Dark Photon

・ A candidate of DM (Dark Matter)

・ U(1) Gauge boson (A’) associated with dark sector.

→ It has very similar structure as QED, like “dark(invisible) photon”

・ Re-normalizable theory

There are many models which is not re-normalizable, called as a Effective Field Theory (EFT)

QED Analogy

Lagrangian of QED

$$L_{QED} = \bar{\varphi}\left(i\gamma_{\mu}D^{\mu} - m\right)\varphi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$= \bar{\varphi}\left(i\gamma_{\mu}\partial^{\mu} - m\right)\varphi + e\cdot\bar{\varphi}\gamma_{\mu}\varphi\cdot A^{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

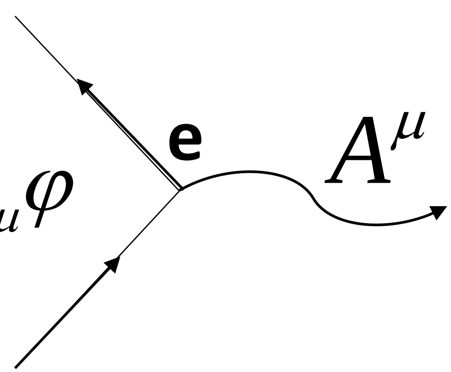
Dirac equation

Maxwell's equations

$(F^{\mu\nu} = \partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu})$

Interaction

$$j_{\mu} = \bar{\varphi}\gamma_{\mu}\varphi$$



QED Analogy

Lagrangian of Dark Photon

$$L_D = \bar{\chi}\left(i\gamma_\mu D^{\mu\prime} - m_\chi\right)\chi - \frac{1}{4}F_{\mu\nu}{}'F^{\mu\nu\prime}$$

$$= \bar{\chi}\left(i\gamma_\mu \partial^\mu - m_\chi\right)\chi + (-g_D)\cdot\bar{\chi}\gamma_\mu\chi\cdot A^{\mu\prime} - \frac{1}{4}F_{\mu\nu}{}'F^{\mu\nu\prime}$$

$$+ \frac{1}{2}m_{A'}{}^2 A_\mu{}' A^{\mu\prime} \ ① + \varepsilon \cdot F_{\mu\nu}F^{\mu\nu\prime} \ ②$$

① Mass term by spontaneous symmetry breaking

② Mixing term with QED (SM) side

Mixing

Notation from, Nuclear Physics B 887 (2014) 441

$$\mathcal{L}_{gauge} = -\frac{1}{4}F^1_{\mu\nu}F^{1\mu\nu} - \frac{1}{4}F^2_{\mu\nu}F^{2\mu\nu} - 2cF^1_{\mu\nu}F^{2\mu\nu}$$

$$\mathcal{L}_{int} = g_1 j_1^\mu A^1_\mu + g_2 j_2^\mu A^2_\mu = \begin{pmatrix} j_1^\mu & j_2^\mu \end{pmatrix} \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \end{pmatrix} \begin{pmatrix} A^1_\mu \\ A^2_\mu \end{pmatrix}$$

Change of Base ($A_\mu \leftrightarrow B_\mu$)

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^1_{\mu\nu}G^{1\mu\nu} - \frac{1}{4}G^2_{\mu\nu}G^{2\mu\nu}$$ ---- Diagonal

$$\mathcal{L}_{int} = \frac{1}{2\sqrt{2}} \begin{pmatrix} j_1^\mu & j_2^\mu \end{pmatrix} \begin{pmatrix} \frac{g_1}{\sqrt{\lambda_1}} & \frac{-g_1}{\sqrt{\lambda_2}} \\ \frac{g_2}{\sqrt{\lambda_1}} & \frac{g_2}{\sqrt{\lambda_2}} \end{pmatrix} \begin{pmatrix} B^1_\mu \\ B^2_\mu \end{pmatrix}$$

---- But, both A^μ / $A^{\mu\prime}$ couple to currents

Experimental Constraint

-- Four categories are explained in the paper --

A. Beam-dump constraints

B. Precision QED constraints

C. Cosmological bounds

D. Supernova → Almost no constraint to compared with the other

A. Beam(-dump) constraints

- *LSND experiment:*

famous for motivation of sterile-neutrino,
but this time, the upper limit on B.R. of $\Gamma(\pi^0 \to \nu_\mu \bar{\nu}_\mu) / \Gamma(\pi^0 \to all)$

➡ $\pi^0 \to \gamma A' \to \gamma \chi \bar{\chi}$, and $\chi e \to \chi e$

Where Cherenkov light is observed from final electron as if

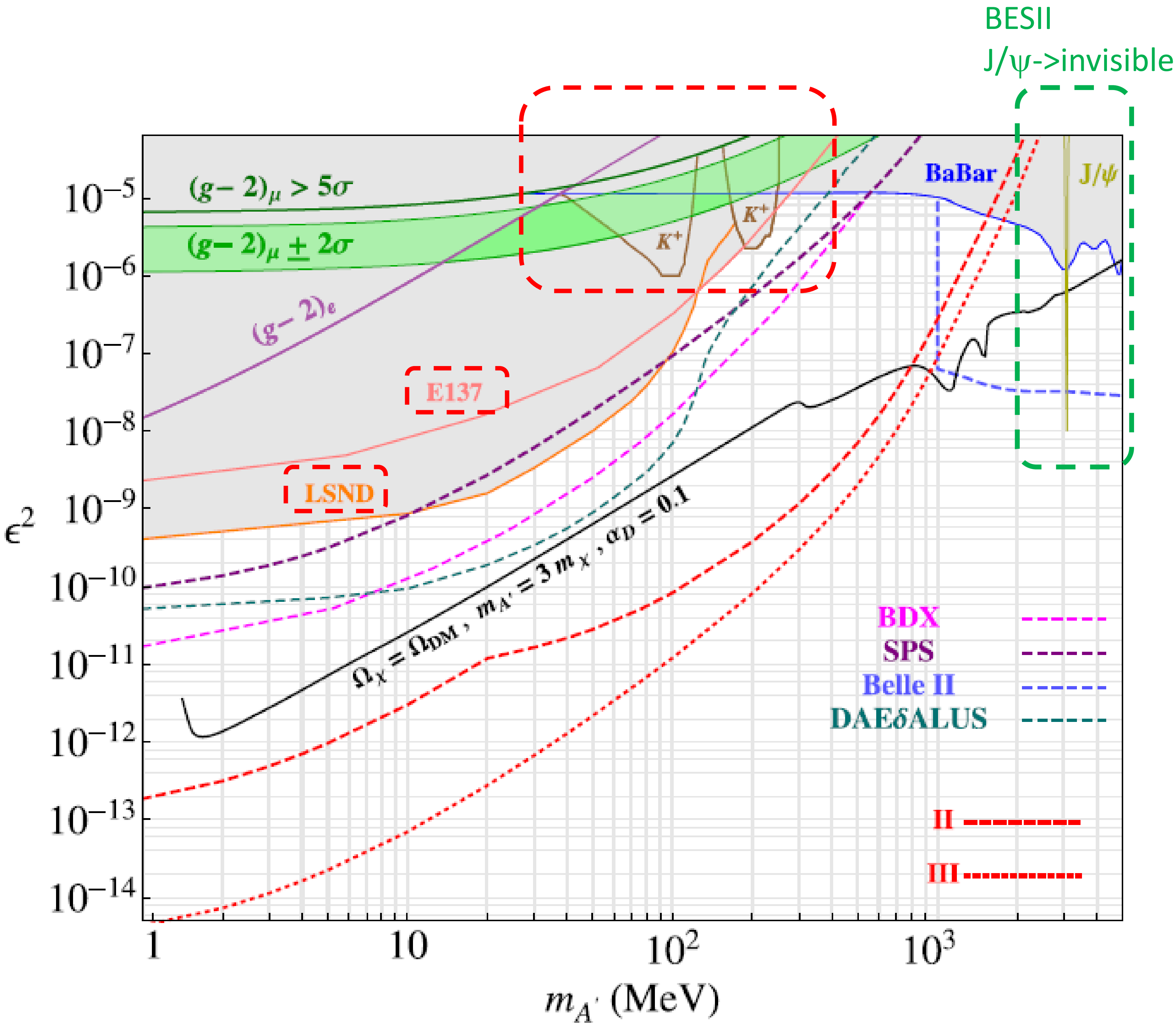
$\bar{\nu}_\mu + p \to \mu^+ + n.$ ……

- *E787/E949 experiments @ BNL*

Upper limit on B.R. of $K^+ \to \pi^+ \nu \bar{\nu}$

➡ $K^+ \to \pi^+ A' \to \pi^+ \chi \bar{\chi}$

- Axion search from E137 @ SLAC



BESII
J/ψ->invisible
$(g-2)_\mu > 5\sigma$
$(g-2)_\mu \pm 2\sigma$
$(g-2)_e$
K^+
K^+
BaBar
J/ψ
E137
LSND
$\Omega_\chi = \Omega_{DM}$, $m_{A'} = 3\, m_\chi$, $\alpha_D = 0.1$
BDX
SPS
Belle II
DAEδALUS
II
III
ϵ^2
$m_{A'}$ (MeV)

B. Precision QED constrains (g-2 experiments)

Spin $\vec{S}$ and the magnetic moment $\vec{M}$ of a particle is given as

$$\vec{M} = g\frac{q}{2m}\vec{S}$$

where g==2 is determined from Dirac-equation

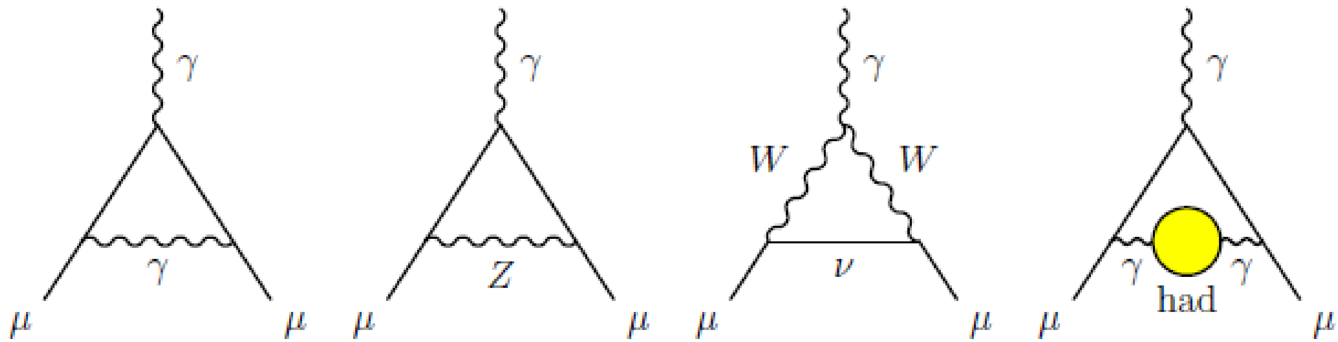
$$a = (g-2)/2 \quad = 0 \ , \quad \text{if } g=2$$

- But if we calculate the process with higher order, , ,

$$a^{\text{SM}} = a^{\text{QED}} + a^{\text{EW}} + a^{\text{hadrons}}$$

$$\neq 0$$

Order of the correction , , ,



$$a_\mu^{\mathrm{QED}} = 116\,584\,718.09(0.15) \times 10^{-11}$$

$$a_\mu^{\mathrm{EW}}[\text{1-loop}] = \frac{G_\mu m_\mu^2}{8\sqrt{2}\pi^2}\left[\frac{5}{3} + \frac{1}{3}\left(1 - 4\sin^2\theta_{\mathrm{W}}\right)^2 + \mathcal{O}\left(\frac{m_\mu^2}{M_W^2}\right) + \mathcal{O}\left(\frac{m_\mu^2}{m_H^2}\right)\right], = 194.8 \times 10^{-11},$$

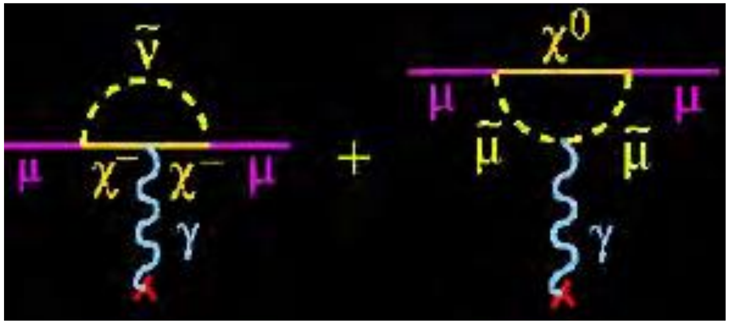
$$a_\mu^{\mathrm{Had}}[\mathrm{LO}] = 6\,955(40)(7) \times 10^{-11}$$

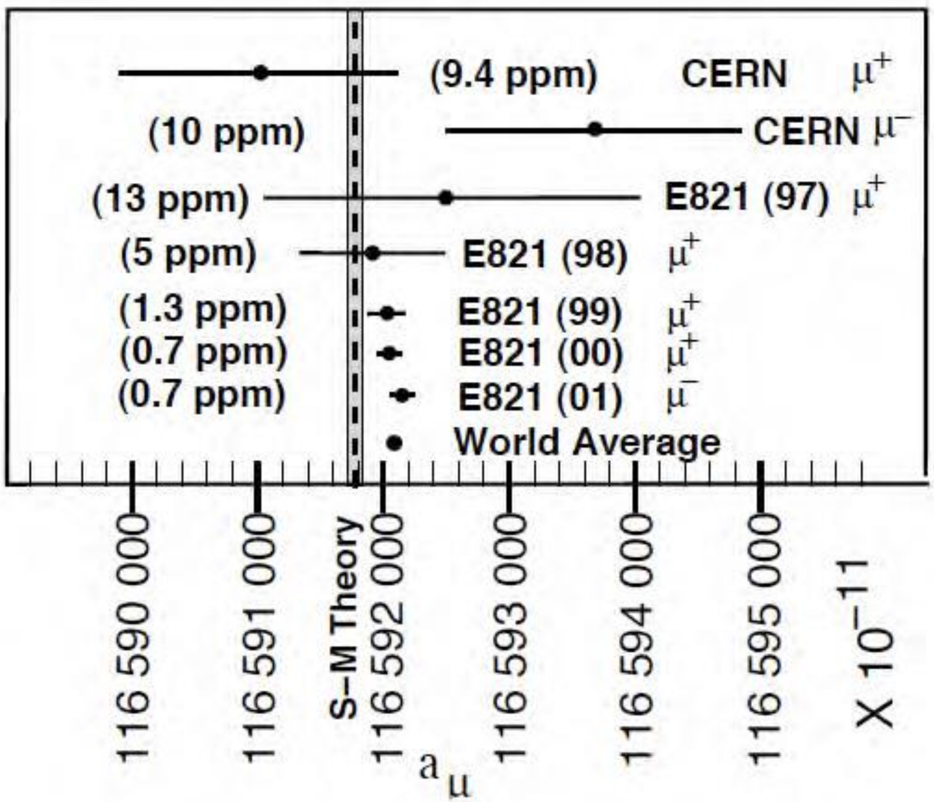
From "The muon anomalous magnetic moment" by A. Hocker (CERN) and W. J. Marciano (BNL)

Discrepancy between experiment and theory calculation

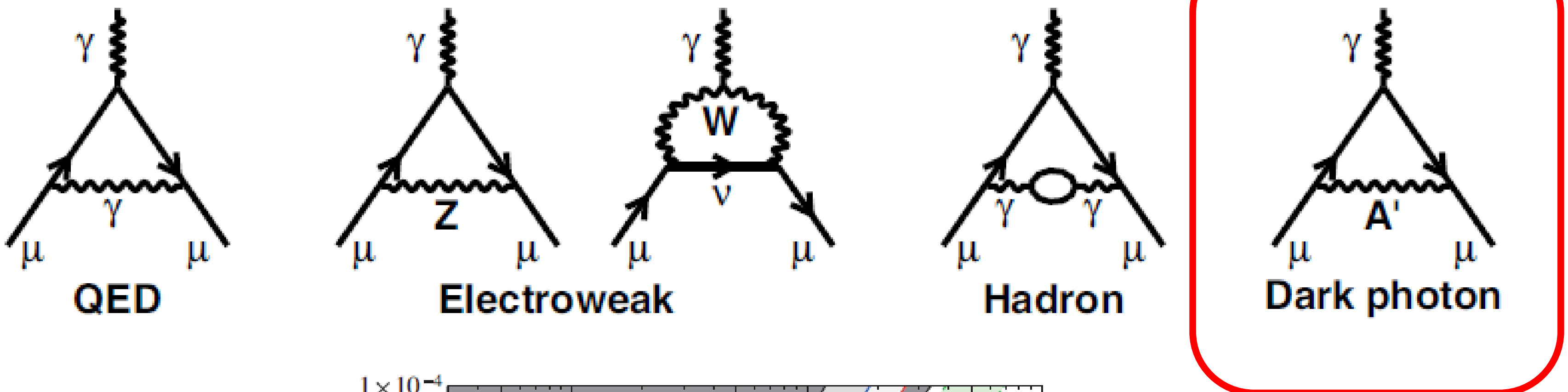
$$\Delta a_\mu^{\text{Exp-SM}} = 255(63)(49)\times 10^{-11} \Rightarrow 3.2\sigma$$

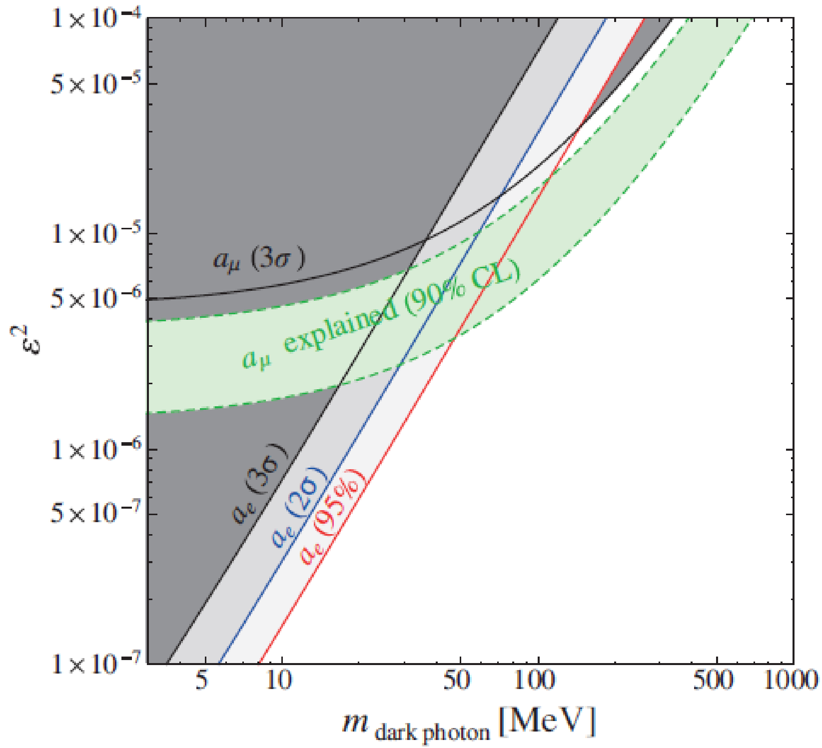
Contribution from SUSY ?



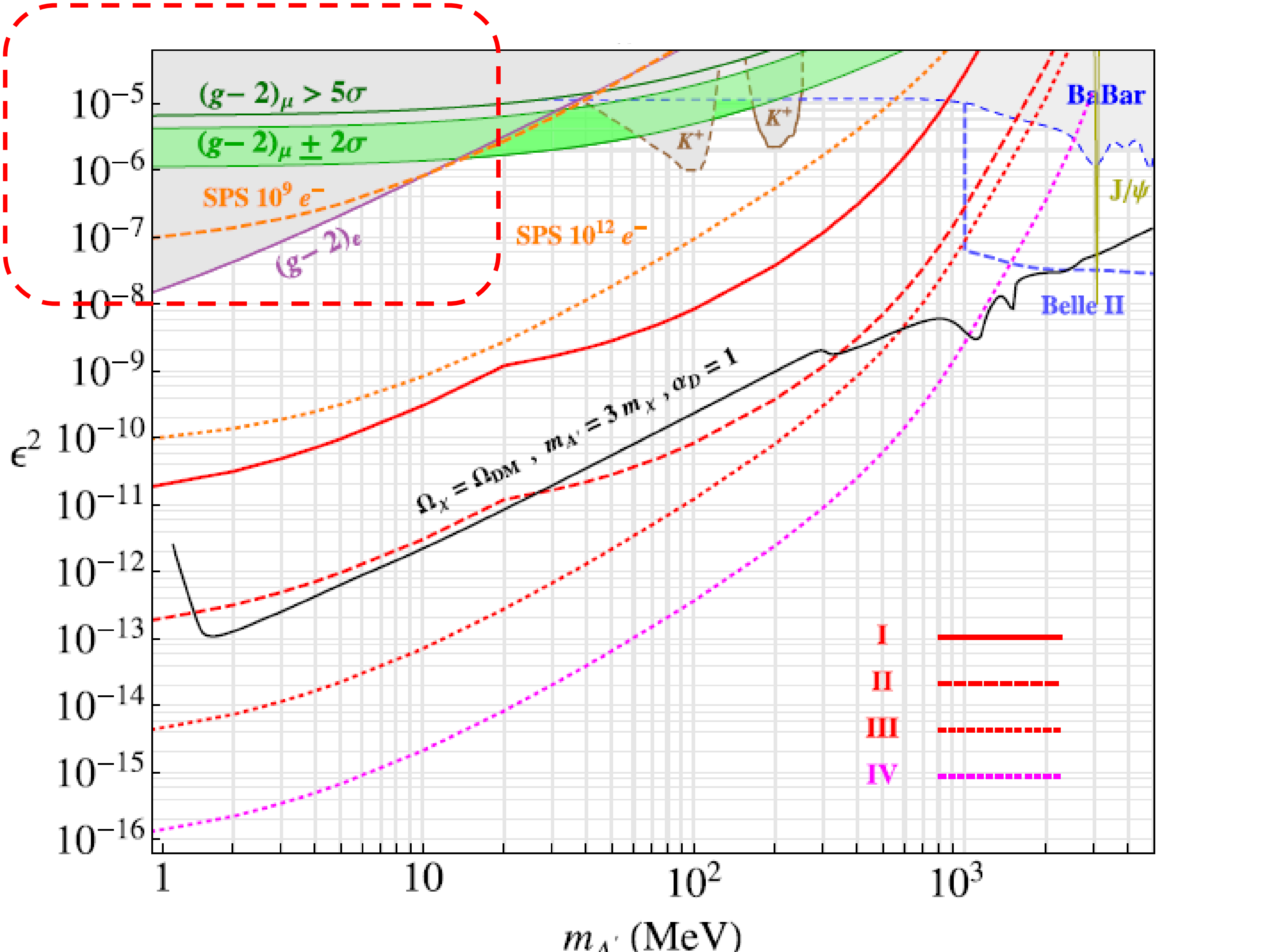


Contribution from dark photon





From "Results and perspectives in dark photon physics" by M. Raggi and V. Kozhuharov



$(g-2)_\mu > 5\sigma$
$(g-2)_\mu \pm 2\sigma$
SPS 10^9 e^-
SPS 10^{12} e^-
$(g-2)_e$
K^+
K^+
BaBar
J/ψ
Belle II
$\Omega_\chi = \Omega_{DM}$, $m_{A'} = 3\, m_\chi$, $\alpha_D = 1$
I
II
III
IV
ϵ^2
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1
10
10^2
10^3
$m_{A'}$ (MeV)

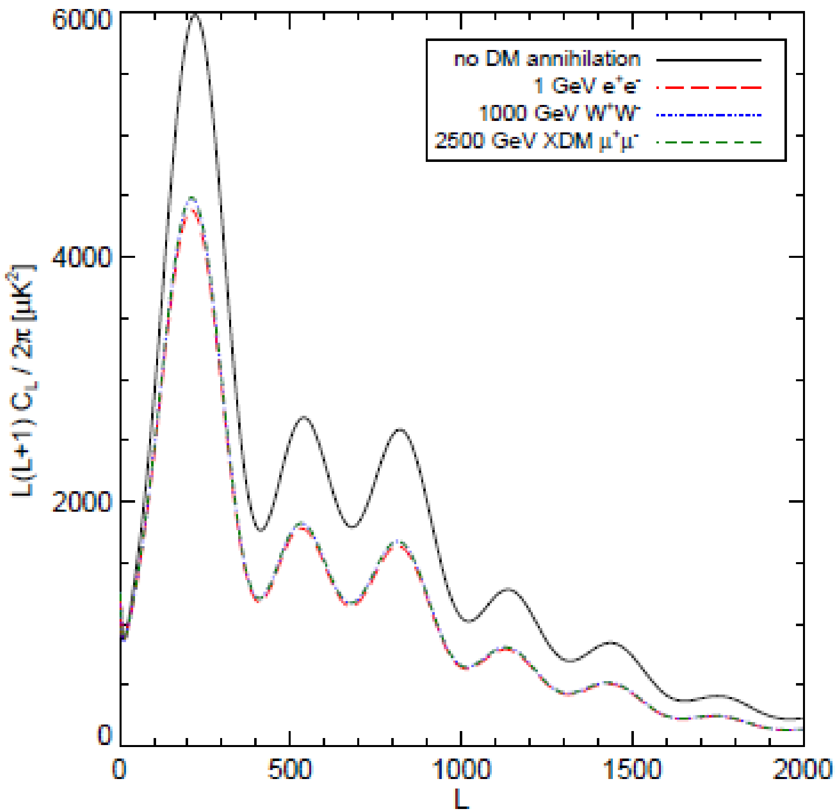
C. Cosmological constraints -- CMB

Dark matter annihilation can modify the observed temperature and polarization fluctuations of the CMB.

・ Abundance of the DM is known

・ CMB fluctuation is measured by COBE, WMAP, Plank, , ,

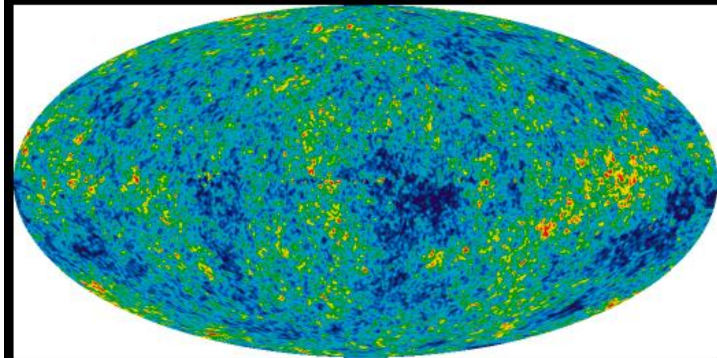
$$\chi\bar{\chi} \rightarrow (A) \rightarrow e^+e^-$$



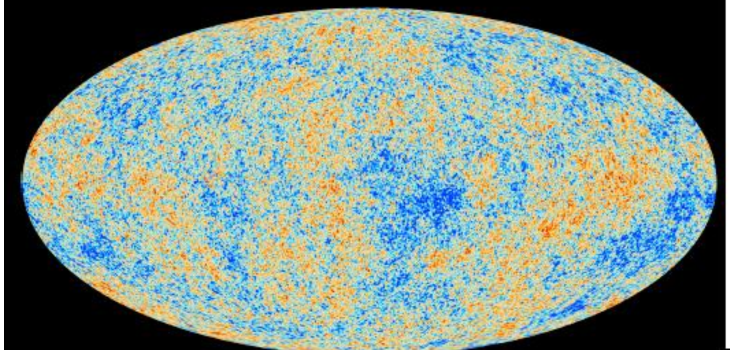
T. R. Slatyer, N Padmanabhan, and D. P. Finkbeiner, Phys. Rev. D 80, 043526 (2009)

Constrain about this cross-section is derived.

Reference : CMB fluctuation from WMAP/Plank

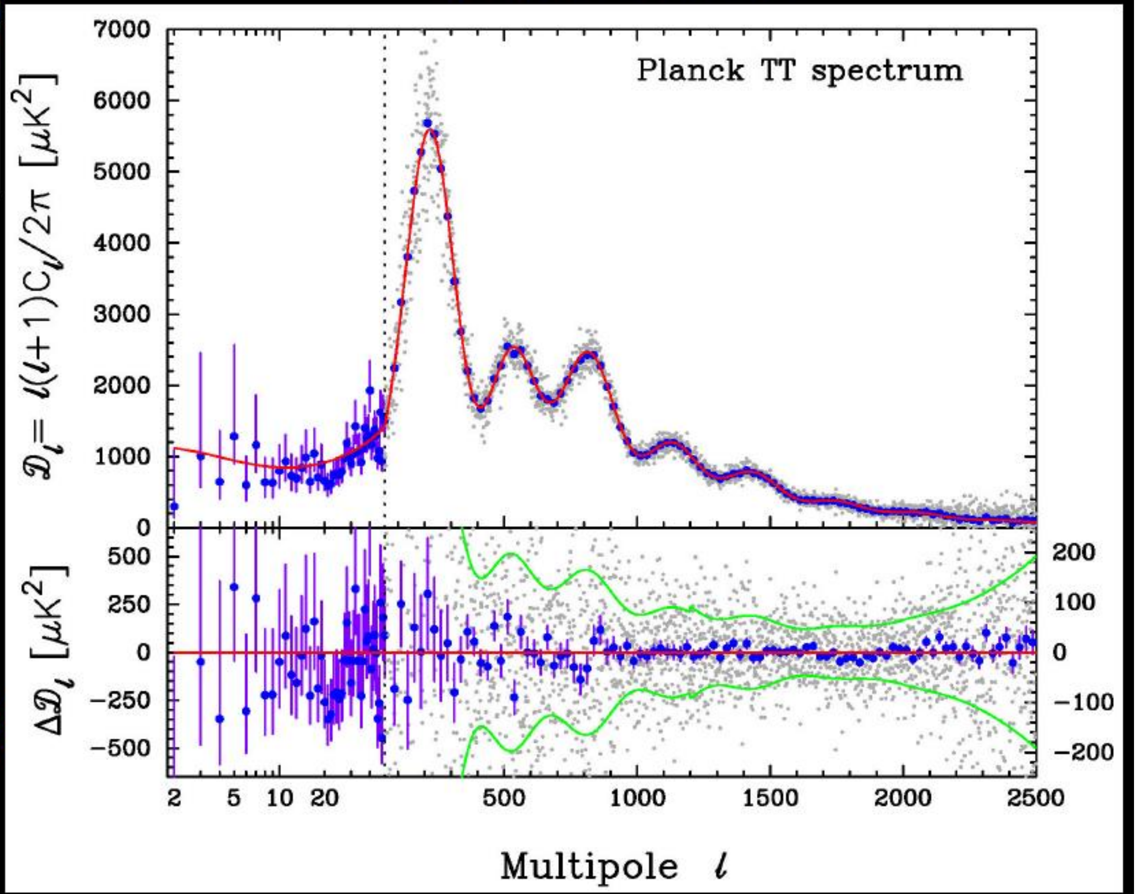


WMAP 9year map



Planck 15.5month map

Planck 2013 results XVI
Cosmological Parameters
arXiv:1303.5076

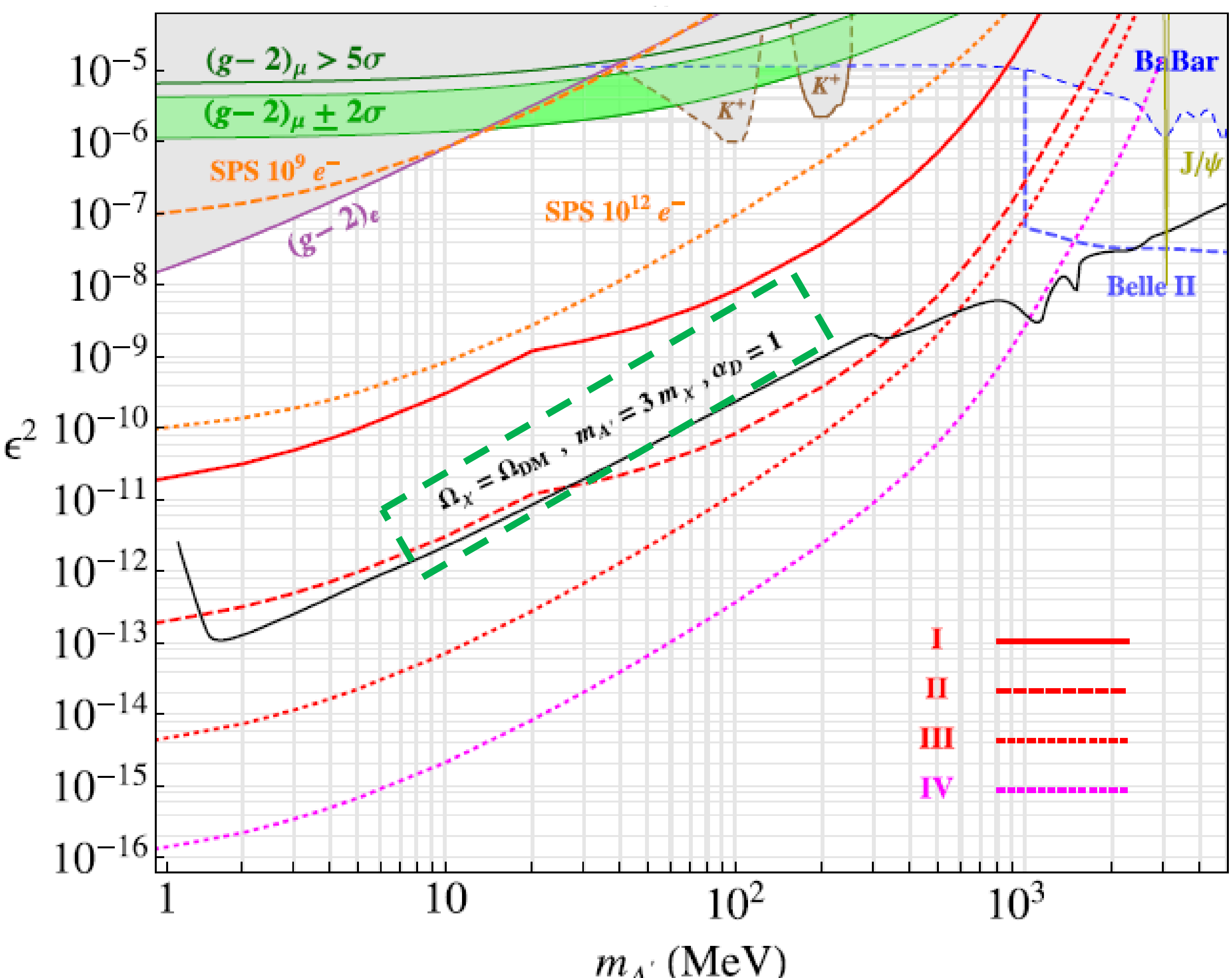


- $$\epsilon^2 \simeq 1.3 \times 10^{-8} \left(\frac{m_{A'}}{10\ \mathrm{MeV}}\right)^4 \left(\frac{\mathrm{MeV}}{m_\chi}\right)^2 \left(\frac{10^{-2}}{\alpha_D}\right). \quad (3)$$

-- It is explained that above relation is derived from the result of the observations with constraints by assuming mass hierarchy, particle-antiparticle symmetry , and so on.

- If mixing ε is large enough, then annihilation process happens so frequently → $\Omega_\chi < \Omega_{DM}$

(χ is not dominant component of DM)



(g− 2)μ > 5σ
(g− 2)μ ± 2σ
SPS 10^9 e^−
SPS 10^12 e^−
(g− 2)e
K+
K+
BaBar
J/ψ
Belle II
Ωχ = ΩDM , mA′ = 3 mχ , αD = 1
I
II
III
IV
ϵ^2
mA′ (MeV)

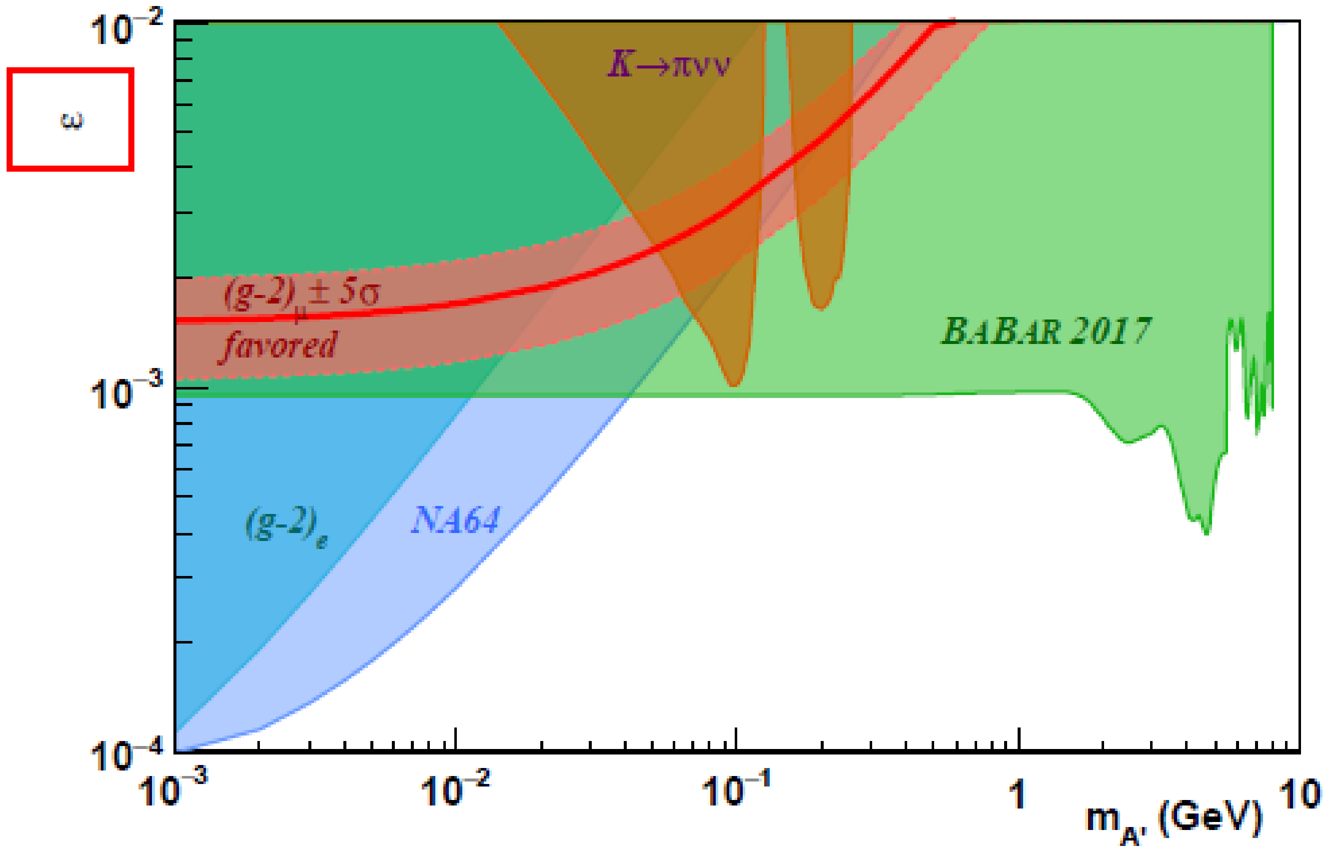
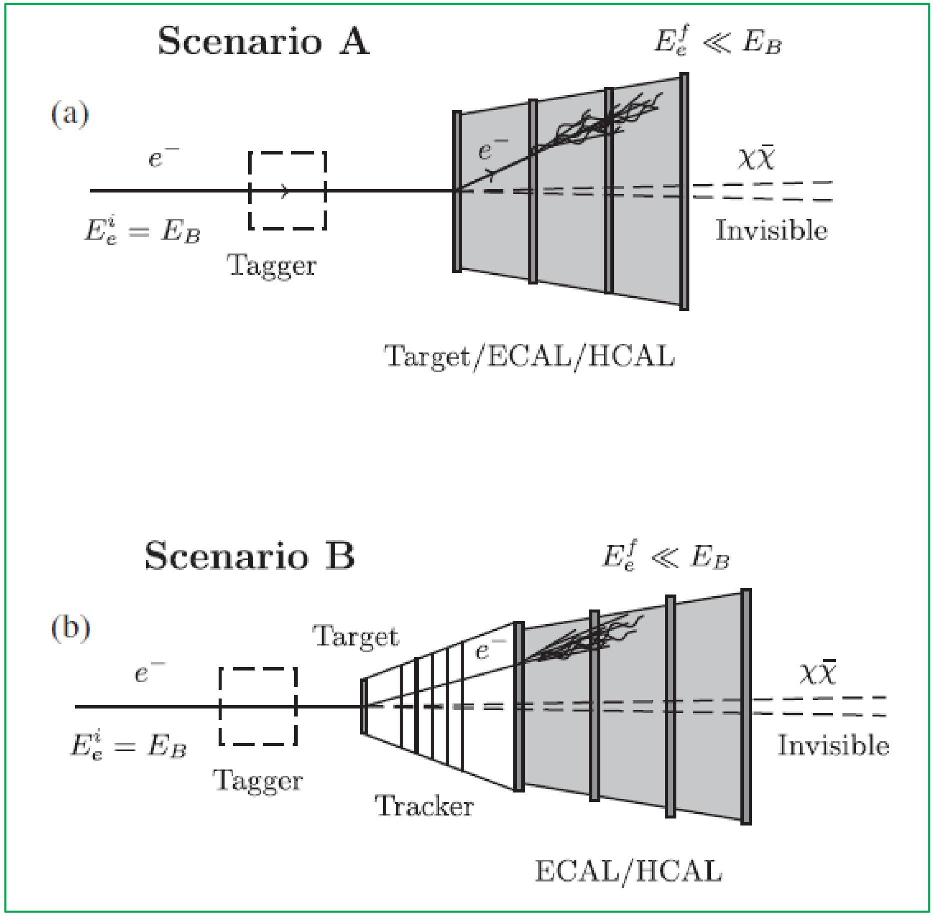


FIG. 5: Regions of the A' parameter space (ε vs $m_{A'}$) excluded by this work (green area) compared to the previous constraints [7, 18–20] as well as the region preferred by the $(g-2)_\mu$ anomaly [5].

arXiv:1702.03327v1 [hep-ex] from BaBar collaboration

Main arguments of this paper (especially, after $4 (page 5))

-- Limits of a forward calorimeter experiment --



Schematic of assumed experiment setups

Real Missing Energy	Magnitude (10^{16}EOT$_{\rm eff}$)
Brem + CCQE	<1 ($T \lesssim 0.1$)
CCQE + π^0	<1 ($T \lesssim 0.1$)
Moller + CCQE	$\ll 1$ ($T \lesssim 0.1$)
$eN \to eN\nu\bar{\nu}$	$\sim 10^{-2}$

Reducible Backgrounds	Fake Rate/10^{14}EOT$_{\rm eff}$
γ non-interaction	$\sim 3\times 10^8 e^{-\frac{7}{9}(T/X_0=45)} \ll 1$
$\gamma p \to \pi^+ n$	$\sim 10^2 \times \epsilon_\pi \epsilon_n$
$\gamma^* p \to \pi^+ n$ (backscatter π^+)	$\sim 3\times 10^1 \times \epsilon_n$ (see text)
$\gamma N \to (\rho, \omega, \phi) N \to \pi^+\pi^- N$	$\sim 2\times 10^4 \epsilon_\pi^2$
$\gamma^* n \to n\bar{n}n$	$\sim 3\times 10^3 \times \epsilon_n^3$
$eN \to eN(\mu^+\mu^-, \pi^+\pi^-)$	$\sim 10^4 \times \epsilon_{\mu/\pi}^2$
$\gamma N \to N\mu^+\mu^-$	$\sim 6\times 10^3 \times \epsilon_\mu^2$

Summary of backgrounds (Scenario B)

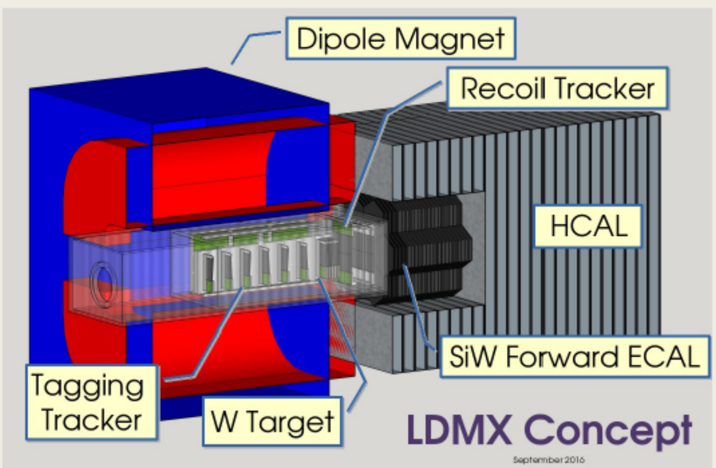
Since it is too detail,,, I just bring a slide of “LDMX” next

Light Dark Matter eXperiment (LDMX)

Project Status

SLAC

- DASEL beamline design is at an advanced stage
  - *Project is being discussed with DOE to allow installation of the DASEL beamline during the LCLS-II construction stop in 2019*

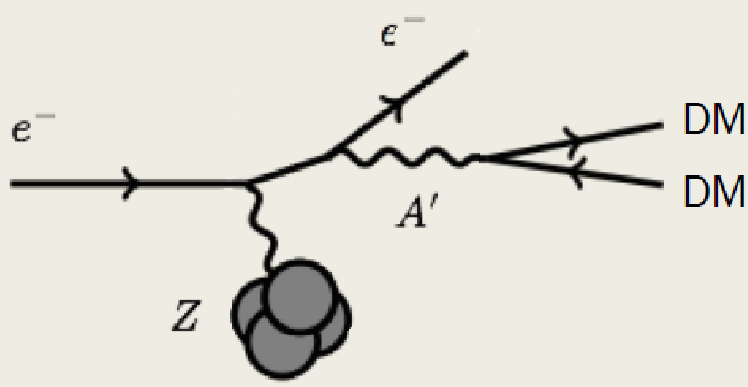


- LDMX experiment design process is making good progress
  - *Current studies are focused on identifying photonuclear backgrounds in the calorimeters and target*
- Construction schedule focused on 2020/21 operation
  - *Compatible with CMS endcap calorimeter construction schedule*

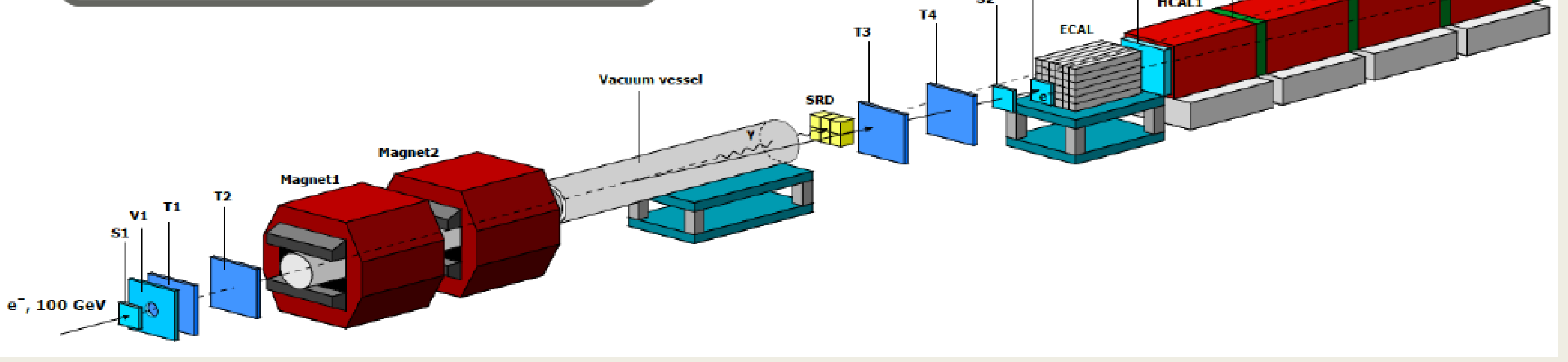
From a slide “The LDMX EXPERIMENT” , Jeremiah Mans (University of Minnesota), Oct 2016

Missing Momentum Concept

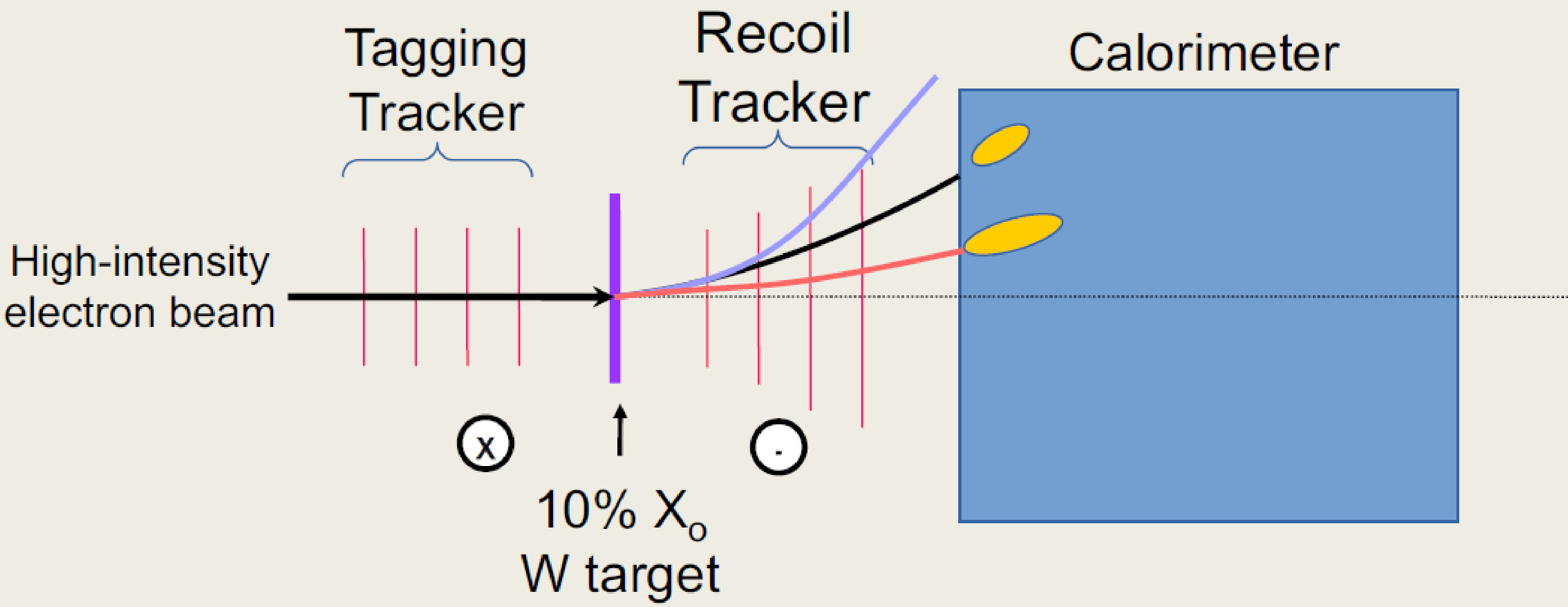
- Disappearance measurement: Use an electron beam on an active fixed target and identify events where momentum (energy) is lost
  - Use of a moderate energy electron beam suppresses neutrino backgrounds compared with proton beams



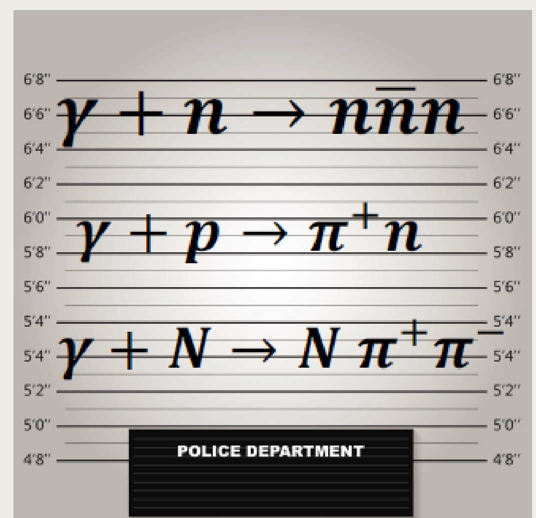
First generation, fixed-target missing energy search : NA64



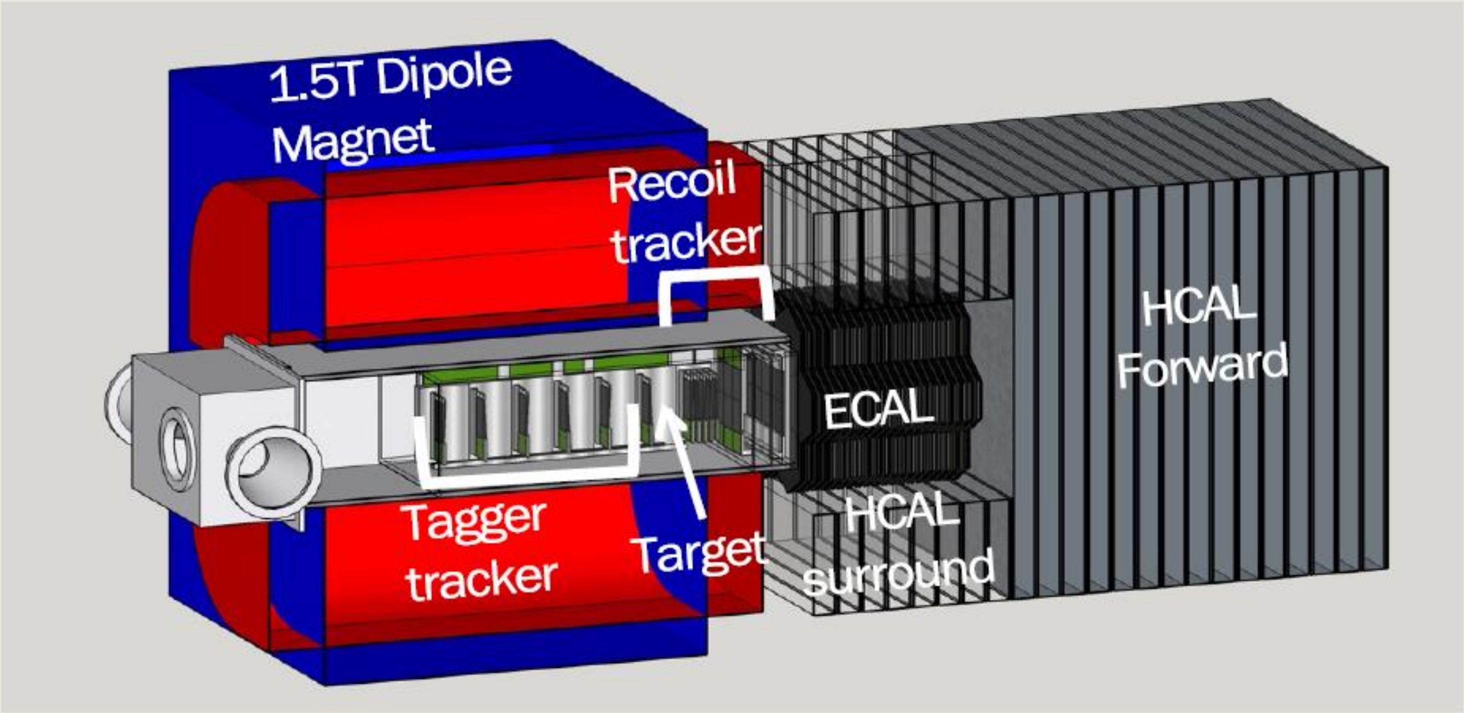
Cartoon Guide to LDMX



- Signal definition is a low energy, moderate p_T electron and an otherwise empty calorimeter given a full-energy beam electron
  - Recoil p_T between ~80 MeV and 800 MeV
- Backgrounds come from hard interactions in the target (e.g brehmstrahlung)
  - Several challenging backgrounds arise when the forward photon has a photonuclear interaction

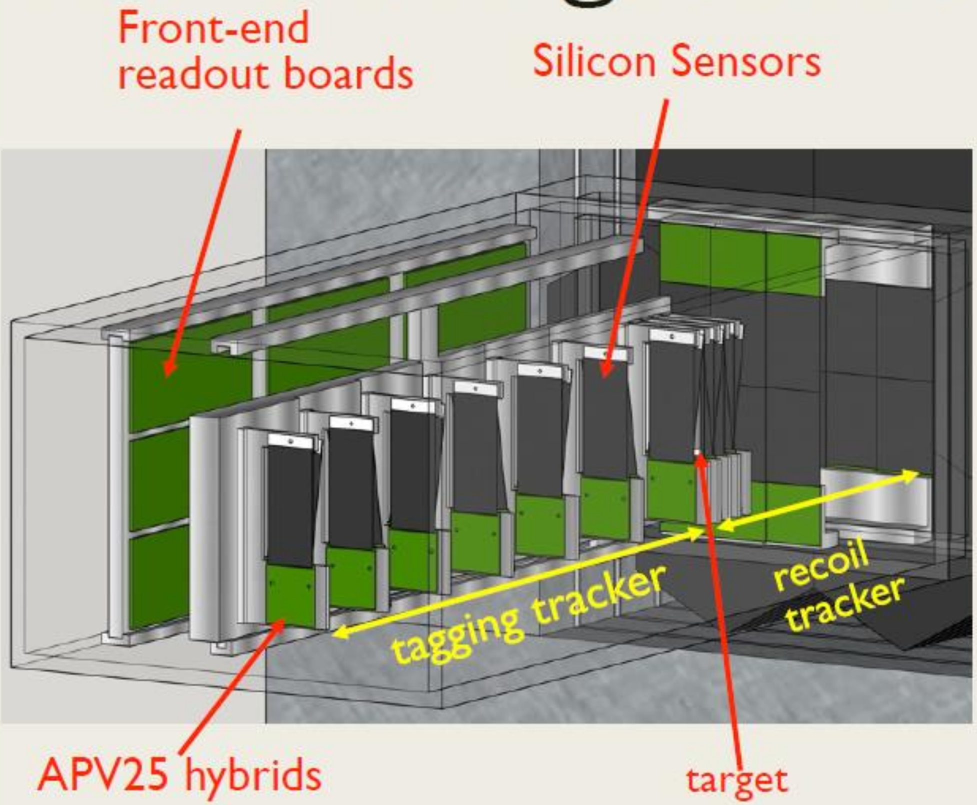


The LDMX Detector Concept



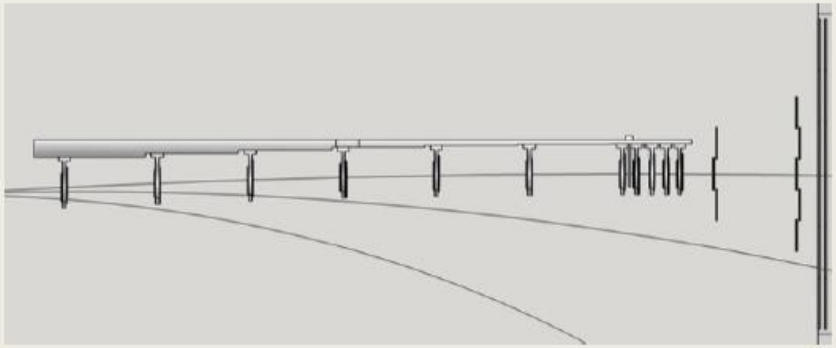
- Dual purpose Magnet and Tracking
  - *Collimated precision tagger tracker in full field → 10% X_0 target → compact and precision recoil tracker in fringe field*
- Si-W sampling calorimeter (ECAL)
  - *40 X_0, 30 Layers, 7 modules per layer of high efficiency, high granularity calorimetry*
- Scintillator-Steel sampling calorimeter (HCAL) behind and around ECAL
  - *15 layers, un-segmented for simplicity : Veto any event with hadronic activity*

Tracker designs based on HPS



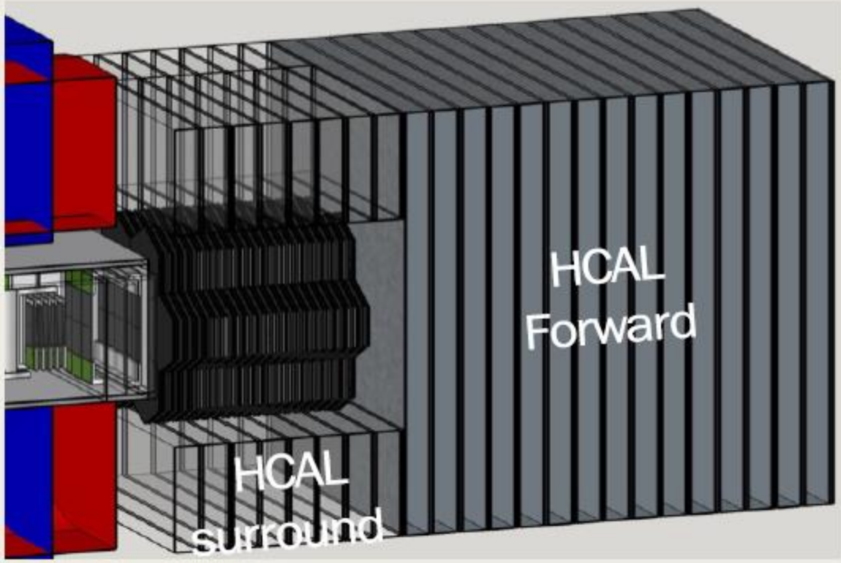
- Tagging tracker: Tag incoming e-
  - Precise p and (x,y) position at target.
- Recoil tracker:
  - Associate tag to recoil
  - Determine p after the target down to 50 MeV

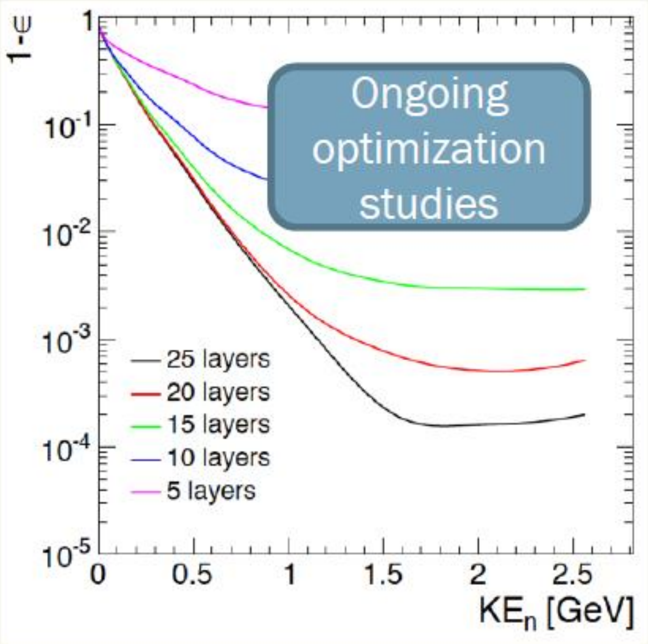
- Screen out straggling (off E_{Beam}) electrons
- Measure Δp across target
  - The key discriminator



Hadronic Veto Calorimeter

- Critical role is in the identification of neutron-containing backgrounds
- Technology concept is based on iron absorber and plastic scintillator read out using CMS Phase 1 SiPM-based electronics





- Ongoing optimization studies including a "surrounding" HCAL to catch large-angle (45) neutrons and catch wide-angle brehmstrahlung in the target

Physics potential