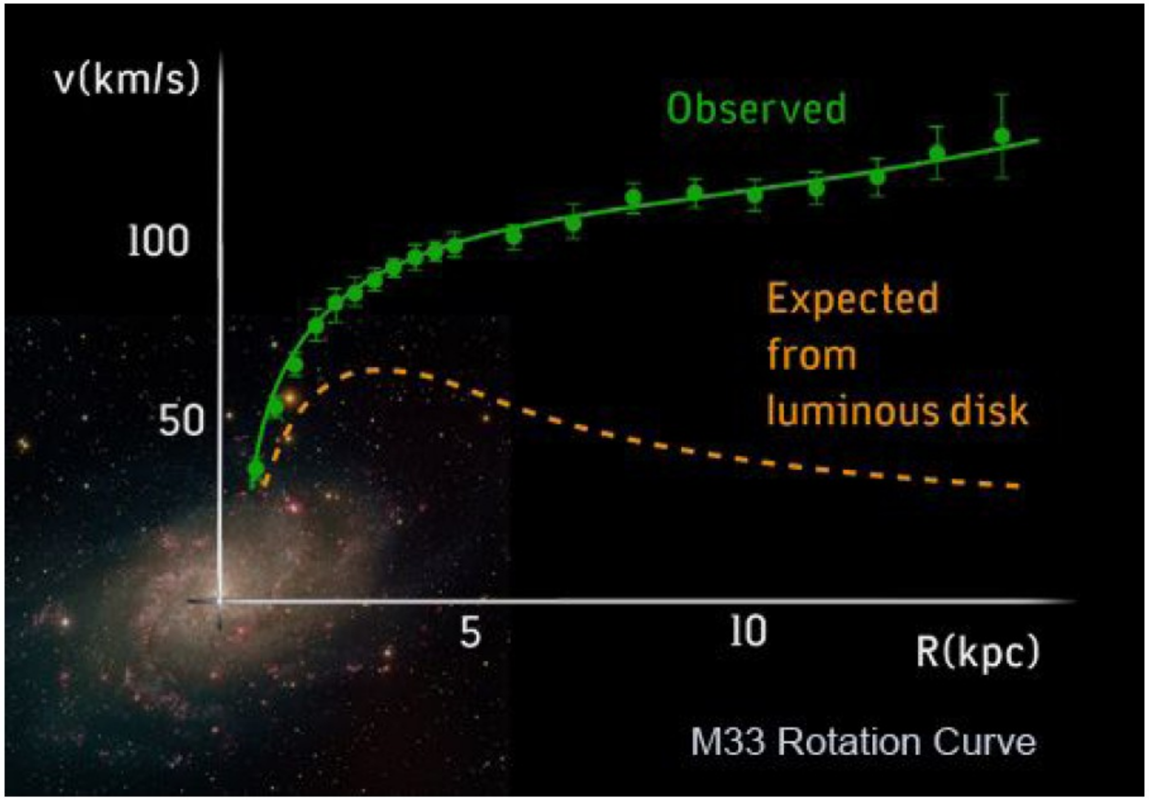
Ricerca di nuova fisica alla frontiera dell'alta intensita'

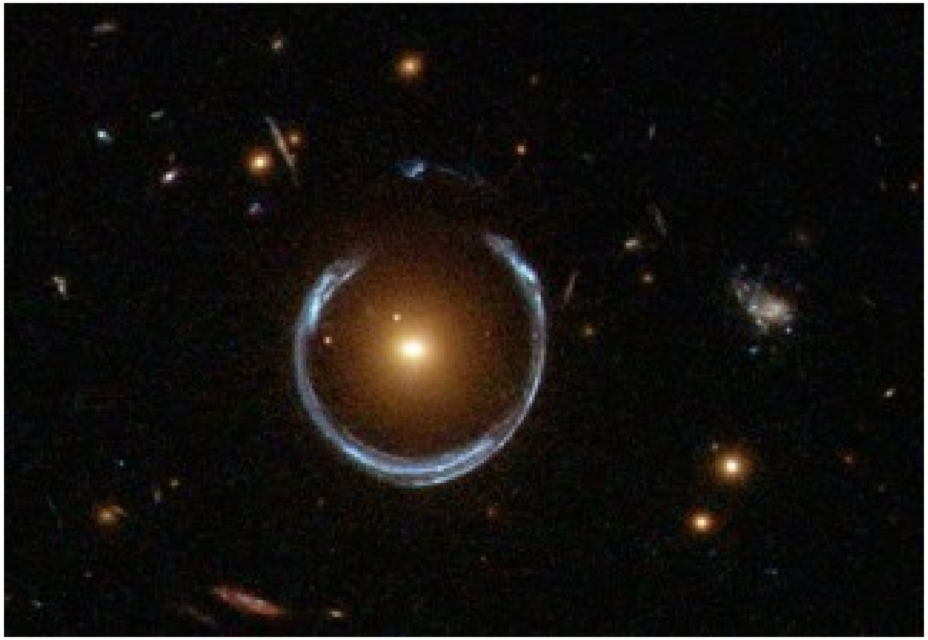
Light dark matter searches at accelerators

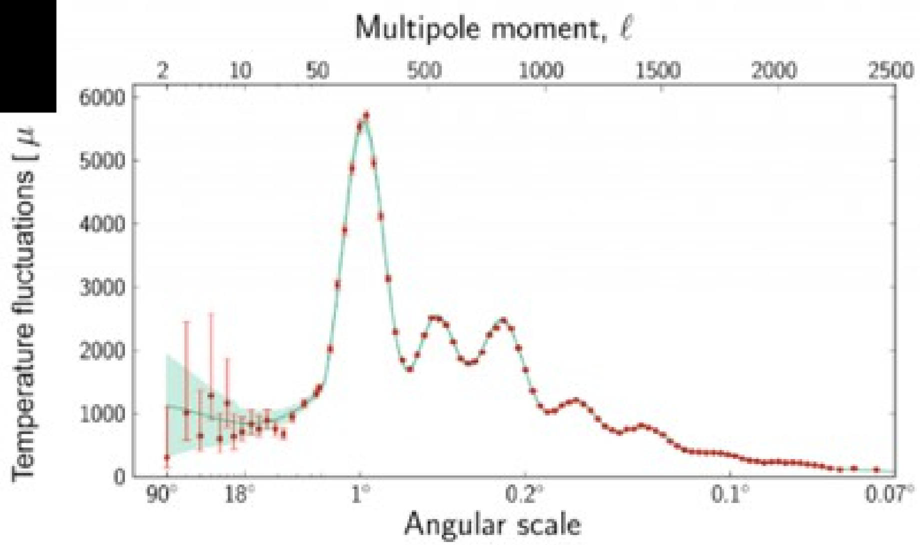
A. Celentano

INFN – Genova

There is a dark sector!







But all **cosmological/astrophysical** observations...

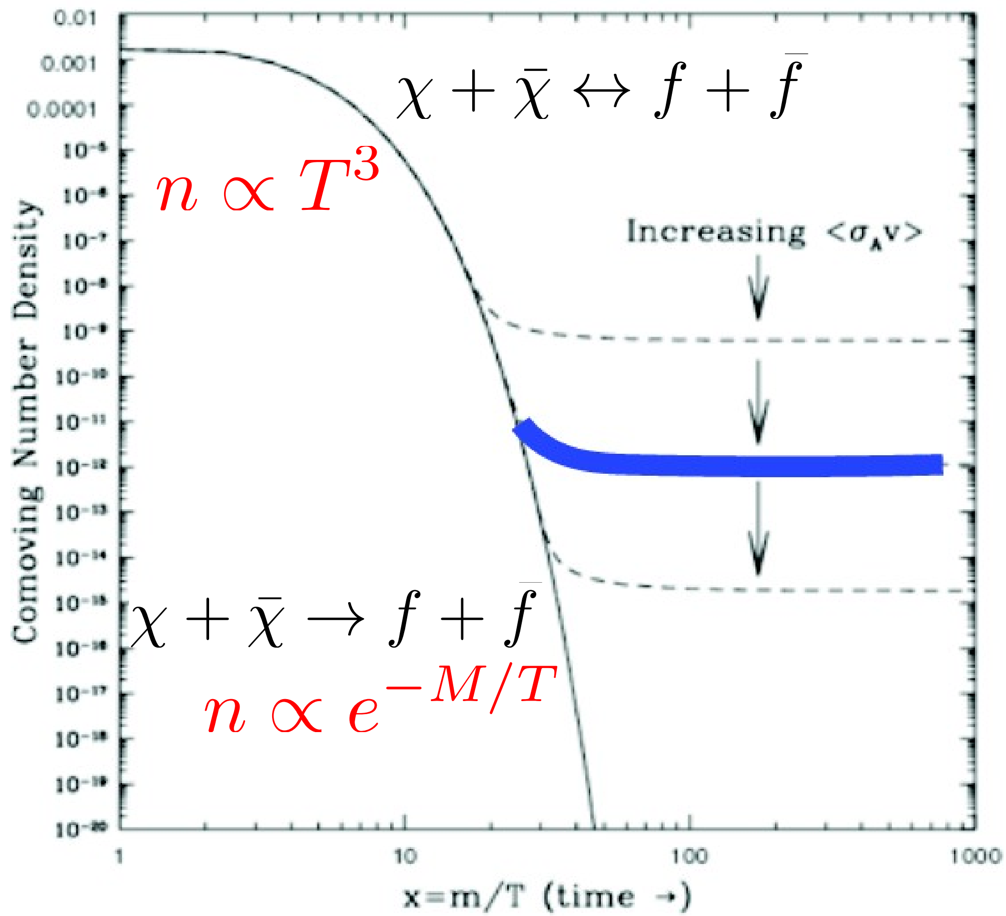
Need to introduce **some hypothesis** about DM origin / properties / interactions

Dark sector: thermal origin hypothesis

Cosmological hypothesis: dark matter particles were in equilibrium with the primordial thermal bath in early Universe

Can describe following reaction trough statistical mechanics:

$$\chi + \bar{\chi} \leftrightarrow f + \bar{f}$$



- Early Universe: high-T, relativistic-regime. Both reactions ($\leftarrow$ and $\rightarrow$) are permitted

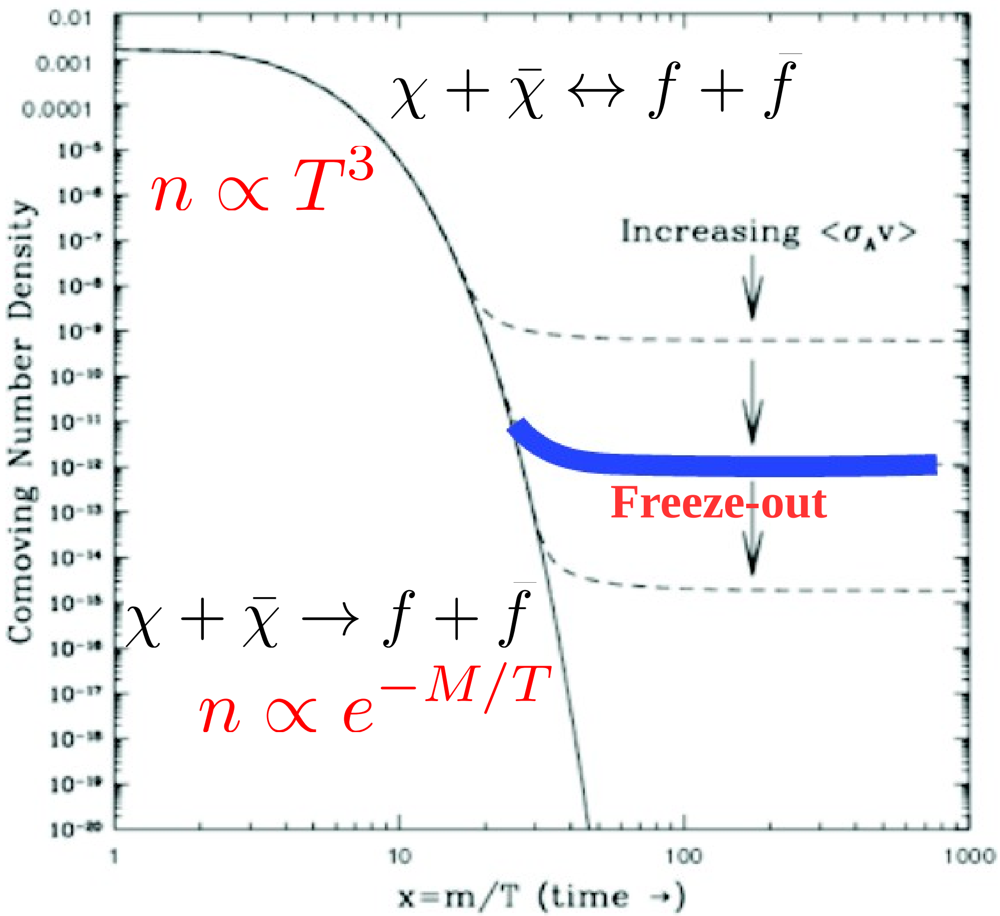
- As Universe expands and cools down below χ mass, only $\rightarrow$ reaction occurs.
  - χ number density is exponentially suppressed: Boltzmann regime

- Eventually, dark matter particles can't find each other to annihilate, **thermal equilibrium breaks** ⟶ **Freeze-out**

Dark sector: thermal origin hypothesis

Dark matter density today **-from cosmological observations-** can tell us about DM → SM model annihilation cross-section

$$\chi + \bar{\chi} \to f + \bar{f}$$



- If **annihilation cross-section** is too high (too small), DM particles would stay longer in equilibrium in the Boltzmann regime, resulting in a lower (higher) density at present

- Observed abundance requires:

$$\langle \sigma v \rangle_{ann} \simeq 3 \times 10^{-26} cm^{-3} s^{-1}$$

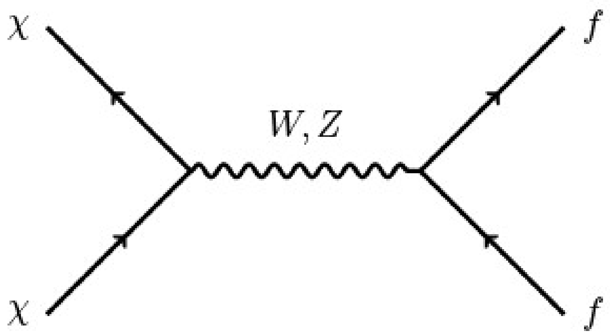
- **This corresponds to weak-scale cross-sections**

Dark sector: WIMP hypothesis

"WIMP miracle": weak-scale DM particle – O(100 GeV) – interacting with SM trough weak force reproduces the observed DM relic density today

Particle physics hypothesis: if DM is made of WIMPs, no necessity for new interactions

DM-SM interaction in the WIMP paradigm:



$$\langle \sigma v \rangle_{\mathrm{WIMP}} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{\mathrm{TeV}}{m_\chi} \right)^2$$

Successful thermal freeze-out for weak scale-masses and cross sections

Predicts direct-detection cross-section
Driven experimental effort (Direct Detection) for ~ 30 years

Dark sector: WIMP searches in direct detection

Current **WIMP exclusion limits** from direct detection experiments / **projected sensitivities** for future experiments

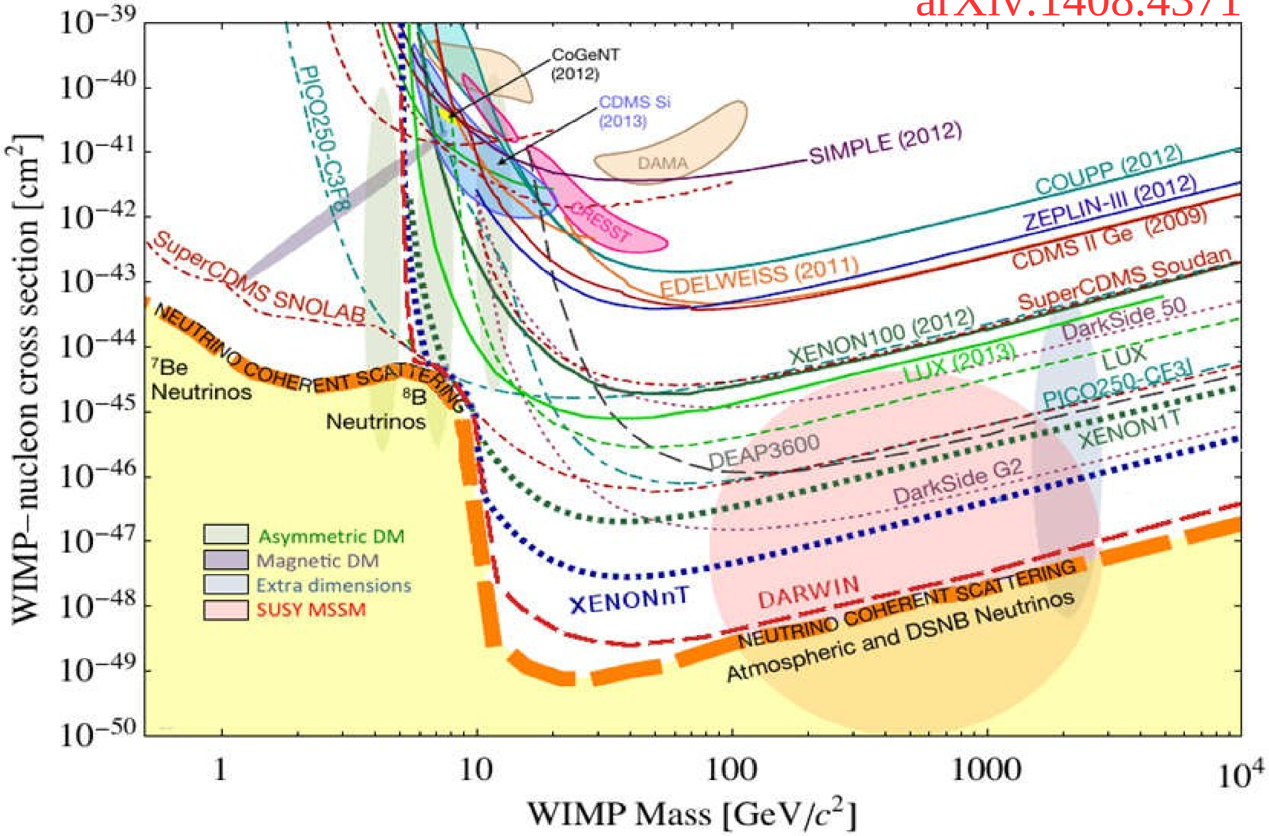
Elastic Z exchange

Thermal targets for different scattering hypothesis

Higgs exchange

1-loop EW box

arXiv:1408.4371



- So far, no positive evidences for WIMP-like DM from direct search
- Experiments are reaching coherent neutrino floor.
- **Where to look next?**

(**Direct detection program is still crucial**, only way to probe cosmogenic DM signals)

Light Dark sector

Broad the DM research by taking one step back in prior hypothesis

Cosmology prior: thermal origin
Particle physics prior: interaction with SM trough EW force

Light Dark sector

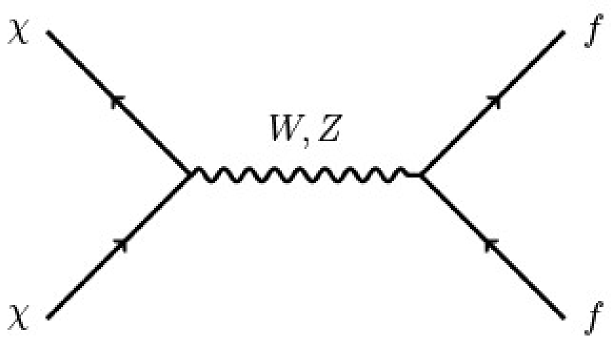
Broad the DM research by taking one step back in prior hypothesis

Cosmology prior: thermal origin
~~**Particle physics prior:** interaction with SM trough EW force~~

- WIMPs are natural if DM has ~ O(1) coupling to SM trough EW force
- < GeV scale arises if coupling is << O(1) → Search for < GeV scale DM

Light DM (m_χ < 1 GeV) requires new interactions with SM

A light WIMP does not reproduce correct relic abundance:



$$\langle \sigma v \rangle_{\rm WIMP} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1} \left(\frac{\rm TeV}{m_\chi} \right)^2$$

→ **If m_χ ~ 1 GeV,** $\langle \sigma v \rangle \ll \langle \sigma v \rangle_{\rm relic} \simeq 3 \times 10^{-26} cm^3 s^{-1}$

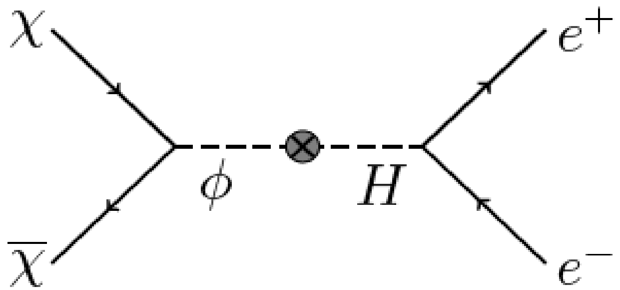
Light Dark sector: mediators

Different possibilities for SM-*l*DM mediator.

Mediator: new particle interacting both with *l*DM and with SM. Coupling with DM can be "large", coupling with SM expected to be "small"

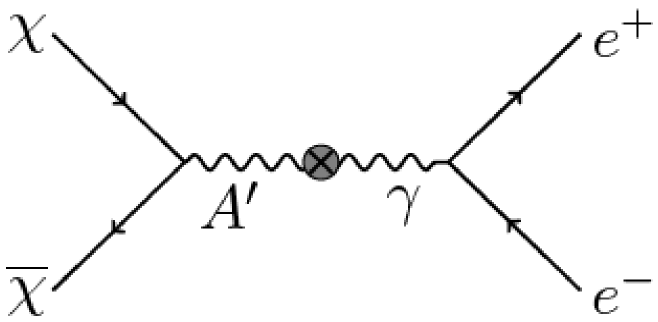
Possibilities (not exhaustive list!)

New scalar mediator mixing w/ Higgs



New vector mediator *A′* mixing w/ photon

A' ↔ dark photon



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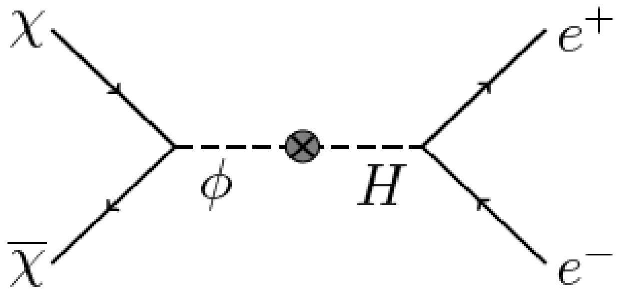

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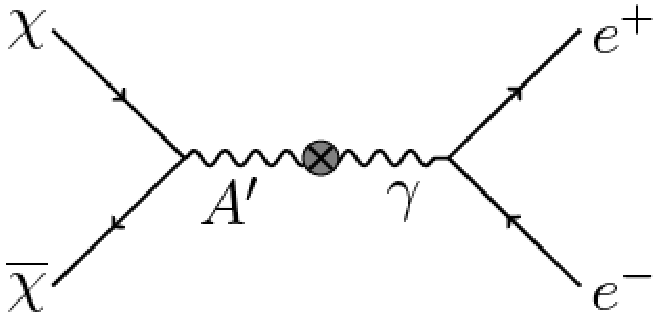


Main subject of the talk

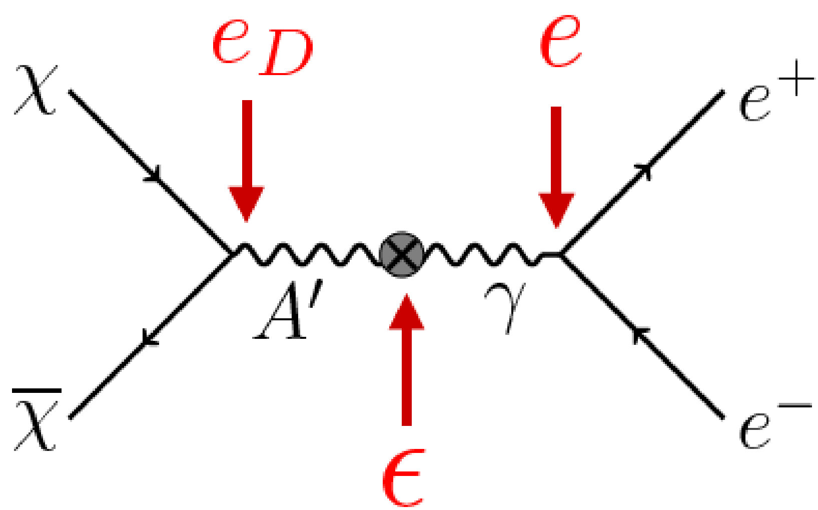
Light Dark sector – SM interaction trough A'

Specific case, representative for all viable choices:

"Dark – QED"

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$

DM



SM

$$\alpha \equiv \frac{e^2}{4\pi}$$

- **DM charged under new mediator: e_D ~ e**
- **Small A' – photon mixing: ε << 1**

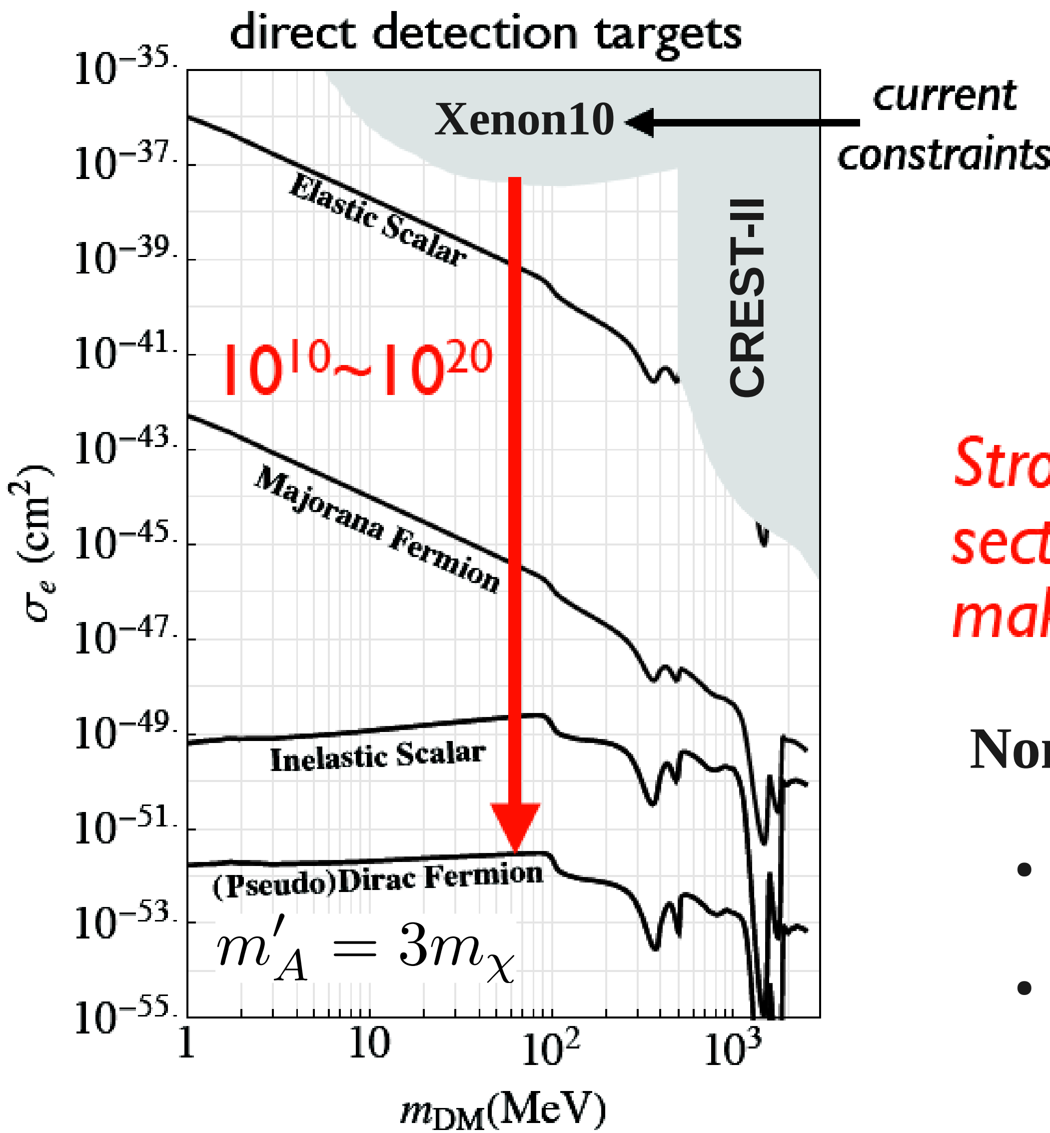
The thermally-averaged χ annihilation cross section is:

$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 e_D^2 m_\chi^2}{m_{A'}^4} \longrightarrow$$

By requiring that freeze-out mechanism reproduces today's relic abundance, a **target in the parameters space** can be derived.

Light Dark matter direct detection

Targets in the *l*DM Direct Detection plane (mass / cross section) are derived from **relic abundance requirement**, for different mediators (elastic scalar: see prev. slide)



Only **few data** for < GeV direct detection: non-relativistic *l*DM particles scattering on a nuclei results in tiny recoil kinetic energy, making **DD difficult**

Strong velocity dependence in cross section for all but the elastic scalar case makes direct detection very challenging.

Non-relativistic thermal *l*DM:

- Hard to measure in direct detection (although DD is crucial to probe cosmogenic origin!)
- Huge parameters space due to different low-energy behavior of different mediators

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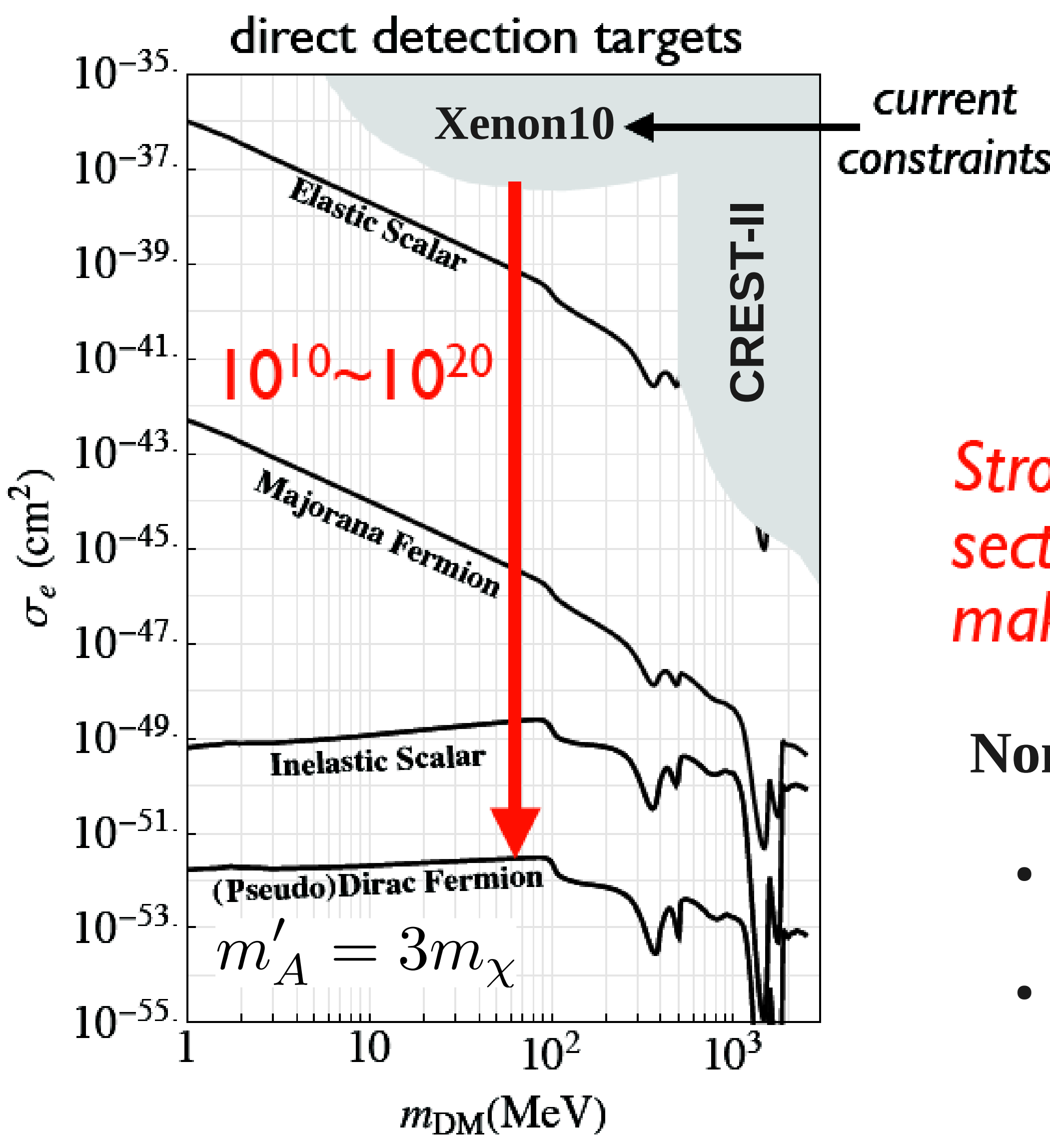

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- Hard to measure in direct detection (although DD is crucial to probe cosmogenic origin!)
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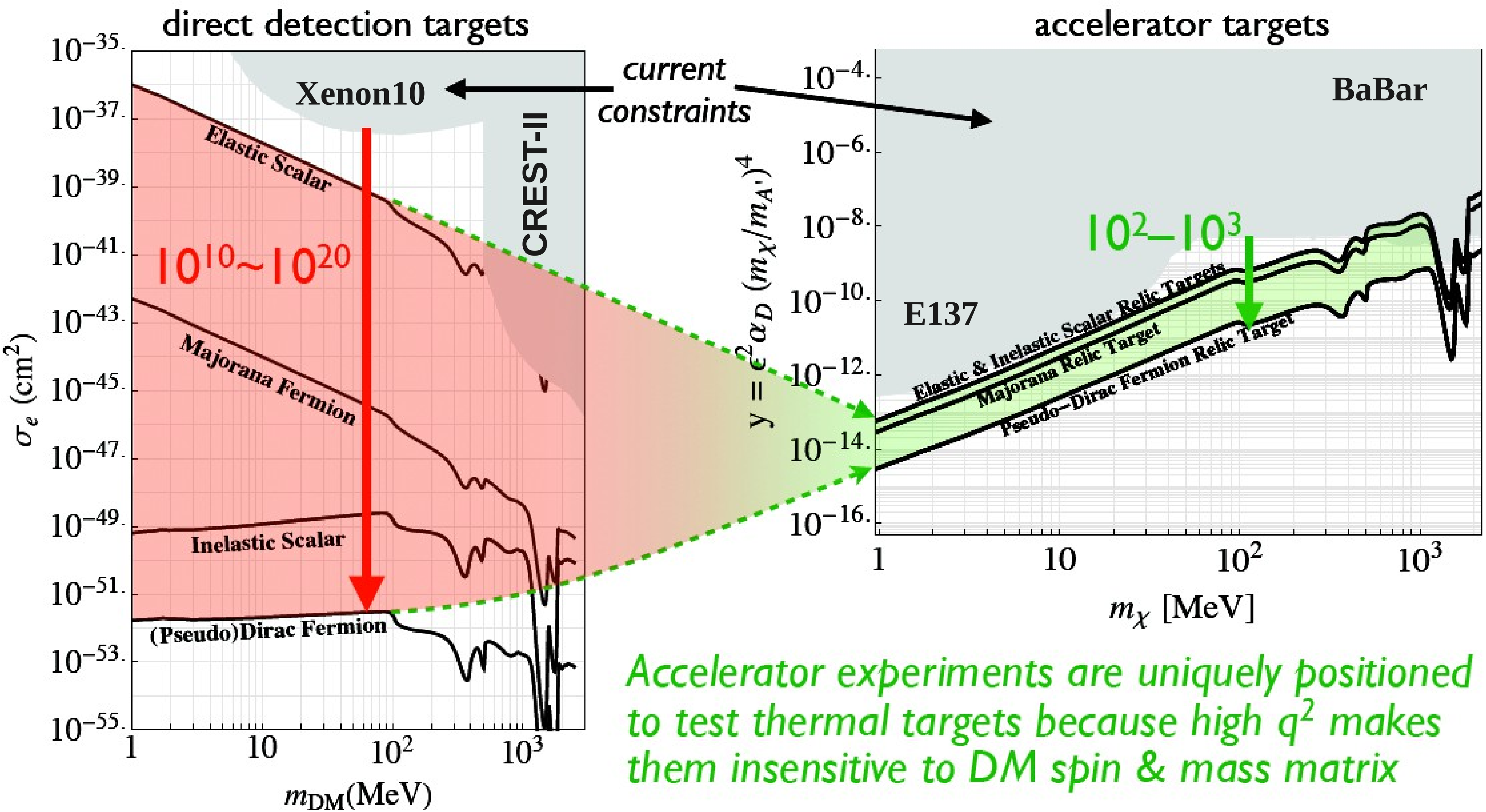
→ **What about relativistic *l*DM?**

Light Dark matter at accelerators

Thermal targets for relativistic *l*DM at accelerators (y – m plane) are concentrated in a much narrower region: **target for new experiments**



Accelerator experiments are uniquely positioned to test thermal targets because high q^2 makes them insensitive to DM spin & mass matrix

Light Dark matter at accelerators: parameters space

Introduce a new variable convenient for accelerator searches

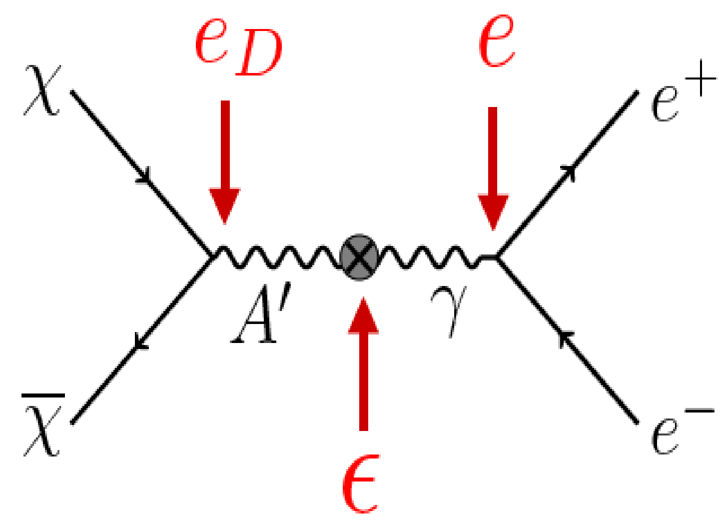
Thermal origin requires (freeze-out mechanism):

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} cm^{-3} s^{-1}$$

Annihilation cross-section for *l*DM (A'-mediated process):

$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 e_D^2 m_\chi^2}{m_A^4{}'}$$

DM



SM

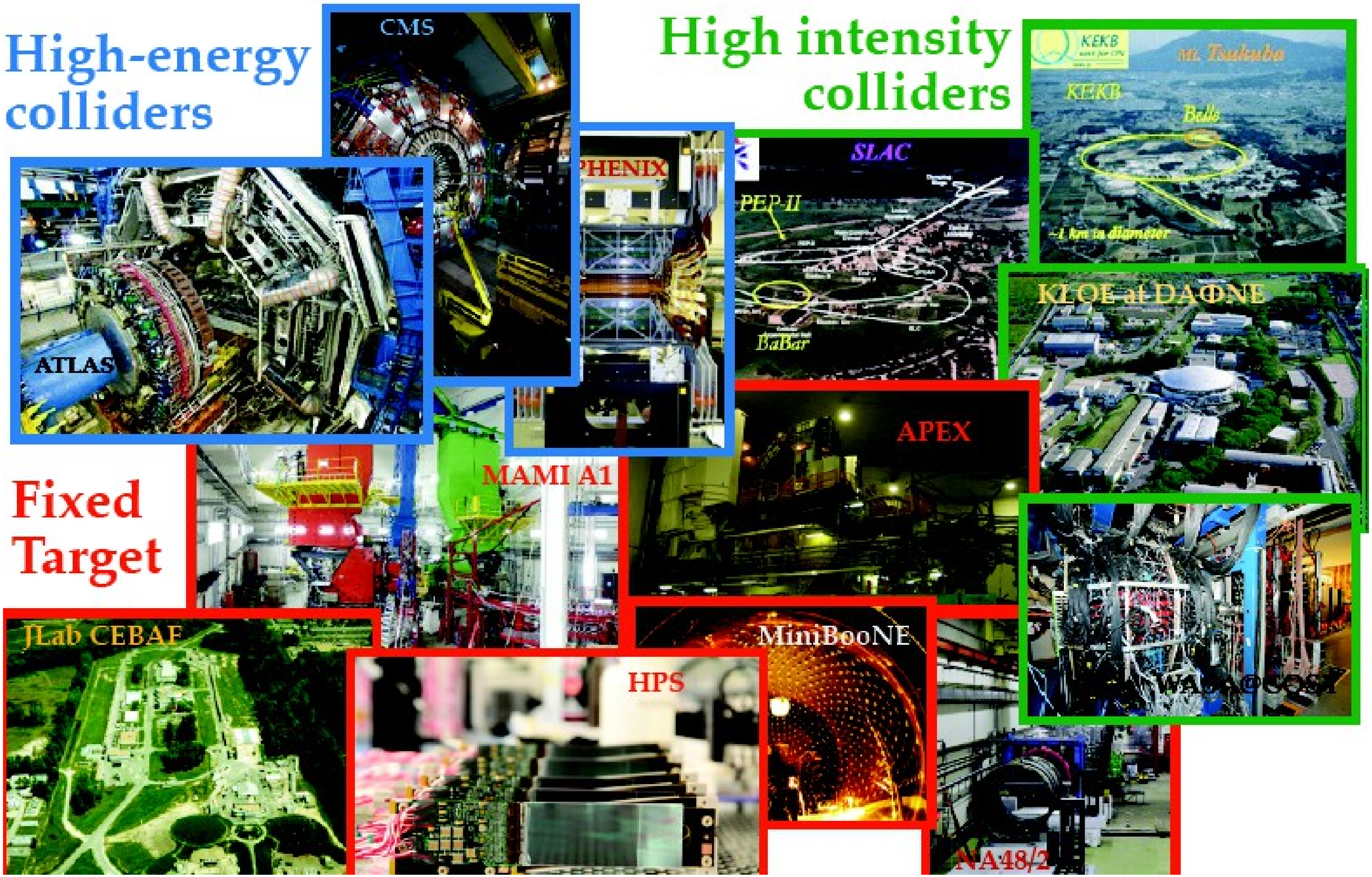
Define a new variable optimized for thermal targets:

$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 e_D^2 m_\chi^2}{m_A^4{}'} = [e_D^2 \varepsilon^2 (\frac{m_\chi}{m'_A})^4] \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

For a given m_χ, thermal origin imposes a unique value of "y"

Light Dark matter at accelerators: experiments

In the past few years, many different and complementary programs were proposed (and some already started) to experimentally search for *l*DM at accelerators, looking **both** for ***l*DM particles** and for **mediators**



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This talk will focus on experiments performed at Jefferson Laboratory (Newport News, VA), with a significant contribution by INFN-Genova

Light Dark matter at accelerators: mediator search

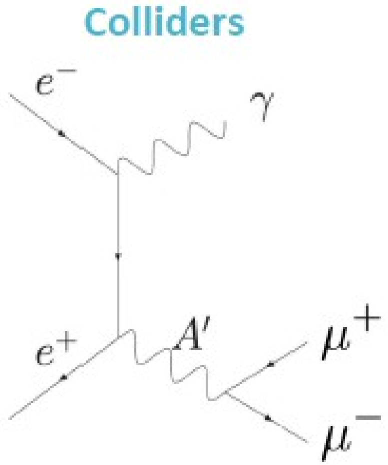
"If there are photons, there will also be heavy photons"

Multiple experimental techniques have been exploited to search for dark photons

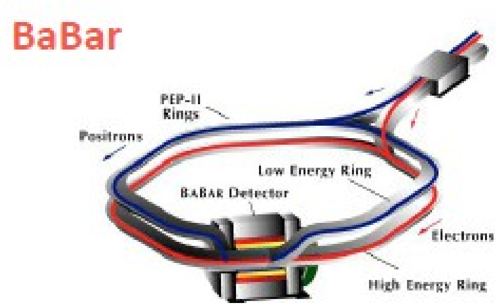
Common assumption: $m_{A'} < 2m_\chi$ → **Dark photons decay visibly to SM particles ($e^+ e^-$, $\mu^+\mu^-$,...)**

$e^+ e^-$ colliders:

- $e^+ e^-$ beams colliding head-on, different EM processes may happen
  - Production of $\gamma\gamma$ pair
  - If dark photon exists, $e^+ e^-$ may produce γ A' pair
- The dark photon can be detected by measuring the decay products (e.g. $\mu^+\mu^-$)



$$\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2}$$



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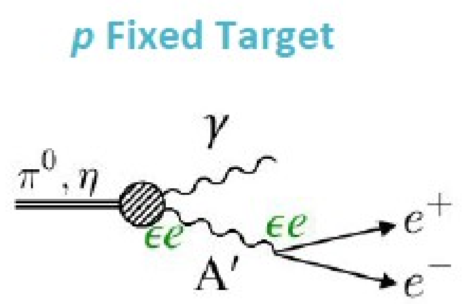
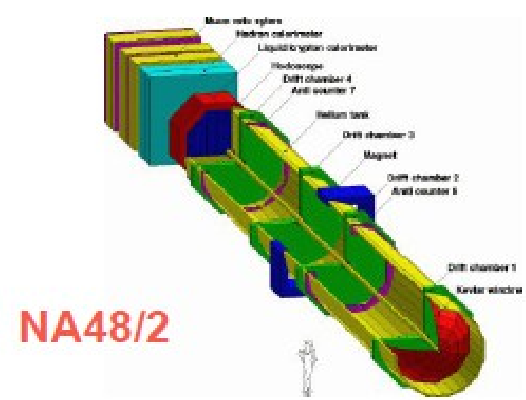
Proton beam, fixed target (meson factories):



$\sigma \sim \varepsilon^2$

- High energy, high intensity proton beam impinging on fixed target. Many hadronic processes happen.
  - Production of π^0 and η mesons, decaying mainly to γγ pairs
  - If dark photon exists, mesons may also decay to γ A' pair
- The dark photon can be detected by measuring the decay products (e.g. $e^+ e^-$)



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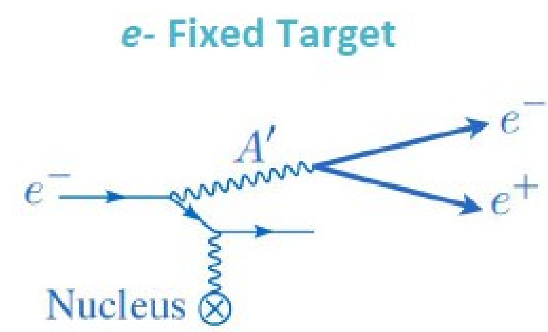
Multiple experimental techniques have been exploited to search for dark photons

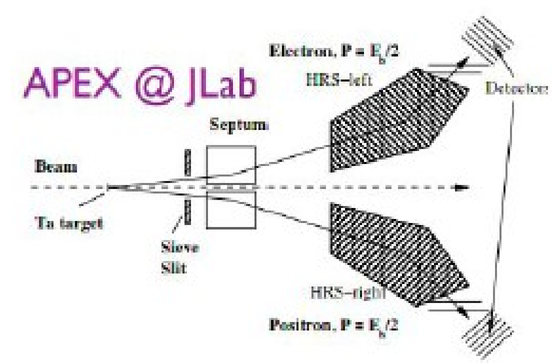
Common assumption: $m_{A'} < 2m_\chi$ → **Dark photons decay visibly to SM particles ($e^+ e^-$, $\mu^+\mu^-$,...)**

Electron beam, fixed target:

- High energy, high intensity electron beam impinging on fixed target. Many EM processes happen.
  - Bremmstrahlung: production of high energy photon by the electron
  - If dark photon exists, A'-strahlung may also happen: emission of dark photon by the electron
- The dark photon can be detected by measuring the decay products (e.g. $e^+ e^-$)



$$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2}$$

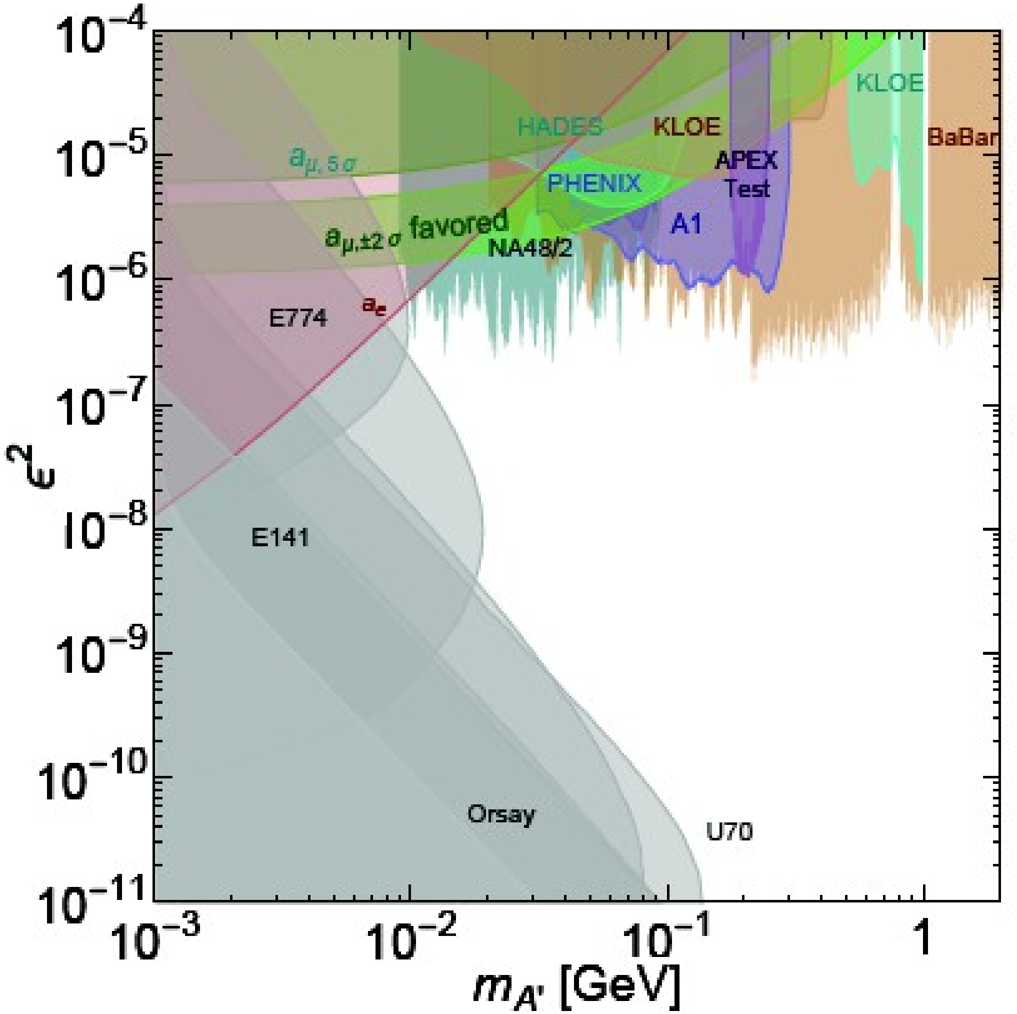


Light Dark matter at accelerators: mediator search

Current status of experimental searches: so far, **no positive results**, only exclusion limits in the parameters space

Results have been reported by many experiments!

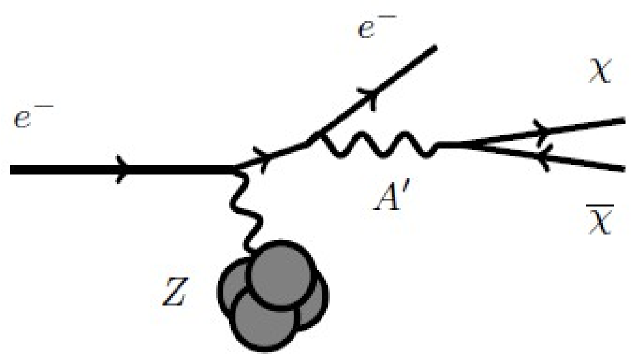
- e^-, fixed target
  - Jlab (APEX/HPS), Mainz (A1)
- p, fixed target
  - Fermilab, NA48
- Colliders
  - BaBar, Belle, Kloe
- Meson decay
  - KLOE, BES-3, WASA-COSY



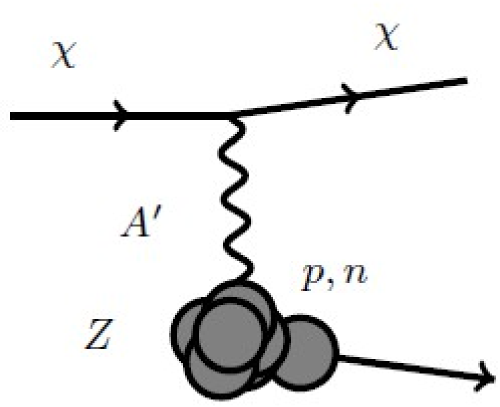
Light Dark matter at accelerators: χ search

Prototype experiment: electron beam-dump experiment.

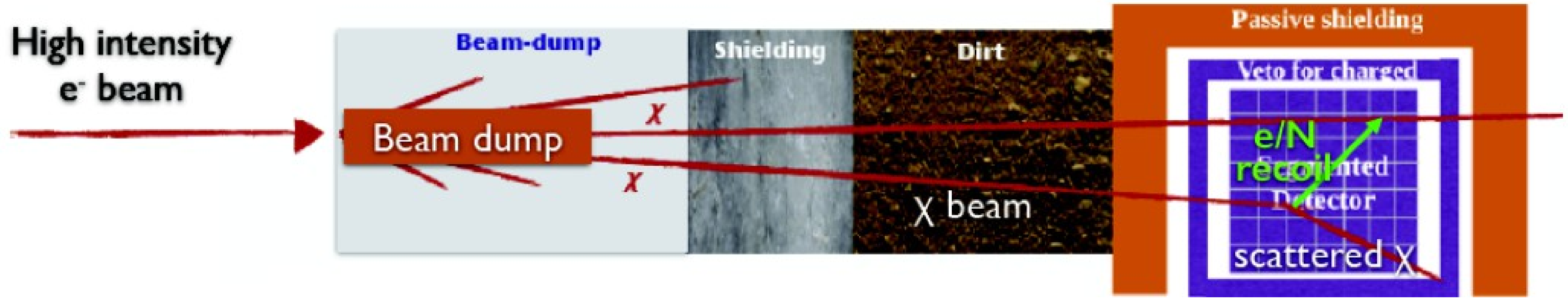
High-energy e⁻ beam impinges on a fixed, thick target. Detector placed after the target, with shielding in between



- Multiple reactions occurs, mostly SM-particles production
- Rare process: e⁻ emits a dark-photon, that decays to *l*DM particles
- If target/shielding thick enough to absorb all SM particles but ν: effective high-energy *l*DM beam after the dump
- χ particles may scatter in the detector, resulting in recoil kinetic energy that can be measured



$$N_{counts} \propto N_{EOT} \cdot y^2 \frac{1}{e_D^2} \left(\frac{m_{A'}}{m_\chi}\right)^4$$

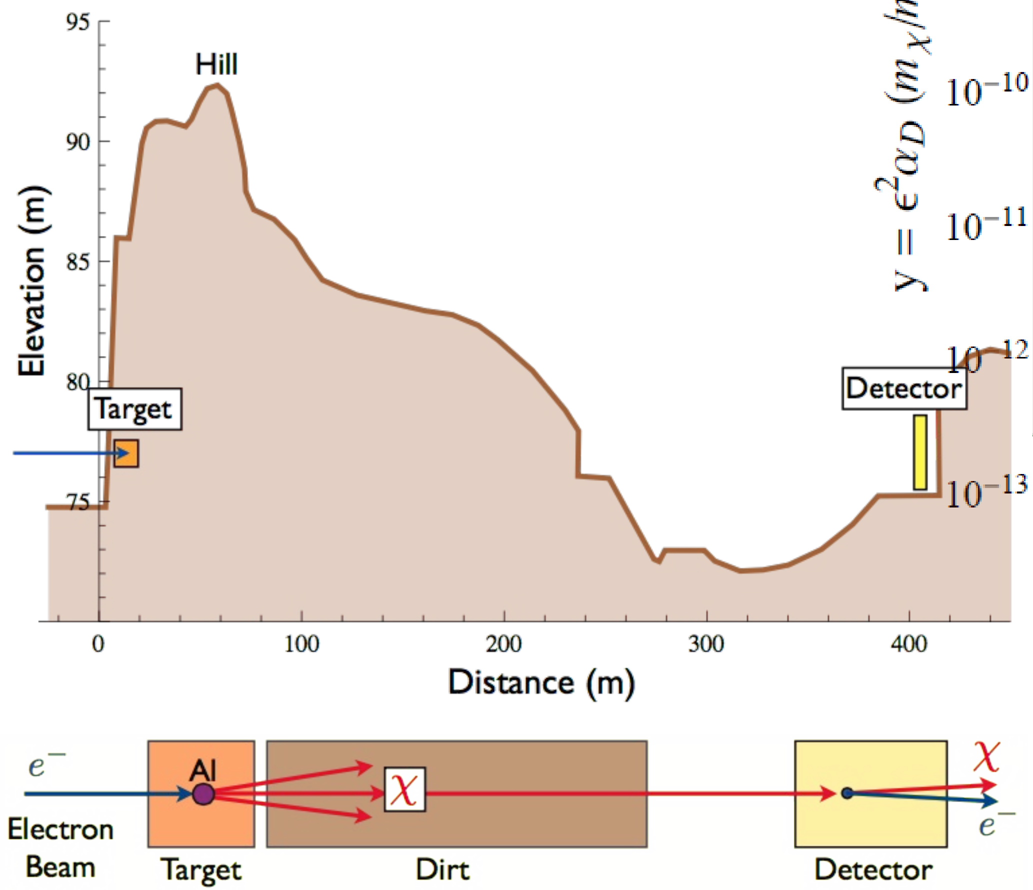


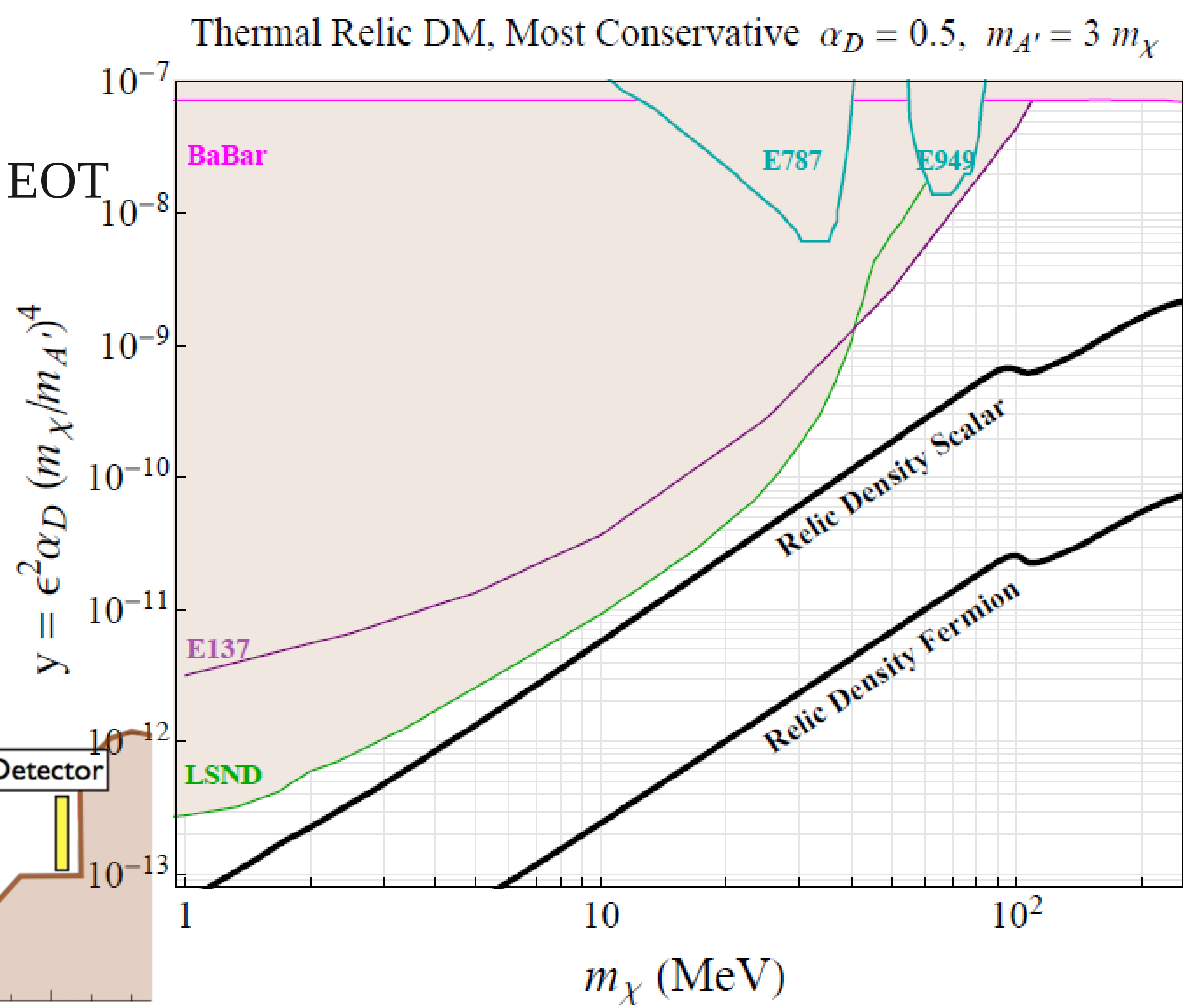
Light Dark matter at accelerators: χ search

Current constrains for *l*DM search @ accelerators:

E137 @ SLAC (1988)

- 20 GeV e[-] beam on Al target, 10^{20} EOT
- Detector placed at z~400 m
- No events seen (1 GeV threshold)





*l*DM searches @ Jefferson Laboratory

JLab is home for 4 *l*DM experiments: **APEX, HPS, DarkLight, BDX**.

Complementary searches: visible and invisible A' decay and for χ detection

APEX

HEAVY PHOTON SEARCH

DM

DARKLIGHT

BDX @ JLAB

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APEX

HEAVY PHOTON SEARCH

DM

Argument of this talk

DARKLIGHT

BDX @ JLAB

Jefferson Laboratory

Jefferson Laboratory (Newport News, VA) is home for two electron machines based on superconducting RF technology: **CEBAF** and **ERL-FEL**

Jefferson Lab main science program topics:

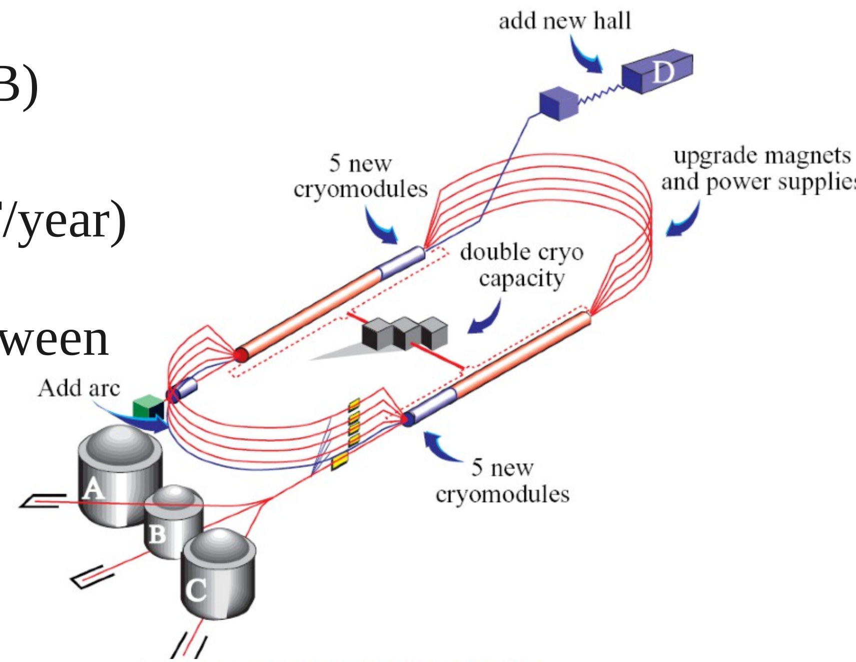
- Hadron structure
- Hadron spectroscopy
- Hadrons and cold nuclear matter

Availability of **high intensity**, **high quality beams** with energies from **100 MeV to 12 GeV** provide opportunities for high precision, high statistics experiments needed for *l*DM searches

Jefferson Laboratory facility for lDM searches

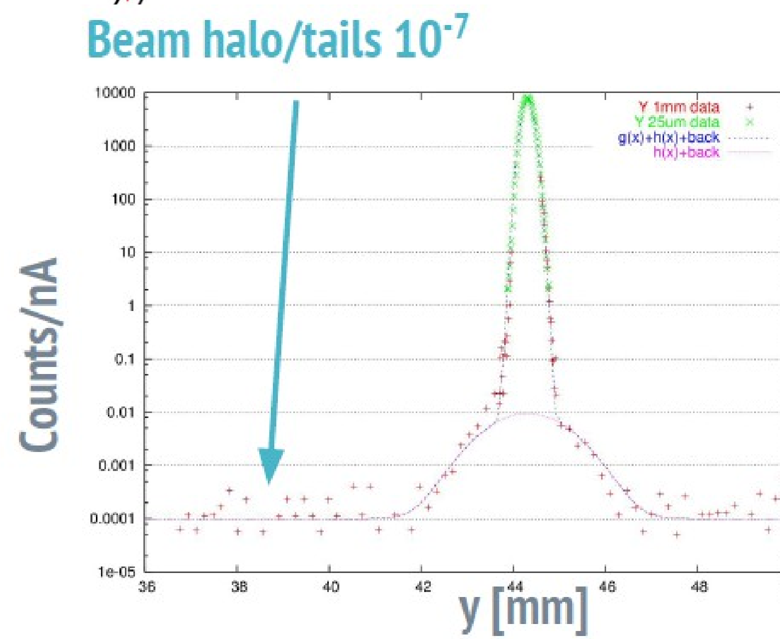
CEBAF: multi-pass acceleration scheme (1.1 GeV / linac, 2.2 GeV / pass), magnets and cavities based on superconductive technology.

- **High Intensity**: I_{beam} < 100 uA (A,C), < 800 nA (B)
  - HPS: Hall-B, 50-400 nA
  - BDX: behind Hall-A beam-dump, O(1022 EOT/year)
- **High Frequency:** ~DC beam, 4 ns separation between bunches
- **High Quality:** beam stable during time, tight beam spot on target
  - HPS: better tracking and vertexing
  - BDX: χ beam focused forward



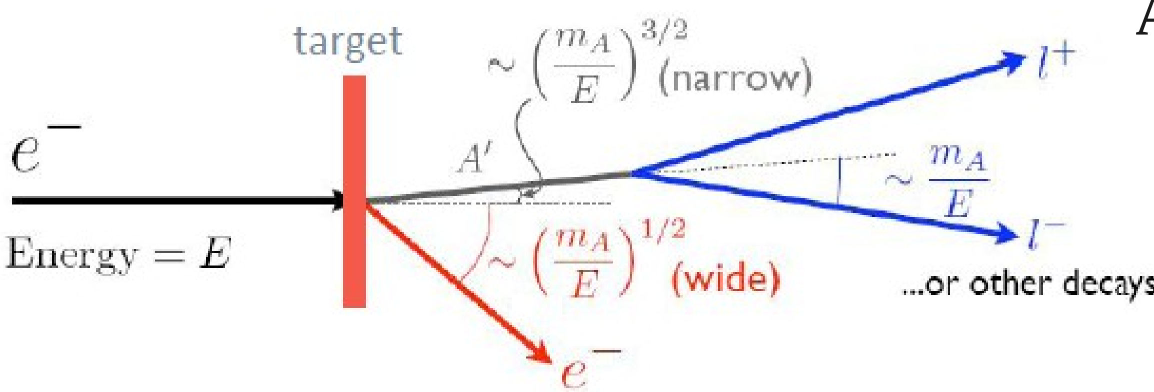
Beam profile on target (HPS setup):

- σ_y ~ 50 um (similar results for σ_x)
- Beam tails ~ 10^{-7}



HPS experiment

Trough γ-A' mixing (coupling ε), dark photons can be produced in a process analogous to ordinary Bremmstrahlung, and subsequently decay to $e^+ e^-$



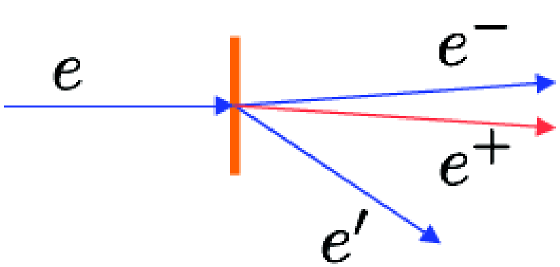
A' signal kinematic features:

- Forward A' emission, with $E_{A'} \sim E$
- Small decay products opening angle $\sim m_{A'} / E$
- Possible detached decay vertex for small coupling

The Heavy Photon Search (HPS) experiment in Hall-B at Jefferson Laboratory was designed to search for dark photons trough two complementary techniques

"Bump-hunt"

- "Large" ε coupling: prompt decay
- Detect $e^+ e^-$ pairs and measure invariant mass
- Search for a peak on top of large QED background
- **Requirements:** high invariant mass resolution



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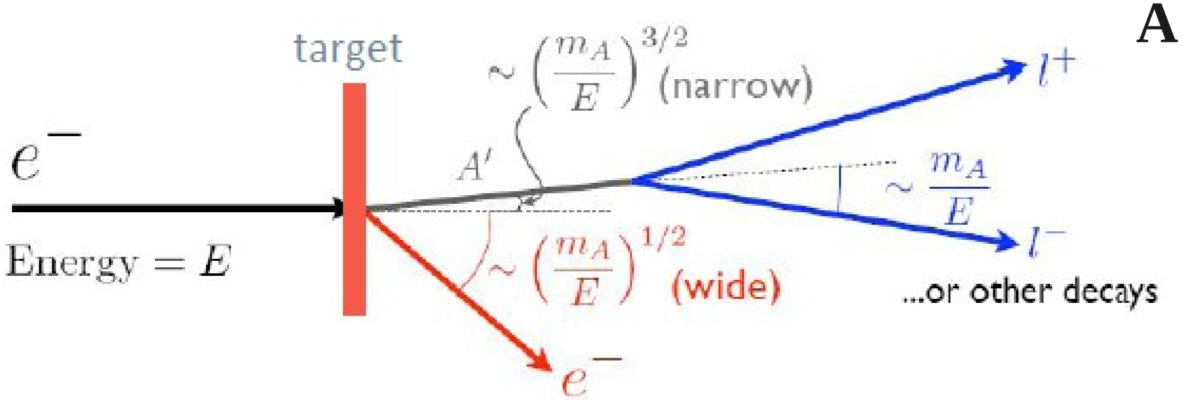

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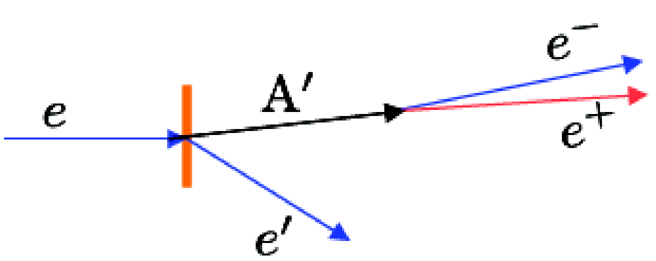
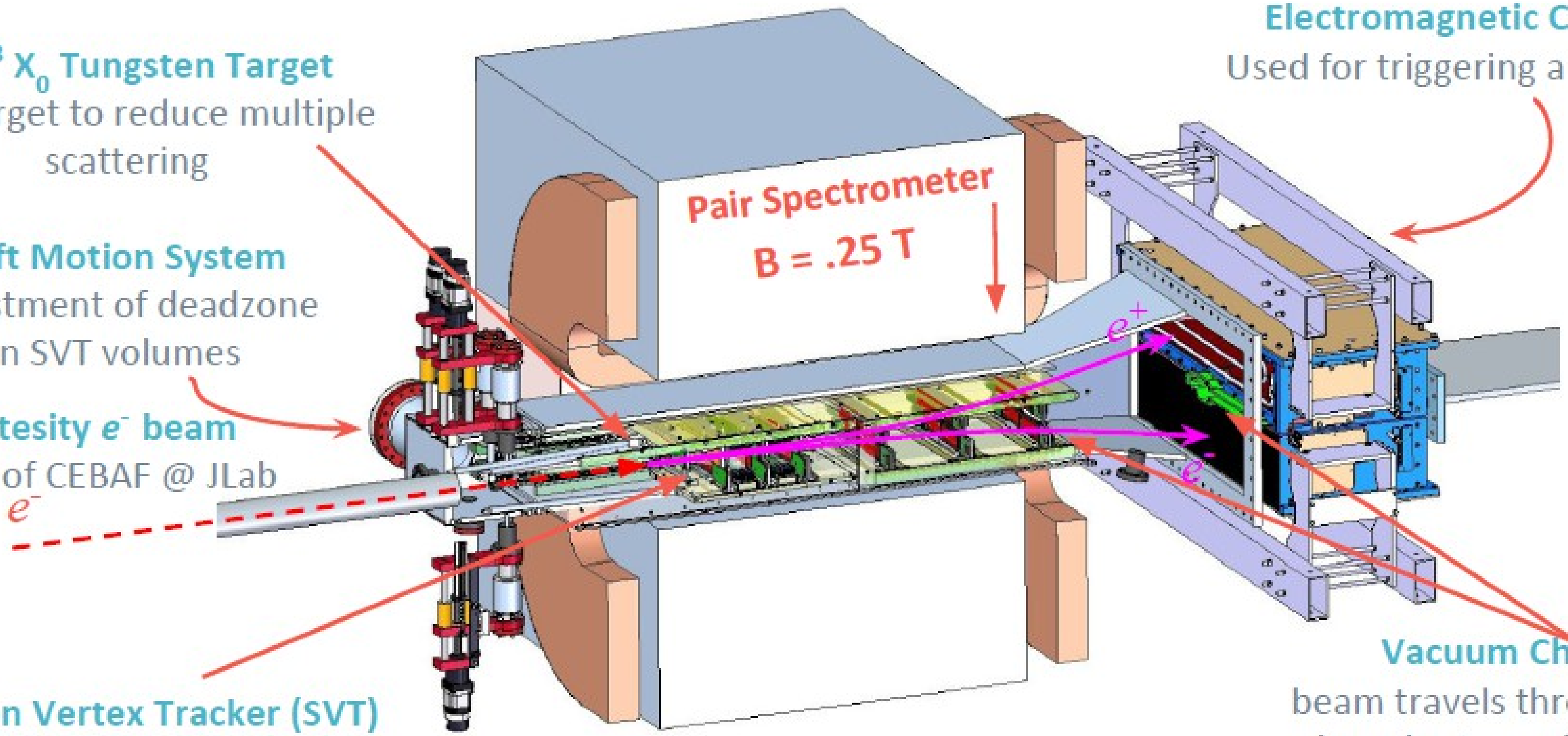
“Detached-vertexing”

- “Small” ε coupling: A' long lived
- Measure invariant mass AND detached vertex
- Use vertex-cut to reject all (prompt) QED backgrounds – 0 background search
- **Requirements:** high statistics, high tracking/vertexing resolution



HPS setup

HPS setup: **compact spectrometer**, made of Si-strips tracker and $PbWO_4$ EM calorimeter

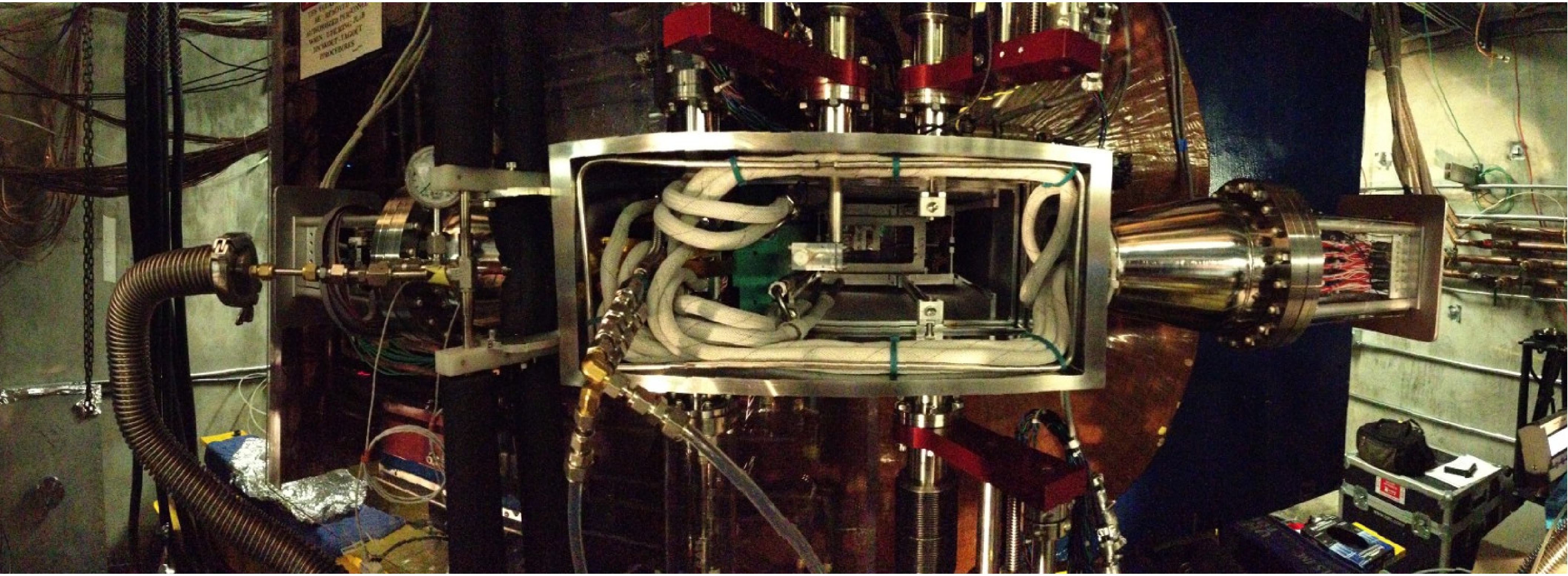


SVT + ECal DAQ capable of 50 kHz

Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

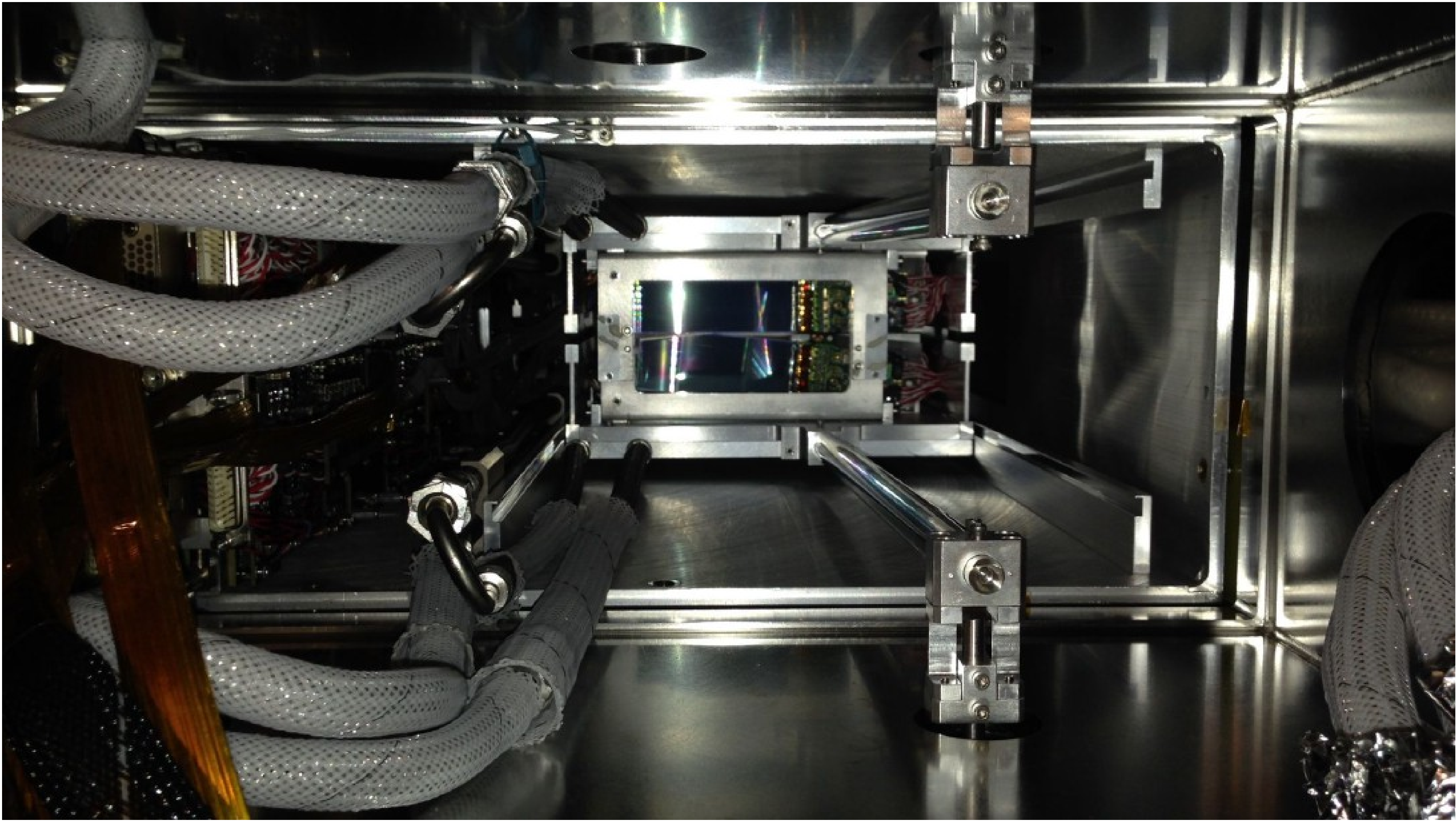
HPS setup

Beam's view of HPS setup (target not present)



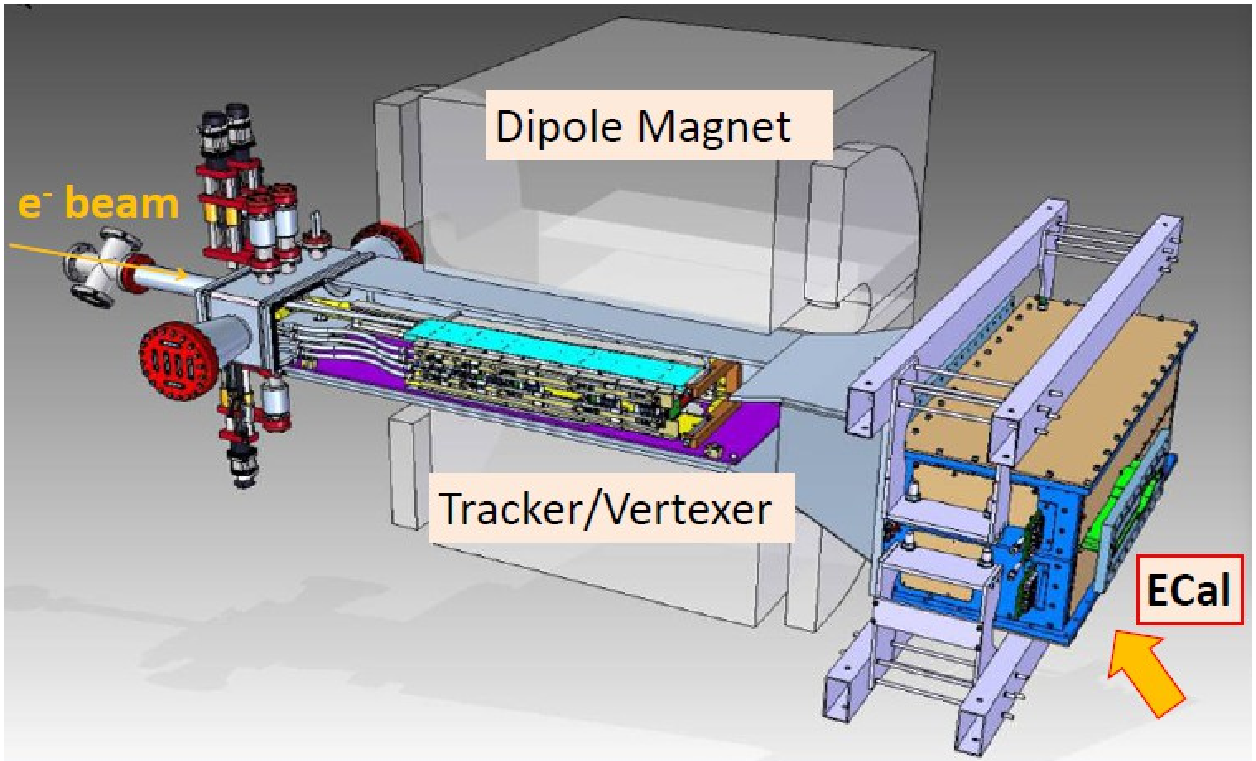
HPS setup

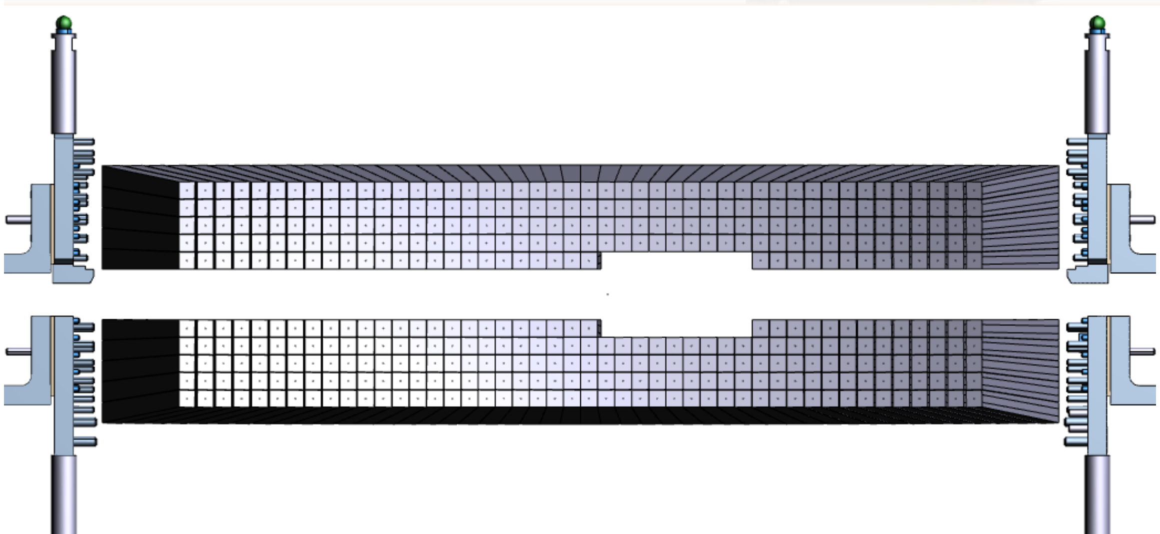
Beam's view of HPS setup – close to SVT



HPS setup: EM calorimeter

Main INFN hardware contribution to HPS: **Electromagnetic Calorimeter** construction





Design: $PbWO_4$ crystals with LA-APD readout

- Top and bottom modules
  - 5 layers each
  - 442 crystals in all
- APD readout through custom preamplifiers
  - Data recorded with 250 MHz 12 bit FADCs
- Thermal enclosure to hold crystal temperature to 18 ^{0}C to stabilize gains

ECal beam view

Central hole: primary deflected beam not interacting with the thin target

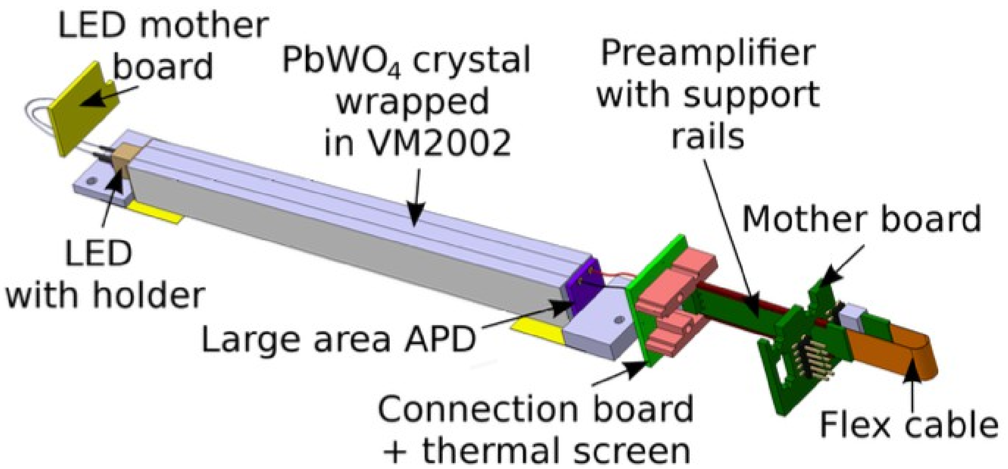
HPS setup: EM calorimeter activity @ INFN

ECal APD installation

- APD characterization: measure and data analysis.
- APD gluing: tools design, production and installation.
- Crystal assembly test: tools design, production and installation.

ECal motherboard replacement

- Design and test of the new ECal motherboards



ECal LED monitoring system

- LED holders design and construction
- “Connection boards” design and construction
- System test in Italy and at Jlab
- System installation

Software development

- Study and development of ECal calibration algorithms.
- ECal online monitoring system development

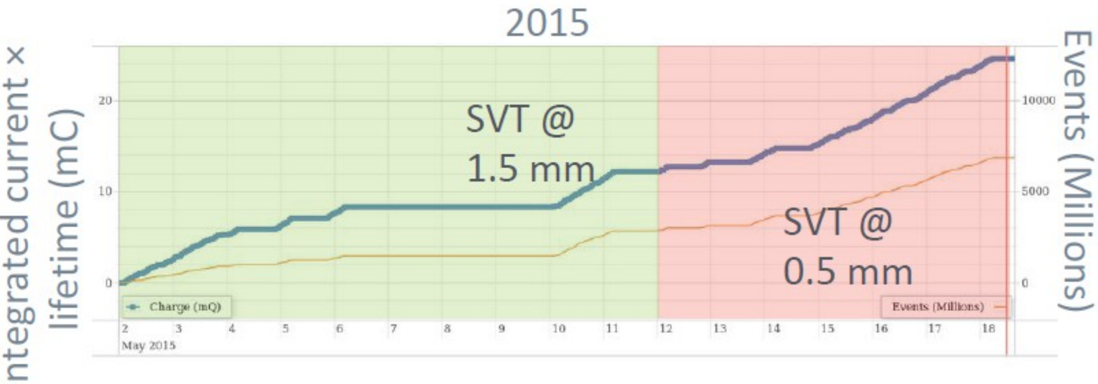
HPS status

HPS successfully completed two engineering runs

- **Spring 2015:** 50 nA, 1.056 GeV electron beam
- **Spring 2016:** 200 nA, 2.3 GeV electron beam

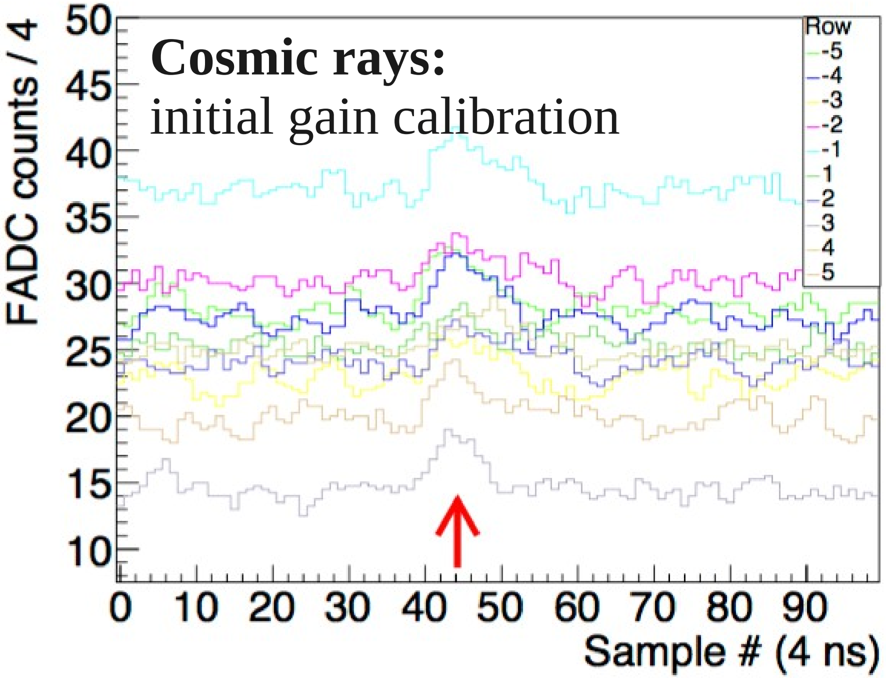
Goals: understand the performance of the detector, measure performances, and take physics data (limited statistics)

- **2015:** data taken with SVT in two configurations, active edge at 1.5 mm / 0.5 mm from beam plane
  - 10 mC @ 1.5 mm, 10 mC @ 0.5 mm → 30% of proposed data
- **2016:** SVT @ 0.5 mm, 92 mC → 77% of proposed data

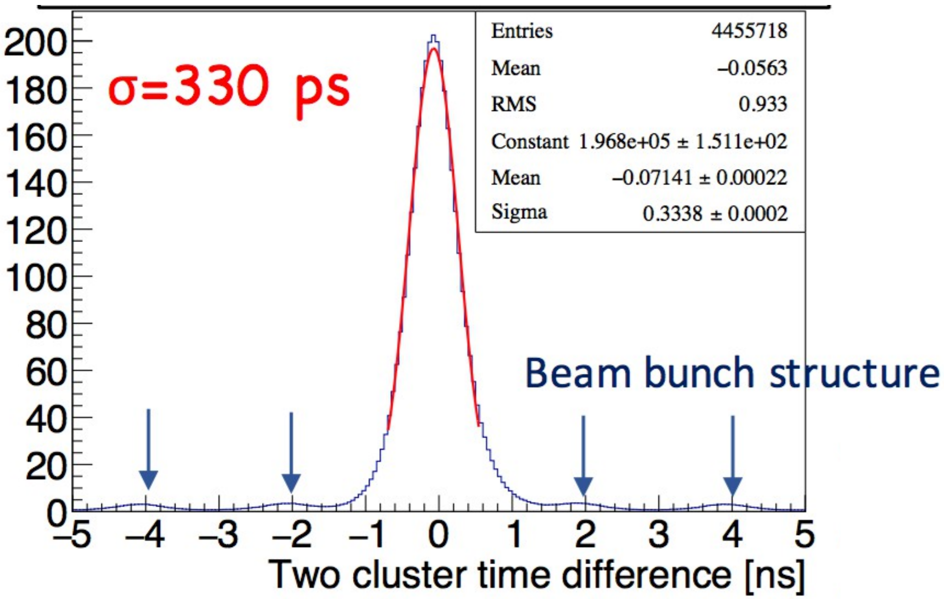


Results from 2015 data have been **fully analyzed and presented**. First publication expected by end of summer

HPS ECal performances – 2016 run

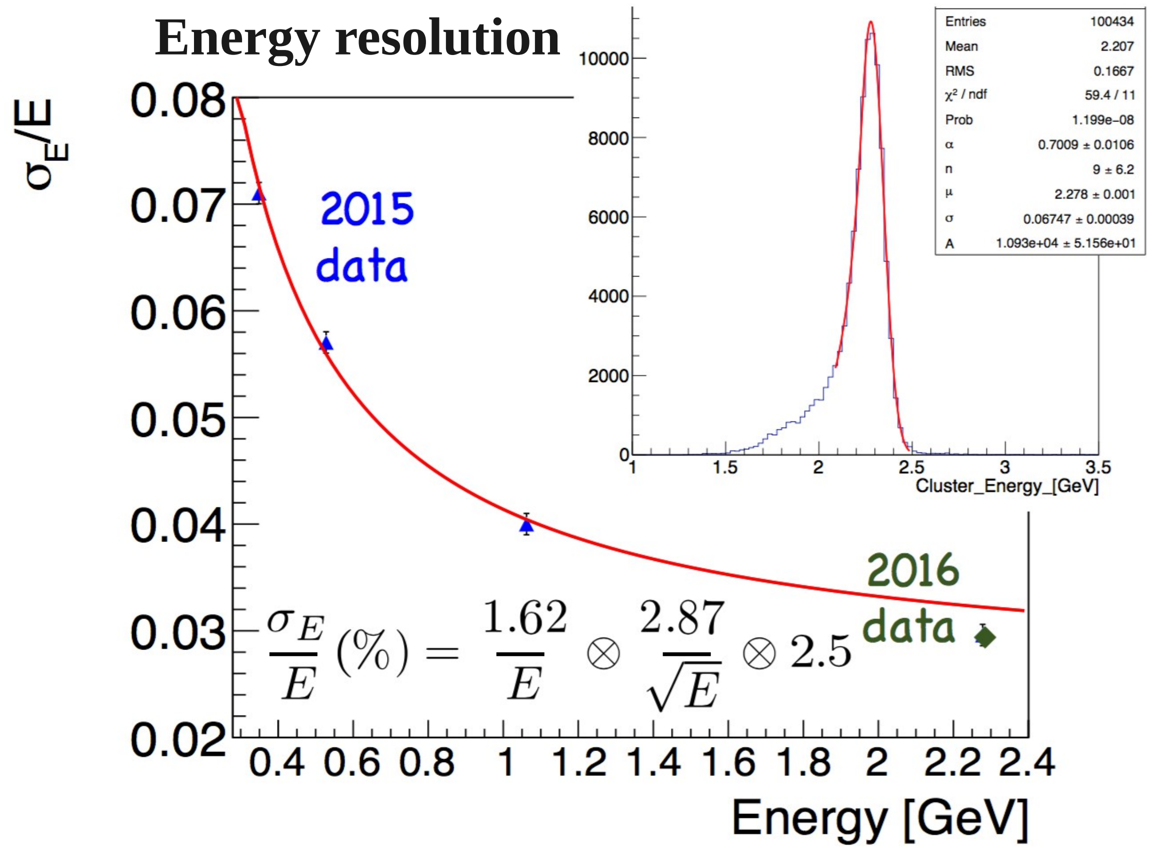


Time resolution



Energy resolution

Resolution measured from e^- elastic scattering



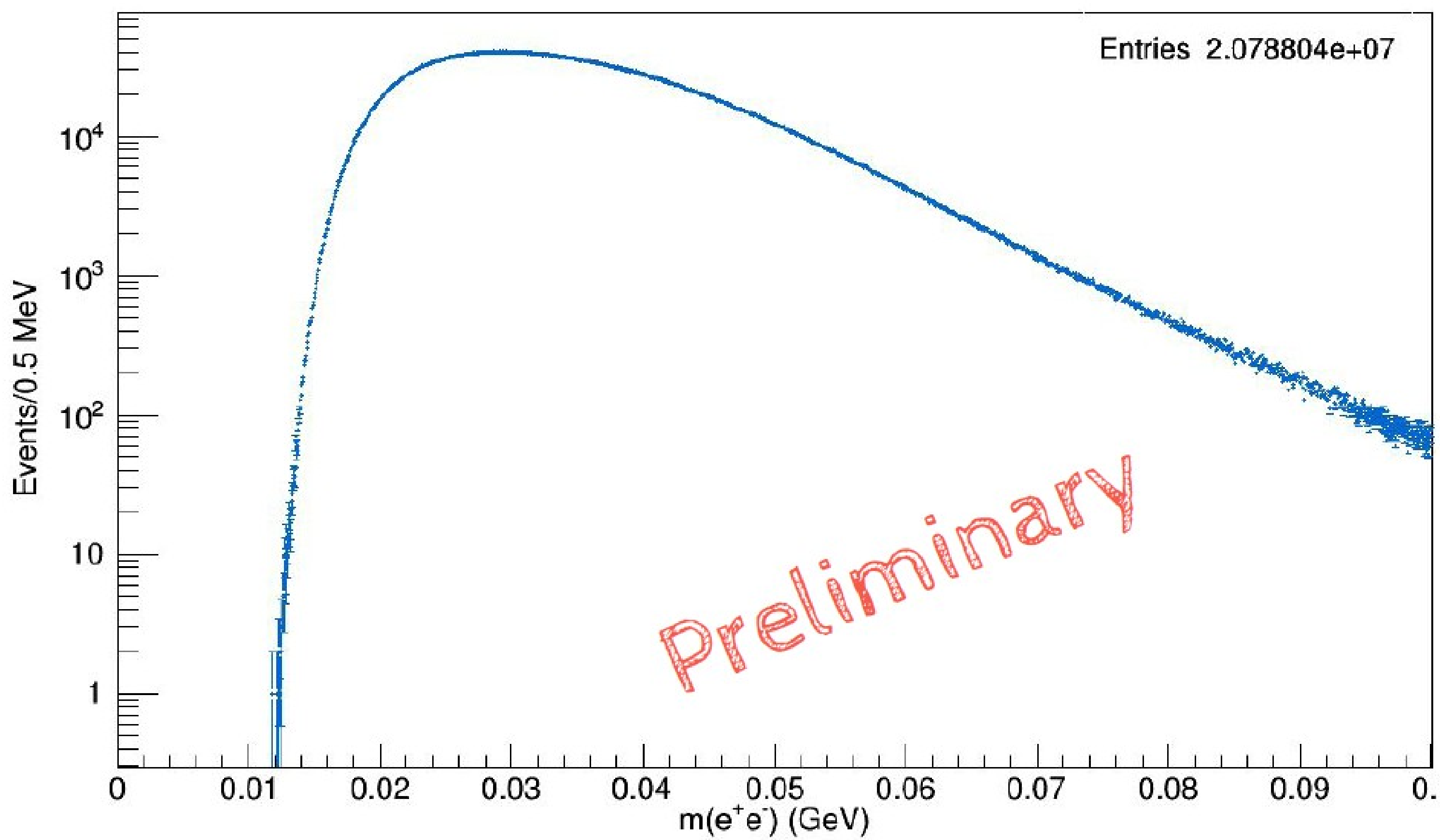
HPS first results

HPS first analysis: 2015 data, “bump-hunt” search for A'

- Select “good” events with e^+e^- pairs measured in SVT+ECAL
- Measure e^+e^- invariant mass distribution
- Search for a “small” peak – due to A' decay – on top of huge QED background
  - Make use of sophisticated statistical techniques to evaluate the presence of peak / put upper limit in case of no signal

Full 2015 statistics

- 20.7 Million events, SVT @ 0.5 mm

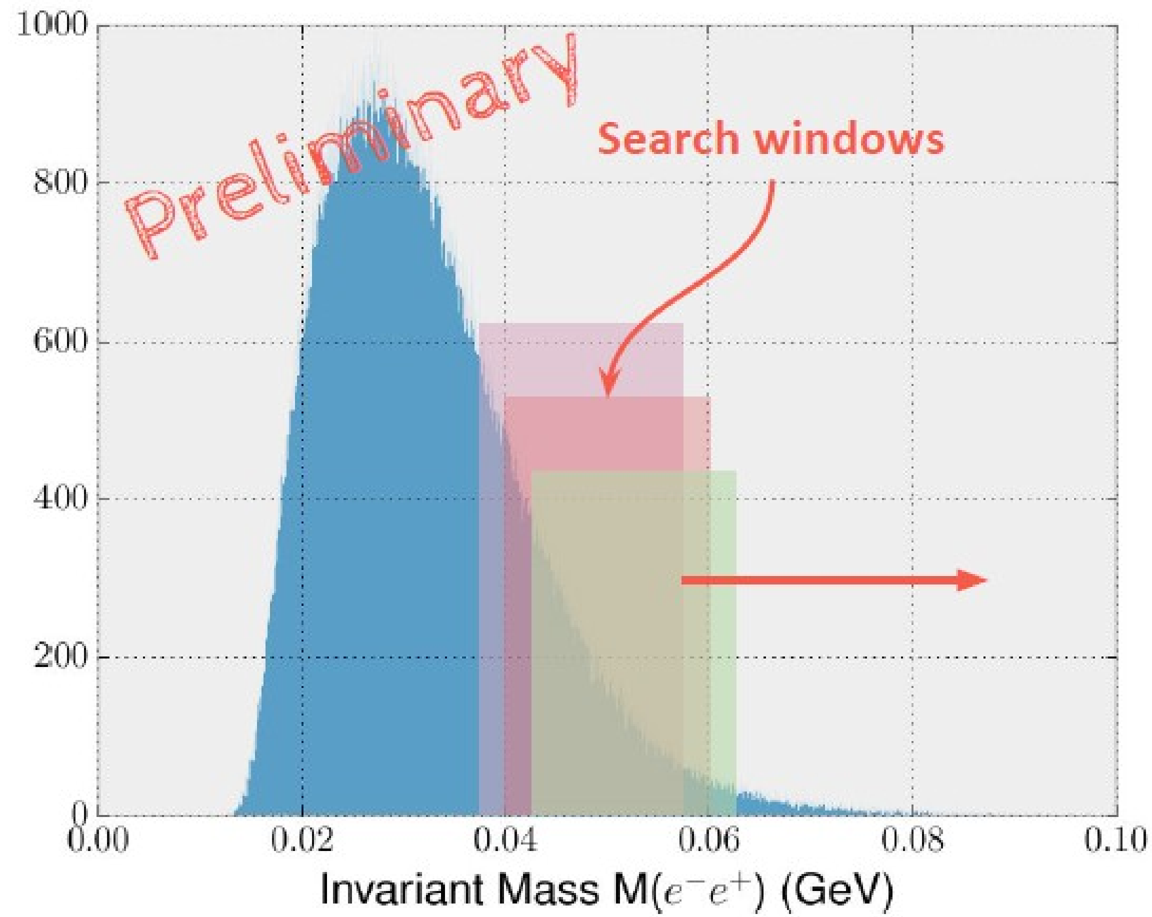


Analysis by O. Moreno, SLAC

HPS first results – analysis overview

Goal: identify a possible peak over large QED background. In case of no observation, quote an upper limit on the coupling at each mass

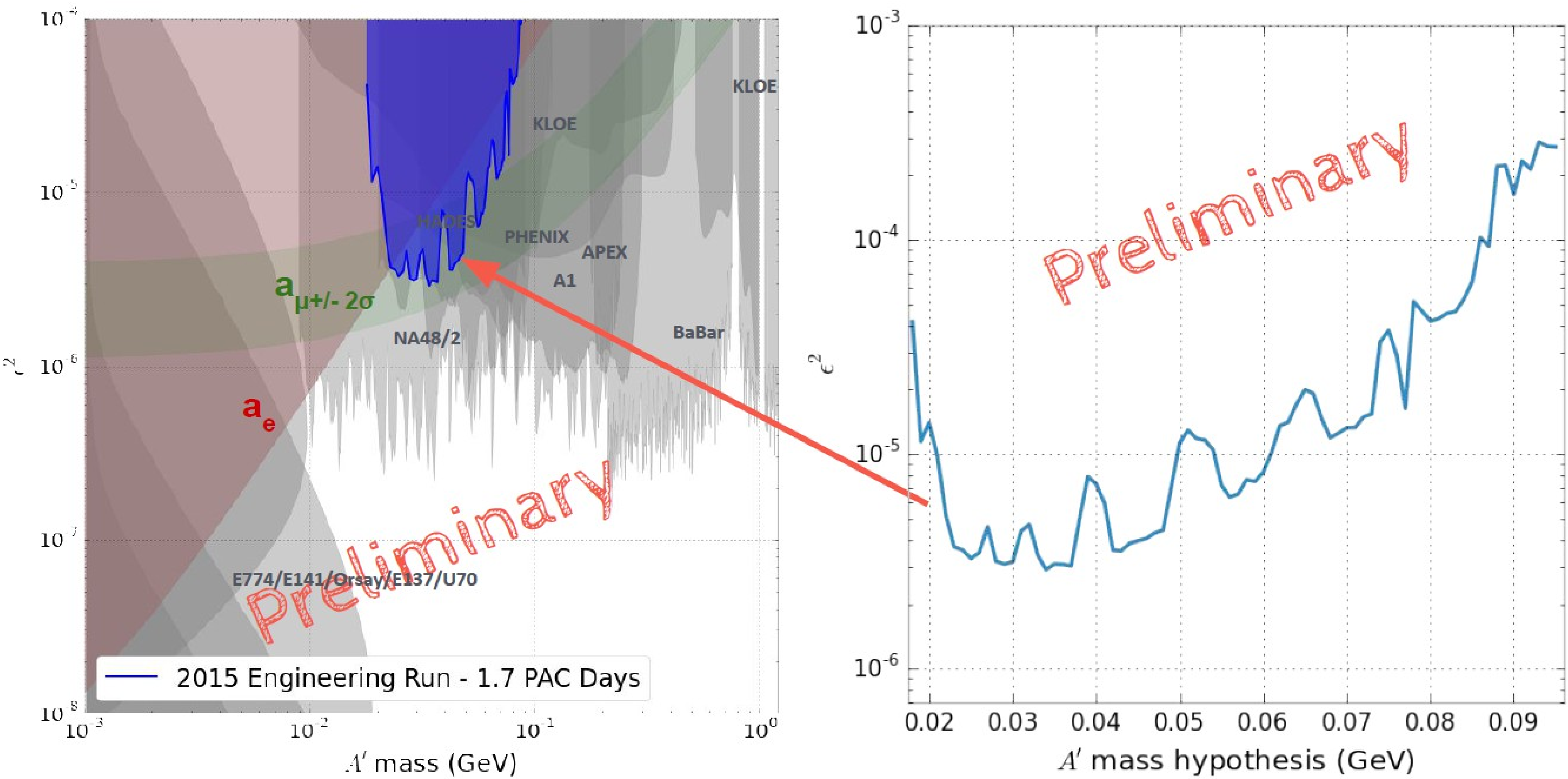
- Search for a resonance in the mass window 18 – 95 MeV, in steps of 1 MeV
- At each step:
  - Select a proper window (width ~ 10 σ_{mass})
  - Perform a fit to the spectrum with signal (gaussian) + background (polynomial)
  - From signal strength, quantify the significance of a possible "bump"
  - Translate the significance into a signal upper limit in the coupling-mass plane



Analysis by O. Moreno, SLAC

HPS first results

HPS first analysis: 2015 data, no evidence for a statistically-significant bump in $e^+ e^-$ spectrum. Put upper limit on coupling strength in parameters space

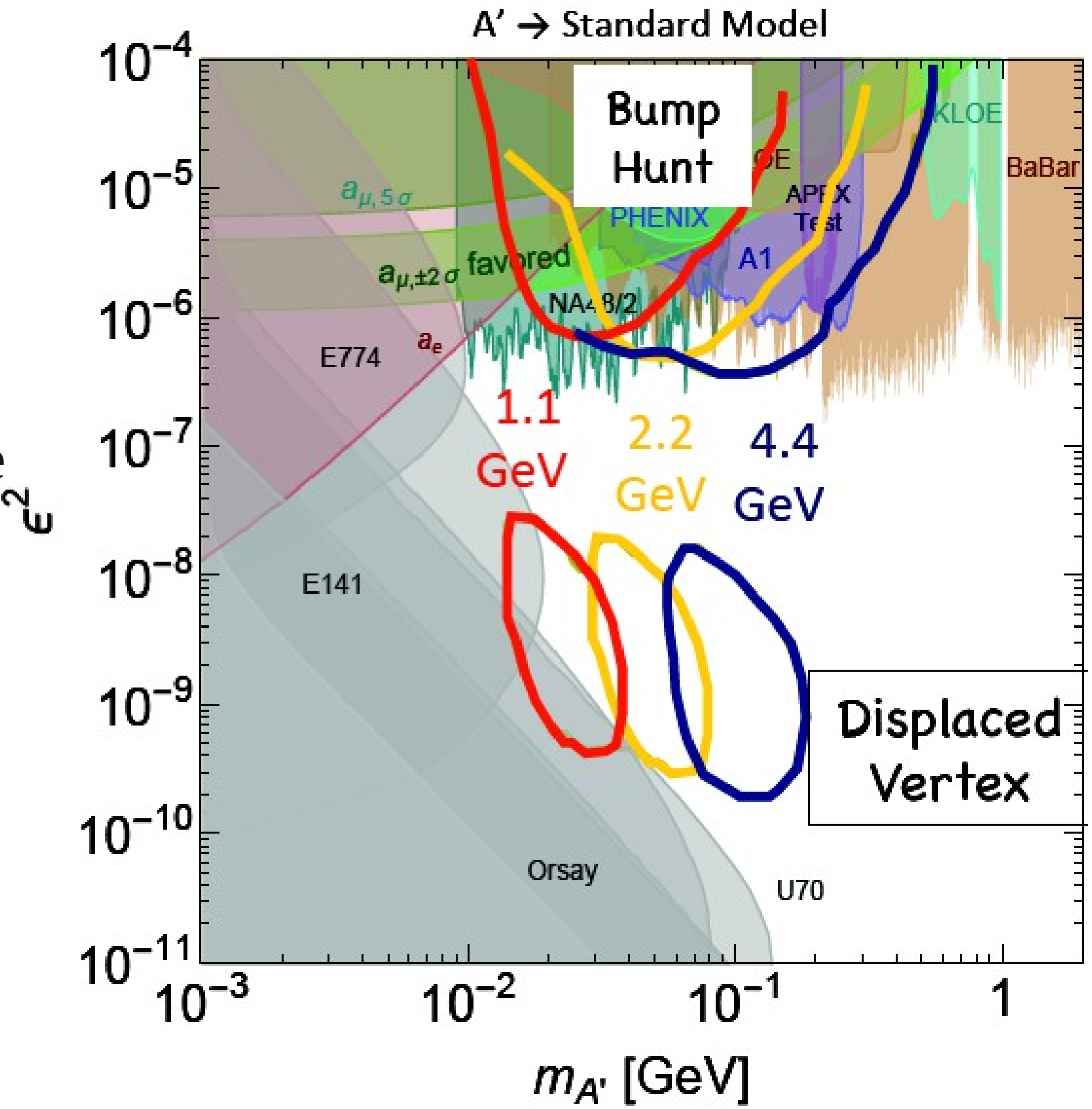


Analysis by O. Moreno, SLAC

HPS expected results – full statistics

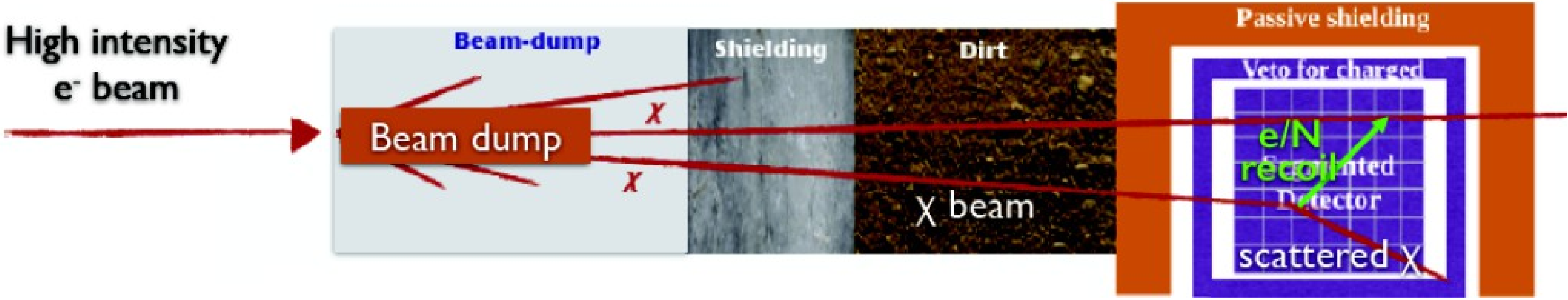
HPS has been approved for 180 days of run! (2015 data: 1.7 days)

- First extended run taking place in 2018
- Enough statistics to explore new territories with bump-hunt technique
- Enough statistics to explore detached-vertex territories (unique to HPS!)



BDX experiment

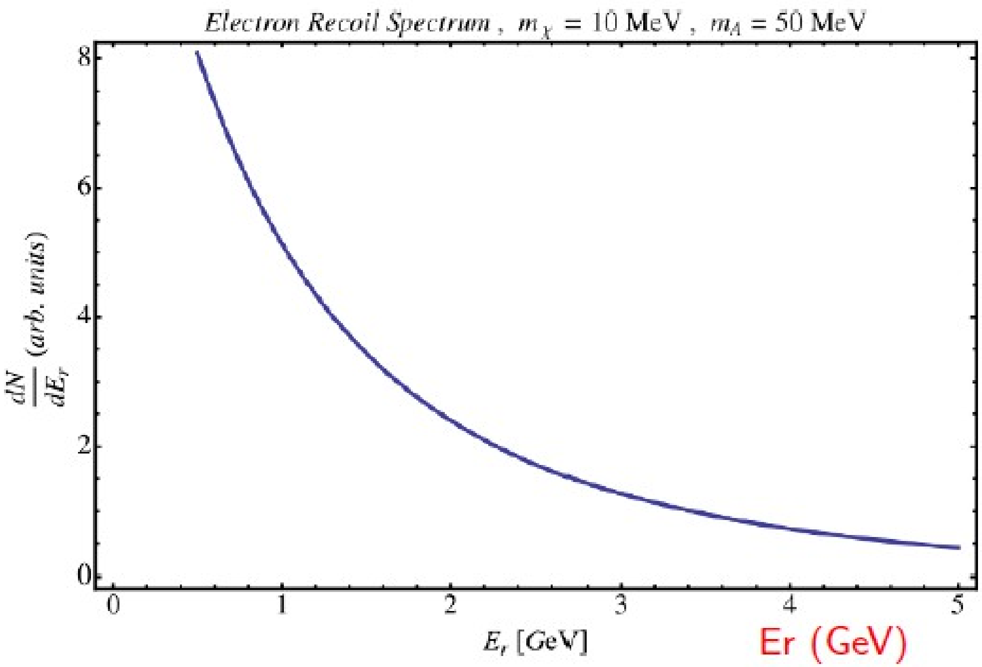
Beam Dump eXperiment at Jefferson Laboratory: *l*DM direct detection in **e$^-$ beam**, **fixed-target** setup



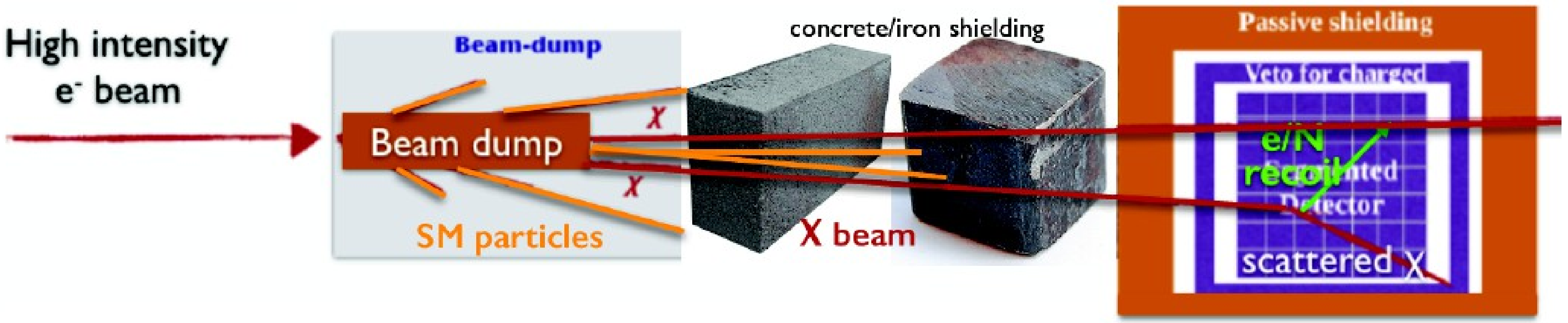
***l*DM production:** high-energy, forward-focused χ beam exiting from the dump/shielding

***l*DM detection:** χ-e$^-$ scattering in the detector

- e$^-$ recoil: EM shower (GeV energy)
- Background rejection is not critical



BDX experiment



The BDX experiment is designed with two goals:

Producing and detecting LDM

- High-intensity e^- beam, $\simeq 10^{22}$ electrons-on-target (EOT)/year
- Medium-high energy, $>$10 GeV
- $\simeq 1\ m^3$ (1-5 tons) detector
- EM-showers detection capability

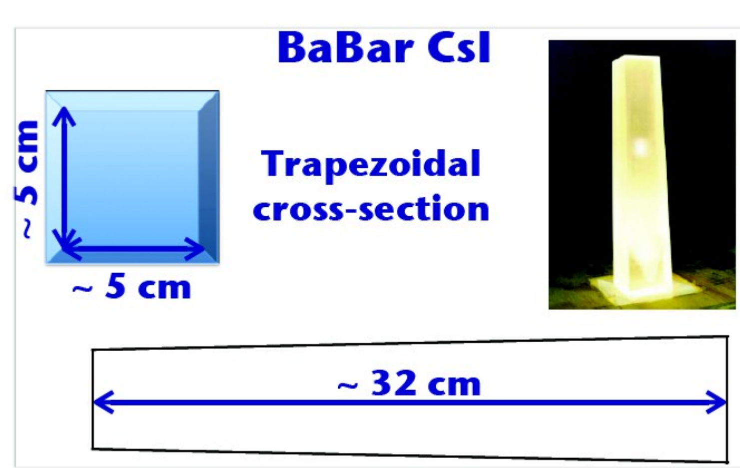
Reducing background

- Passive shielding between beam-dump and detector to filter beam-related backgrounds (except νs)
- Passive shielding and active vetos surrounding the active volume to reduce and identify cosmogenic backgrounds
- Segmented detector for background discrimination based on event topology
- Good time resolution to perform detector-veto coincidence

BDX detector

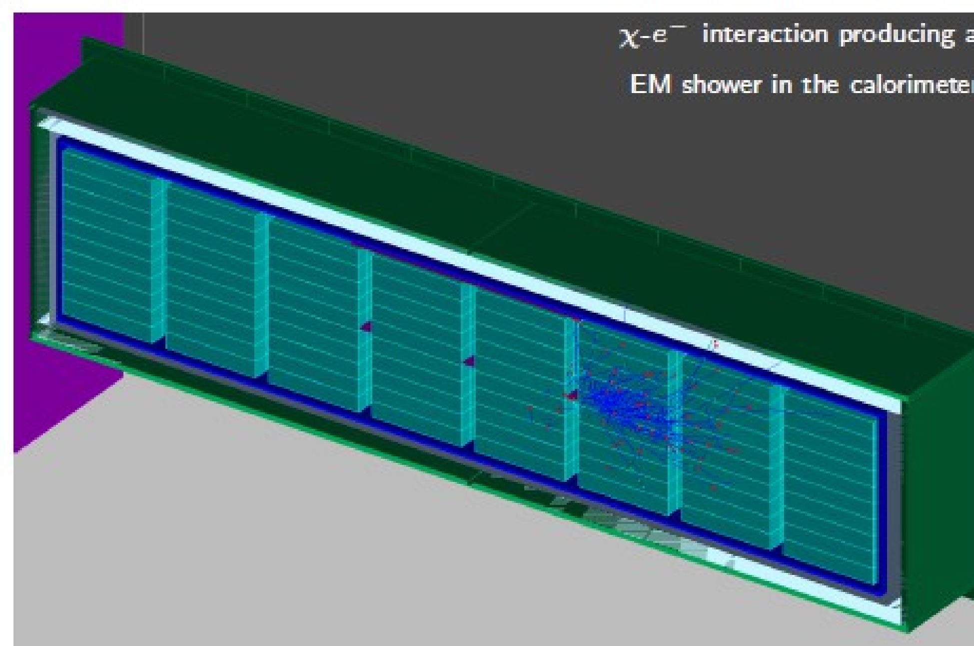
BDX detector: state-of-the-art **EM calorimeter,** CsI(Tl) crystals with SiPM-based readout, surrounded by two layers of **active veto counters**, plastic scintillator + SiPM/PMT readout

Calorimeter design:



- ~ 800 CsI(Tl) crystals, total interaction volume ~ 0.5 m^3
- Modular detector: change front-face dimensions and total length by re-arranging crystals

Crystals arrangement:



- 1 module: 10x10 crystals, 30-cm long.
- 8 modules: 2.4 m interaction length

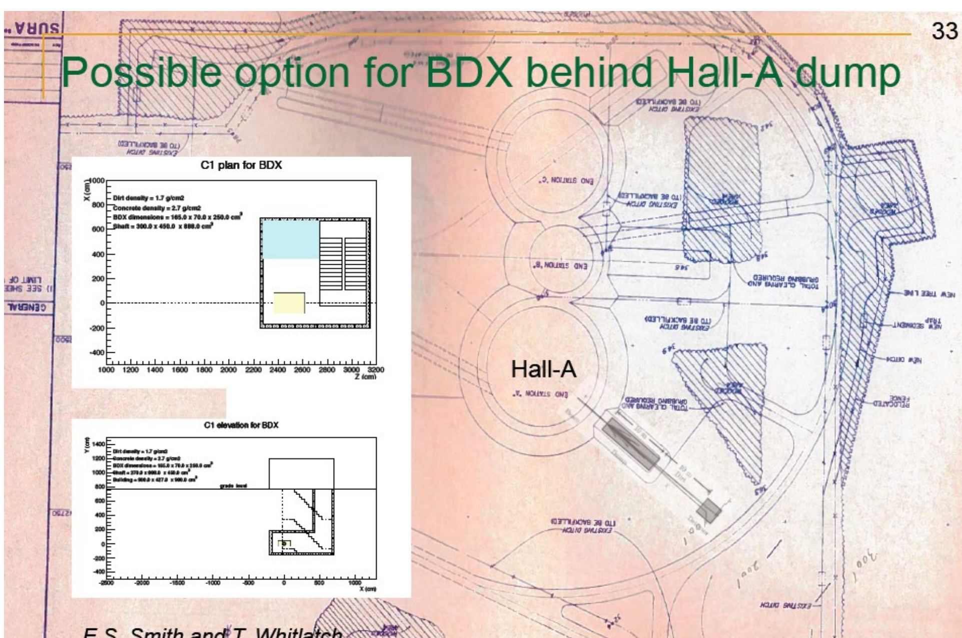
Signal:

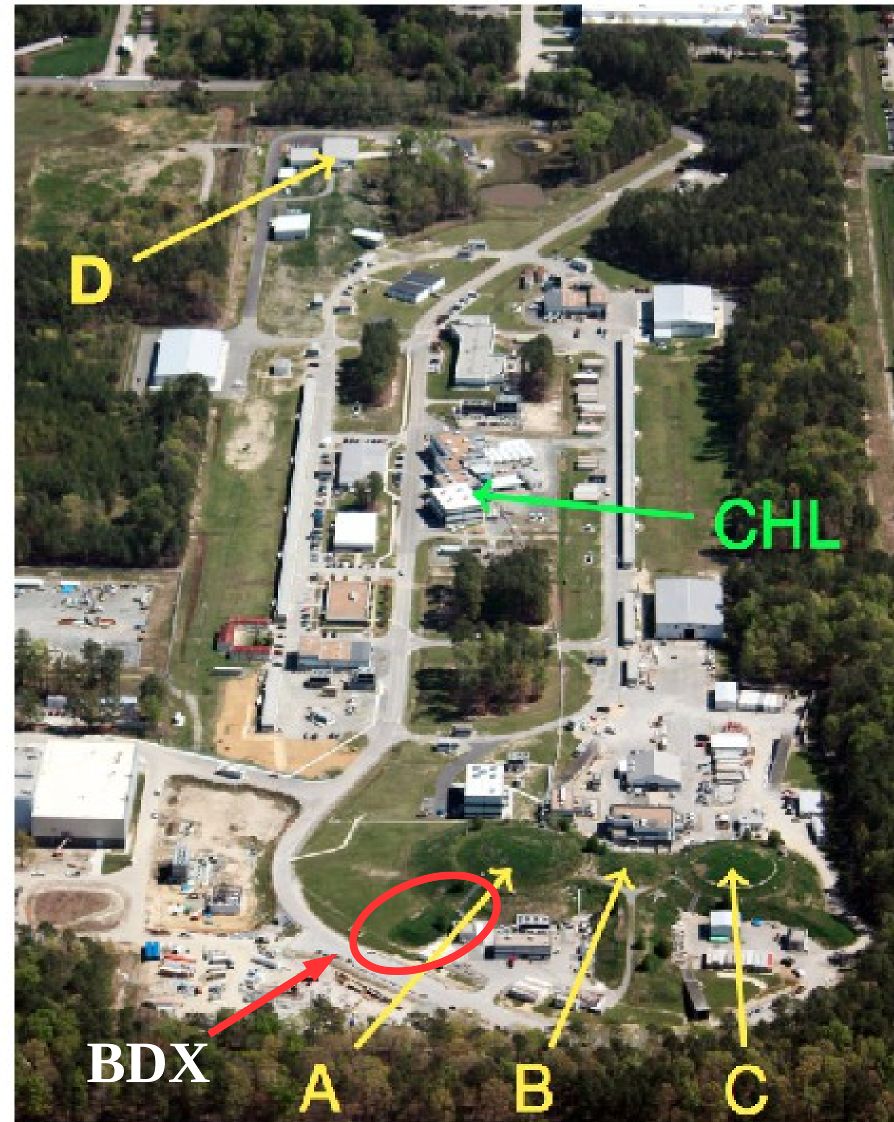
- EM-shower, E_{thr} ~ 300 MeV,
  anti-coincidence with VETO systems
- Efficiency: ~ 20% (due to EM shower leakage in veto)

BDX at JLab

BDX detector will be placed in a **new experimental Hall**, behind the existing **Hall-A beam-dump**

- **Highest beam current** at Jlab (up to 100 uA), with already-approved experiments with more than 10^{22} 11 GeV EOT
- E_{beam} up to 11 GeV
- New underground facility cost ~ 1.5 M$

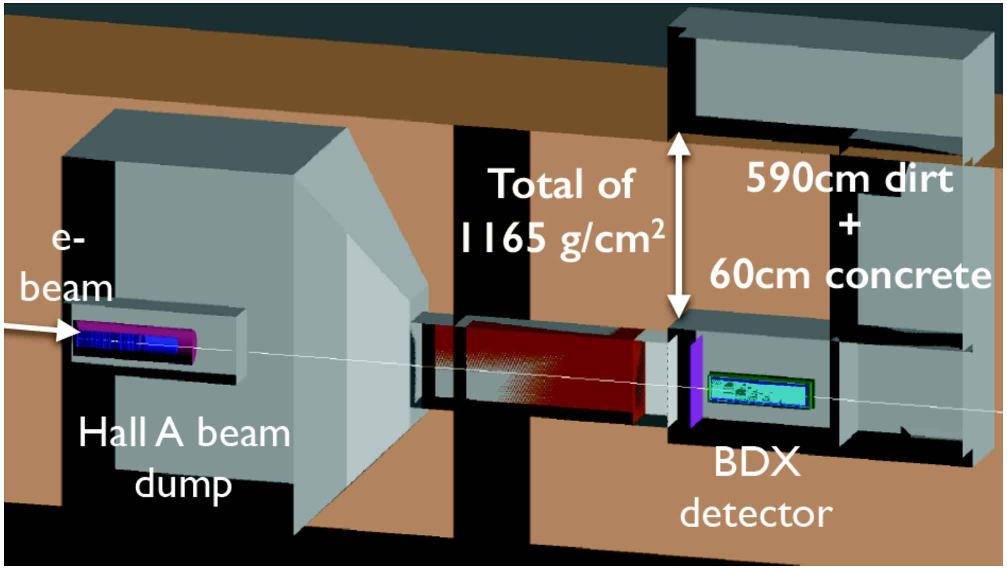


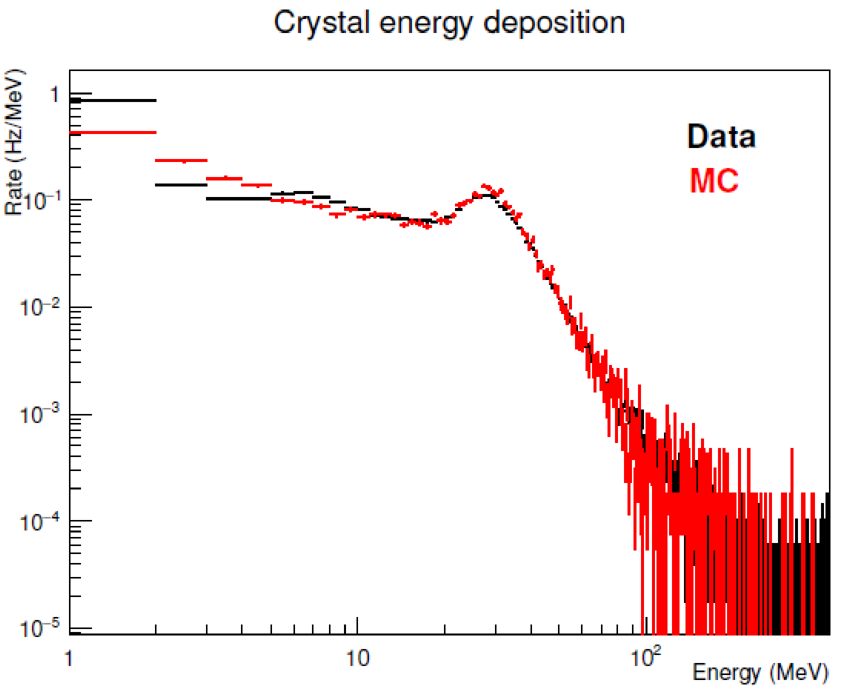


BDX backgrounds

Cosmogenic background (μ / n):

- Background **measured** with a **small-scale prototype** at INFN-LNS, with similar overburden as expected at Jlab
- Detector simulation in excellent agreement with measurement
- After requiring anti-coincidence with VETO system, **no high-energy events** are measured (~ month time scale)
  - Low-energy results extrapolated to higher-energy for JLab setup: **< 0.1 counts expected**





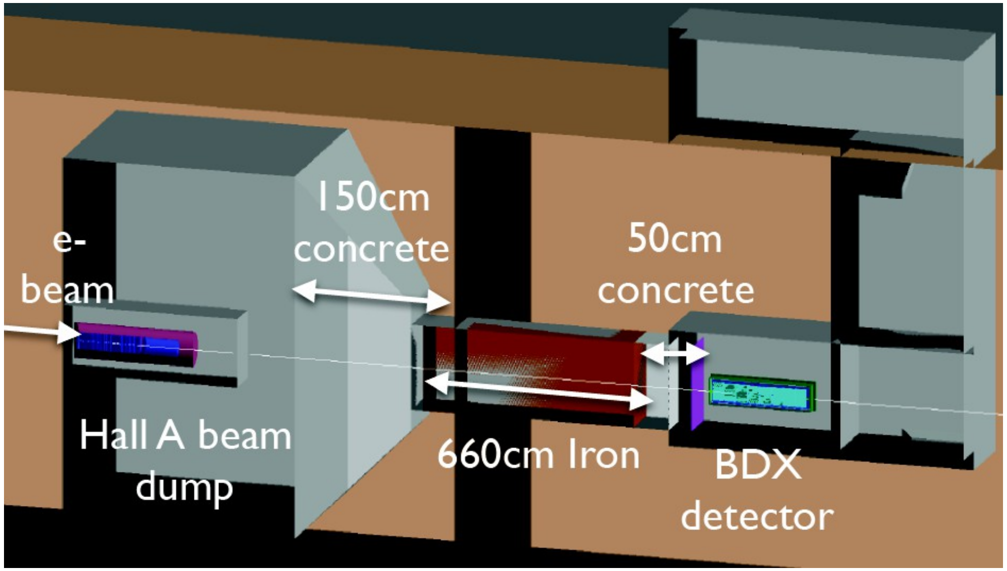
Cosmogenic background is **negligible** with high-energy threshold

It will be **measured on-site** when beam is off

BDX backgrounds

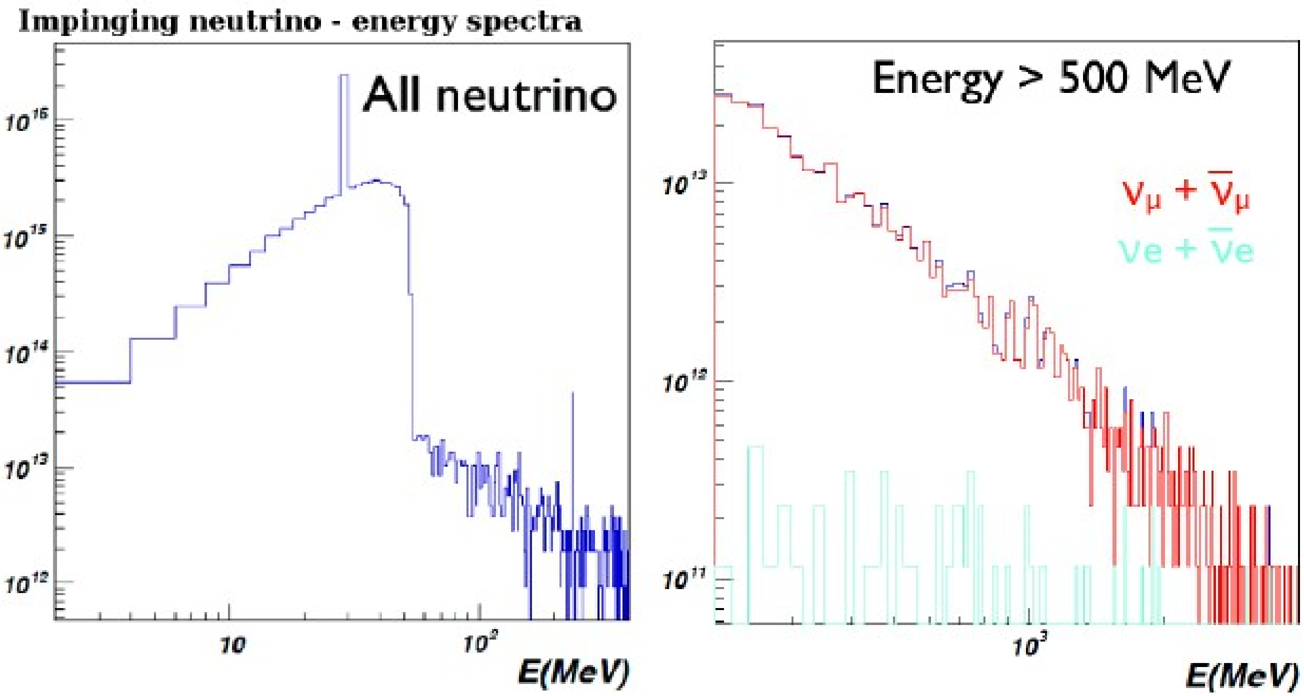
Beam-related background (μ / n / ν):

- Background **estimated** with a **MonteCarlo simulations** (Geant4/FLUKA)



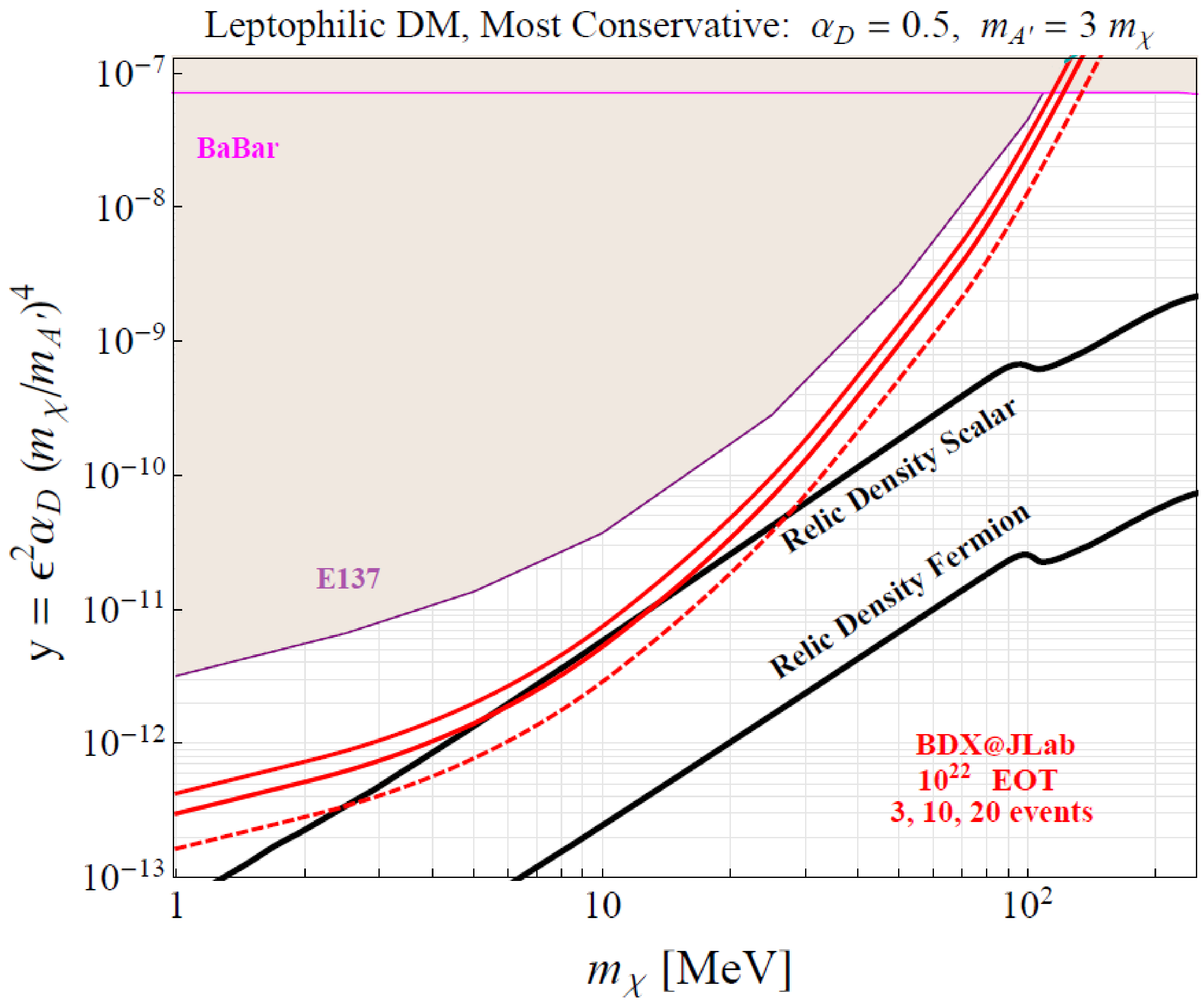
- Only background contribution: **neutrinos,** other particles absorbed in shielding
  - Energy spectrum concentrated at low energy (μ/π decay at rest)
  - Sizable high-energy component

- Background count estimate:
  N_ν < 10 counts per 10^{22} EOT



BDX reach

BDX is an **optimized beam-dump experimen**t that can be conclusive for some *l*DM scenarios. Obtained results will guide future second-generation experiments



BDX status

Experiment status:

- R&D activity ongoing from 2014 – LOI submitted to JLab PAC42, with strong positive feedback

- Full proposal presented to JLab PAC44 (2016), **approved**
  - Conditional to MC benchmarking and detector optimization
  - Facility design / detector optimization currently in progress

Collaboration:

- BDX proposal signed by more than 100 researchers
- INFN-lead project (4 INFN spokespersons, 3 from INFN-Genova)
- Strong connection with *l*DM community (SLAC / CERN / MAINZ / LNF)

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

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Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510

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[*]Contact Person, email: Marco.Battaglieri@ge.infn.it
[†]Spokesperson

Within 2 years (detector assembly + civil work), BDX can be ready to run at JLab, to explore unknown territories in the *l*DM space, and to provide directions for future activities in this field

BDX activity at INFN-Genova

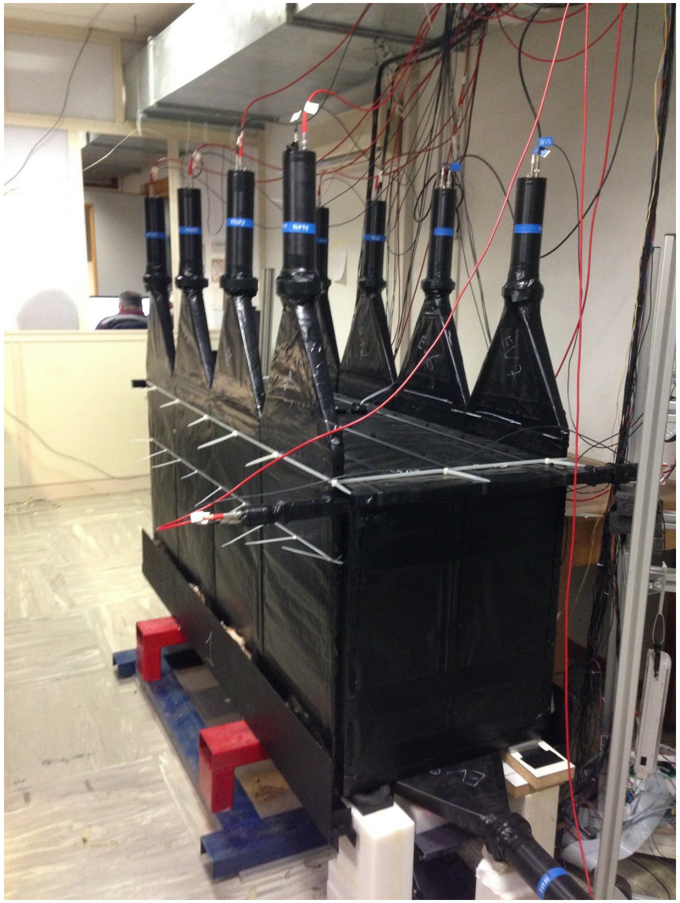
The experiment is currently in design / optimization phase: new ideas / new people are highly welcome!!!

- **Hardware activity**
  - Detector design / characterization: Calorimeter / InnerVeto / Prototype
  - Electronics: analogue readout / DAQ system (custom, FADC-based)

- **Data analysis**
  - Prototype data for cosmogenic backgrounds
  - On-site (JLab) background measurements

- **Simulations**
  - Beam-related backgrounds
  - χ signal estimation
  - Reach optimization

- **Phenomenology/theory**
  - New *l*DM models
  - New targets for BDX



Conclusions

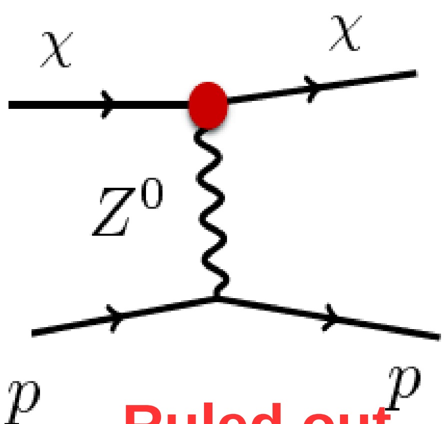
- Traditional DM search was mainly driven by **WIMP hypothesis**, leading to a broad Direct Detection experimental program. So far, no positive results have been found: time to look (also) in another direction?
  - **Direct Detection will always be crucial and complementar:** any DM-candidate signal **must be confirmed** to have a cosmological origin

- Light Dark Matter hypothesis (M < 1 GeV) provides a new territory that can be experimentally investigated
  - **Theoretically well-founded hypothesis**, compatible with cosmological prior (thermal origin), requires **new interaction mechanism** with SM
  - Direct Detection experiments have (so far) limited reach in this region
  - Accelerator searches (relativistic *l*DM) provides an unique opportunity

- A **broad experimental program** is currently searching for *l*DM – looking both for χ particles and mediator
  - **Jefferson Laboratory** is leading this effort with 4 approved experiments (2 already running)
  - INFN-Genova (Gruppo 3) strongly involved in two experiments: **HPS** (A' search) and **BDX** (χ search)

Backup slides

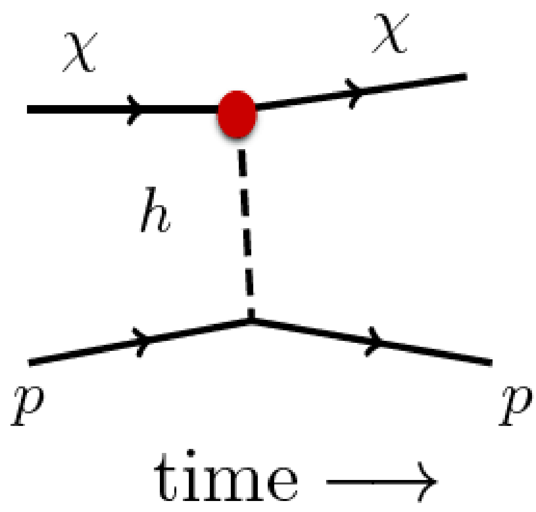
WIMP interactions



Ruled out
by current experiments

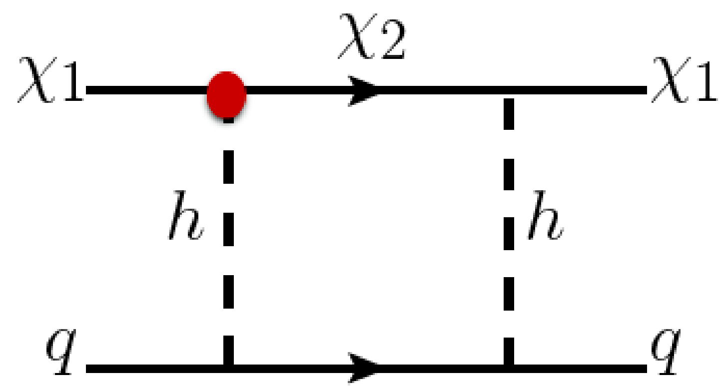
Z Exchange

$$\sigma_p \sim 10^{-39}\,\mathrm{cm}^2$$



Higgs Exchange

$$\sigma_p \sim 10^{-45}\mathrm{cm}^2$$



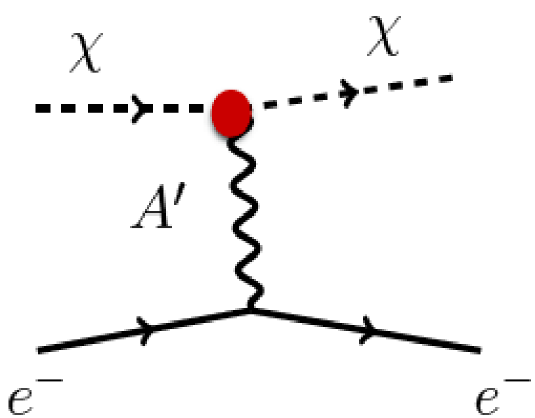
Inelastic coupling EW loop

$$\sigma_p \sim 10^{-47}\mathrm{cm}^2$$

Very different mechanisms at low energy (Direct Detection case), despite similar at high energy.
Each vertex can realize thermal annihilation freeze-out at T~M

lDM interactions

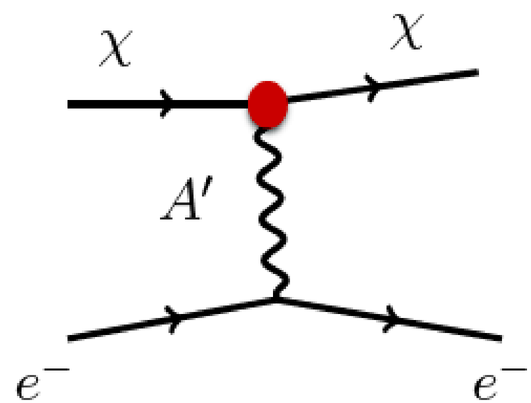
Scalar DM



$$A'_\mu \chi^* \partial_\mu \chi$$

$$\sigma_e \sim 10^{-39} \mathrm{cm}^2$$

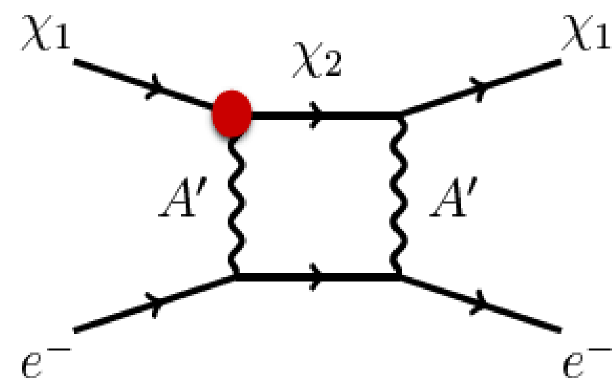
Majorana DM



$$A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

$$\sigma_e \sim 10^{-39}\, v^2\, \mathrm{cm}^2$$
$$\sim 10^{-45}\, \mathrm{cm}^2$$

Pseudo-Dirac DM inelastic



$$A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$

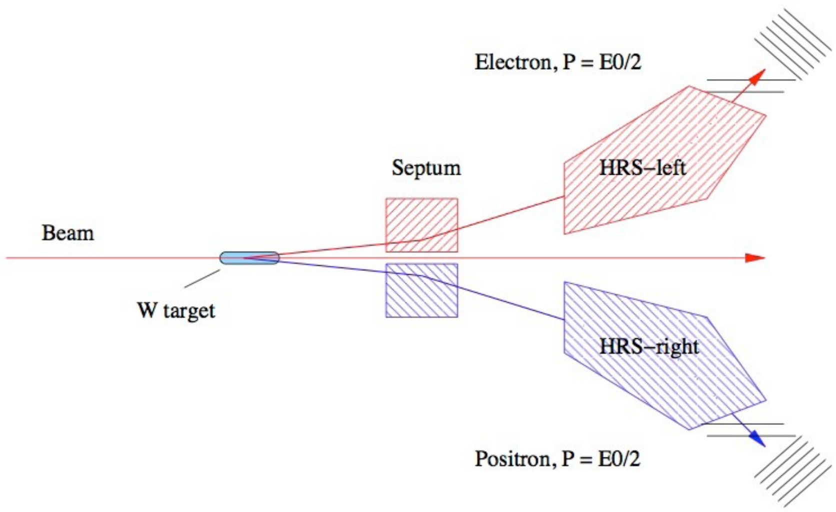
$$\sigma_e \sim 10^{-48}\, \mathrm{cm}^2$$

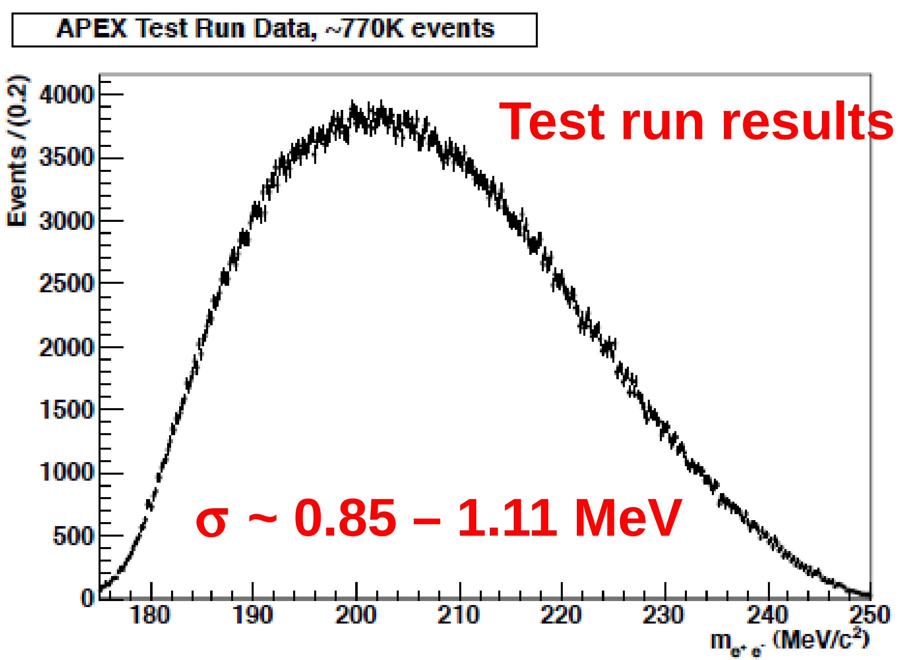
Very different mechanisms at low energy (Direct Detection case), despite similar at high energy.
Each vertex can realize thermal annihilation freeze-out at T~M

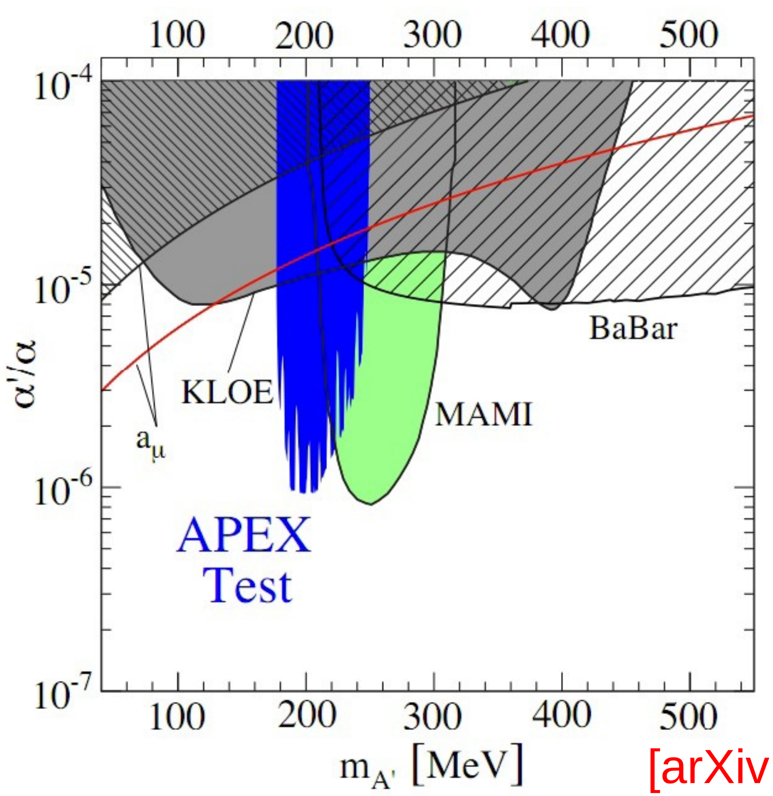
APEX

Direct production of A' at JLab (Hall-A)

- Fixed target experiment with W target.
- A' search in invariant $e^+ e^-$ mass.
- Measure $e^+ e^-$ pairs with Hall-A High-resolution spectrometer.
- Dipole septum magnets allow for detection of produced pairs at small angles (~5^0)
- **Successful2012 test-run: ~ 770 k events**
- **Plans for 2015 run (200x statistics)**







[arXiv:1108.2750]

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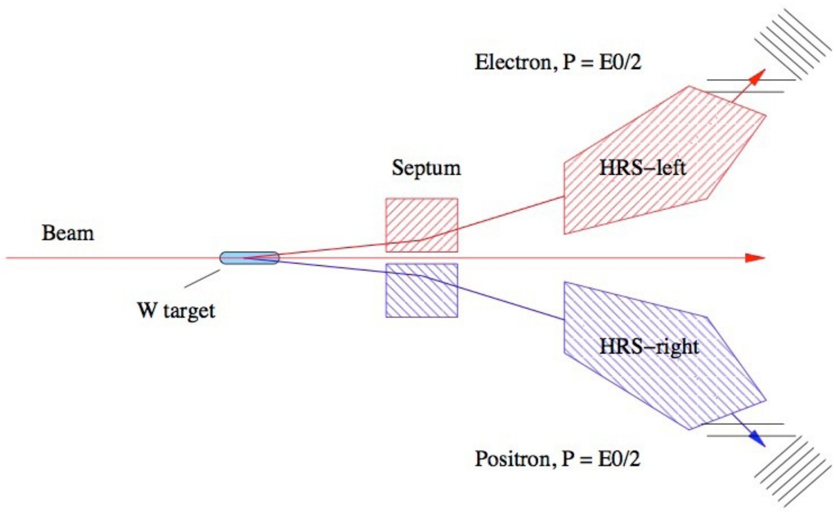
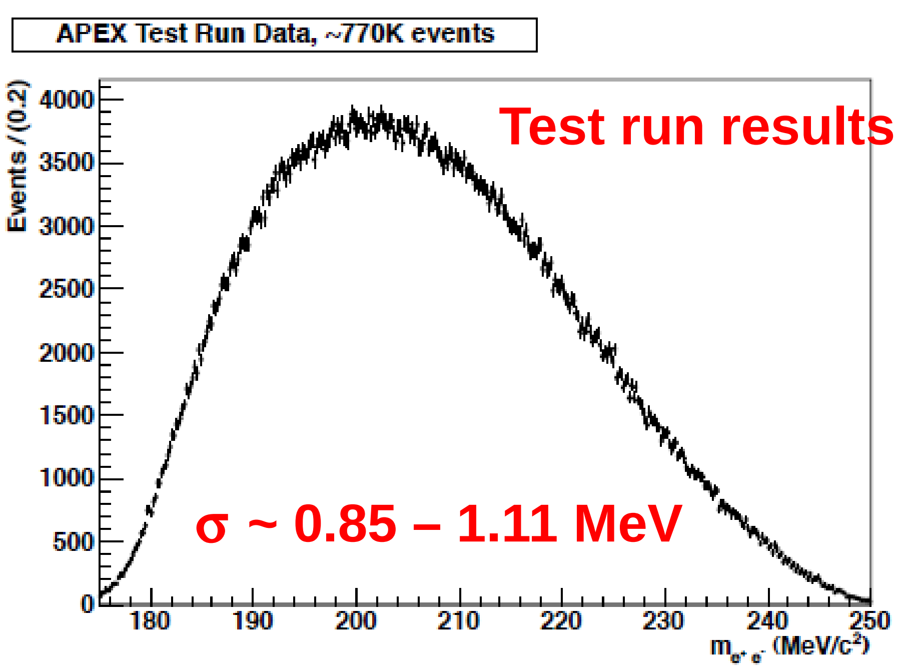
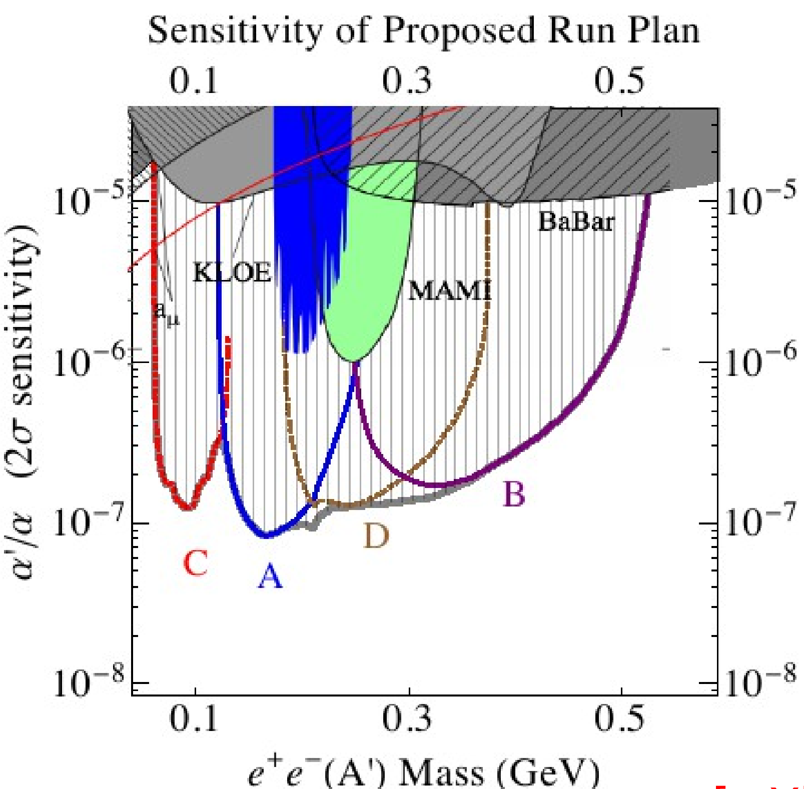




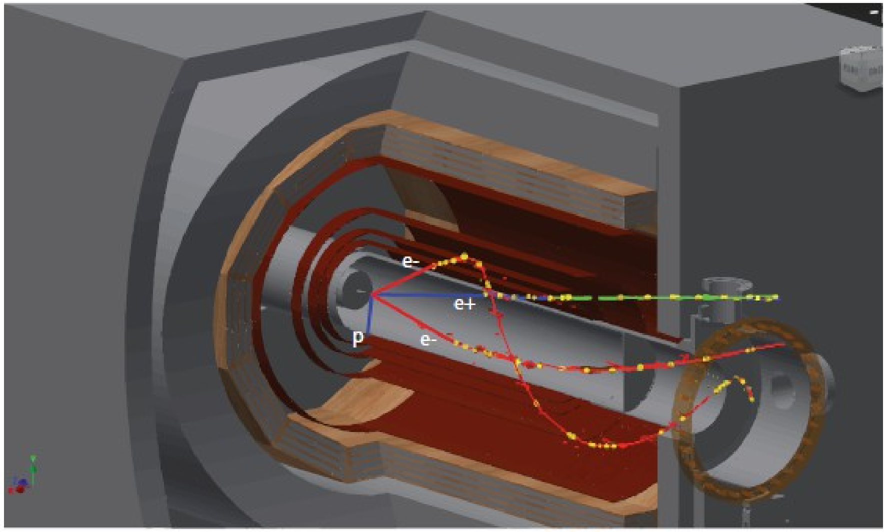


[arXiv:1108.2750]

DarkLight

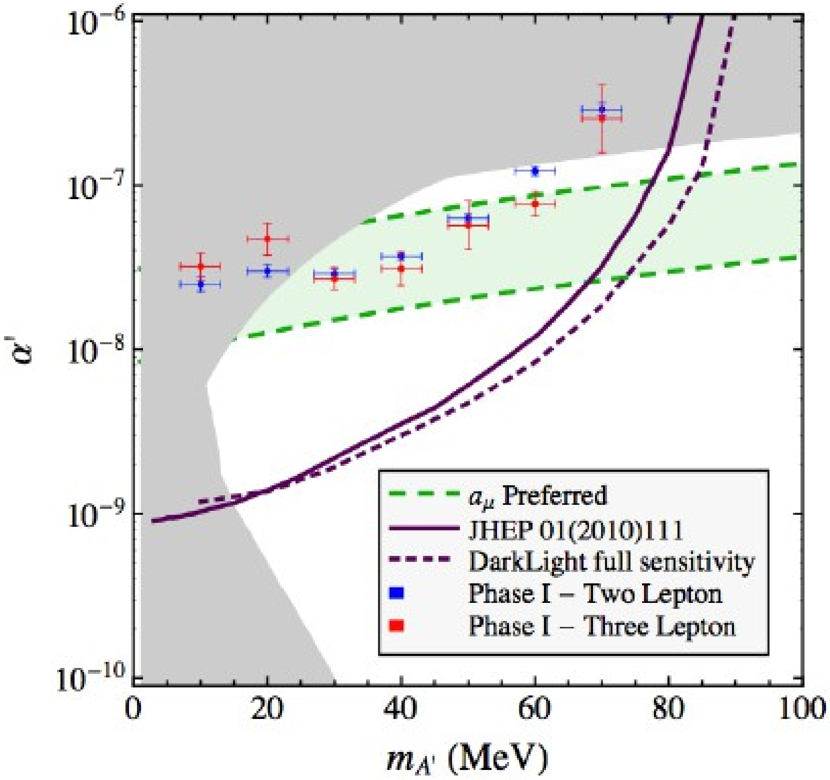
Direct production of A' at JLab Free Electron Laser

- 100 MeV, 10 mA beam
- Internal H_2 target in 0.5 T solenoid
- Successful 2012 technical test run demonstrated FEL has the required performances and stability



Experiment status:

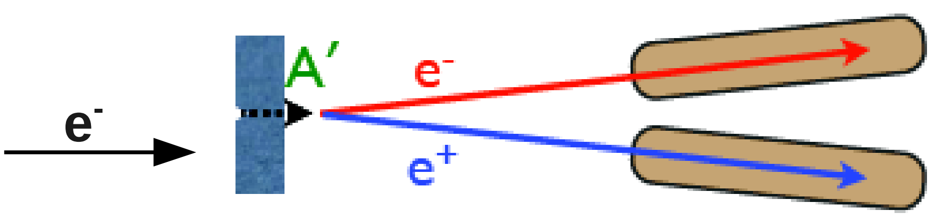
- Full scientific approval from Jefferson Lab received in June 2013
- January 2014: NFS MRI proposal submitted for Phase 1 (2015)
- Work in progress to finalize full design by summer 2014

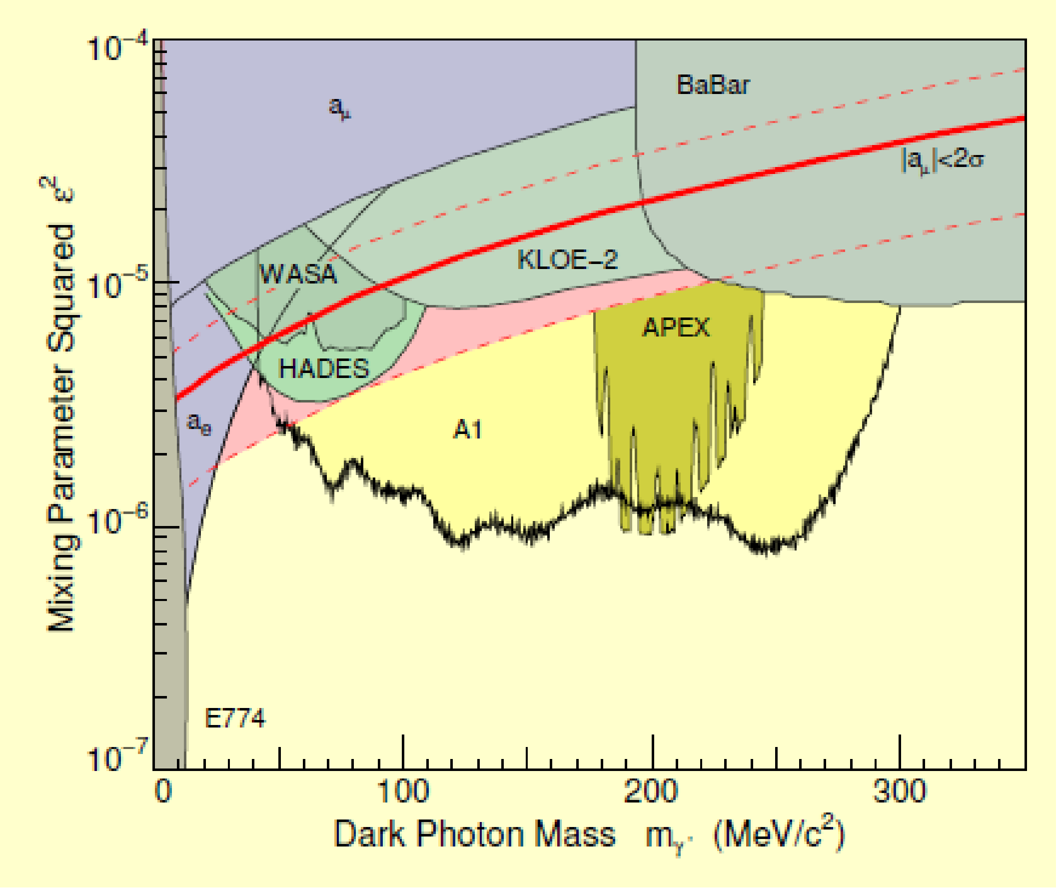


A1 (Mainz)

Search for A' in fixed-target experiment

- APEX-style experiment, double-arm A1 spectrometer
- 2012-2013 run: 0.05 mm ^{151}Ta target, E_0=855 MeV, 22 kinematic settings
- Idea for detached-vertex search trough variable beam-stoppers abandoned (too much background)
- Future search: low A' mass





[arXiv:1404.5502]

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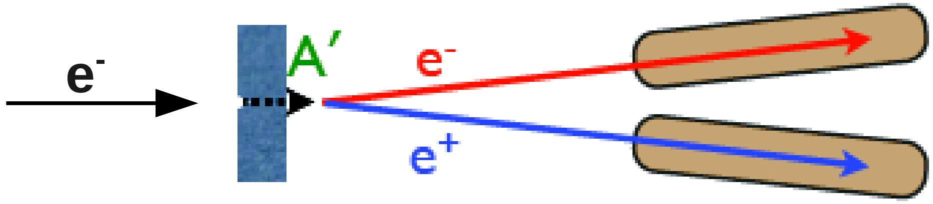
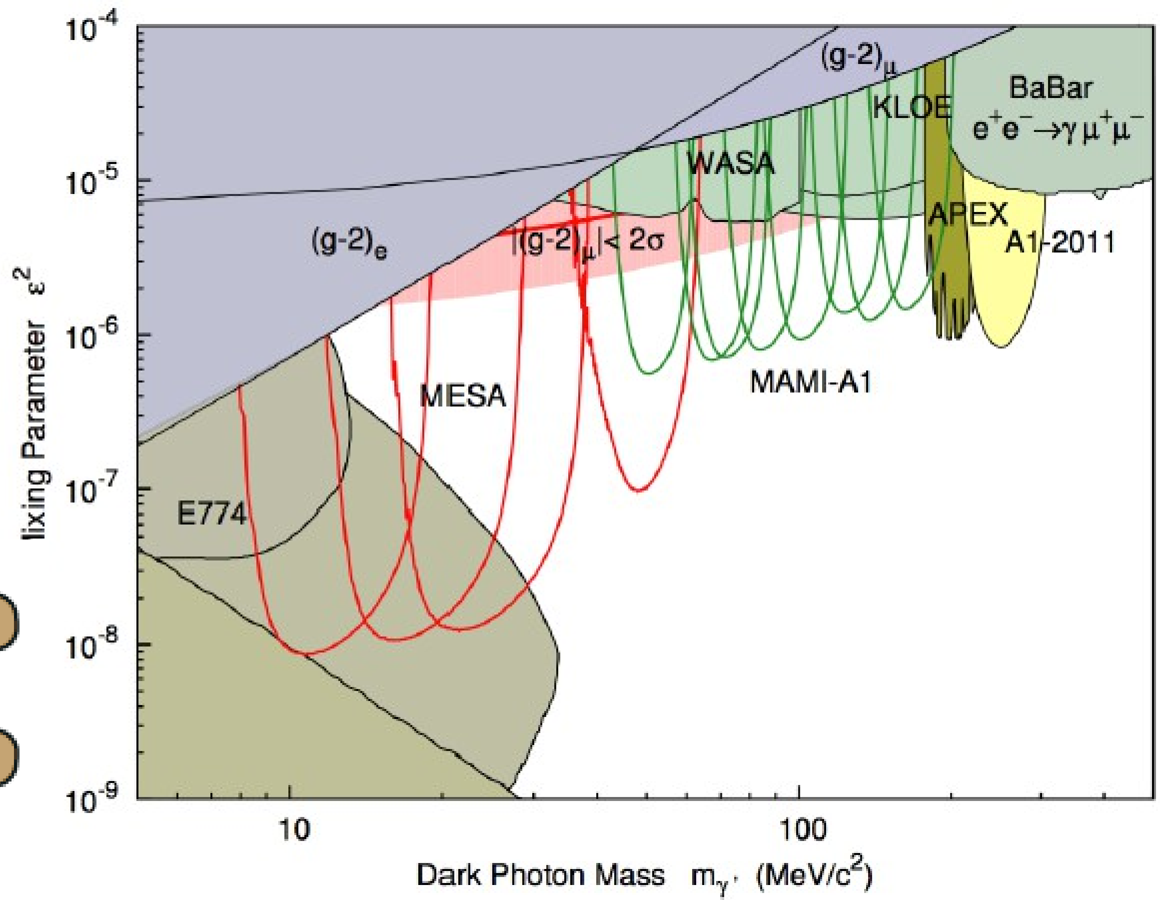


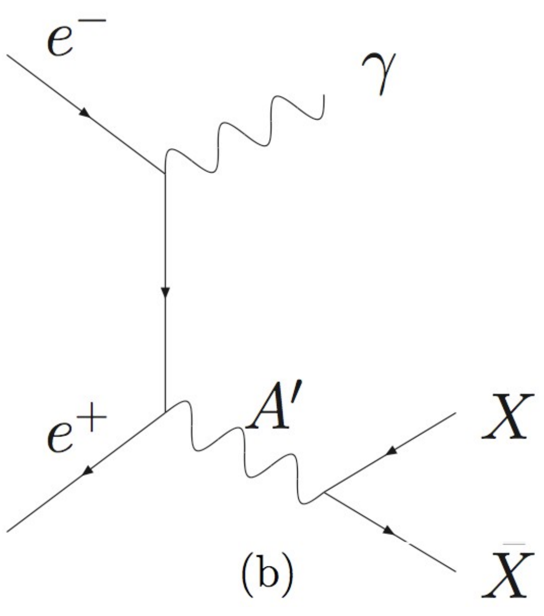


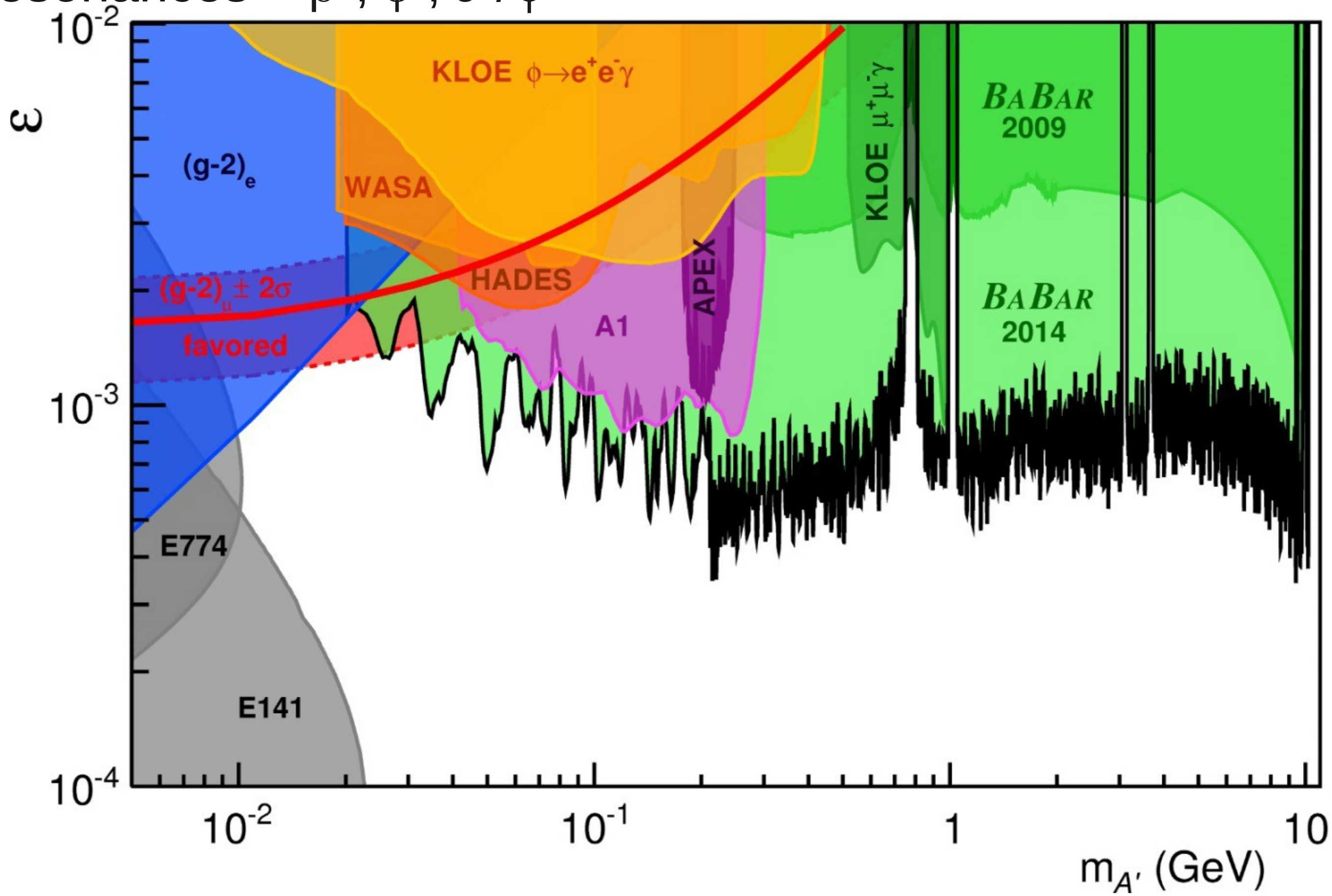
[arXiv:1404.5502]

BaBar

Search for A' in $e^+ e^-$ annihilation: $e^+ e^- \rightarrow \gamma A' \rightarrow \gamma e^+ e^- / \gamma \mu^+ \mu^-$

- Select events with 1 γ and two opposite charged leptons.
- Scan the di-lepton mass and fit a background plus signal function at each step.
  - Background includes resonances – ρ^0, ϕ , J/ψ





[arXiv:1406.2980]

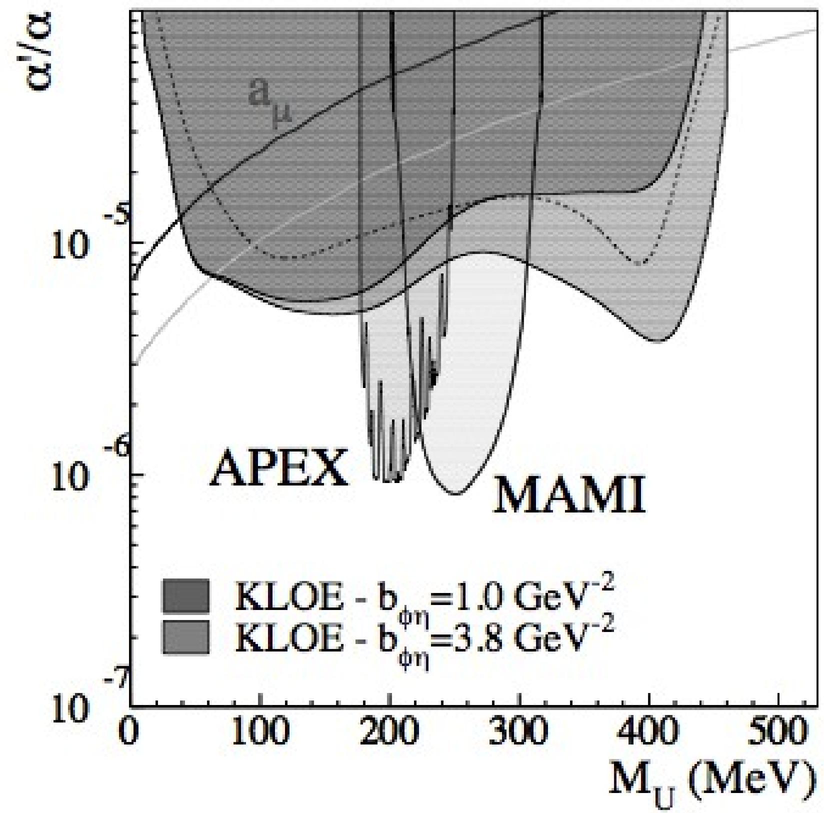
KLOE

Search for A' in ϕ decay: $\phi \rightarrow A' \eta \rightarrow e^+ e^- \eta$

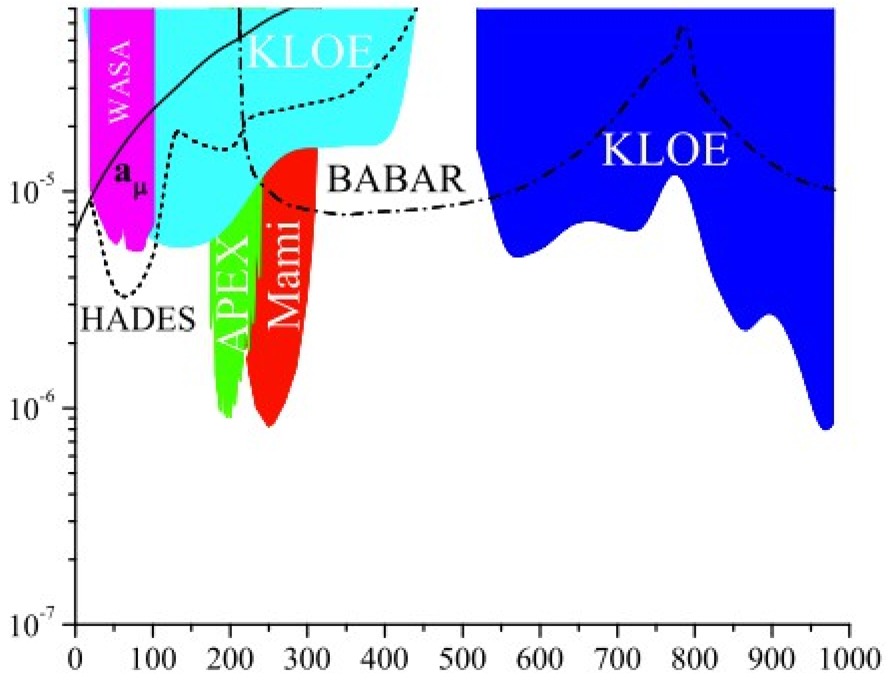
- Search for excess in electron-positron invariant mass distribution of irreducible $\Phi \rightarrow \eta\, e^+ e^-$ background
- $\sigma_M < 2$ MeV

Search for A' in e+ e- annihiliation (Babar-like)

- Search for peak in $\mu^+ \mu^-$ invariant mass distribution



Note: limit depends on the meson form factor, b= $dF/dq^2(q^2=0)$

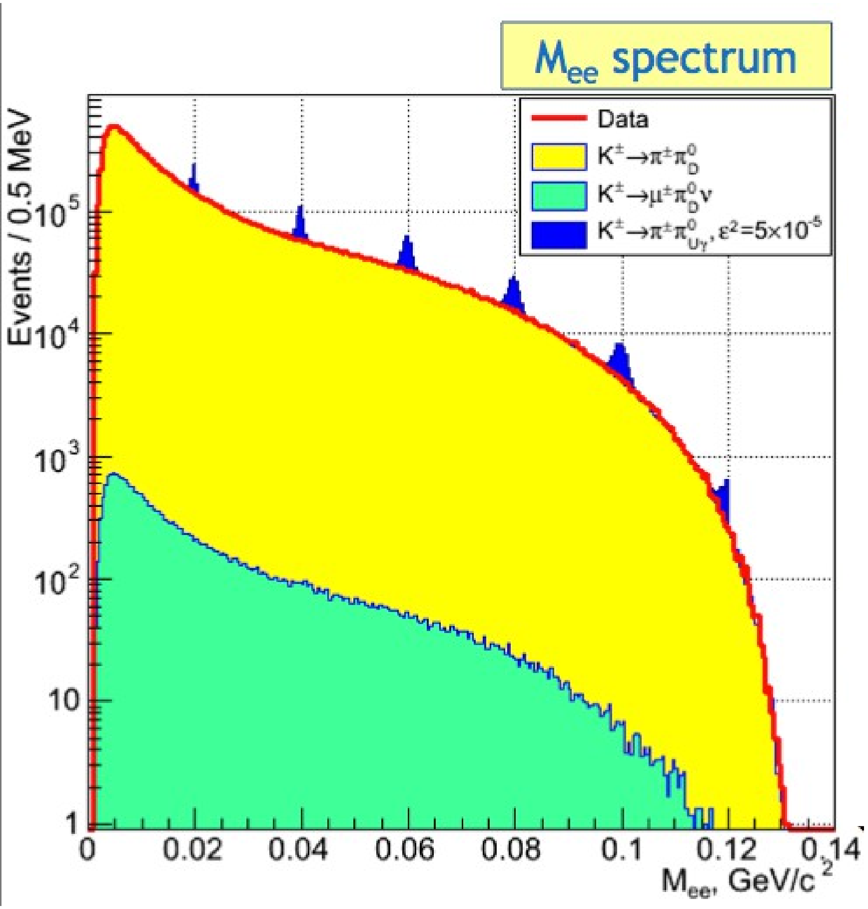


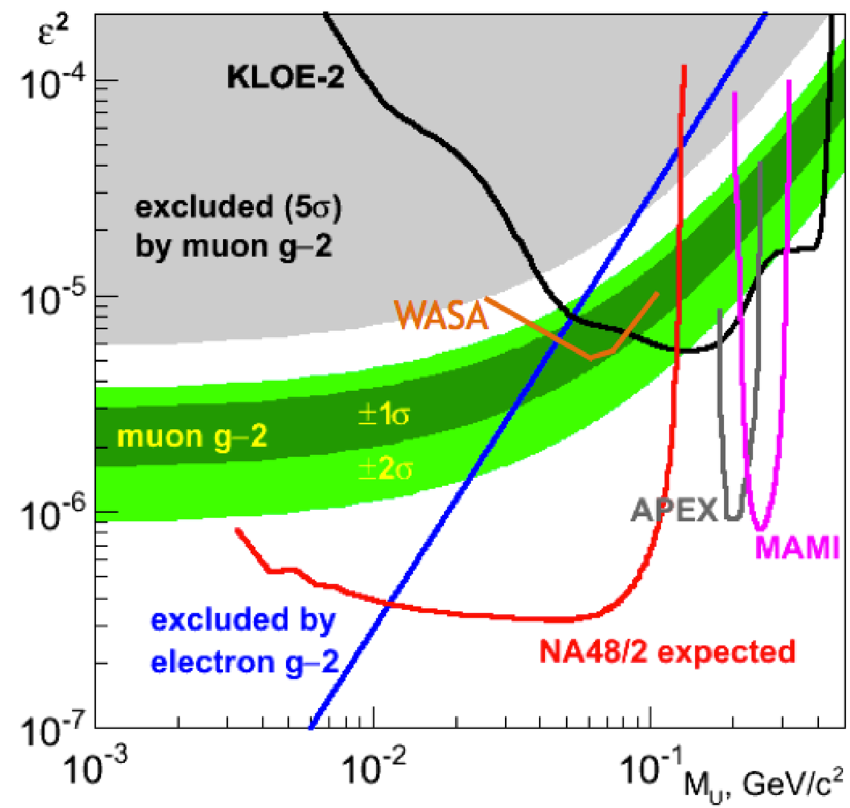
[arXiv:1210.3927]
[arXiv:1404.7772]

NA48/2

Search for A' in π^0 Dalitz decay: $\pi^0 \to A' \gamma \to e^+ e^- \gamma$

- Data from 2003-2004 run, large flux of tagged π^0 from $K^\pm \to \pi^\pm \pi^0$
- Search for A' in invariant $e^+ e^-$ mass (~ 1.2% mass resolution): analysis in progress
- Searches from $K+ \to \pi^+ A' \to \pi^+ l^+ l^-$ are also in progress [arXiv: 0903.3130]

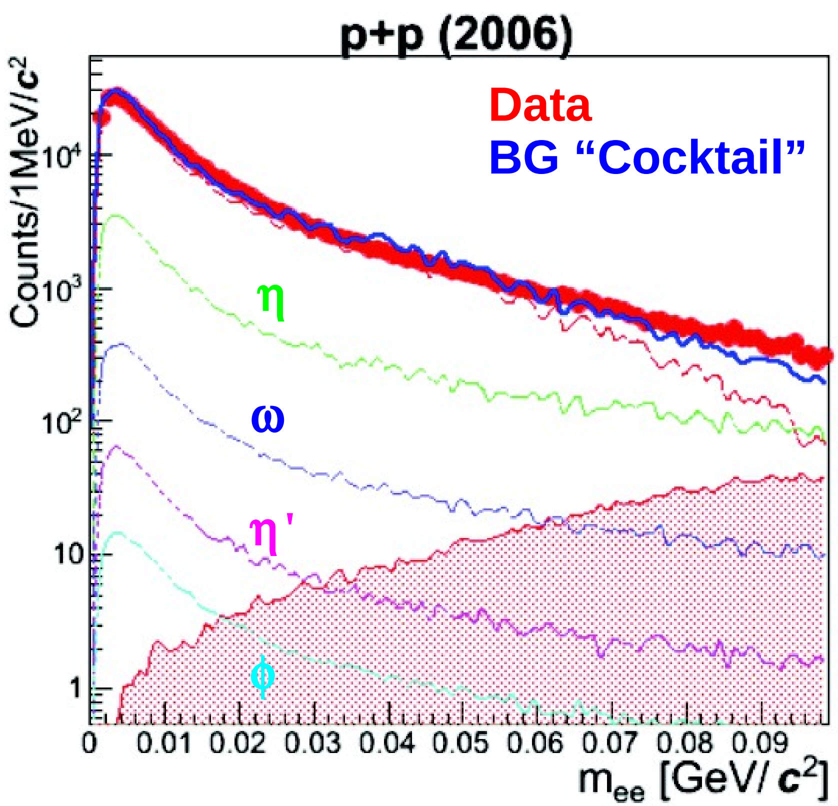


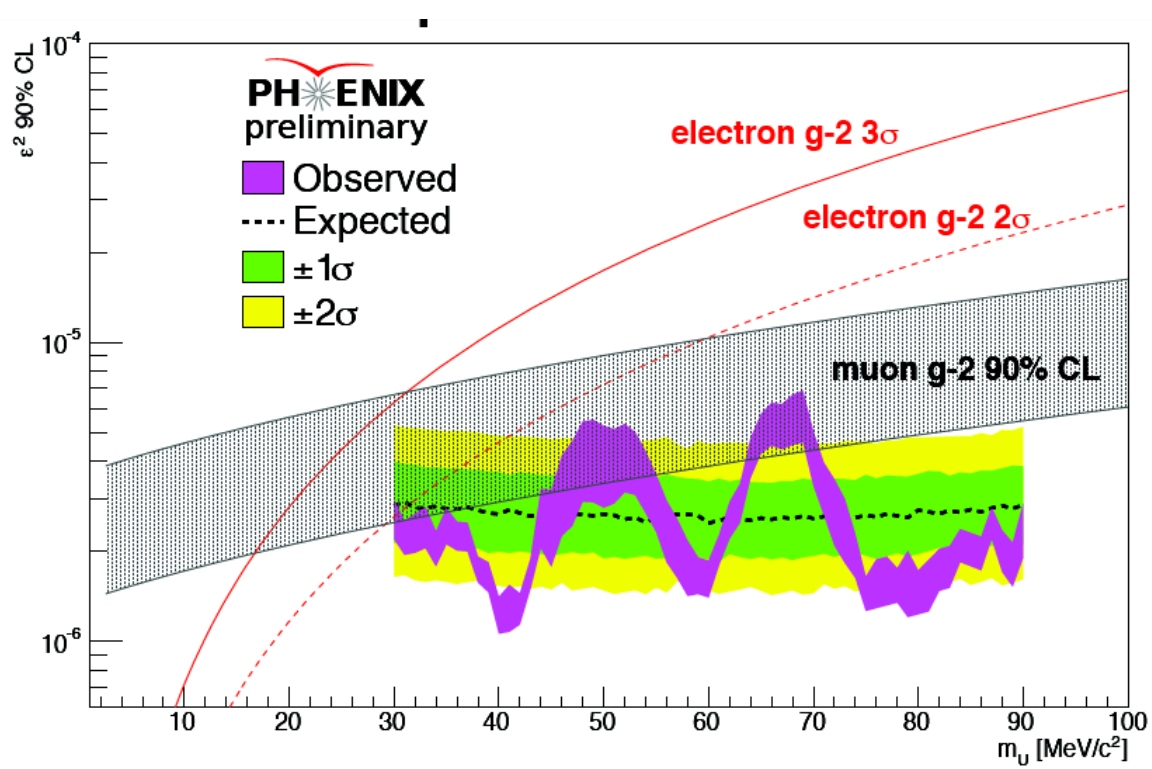


[E. Goudzovski: MesonNet workshop, 2013]

PHENIX detector @ BNL RHIC :Search for A' in π^0 / η Dalitz decay

- 1.4M $e^+ e^-$ pairs in p+p(2006) and d+Au (2008) datasets
- Mass resolution ~ 3 MeV
- **Background well under control:** "cocktail" of hadron decays
- Future plans:
  - Increase statistics adding 2009 p+p dataset
  - Use 2014 Au + Au dataset for vertex search

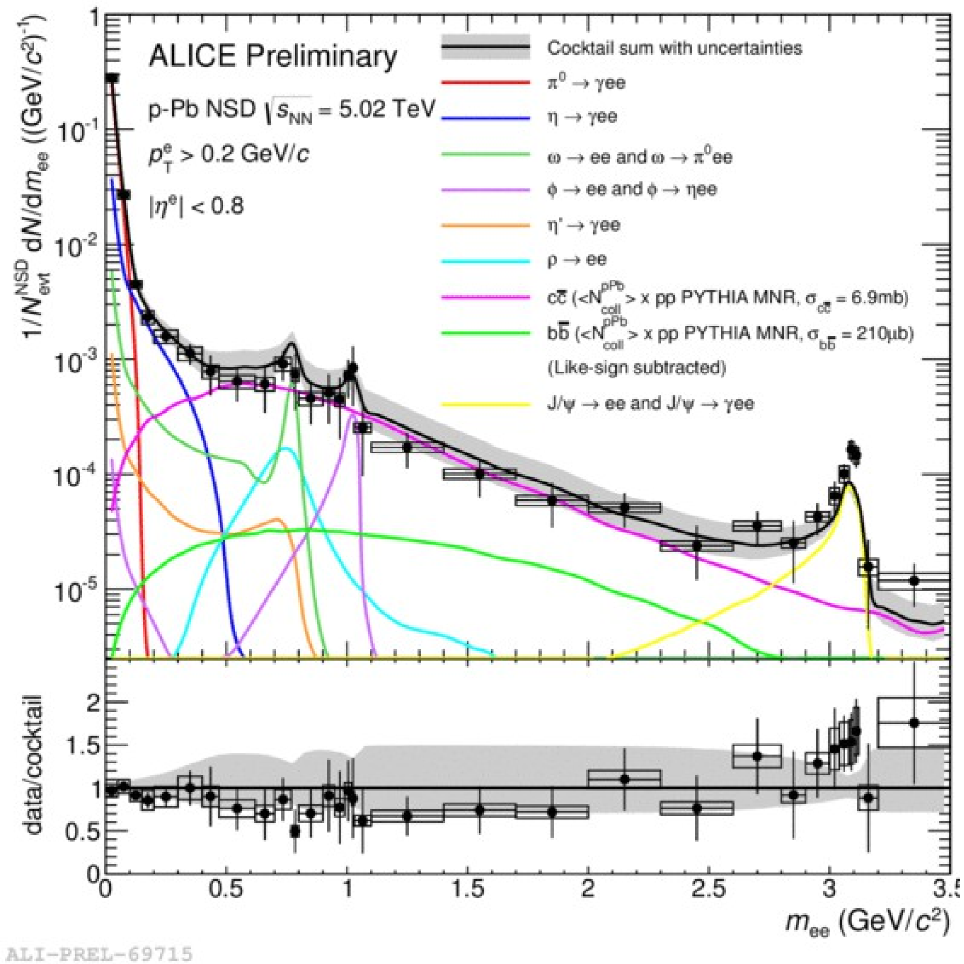


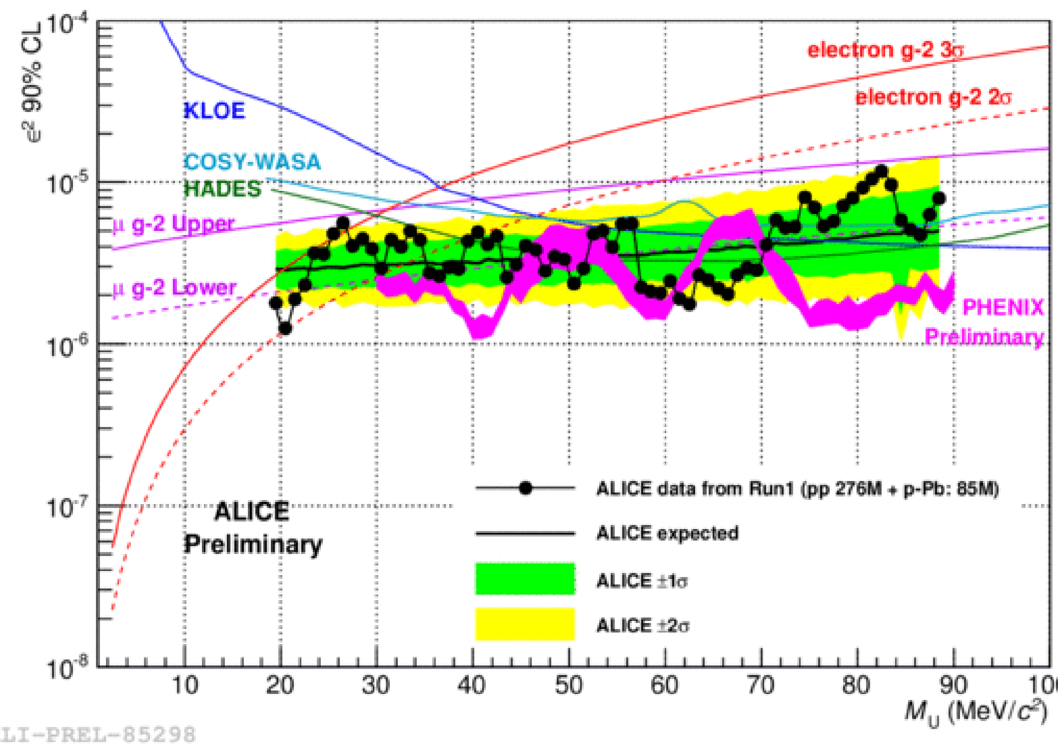


[Y. Yamaguchi: BNL DI workshop, 2014]

ALICE detector @ CERN LHC: search for A' in π^0 / η Dalitz decay

- $e^+ e^-$ pairs from p+p (276M) and p+Pb (85M) datasets
- Mass resolution ~ 1%
- **Background well under control:** "cocktail" of hadron decays





[T. Gunji: BNL DI workshop, 2014]

ALICE detector @ CERN LHC: search for A' in π^0 / η Dalitz decay

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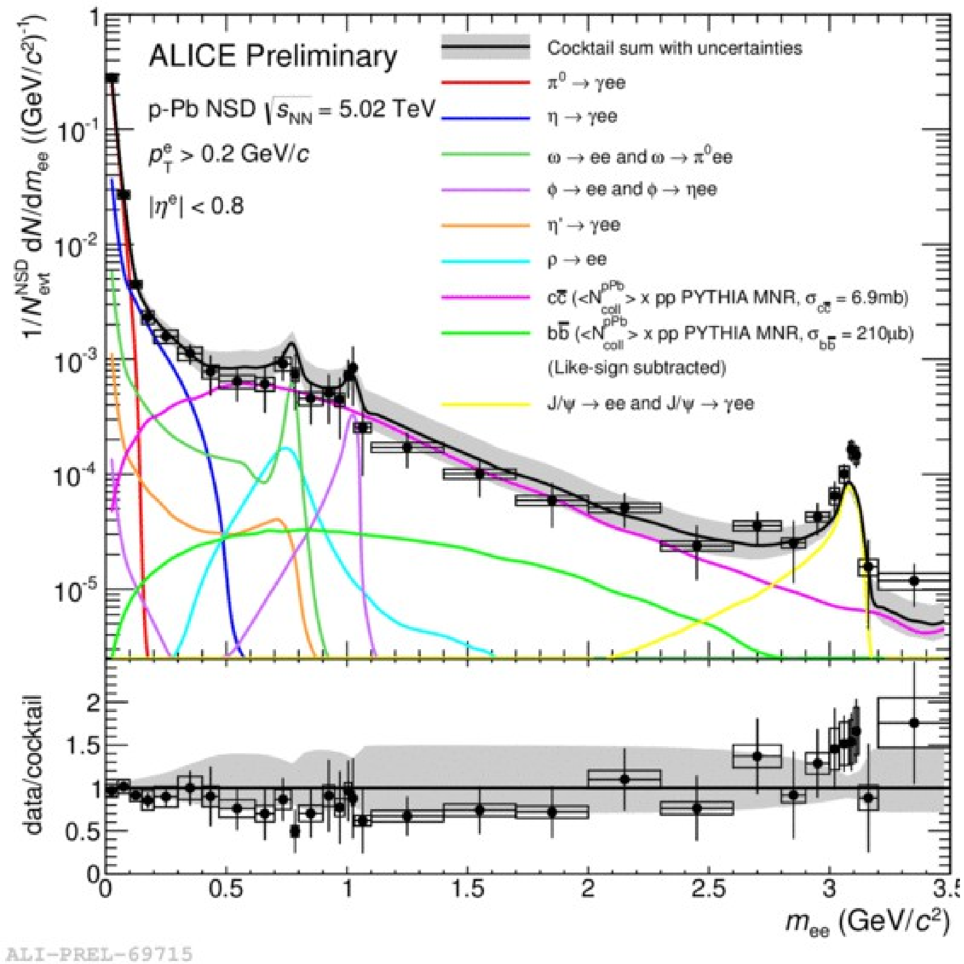
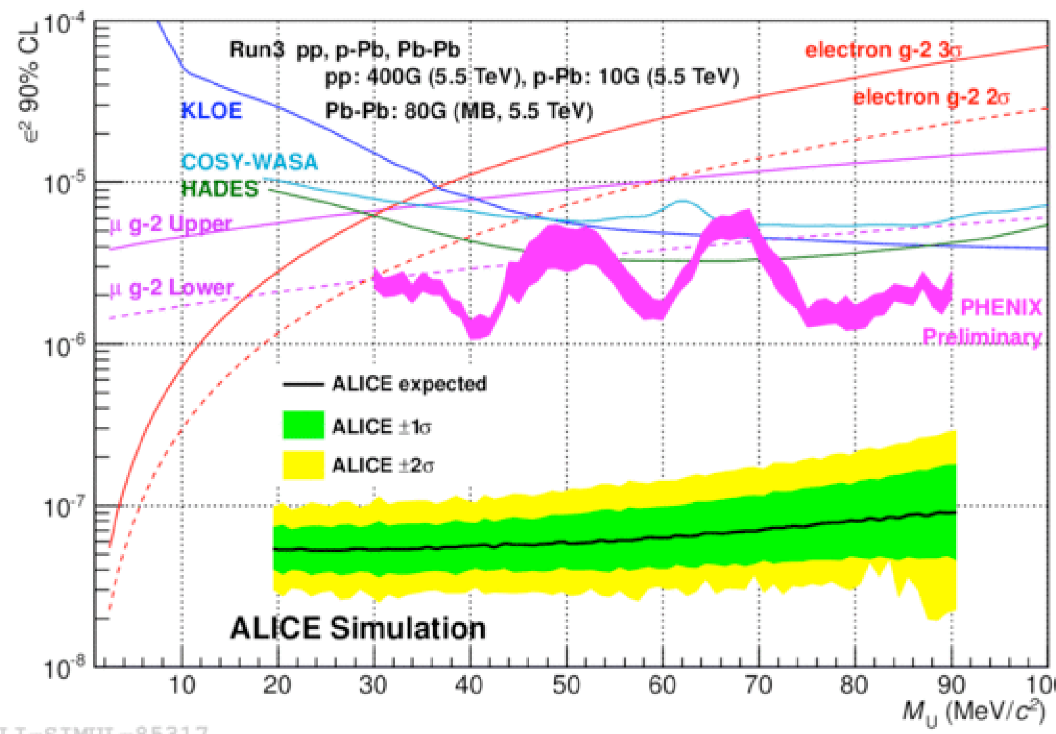


Very promising sensitivity from ALICE upgrade

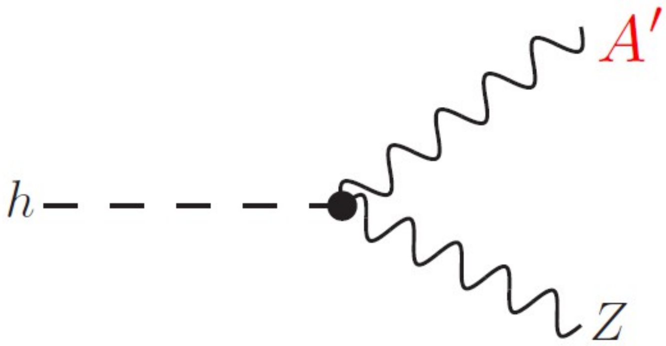


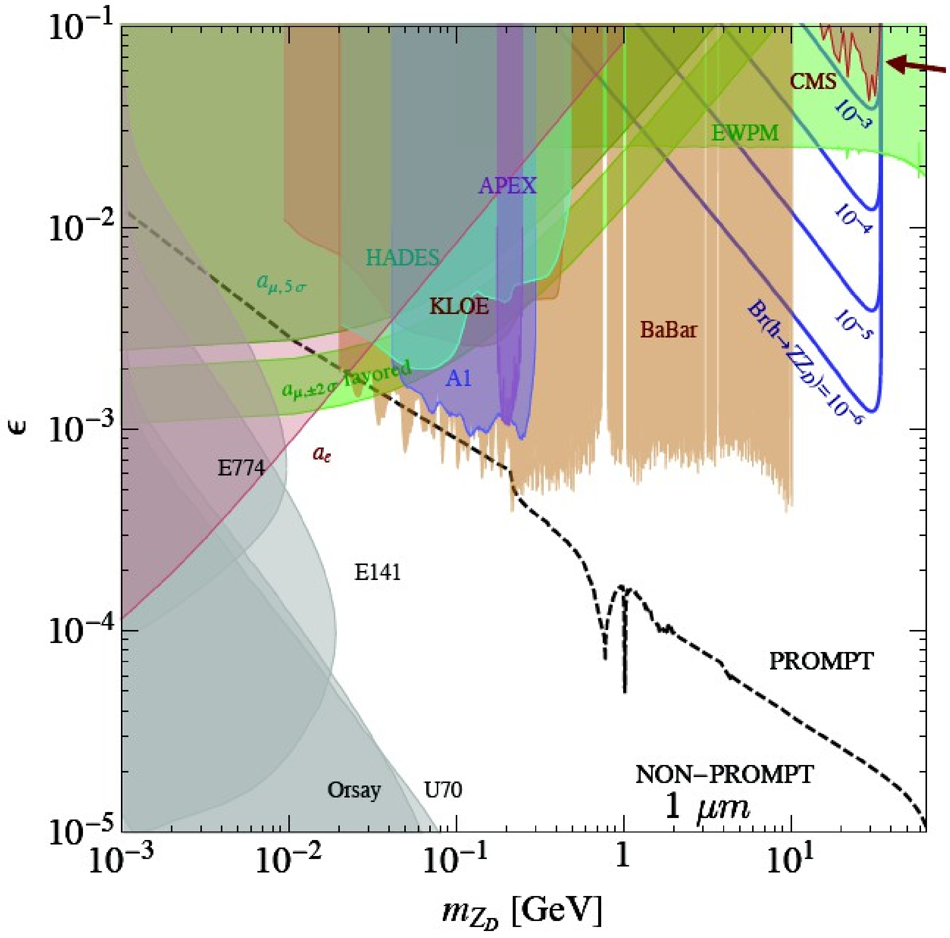
[T. Gunji: BNL DI workshop, 2014]

CMS/ATLAS

Search for A' in exotic Higgs Decay

- Kinetic mixing Z-A'





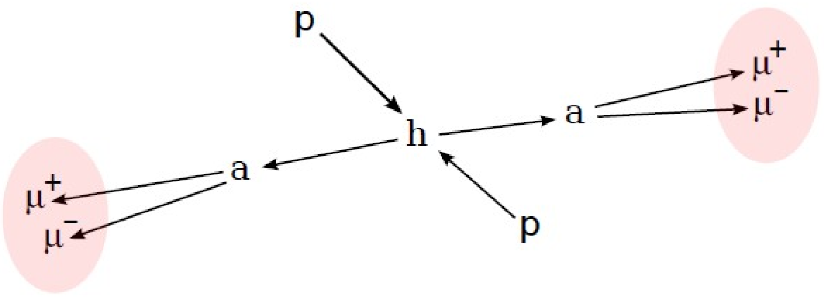
CMS limits
(ATLAS similar)

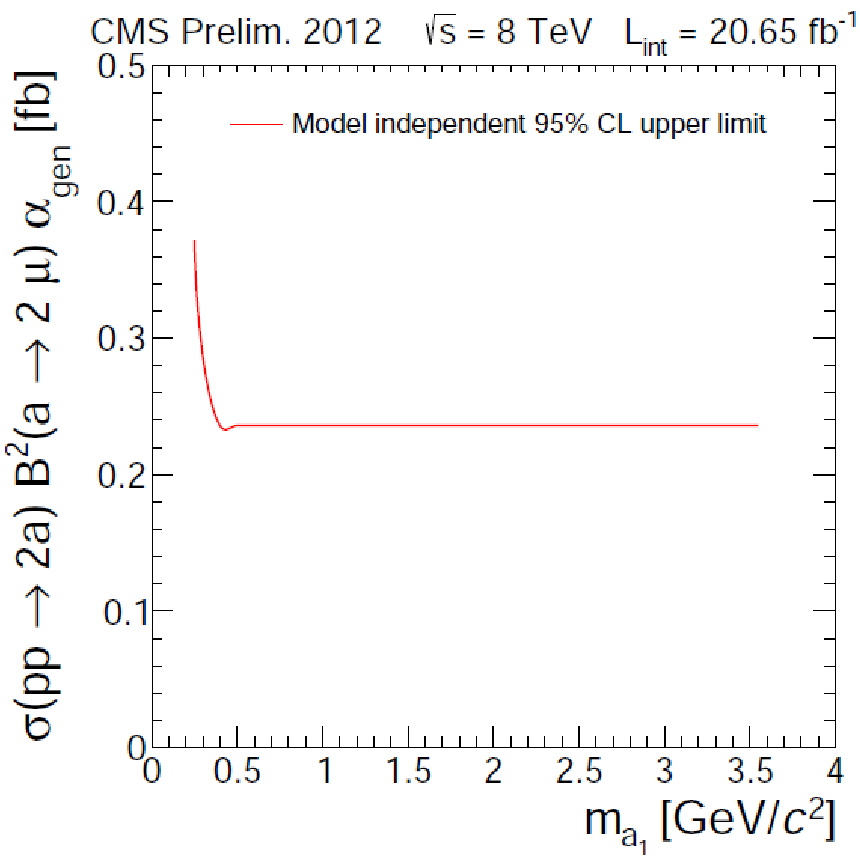
- Unoptimized limit almost competitive with dedicated precision measurements
- 14 TeV run with 300 fb^{-1} may be sensitive to very low BR

[arXiv:1312.4992]

Search for A' in exotic Higgs Decay

- Kinetic mixing Z-A'
- Non-SM Higgs decay to an A' pair, each decays to an isolated lepton pair





95 % CL limit (model-independent!) on

$$\sigma(pp \to h \to 2a) \times \mathcal{B}^2(a \to 2\mu) \times \alpha_{gen}$$

α_{gen} : kinematic and geometric acceptance (on generator level)