Quest for
a New fundamental force

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Quest for
a New fundamental force

with an emphasis on "Dark gauge interaction"

Dark gauge boson

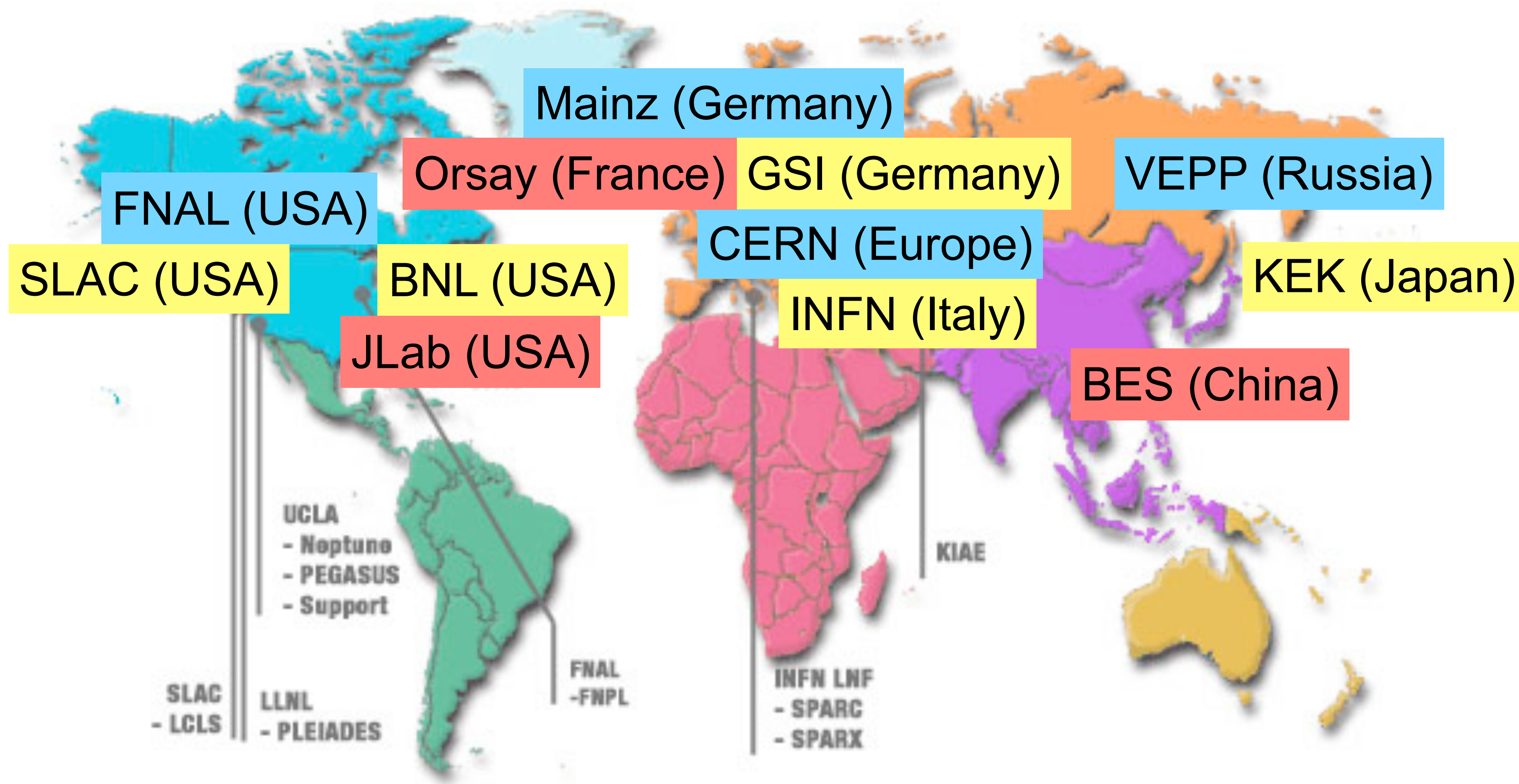
Dark gauge boson : a gauge boson with very small mass and very small coupling, with motivations from the Dark matter physics [e.g. positron excess] and others [e.g. g_μ-2 anomaly]. (Ex: Dark Photon)

Z' (Dark Force carrier)

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

Dark Force searches in the Labs

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



Typical searches for Dark Force exploit the small Z' coupling to the SM particles (not necessarily using the DM particles).

Particularly attractive feature: New physics scenario that can be tested at both High-E & Low-E experimental facilities.

[Dark force carrier Z' scale (~GeV) ≈ 1/1000 × Typical new physics scale (~TeV)]

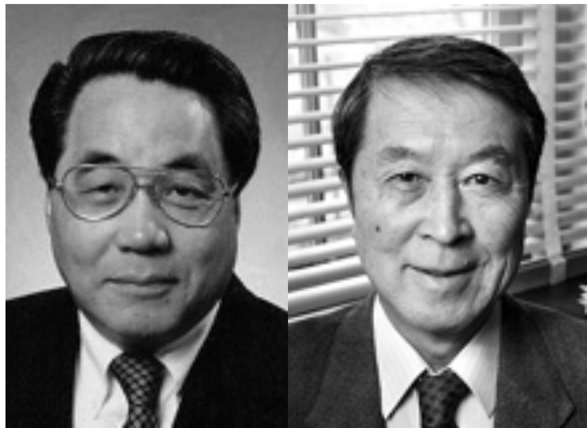
"various Low-E Labs" "LHC"

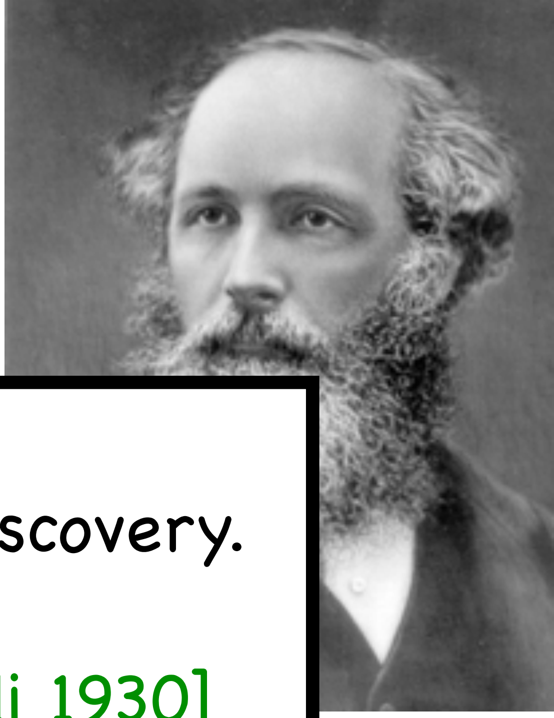
Hunt for New fundamental force

Fundamental forces (interactions) in nature:
(1) Gravity [Newton, ... in 17C]
(2) Electromagnetic force [Maxwell, ... in 19C]
(3) Weak nuclear force [Fermi, Glashow, … in 20C]
(4) Strong nuclear force [Yukawa, Han & Nambu, … in 20C]
...

Each and every fundamental force made huge impact in understanding physical world.

Discovery of another fundamental force will do the same, and bring the **revolutionary effects** in our life.





Hunt for New fundamental force

New force discovery often followed New matter particle discovery.

(i) Neutrino (to explain energy spectrum in beta decay) [Pauli 1930]
→ **Weak Force** [Fermi 1934]

(ii) Quark (to explain plethora of hadrons) [Gell-Mann, Zweig 1964]
→ **Strong Force** of gauged SU(3) [Han & Nambu 1965]

(iii) Dark Matter (to explain galaxy rotation curve) [Rubin 1970's]
→ **Dark Force?**

New force may help understanding the New matter particles better.

Discovery of another fundamental force will do the same, and bring the **revolutionary effects** in our life.

Outline

1. Dark force models (Dark Photon vs. Dark Z)
2. Typical Dark force searches (mostly based on dilepton channels)
3. Invisibly decaying Dark gauge boson (Z' $\rightarrow \chi\chi$)
4. Dark force searches through Low-energy parity test (Dark Z)
5. Implications for the LHC experiments
6. Some other aspects

Low-E searches (items 2–4)

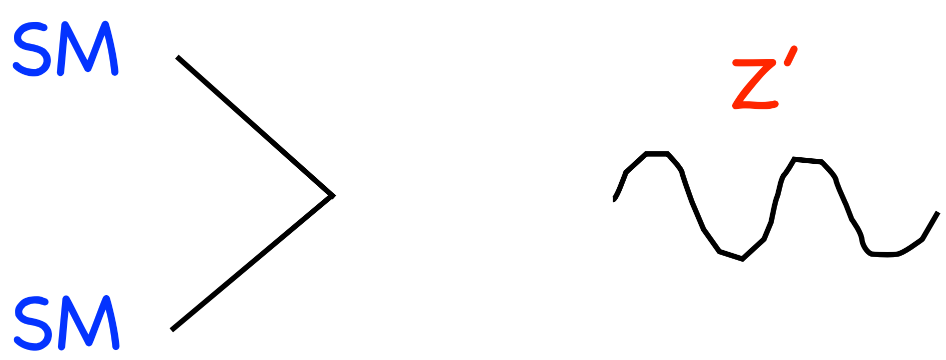
High-E searches (item 5)

Dark Force Models

Kinetic mixing portal (vector portal) to Dark sector

Dark sector gauge symmetry $U(1)_{dark}$

: it may interact with DM, but SM particles have zero charges.

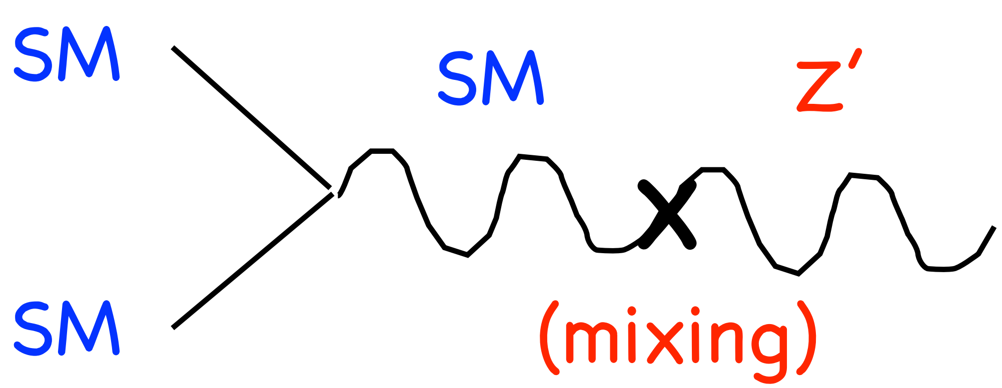


(no direct coupling)

Z' can couple to SM particles through <u>kinetic mixing</u> of $U(1)_Y$ & $U(1)_{dark}$.

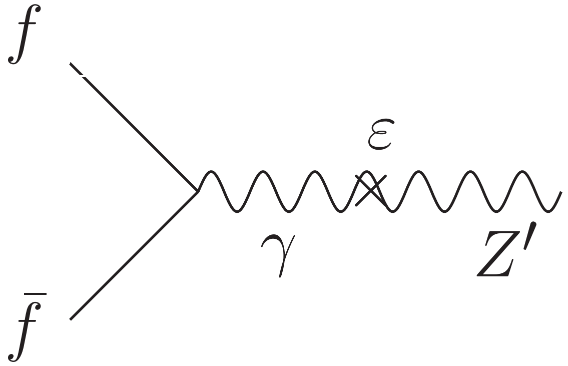
[Holdom (1986)]

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

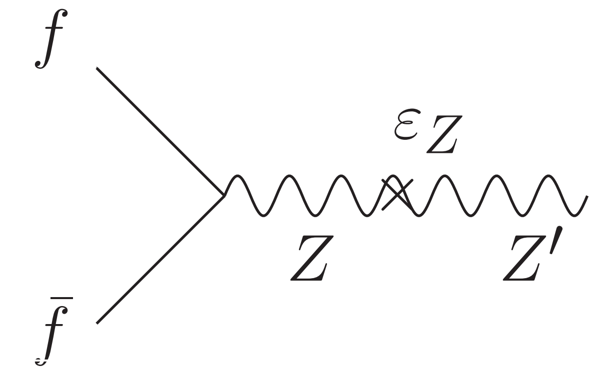


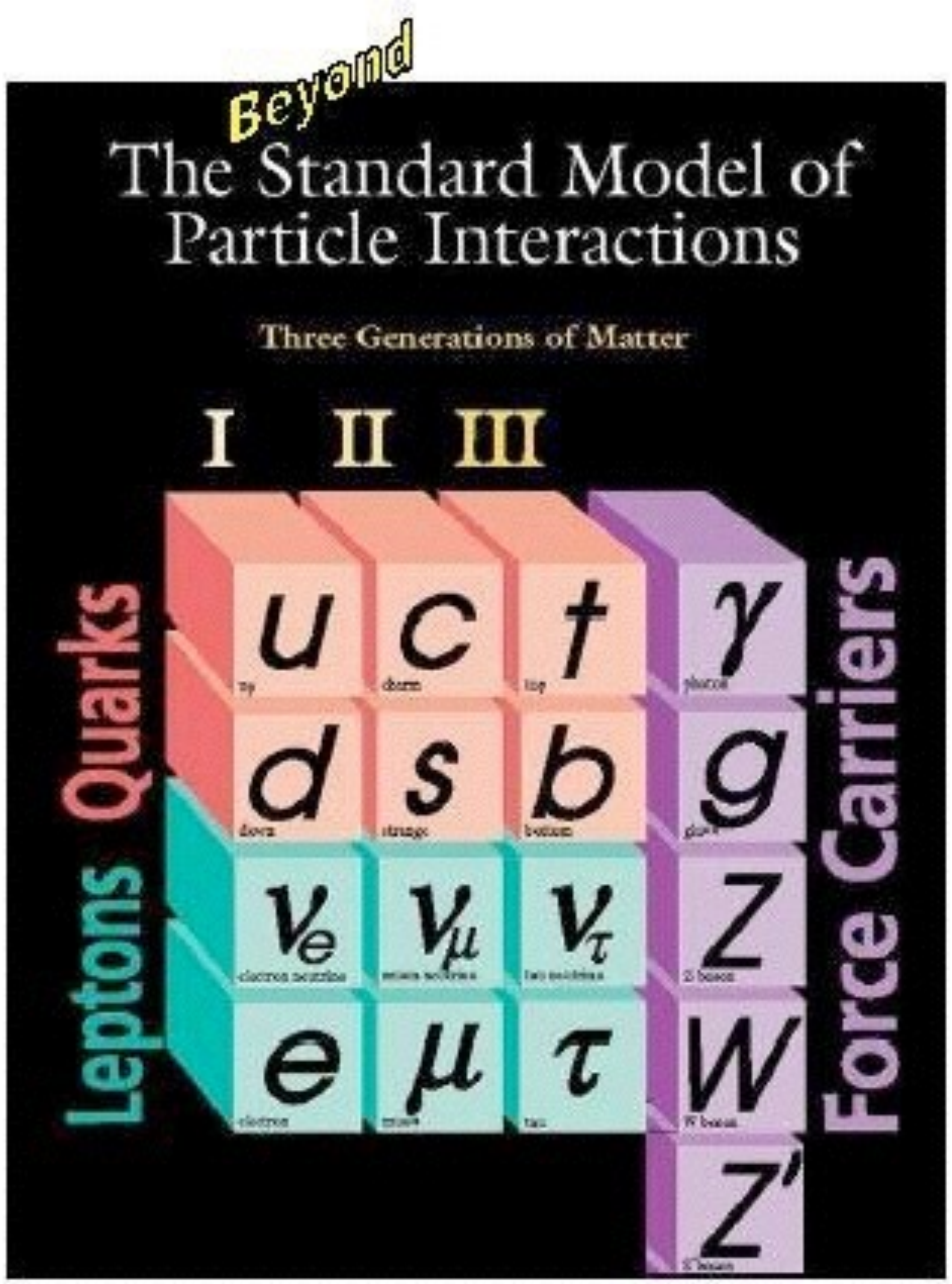
(couples through SM gauge bosons)

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$



Types of Dark Force





Z' : <u>couplings</u> to the SM particles are suppressed by small <u>mixing</u>.

(model-dependent)

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

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

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

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

inherits properties of Z boson like <u>parity violation</u>.
(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)

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

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

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

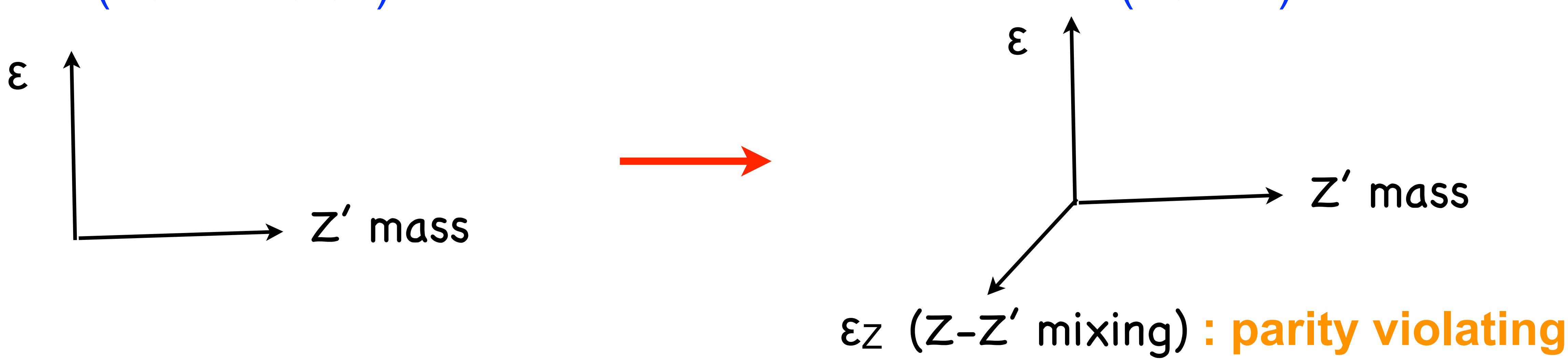
(depends on Higgs sector) *(for Higgs singlet)*

Dark Force couplings depend on "Higgs sector".

Effects of New Model (Dark Z)

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

(Dark Photon) (Dark Z)



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

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

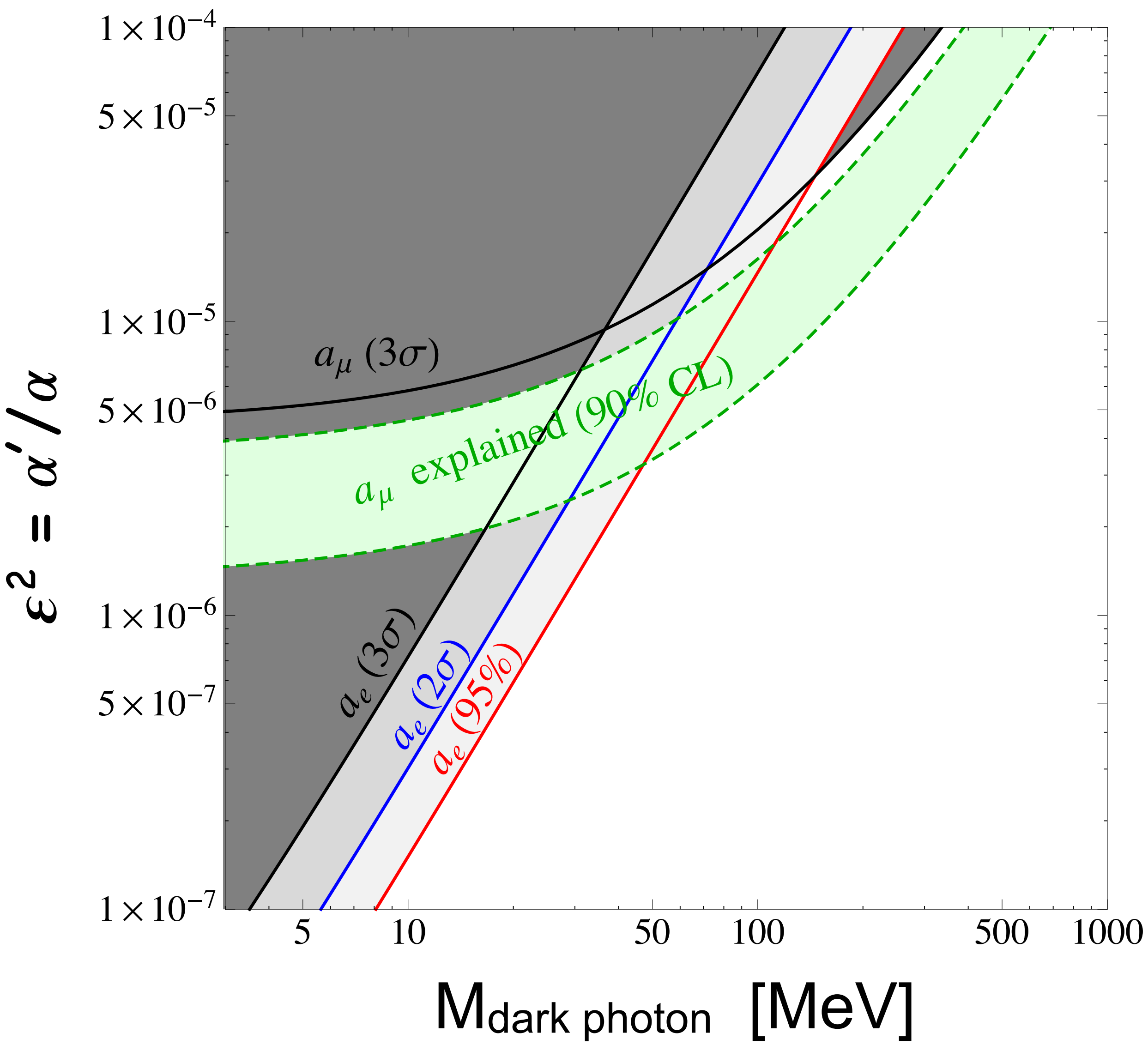
- Dark Z = Dark Photon with more general coupling.
- Dark Photon = a special case of Dark Z ($\varepsilon_Z = 0$ limit).

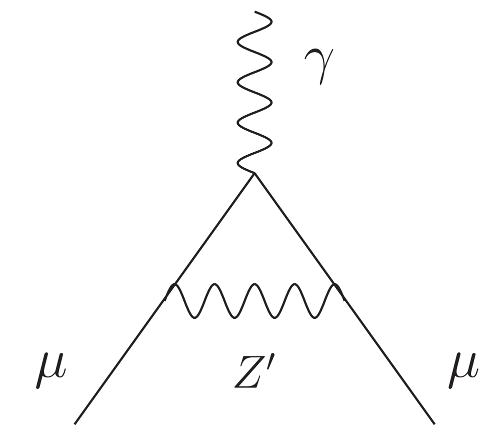
Some experiments irrelevant to Dark Photon searches <u>become relevant</u> to Dark Z searches. They include

(1) Rare Higgs decay (Z–Z' mixing),
(2) Rare Top decay (with $H^{\pm} \to W Z'$s as the dominant $H^{\pm}$ decay),
(3) Low-Q^2 parity violation (in Polarized electron scattering),
(4) Different properties in FCNC meson decays.

Typical Dark Force Searches
(in Low-energy experiments)

Anomalous Magnetic Moment





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

Green band: explains the 3.6σ deviation in a_μ

(possibly early 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 independent of the unknown DM properties.
- It is independent of the Z' decay BR.

Constraints on the Parameter Space

Mostly from the Z' $\rightarrow \ell^+\ell^-$ searches

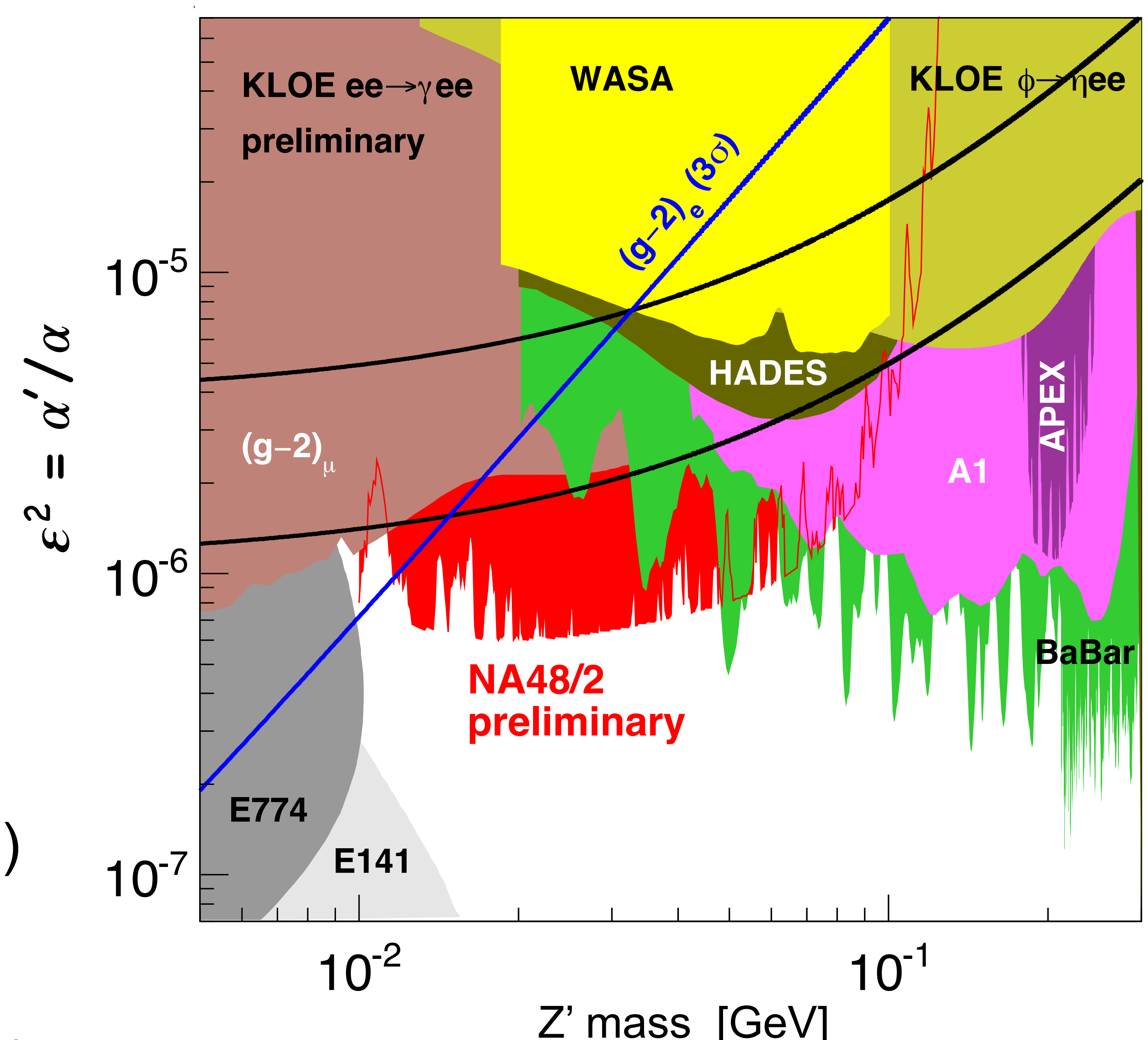
(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) Meson (quarkonium) decays
(iv) e+e- collision (radiation)
(v) Fixed target experiments

With 2014 results: whole green band (g_μ-2 favored) is excluded now.
[CERN NA48/2 preliminary (1412.8053)]

The claim by BNL PHENIX (1409.0851) was withdrawn.

We need to keep probing the other parameter space.

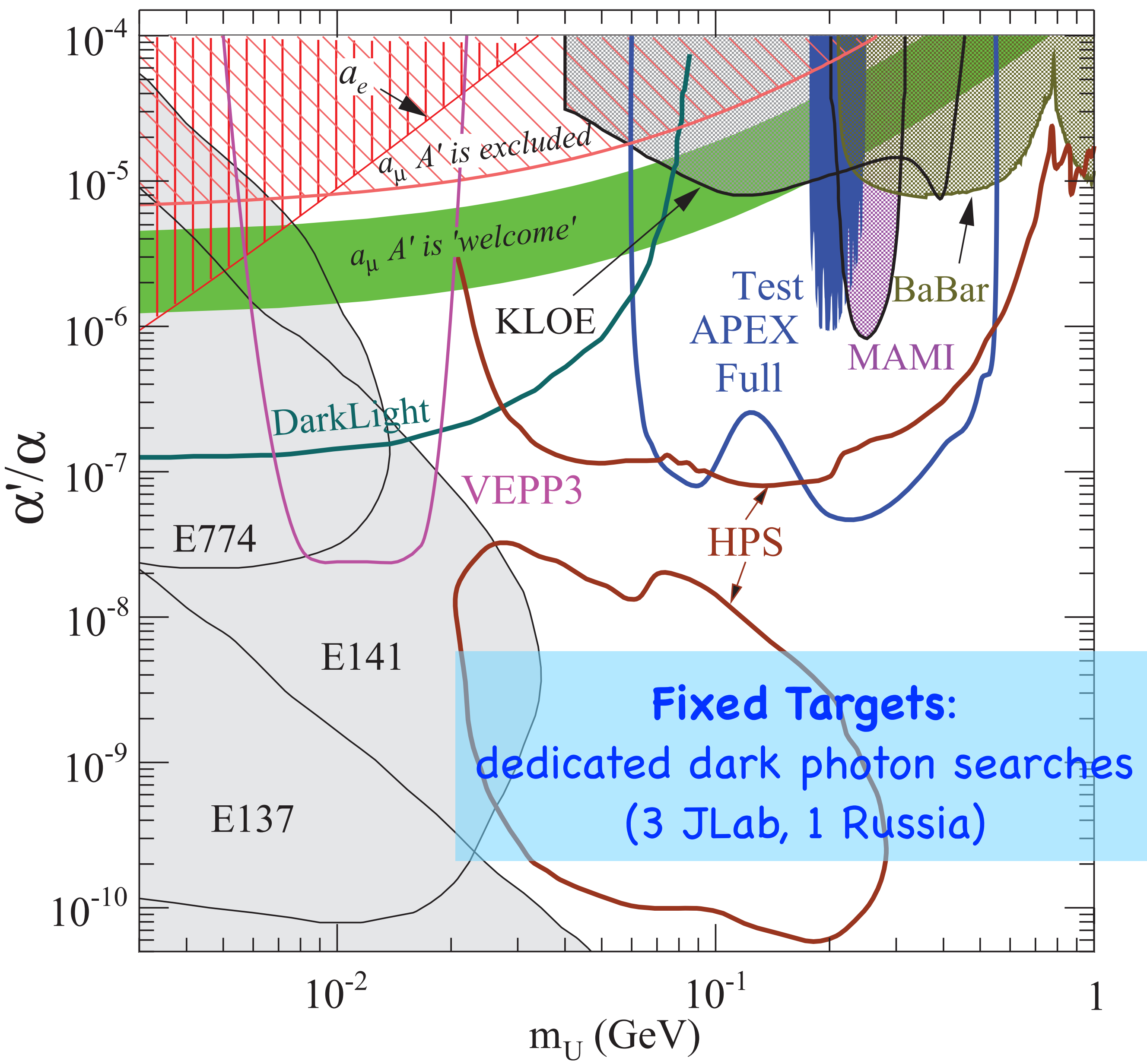
[current constraints]



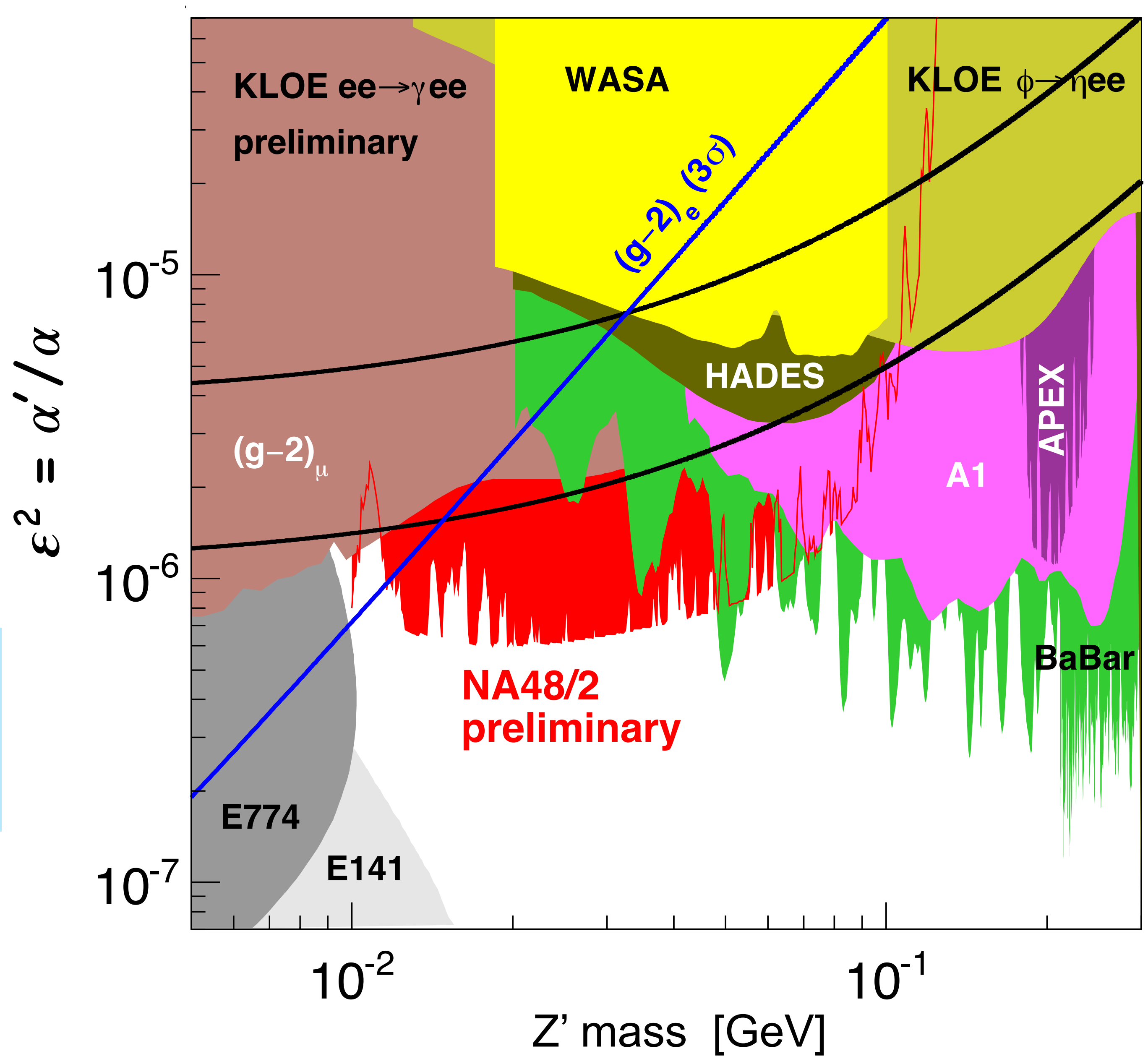
[Dark Photon & Dark Z boson]
(as ε_Z is tiny)

Constraints on the Parameter Space

[2011 constraints and plans]



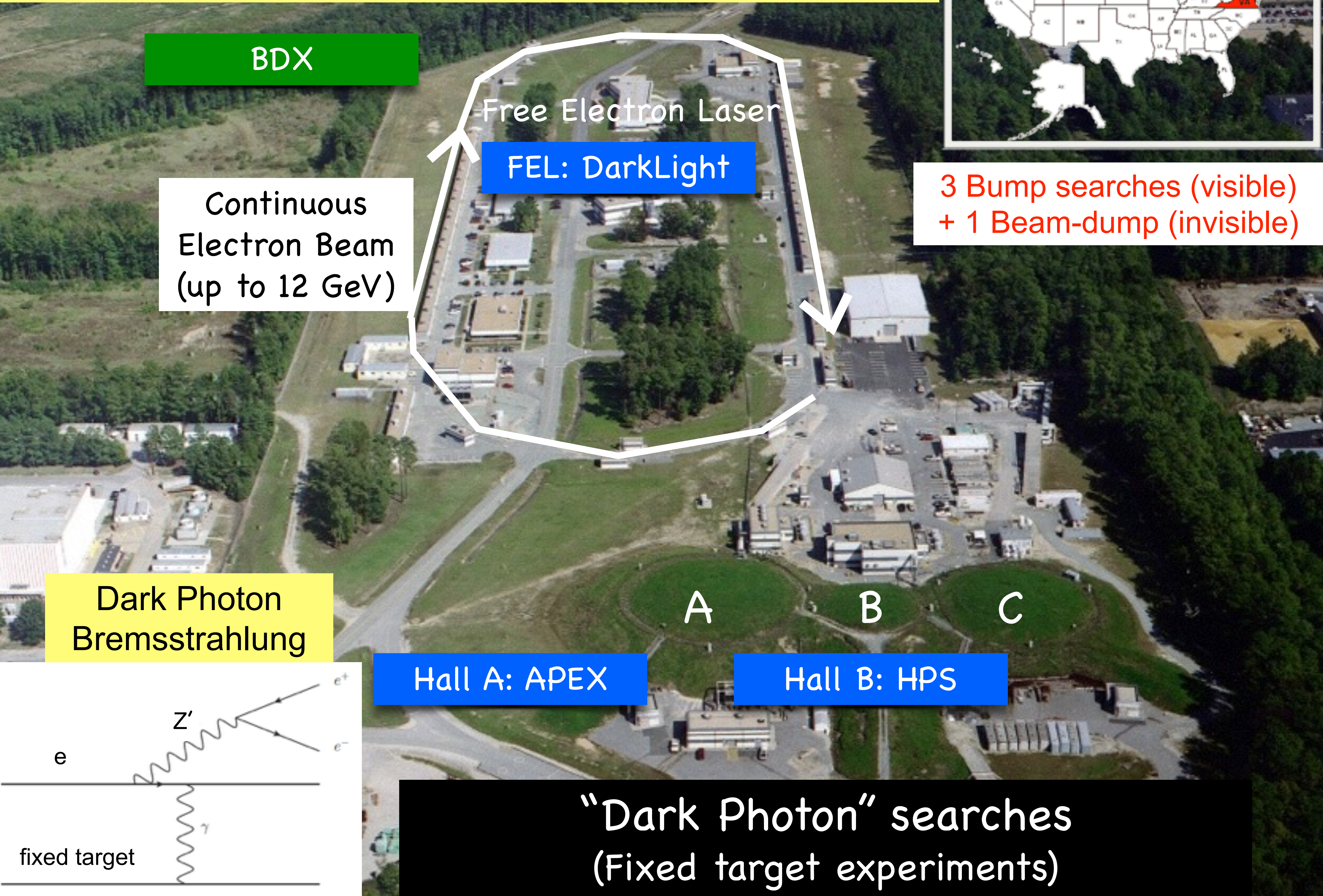
[current constraints]



"Dark gauge boson" physics is a rapidly-developing field.

Dark Force searches at Jefferson Lab

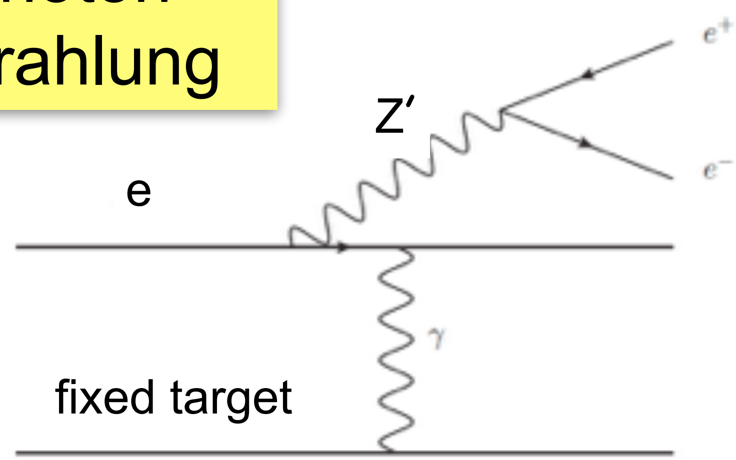
Nuclear/Hadronic Physics Lab

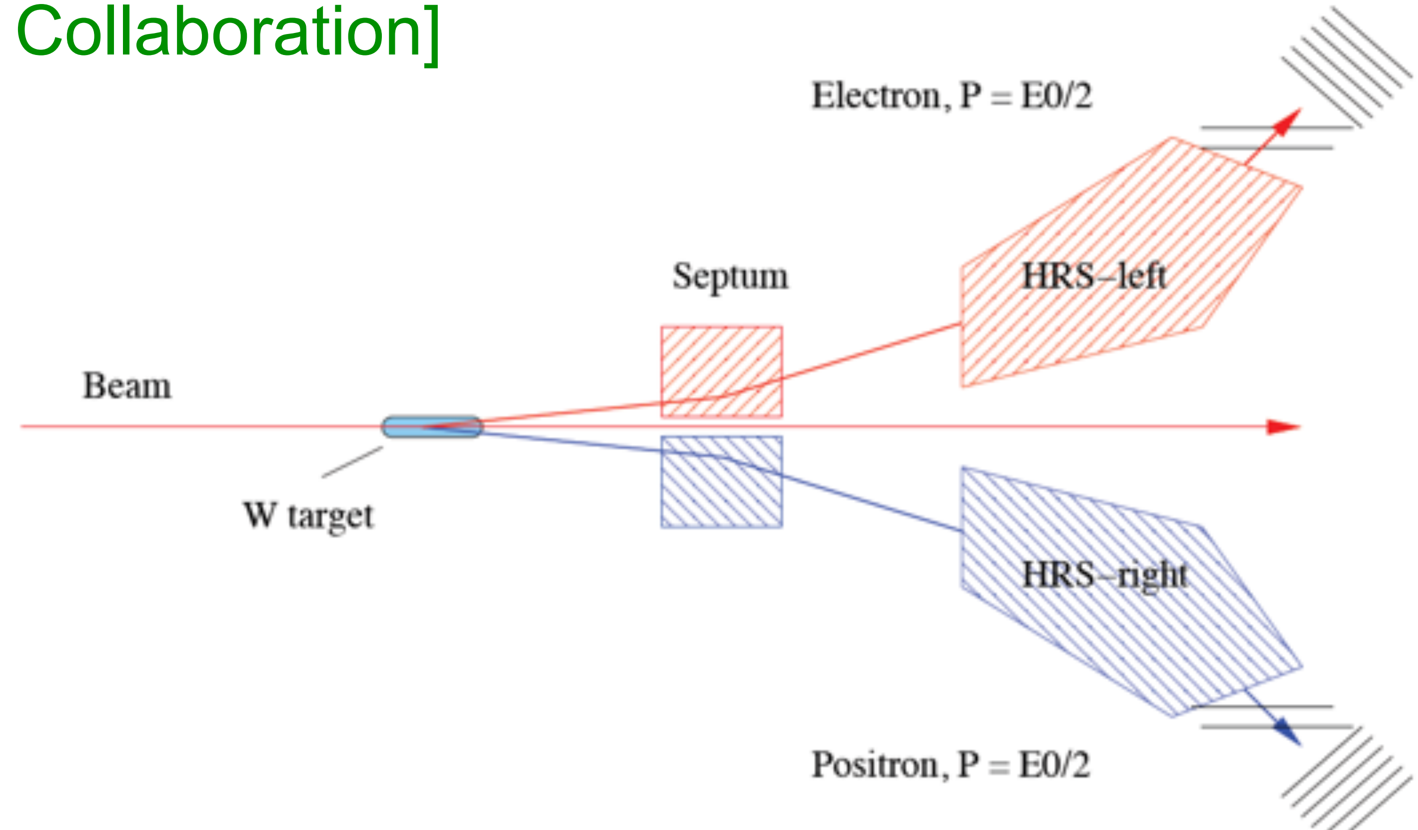


Example: A' Experiment (APEX) at JLab - Hall A

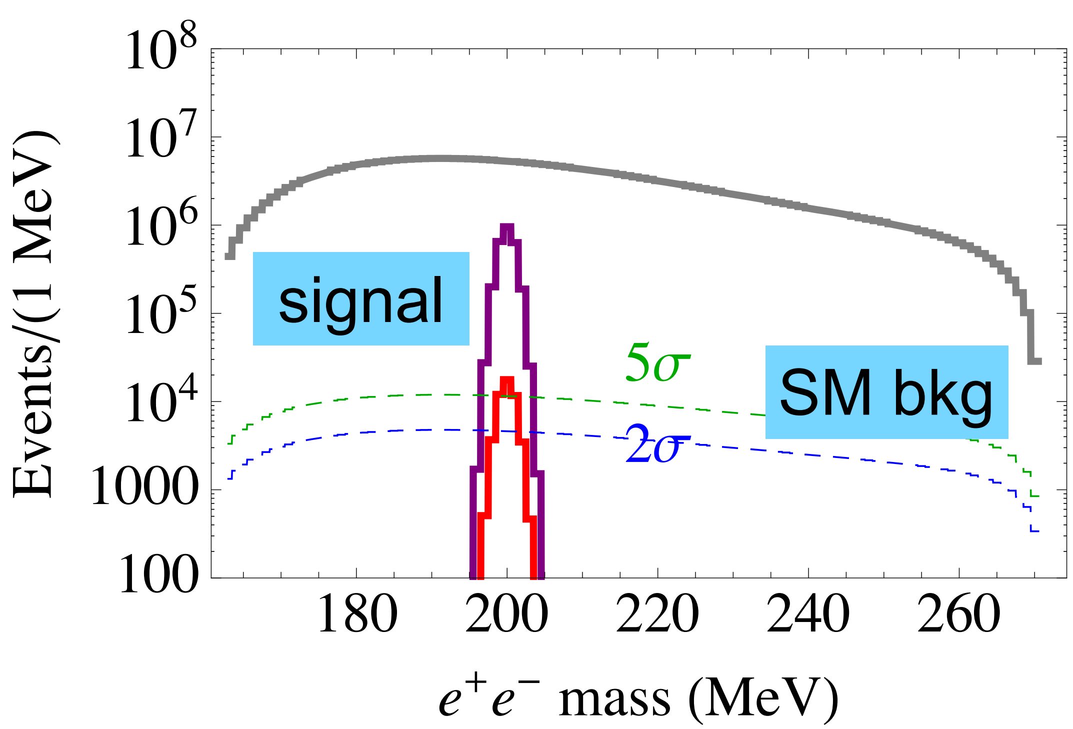
[APEX Collaboration]

Dark Photon Bremsstrahlung





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



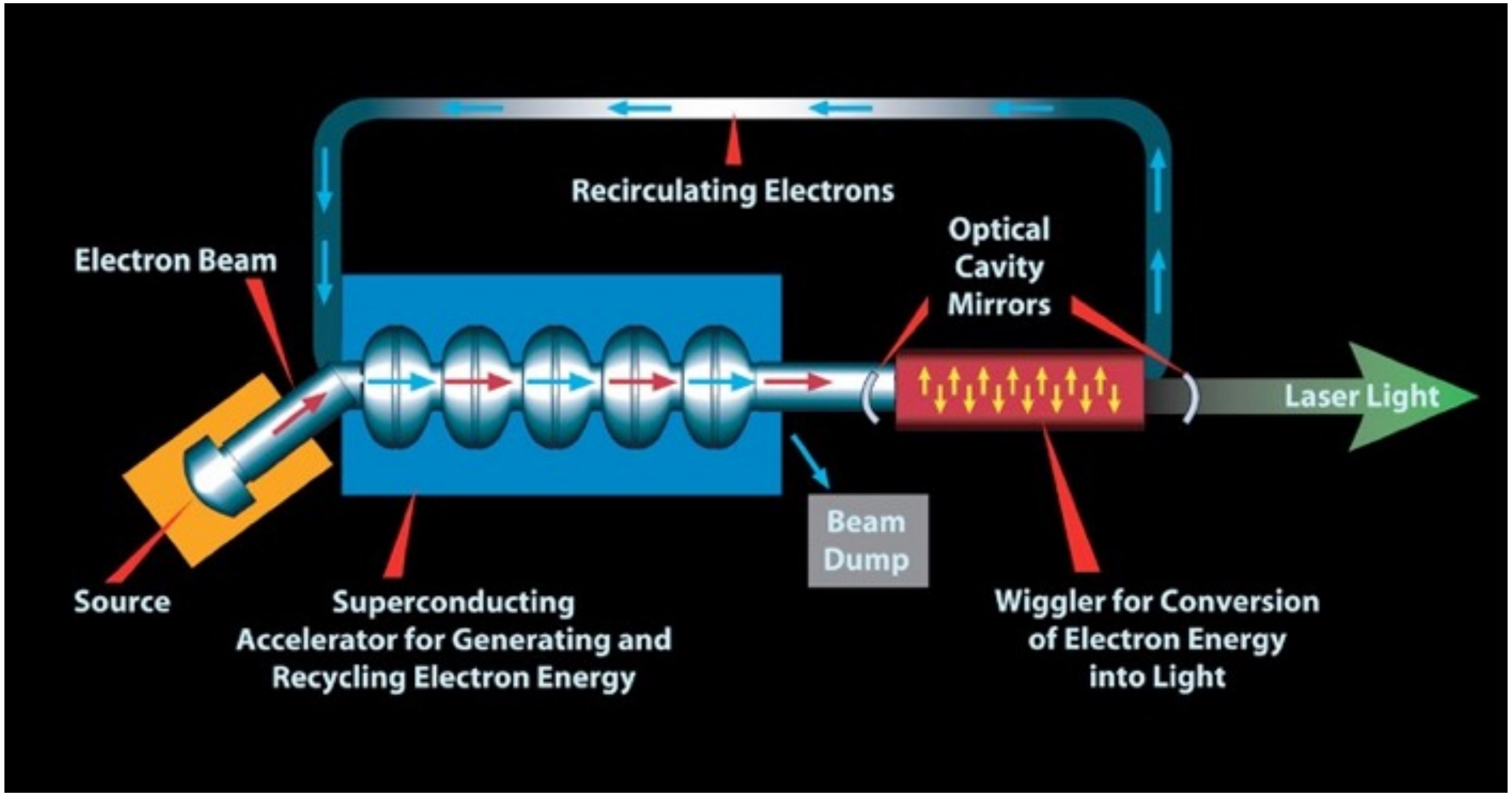
Z' ➞ e^+e^- narrow resonance at Z' mass
(Direct bump search at Low-energy facility).

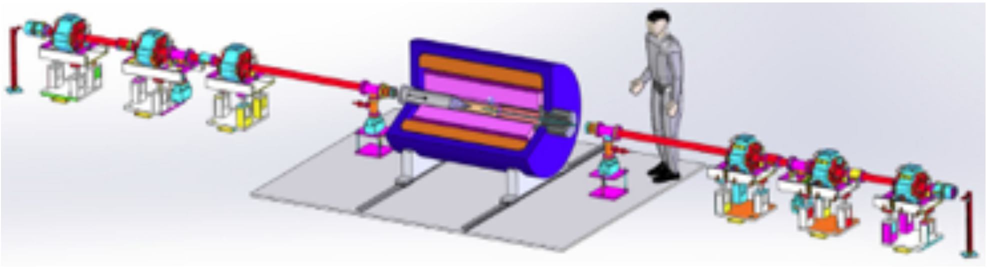
The *High Resolution Spectrometers (HRS)* at Hall A are used.

Example: DarkLight Experiment at JLab - FEL

[DarkLight Collaboration]

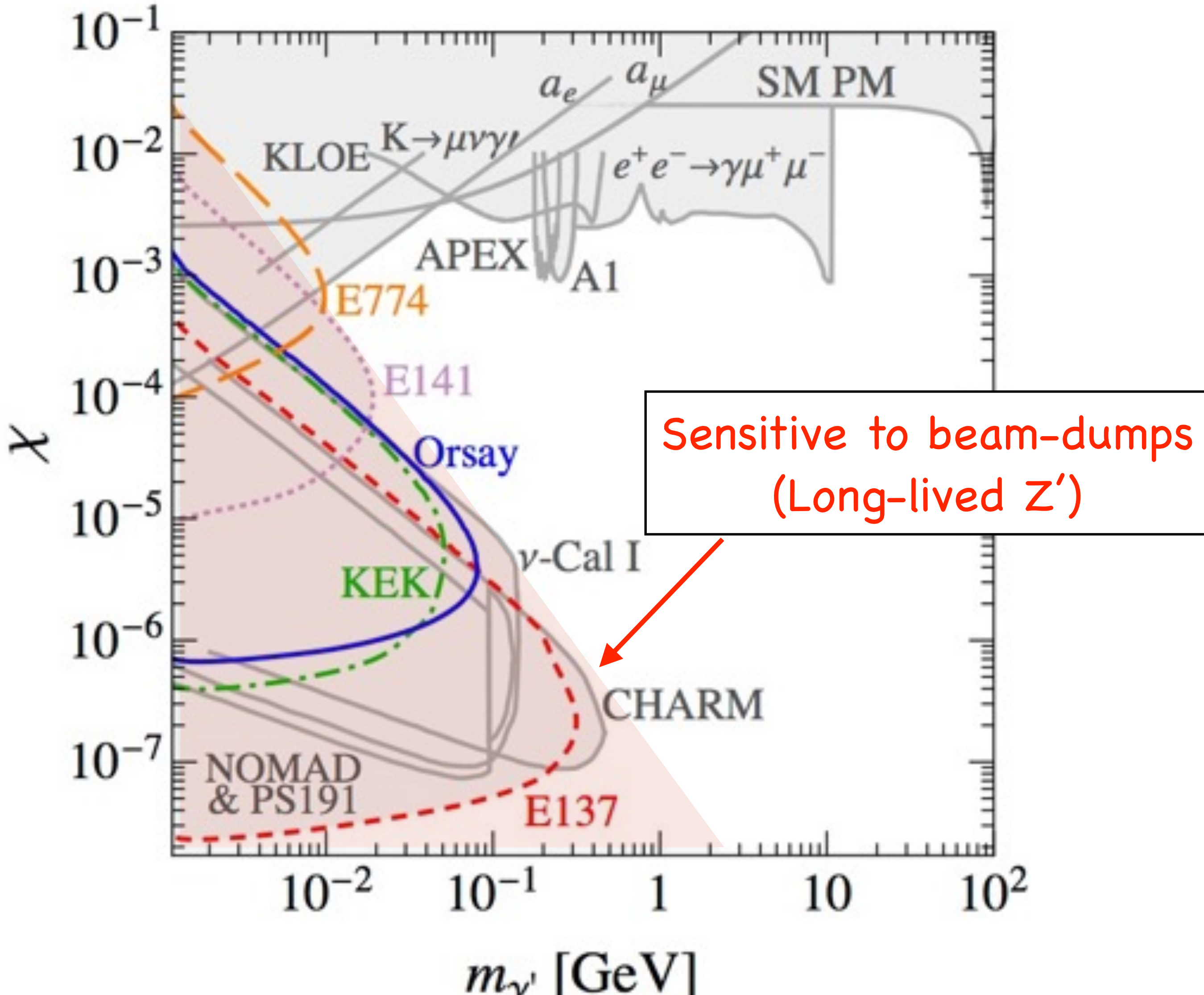
Free Electron Laser facility at Jefferson Lab
(e-beam: 100 MeV, 10 mA, 1 MW)





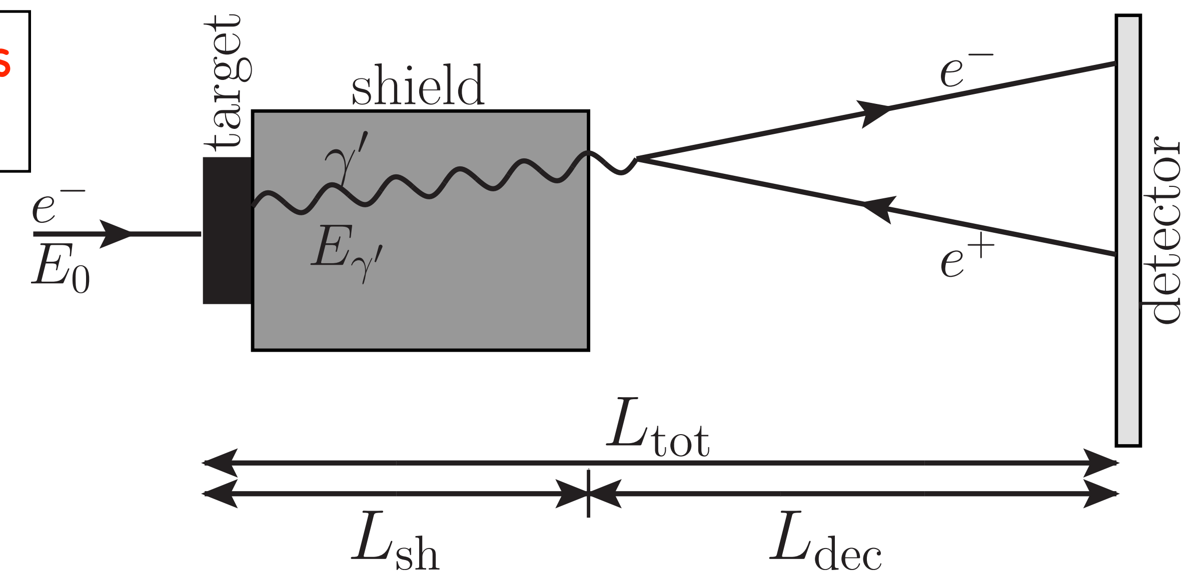
Electrons incident on Gaseous Hydrogens

Beam-dump Experiments



[Andreas, Niebuhr, Ringwald (2012)]

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

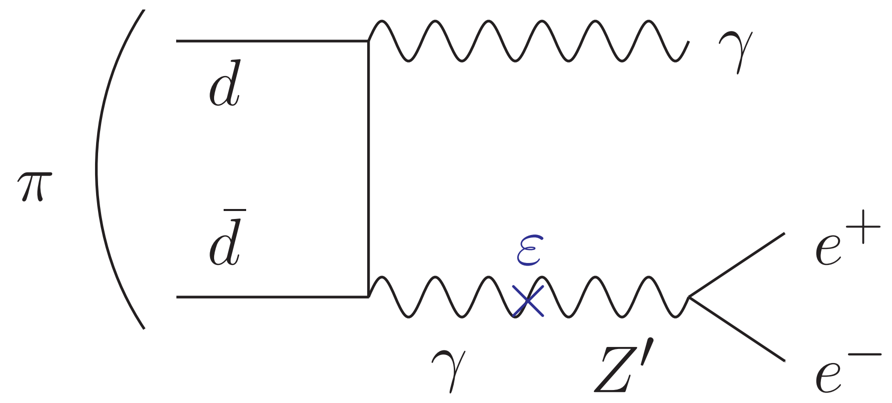


Z' is produced via Dark Photon bremsstrahlung (like Fixed target experiments).
Z' decays after shield (long-lived Z': very small mass, very small coupling).

(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.

Meson decays into Light Z'

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



π(dd) → γ Z' → γ + dilepton-resonance

Flavor-conserving meson decays

- π(dd), η(dd) → γ Z' (WASA, HADES, PHENIX, NA48/2)
- ϕ(ss) → η Z' (KLOE)
- Υ(bb) → γ Z' (BABAR)

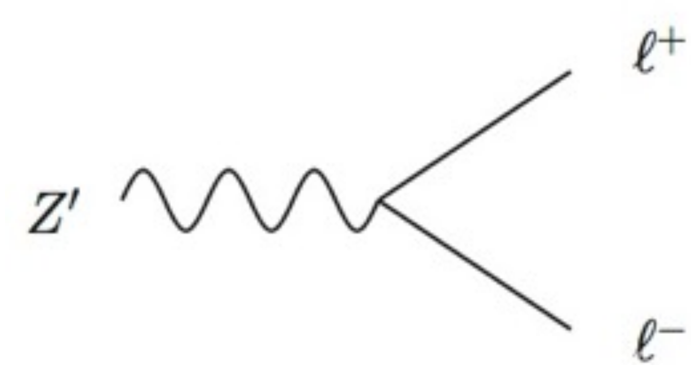
: Important searches for the Dark Force

Invisibly decaying Dark gauge boson

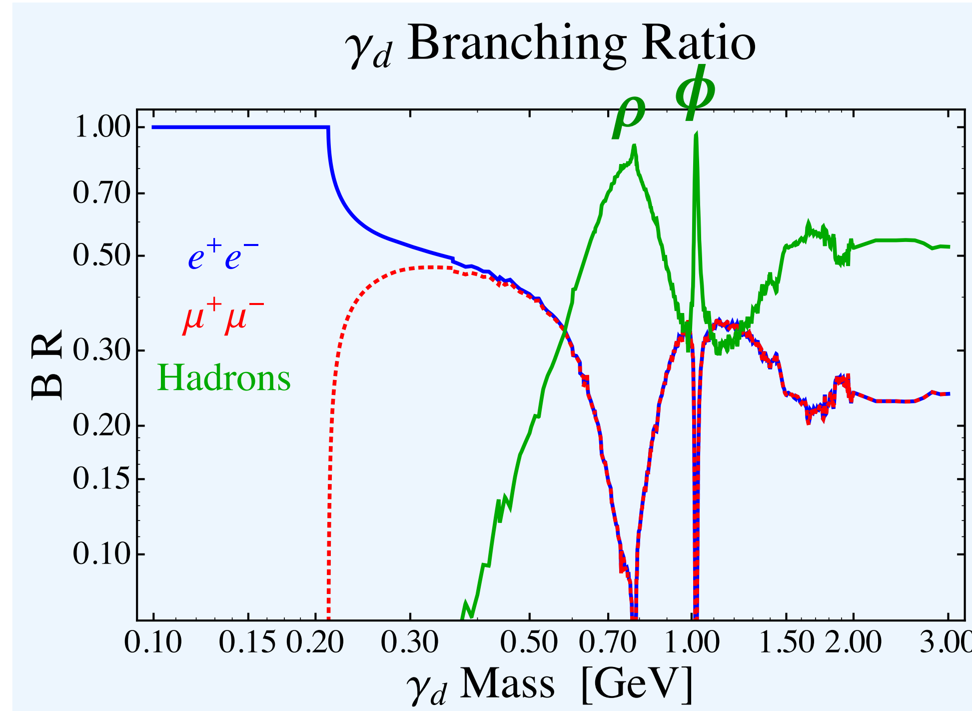
Visible/Invisible decay of Dark gauge boson

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

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



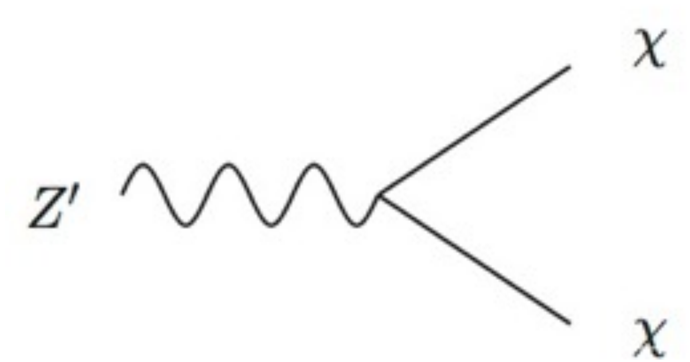
Z' → $\ell^+\ell^-$ is the major decay mode in an ordinary scenario.



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

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

(ii) "Missing Energy" (or invisible) search

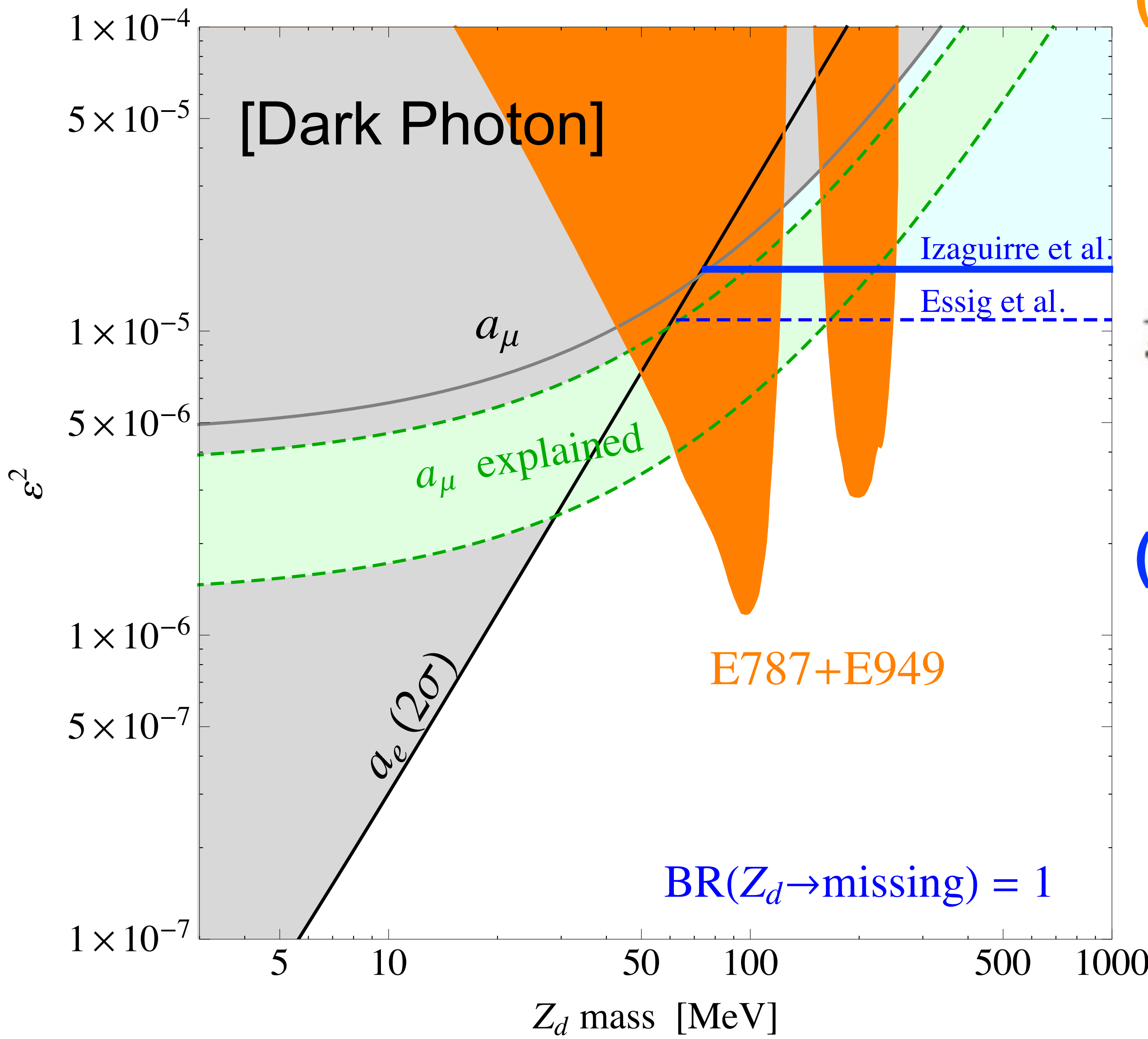


Z' → $\chi\chi$ is the major decay mode,
if χ **(very light dark sector particle)** exists.

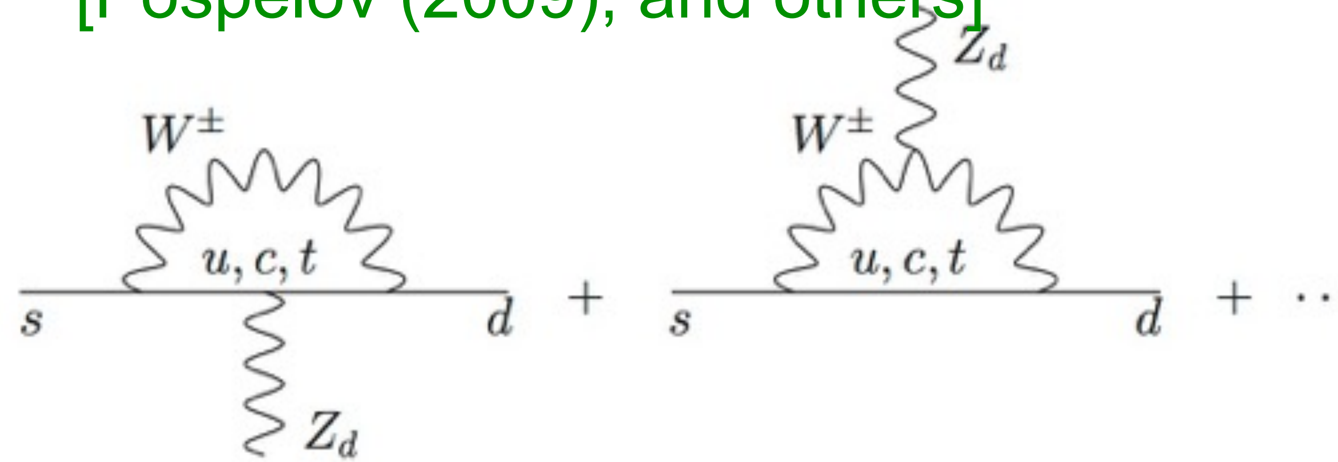
BR(Z' → MET) ≈ 1 is taken.

Invisibly decaying Dark gauge boson

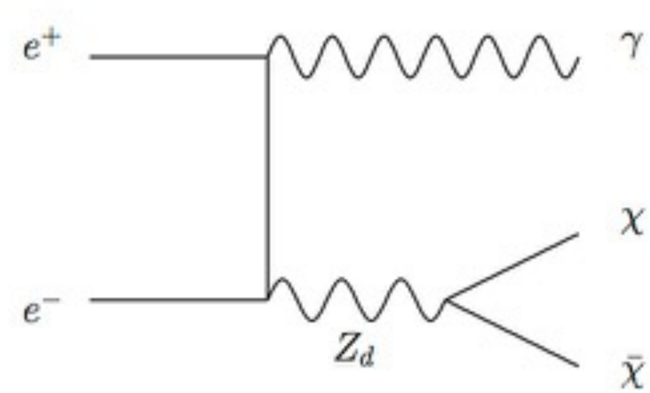
(ii) Missing Energy (Z' → $\chi\chi$) searches



(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)]



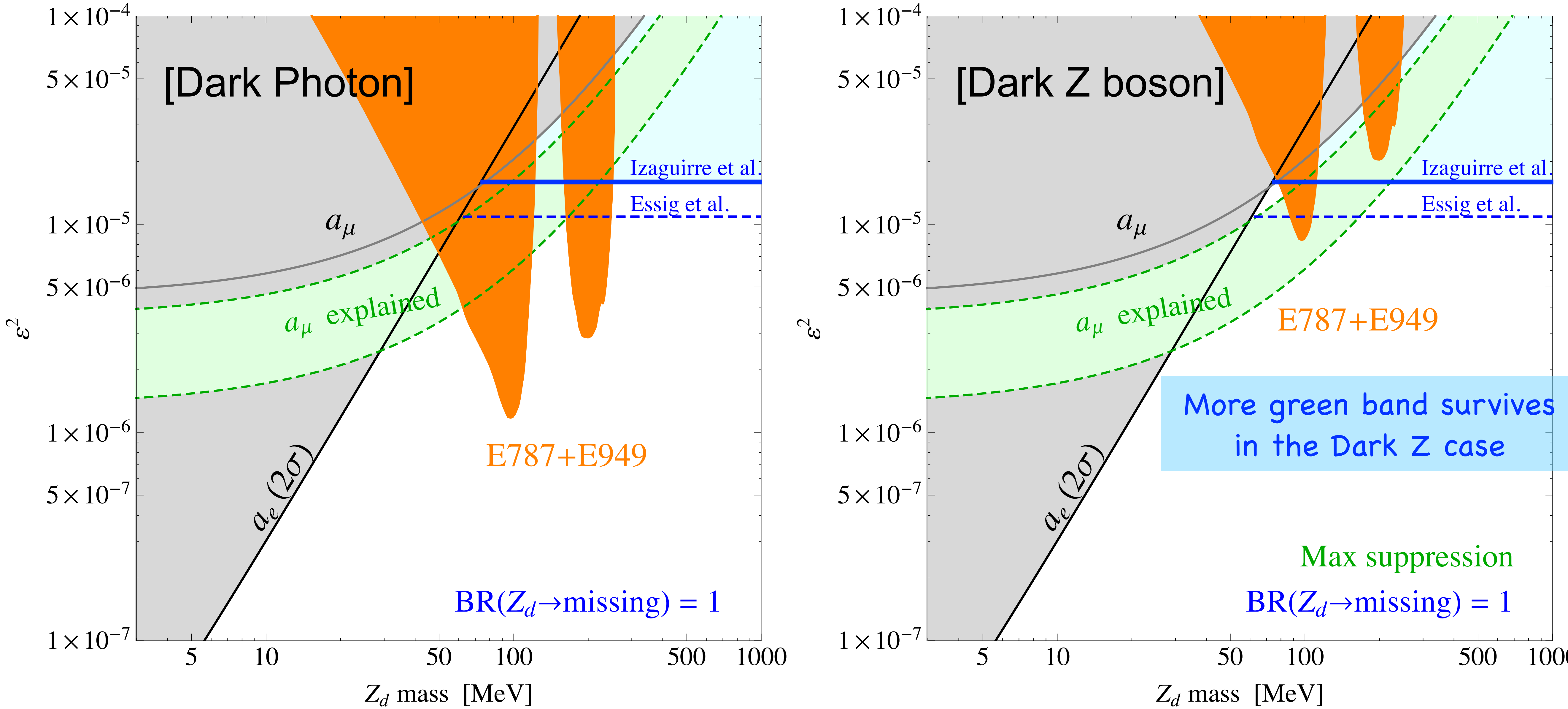
More constraints through χ interaction at detectors in some beam-dump experiments are possible, but they depend on the χ coupling (α_D). *(will come back to this later)*

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

Invisibly decaying Dark gauge boson

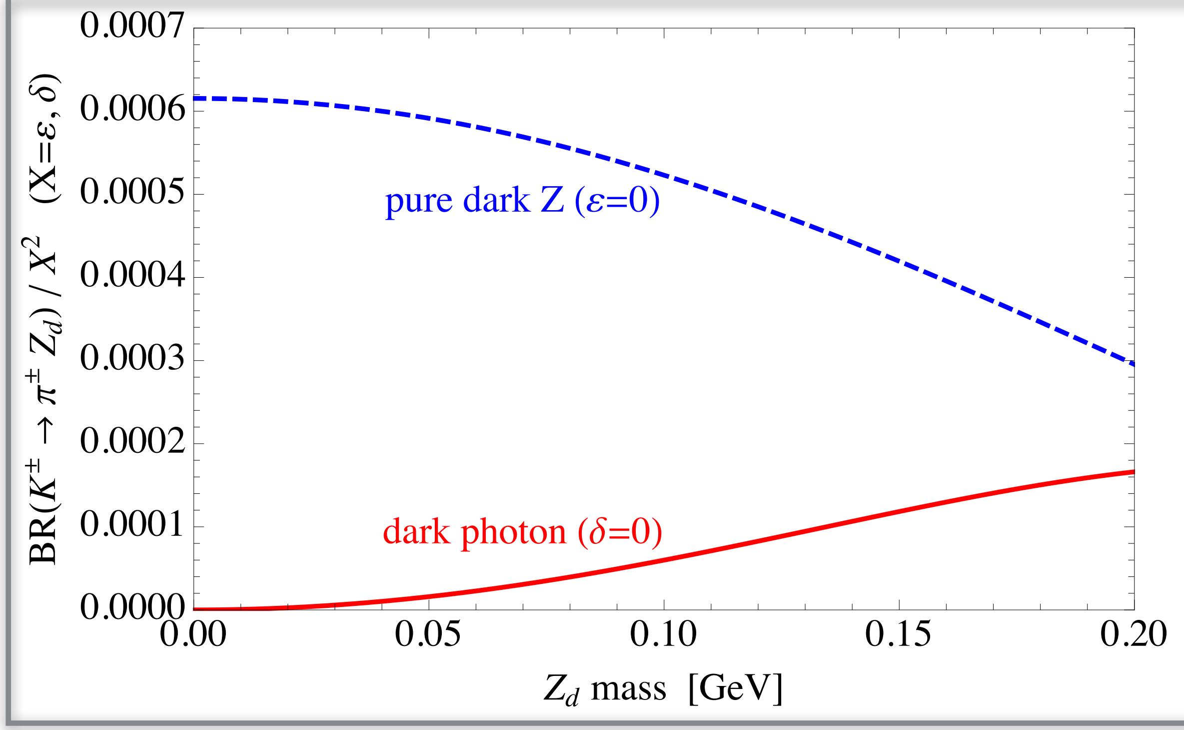
(ii) Missing Energy (Z' → $\chi\chi$) searches

[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’



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

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

Additional term of Dark Z model

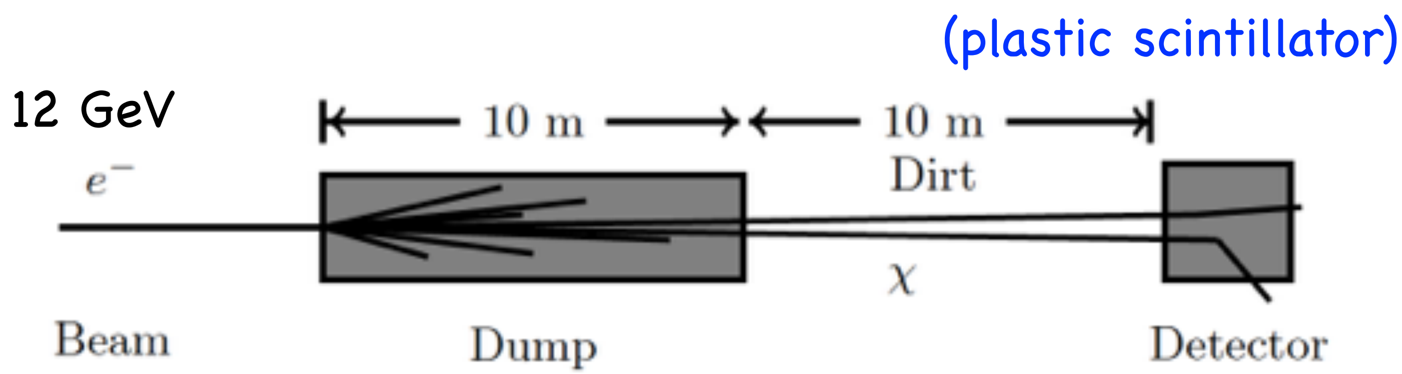
- Dark Photon :
  (loop-suppression with γ)×(small ε)

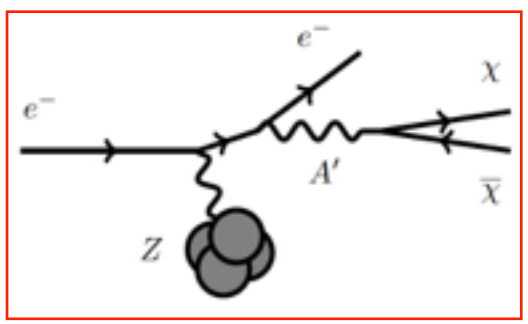
- pure Dark Z :
  (loop-suppression with Z)×(small ε_Z)×(enhancement factor)

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

Example: JLab BDX (Beam-Dump eXperiment)

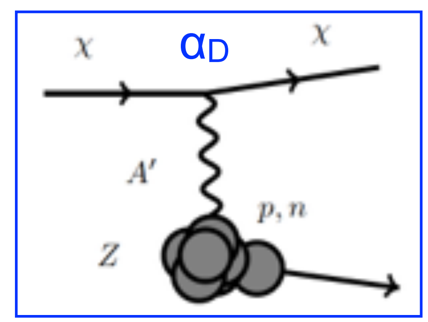
[BDX Collaboration]





scattering to produce Z′
(promptly decaying to χ)

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

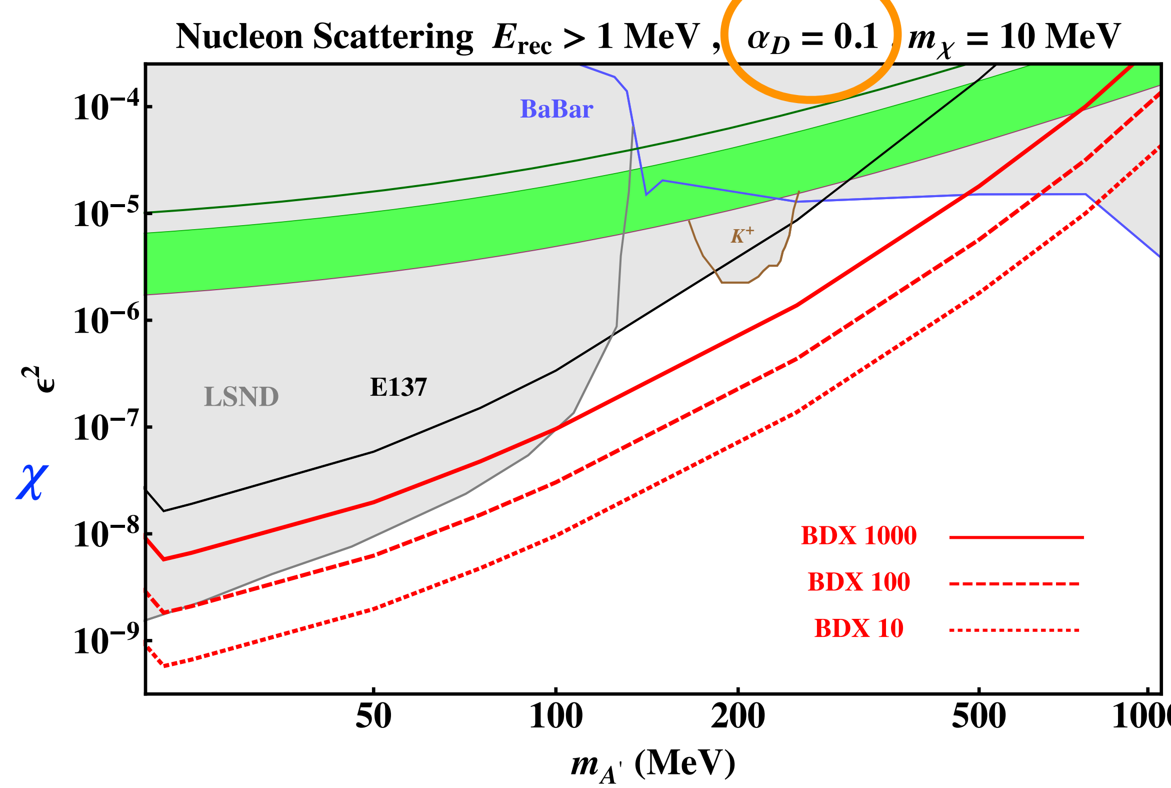


scattering to detect χ
(via Z′)

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

JLab experiment
to test invisibly decaying Z′

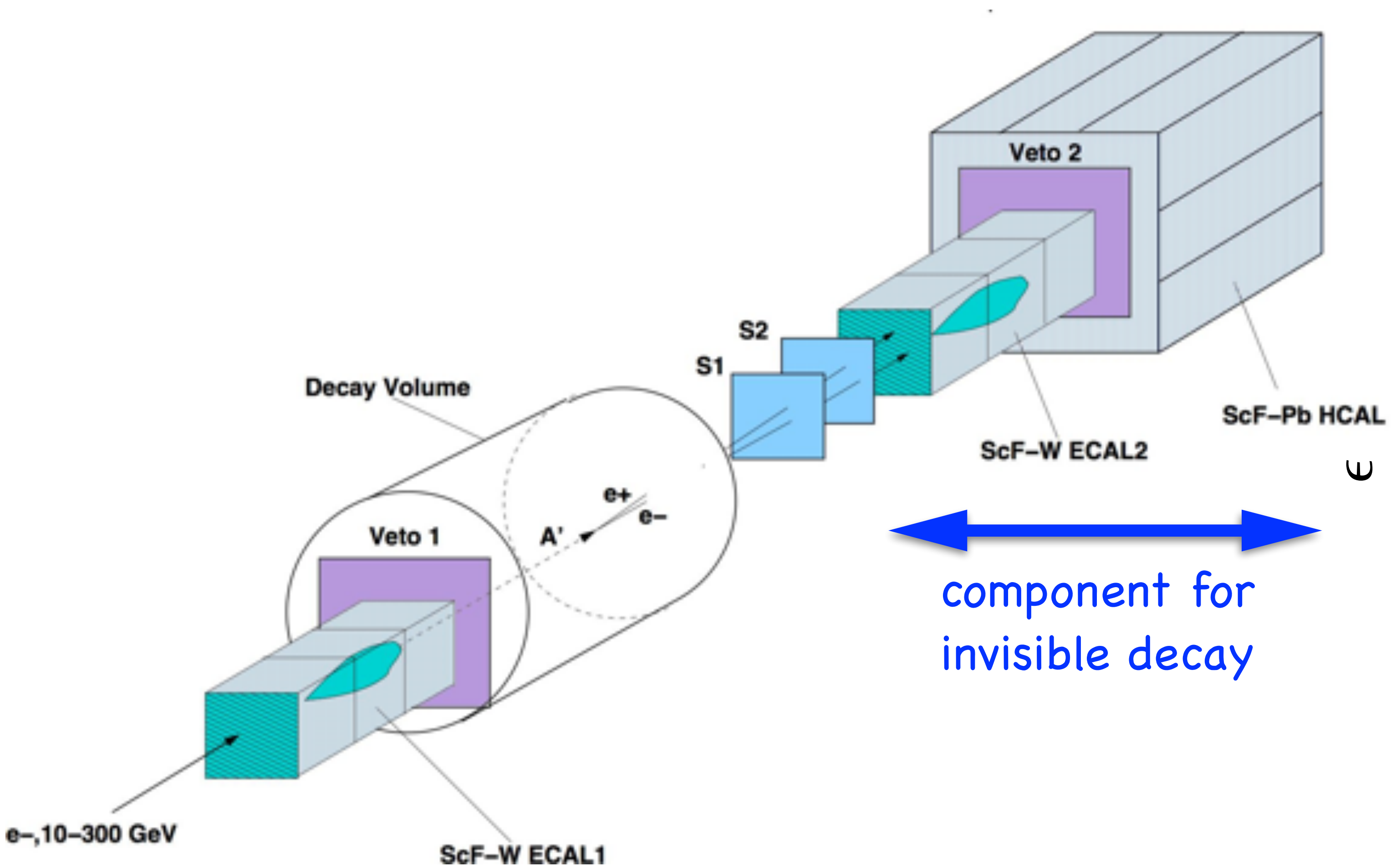
unknown DM coupling



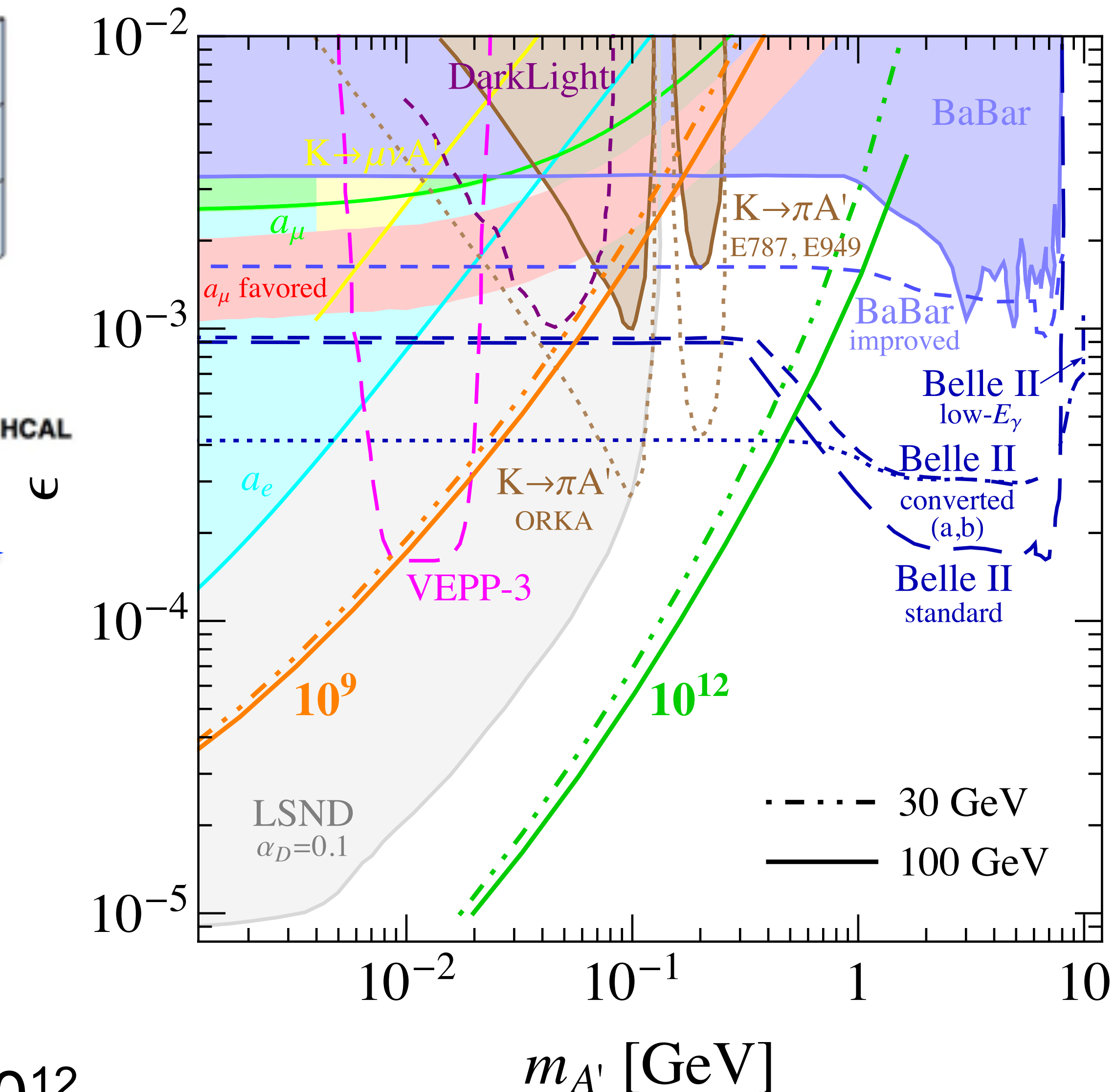
(i) Test experiment at JLab Hall D with low current (0.2 μA).
(ii) Full experiment at JLab Hall A or C with high current (100 μA). EOT ~ 10^{12}.
(iii) Signals: nucleon/electron recoils.
(iv) 2 scatterings are required to produce and detect. $N_\chi \sim \dfrac{\alpha_D\,\epsilon^4}{m_{A'}^4}$
(v) BKG from comic rays (neutrons, muons).

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

[P348 Collaboration]



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.

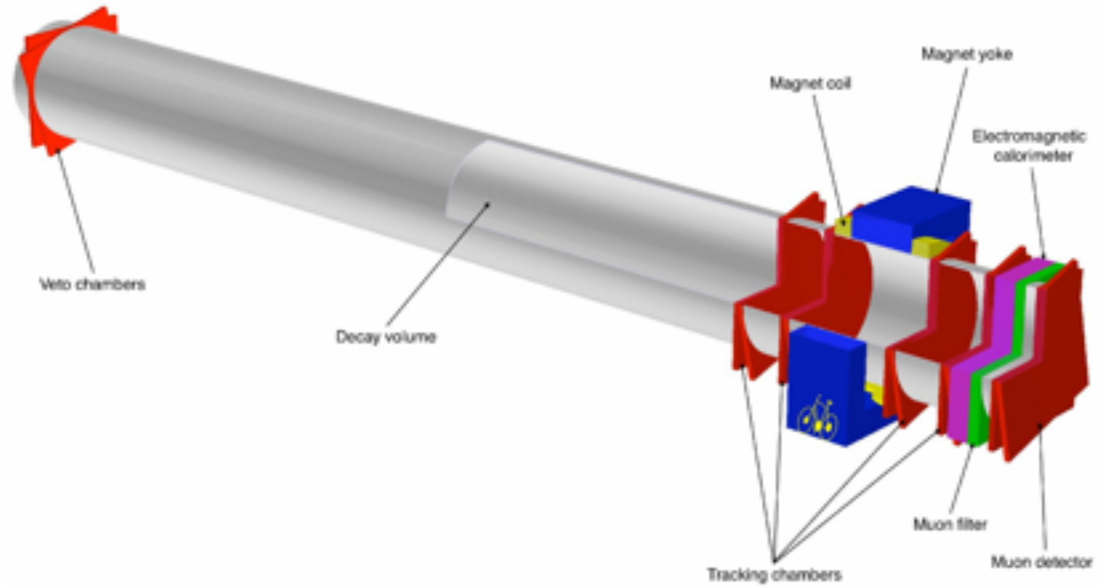
(iii) Test "energy loss" (Missing E) by invisibly decaying Z'. (Essentially BKG free.)

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

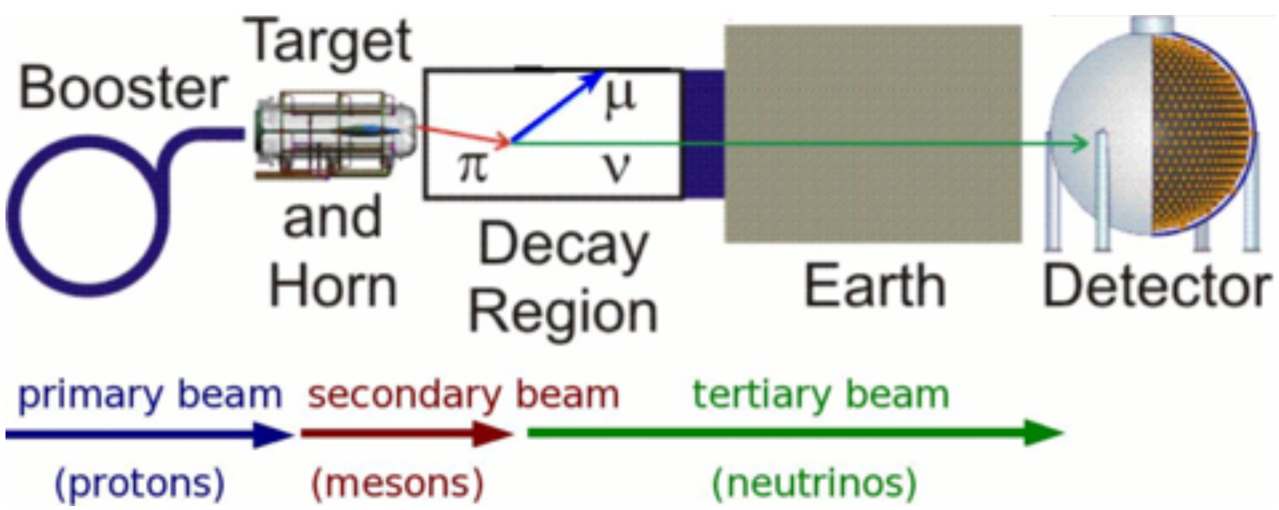
(v) Can search for the visibly-decaying Z' as well.

Example: Proton beam-dumps

(i) SHiP (Search for Hidden Particles) at CERN SPS. *visible Z' decays*



(ii) Fermilab MiniBooNE (Short-baseline neutrino oscillation). *invisible Z' decays*



Originally designed for other purposes (sterile neutrinos, neutrino oscillations), but can also search for the dark gauge bosons.

Dark force searches through Low-Energy Parity Test

(applying to Dark Z)

“Dark Z” effects on Weak Neutral Current phenomenology

[Davoudiasl, LEE, Marciano (2012)]

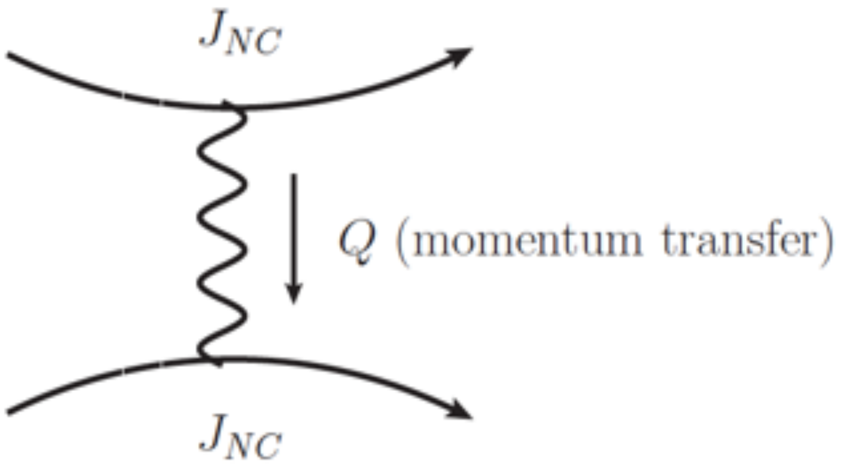
Dark Z : $\mathcal{L}_{\rm int} = -[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\,(g/2\cos\theta_W) J^{\mu}_{NC}]\, Z'_{\mu}$

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

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

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

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



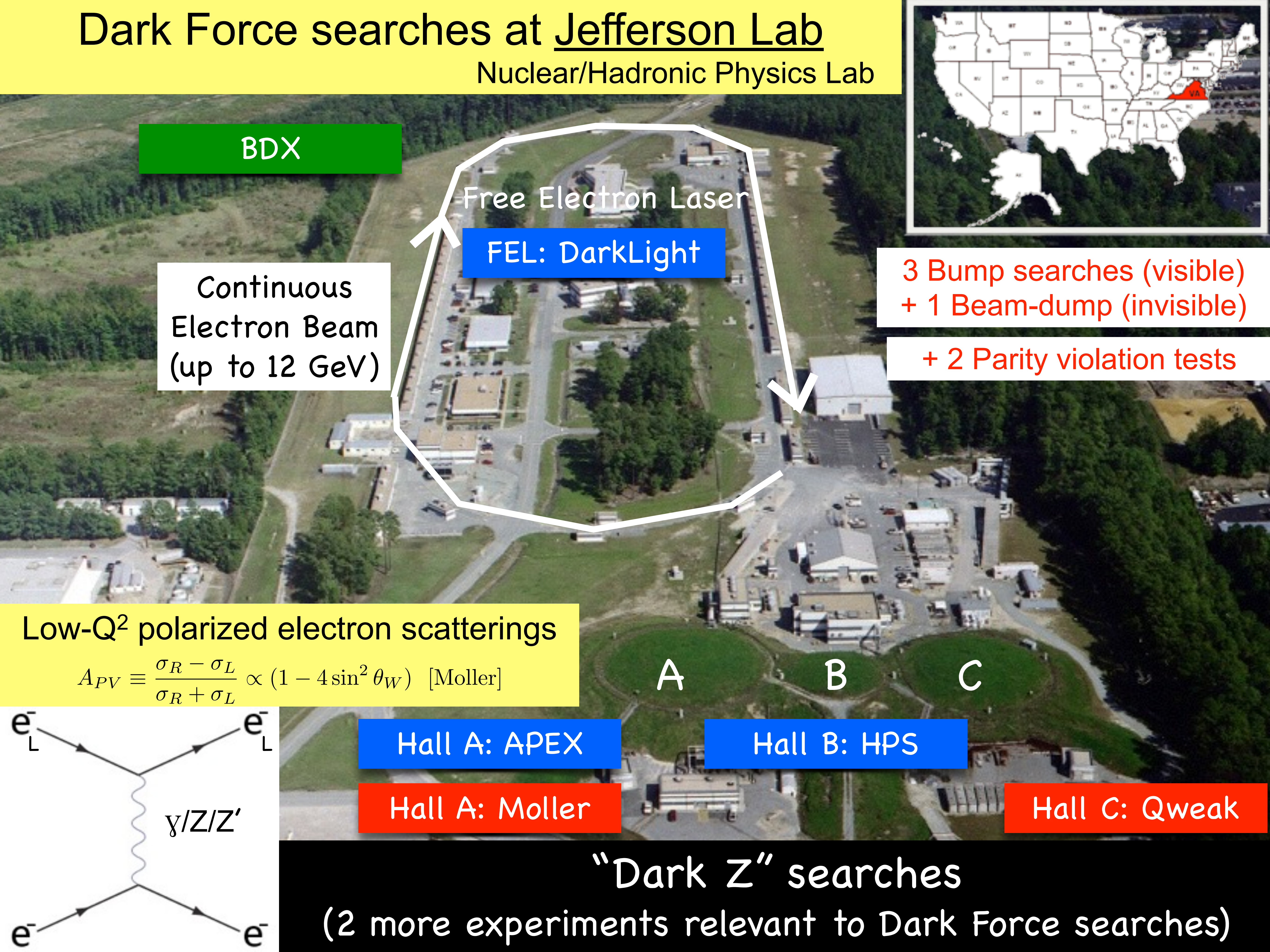
- Sensitive only to Low-Q² (momentum transfer). $\frac{g_X^2}{m_X^2 + Q^2} \longrightarrow 0 \quad (\text{for } Q^2 \gg m_X^2)$

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

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

Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab



BDX

Continuous Electron Beam (up to 12 GeV)

FEL: DarkLight

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

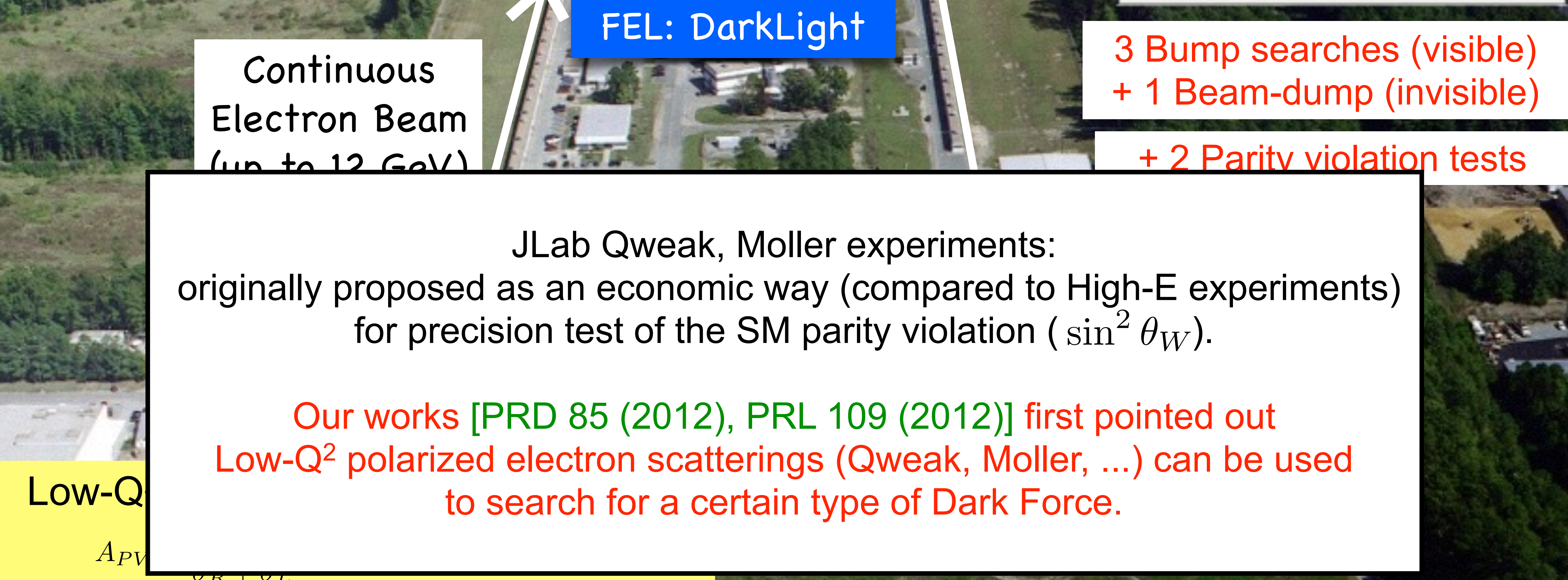
Hall C: Qweak

“Dark Z” searches

(2 more experiments relevant to Dark Force searches)

Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab

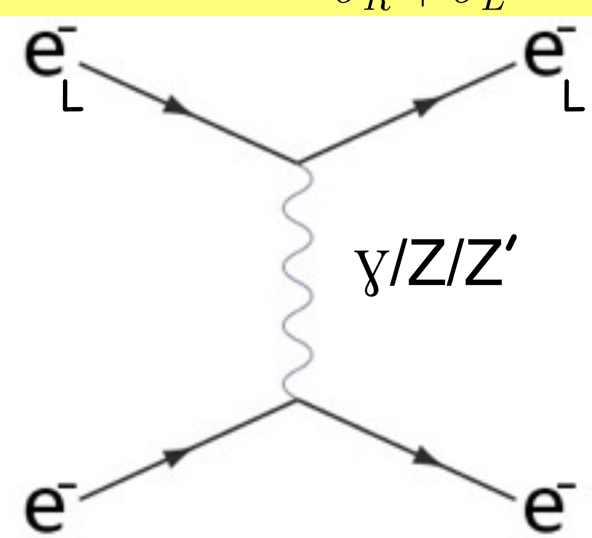


3 Bump searches (visible)
+ 1 Beam-dump (invisible)

+ 2 Parity violation tests

JLab Qweak, Moller experiments:
originally proposed as an economic way (compared to High-E experiments) for precision test of the SM parity violation ($\sin^2\theta_W$).

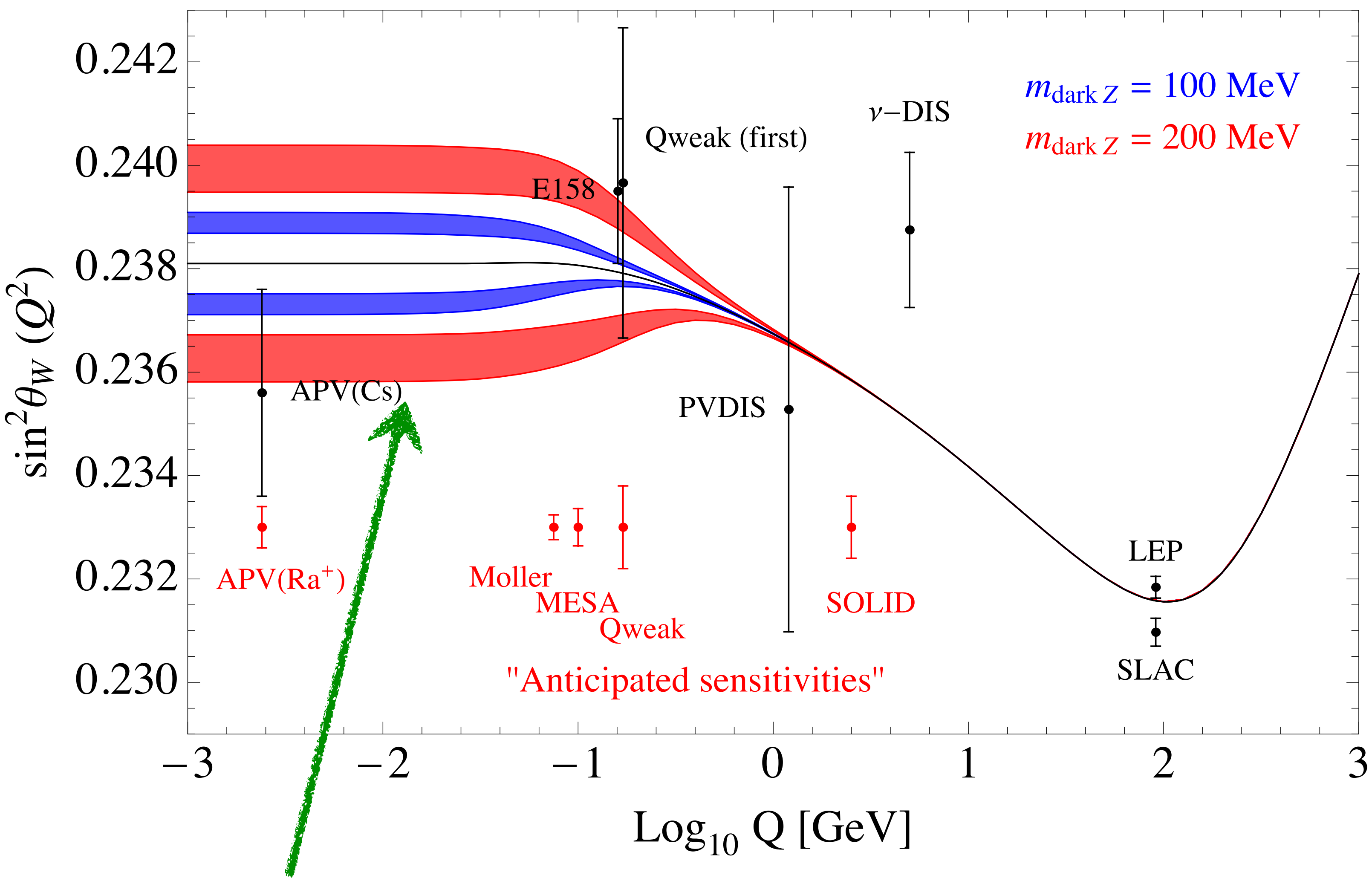
Our works [PRD 85 (2012), PRL 109 (2012)] first pointed out Low-Q^2 polarized electron scatterings (Qweak, Moller, ...) can be used to search for a certain type of Dark Force.



"Dark Z" searches
(2 more experiments relevant to Dark Force searches)

Weinberg angle shift in Low-Q^2

[Davoudiasl, LEE, Marciano (2014)]



(Example)
For invisibly-decaying Dark Z.

Colored regions are predictions for the Weinberg angle shift by the Δa_μ solution (green band).

$$\Delta \sin^2\theta_W(Q^2) \simeq -0.42\,\varepsilon\delta\,\frac{m_Z}{m_{Z'}}\,\frac{1}{1+Q^2/m_{Z'}^2}$$

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

For the Low-Q^2 Parity Test (measuring Weinberg angle), we can use

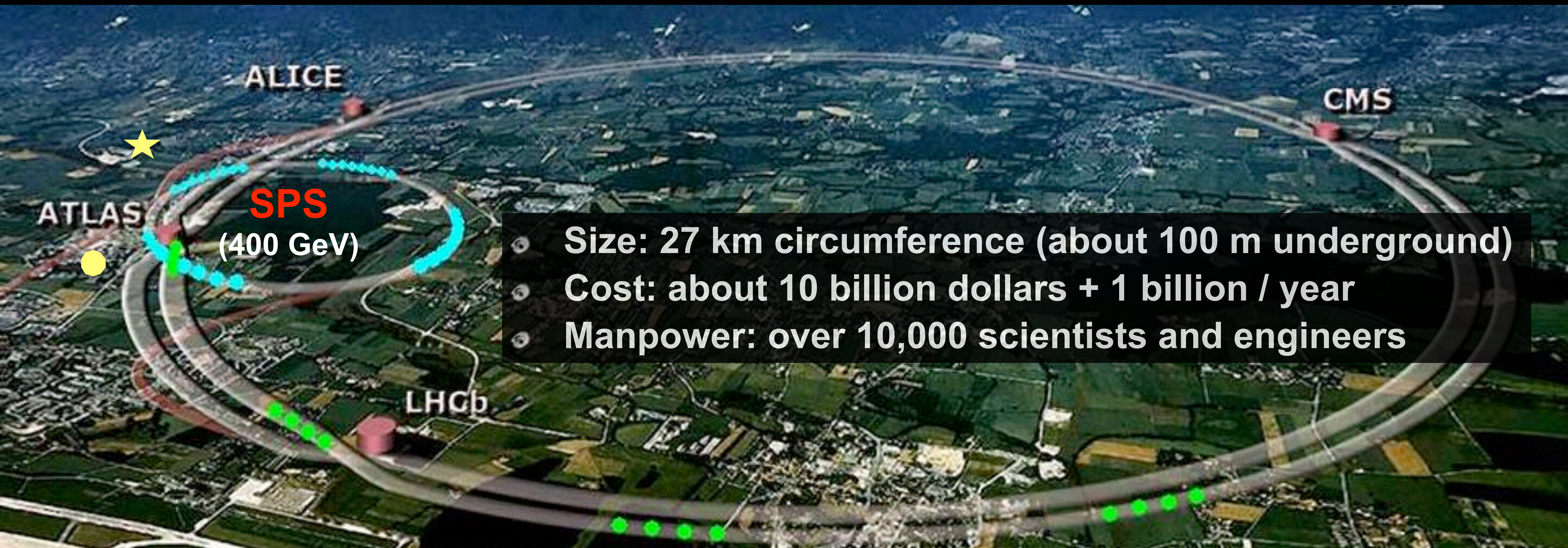
(i) Atomic Parity Violation (Cs, Ra⁺, …)

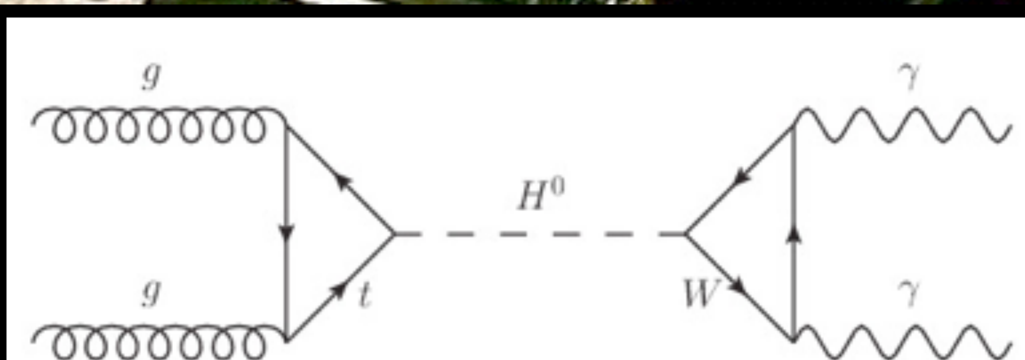
(ii) Low-Q^2 Polarized Electron Scattering (E158, Qweak, MESA P2, Moller, …)

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

Implications for the LHC
(High-E searches for a New light particle)

Dark Force at Large Hadron Collider (LHC)?
in Geneva, Switzerland





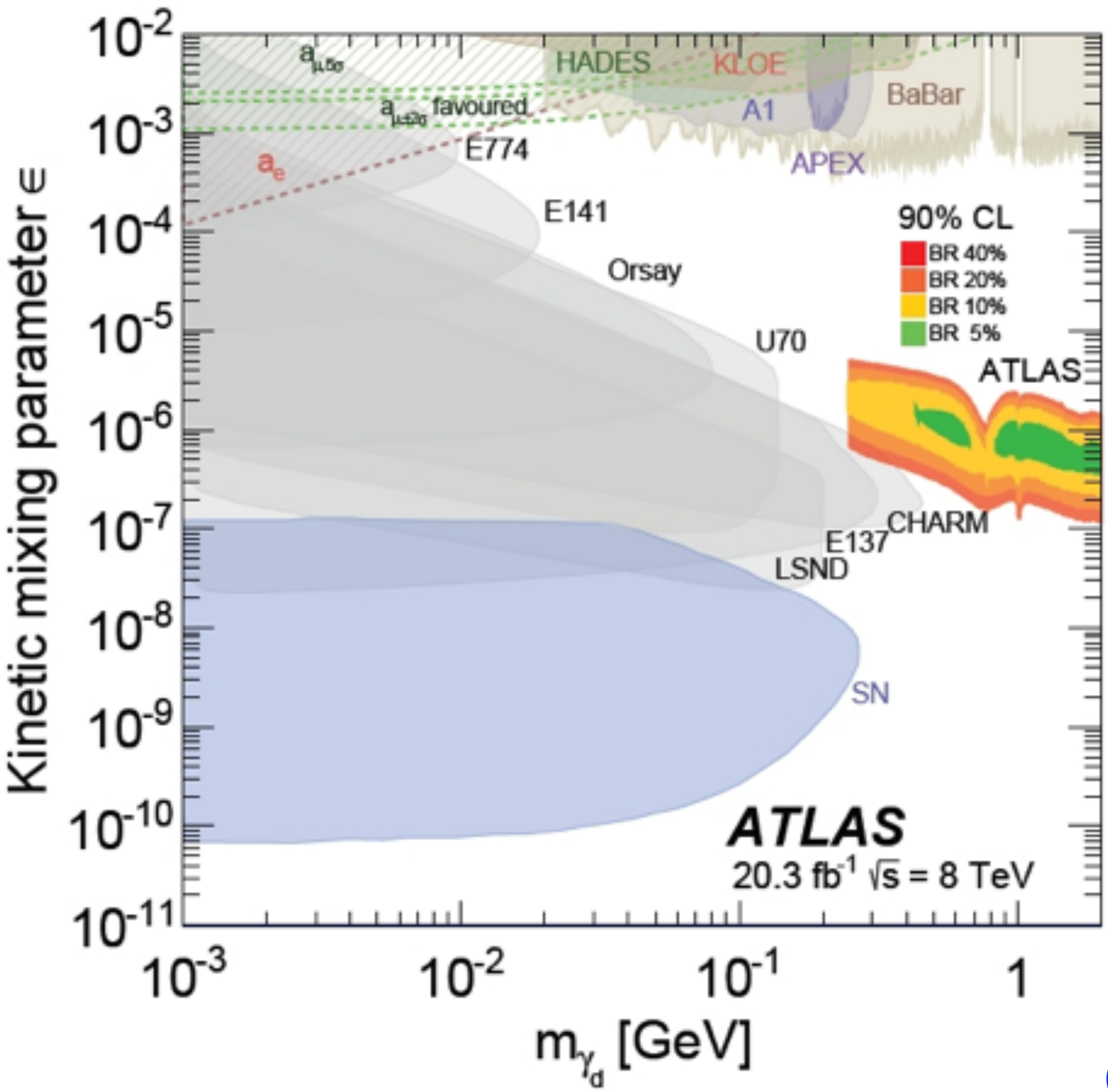
2013 Nobel prize winners

F. Englert (Belgium) and P. Higgs (UK)

SM-like Higgs boson (mass ~ 125 GeV) was discovered at the LHC experiments (in 2012) using <u>13b dollars</u>.

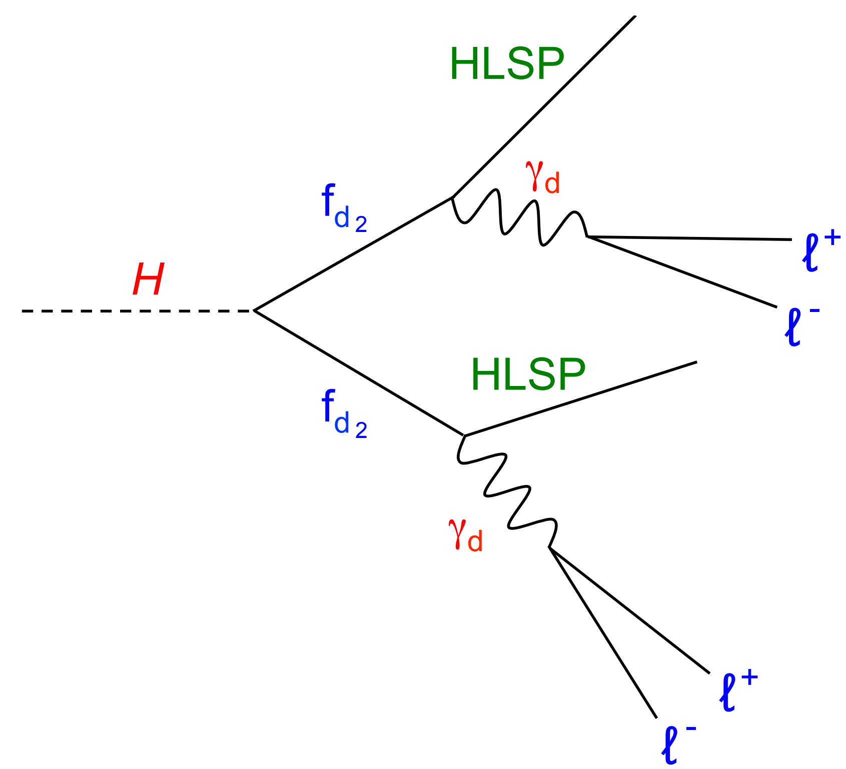
Next step: Precision study (detailed decay modes, ...)

Dark force searches at the LHC



[ATLAS 1409.0746]

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

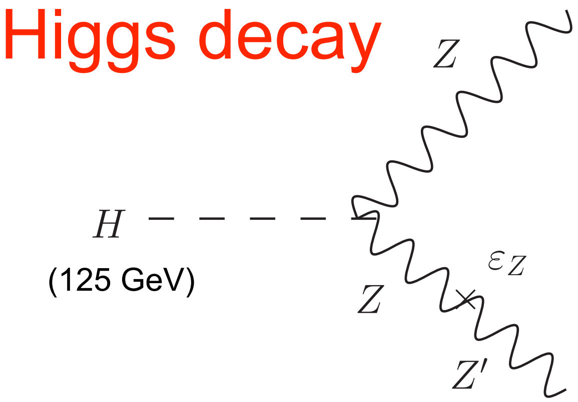


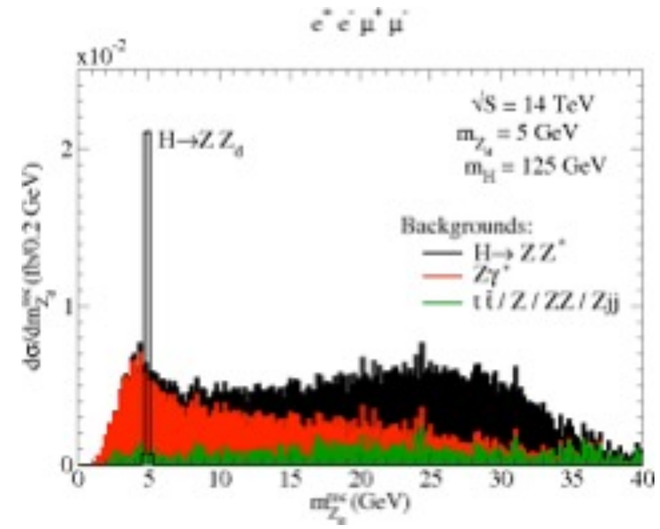
(Lepton-Jet: Highly collimated leptons in a small cone R < 0.1 without nearby hadronic activity)

Dark force searches at the LHC

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

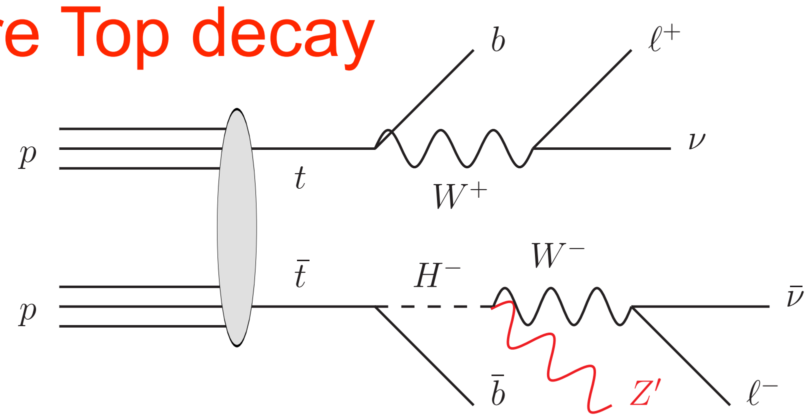
rare Higgs decay

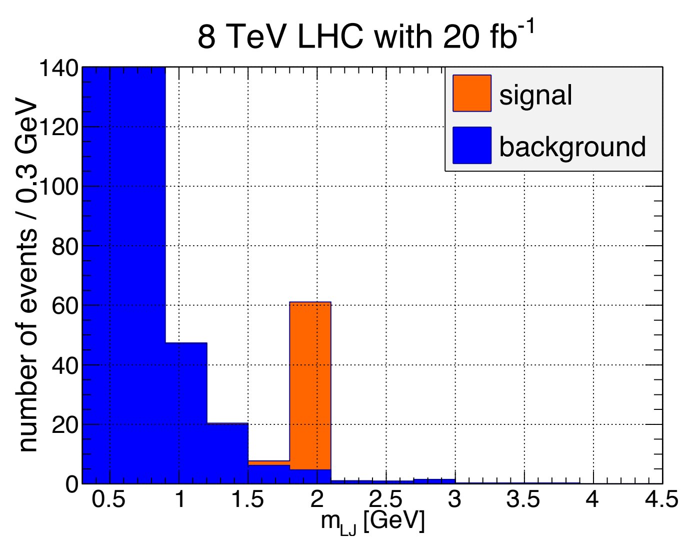


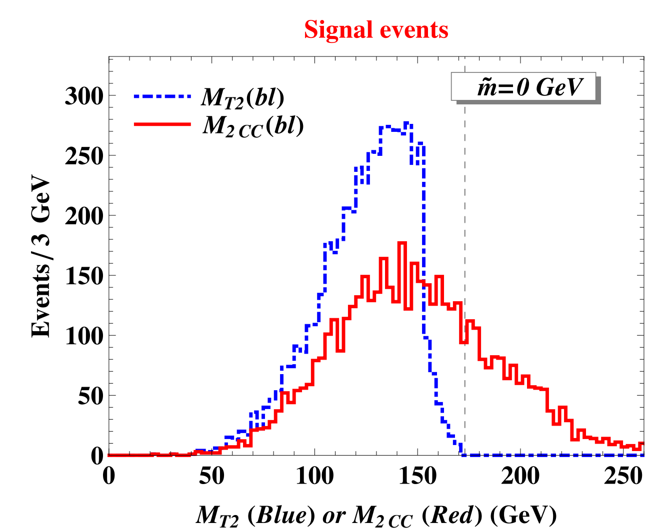


[Davoudiasl, LEE, Lewis, Marciano (2013)]

rare Top decay



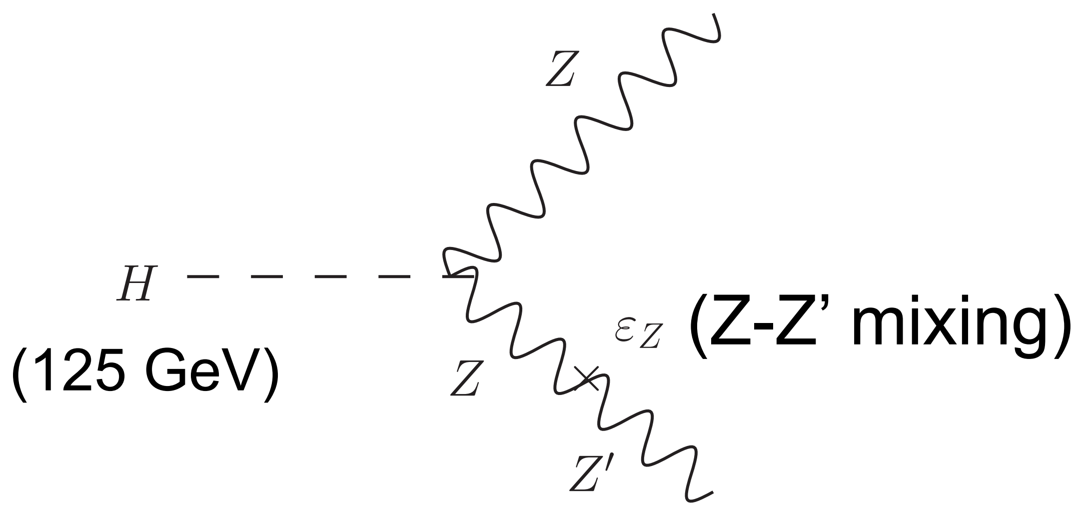




[KC Kong, LEE, M Park (2014)] [D Kim, LEE, M Park (2014)]

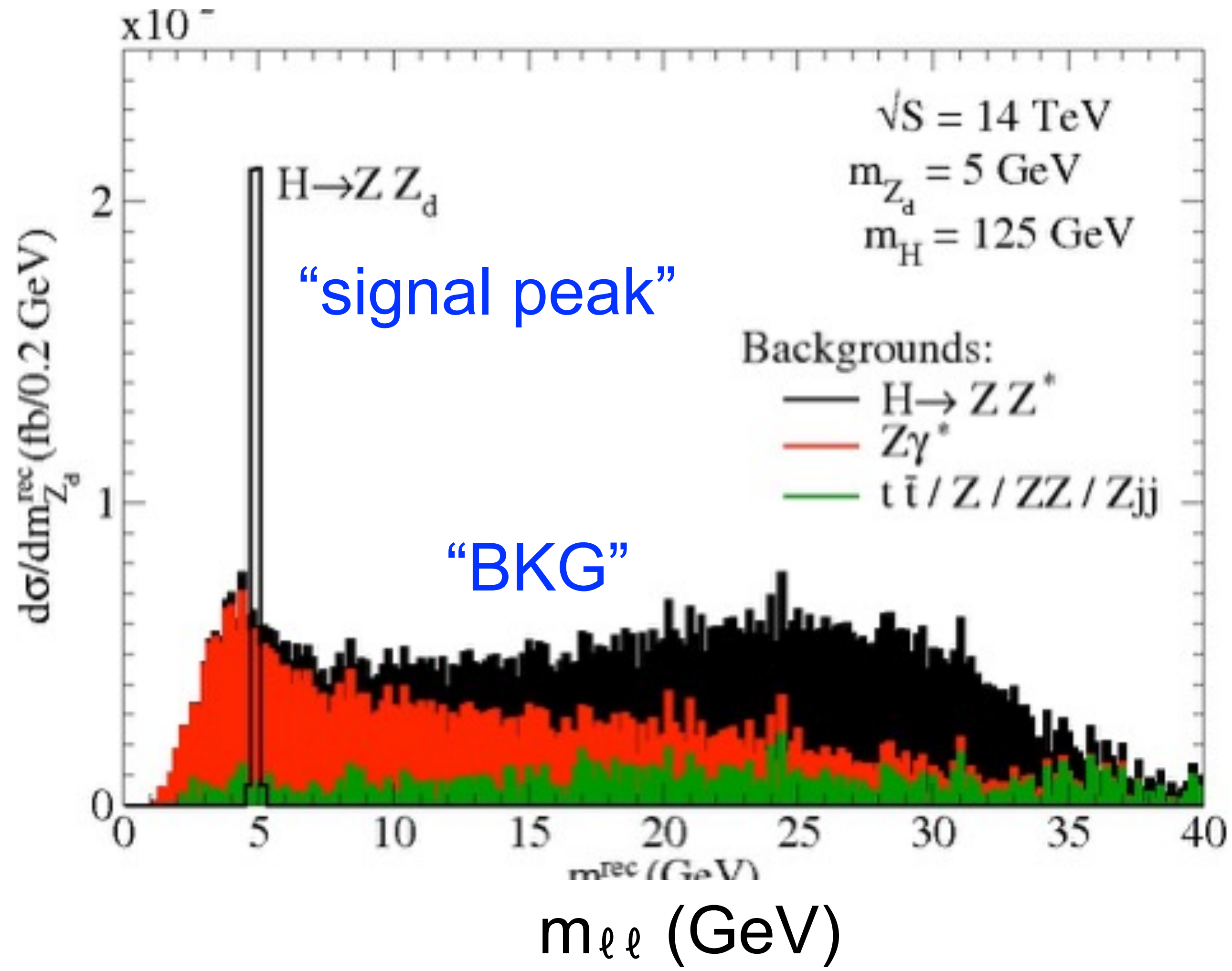
(i) Look for a narrow dilepton resonance or LJ (for visibly-decaying Z′), or (ii) Employ a kinematic method (for invisibly-decaying Z′).

Higgs-to-Dark decay at the LHC



[Higgs → Z Z'   in Dark Z model]

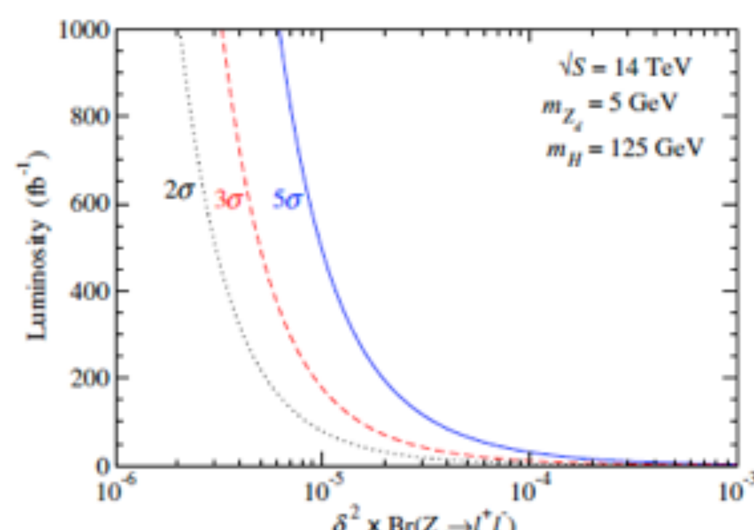
[Davoudiasl, LEE, Lewis, Marciano (2013)]



[Reconstructed Z' events after some cuts]

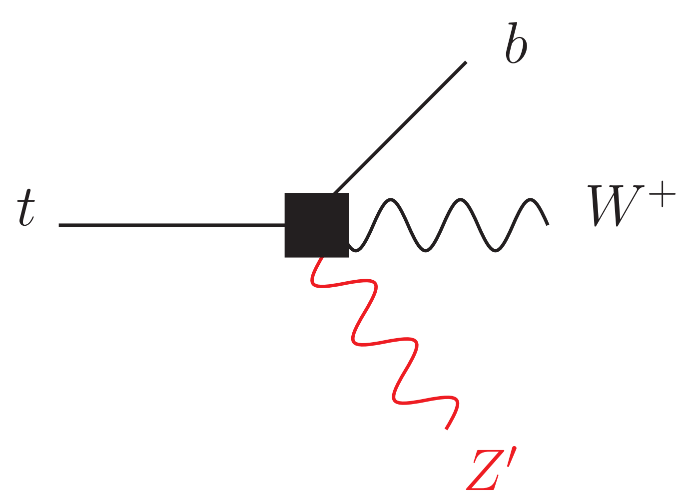
- Signal: H → Z Z' → 4-leptons
- Major BKG: Z γ*, H → Z Z*

The LHC can search for Dark Force too (even without producing Dark sector particles).



Top-to-Dark decay at the LHC

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

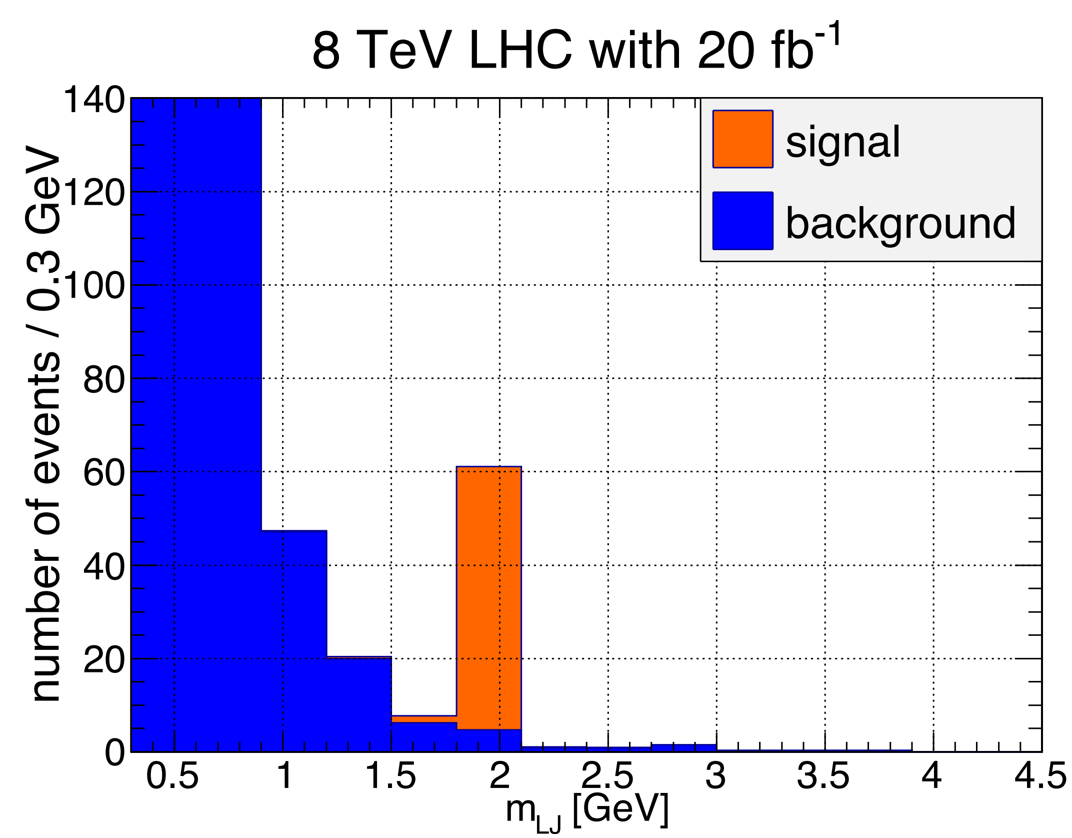


Good chance of New physics in Top (173 GeV) decay.
[Current top decay BR have O(10%) uncertainty.]

Top may decay into Z' (through a light charged Higgs)
$t \to bH^+ \to bW + Z'$s (on-shell decay)
: dominant top decay products (bW) + elusive Z's
[easily mis-identifiable as $t \to bW$]

(Ex) With Lepton-jet analysis
for BR($t \to bW + Z'$) = 10^{-3} and
BR($Z' \to \ell\ \ell$) = 0.2

We suggest re-analysis of the existing 8 TeV t tbar data (L_{tot} = 20 fb^{-1}) may give you a discovery (at 15σ level) now!

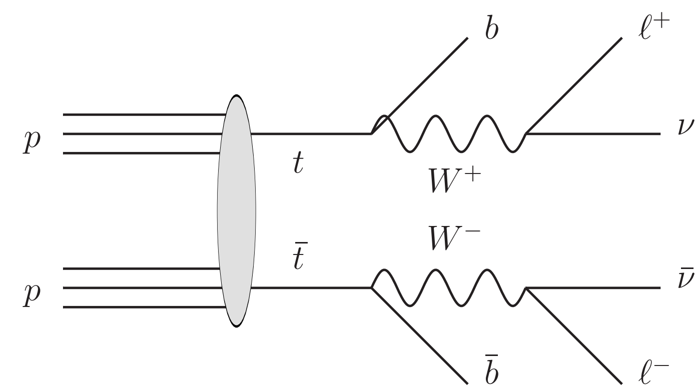


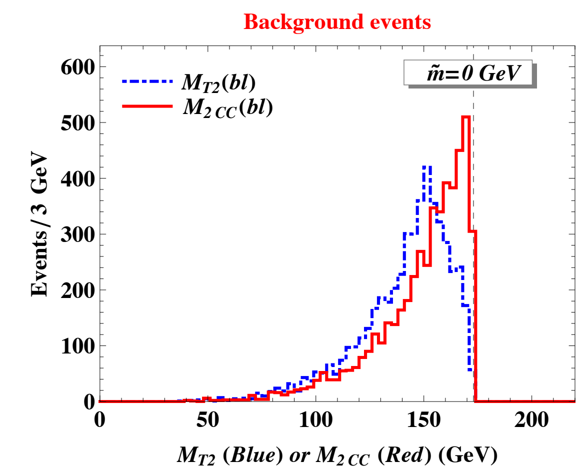
Top-to-Dark decay at the LHC (invisibly-decaying case)

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

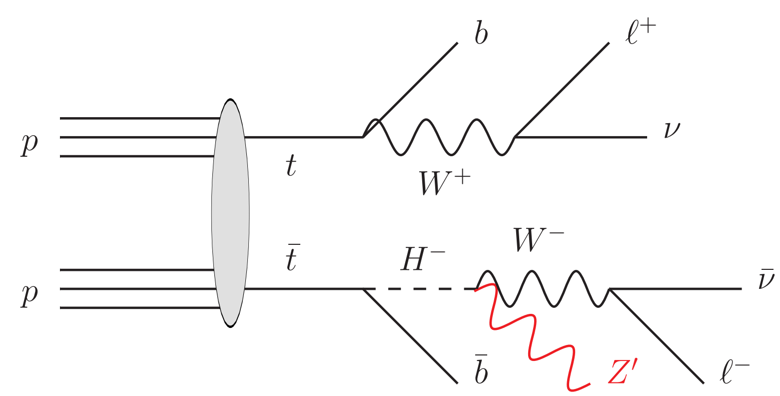
To search for the invisibly-decaying Z', one can use a **kinematic method.**

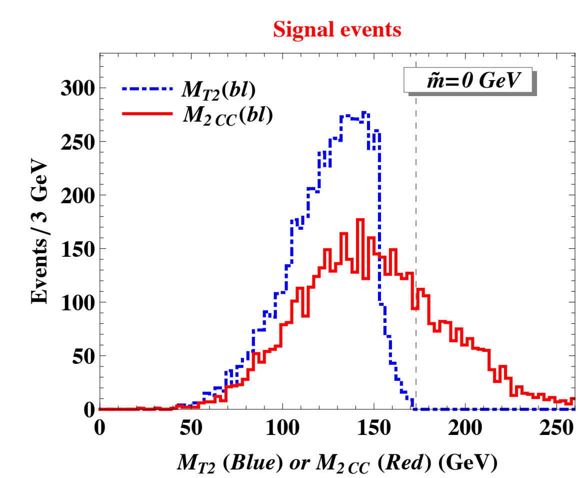
t tbar in the SM
(symmetric events)





t tbar with Dark Z
(asymmetric events)





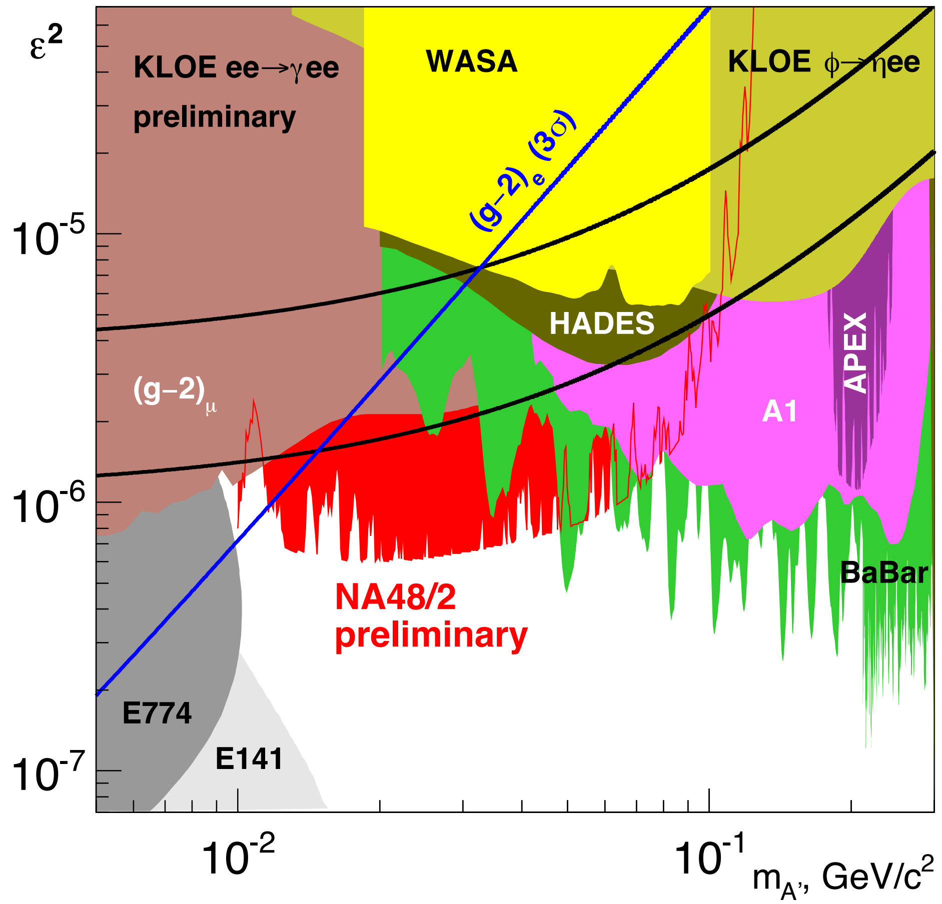
(ex) M_2 method: (i) Apply kinematic variables designed for symmetric events. (ii) It evokes a contradiction for asymmetric events.

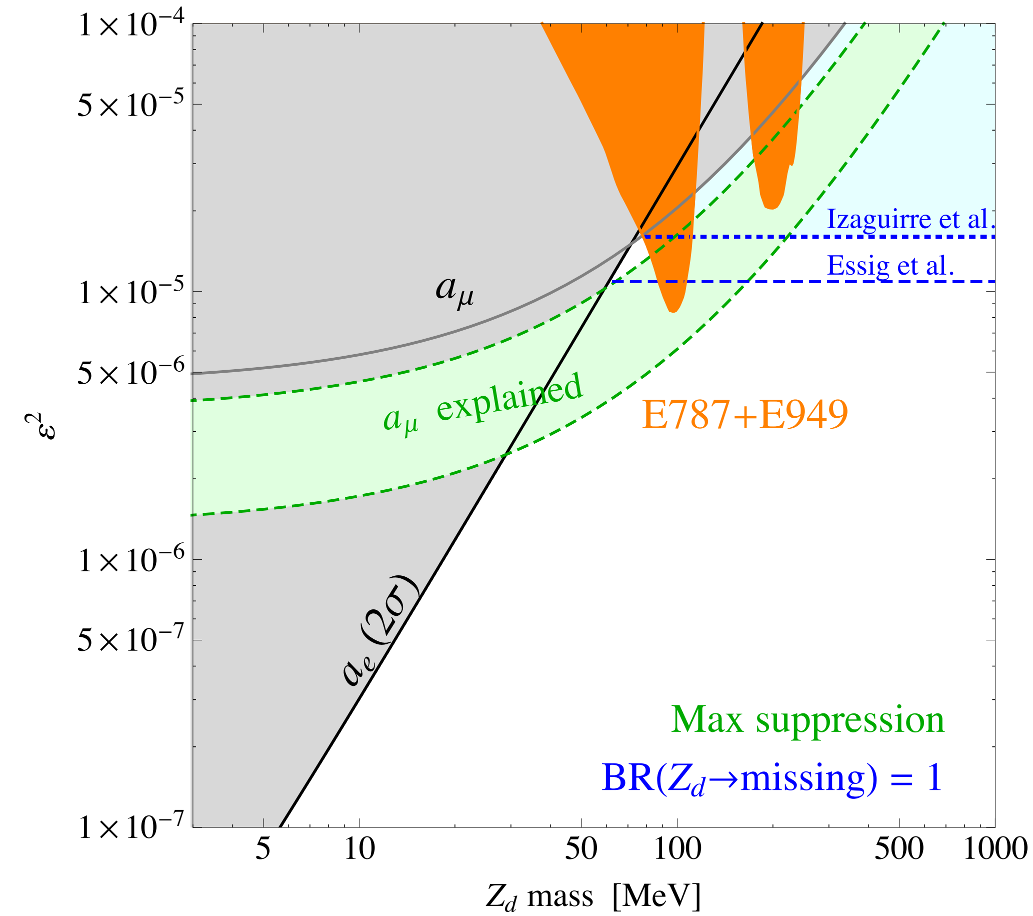
	$m_{H^\pm}$	$m_{Z'}$	$\mathcal{L}$ (fb^{-1})	c_1	c_2	$S\,(\times 10^3)$	$B\,(\times 10^3)$	$X\,(\times 10^{-3})$
BP1	130	1	300	360	90	1.10(0.44)	48.1	11.0(4.4)
			3000	305	90	3.49(1.40)	485	3.5(1.4)
BP2	130	20	300	330	92	1.04(0.42)	43.3	12.5(5.0)
			3000	285	92	3.32(1.33)	440	4.0(1.6)
BP3	130	5	300	330	90	1.10(0.44)	48.3	11.0(4.4)
			3000	305	90	3.49(1.40)	485	3.5(1.4)
BP4	120	5	300	305	87	1.21(0.48)	58.3	17.3(6.9)
			3000	285	87	3.83(1.53)	587	5.5(2.2)
BP5	110	5	300	360	87	1.21(0.48)	57.9	34.3(13.7)
			3000	305	87	3.82(1.53)	583	10.9(4.4)

Table 1. 5σ discovery reach and 2σ exclusion limit (numbers in the parentheses) in $X = \mathrm{BR}(t \to bW + Z')$ for several benchmark points with integrated luminosities of 300 fb^{-1} and 3000 fb^{-1} at $\sqrt{s} = 14$ TeV LHC. c_1, c_2, and the masses of $H^\pm$ and Z' are given in GeV.

1. **On-shell constrained M_2 variables with applications to mass measurements and topology disambiguation**
Won Sang Cho, James S. Gainer, Doojin Kim, Konstantin T. Matchev (Florida U.), Filip Moortgat, Luc Pape (CERN), Myeonghun Park (Tokyo U., IPMU).
Jan 7, 2014. 46 pp.
Published in **JHEP 1408 (2014) 070**
DOI: 10.1007/JHEP08(2014)070
e-Print: **arXiv:1401.1449** [hep-ph] | PDF

Recap of Dark force searches





"Dark gauge boson (MeV-GeV scale) searches" include

(i) g-2 : 3.6σ deviation in a_μ may be explained by the Dark gauge boson (Green band).

(ii) Z' → $\ell^+\ell^-$: Direct bump searches. (Green band is closed now.)

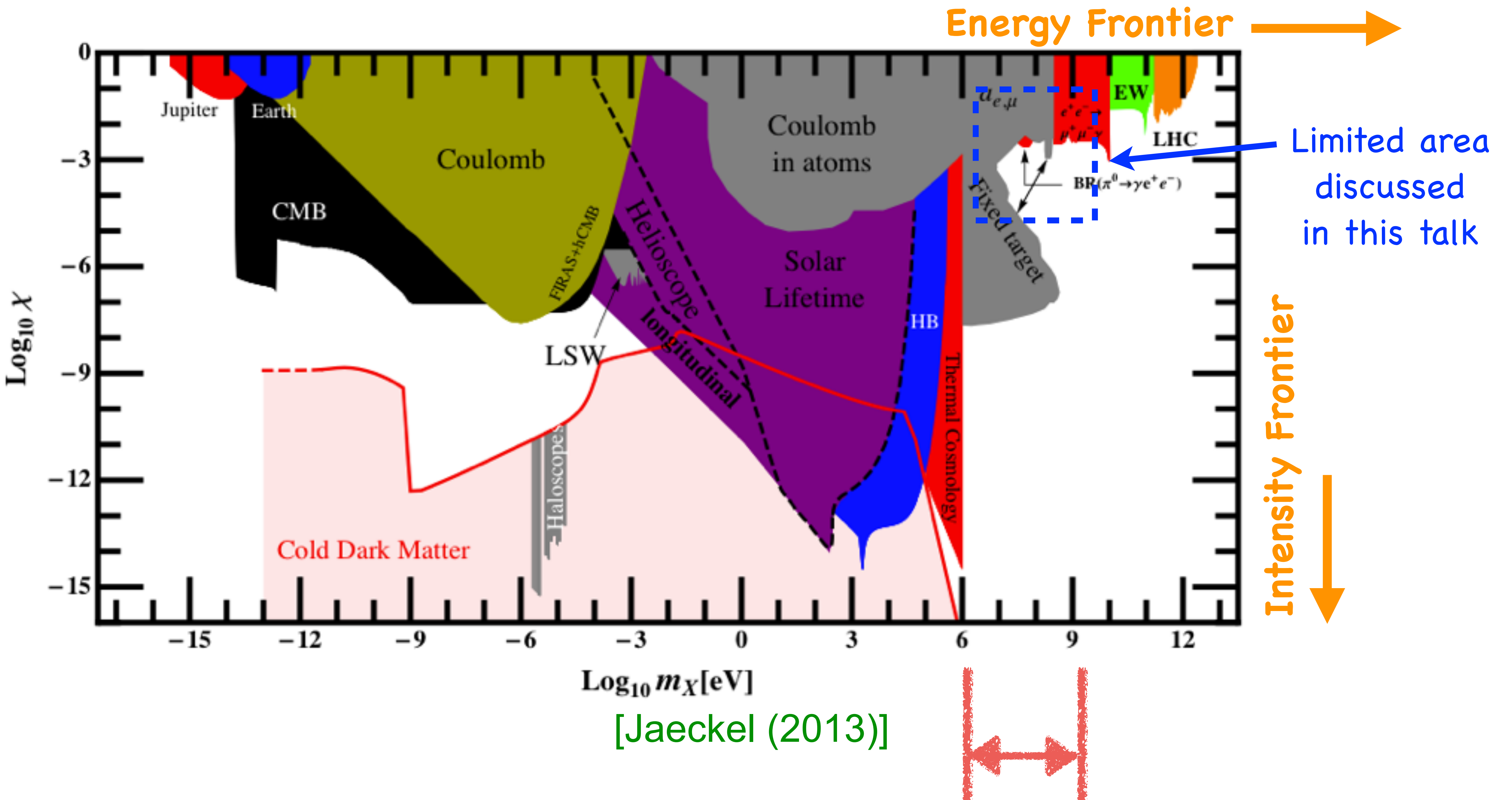
(iii) Z' → invisible : Requires light Dark particles ($m_\chi \lesssim m_{Z'}/2$). (Green band survives.)

(iv) Low-Energy Parity Test (APV, Polarized Electron Scattering) :
Another excellent probe. It is independent of Z' decay BR
and a small axial coupling may be present (Dark Z model).

(v) LHC searches : Decay from heavy particles (more model-dependent).

Some other aspects

Extended range of parameters (of Dark Photon)



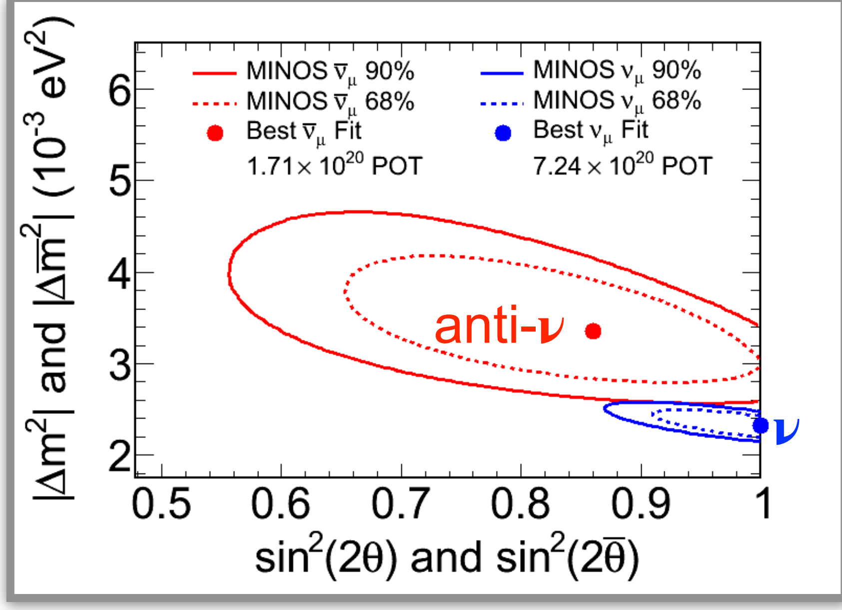
[Jaeckel (2013)]

(i) Extremely light Z' (invisible) **(ii) Typical Dark photon (MeV - GeV)** **(iii) Heavy Z' (traditional)**

Different regions of parameter space require different kinds of experiments to explore.

Extremely light Z' case

An extremely light Z' with a flavor-dependent interaction to explain the 2010 MINOS anomaly in neutrino oscillation.



[MINOS 2010]

PHYSICAL REVIEW D **84,** 013009 (2011)

Long-range lepton flavor interactions and neutrino oscillations

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Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 14 March 2011; published 19 July 2011)

Recent results from the MINOS accelerator neutrino experiment suggest a possible difference between ν_μ and $\bar{\nu}_\mu$ disappearance oscillation parameters, which one may ascribe to a new long-distance potential acting on neutrinos. As a specific example, we consider a model with gauged $B - L_e - 2L_\tau$ number that contains an extremely light new vector boson $m_{Z'} < 10^{-18}$ eV and extraordinarily weak coupling $\alpha' \lesssim 10^{-52}$ (or larger $m_{Z'}$ if cosmology bounds on neutrino decay apply). In that case, differences between $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ oscillations can result from a long-range potential due to neutrons in the Earth and the Sun that distinguishes ν_μ and ν_τ on Earth, with a potential difference of $\sim 6 \times 10^{-14}$ eV, and changes sign for antineutrinos. We show that existing solar, reactor, accelerator, and atmospheric neutrino oscillation constraints can be largely accommodated for values of parameters that help explain the possible MINOS anomaly by this new physics, although there is some tension with atmospheric constraints. A long-range interaction, consistent with current bounds, could have very pronounced effects on atmospheric neutrino disappearance in the 15–40 GeV range that will be studied with the IceCube DeepCore array, currently in operation, and can have a significant effect on future high-precision long-baseline oscillation experiments that aim for $\pm 1\%$ sensitivity, in ν_μ and $\bar{\nu}_\mu$ disappearance, separately. Together, these experiments can extend the reach for new long-distance effects well beyond current bounds and test their relevance to the aforementioned MINOS anomaly. We also point out that long-range potentials originating from the Sun could lead to annual modulations of neutrino data at the percent level, due to the variation of the Earth-Sun distance. A similar phenomenology is shown to apply to other potential new gauge symmetries such as $L - 3L_\tau$ and $B - 3L_\tau$.

DOI: 10.1103/PhysRevD.84.013009 PACS numbers: 14.60.Pq, 12.60.−i, 13.15.+g

TeV-scale Z’ case

Physics Letters B 663 (2008) 255–258

R-parity (dual role): stable proton & stable LSP DM

$U(1)' \rightarrow Z_6$ where $Z_6 = B_3 \times U_2$

introduced to solve μ-problem

MSSM sector discrete symmetry: $B_3 \rightarrow$ Proton is stable

Hidden sector discrete symmetry: $U_2 \rightarrow$ Hidden sector DM is stable

Lightest *U*-parity particle (LUP) dark matter

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A R T I C L E   I N F O

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A B S T R A C T

We suggest a $U(1)'$ gauge symmetry as an alternative to the usual R-parity of supersymmetric standard models, showing that it can also work as a common source of stabilities of proton and dark matter in addition to other attractive features. The residual discrete symmetries of a single $U(1)'$ can provide stabilities to both the MSSM sector (proton) and the hidden sector (new dark matter candidate, LUP). The LUP can expand the viability of many models such as R-parity violating models and gauge mediation models regarding dark matter issue.

1. Introduction

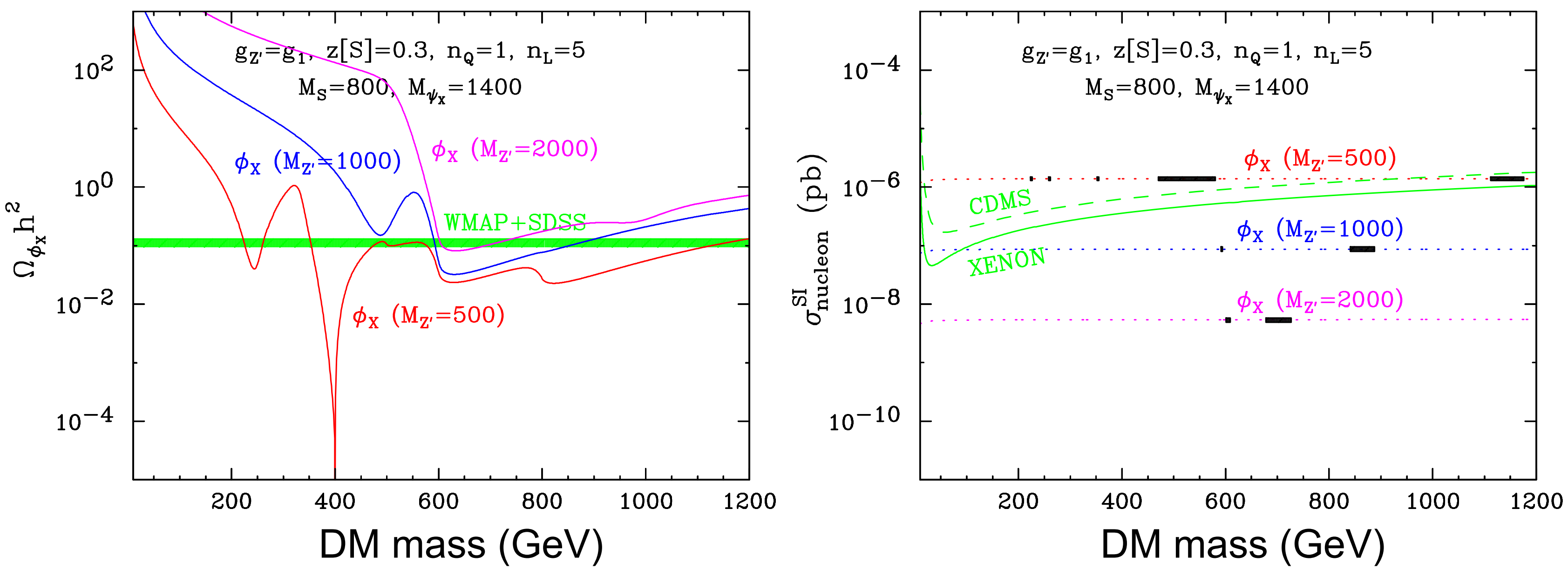
It is now an established fact that matters in our Universe is

TeV scale Abelian gauge symmetry $U(1)'$ [3] may be a phenomenologically more attractive companion symmetry for the TeV scale SUSY model. The μ-problem can be solved very naturally [4],

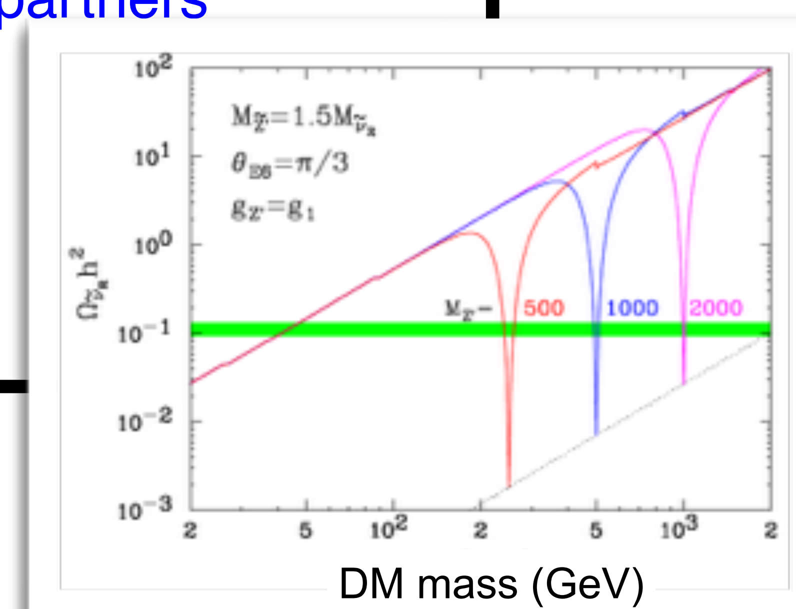
Annihilation channels for the Hidden sector DM under $Z_6 = B_3 \times U_2$

LUP dark matter
(with mZ' ~ TeV-scale)

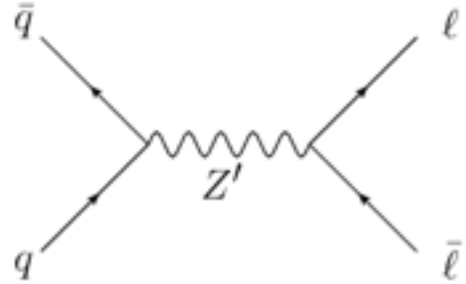
1. DM+DM $\longrightarrow Z' \longrightarrow f\bar{f}$
2. DM+DM $\longrightarrow Z' \longrightarrow \widetilde{f}\widetilde{f}^* \longrightarrow$ SM particles (no R-Parity)



Hidden sector DM connected by Z' can satisfy both the relic density and direct detection constraints. (More annihilation channels open as more superpartners are kinematically allowed.)

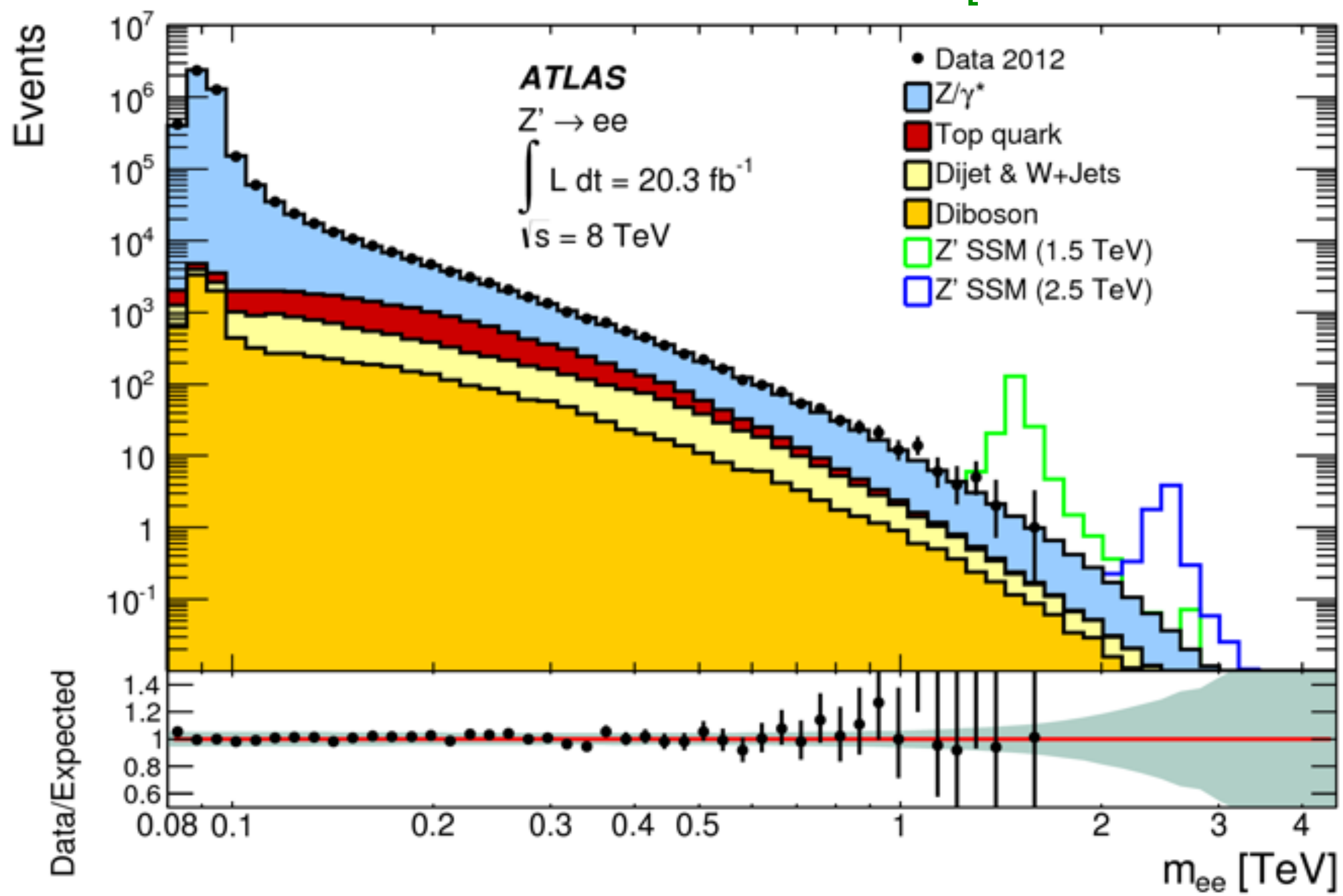


Typical hidden sector DM with Z'
[LEE, Matchev, Nasri (2007)]



Collider searches of Heavy Z'

[ATLAS 1405.4123]



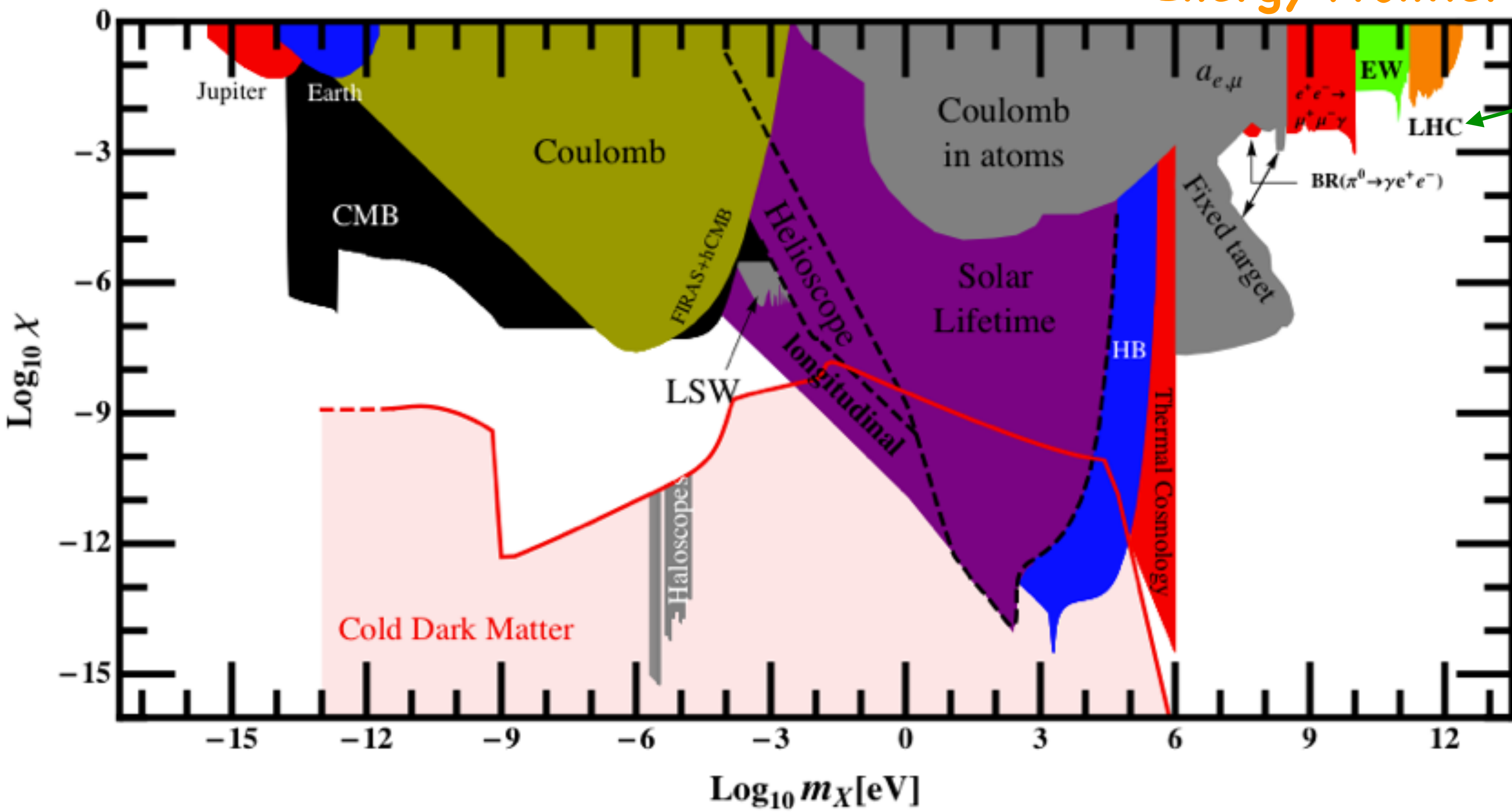
The heavy Z' search using Drell-Yan process is a standard program at High-E collider experiments.

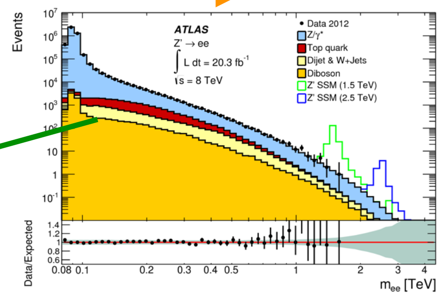
Current ATLAS, CMS bounds: mZ' > 2.5 - 2.9 TeV.
(assumption: Z' coupling size ~ SM coupling size.)

Model	Width [%]	Observed Limit [TeV]	Expected Limit [TeV]
Z'_{SSM}	3.0	2.90	2.87
Z'_{χ}	1.2	2.62	2.60
Z'_{ψ}	0.5	2.51	2.46
Z^*	3.4	2.85	2.82

Current lower bounds on Z' mass

Extended range of parameters (of Dark Photon)



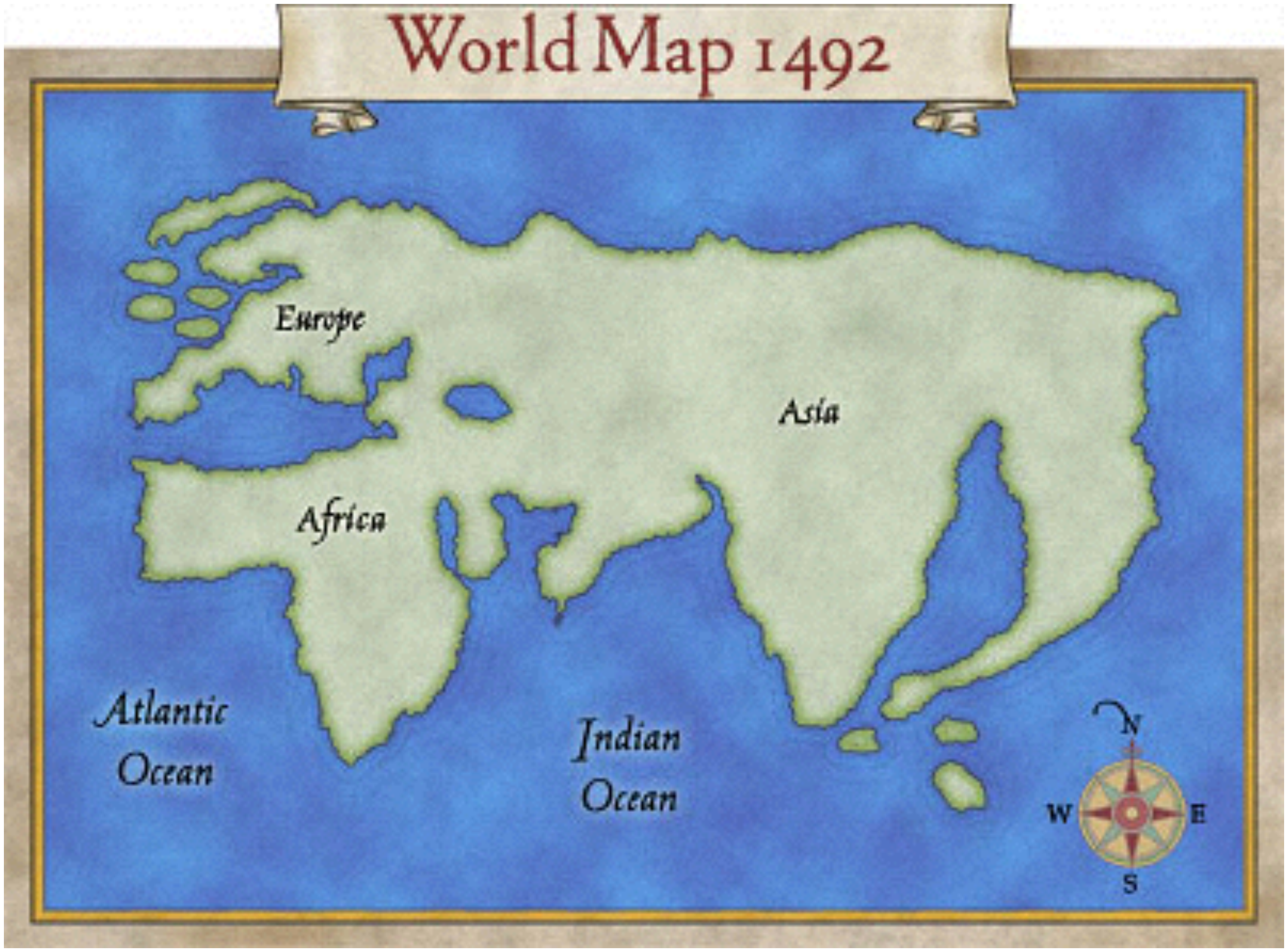


O($10b) search

[Jaeckel (2013)]

Concluding remarks

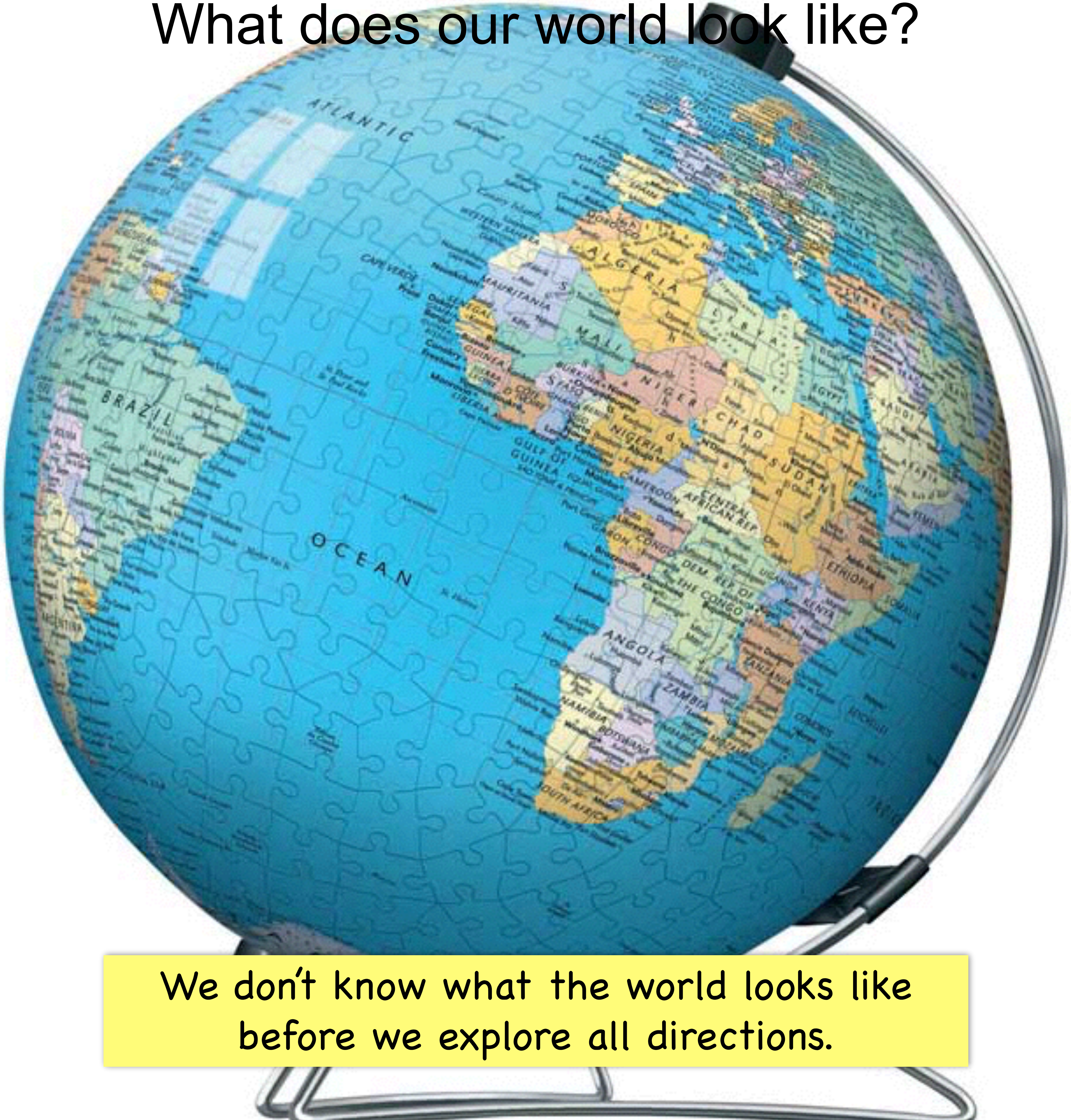
What does our world look like?



Do we know what the world looks like, leaving some directions unexplored?

Concluding remarks

What does our world look like?



We don't know what the world looks like before we explore all directions.

- Thank you -