Physics of Dark Gauge Interaction

(with an emphasis on low-energy parity test implications)

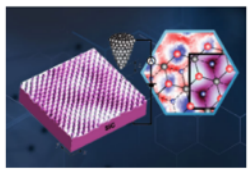
Hye-Sung Lee

Institute for Basic Science
CTPU

CosPA 2015
(Daejeon, October 2015)

Before my talk,
Let me introduce CTPU.

Institute for Basic Science



Center for Artificial Low Dimensional Electronic Systems

Our society in the twenty-first century is based on information technology, which is supported by logic and memory devices produced by the semiconductor industry. So far, the development of the device indus...

Director | Han Woong Yeom

Detail

Center for Underground Physics

We now know that neutrinos are massive. But we do not know their absolute masses nor their natures. Discovering these important unknowns can be related to leptogenesis theories that make attempts to ...

Director | Yeong Duk Kim

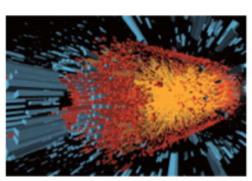
Detail

Center for Relativistic Laser Science

The Center for Relativistic Laser Science (CoReLS) was established in December 2012 to explore novel physical phenomena in the relativistic laser intensity regime. The electron motion enters the relativistic regime ...

Director | Chang Hee Nam

Detail

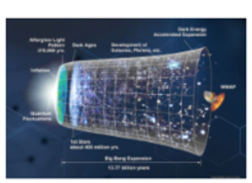


Center for Axion and Precision Physics Research

The IBS Center for Axion and Precision Physics Research (CAPP) is located in Daejeon City at the Korea Advanced Institute of Science and Technology (KAIST). Our center aims to launch a state of the art ...

Director | Yannis K. Semertzidis

Detail

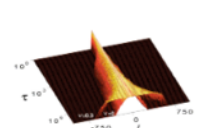


Center for Theoretical Physics of the Universe

The IBS Center for Theoretical Physics of the Universe carries out research on particle physics and cosmology, which aims to understand nature at the most fundamental level and answer the questions about the ...

Director | Kiwoon Choi

Detail



Center for Theoretical Physics of Complex Systems

Today the eyes looking for novel technologies and new generation devices focus on nano- structured materials with unprecedented electrical, mechanical, optical and other properties like graphene, nanotubes, ...

Director | Sergej Flach

Detail

Center for Theoretical Physics of the Universe (CTPU)

- One of the IBS centers (at Headquarter)
- Since November 2013
- Particle Theory and Cosmology
- Faculty members, Postdoctoral fellows, Administrative staff
- Intern students, Visitors

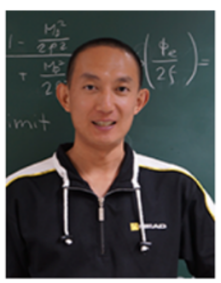
CTPU faculty members

- **Kiwoon Choi**
- Tel. 8400
- kchoi(AT)ibs.re.kr

Kiwoon Choi (Director)

- **Sang Hyeon Chang**
- Physics beyond the Standard Model, Supersymmetry, Particle cosmology
- Tel. 8420
- schang(AT)ibs.re.kr

Sang Hyeon Chang



- **Kenji Kadota**
- Particle Cosmology: early Universe (inflation, baryo/leptogenesis), particle phenomenology(dark matter, supersymmetry, collider), cosmology (galaxy clusters, CMB)
- Tel. 8414
- kadota(AT)ibs.re.kr
- http://ctpu.kaist.ac.kr/~kenji/

Kenji Kadota

- **Hye-Sung Lee**
- Particle Theory (especially, physics beyond the standard model)
- Tel. 8416
- hlee(AT)ibs.re.kr
- https://sites.google.com/site/leeprime/

Hye-Sung Lee

- **Myeonghun Park**
- Collider Physics and Dark matter phenomenology of the physics beyond the Standard Model
- https://sites.google.com/site/ishaed/

Myeonghun Park

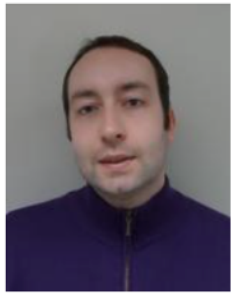
At CTPU, we study New Physics in Particle Physics and Cosmology.

Our emphasis is particularly on the Dark sector of the Universe.

(Dark matter physics,
Dark gauge interaction,
Collider searches of dark sector, …)

Axion, Inflation, Dark matter, CMB, Supersymmetry, New gauge symmetry, Dark force, Collider signals, Electroweak symmetry breaking, Higgs boson, …

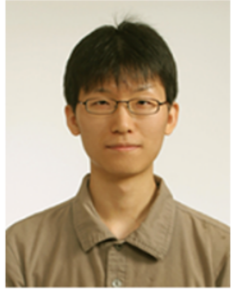
CTPU postdoctoral fellows



- **Stephen Angus**
- String phenomenology, BSM
- Tel. 8419

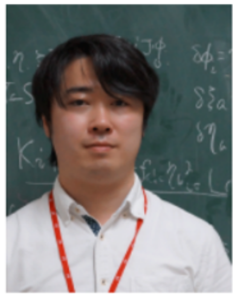
- **Wonsang Cho**
- Collider phisics, Beyond the Standard Mode Optimization, Evolutionary algorithms, Info
- Tel. 8417
- hepkosmos(AT)ibs.re.kr

- **Arsham Farzinnia**
- Beyond the Standard Model physics, Electro massive color-octets, Collider phenomenolo
- Tel. 8412
- farzinnia(AT)ibs.re.kr



- **Sang Hui Im**
- Supersymmetry (NMSSM), Axion physics, F
- Tel. 8415
- shim(AT)ibs.re.kr

- **Min-Seok Seo**
- Physics beyond the Standard Model, Supersymr
- Tel. 8411
- minseokseo(AT)ibs.re.kr



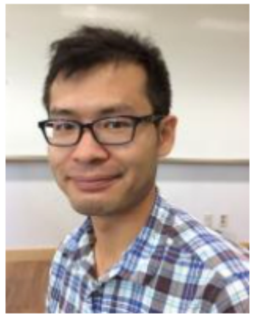
- **Ryoutaro Watanabe**
- Flavor physics, B physics, Higgs sector, Lepton f
- Tel. 8413
- wryou1985(AT)ibs.re.kr

- **Yang Hwan Ahn**
- Particle Theory (especially, physics beyond the
- yhahn(AT)ibs.re.kr

- **Kunio Kaneta**
- Particle Theory (collider phenomenology, electrowe matter, neutrino physics, leptogenesis, physics bey

- **Andrew Spray**
- Beyond the Standard Model physics, Dark Matte Phenomenology

- **Doh Young Mo**
- Beyond the Standard Model, Supersymmetry, Co Physics

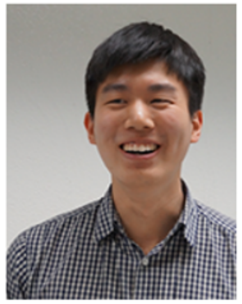


- **Toyokazu Sekiguchi**

- **Ohkyung Kwon**
- Particle Astrophysics, Quantum Geometry and Quantum Principle, Interferometric Phenomenology
- o.kwon(AT)kaist.ac.kr

a dozen postdoctoral fellows in various research fields

CTPU intern students, visitors, staffs



- **Hyungjin Kim**
- KAIST
- Inflationary Cosmology
- hjkim06(AT)kaist.ac.kr
- http://sites.google.com/site/hyungjii

- **Hyeon Seok Seong**
- KAIST
- Cosmology
- sbravos(AT)kaist.ac.kr

- **Eunkyung Bang**
- Administrative staff
- Tel. 8401
- bek0328(AT)ibs.re.kr

- **Sang Joon Lee**
- KAIST

- **Inwoo Park**
- jegallyang(AT)gmail.com

- **Junghyun Kim**
- Administrative staff
- wjdgus06(AT)ibs.re.kr

- **Sung Hak Lim**
- KAIST
- sunghak.lim(AT)kaist.ac.kr

- **Subeom Kang**
- KAIST

- **Mijin Kim**
- Administrative staff
- Tel. 8402
- mijin1024(AT)ibs.re.kr

- **Seok Hoon Yun**
- KAIST

- **Minho Kim**
- POSTECH
- kmhmon(AT)postech.ac.kr

- **Sung Yeop Na**
- Administrative staff
- Tel. 8403
- nsy0128(AT)ibs.re.kr

many intern students, frequent visitors, and administration staff

Center for Theoretical Physics of the Universe (CTPU)

Center for Theoretical Physics of the Universe (CTPU)

Physics of Dark Gauge Interaction

(with an emphasis on low-energy parity test implications)

Hye-Sung Lee

(IBS Center for Theoretical Physics of the Universe)

CosPA 2015
(Daejeon, October 2015)

Outline

1. Brief history of $\sin^2 \theta_W$ physics
2. Dark Force Models (Dark Photon, Dark Z)
3. Typical Dark force searches (based on dilepton decay channels)
4. Invisibly decaying Dark gauge boson ($Z' \rightarrow \chi\chi$)
5. Importance of Low-Q^2 parity test (precise measurement of $\sin^2 \theta_W$)

History of $\sin^2\theta_W$ physics

1961. Glashow introduced $SU(2)_L \times U(1)_Y$ symmetry ($W^\pm$, W^0, B).

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W^0_\mu \ , \quad Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W^0_\mu$$

1967. Weinberg added the Higgs mechanism (with a Higgs doublet and a vev).

$m_W = m_Z \cos\theta_W$ (mass relation with θ_W is given)

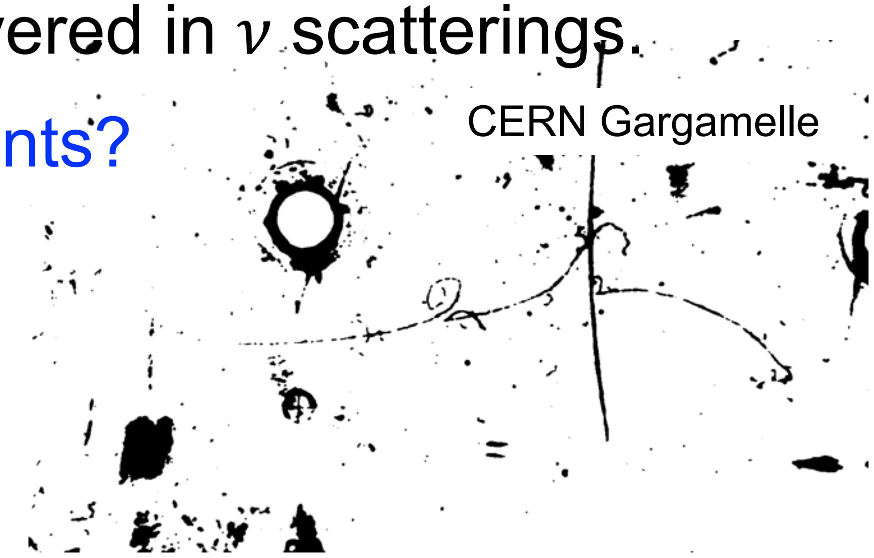
and also predicted the weak neutral currents mediated by Z.

1973. Neutral currents (predicted in the SM) were discovered in ν scatterings.

But is the SM a correct theory for the neutral currents?

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu \left(T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5\right) f$$

Parity Test (weak mixing angle) can tell.



1978. SLAC E122 (polarized eD scattering) measured Parity Violation asymmetry ($\sigma_R - \sigma_L / \sigma_R + \sigma_L$), which gave $\sin^2\theta_W \approx 0.22(2)$. (Agree with the SM)

Parity Test established $SU(2)_L \times U(1)_Y$ as the EW interaction structure.

Lessons from the history

Establishment of the $SU(2)_L \times U(1)_Y$ by the parity test (1978) at SLAC occurred much earlier than the direct discovery of the $W^{\pm}/Z$ boson resonances (1983) at CERN SPS.

The Nobel Prize in Physics 1979

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".*

In the Press release from Nobel foundation:

Neutral Current

The first observation of an effect of the new type of weak interaction was made in 1973 at the European nuclear research laboratory, CERN, in Geneva in an experiment where nuclei were bombarded with a beam of neutrinos. Since then a series of neutrino experiments at CERN and at the Fermi Laboratory near Chicago have given results in good agreement with theory. Other laboratories have also made successful tests of effects of the weak neutral current interaction. Of special interest is a result, published in the summer of 1978, of an experiment at the electron accelerator at SLAC in Stanford, USA. In this experiment the scattering of high energy electrons on deuterium nuclei was studied and an effect due to a direct interplay between the electronmagnetic and weak parts of the unified interaction could be observed.

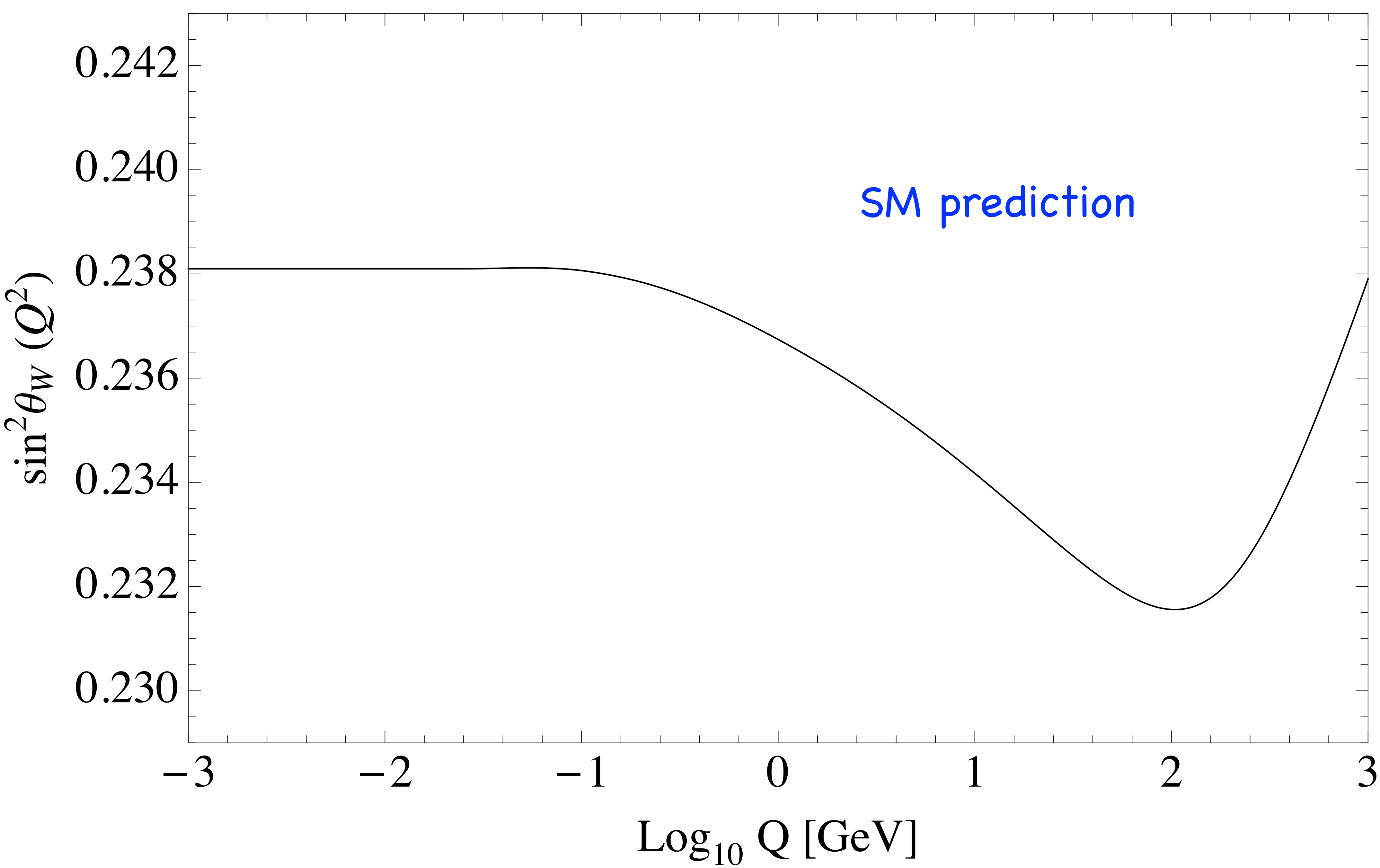
Parity Test

LESSONS from the history:

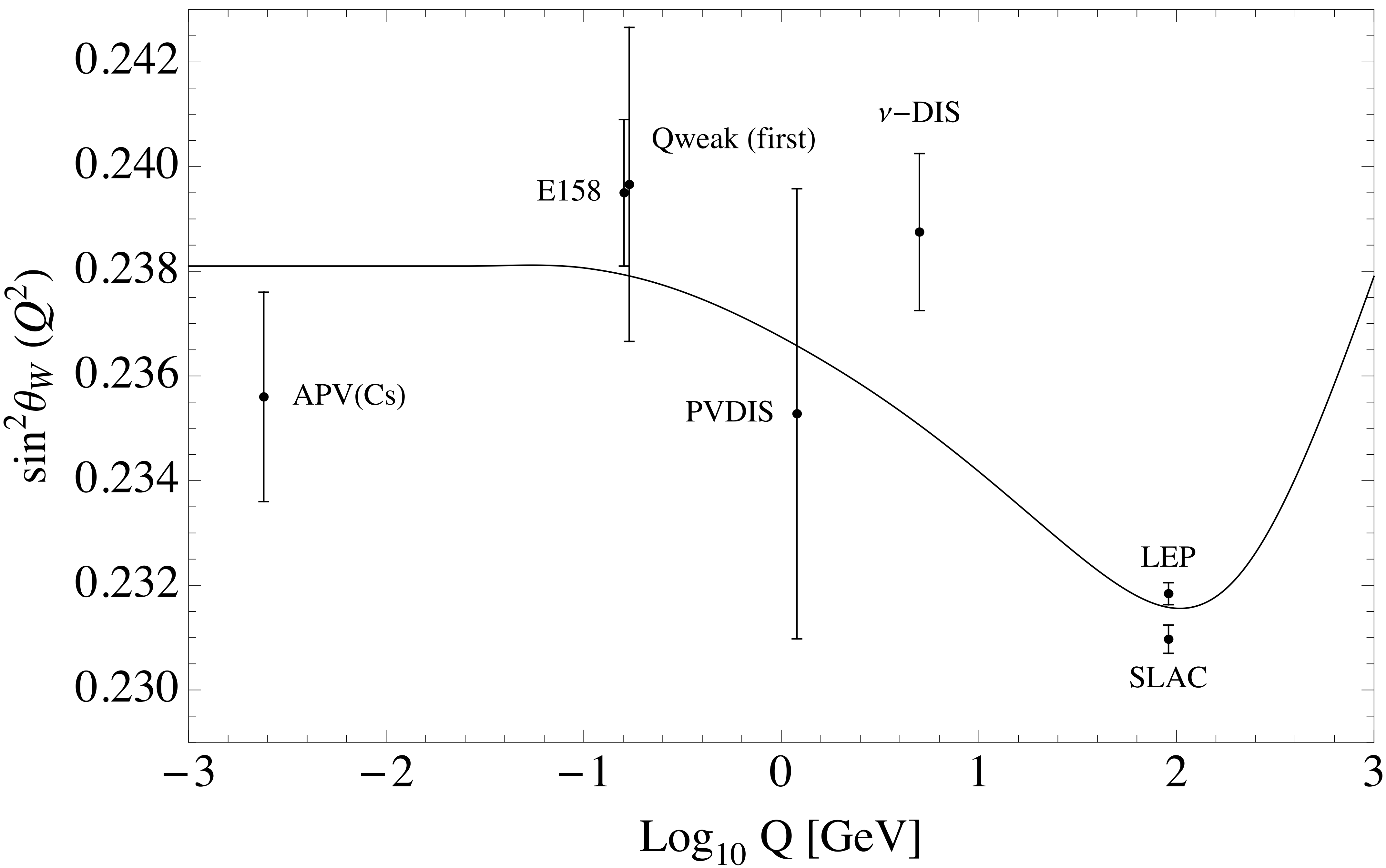
(i) Parity Test (by precise measurement of $\sin^2\theta_W$) can be a critical way to search for a new gauge interaction.

(ii) Its finding may precede the direct discovery of a gauge boson (by bump search).

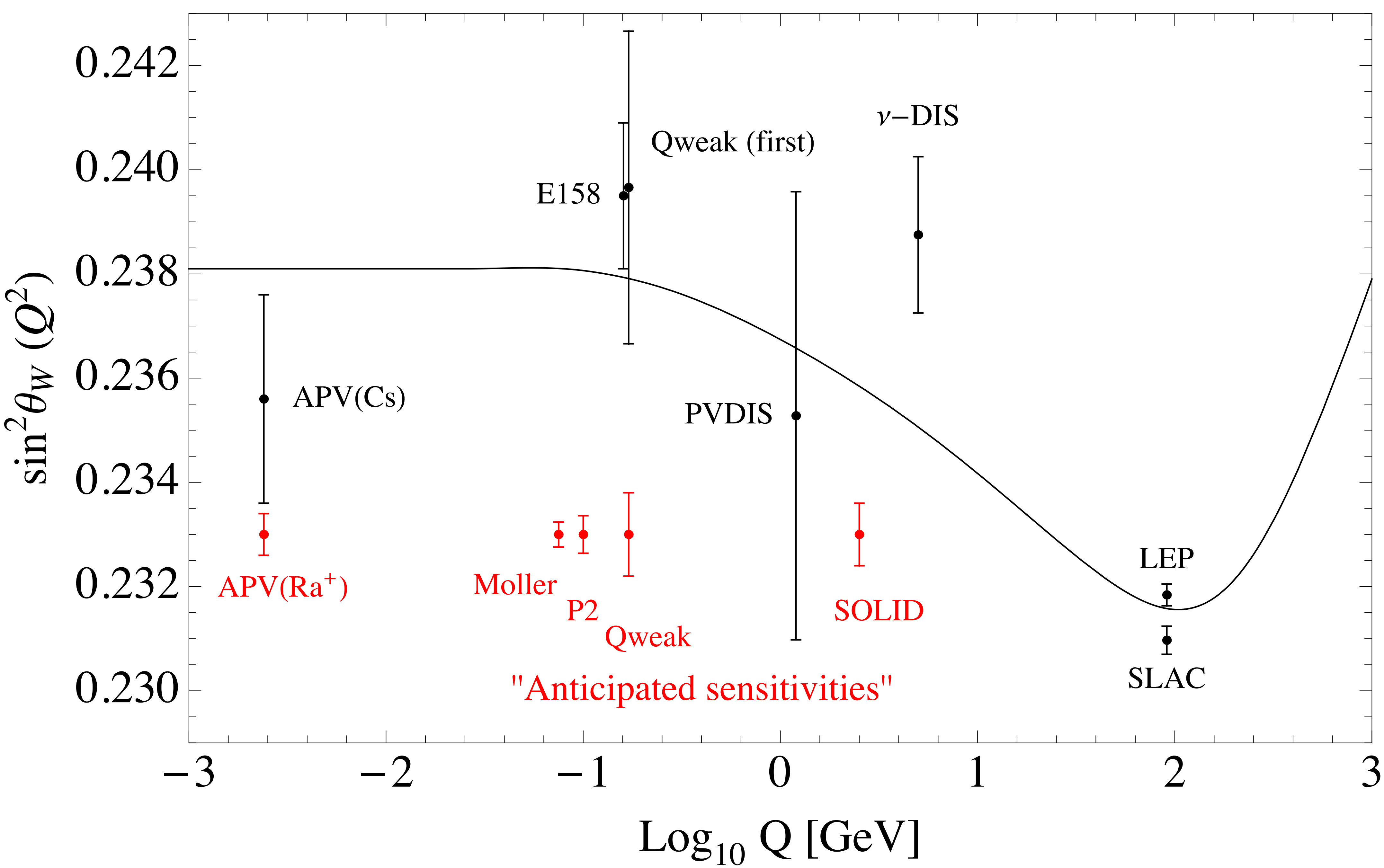
Weak mixing angle running and current constraints



Weak mixing angle running and current constraints



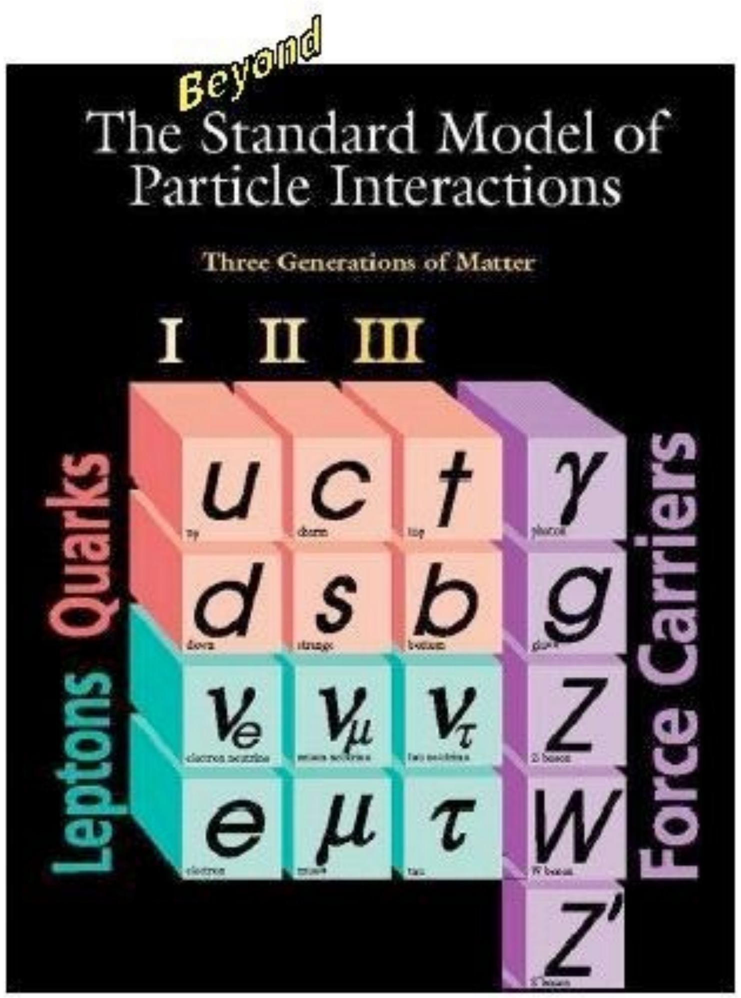
Weak mixing angle running and current constraints

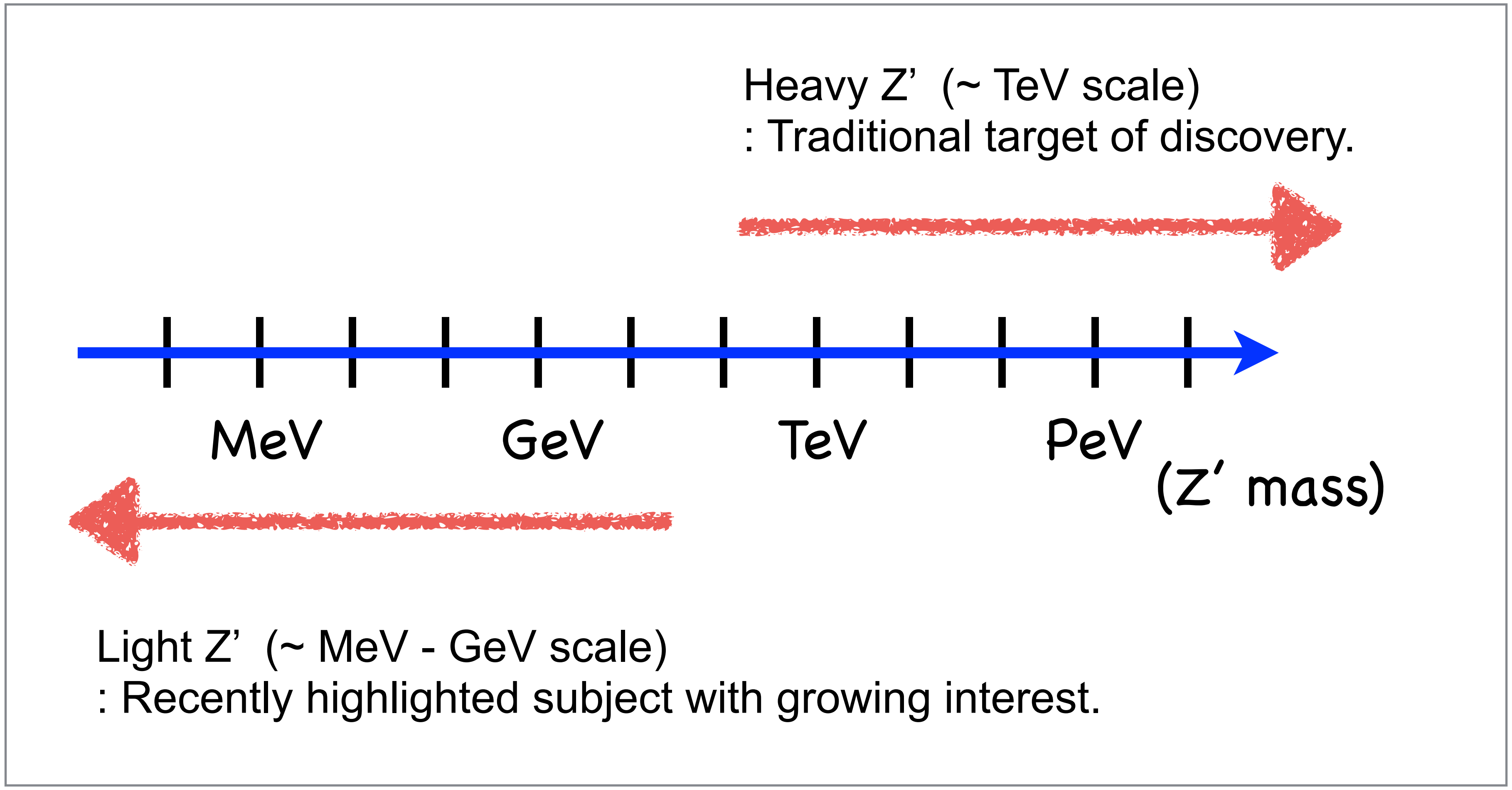


Dark force (Light Z’) models

Dark gauge boson

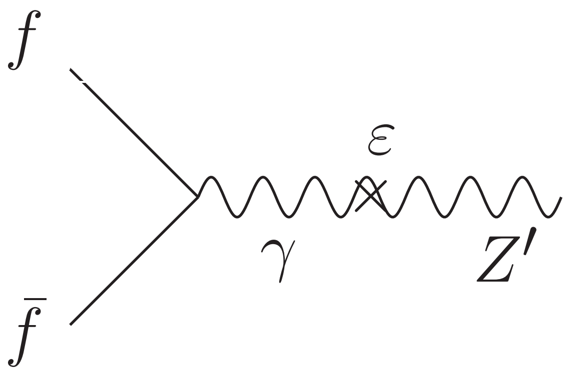
Dark gauge boson : a gauge boson with very small mass and very small coupling, with motivations from the Dark matter physics [e.g. positron excess] and others [e.g. g_μ-2 anomaly]. (Ex: Dark Photon)



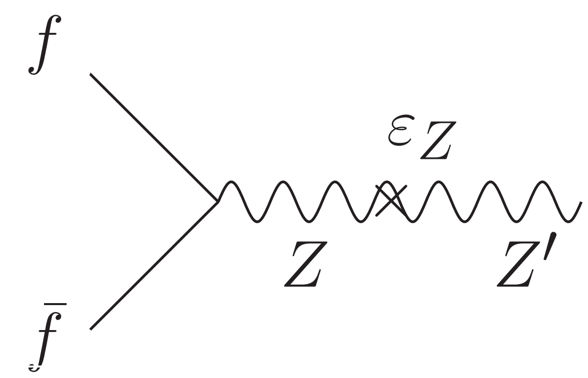


Z'
(Dark Force carrier)

- **Roughly, MeV - GeV scale**
- **Extremely weak couplings to the SM particles**



Light Z' models



Z' : a gauge boson of dark sector U(1). $\mathcal{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$

couples to the SM particles only through small mixing with SM gauge bosons.

model-dependent

(i) Popular Model: **"Dark Photon"** [Arkani-Hamed *et al* (2008); and others]

- Z' mass = MeV - GeV
- Z' coupling = ε×(Photon coupling)

(ii) New Model: **"Dark Z"** [Davoudiasl, LEE, Marciano (2012)]

- Z' mass = MeV - GeV *(cf. Z mass = 91 GeV)*
- Z' coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

inherits properties of Z boson like parity violation.
(different couplings for left/right-handed particles)

Higgs structure matters

Model-dependence in coupling comes from **how Z' gets a mass** (or Higgs sector).

- Dark Photon: (Example) additional Higgs singlet gives mass to Z'

  coupling = ε×(Photon coupling)

  $$\mathcal{L}_{\rm int} = -\varepsilon\, e J^\mu_{em} Z'_\mu$$

  (Coupling to J_{NC} is largely cancelled, for $m_{Z'} \ll m_Z$.)

- Dark Z: (Example) additional Higgs doublet (+ singlet) gives mass to Z'

  coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

  $$\mathcal{L}_{\rm int} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$$

  $$J_\mu^{NC} = \left(\frac{1}{2}T_{3f} - Q_f \sin^2\theta_W\right)\bar{f}\gamma_\mu f - \left(\frac{1}{2}T_{3f}\right)\bar{f}\gamma_\mu\gamma_5 f$$

(Example) Dark Photon case

: Z-Z' kinetic mixing is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading Order.

$$\mathcal{L}_{\rm int} \sim -eJ^\mu_{em}A_\mu - (g/2\cos\theta_W)J^\mu_{NC}Z_\mu$$

(Kinetic mixing diagonalization) $\rightarrow -eJ^\mu_{em}[A_\mu + \varepsilon Z'_\mu] - (g/2\cos\theta_W)J^\mu_{NC}[Z_\mu + O(\varepsilon)Z'_\mu]$

(Z-Z' mass matrix diagonalization) $\rightarrow -eJ^\mu_{em}[A_\mu + \varepsilon Z'_\mu] - (g/2\cos\theta_W)J^\mu_{NC}Z_\mu$

(depends on Higgs sector) *(for Higgs singlet)*

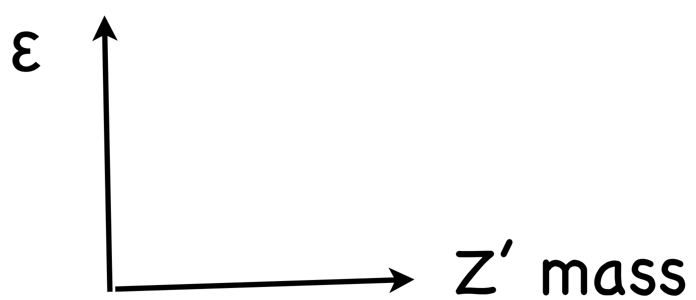
Dark Force couplings depend on "Higgs sector".

Effects of New Model (Dark Z)

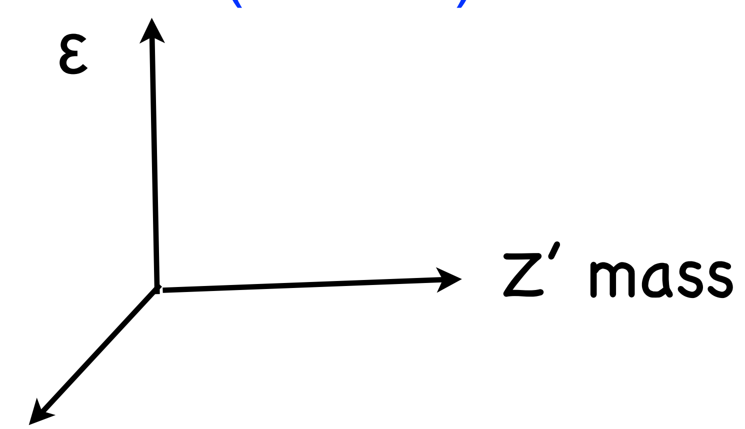
$m_{Z'} \ll m_Z$

Parameter space (Z' mass and coupling to the SM) is extended from 2D to 3D.

(Dark Photon)



(Dark Z)



ε_Z (Z-Z' mixing) **: parity violating**

$$\mathcal{L}_{\rm int} = -\varepsilon\, e J^{\mu}_{em} Z'_{\mu}$$

$$\mathcal{L}_{\rm int} = -[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^{\mu}_{NC}]\, Z'_{\mu}$$

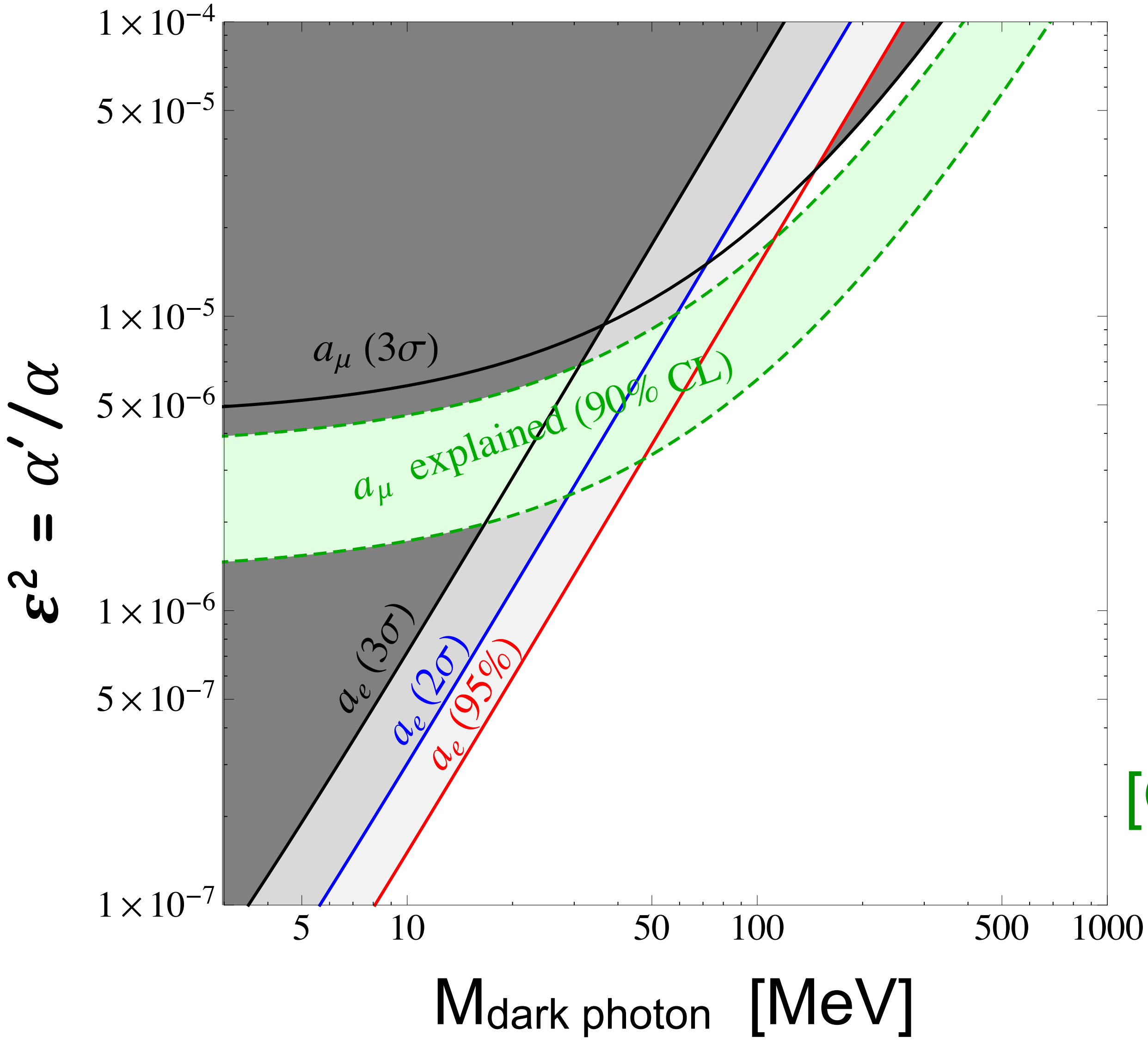
- Dark Z = Dark Photon with more general coupling.
- Dark Photon = a special case of Dark Z ($\varepsilon_Z = 0$ limit).

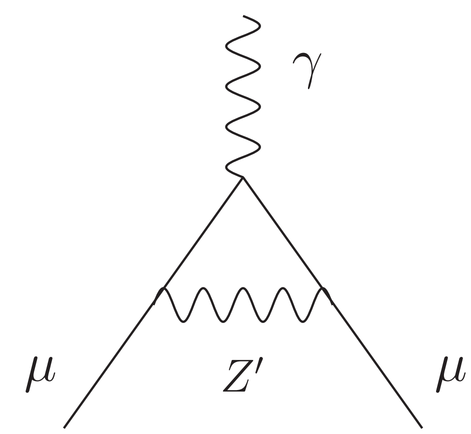
Some experiments irrelevant to Dark Photon searches <u>become relevant</u> to Dark Z searches. They include "**Low-Q^2 Parity Tests**".

(will be back to this later)

Typical Dark Force Searches
(Bump hunt of a new resonance)

Anomalous Magnetic Moment





$$(\text{magnetic moment}) = -\frac{g\mu_B S}{\hbar}$$

Green band: explains the <u>3.6σ deviation in a_μ</u>

(Cf. Tau data now agrees with e+e- data.)

a possible hint of Dark Force

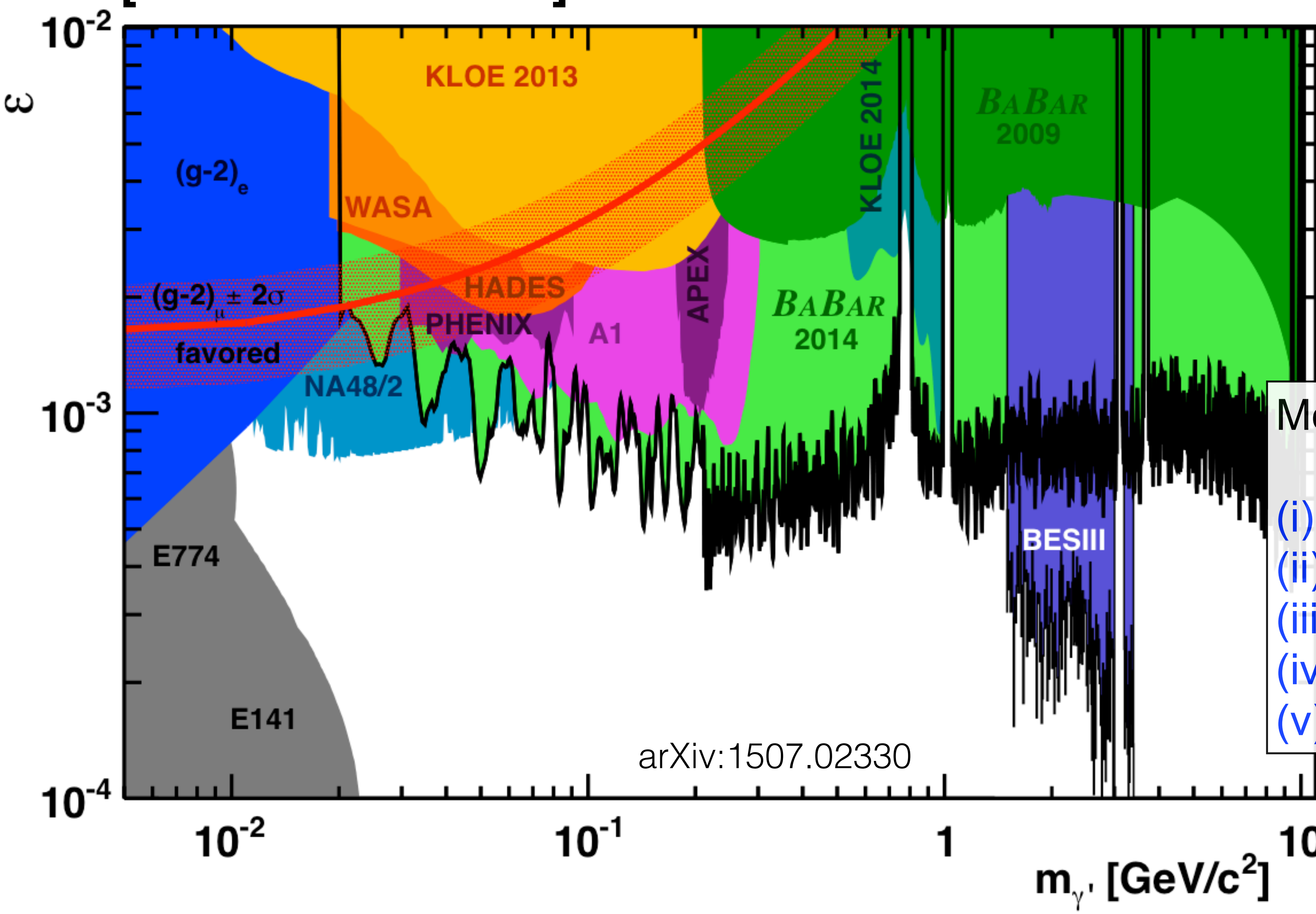
[Gninenko, Krasnikov (2001); Pospelov (2008)]

a_μ **= (g_μ - 2) / 2** : Always an important motivation/constraint for New Physics.

- One of the major motivations for the light Dark gauge boson (Z').
- Unlike other motivations, it is <u>independent of</u> the unknown DM properties.
- It is <u>independent of</u> the Z' decay BR.

Bump searches of Light Z'

[2015 constraints]



[Dark Photon & Dark Z boson]
(as ε_Z is tiny)

Mostly from the Z' → l+l− searches

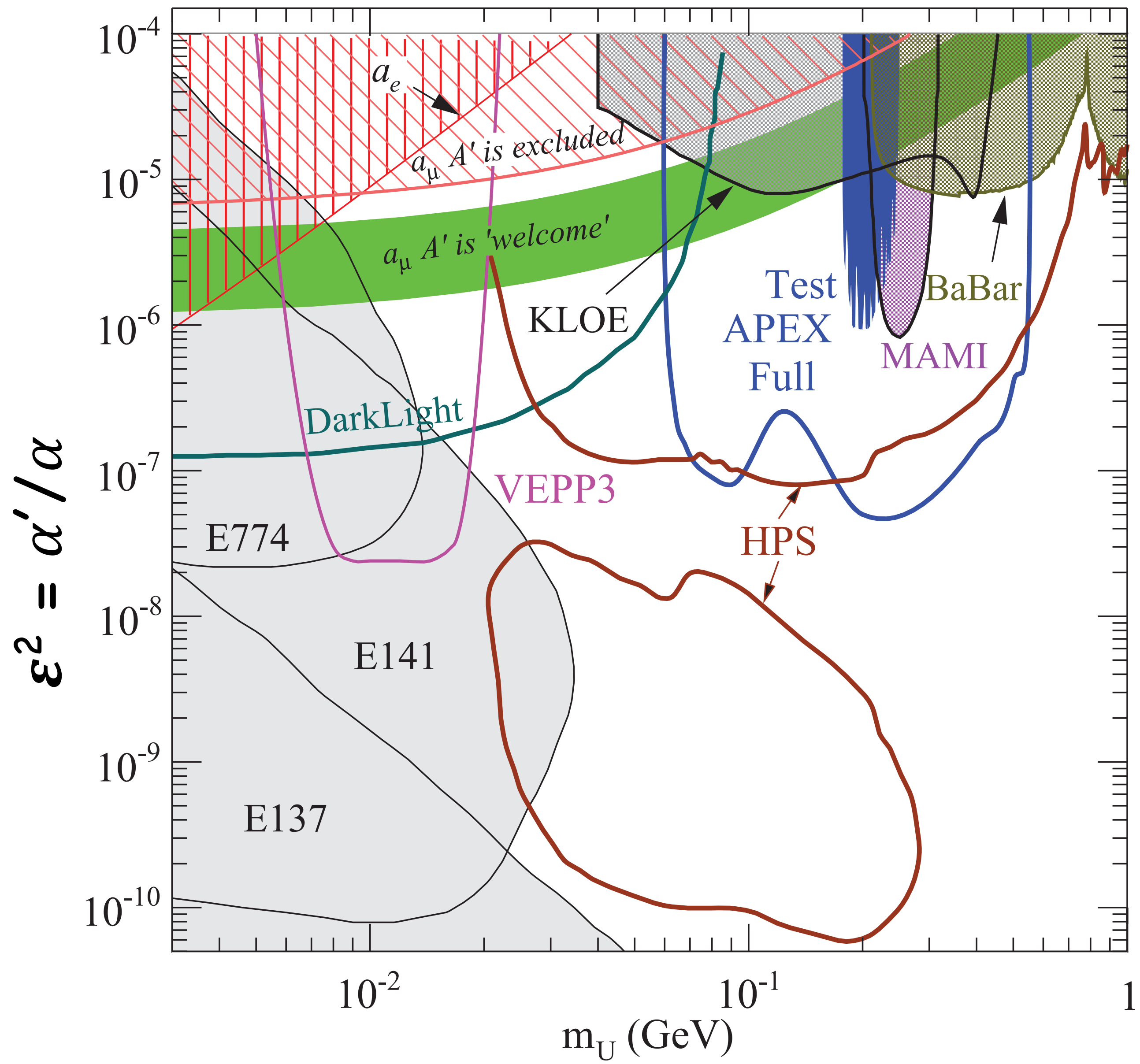
(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) Meson (quarkonium) decays
(iv) e+e- collision (radiation)
(v) Fixed target experiments

With 2015 results [CERN NA48/2 using pion decay closes the last gap (April 2015)]:
whole green band (g_μ-2 favored) is excluded now.

We need to keep probing the other parameter space (Intensity Frontier).

Bump searches of Light Z’

[2011 constraints and plans]

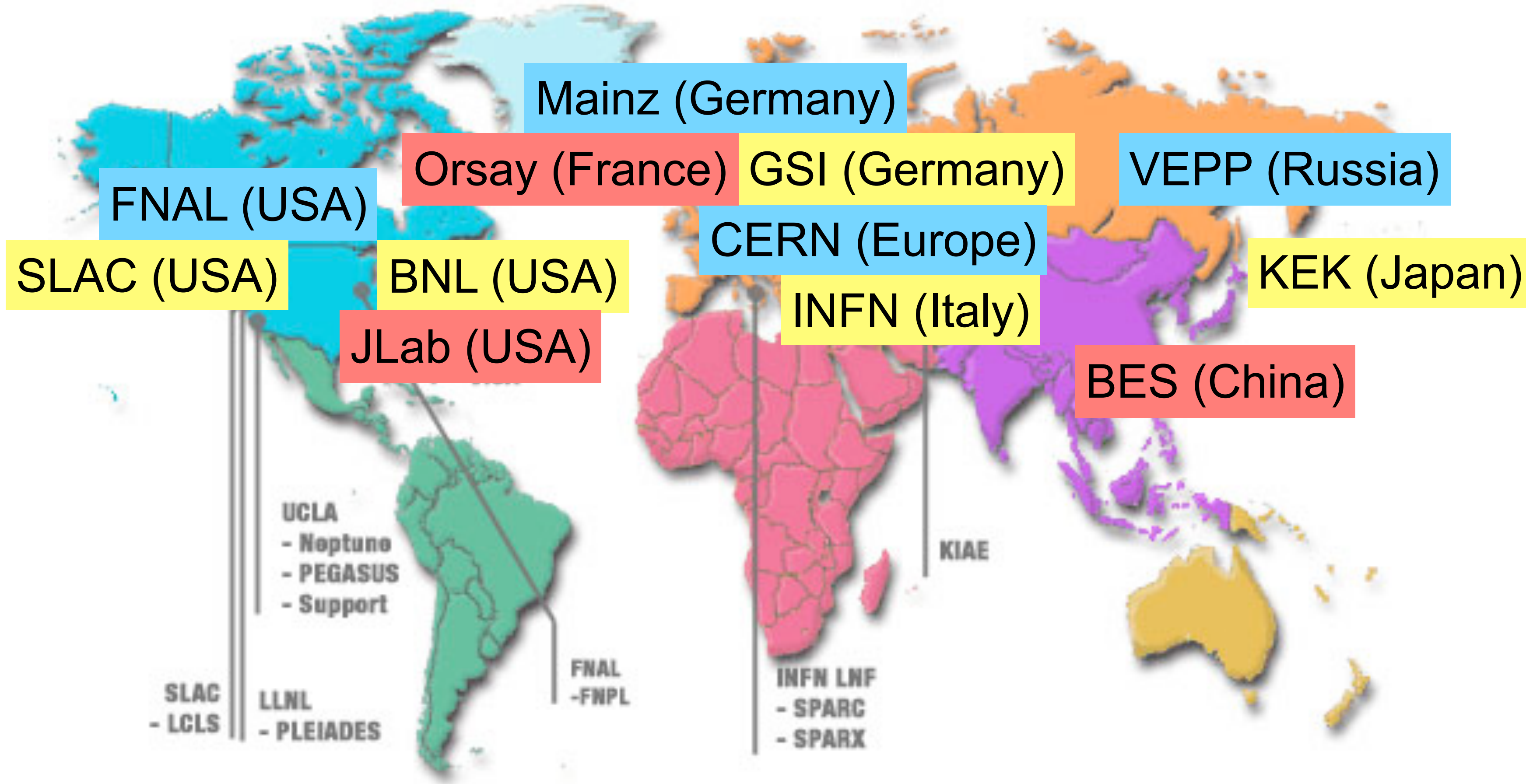


Unfilled curves: proposed experiments

arXiv:1109.4855

“Dark gauge boson” physics is a rapidly-developing field.

Dark Force searches in the Labs



Many searches for Dark Force in the Labs around the world (ongoing/proposed).

Exciting time!

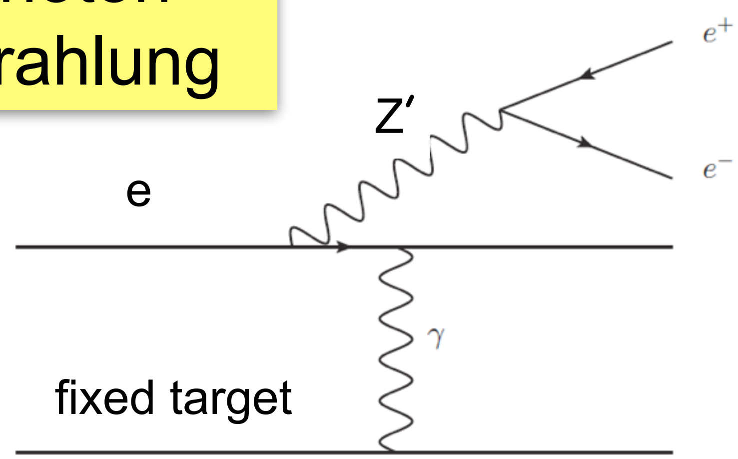
(With some exaggeration)

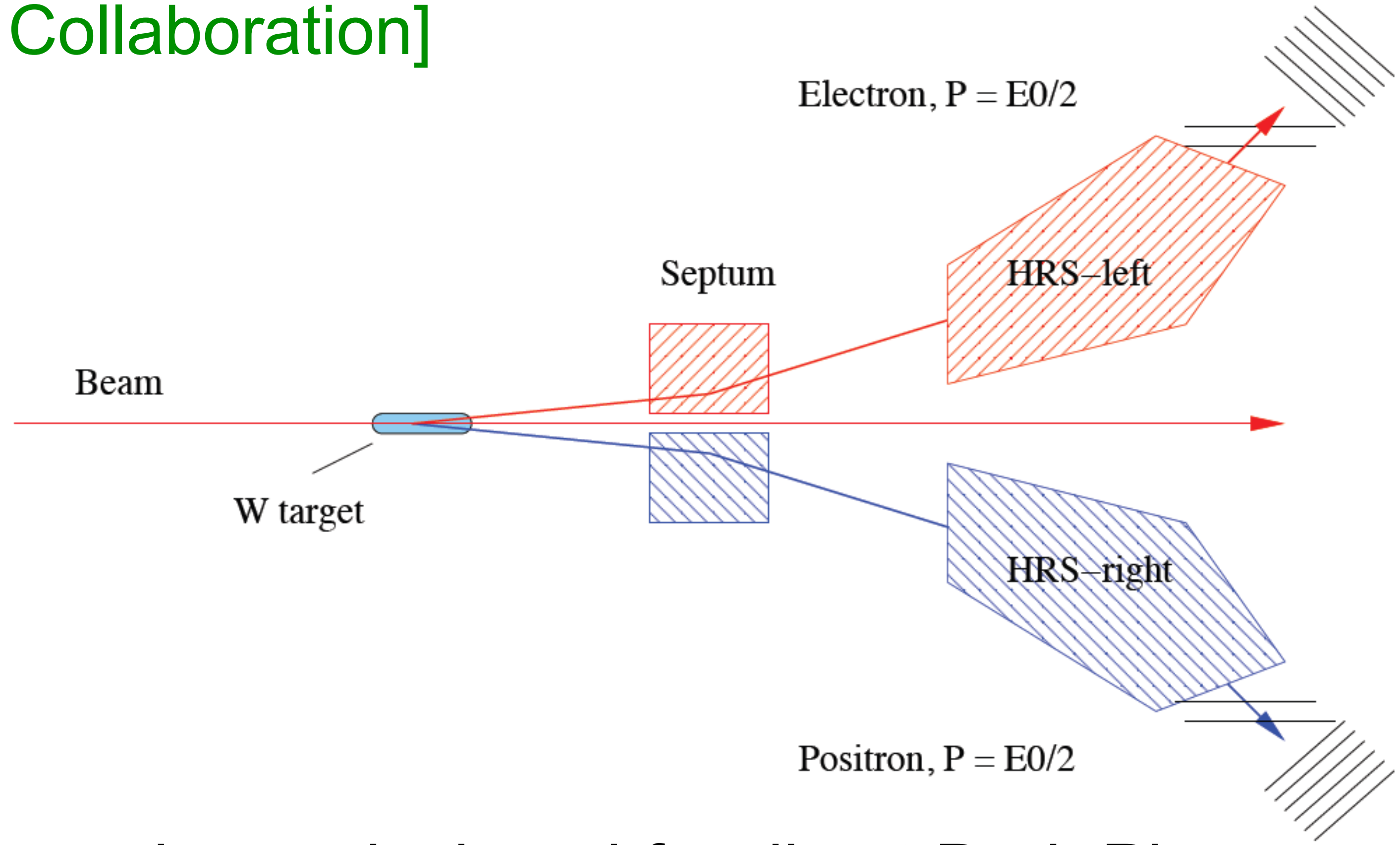
Whole world is searching for a new fundamental force.

Example: A' Experiment (APEX) at JLab - Hall A

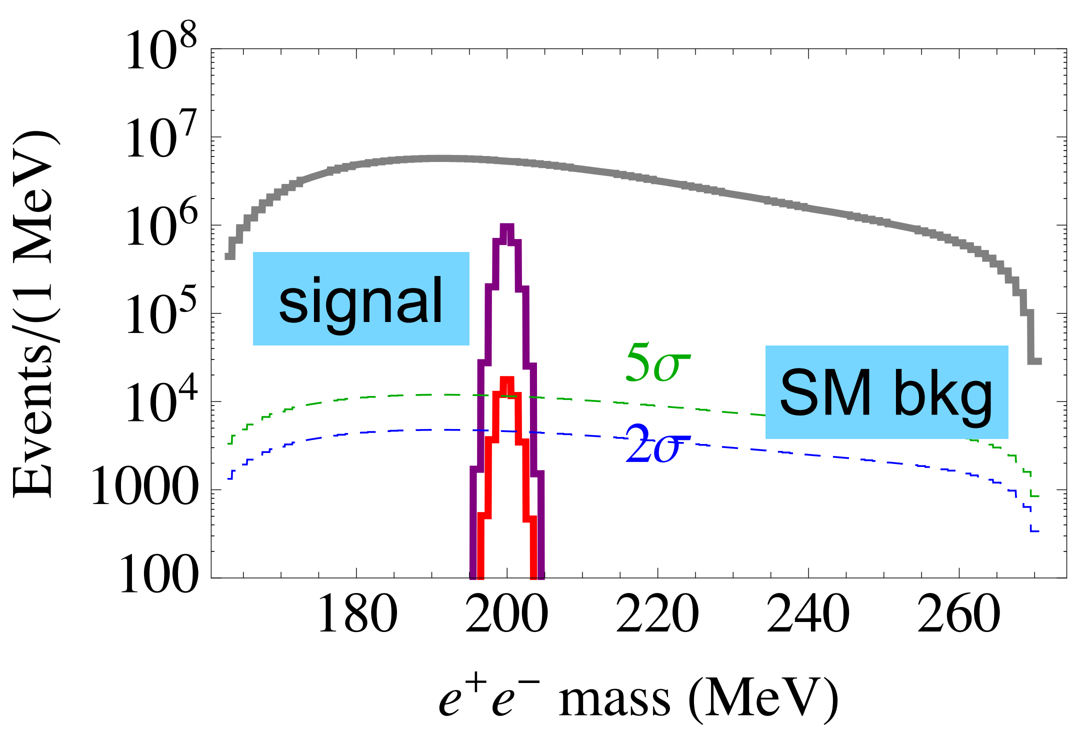
[APEX Collaboration]

Dark Photon Bremsstrahlung





New Fixed target (Tantalium Z=73) experiment designed for direct Dark Photon production/detection.



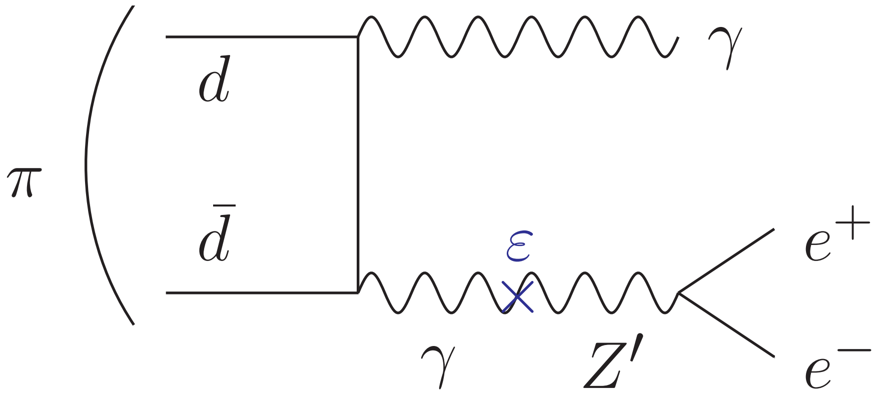
Z' ➞ e^+e^- narrow resonance at Z' mass
(Direct bump search at Low-energy facility).

The *High Resolution Spectrometers (HRS)* at Hall A are used.

Example: Meson decays into Light Z'

Typical Dark Force searches in meson decays are performed in flavor-conserving ones with quarkoniums (qqbar-type mesons).

Dark Photon from Meson decays



π(dd) ➞ ɣ Z' ➞ ɣ + dilepton-resonance

(Direct bump search)

Flavor-conserving meson decays

π(dd), η(dd) ➞ ɣ Z' (WASA, HADES, PHENIX, NA48/2)

ϕ(ss) ➞ η Z' (KLOE)

Υ(bb) ➞ ɣ Z' (BABAR)

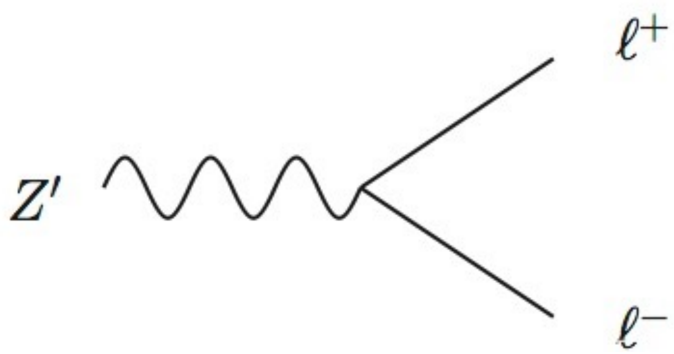
: Important searches for the Dark Force

Invisibly decaying Dark gauge boson
(Missing energy search)

Visible/Invisible decay of Dark gauge boson

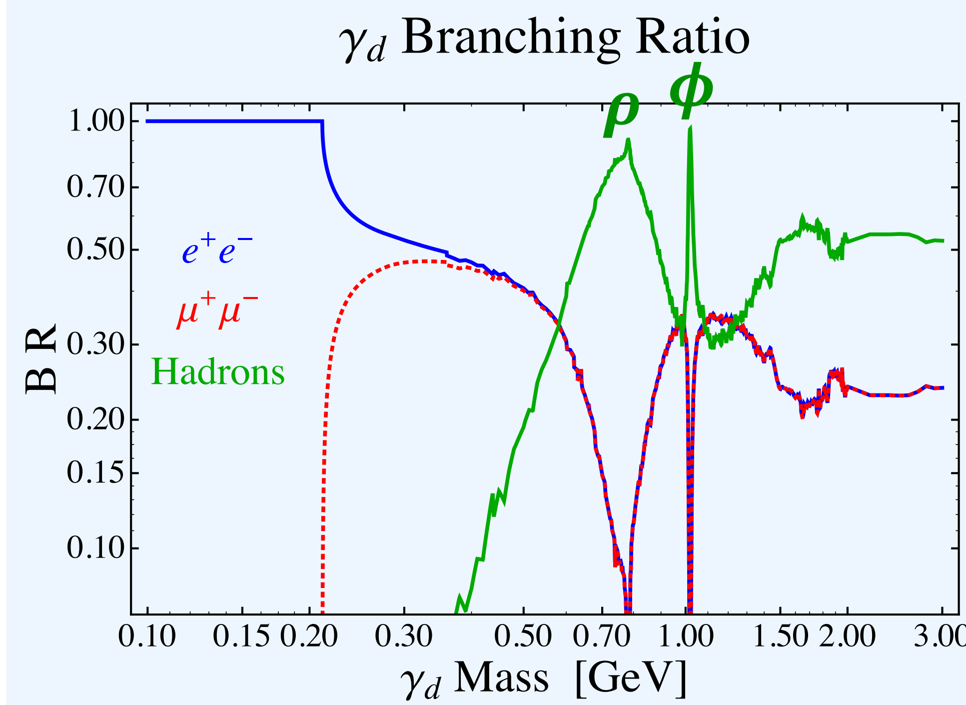
2 main categories of Dark force search (in terms of the dominant decay modes) :

(i) "Dilepton Resonance" search (typical search)



Visible Dark Gauge Boson

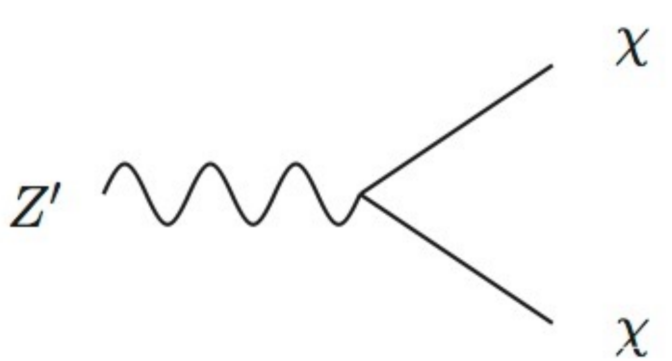
Z' $\rightarrow \ell^+\ell^-$ is the major decay mode in an ordinary scenario.



[Batell, Pospelov, Ritz (2009)]
[Falkowski *et al* (2010)]

Whole green band (g_μ-2 favored) is excluded.

(ii) "Missing Energy" search



Invisible Dark Gauge Boson

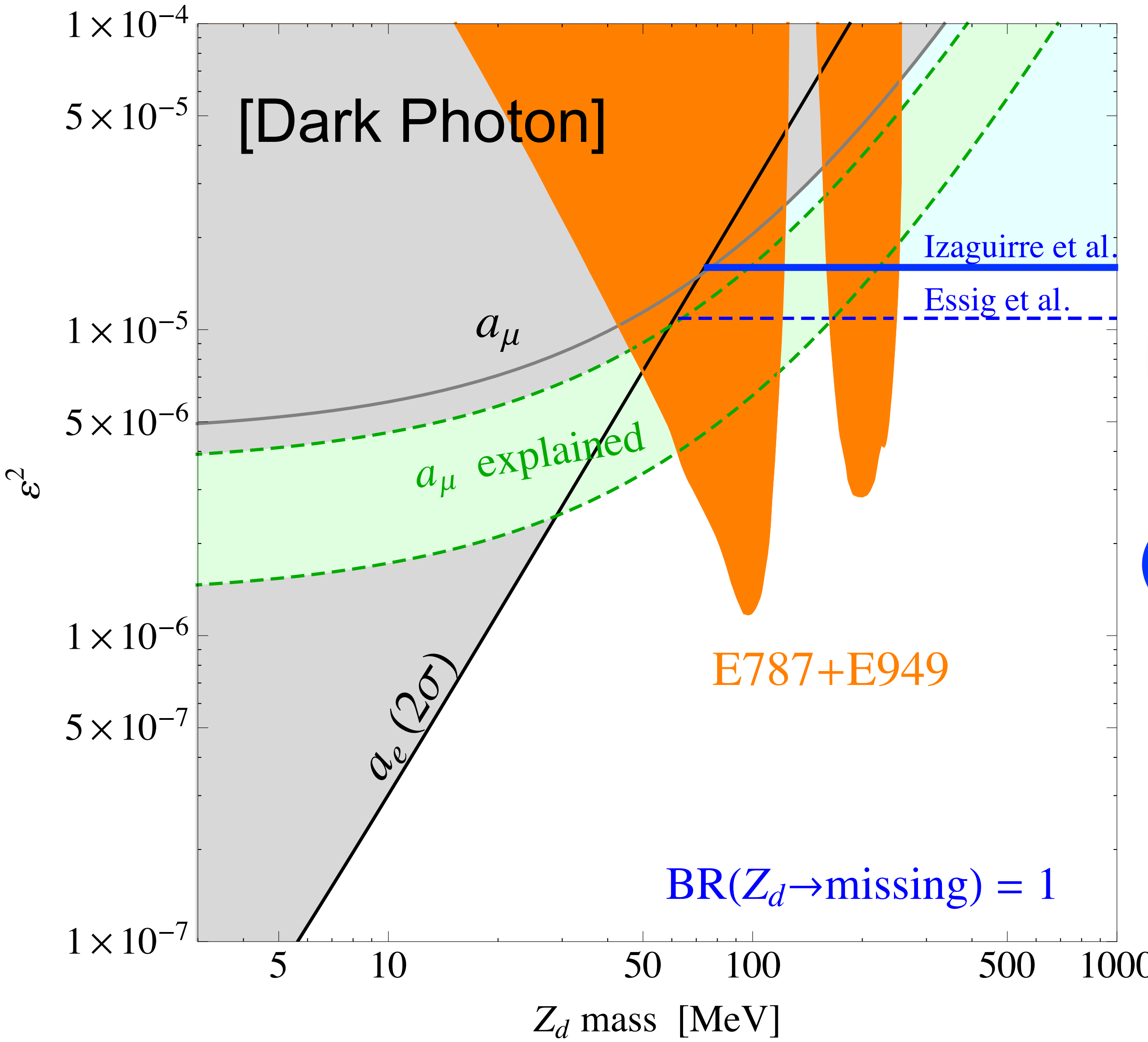
Z' $\rightarrow \chi\chi$ is the major decay mode,
if χ **(very light dark sector particle)** exists.

BR(Z' $\rightarrow$ missing energy) $\approx$ 1 is taken.

Does the green band (g_μ-2 favored) survive?

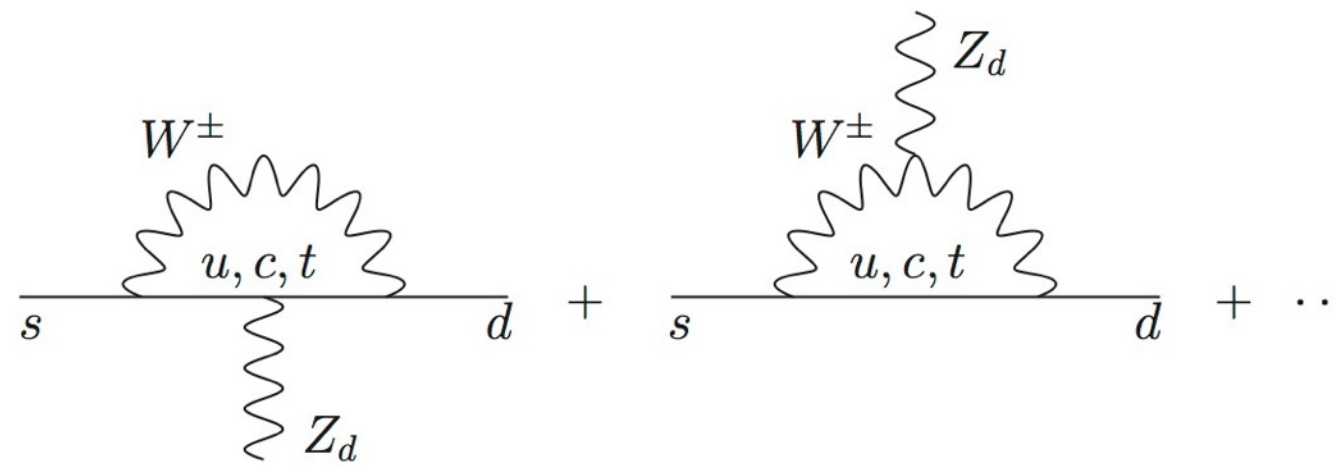
Invisibly decaying Dark gauge boson

(ii) Missing Energy (Z' → $\chi\chi$) searches



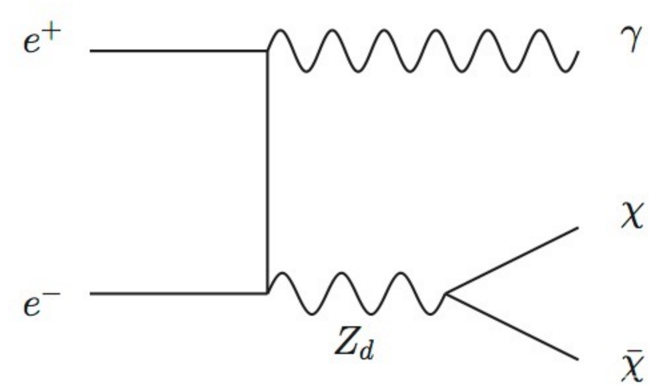
(i) $K^+ \to \pi^+$ + nothing (BNL E787+E949)

[Pospelov (2009); and others]



(ii) $e^+e^- \to \gamma$ + nothing (BABAR)

[Izaguirre *et al* (2013); Essig *et al* (2013)]



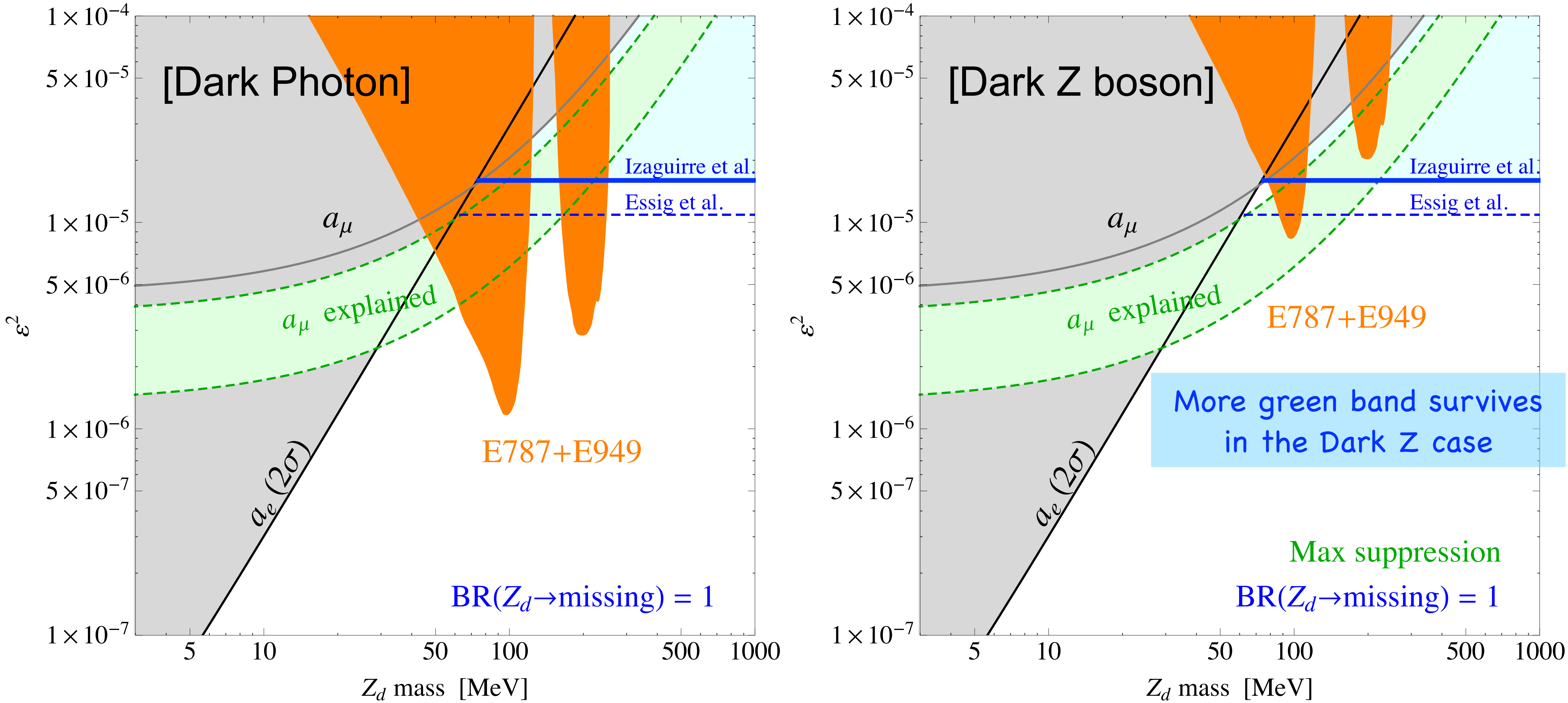
<u>More constraints</u> through χ interaction at detectors in some beam-dump experiments are possible, but they <u>depend on the χ coupling (α_D)</u>. *(will come back to this later)*

In Dark Photon model, small portion of the green band survives the constraints.

Invisibly decaying Dark gauge boson

(ii) Missing Energy (Z' → $\chi\chi$) searches

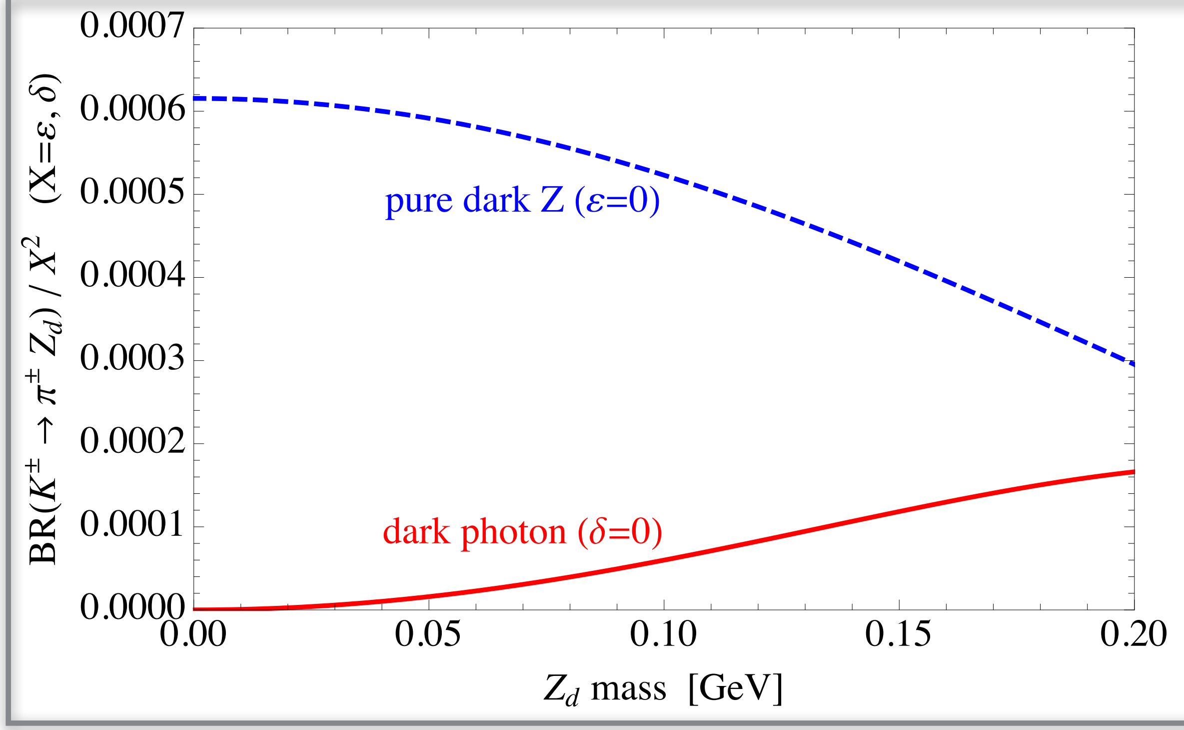
[Davoudiasl, LEE, Marciano (2014)]



In Dark Z model, because of the additional term (ε_Z term), there can be a sizable interference in the flavor-changing meson decays.

The "K → π + Z' (nothing)" <u>constraints (orange) can be much weaker</u> (1/7 times).

K → π + Z’



$$\Gamma(K^+ \to \pi^+ Z_d) = 4\pi \frac{\sqrt{\lambda(m_K^2, m_\pi^2, m_{Z_d}^2)}}{64\pi^2\, m_K^3} \sum_{\rm pol} |\mathcal{M}|^2$$

with $$\sum_{\rm pol} |\mathcal{M}|^2 = \frac{1}{4}(f_+)^2 \left[\left(\frac{m_K^2 - m_\pi^2}{m_{Z_d}} \right)^2 - (2m_K^2 + 2m_\pi^2 - m_{Z_d}^2) \right] \left| \varepsilon m_{Z_d}^2 A \pm \delta \frac{m_{Z_d}}{m_Z} B \right|^2$$

Additional term of Dark Z model

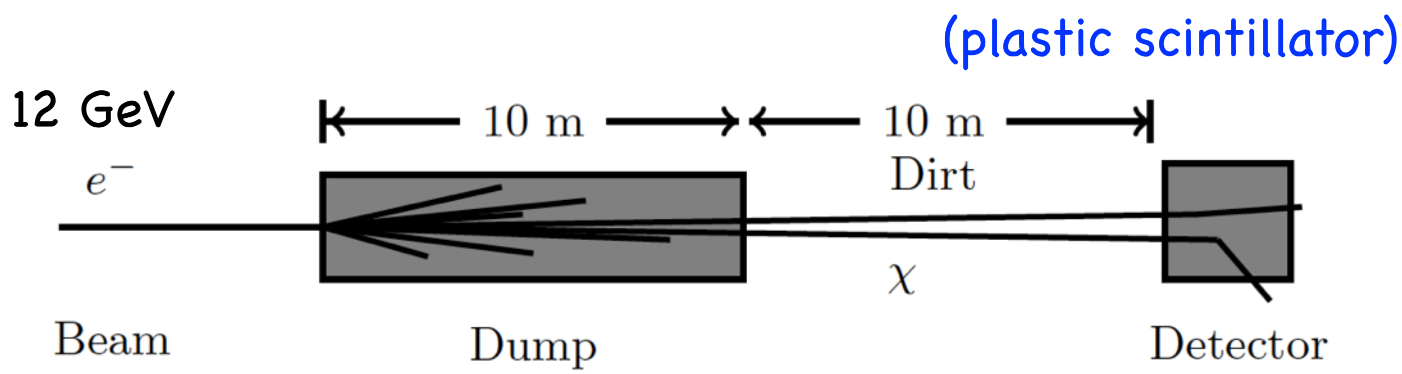
- Dark Photon :
  (loop-suppression with γ)×(small ε)

- pure Dark Z :
  (loop-suppression with Z)×(small ε_Z)×(enhancement factor)

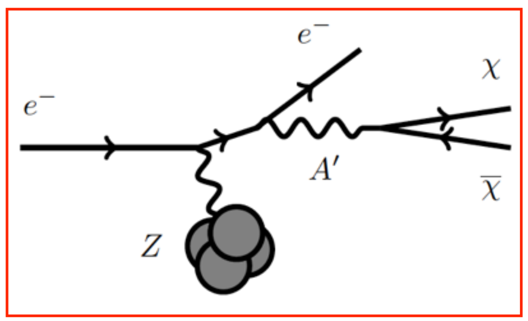
$$\left(\varepsilon_Z = \frac{m_{Z'}}{m_Z} \delta \right)$$

Example: JLab BDX (Beam-Dump eXperiment)

[BDX Collaboration]

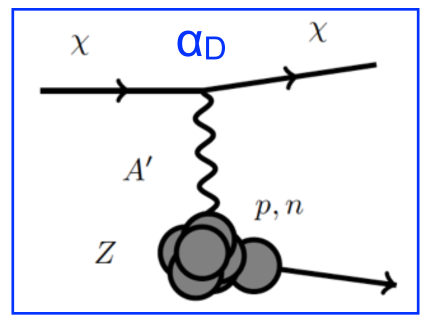


JLAB experiment (proposal) to test invisibly decaying Z′



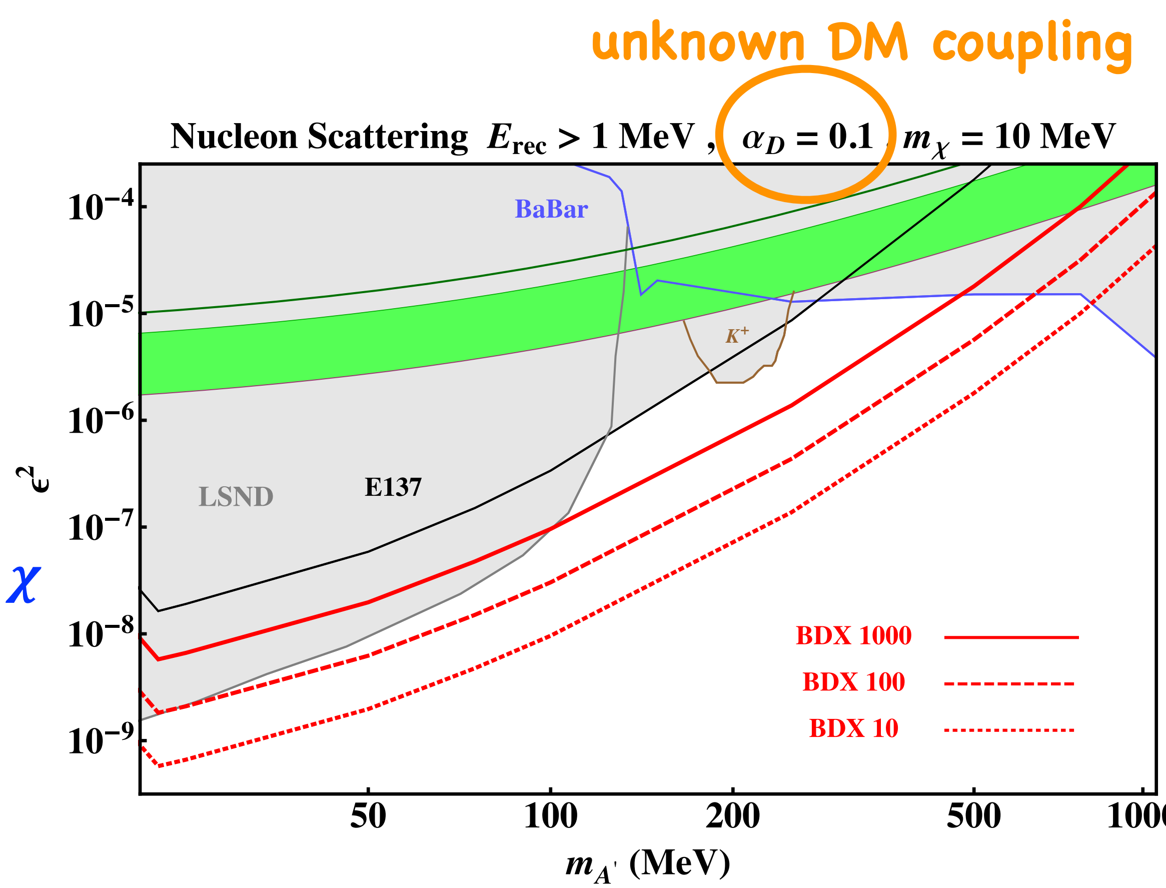
scattering to produce Z′ (promptly decaying to χ)

$\epsilon^2/m_{A'}^2$



scattering to detect χ (via Z′)

$\alpha_D\,\epsilon^2/m_{A'}^2$



(i) Test experiment at JLab Hall D with low current (0.2 μA).

(ii) Full experiment at JLab Hall A or C with high current (100 μA). EOT ~ 10^{12}.

(iii) Signals: nucleon/electron recoils.

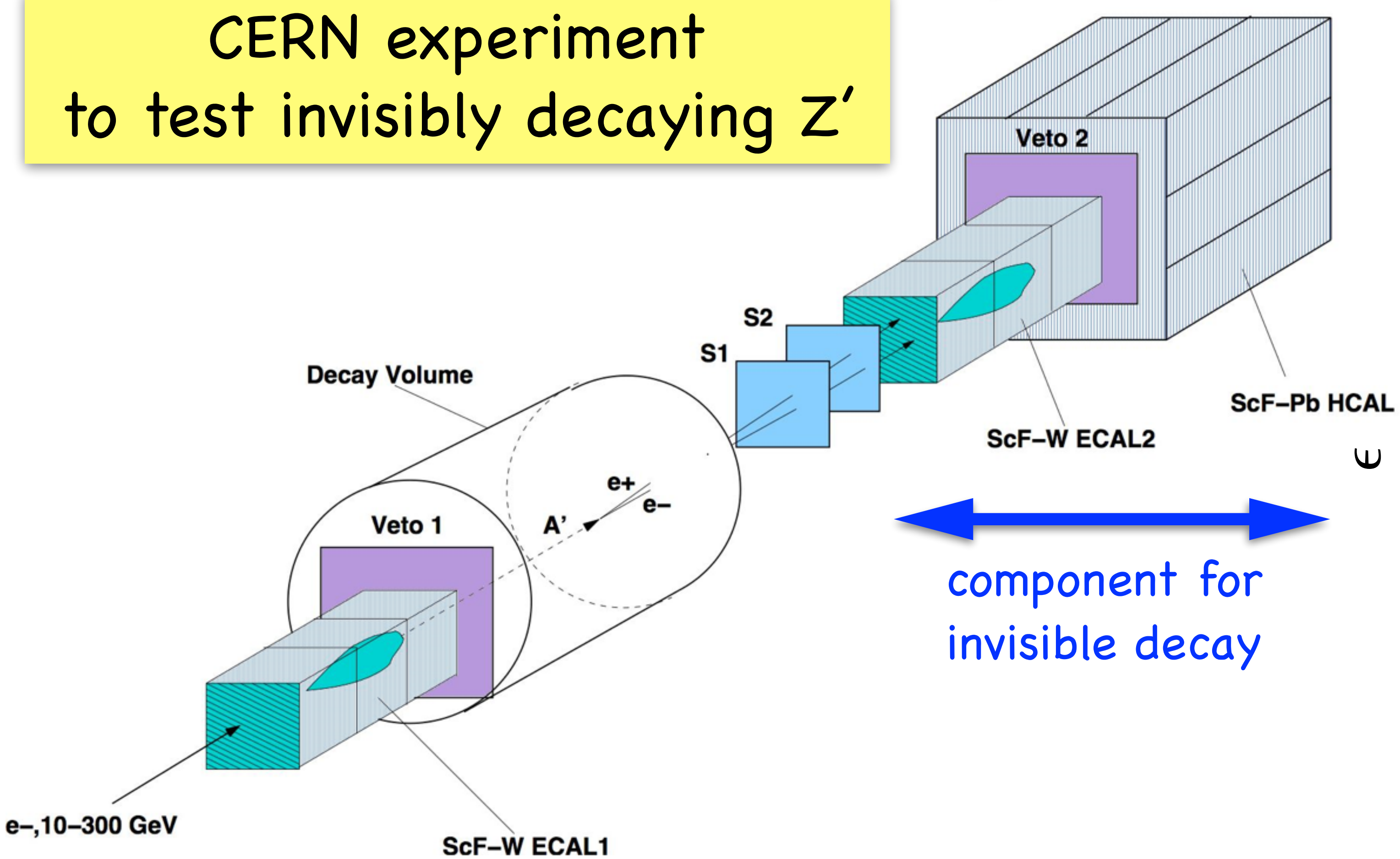
(iv) 2 scatterings are required to produce and detect. $N_\chi \sim \dfrac{\alpha_D\,\epsilon^4}{m_{A'}^4}$

(v) BKG from comic rays (neutrons, muons).

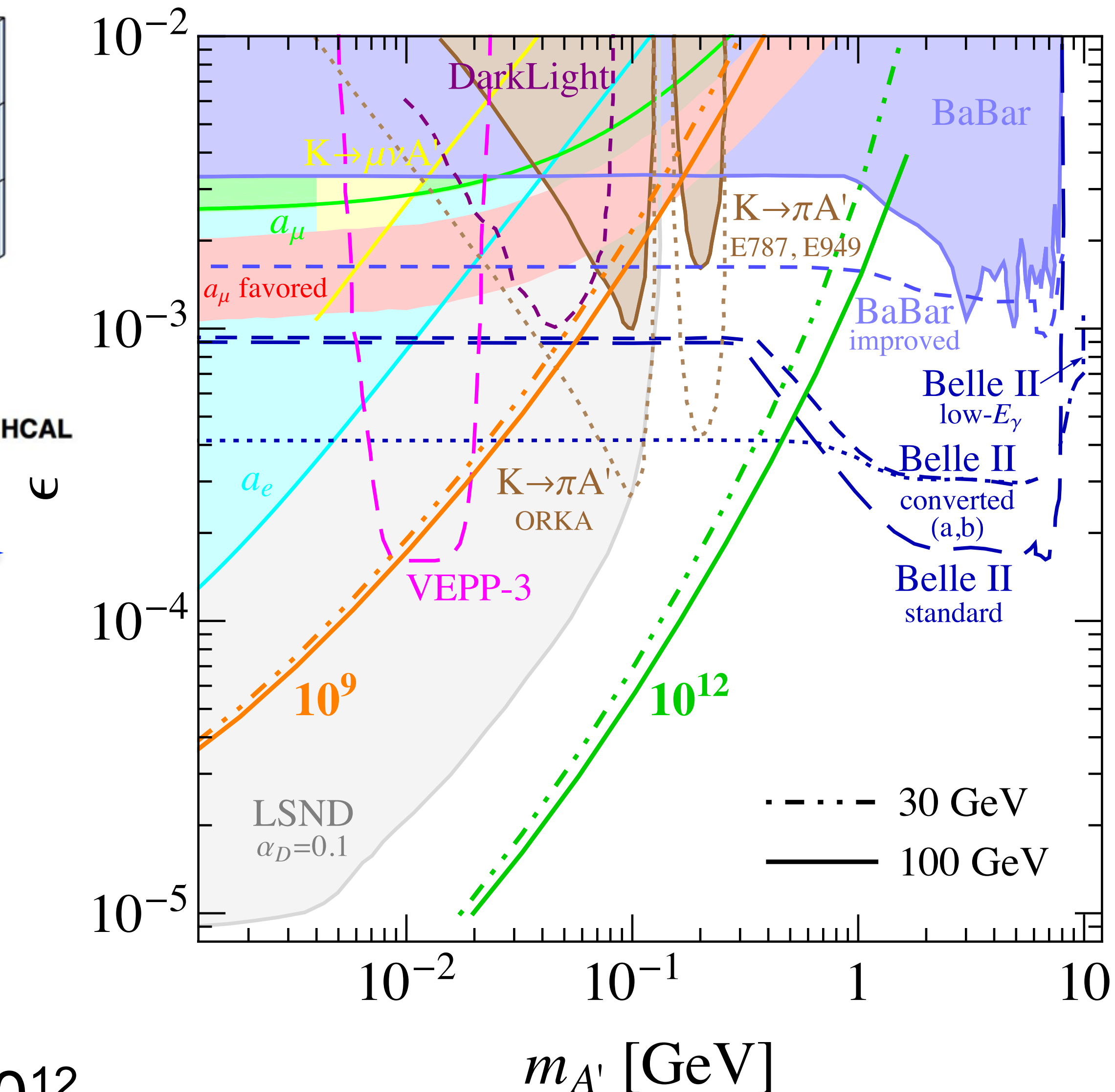
Example: P348 (beam-dump for dark gauge boson) at CERN SPS

[P348 Collaboration]

CERN experiment to test invisibly decaying Z′



component for invisible decay



(i) Primarily e-beam (10-300 GeV). EOT ~ 10^{12}.

(ii) Detector is hermetic (catching all SM particles except for neutrinos) and measures total energy deposit.

(iii) Test "energy loss" (Missing E) by invisibly decaying Z'. (Essentially BKG free.)

(iv) Does not depend on unknown α_D (DM coupling).

(v) Can search for the visibly-decaying Z' as well.

Another possible Dark force searches : Low-Energy Parity Test

(applying to Dark Z)

“Dark Z” effects on Weak Neutral Current phenomenology

[Davoudiasl, LEE, Marciano (2012)]

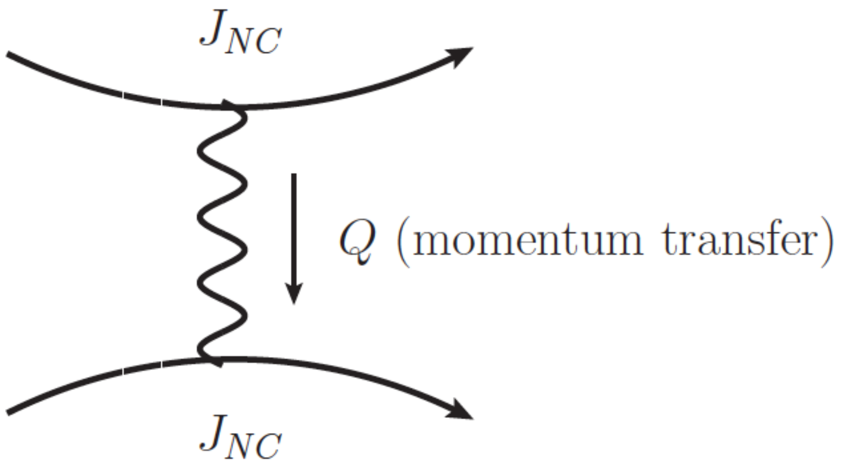
Dark Z : $\mathcal{L}_{\rm int} = -[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^{\mu}_{NC}]\, Z'_{\mu}$

Dark Z **modifies** the effective Lagrangian of Weak Neutral Current scattering.

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} J^{\mu}_{NC}(\sin^2\theta_W) J^{NC}_{\mu}(\sin^2\theta_W)$$

$$G_F \to \left(1 + \delta^2 \frac{1}{1 + Q^2/m^2_{Z'}}\right) G_F \qquad \left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$$

$$\sin^2\theta_W \to \left(1 - \varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{\cos\theta_W}{\sin\theta_W} \frac{1}{1 + Q^2/m^2_{Z'}}\right) \sin^2\theta_W$$

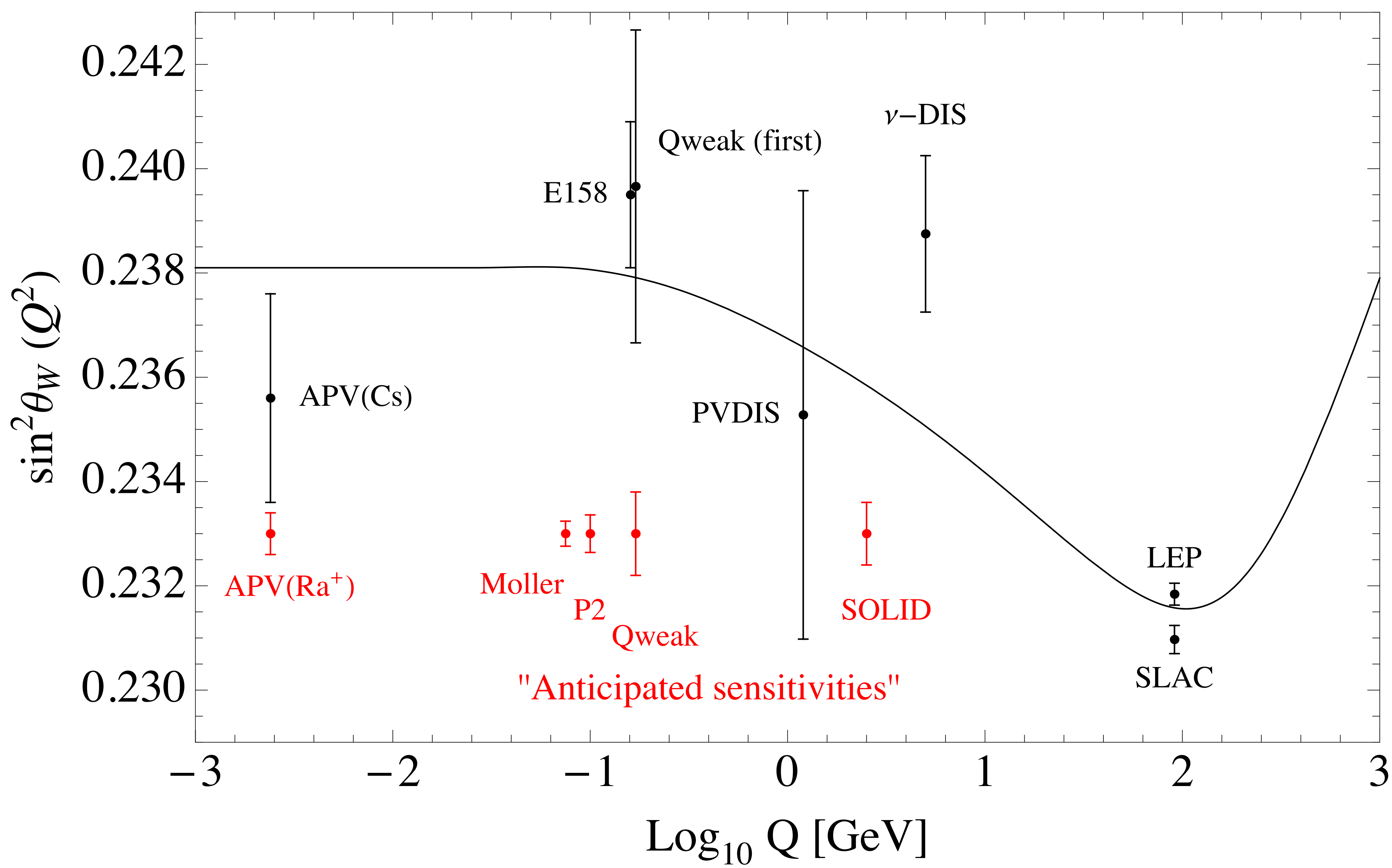


- Sensitive only to Low-Q² (momentum transfer). $\quad \frac{g_X^2}{m_X^2 + Q^2} \longrightarrow 0 \quad (\text{for } Q^2 \gg m_X^2)$

- Low-Q² Parity-Violating experiments (measuring $\sin^2\theta_W$) are good places to look.

Dark Z effectively changes the weak neutral current scattering (including parity), but only for the “Low” momentum transfer (Q).

Weak mixing angle running and current constraints



Low-Q^2 Parity Test (measuring Weinberg angle) can search for the Dark force.

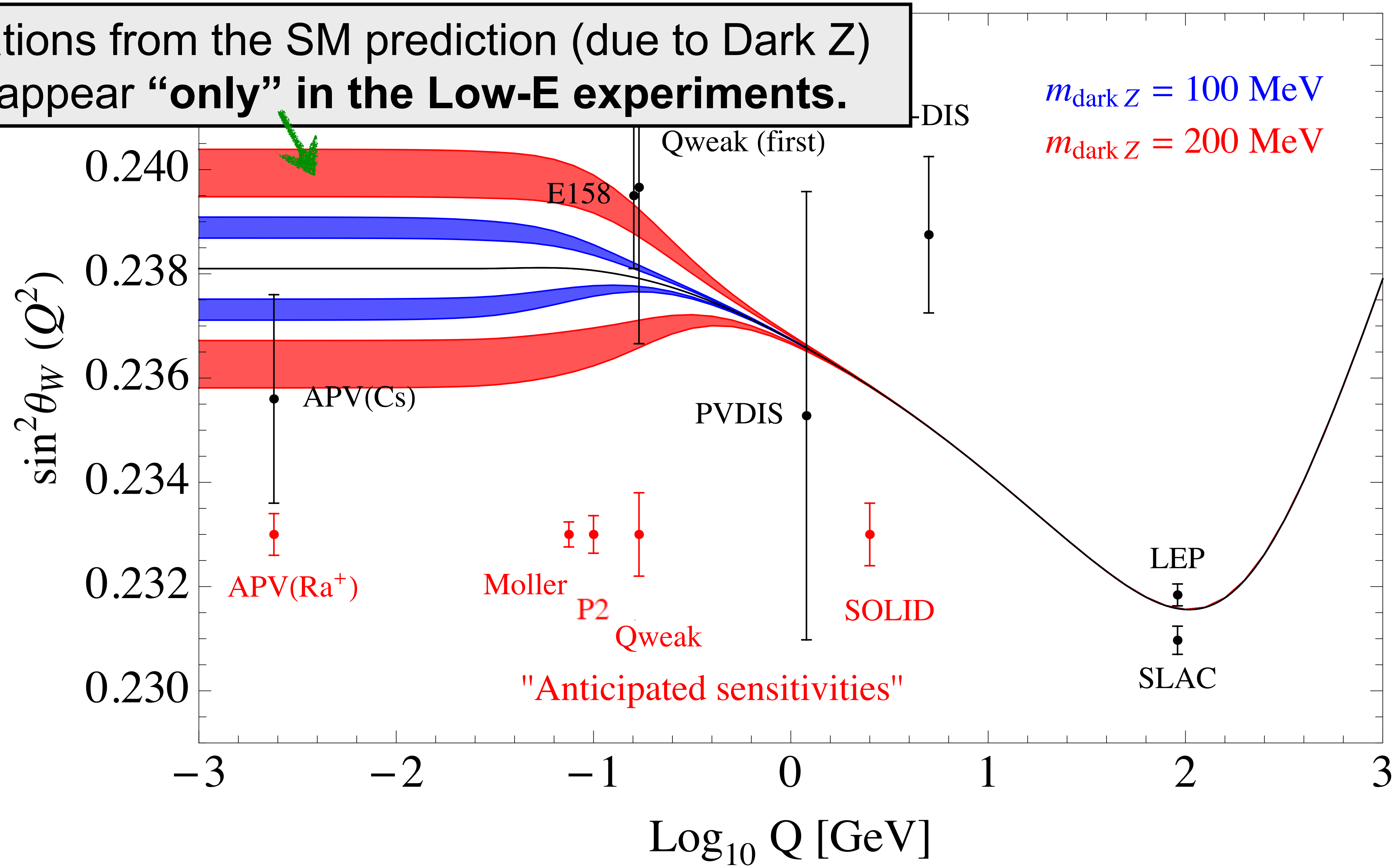
Atomic Parity Violation, Low-Q^2 Polarized Electron Scatterings, DIS

It is independent of Z' decay BR (good for both visibly/invisibly-decaying Z').

Weinberg angle shift due to Dark Z (very light Z')

[Davoudiasl, LEE, Marciano (2014)]

Deviations from the SM prediction (due to Dark Z) can appear **"only" in the Low-E experiments.**

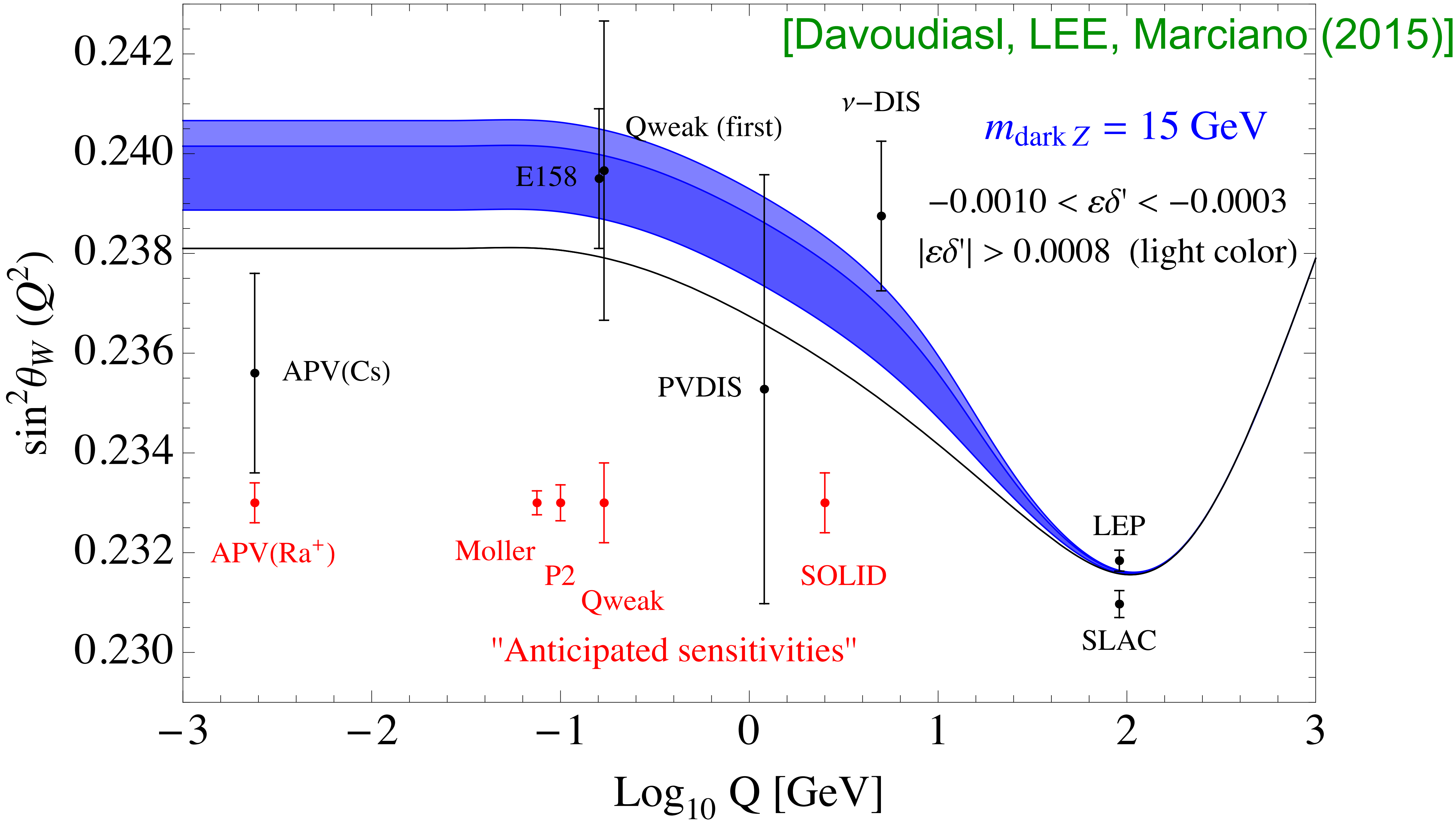


<u>Low-Q^2 Parity Test</u> (measuring Weinberg angle) can search for the Dark force.

Atomic Parity Violation, Low-Q^2 Polarized Electron Scatterings, DIS

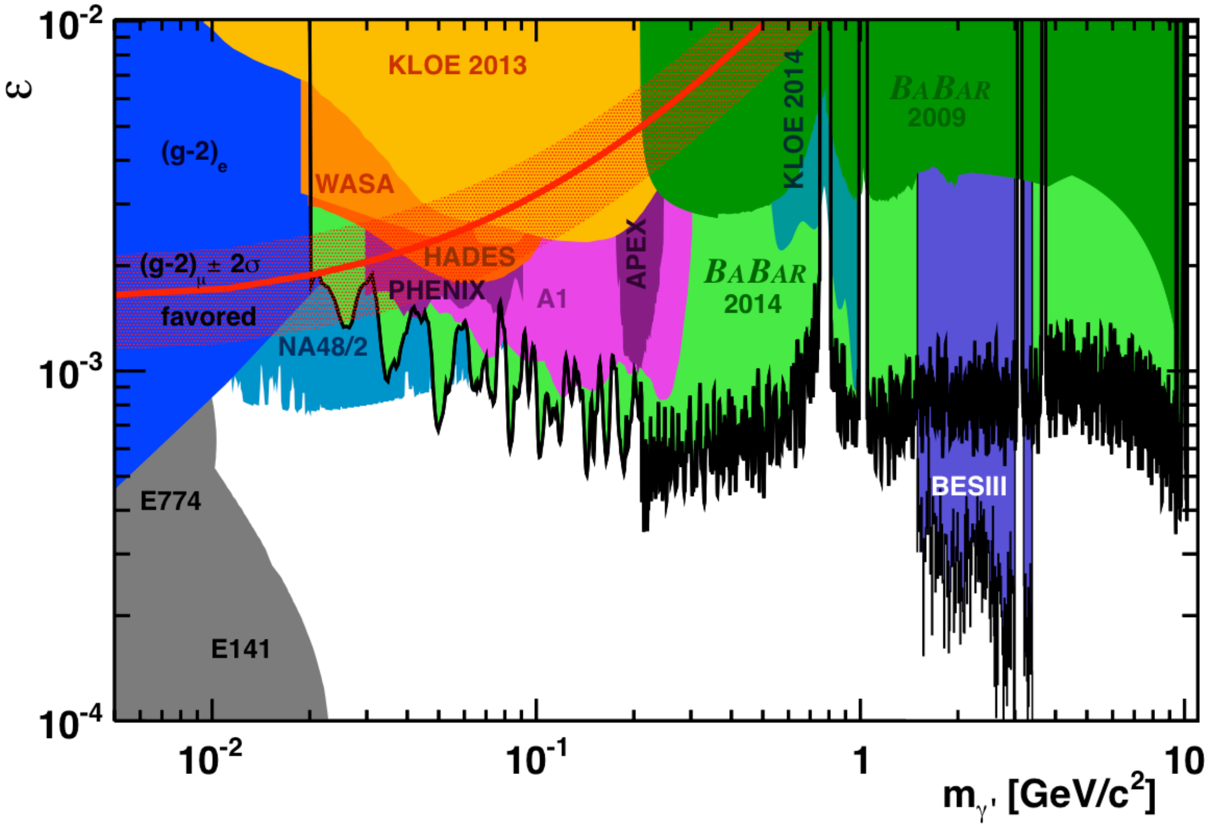
It is independent of Z' decay BR (good for both visibly/invisibly-decaying Z').

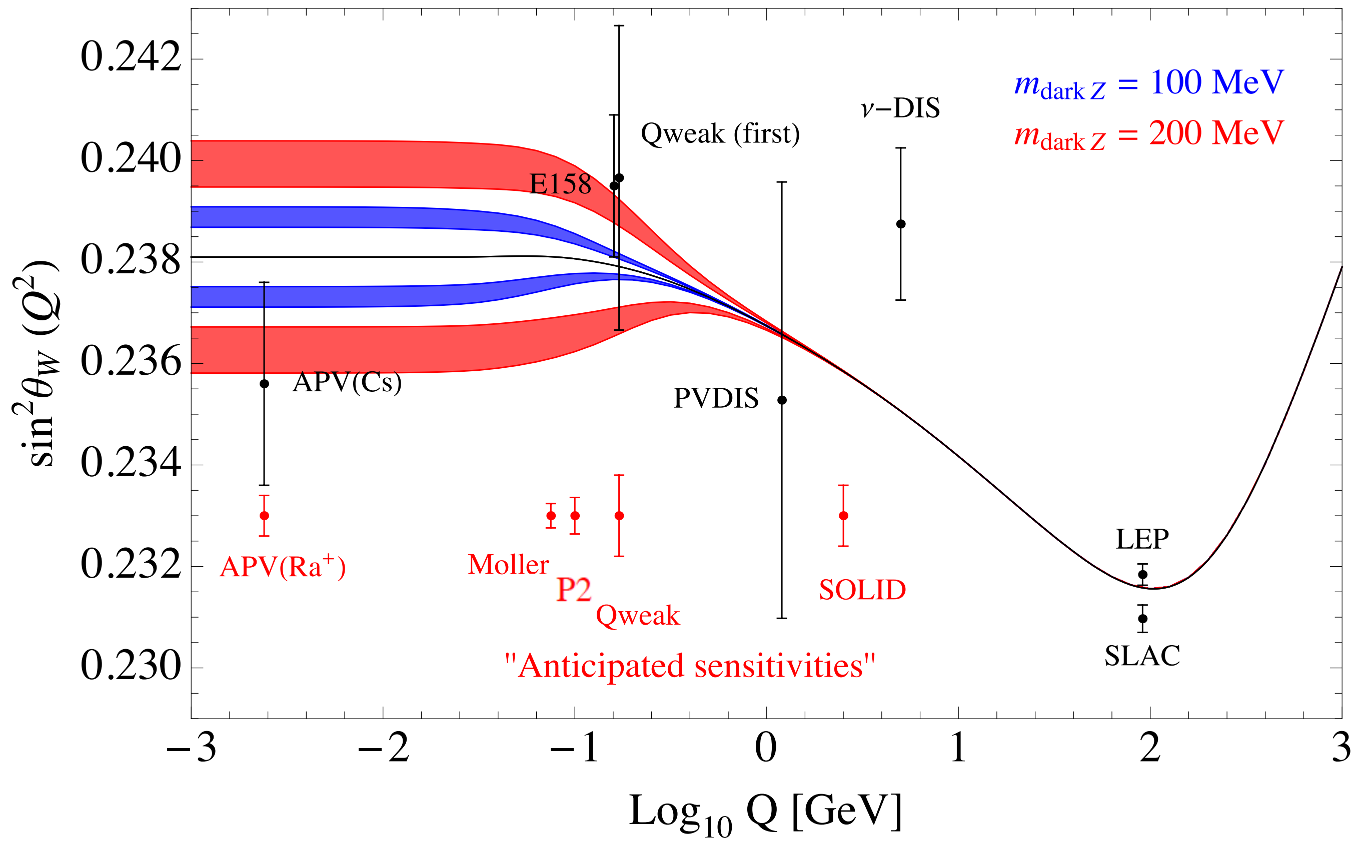
Weinberg angle shift due to Dark Z (intermediate mass case)



Low-Q^2 measurements (Cs APV, E158, NuTeV) show 1.8σ deviation from the SM.
Introduction of Dark Z (~ 10 GeV) can help fitting. (Blue band: Less than 1σ deviation)

Summary





The Parity Test (precise measurement of $\sin^2\theta_W$) has been important in studying new gauge interactions. (Critically helped establishing the $SU(2)_L \times U(1)_Y$ model.)

There is a growing interest in the dark gauge interaction (mediated by a light Z') around the world. (Partly because many existing low-energy facilities can join the searches.)

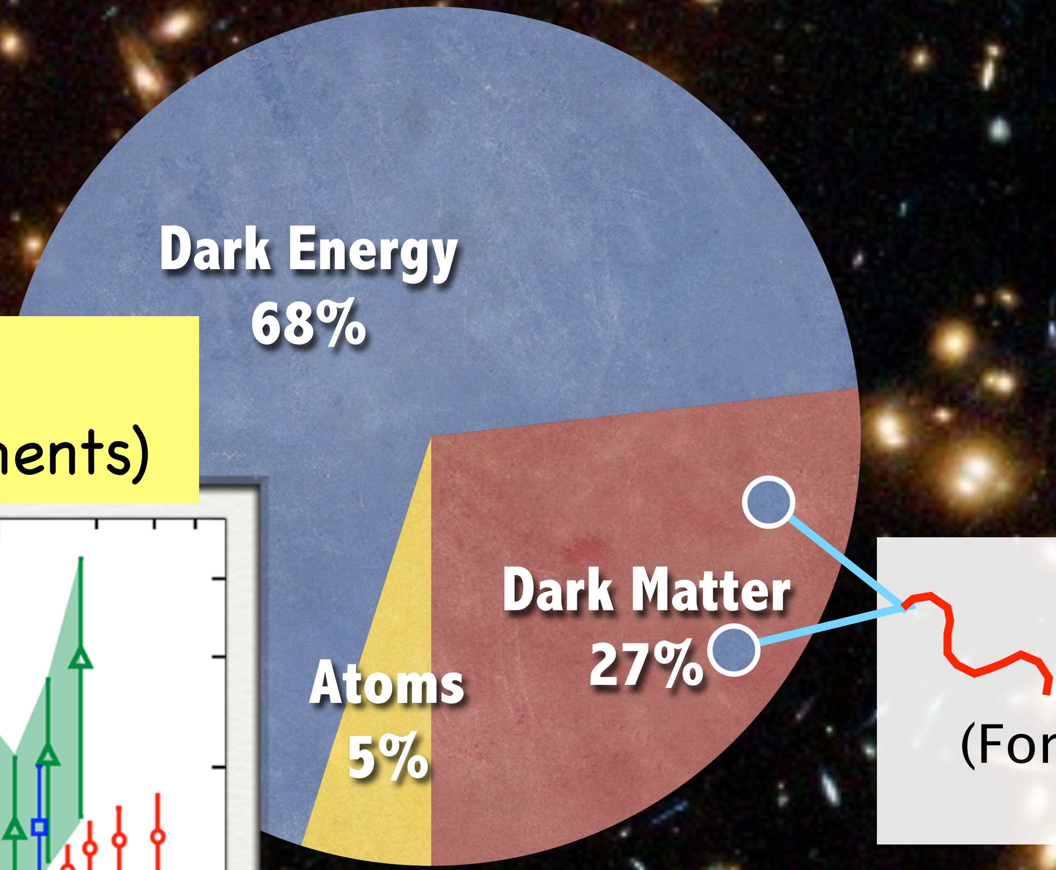
While most searches of the light Z' are based on the direct resonance searches or missing energy searches, the parity tests in Low-Q^2 (APV, Polarized e scatterings, DIS) are important and complementary searches, independent of Z' decay BR.

History may repeat! (Dark Force evidence from Low-Q^2 parity test before bump/missing?)

- Thank you. -

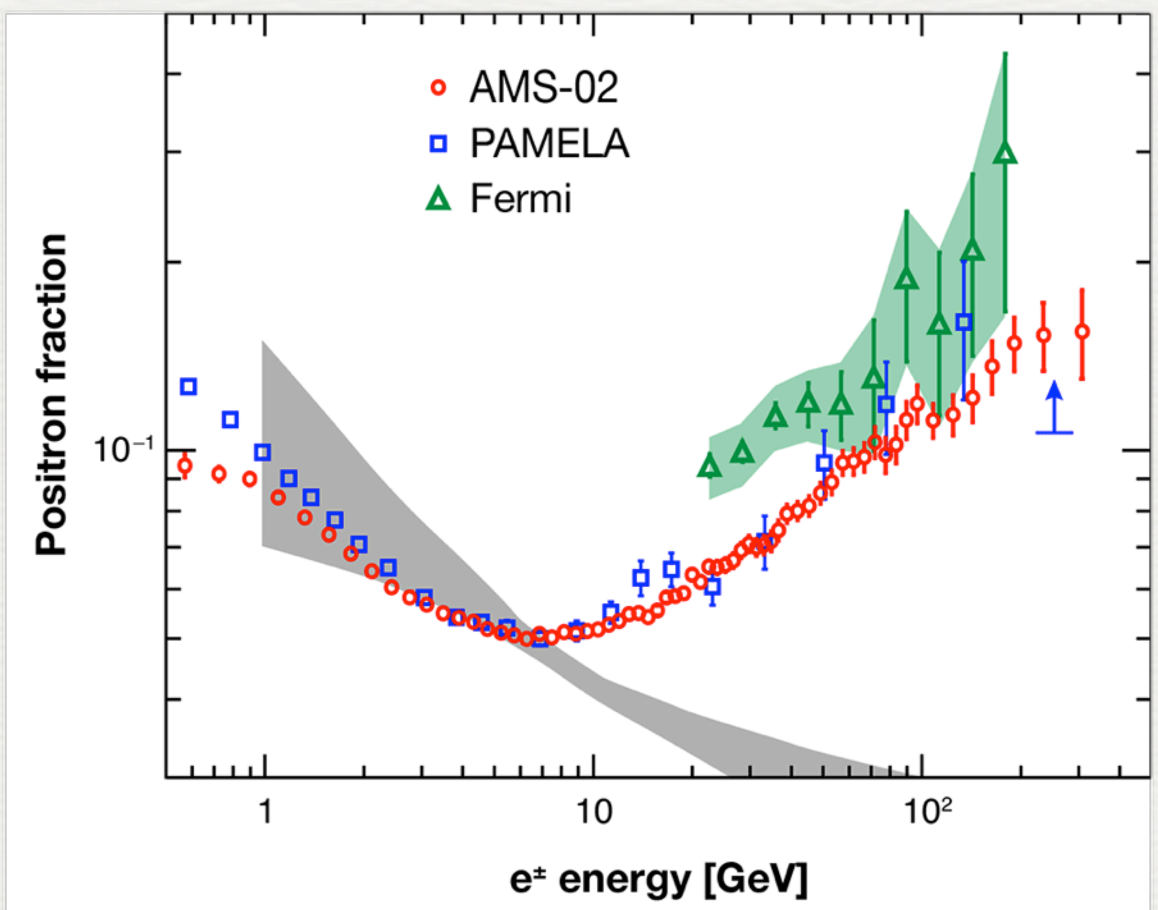
Backup Slides

We live in a Dark World



“Dark Force”
(Force among Dark Matters)

Positron excess
(observed in satellite experiments)

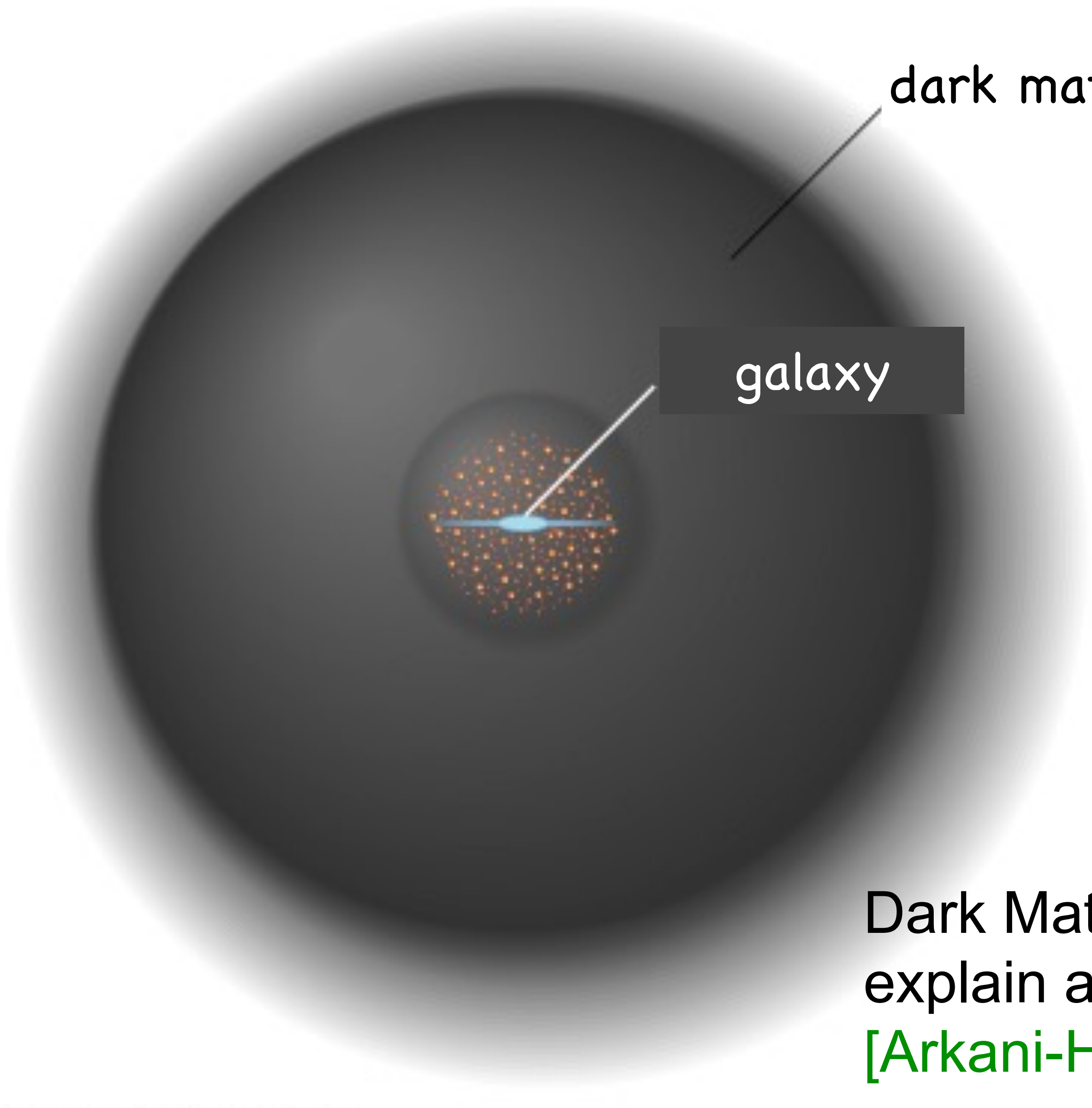


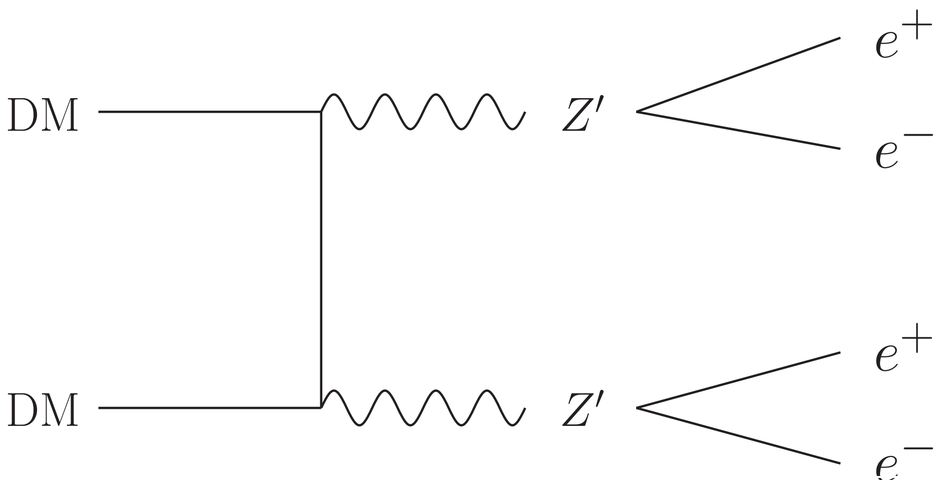
No corresponding antiproton excess
: Typical DM annihilation would produce both e+e- and p+p-

Dark Force (Force among Dark Matters)

Z'
(Dark Force carrier)

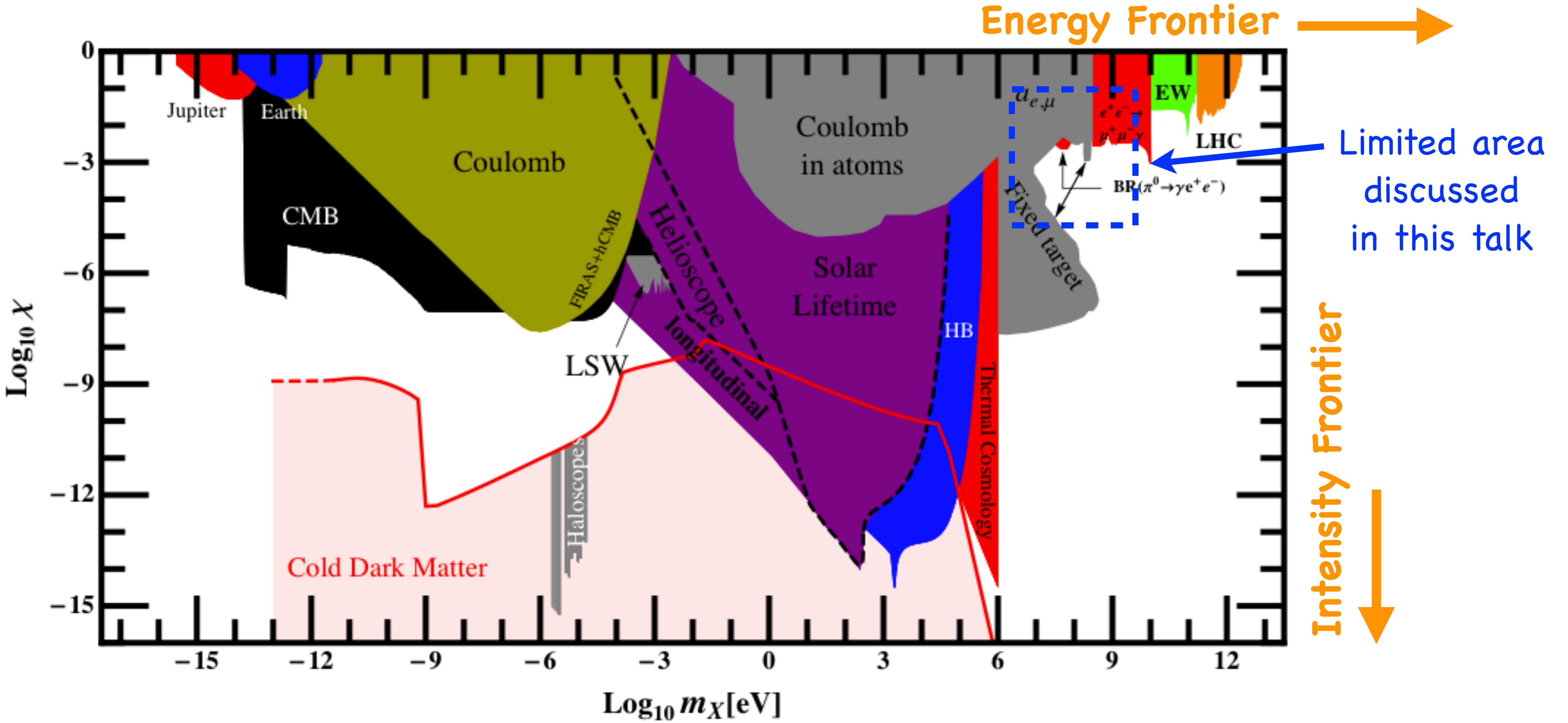
- New gauge boson of MeV-GeV scale *(cf. Proton: 1 GeV)*
- Extremely weak couplings to the SM particles





Dark Matter annihilations with Dark Force can explain anomalies including the positron excess.
[Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)]

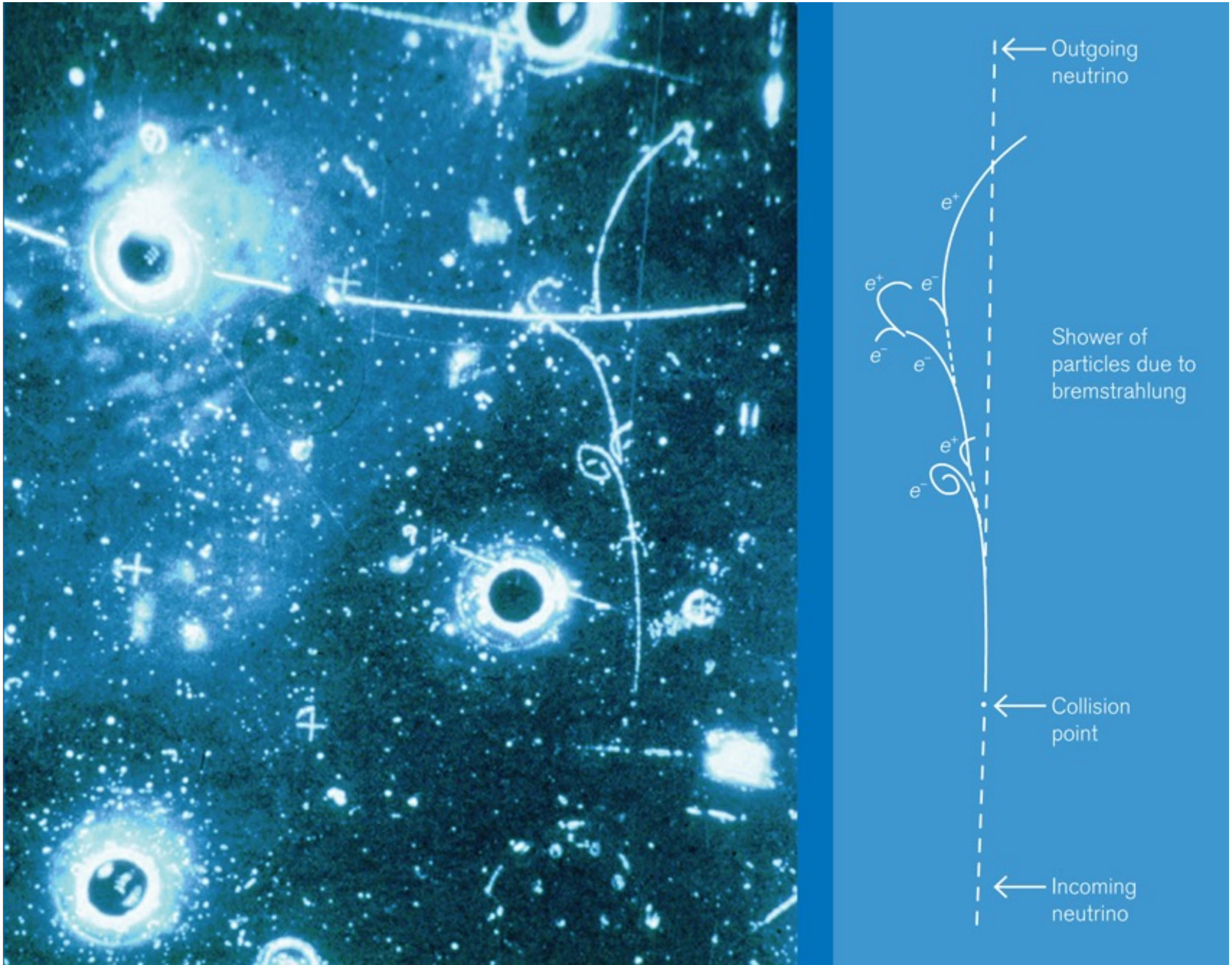
Extended range of parameters (of Dark Photon)



[Jaeckel (2013)]

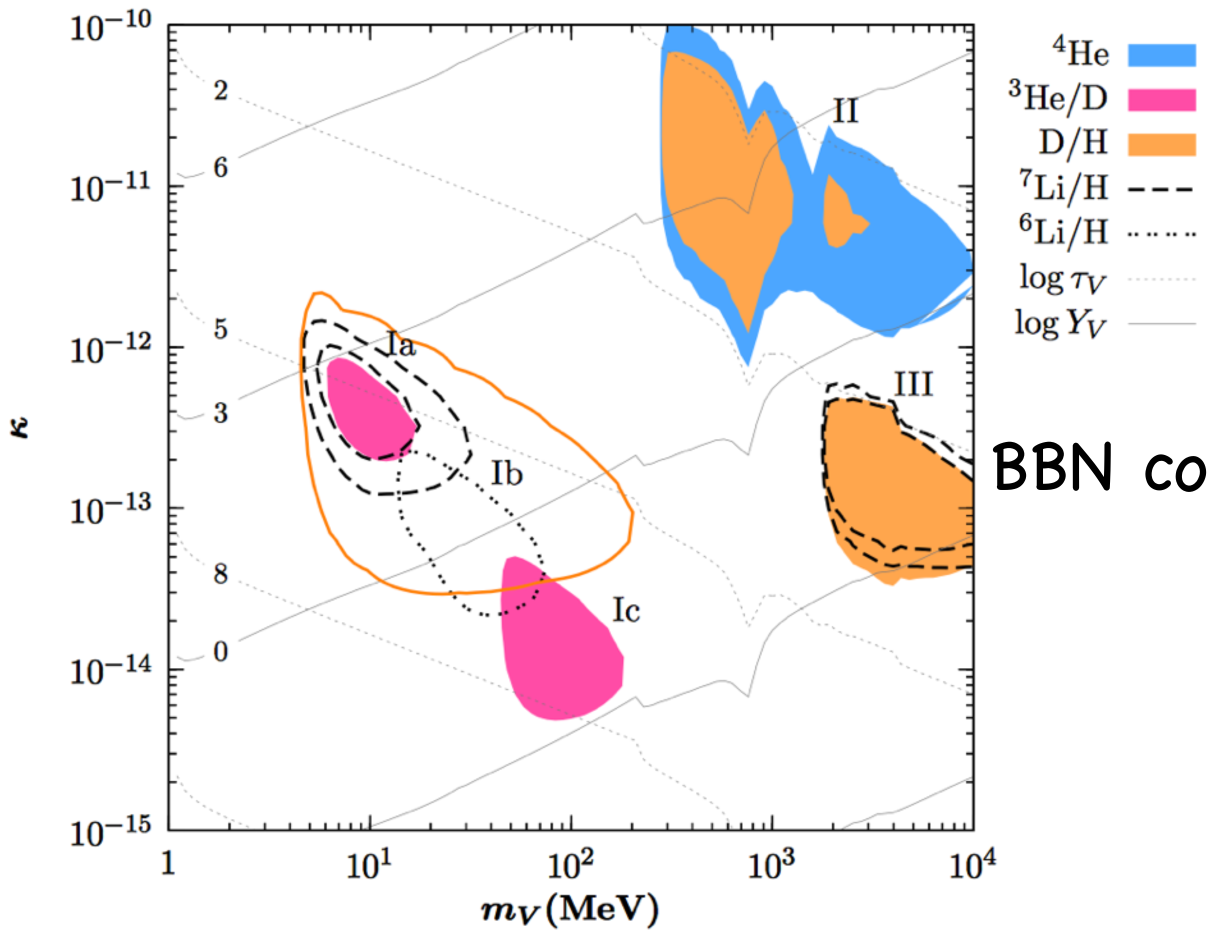
Different regions of parameter space require different methods to explore.
More theoretical studies and experimental innovations are needed.

Neutral currents observed at CERN Gargamelle



BBN & CMB constraints on Dark Photon

[Fradette,Pospelov,Pradler,Ritz (2015)]



BBN constraints

Figure 4. Vector mass m_V and k
rameter space with BBN sensiti
depict τ_V (solid) or n_V/n_b prior t
gions are excluded by observation
closed line is a 2σ constraint fro
rived from (12). Dashed black li
^{7}Li/H, 4×10^{-10} and 3×10^{-10},
ones, respectively. Along the dott
ing an two orders magnitude enha
not yet constrained by observatio

CMB constraints

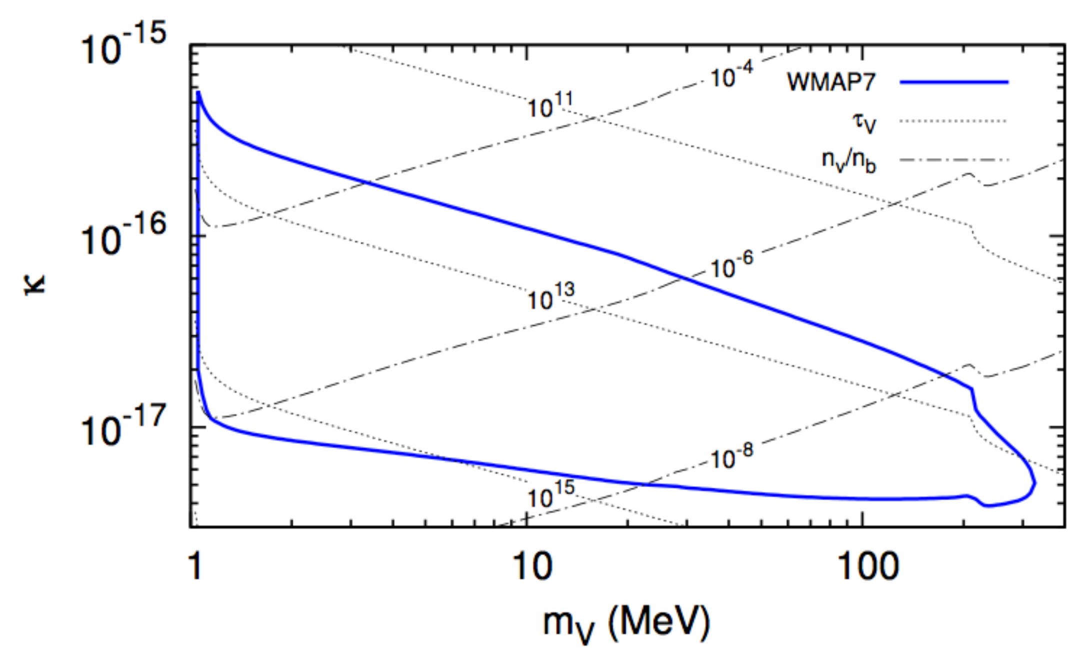


Fig. 3. CMB constraints on VDP. The lifetime in seconds and relative number density of dark photons to baryons prior to their decay is included.

Dark Z lifetime

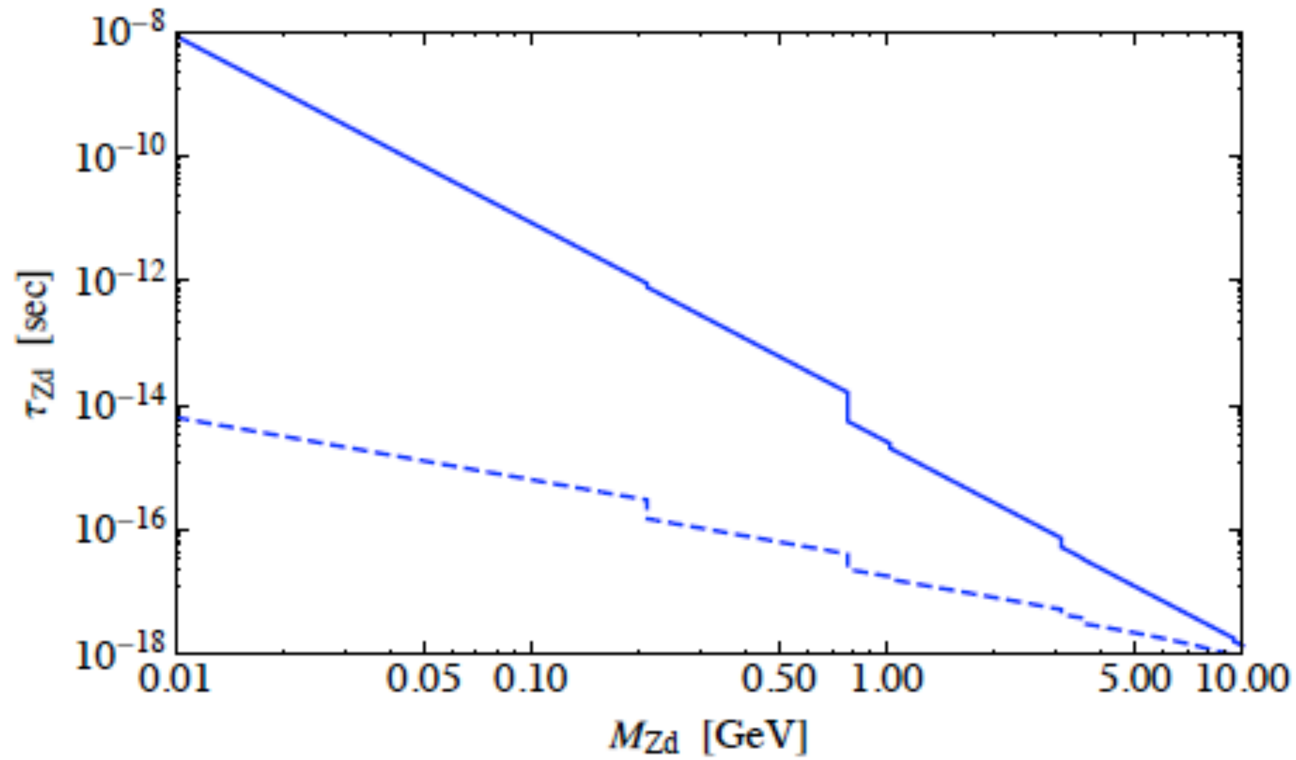


FIG. 2: Z_d lifetime with Z_d mass for $\delta^2 = 10^{-4}$ with $\varepsilon = 0$ (solid blue curve) and $\varepsilon = 2 \times 10^{-3}$ (dashed blue curve) cases. We take ρ, ϕ, J/ψ, Υ masses as the representative threshold for decays to mesons.

$$\mathcal{L}_{\rm int}^{Z'} = -\left[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\,(g/\cos\theta_W) J^\mu_{NC}\right] Z'_\mu$$

$$\frac{\mathrm{BR}(Z' \to e^+e^-)}{\mathrm{BR}(Z' \to 3\nu\bar{\nu})} \simeq \frac{1}{6} + \frac{1}{2}\left(\frac{\varepsilon}{\varepsilon_Z}\right)^2$$

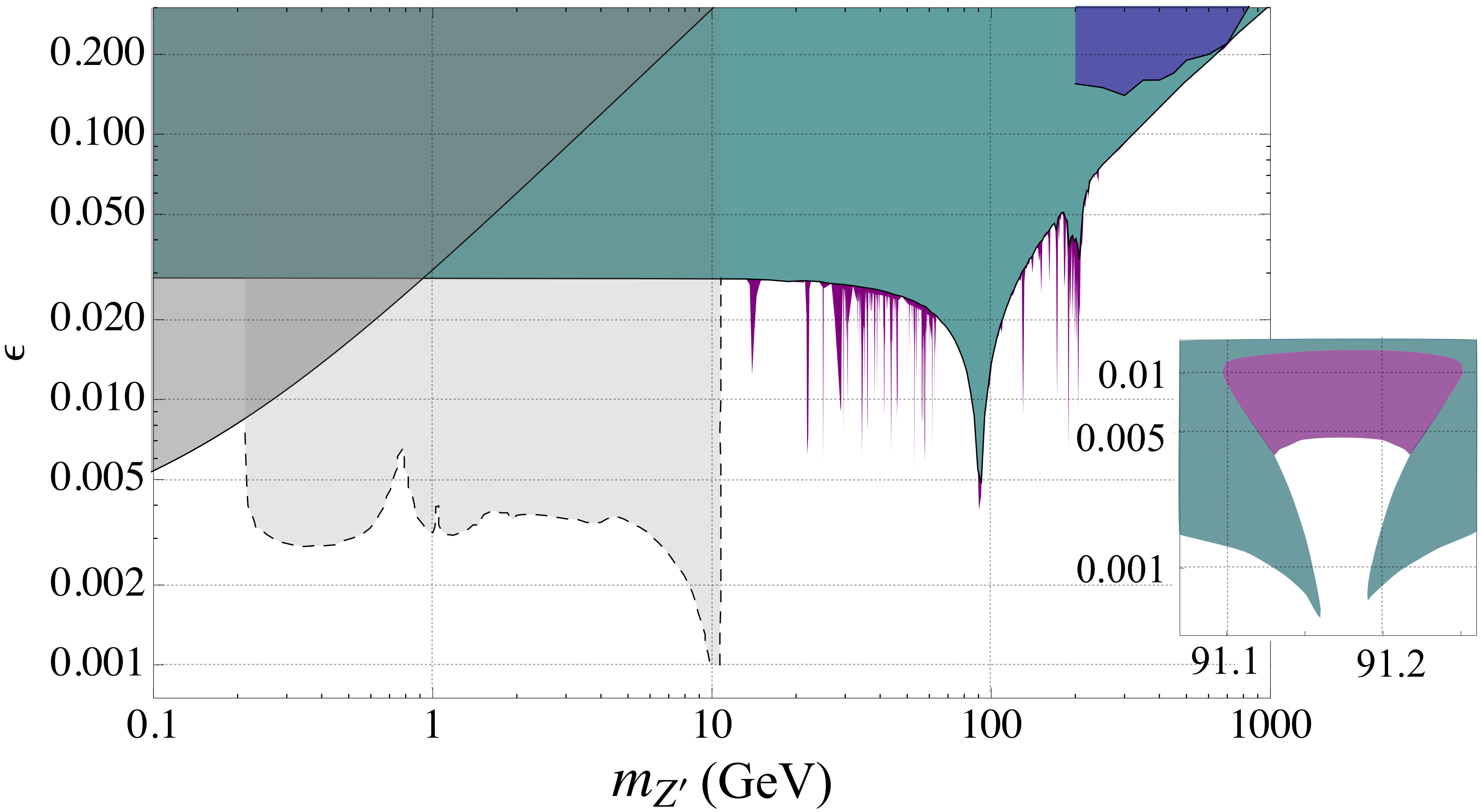
Bounds on δ (in Dark Z)

Process	Current (future) bound on δ	Comment
Low Energy Parity Violation	$\|\delta\| \lesssim 0.08 - 0.01\ (0.001)$	Fairly independent of m_{Z_d}. Depends on ε.
Rare K Decays	$\|\delta\| \lesssim 0.01 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_K^2$. Depends on BR($Z_d$).
Rare B Decays	$\|\delta\| \lesssim 0.02 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$. Depends on BR($Z_d$). Some mass gap ~ 3 GeV.
$H \to ZZ_d$	$\|\delta\| \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$. Depends on BR($Z_d$) and background.

TABLE II: Rough ranges of current (future) constraints on δ from various processes examined along with commentary on applicability of the bounds. These processes have negligible sensitivity to pure kinetic mixing effects.

$$\left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$$

Electroweak precision constraints



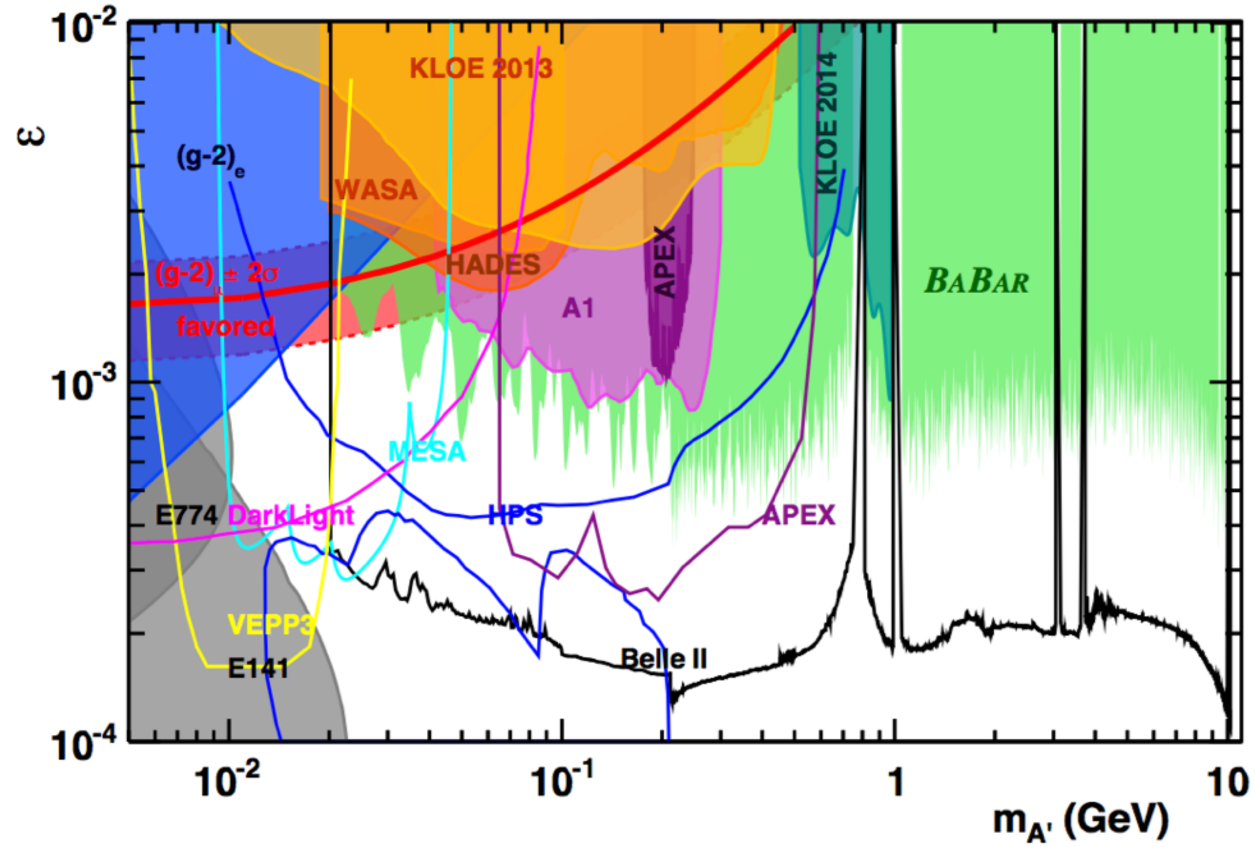
[Hook, Izaguirre, Wacker (2010)]

The constraints from the EWPT are not strong (Z pole shift [cyan] is strongest).

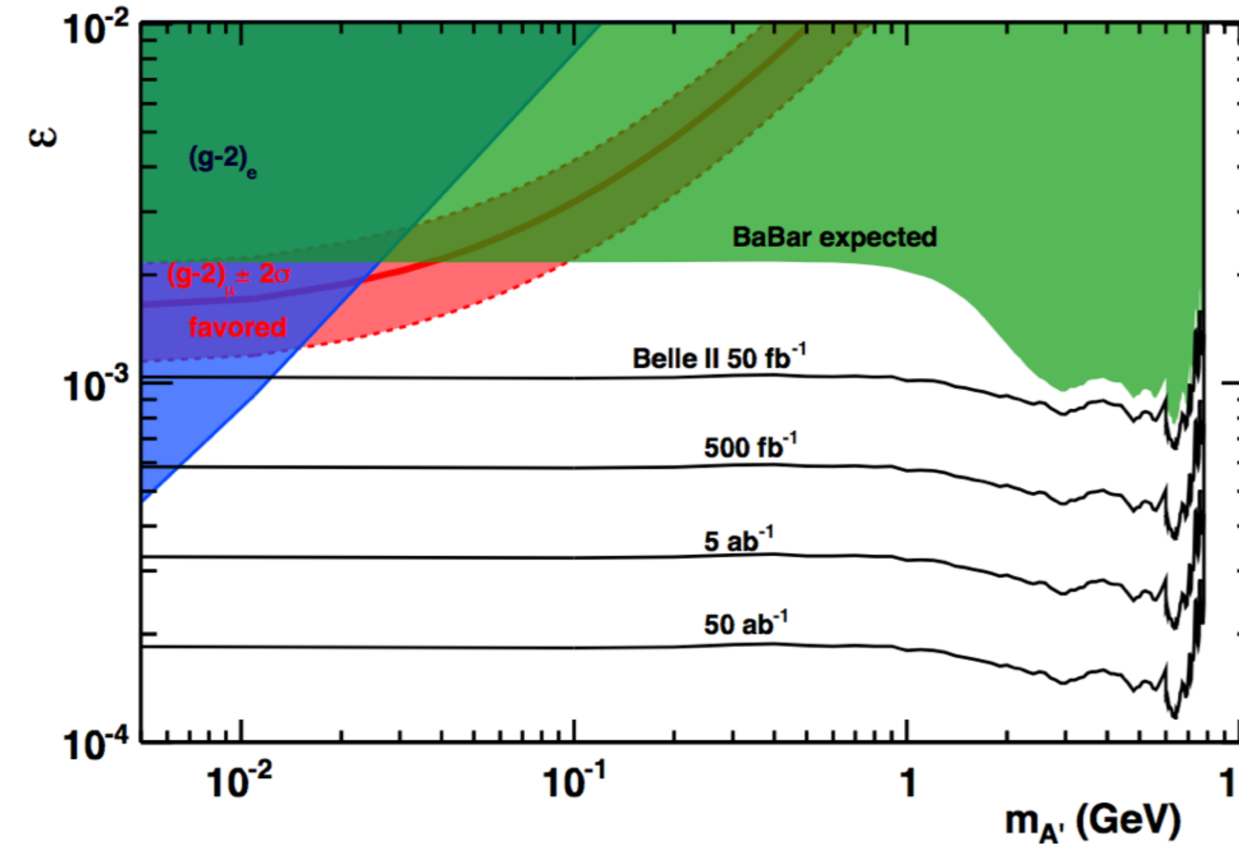
Future experimental prospects for Dark Photon searches

Chris Hearty, "Dark Sector", Belle II Theory Interface Platform meeting, Oct 2014 reviewed the Dark Photon sensitivity of future experiments

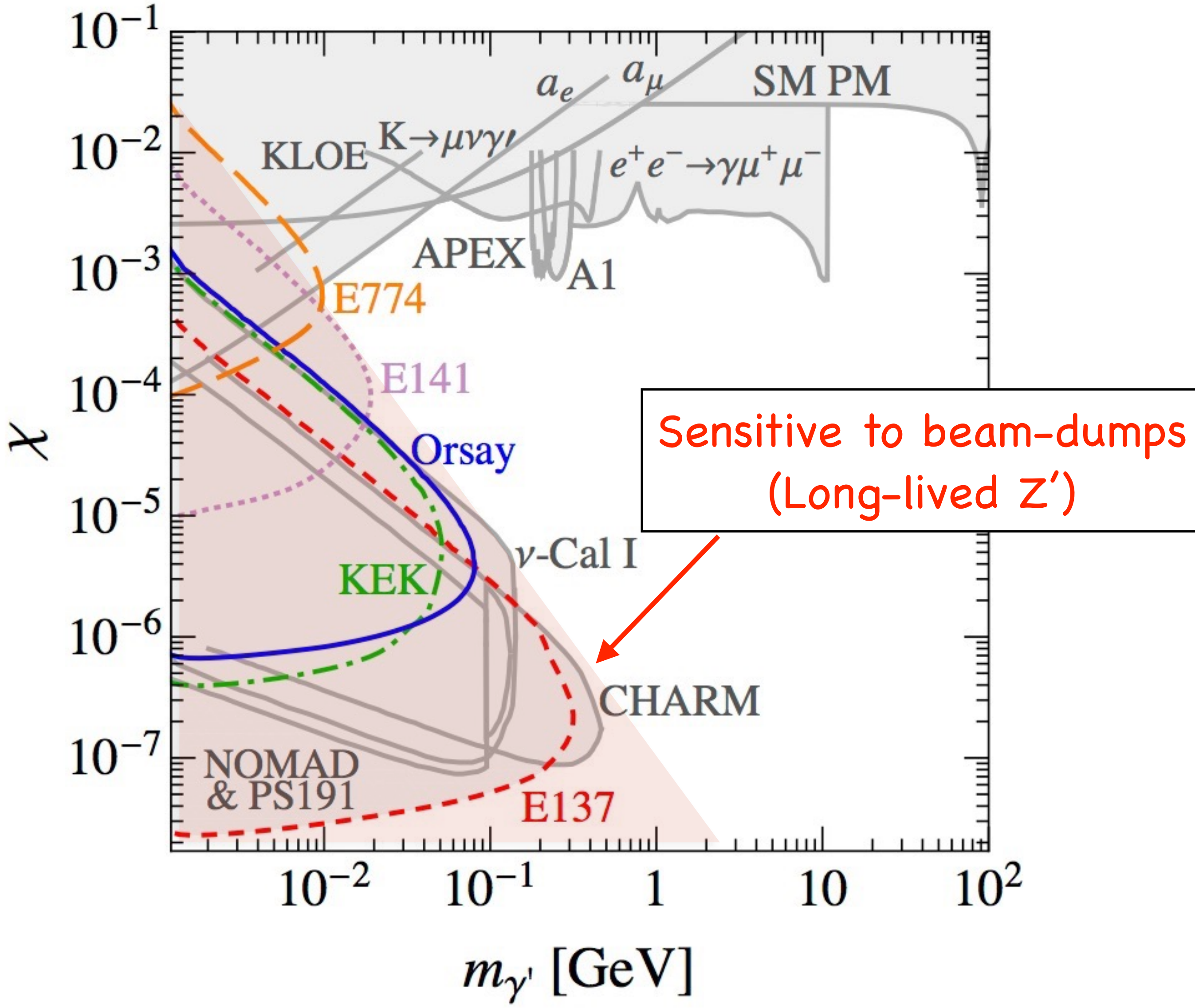
$e^+e^- \to \gamma A', \quad A' \to f\bar{f}$



$e^+e^- \to \gamma A', \quad A' \to \text{invisible}$

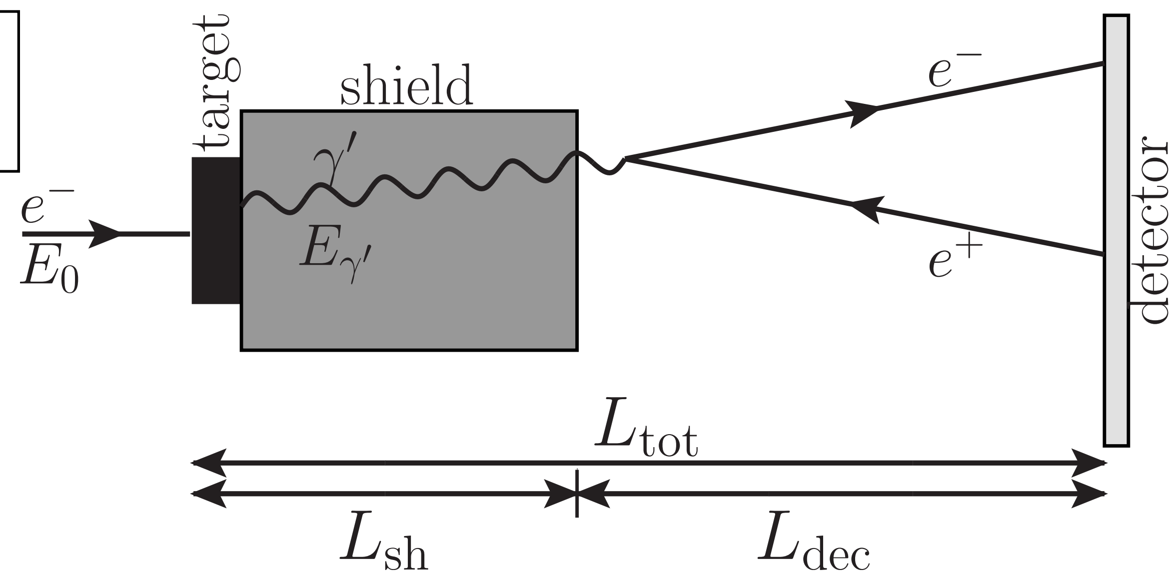


Beam-dump Experiments



[Andreas, Niebuhr, Ringwald (2012)]

In most beam facilities, beams are dumped to **thick shield** at the end of the experiments.

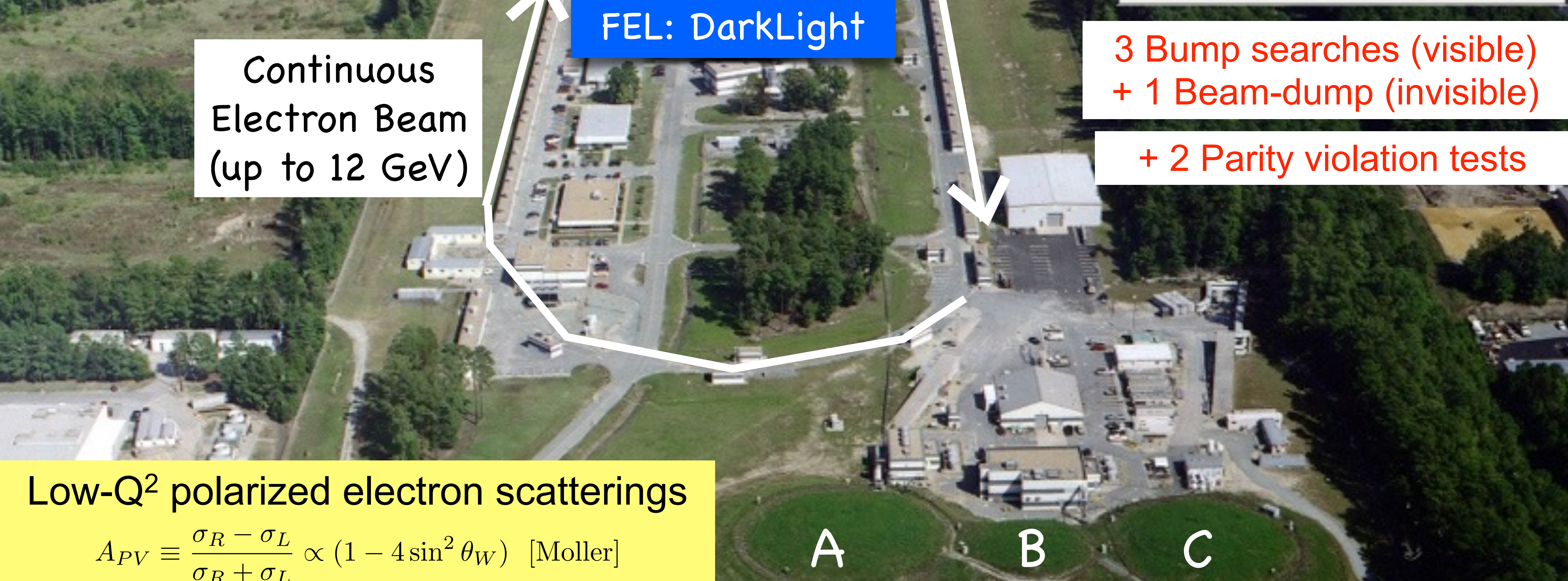


Z' is produced via Dark Photon bremsstrahlung (like Fixed target experiments).
Z' decays after shield (long-lived Z': very small mass, very small coupling).

(Ex) SLAC E141 (1986): 9 GeV e- beam, 10-12cm tungsten shield, 35m decay chamber, to search for high-E e+ (from Z' or Axion) at 0º angle with spectrometer.

Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab



BDX

FEL: DarkLight

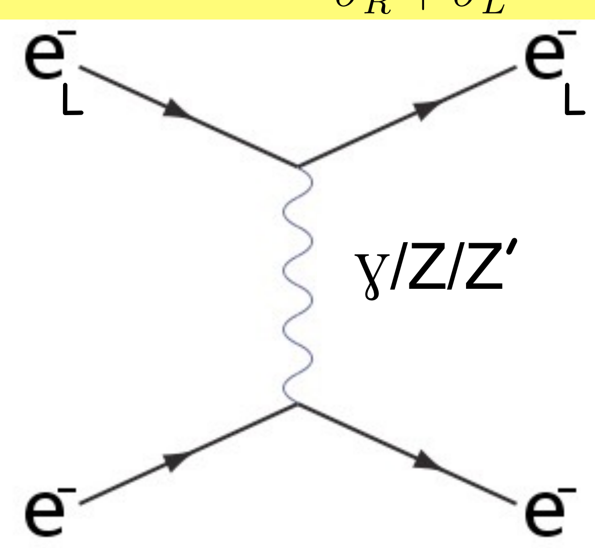
Continuous Electron Beam (up to 12 GeV)

3 Bump searches (visible)
+ 1 Beam-dump (invisible)

+ 2 Parity violation tests

Low-Q^2 polarized electron scatterings

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto (1 - 4\sin^2\theta_W) \quad \text{[Moller]}$$



Hall A: APEX

Hall B: HPS

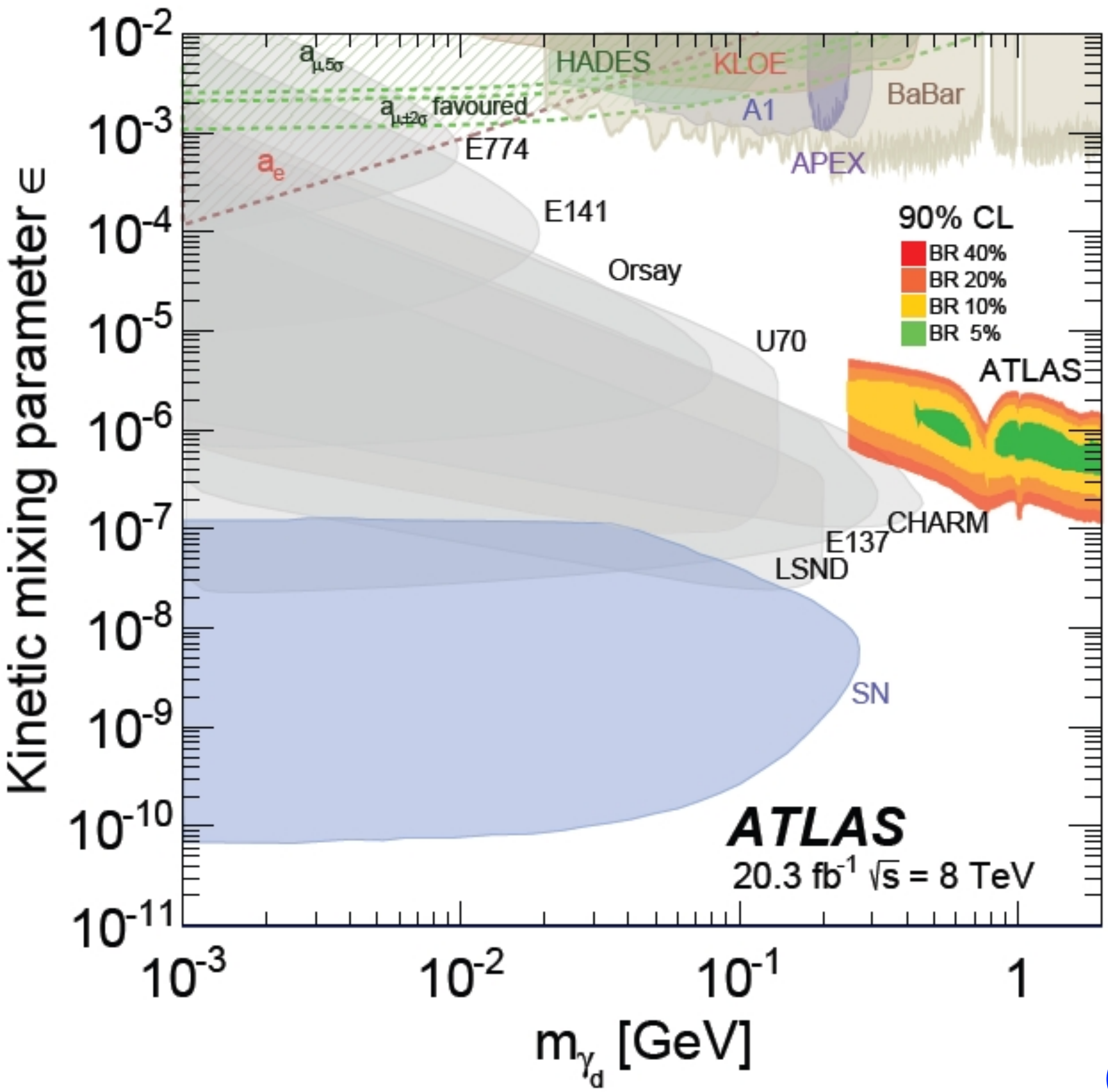
Hall A: Moller

Hall C: Qweak

“Dark Z” searches

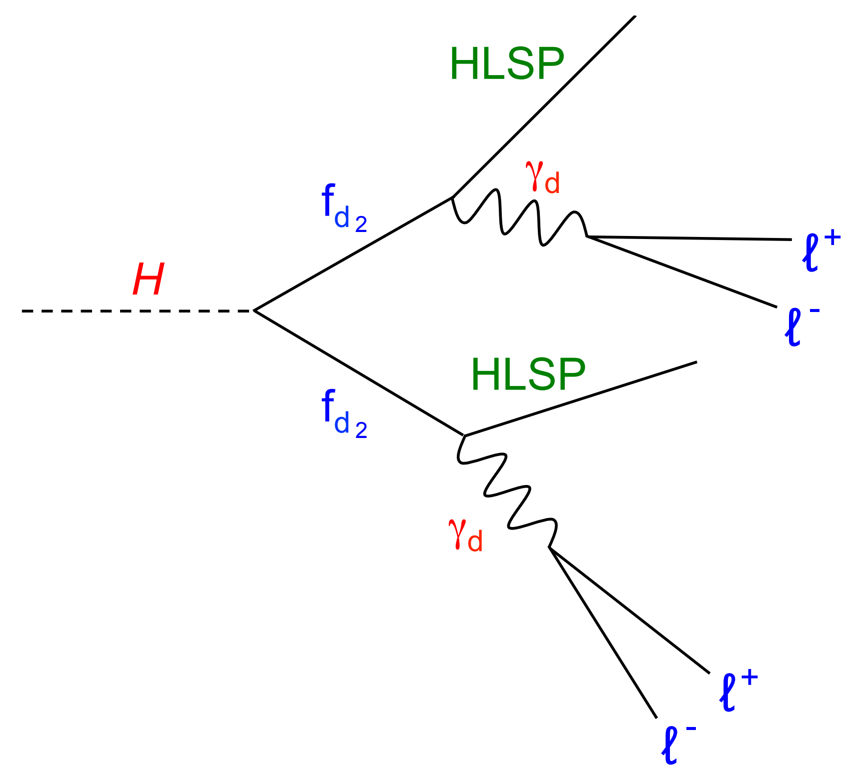
(2 more experiments relevant to Dark Force searches)

Dark force searches at the LHC



[ATLAS 1409.0746]

(Ex) Looking for displaced "Lepton-Jet" objects (from boosted Z' → $\ell^+\ell^-$) in a Hidden sector model. [Falkowski *et al* (2014)]

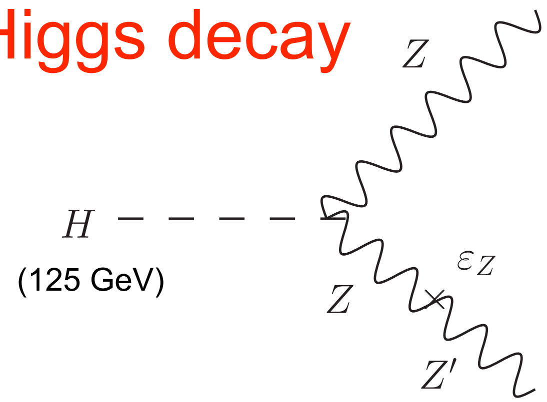


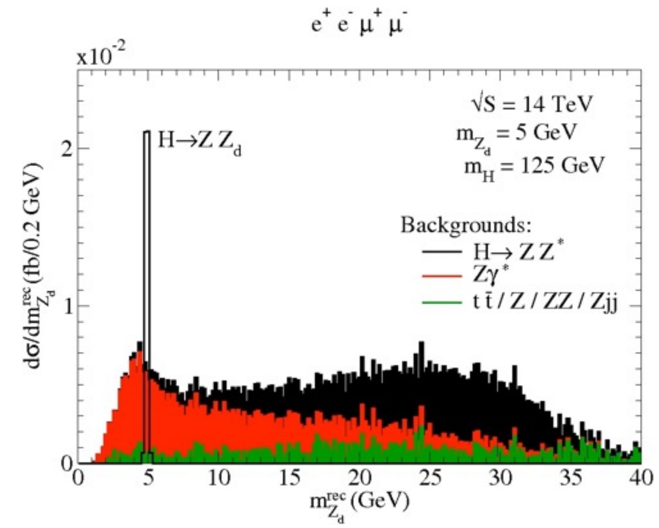
(Lepton-Jet: Highly collimated leptons in a small cone R < 0.1 without nearby hadronic activity)

Dark force searches at the LHC

(Ex) Dark Z produced via decays of heavy particles.

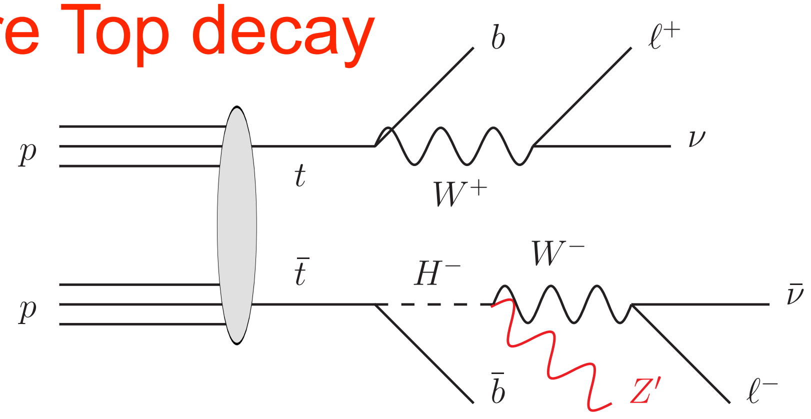
rare Higgs decay

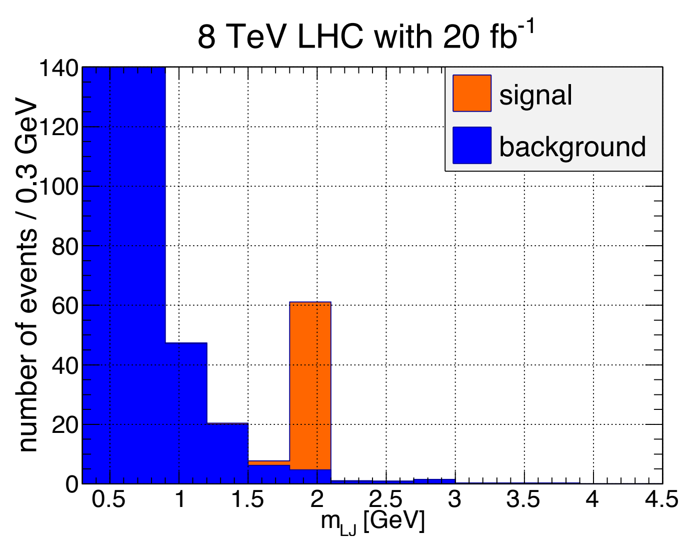


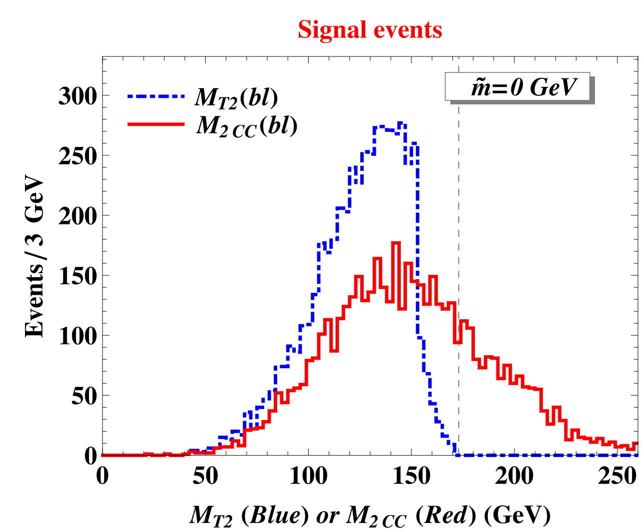


[Davoudiasl, LEE, Lewis, Marciano (2013)]

rare Top decay







[KC Kong, LEE, M Park (2014)] [D Kim, LEE, M Park (2014)]

(i) Look for a narrow dilepton resonance or LJ (for visibly-decaying Z′), or (ii) Employ a kinematic method (for invisibly-decaying Z′).