Attacking Dark Forces with Intense Electron Beams at DESY

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Accelerator Physics Seminar
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1. Motivation

- Models related to dark matter suggest existence of long-range forces mediated by new bosons with masses in the MeV to GeV range and very weak coupling to ordinary matter:

"Hidden" or "Dark" Bosons

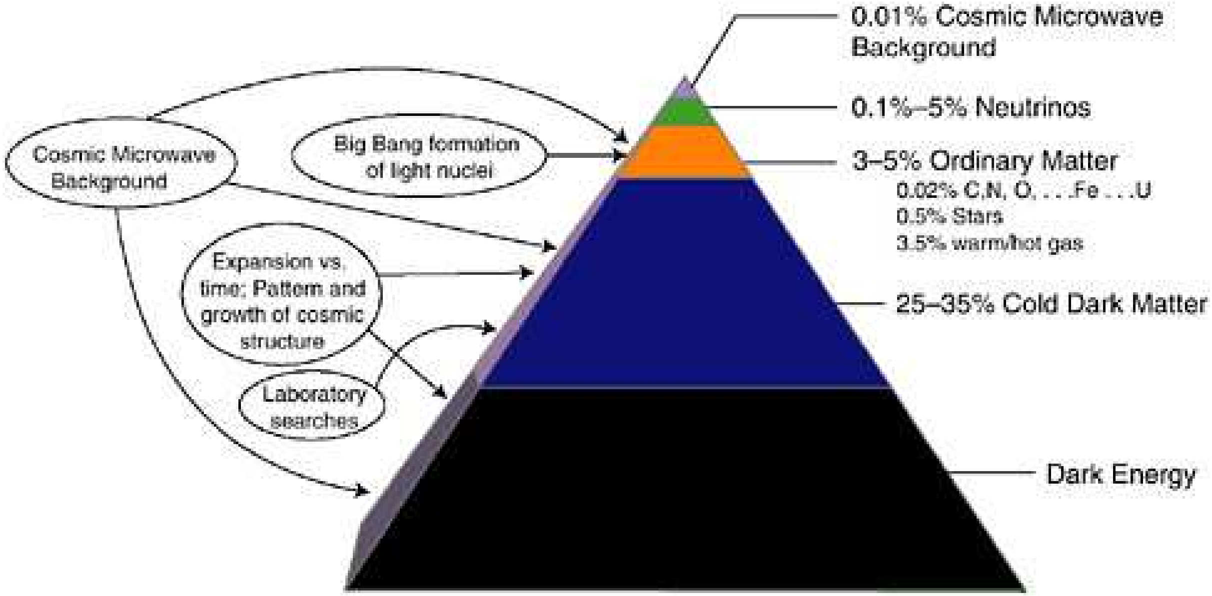
- Appear naturally in supersymmetric models descending from string theory
- Current experimental constraints on such particles quite weak
- Experimental HEP community now starting to develop strategies and to form collaborations to attack these dark forces
  – Fixed-target experiments exploiting electron beams especially sensitive

$\Rightarrow$ Opportunity for new experiments at **DESY**

Table of Content:

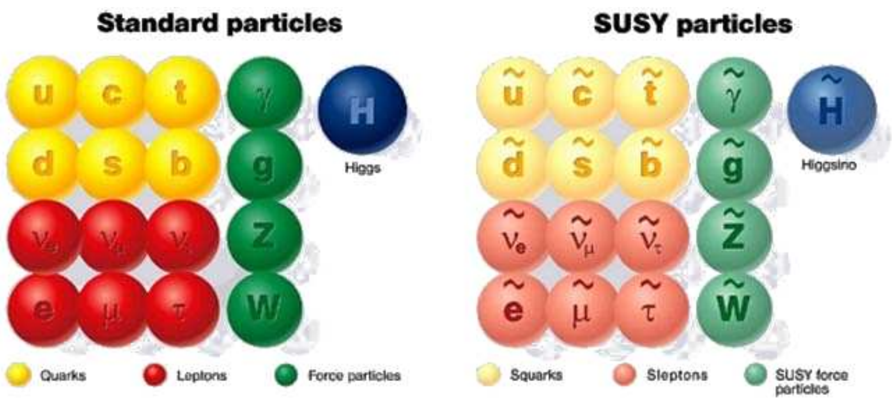
2. Physics case for dark forces

- Standard Model (SM) describes only $\sim 5\,\%$ of the universe:



$\Rightarrow$ There is physics beyond the SM

- Compelling extension of the SM: Minimal Supersymmetric SM (MSSM)

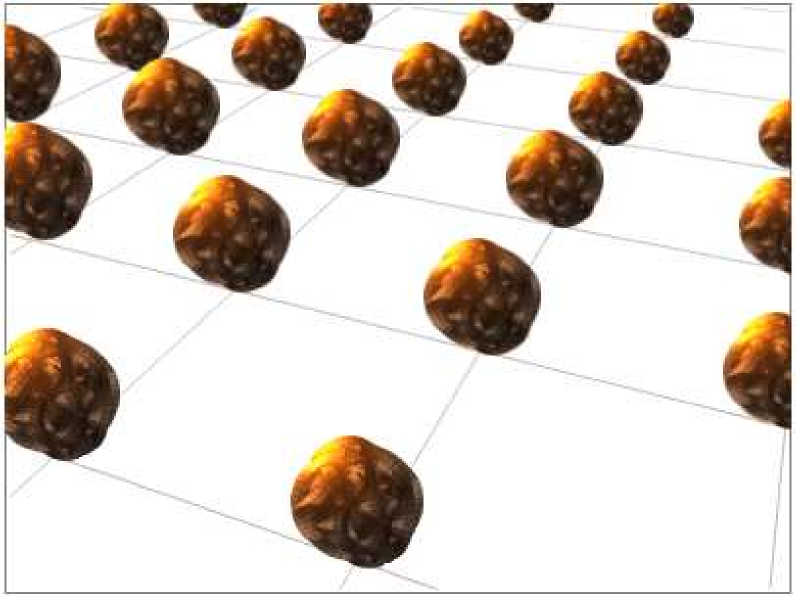


  - Neutralinos are candidates for cold dark matter
  - Hierarchy (weak scale $\ll$ Planck scale) stabilized
  - Unification of gauge couplings

- Next-to-Minimal SSM (NMSSM), having an additional SM singlet Higgs field S, shares all these features, but requires even less fine-tuning

- Extra CP-odd Higgs A in NMSSM may be very weakly coupled and light, $10\ \mathrm{MeV} \lesssim m_A \sim \sqrt{\kappa} A_\kappa \langle S \rangle \lesssim 10$ GeV: GeV-scale dark forces!

- Even more GeV-scale dark force carriers expected if we try to obtain the MSSM or NMSSM from compactification and Kaluza-Klein reduction of supergravity or superstrings:



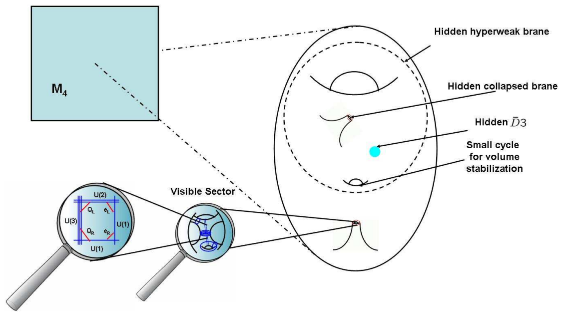
- Compactifications seem to feature often a number of additional particles which belong to a hidden sector, not directly coupled to the MSSM particles, notably hidden-sector U(1) gauge bosons

- Hidden U(1) gauge factors generic feature of string compactifications
  - both in compactifications of the closed heterotic string, e.g.

[Lebedev,Ramos-Sanchez '09]

$$\mathrm{E}_8 \times \mathrm{E}_8 \to \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \times [\mathrm{SU}(6) \times \mathrm{U}(1)]$$

  - as well as in compactifications with open strings and D-branes
    * KK zero modes of form fields
    * Massless excitations of space-time filling D-branes



- Hidden U(1) gauge bosons ("photons") may be light, $m_{\gamma'} \ll$ TeV

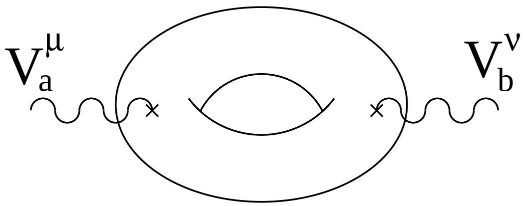
- Dominant interaction with $\mathrm{U}(1)_Y$ or $\mathrm{U}(1)_{\mathrm{em}}$ via kinetic mixing [Holdom'85]

$$\mathcal{L} \supset -\frac{1}{4} F^{(\mathrm{vis})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{vis})} - \frac{1}{4} F^{(\mathrm{hid})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{hid})} + \frac{\chi}{2} F^{(\mathrm{vis})}_{\mu\nu} F^{(\mathrm{hid})\mu\nu} + m^2_{\gamma'} A^{(\mathrm{hid})}_{\mu} A^{(\mathrm{hid})\mu}$$

$\chi \ll 1$ generated at loop level via messenger exchange $\Rightarrow$ U(1) hidden

– Kinetic mixing in compactification of heterotic string:

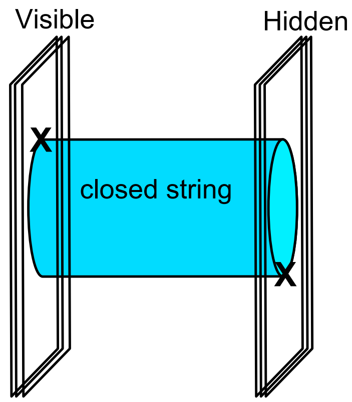
[Dienes,Kolda,March-Russell '97]



$$10^{-17} \lesssim \chi \simeq \frac{e^2}{16\pi^2} C \frac{\Delta m}{M_P} \lesssim 10^{-5},$$

$$\text{for } C \gtrsim 10;\ \ 10^5 \text{ GeV} \lesssim \triangle m \lesssim 10^{17} \text{ GeV}$$

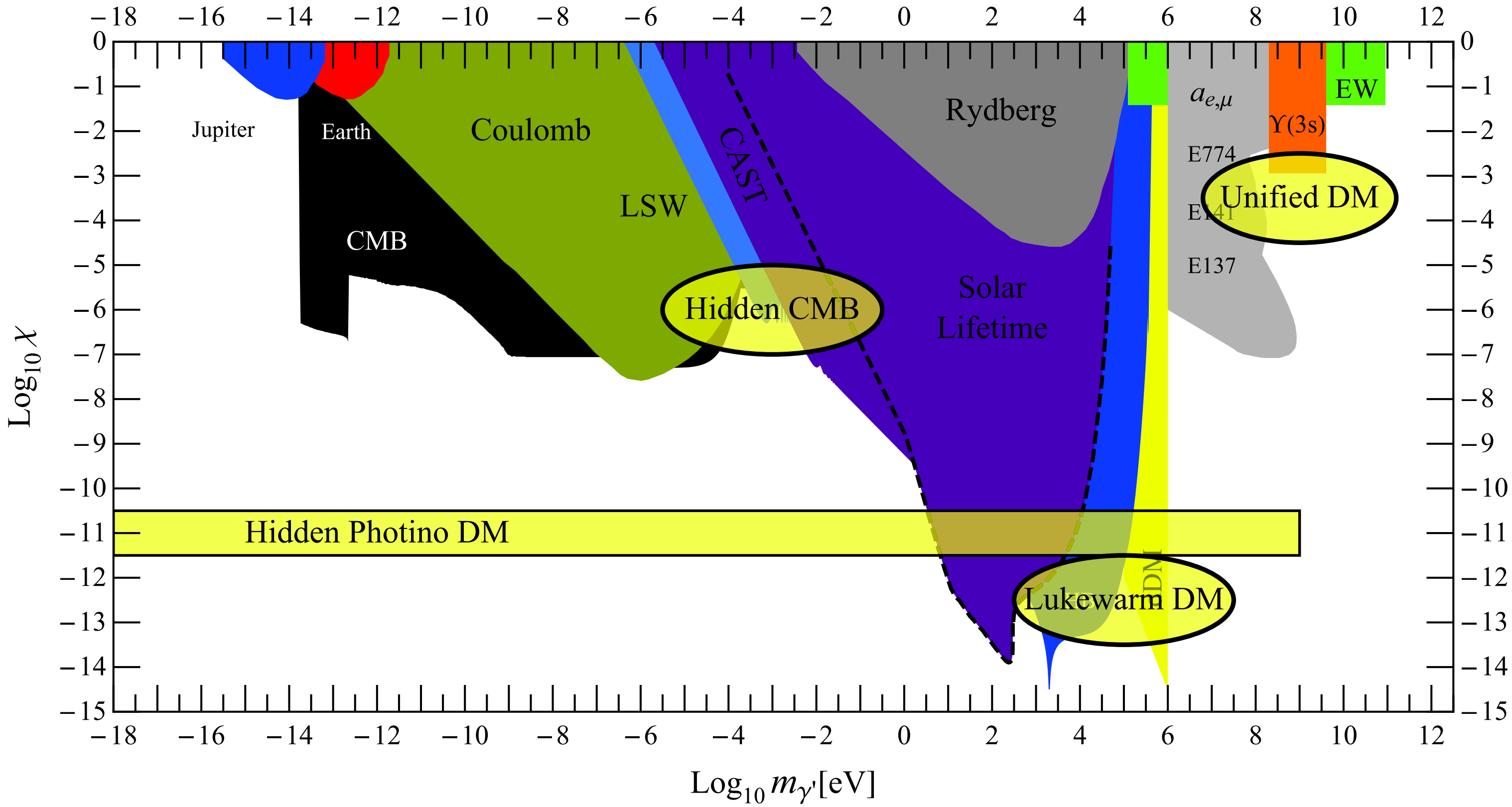
– Kinetic mixing between D-brane localized U(1)s in type II compactifications: [Lüst,Stieberger ‘03;Abel,Schofield ‘04;Berg,Haack,Körs ‘05;..;Goodsell *et al.* ‘09]



$$10^{-12} \lesssim \chi \sim \frac{e e_h}{16\pi^2} \sim 2\pi g_s \left(\frac{4\pi}{g_s^2} \frac{M_s^2}{M_P^2} \right)^{q/12} \lesssim 10^{-3},$$

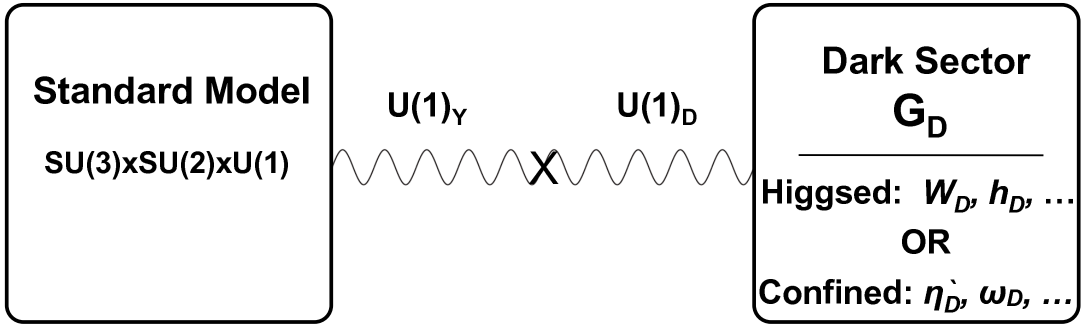
$$\text{for } q = 0, 4;\;\; 10^3 \text{ GeV} \lesssim M_s \lesssim 10^{17} \text{ GeV}$$

- Current constraints on hidden U(1)s vs. phenomenological very interesting islands: [Goodsell,Jaeckel,Redondo,AR '09]



- **Unified dark matter** [Arkani-Hamed,Finkbeiner,Slatyer,Weiner '08;...]

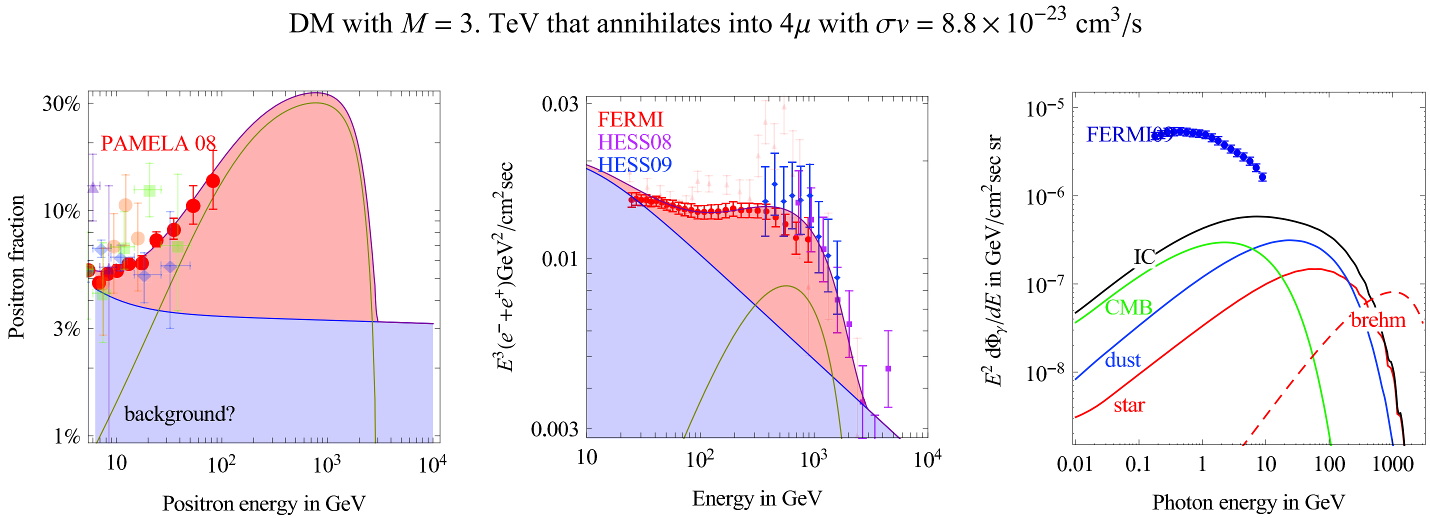
  Hidden sector dark matter interacting via GeV scale hidden sector dark gauge bosons



  may explain astrophysical and terrestrial anomalies

  – electron and/or positron excesses observed by PAMELA, ATIC, FERMI, HESS, ...
  – annual modulation signal from DAMA/LIBRA and reconciliation with null results from other elastic scattering experiments

- Explanation of electron and/or positron excesses by PAMELA, FERMI, ... in terms of thermal relic dark matter annihilation requires
  - enhanced annihilation cross-section (boost factor)
  - leptophilic final state



[Meade,Papucci,Strumia,Volansky '09]

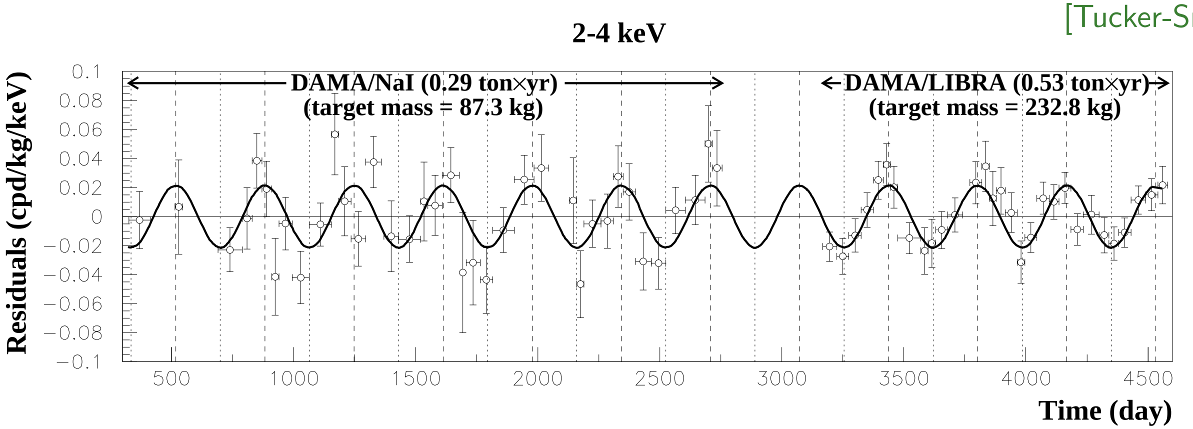
- Can be achieved via $\chi + \chi \to \gamma' + \gamma'$, if $2\, m_e < m_{\gamma'} \lesssim m_p$
- Alternatively, exploit $\chi + \chi \to A + A$, if $2\, m_e < m_A \lesssim m_p$

[Arkani-Hamed,Finkbeiner,Slatyer,Weiner '08;Nomura,Thaler '09;Hooper,Tait '09;Bai,Carena,Lykken '09;...]

- Dark matter interpretation of annual modulation signal observed by DAMA not in conflict with null results of other direct detection experiments if χ-nucleus scattering dominated by an inelastic process,

$$\chi + N \to \chi^* + N, \qquad \text{with mass splitting } \triangle\delta \approx 100 \text{ keV}$$

[Tucker-Smith,Weiner '01]

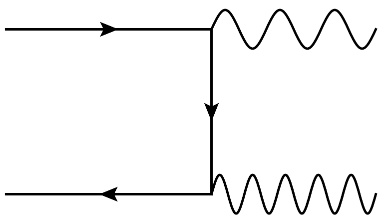


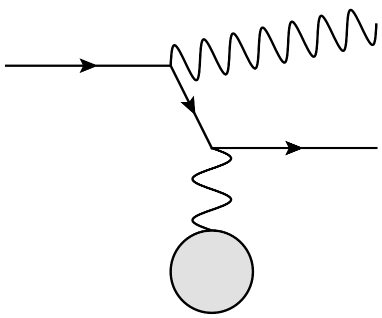
[Bernabei *et al.* [DAMA Collaboration] '09]

$\Leftarrow$ Can be mediated by kinetically mixed γ' scattering off nuclei. Necessary mass splitting from more structure (e.g. additional gauge factors or SUSY) in dark sector [Arkani-Hamed *et al.* '08;...;Cheung *et al.* '09]

3. Attacking Dark Forces with New Fixed-Target Experiments

- High intensity frontier to search for MeV $\div$ GeV-scale γ' (or A):
  - low-energy e^+e^- collider
    - $\mathcal{O}$(few) ab^{-1} per decade
    - $\sigma \sim \frac{\alpha^2\chi^2}{s}$
  - fixed-target experiments
    - $\mathcal{O}$(few) ab^{-1} per day
    - $\sigma \sim \frac{\alpha^3 Z^2 \chi^2}{m^2_{\gamma'}}$





$\Rightarrow$ Beam dump and fixed-target experiments especially sensitive!

[Reece,Wang'09;Bjorken,Essig,Schuster,Toro'09;Batell, Pospelov,Ritz'09;Andreas,Lebedev,Ramos-Sanchez,AR in prep.]

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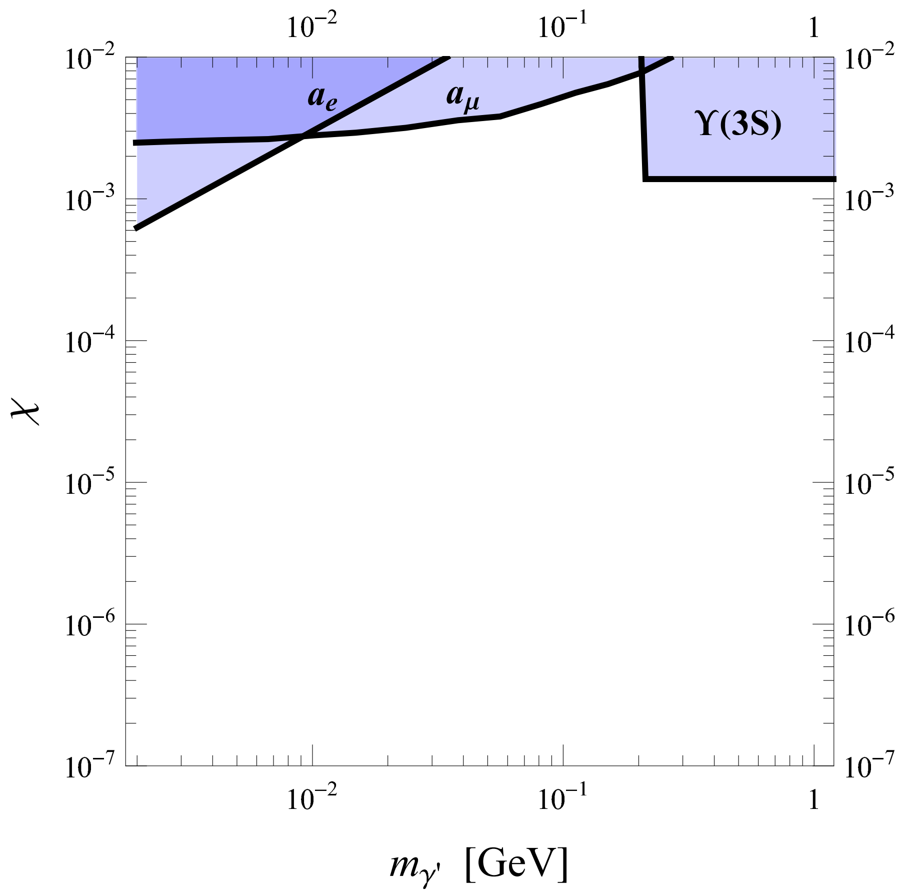

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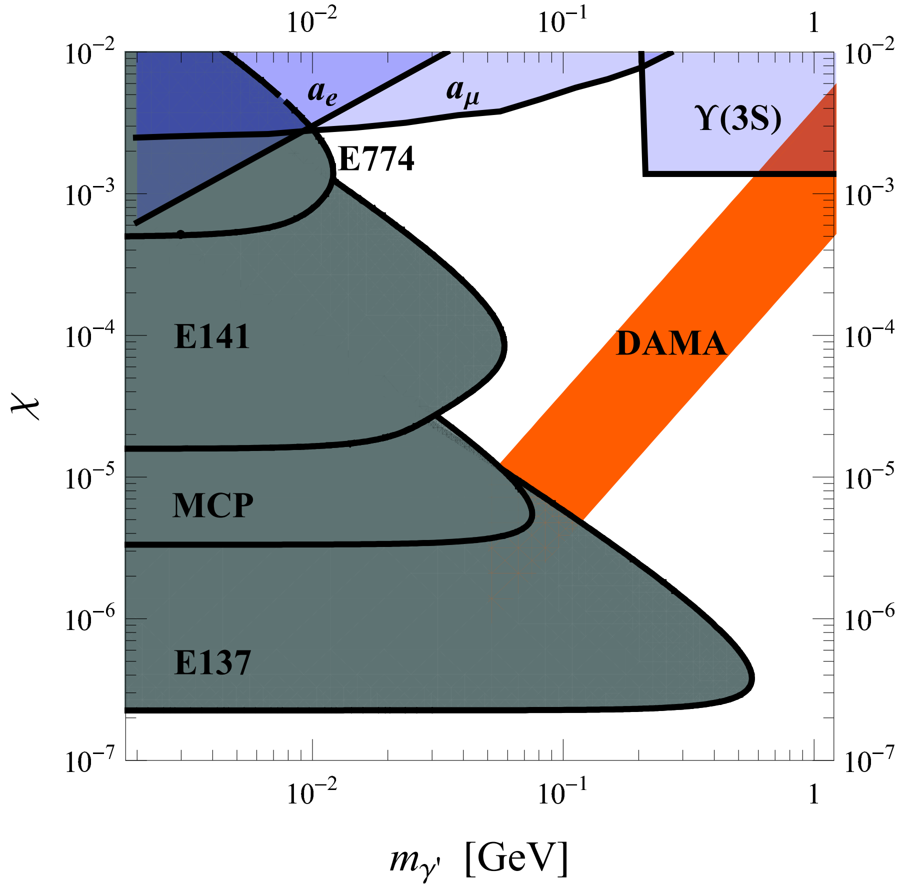

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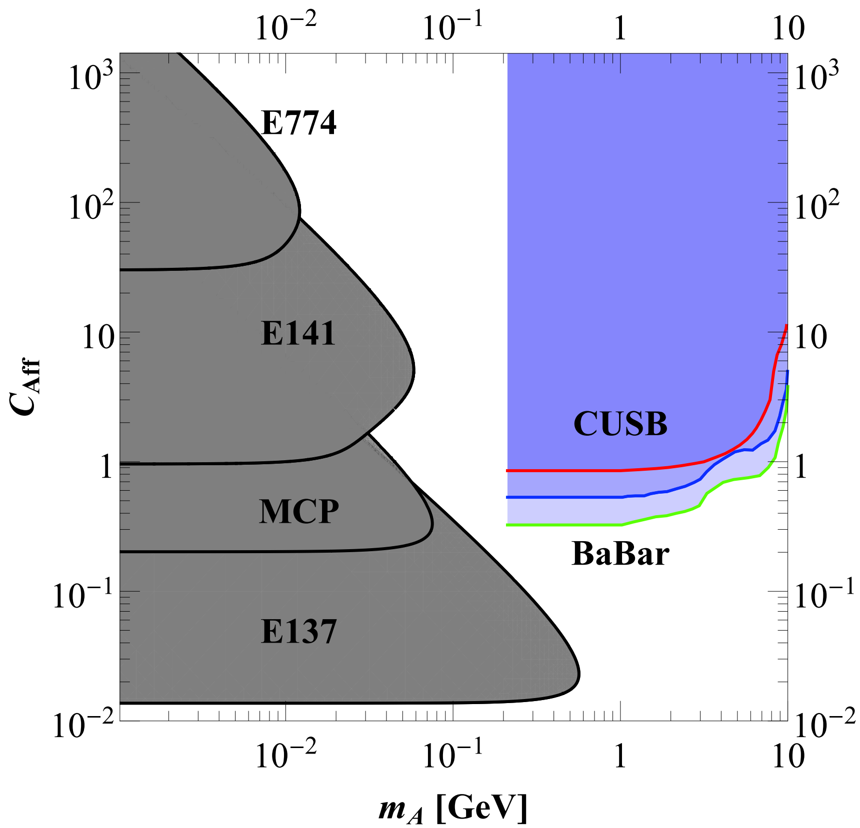


[Andreas,Lebedev,Ramos-Sanchez,AR in prep.]

⇒ Opportunities at DESY, ELSA, JLab, MAMI?

- Production cross-section and decay length of γ',

$$\sigma_{\gamma'} \sim 1\ \mathrm{pb} \left(\frac{\chi}{10^{-5}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)^2$$

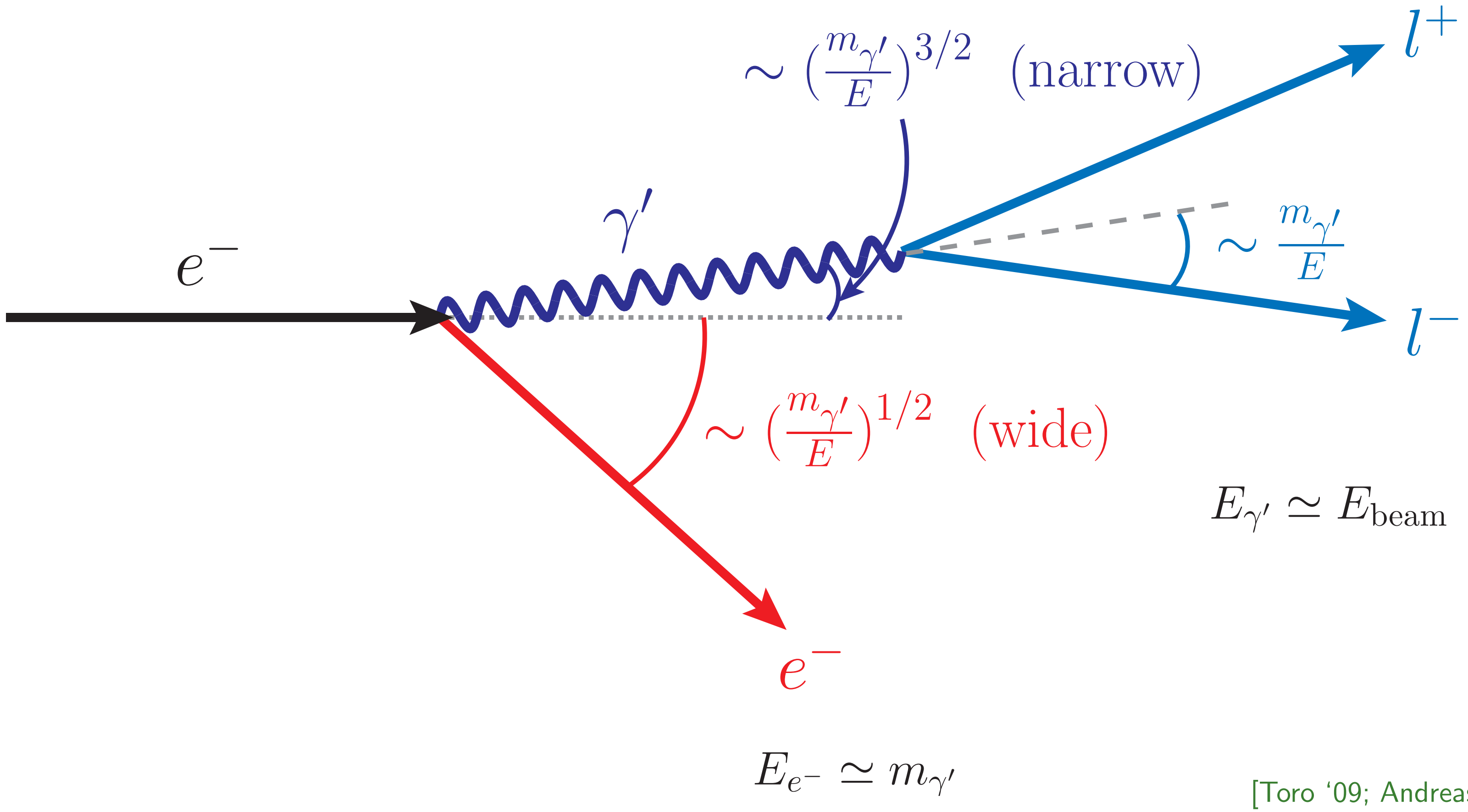
$$\ell_d = \gamma c \tau \sim 10\ \mathrm{cm} \left(\frac{\gamma}{10}\right) \left(\frac{\chi}{10^{-5}}\right)^{-2} \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)$$

Translation to CP-odd Higgs A: $C_{Aee} \sim 10^5\,\chi$

⇒ Multiple experimental approaches, with different strategies for fighting backgrounds

- $\ell_d \gg$ cm: beam dump; low background
- $\ell_d \sim$ cm: vertex; limited by instrumental bkg
- $\ell_d \ll$ cm: bump hunt; fight bkg with high intensity, resolution

Kinematics and geometry:

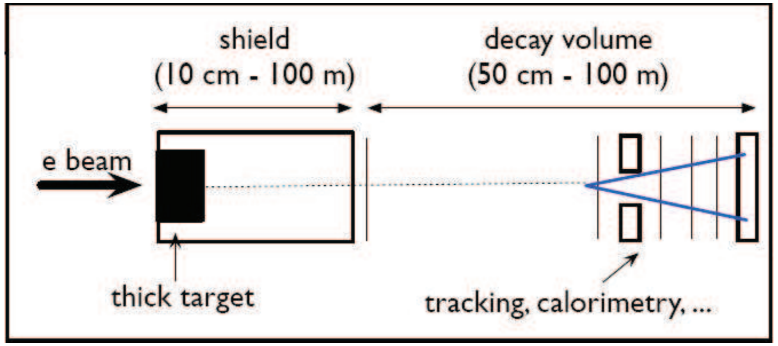


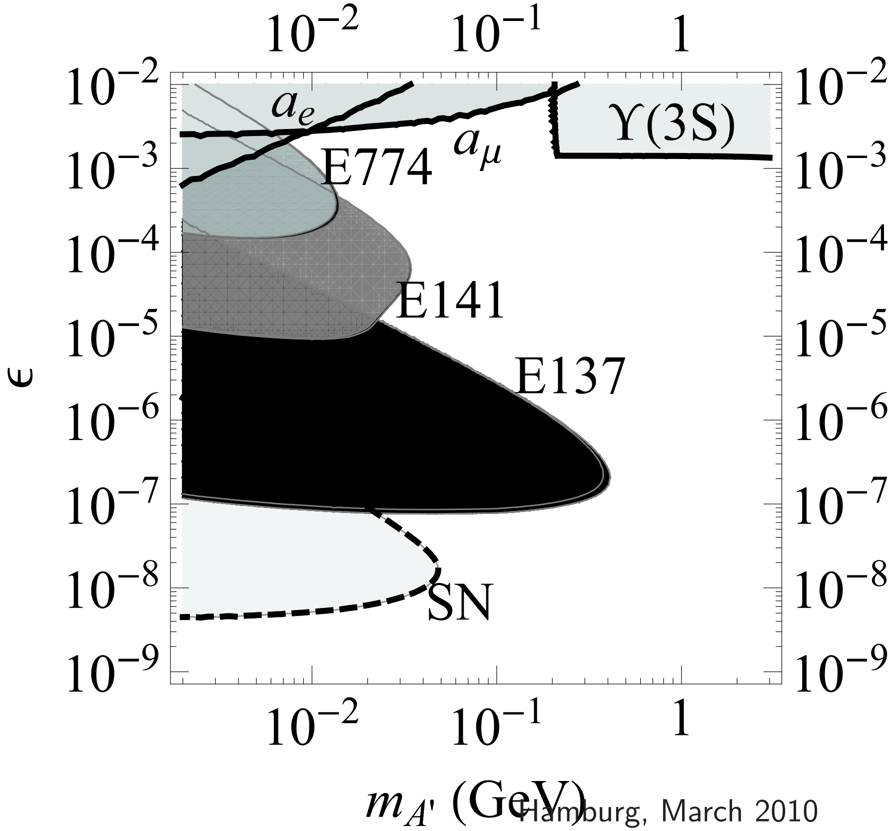
[Toro '09; Andreas '10]

- **Past beam dumps:**

[Bjorken,Essig,Schuster,Toro '09]

  - SLAC E137:
    30 C, 20 GeV, 200 m, 200 m
  - SLAC E141:
    .3 mC, 9 GeV, 10 cm, 35 m
  - Fermilab E774:
    .8 nC, 275 GeV, 30 cm, 7 m





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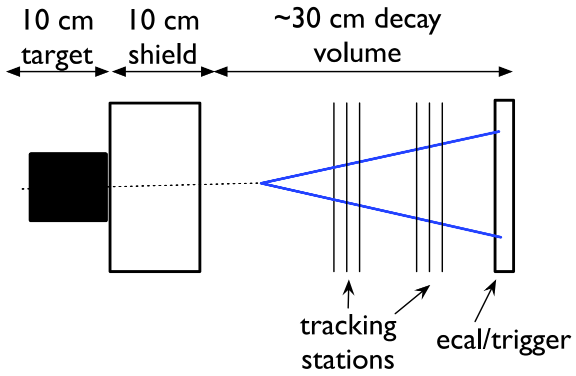
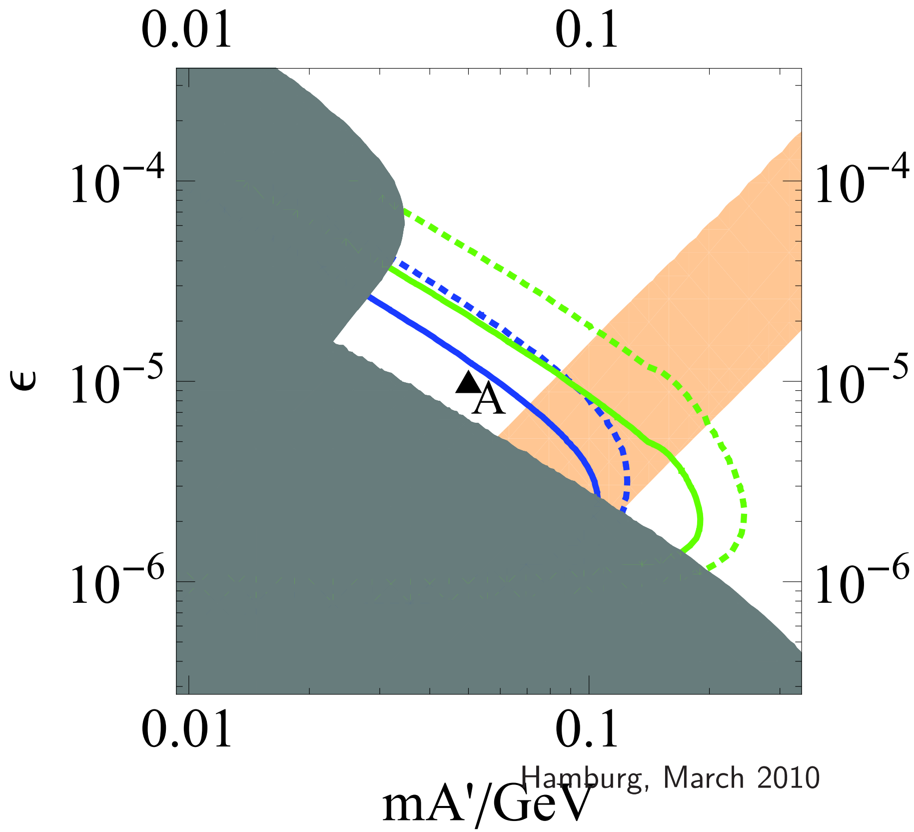
- **New beam dump suggested:**

  [Bjorken,Essig,Schuster,Toro '09]

  - Low power W beam dump
    .3 C, 200 MeV, 20 cm, 50 cm
    .1 C, 6 GeV, 3.9 m, 7 m

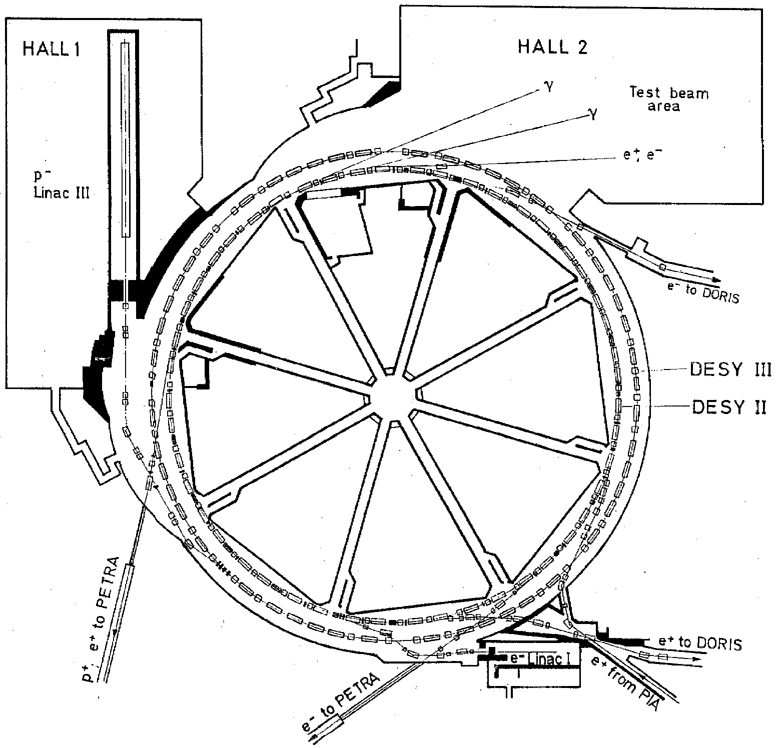


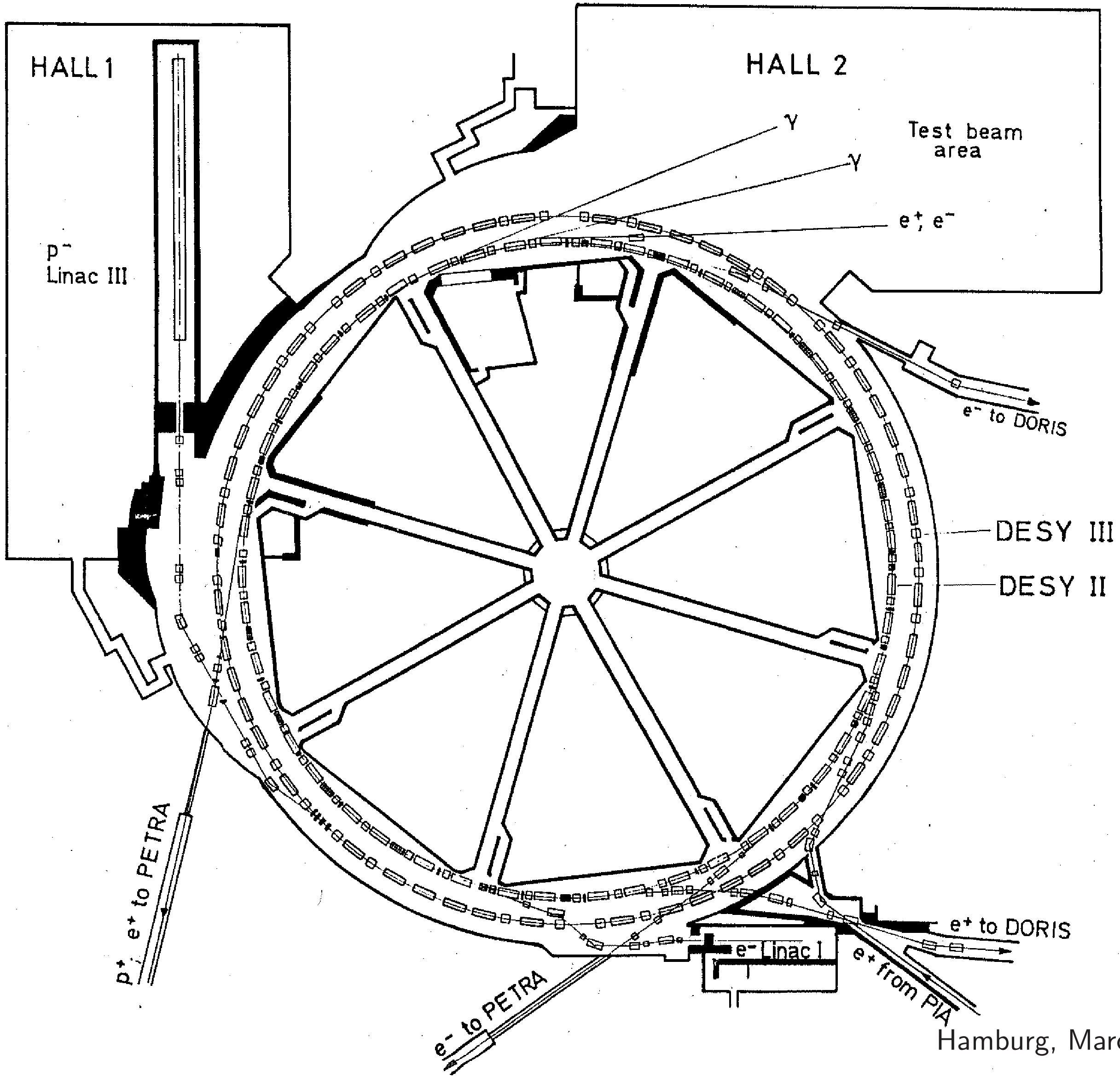


- **New experiment at DESY?**
  - **DarkDESY** at DESY II

    [Andreas,Bechtle,Ehrlichmann,Garutti,Gregor,Lindner,Meyners,Redondo,AR]

    * $\sim$ 10 nA with 0.45 - 7 GeV




HALL 1
p⁻
Linac III
HALL 2
γ
γ
Test beam area
e⁺, e⁻
e⁻ to DORIS
DESY III
DESY II
e⁺ to DORIS
e⁻ Linac I
e⁺ from PIA
e⁻ to PETRA
p⁺, e⁺ to PETRA

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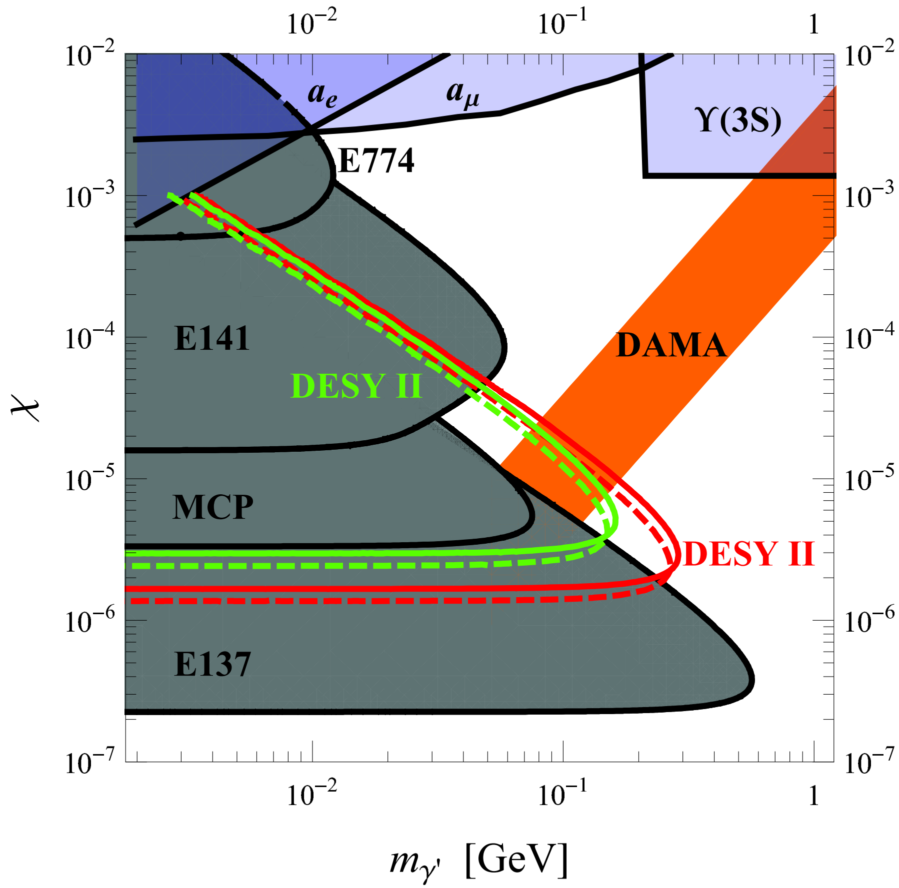

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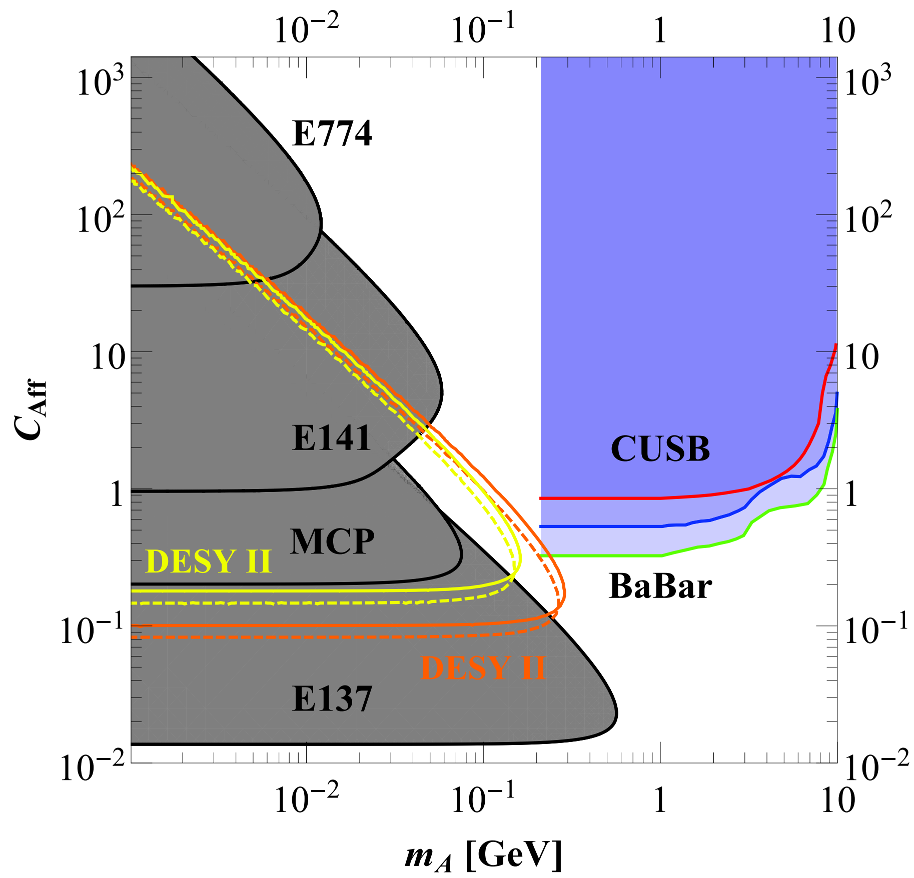

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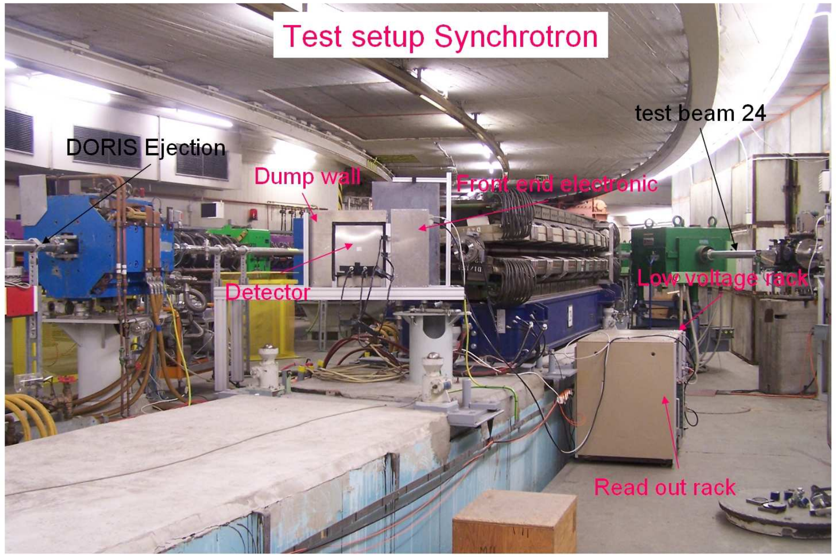

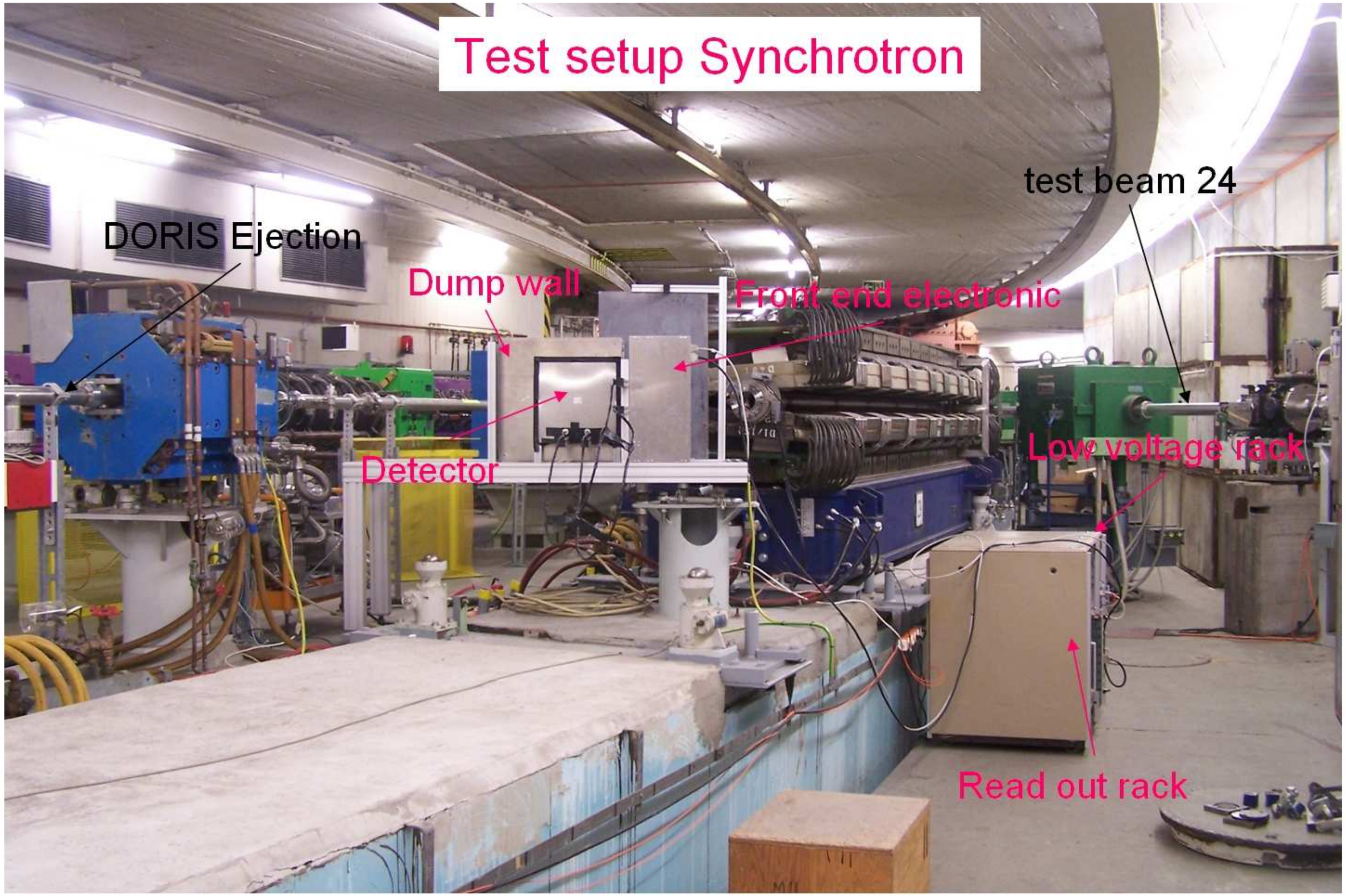
Test setup Synchrotron
test beam 24
DORIS Ejection
Dump wall
Front end electronic
Detector
Low voltage rack
Read out rack

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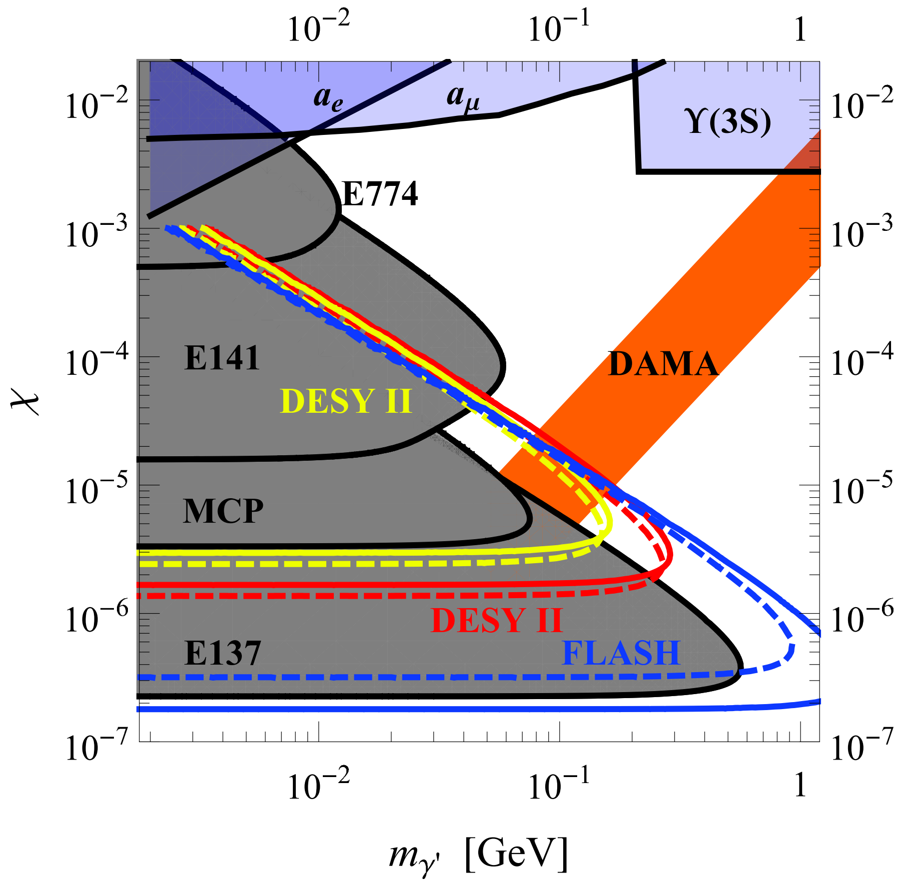

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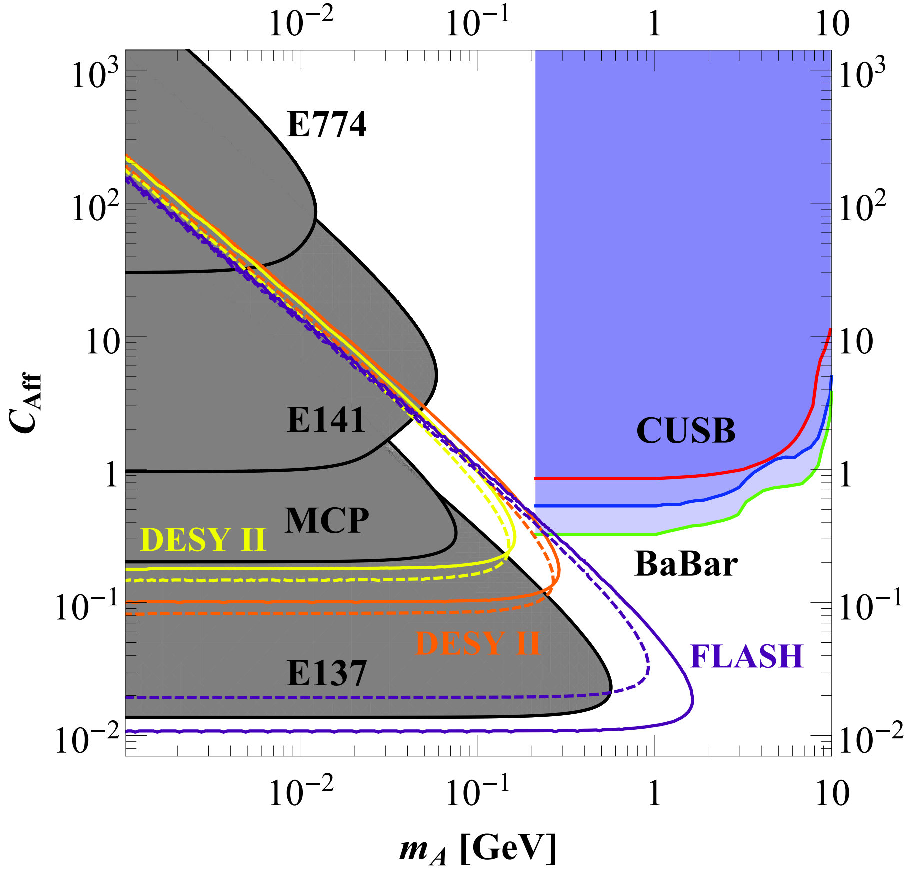

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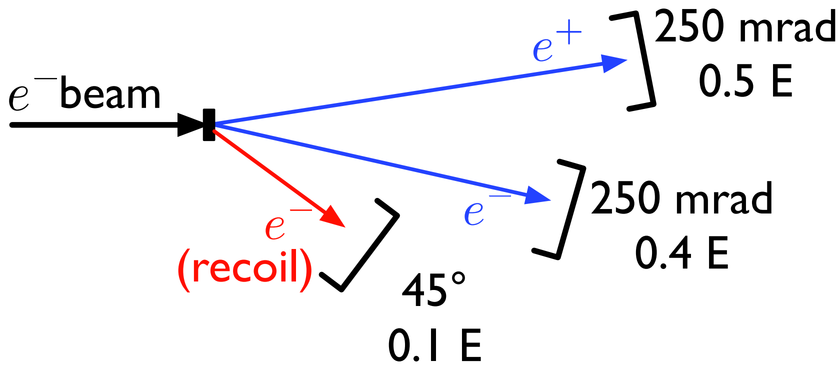
[Bjorken,Essig,Schuster,Toro '09]

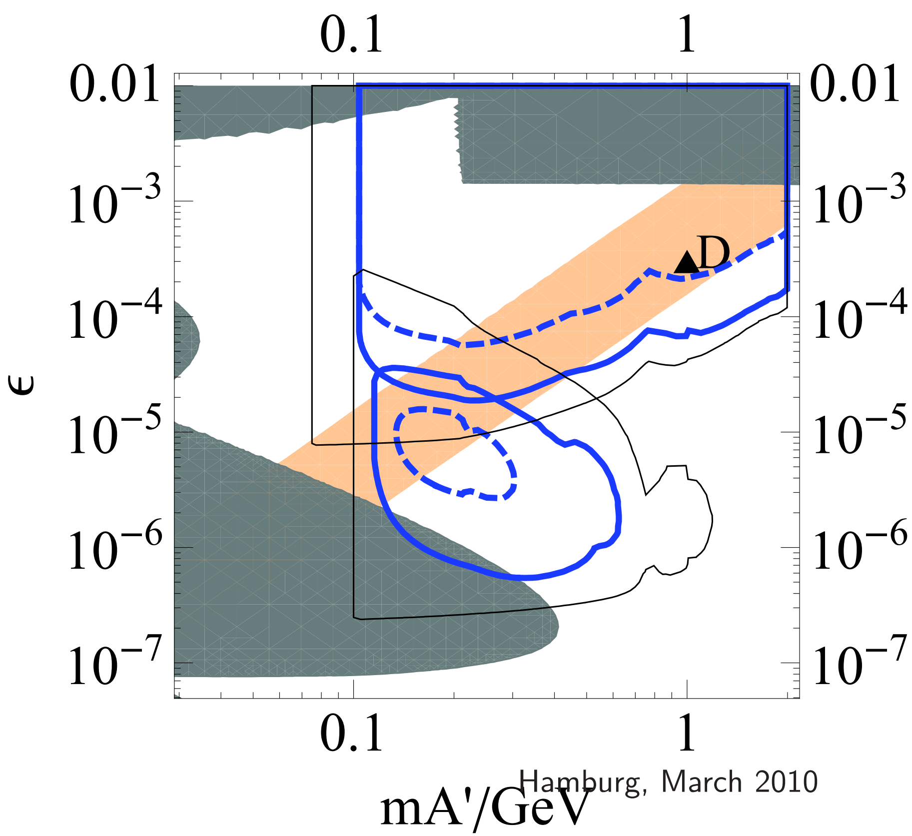


$\Rightarrow$ **New experiment at JLab?**

- **Fixed-target experiment in CEBAF Hall A**

  [Hall A Collaboration]

  * 80 μA at $2 \div 4$ GeV
  * proposed for period after CEBAF upgrade, but first short run in Summer 2010



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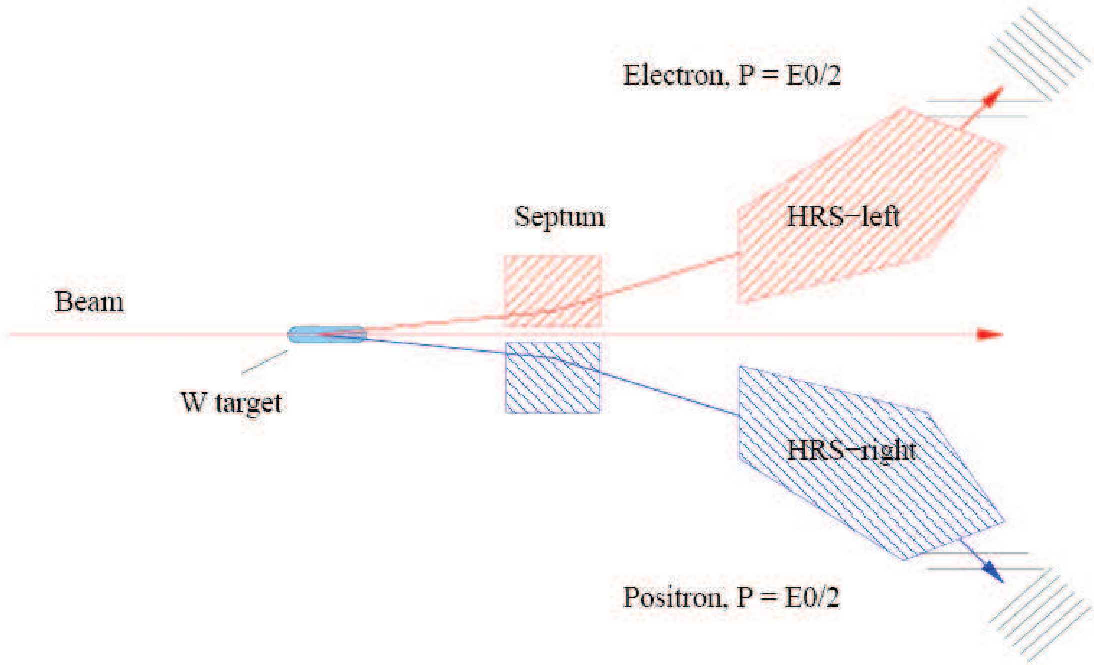

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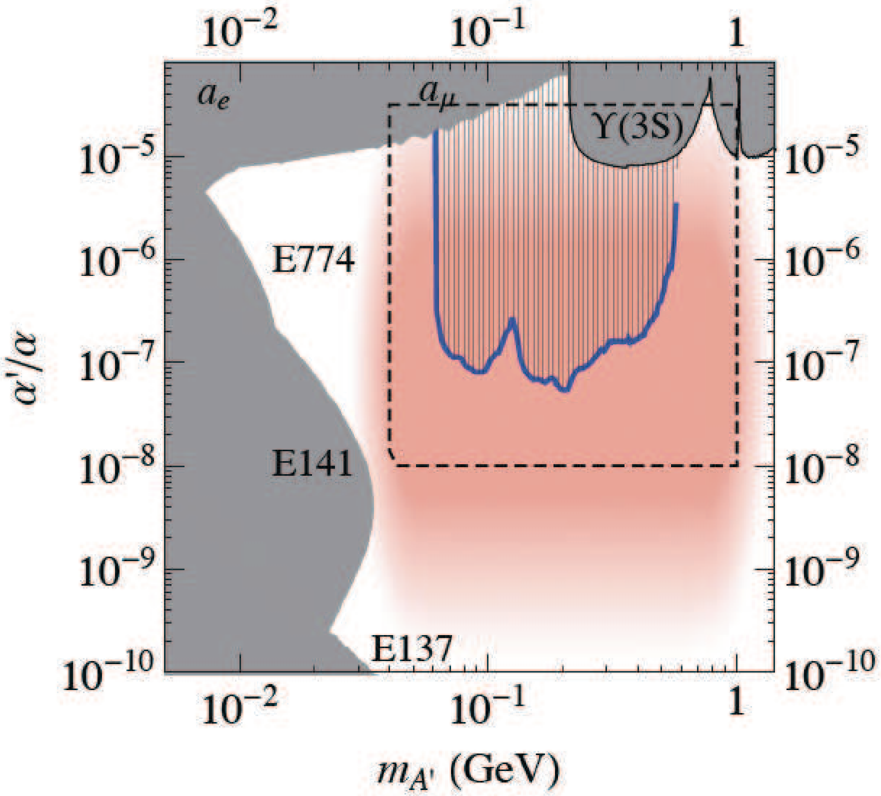

4. Conclusions

- Strong physics motivation for the possible existence of GeV-scale hidden/dark bosons:
  - top down: many extra SM singlets ($\rightarrow$ CP-odd Higgs) and extra U(1)s in string compactifications
  - bottom up: anomalies associated with dark matter
- Fixed-target experiments well suited to attack dark forces
- Large parameter space requires multiple search strategies and experiments
  - low coupling/mass: new beam dump experiments
  - intermediate region: new forward-geometry experiments
  - high coupling/mass: standard wide-angle spectrometers (e.g. JLab)

$\Rightarrow$ Great opportunities for new particle physics experiments at DESY!