Constraining the light neutral gauge boson (shadow Z) from a hidden sector by parity-violating asymmetries and charged lepton (g-2)

We-Fu Chang
National Tsing Hua University
(with Wei-Ping Pang)

MITP Low-Energy Precision Workshop

Mainz, Oct. 2, 2013

Outline

- Motivation
- Mass diagonalization and couplings
- Constraint from PV asymmetries and (g-2)

Why extra $U(1)$?

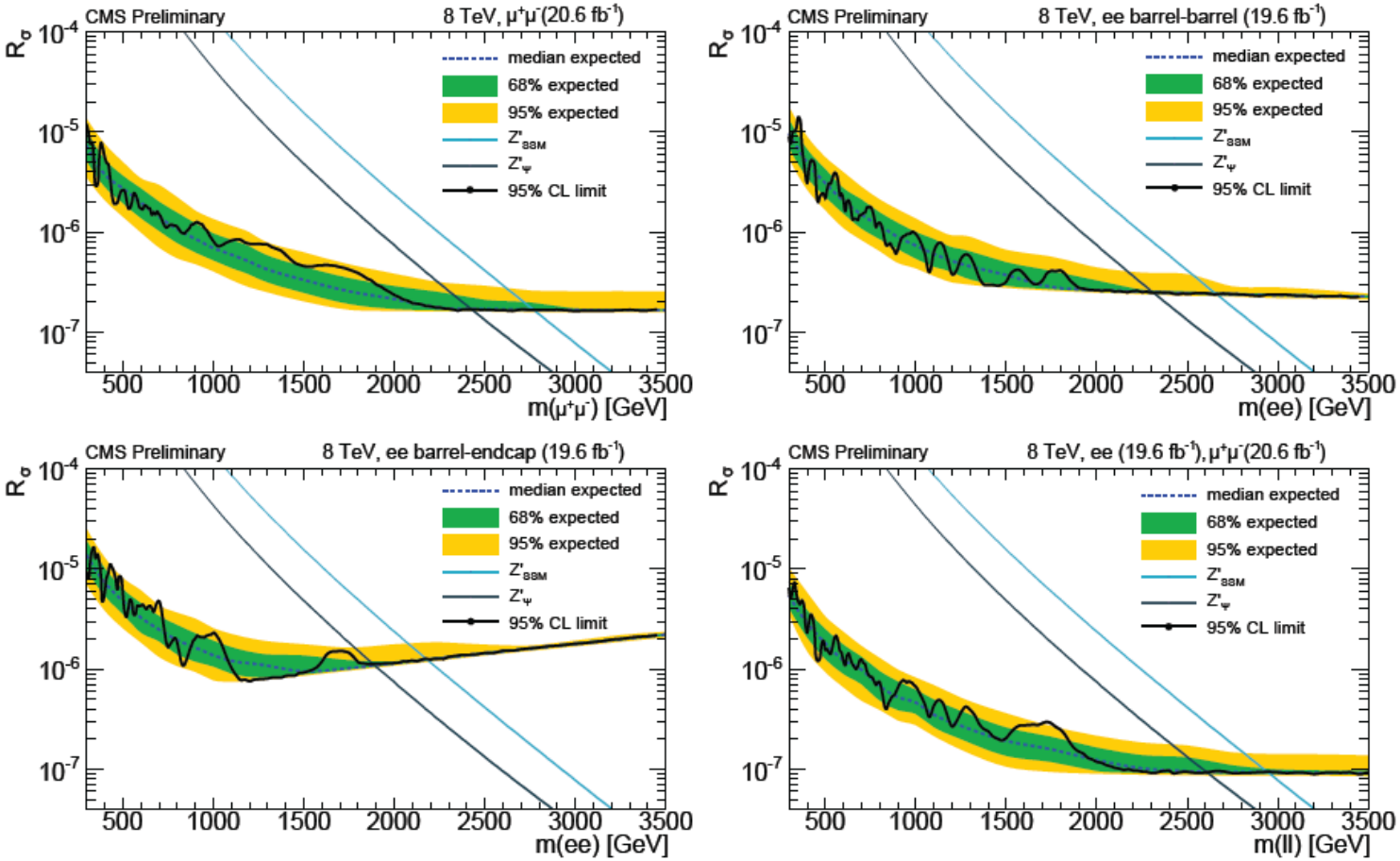
It is very common to have extra $U(1)$ in physics beyond SM.

- For example, in the traditional GUTs,

$$SO(10) \to G_{SM} \times U(1)\,, \text{and}\, E6 \to G_{SM} \times U(1) \times U(1)$$

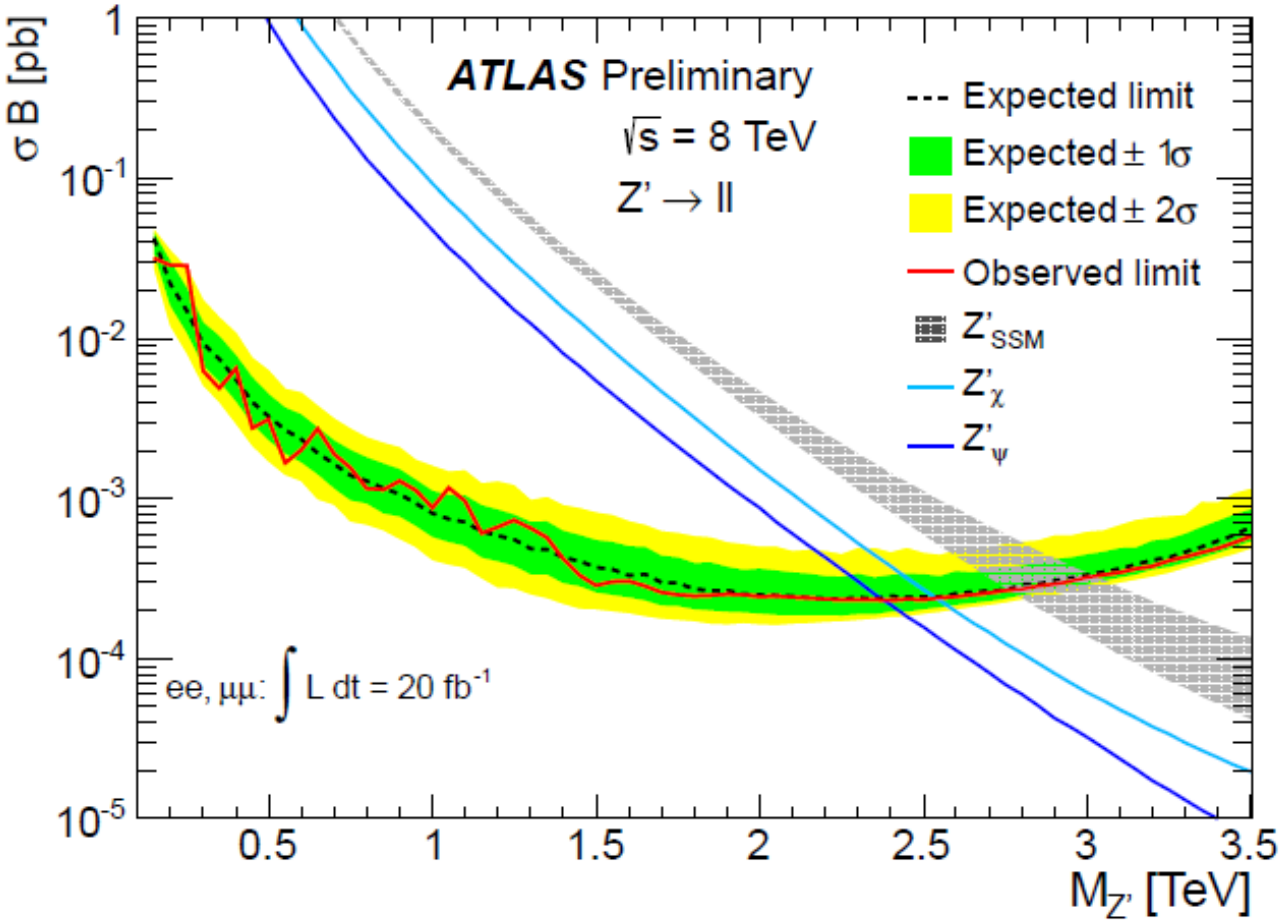
- extra dimension
- strong dynamics for EW symmetry breaking, Little Higgs, super string and so on

Bounds on visible $Z' \to ll^+$ (CMS)



95% C.L.: $Z'_{SSM} > 2.96$ TeV, $Z'_{\psi} > 2.6$ TeV

Bounds on visible Z' (ATLAS)



95% C.L.: $Z'_{SSM} > 2.86$ TeV, $Z'_{\psi} > 2.38$ TeV, $Z'_{\chi} > 2.54$TeV, $Z'_{\eta} > 2.44$ TeV

Invisible $U(1)$ from Hidden sector?

There are only a few ways to communicate between the SM and the hidden sector

- through sterile neutrino (SM singlet) N_R

$$y_N \bar{L} N_R \tilde{\Phi}$$

- through Higgs potential: for any Higgs in the hidden sector ϕ_s there is always a renormalizable term

$$\lambda_{SH} (\Phi^\dagger \Phi)(\phi_s^\dagger \phi_s)$$

- through gauge kinetic mixing between $U(1)_Y$ and $U(1)_s$

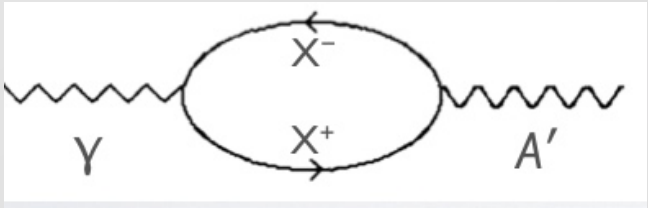
Kinetic mixing from the vector portal

an old idea: if there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson

Holdom, Phys. Lett B166, 1986

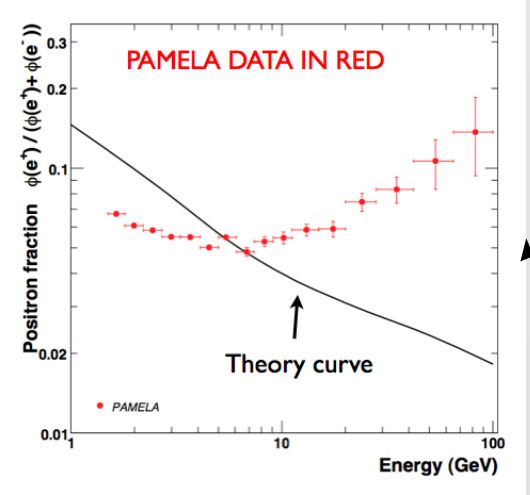
$$\mathcal{L}_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \boxed{\frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu}} + |D_\mu\phi|^2 - V(\phi)$$

Kinetic Mixing term



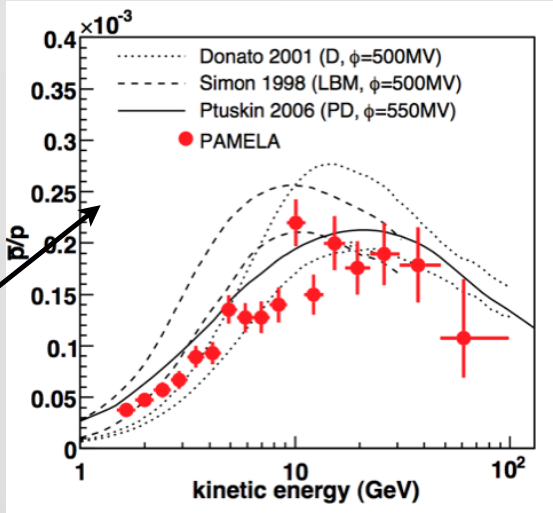
- extremely general conclusion...even arises from broken symmetries
- gives coupling of normal charged matter to the new "dark photon" q=εe

A hint from above?

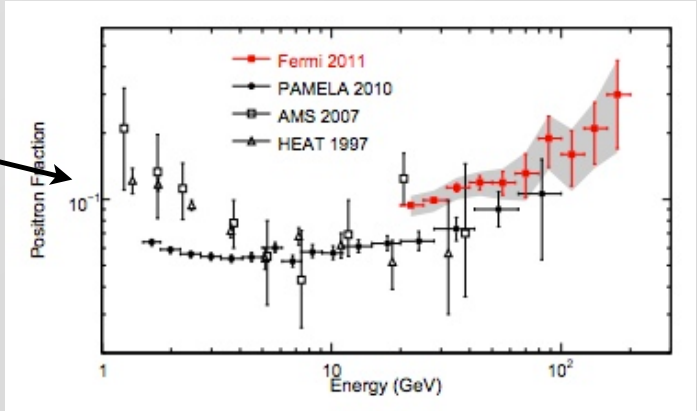


excess in e^+/e^- ratio

...but not in $\bar{p}/p$ ratio



•FERMI sees it too!

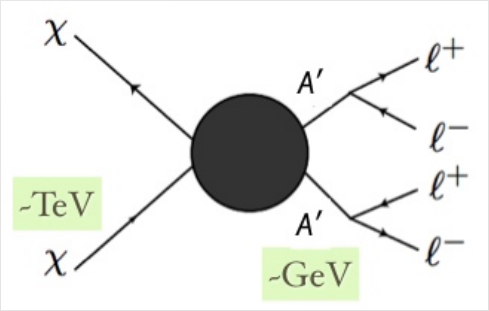


Unknown source of high energy positrons...

Is this astrophysics or particle physics?

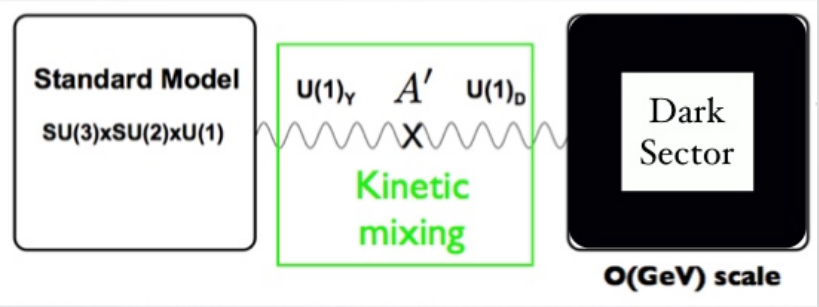
Dark matter annihilation and the dark sector

N. Arkani-Hamed *et al.*, PRD **79**, 015014 (2009).



M. Pospelov and A. Ritz, Phys. Letters B **671**, 391 (2009).

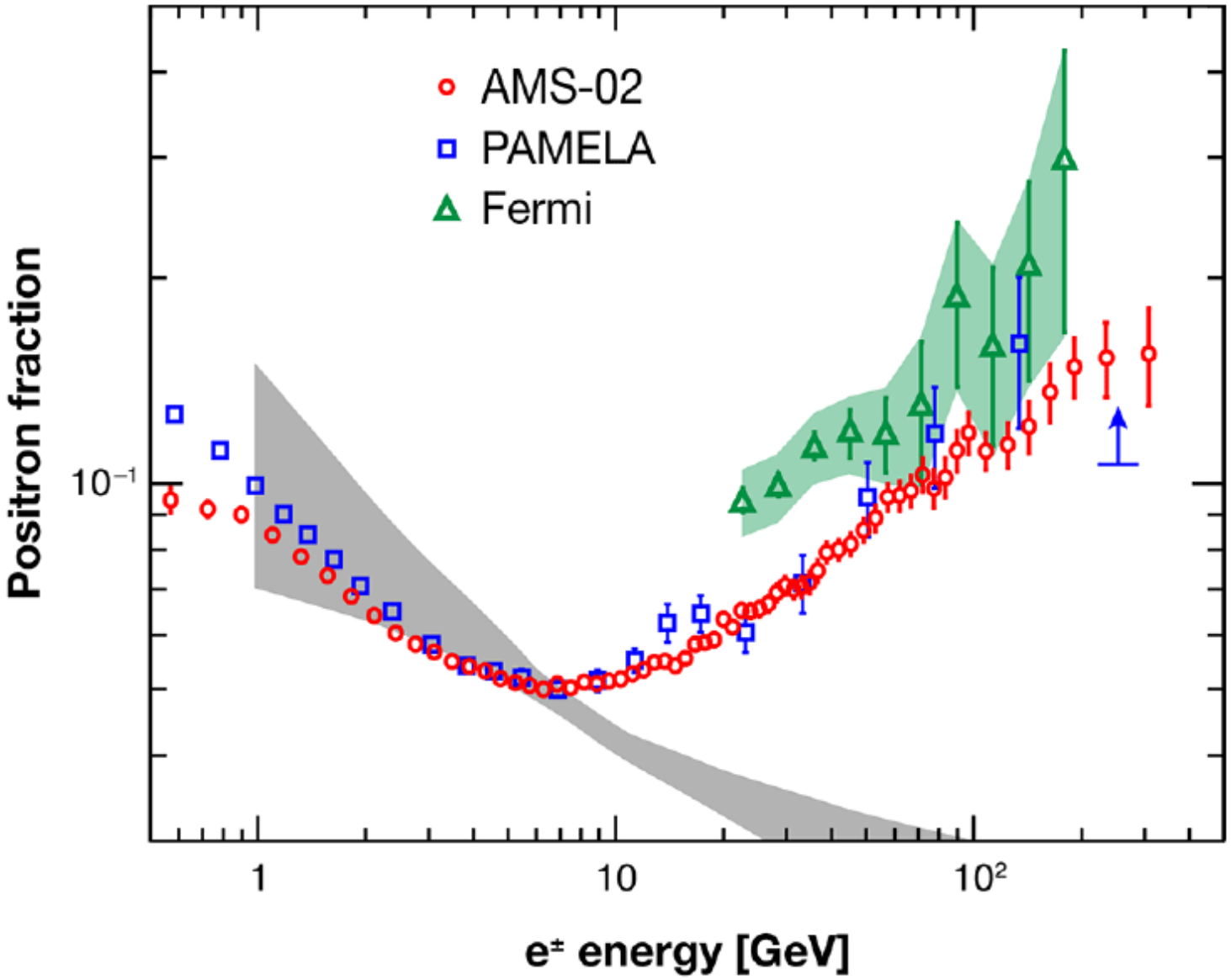
- new "dark force" with gauge boson ~ GeV while the dark matter particle (charged under the new force) ~ TeV
- decays to lepton pairs (e^+e^-, $\mu^+\mu^-$) but $p\bar{p}$ decays are kinematically forbidden



(Also, the Sommerfeld enhancement for low velocity and the 511 keV lines.)

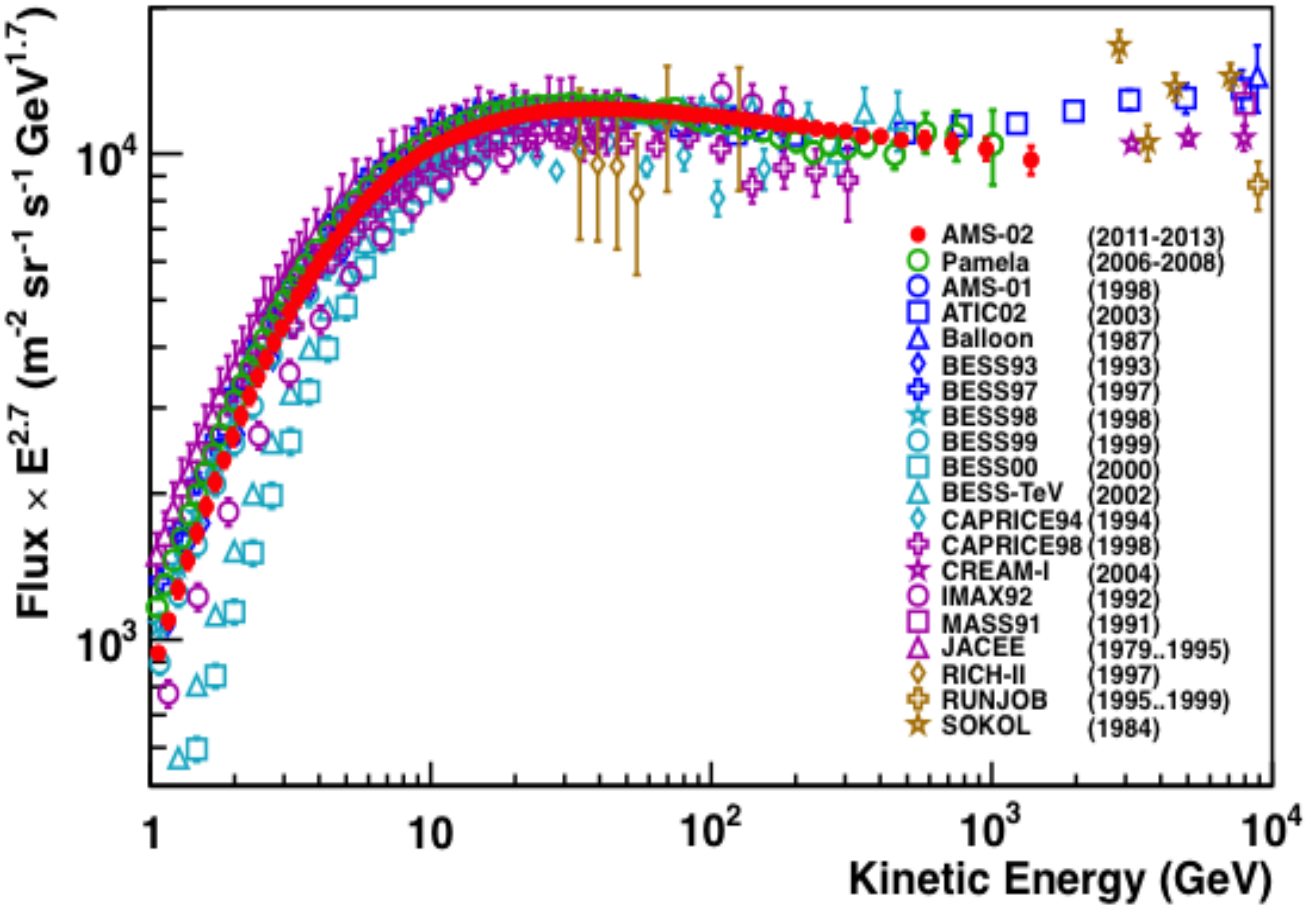
AMS2

AMS2 confirmed the positron excess



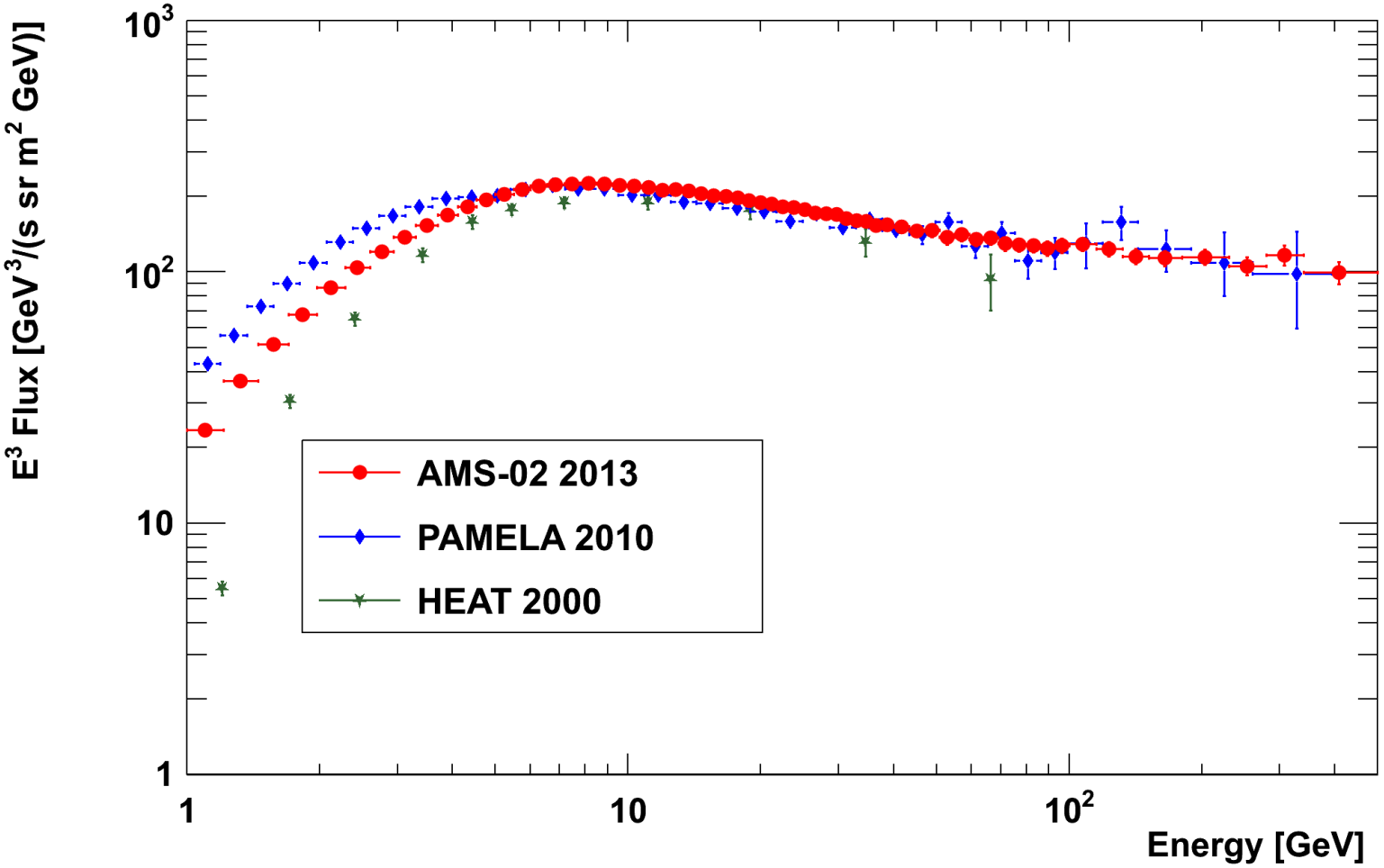
Proton flux

Comparison with past measurements



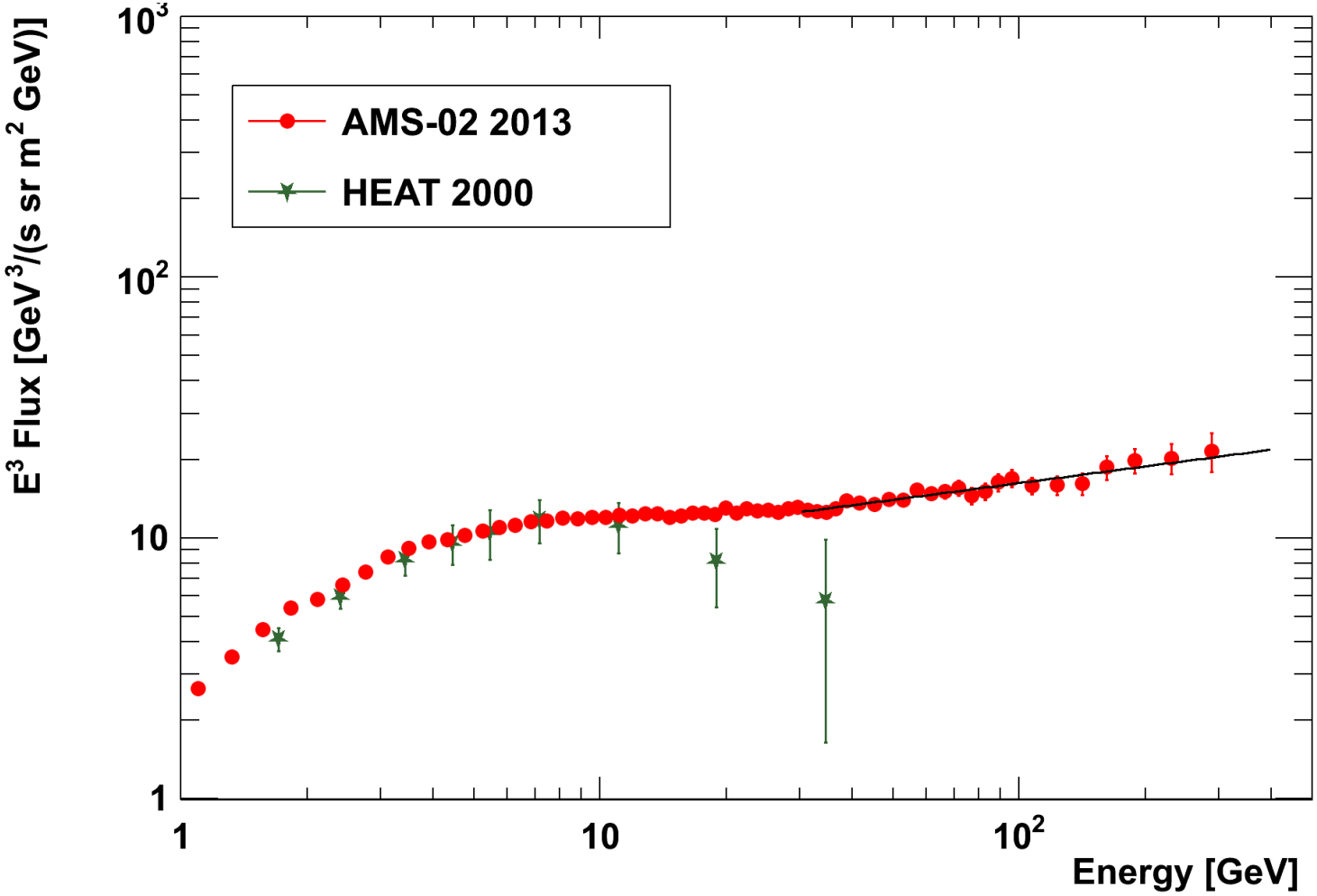
New results from AMS

3) Electron Spectrum , 1GeV to 500GeV

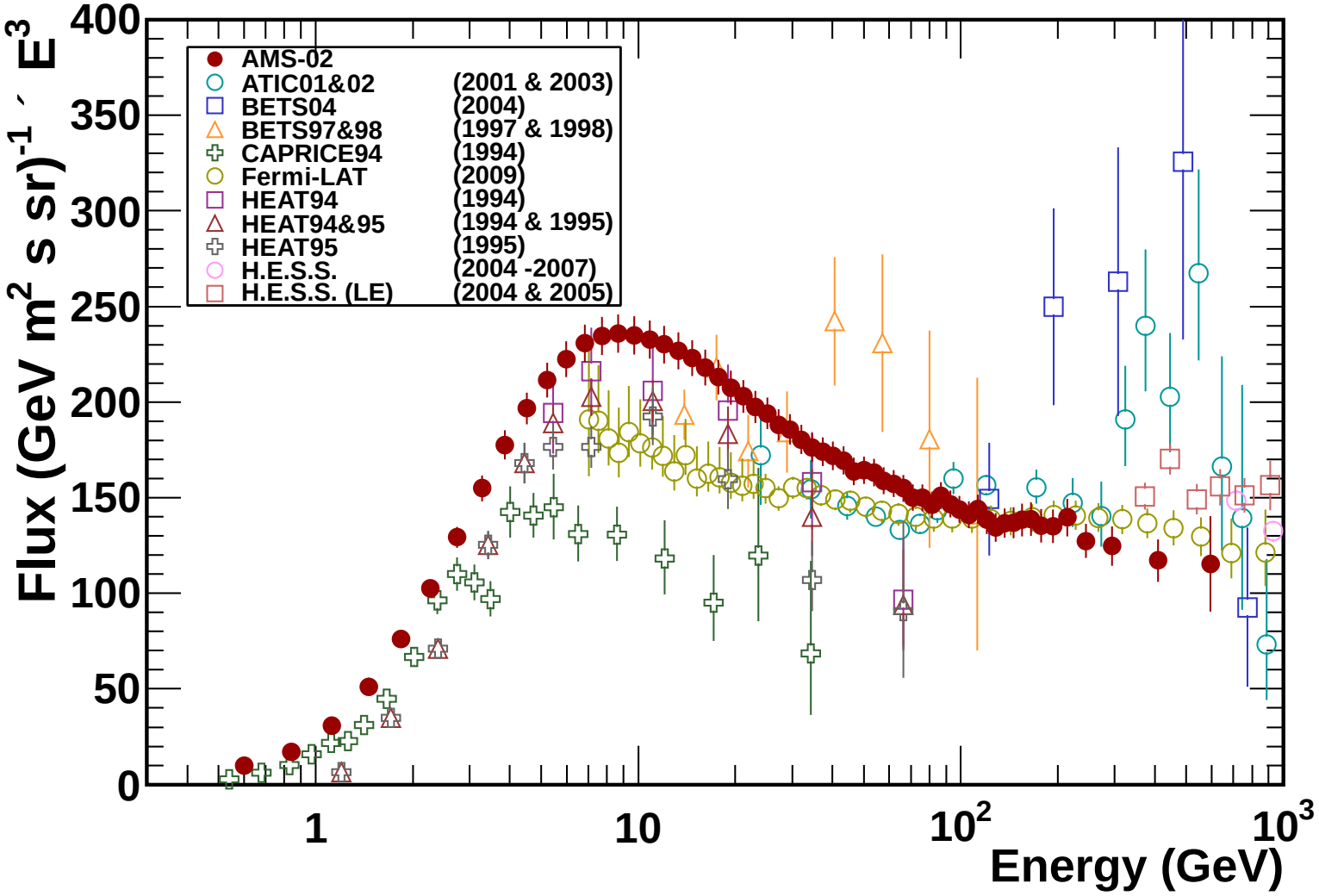


New results from AMS

4) Positron Spectrum, 1GeV to 350GeV



(Electron plus Positron) Spectrum



$U(1)$ is special

- $U(1)$ is the only gauge symmetry whose field strength is gauge invariant by itself.

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \Rightarrow F'_{\mu\nu} = \partial_\mu(A_\nu + ig\partial_\nu\alpha) - \partial_\nu(A_\mu + ig\partial_\mu\alpha) = F_{\mu\nu}$$

- All non-abelian gauge field strengthes are "charged", the only gauge invariant term is

$$Tr[X^{(a)\mu\nu}X^{(a)}_{\mu\nu}]$$

- There are two renormalizable ways to break the $U(1)$: (1) Higgs mechanism (2) Stueckelberg mechanism

$$-\frac{1}{4}F^2 + \frac{1}{2}(\partial^\mu\phi - mA^\mu)(\partial_\mu\phi - mA_\mu)$$

(Nothing but the 5D QED)

A simple hidden $U(1)$ model – 1

General Lagrangian for a hidden gauged $U(1)$ sector.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{\epsilon}{2} B^{\mu\nu} X_{\mu\nu} + \left| \left(\partial_\mu - \frac{i}{2} g_s X_\mu \right) \phi_s \right|^2 - V(\phi_s, \Phi)$$

$B_{\mu\nu}$: field strength $U(1)_Y$, Φ: SM Higgs field

- The SM fermions are singlet under $U(1)_s$.
- This $U(1)_s$ is broken by a shadow Higgs sector which is just the Abelian Higgs model with a complex scalar ϕ_s. The ϕ_s field is a sinlget under G_{SM} but interacts with the SM Higgs bosons via renormalizable interactions.
- g_s is the gauge coupling of the shadow $U(1)_s$. We normalize the shadow charge of ϕ_s to unity.
- The kinematic mixing of the two $U(1)$'s, denoted by ϵ. A priori, there is NO any physical reason for it to be small. (gauge symmetry, Lorentz inv., renormalizable)

A simple hidden $U(1)$ model – 2

- Typically, mixing for a visible Z' is expected to be induced at the loop level. and $|\epsilon| \ll 1$ is generally assumed.
- This is not necessary the case here(nor in brane world models). We leave ϵ as a free parameter to be constrained by experiments, in particular the precision tests.
- The kinetic terms including the mixing can be recast into canonical form through a $GL(2)$ transformation.

$$\begin{pmatrix} X \\ B \end{pmatrix} = \begin{pmatrix} c_\epsilon & 0 \\ -s_\epsilon & 1 \end{pmatrix} \begin{pmatrix} X' \\ B' \end{pmatrix},$$

where

$$s_\epsilon = \frac{\epsilon}{\sqrt{1-\epsilon^2}}, \; c_\epsilon = \frac{1}{\sqrt{1-\epsilon^2}}.$$

(Note:(1) Unitary transformation does not work.(2)they are NOT sine/cosine !)

A simple hidden $U(1)$ model – 3

- The most general renormalizable $G_{SM} \times U(1)_s$ inv. potential is:

$$V(\Phi, \phi_p) = \mu_s^2 \phi_s^* \phi_s + \lambda_s (\phi_s^* \phi_s)^2 + 2\kappa \left(\Phi^\dagger \Phi\right) (\phi_s^* \phi_s) + \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- After SSB the scalars acquire nonzero VEV,

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_0 \end{pmatrix}, \ \langle \phi_p \rangle = \frac{v_s}{\sqrt{2}},$$

with

$$v_0^2 = -\frac{\lambda_s \mu^2 - \kappa \mu_s^2}{\lambda \lambda_s - \kappa^2}, \ v_s^2 = -\frac{\lambda \mu_s^2 - \kappa \mu^2}{\lambda \lambda_s - \kappa^2}.$$

- Positivity of potential requires

$$\lambda, \lambda_s > 0, \ \kappa > 0$$

Remark: pheno study for a CW scenario, $\mu^2 = \mu_s^2 = 0$, see WFC, J.Ng, J.Wu, hep-ph/0701254.

SSB

- In terms of B' , X', and A_3, after SSB, the relevant Lagrangian becomes

$$-\frac{1}{4}(B'_{\mu\nu})^2-\frac{1}{4}(X'_{\mu\nu})^2-\frac{1}{8}(c_\epsilon g_s v_s)^2(X'_\mu)^2-\frac{g^2v^2}{8}(c_W A_{3\mu}-s_W B'_\mu)^2$$

- where $g^2 \equiv g_1^2 + g_2^2$, s_W (c_W) are the shorthanded for $\sin\theta_W = g_1^2/g^2$ $(\cos\theta_W)$
- Observe that $(c_W B' + s_W A_3)$ is massless $\Rightarrow$ physical photon.
- Then, two mass eigenstates are the proper linear combinations of $(c_W A_3 - s_W B')$ and X'

SSB

- The $SU(2)_L \times U(1)_Y \times U(1)_s$ symmetry is broken down to $U(1)_{QED}$.
- The pattern of breaking is peculiar in that the CC sector remains as in the SM at tree-level

$$M_W = (g_2 v_0)/2$$

- The usual SM definition:

$$\tan\theta_W = g_Y/g_2$$

electric charge

$$e = g_2 \sin\theta_W \, , \; Q^f_{L,R} = T^3_{L,R} + Y^f_{L,R}$$

remain intact.
- In the neutral sector we have a massless photon and two massive neutral bosons which are not yet in the mass eigenbasis.

NC

- They can be further diagonalized by

$$\begin{pmatrix} B' \\ A_3 \\ X' \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\eta & -s_\eta \\ 0 & s_\eta & c_\eta \end{pmatrix} \begin{pmatrix} photon \\ Z \\ Z_s \end{pmatrix},$$

- The mixing angle is given by

$$\tan 2\eta = \frac{2 s_W s_\epsilon}{1 - c_W^2 (M_3/M_W)^2 - s_W^2 s_\epsilon^2}, \; M_3 \equiv (g_s v_s c_\epsilon)/2$$

- And

$$M_Z^2 = \frac{M_W^2}{c_W^2} \left\{ c_\eta^2 + s_\eta^2 [s_W^2 s_\epsilon^2 + (M_3 c_W / M_W)^2] + 2 s_\eta c_\eta s_W s_\epsilon \right\}$$

$$M_{Z_s}^2 = \frac{M_W^2}{c_W^2} \left\{ s_\eta^2 + c_\eta^2 [s_W^2 s_\epsilon^2 + (M_3 c_W / M_W)^2] - 2 s_\eta c_\eta s_W s_\epsilon \right\}$$

Shadow Z -fermion coupling

- For the photon (A^μ) the SM result is retained as it should and we have $A^\mu \bar{f} f \ : \ i\gamma^\mu e Q_f$.
- For Z, Z_s, the coupling are slightly different from the SM, but still flavor universal,

$$Z^\mu \bar{f} f \ : \ i\gamma^\mu \frac{g_2}{c_W} \left[\left(c_\eta g_f^L - s_\eta s_W s_\epsilon Y_f^L \right) \hat{L} + \left(c_\eta g_f^R - s_\eta s_W s_\epsilon Y_f^R \right) \hat{R} \right]$$

$$Z_s^\mu \bar{f} f \ : \ i\gamma^\mu \frac{-g_2}{c_W} \left[\left(s_\eta g_f^L + c_\eta s_W s_\epsilon Y_f^L \right) \hat{L} + \left(s_\eta g_f^R + c_\eta s_W s_\epsilon Y_f^R \right) \hat{R} \right]$$

  where $g_{L,R}^f = T^3(f_{L,R}) - s_W^2 Q^f$ is the SM Zff coupling.
- Due to $U(1)_Y - U(1)_s$ mixing, the correction $\propto Y_f$ (Not Q_f)
- Z_s introduces new PV couplings and Z couplings get modified too.
- Exact, no Z_s-photon mixing in the mass basis at tree-level.

NC

- Only two free parameters, ϵ and M_{Z_s}, in this simplest hidden $U(1)$ model. At tree-level, M_3 can be expressed by physical masses

$$M_3 = M_Z M_{Z_s} c_W / M_W$$

- For $M_{Z_s} \ll M_Z$, a useful limit

$$\tan\eta \simeq s_W s_\epsilon + \frac{s_W s_\epsilon}{1 + s_W^2 s_\epsilon^2} \left(\frac{M_{Z_s} M_Z}{M_W^2 / c_W^2} \right)^2 + \mathcal{O}(M_{Z_s}^4 / M_Z^4)$$

- and the $Z_s^\mu ff$ coupling becomes more and more photon- and vector-like

$$-i\gamma^\mu \frac{g_2 c_\eta}{2c_W} \left[t_\eta (T_3^L - 2Q_f s_W^2) + s_w s_\epsilon (2Q - T_3^L) + (s_W s_\epsilon - t_\eta) T_3^L \gamma_5 \right]$$

$$\sim -ie\gamma^\mu \frac{c_\eta s_\epsilon}{c_W} \left[Q_f c_W^2 - \frac{1}{2} \left(\frac{M_{Z_s}}{M_Z} \right)^2 T_3^L \gamma_5 \right]$$

PV in the light Z_s limit

- The PV effective Lagrangian is usually parameterized as

$$\mathcal{L}_{PV} = \frac{G_F}{\sqrt{2}} \left[C_{1q} \left(\bar{e}\gamma^\mu \gamma_5 e \right) \left(\bar{q}\gamma_\mu q \right) + C_{2q} \left(\bar{e}\gamma^\mu e \right) \left(\bar{q}\gamma_\mu \gamma_5 q \right) \right]$$

- In SM, at tree-level,

$$C_{1q} = 2(g_R^e - g_L^e)(g_R^q + g_L^q)\,,\; C_{2q} = 2(g_R^e + g_L^e)(g_R^q - g_L^q)$$

- With Z_s and the modified Z coupling these should be modified to

$$C_{1q} \to C_{1q}^Z + C_{1q}^{Z_s} \left(\frac{M_Z}{M_{Z_s}} \right)^2 , C_{2q} \to C_{2q}^Z + C_{2q}^{Z_s} \left(\frac{M_Z}{M_{Z_s}} \right)^2$$

PV in the light Z_s limit

- More interestingly,

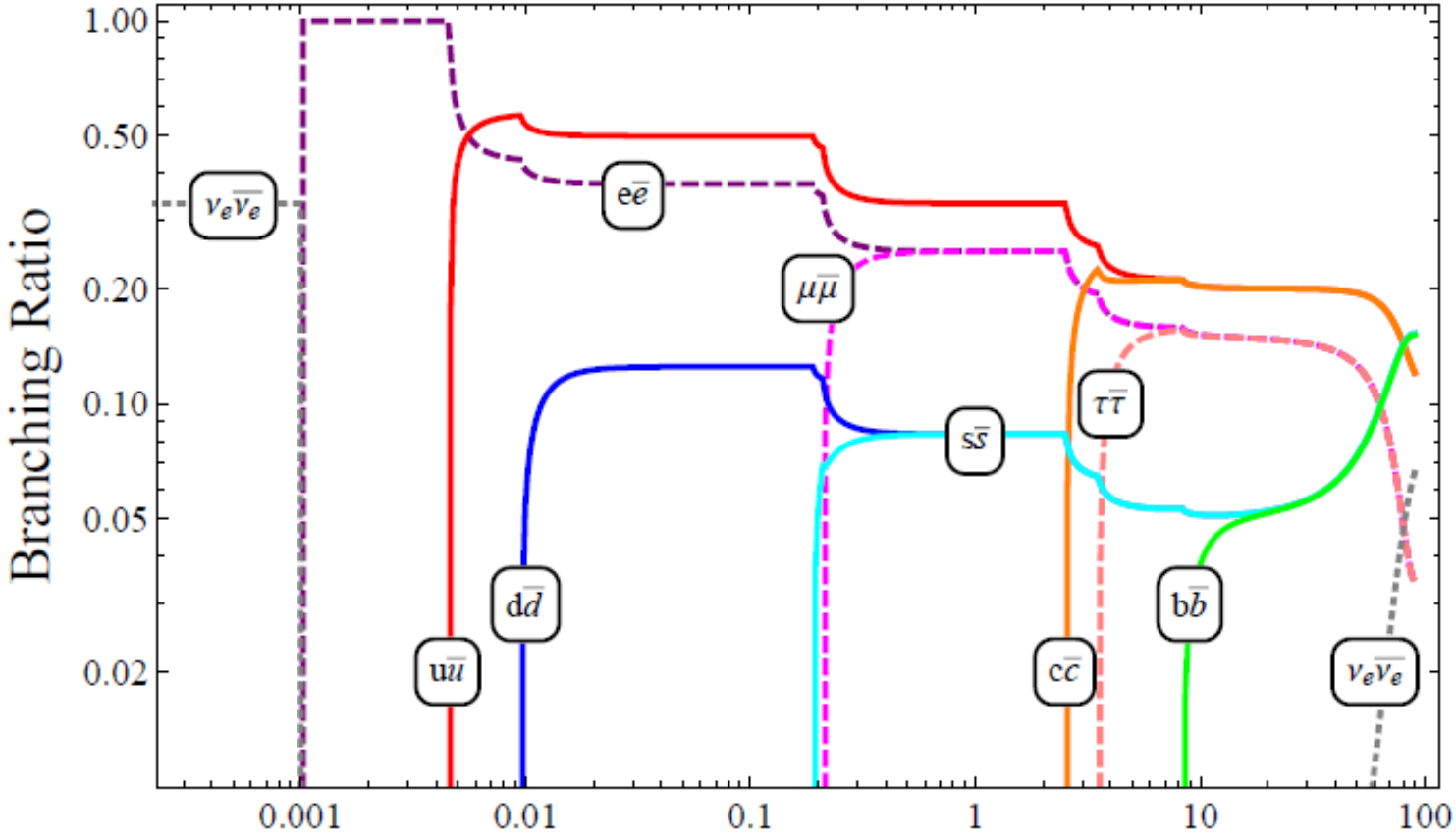
$$
\begin{aligned}
C_{1u}^{SM} &\to C_{1u}^{SM} - \tfrac{5}{6} s_W^2 s_\epsilon^2 + \tfrac{4}{3}(1 - s_W^2)\tfrac{s_W^2 s_\epsilon^2}{(1+s_W^2 s_\epsilon^2)^2}\left(\frac{M_Z^2 c_W^2}{M_W^2}\right)^2 \\
C_{1d}^{SM} &\to C_{1d}^{SM} + \tfrac{1}{6} s_W^2 s_\epsilon^2 - \tfrac{2}{3}(1 - s_W^2)\tfrac{s_W^2 s_\epsilon^2}{(1+s_W^2 s_\epsilon^2)^2}\left(\frac{M_Z^2 c_W^2}{M_W^2}\right)^2 \\
C_{2u}^{SM} &\to C_{2u}^{SM} - \tfrac{3}{2} s_W^2 s_\epsilon^2 + 2(1 - s_W^2)\tfrac{s_W^2 s_\epsilon^2}{(1+s_W^2 s_\epsilon^2)^2}\left(\frac{M_Z^2 c_W^2}{M_W^2}\right)^2 \\
C_{2d}^{SM} &\to C_{2d}^{SM} + \tfrac{3}{2} s_W^2 s_\epsilon^2 - 2(1 - s_W^2)\tfrac{s_W^2 s_\epsilon^2}{(1+s_W^2 s_\epsilon^2)^2}\left(\frac{M_Z^2 c_W^2}{M_W^2}\right)^2
\end{aligned}
$$

- There is large cancelation between Z and Z_s contribution.
- This has been overlooked (including myself in 0901.0613).

Decay Branching ratios

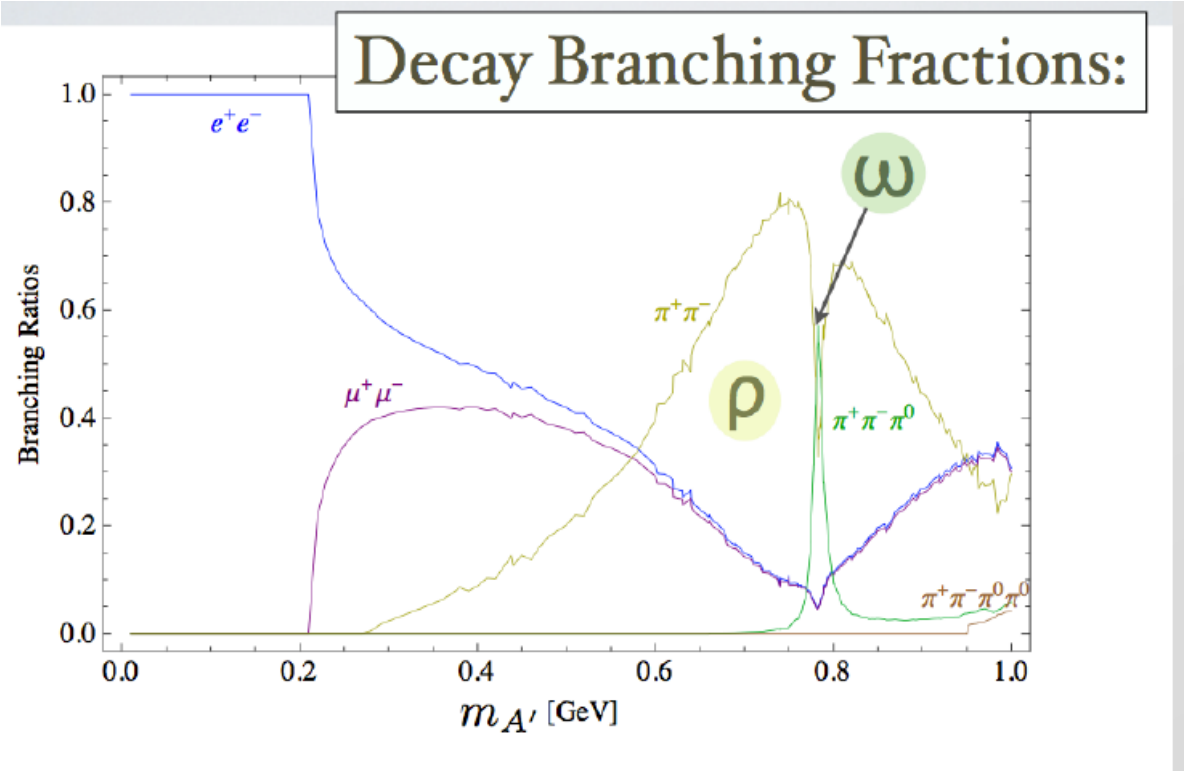
$$\Gamma(Z_s \to \bar{f} f) = \frac{N_c^f g_2^2 M_{Z_s}}{24\pi \cos^2\theta_W} \left[\left(g_L^{Z_s,f} \right)^2 + \left(g_R^{Z_s,f} \right)^2 \right] \sqrt{1-4\beta_f}$$

$$\times \left(1 + \beta_f \frac{6 g_L^{Z_s,f} g_R^{Z_s,f} - (g_L^{Z_s,f})^2 - (g_R^{Z_s,f})^2}{(g_L^{Z_s,f})^2 + (g_R^{Z_s,f})^2} \right), \quad \beta_f \equiv \frac{m_f^2}{M_{Z_s}^2}$$



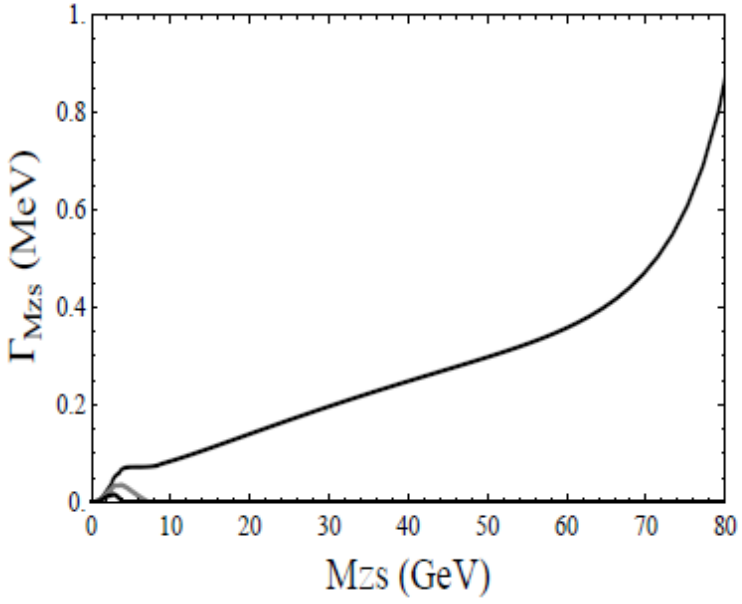
Decay Branching ratios

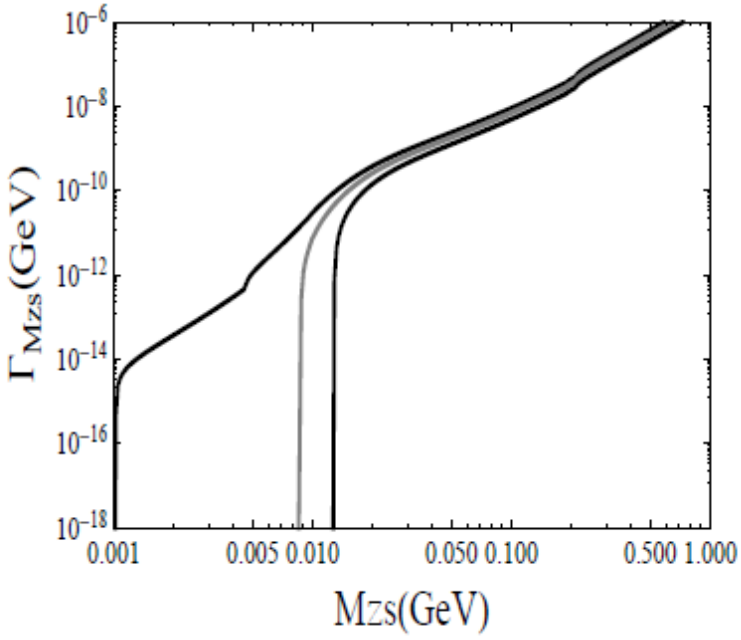
(Figure from M. Graham's talk)



For mass less than $2m_e$, the dominate modes will be $Z_s \to 3\gamma, \nu\bar{\nu}$ (both 1-loop) in the "dark-photon" models.

Decay Width





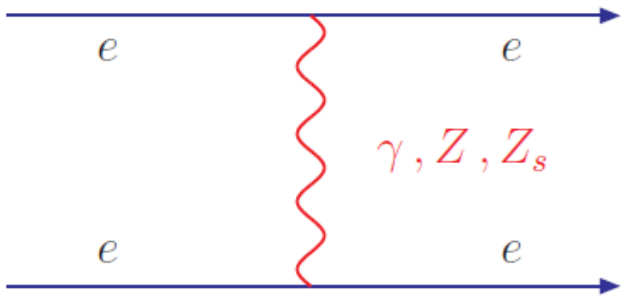
(from 1 σ global fit)

Møller scattering–1

- The SLAC E158 experiment measures the parity violating asymmetry,

$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R},$$

at momentum transfer $Q^2 = 0.026\,\mathrm{GeV}^2$. L/R: incident electron polarization.



- At tree level, the asymmetry is, up to $\mathcal{O}(g_2^2)$:

$$A_{PV} \simeq \frac{G_F s}{\sqrt{2}\pi\alpha} \frac{y(1-y)}{1+y^4+(1-y)^4}((g_L^Z)^2 - (g_R^Z)^2)$$

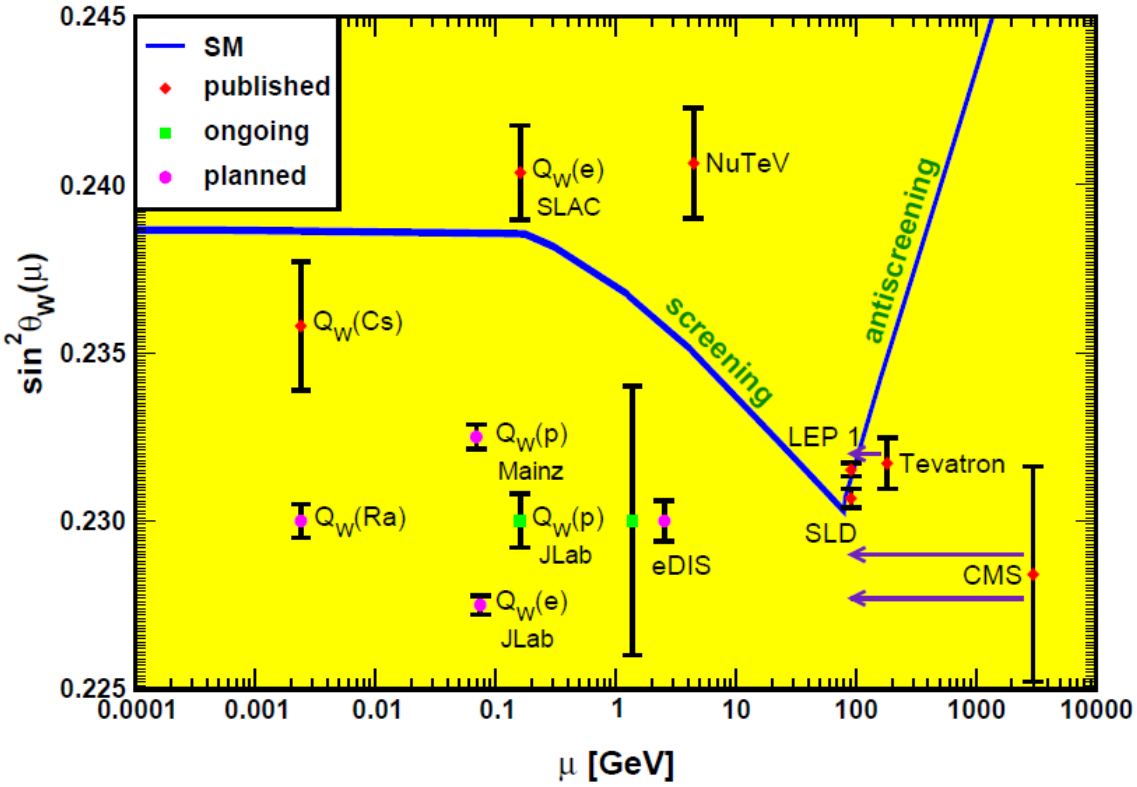
where $y = Q^2/s \simeq 0.6$. Denominator: leading photon exchange cross-section ; numerator: parity violation due to photon-Z interference.

Møller scattering–2

- Also need to include the photon-Z_s interference term:

$$A_{PV}^{Z_s} \simeq \frac{G_F s}{\sqrt{2}\pi\alpha} \frac{y(1-y)}{1+y^4+(1-y)^4}((g_L^{Z_s 2})^2 - (g_R^{Z_s})^2)\left(\frac{M_Z}{M_{Z_s}}\right)^2$$

- Of course, one needs to take s_W^2 running into account:(From J. Erler, S.Su, 1303.5522)



Atomic PV: Q_W

- atomic PV $\propto$ (electron axial coupling) $\times$ (quark vector coupling)
- $Q_W^{SM}(Cs) = -73.23 \pm 0.02$ and $Q_W^{SM}(Tl) = -116.88 \pm 0.03$.
- $Q_W^{exp}(Cs) = -73.20 \pm 0.35$ and $Q_W^{exp}(Tl) = -116.4 \pm 3.6$
- The contributions from SM Z and Z_s largely cancel (except for $M_{Z_s} < 1$ GeV)

$$
\begin{aligned}
Q_W &= 4(g_R^{Z,e} - g_L^{Z,e})[(2Z+N)(g_L^{Z,u} + g_R^{Z,u}) \\
&\quad +(2N+Z)(g_L^{Z,d} + g_R^{Z,d})] + 4\left(\frac{M_Z}{M_{Z_s}}\right)^2 (g^Z \to g^{Z_s})
\end{aligned}
$$

$$
= 2\left(C_{1u}^Z + C_{1u}^{Zs}\frac{M_Z^2}{M_{Z_s}^2}\right)(2Z+N) + 2\left(C_{1d}^Z + C_{1d}^{Zs}\frac{M_Z^2}{M_{Z_s}^2}\right)(2N+Z)
$$

Charged lepton (g-2)-1

- For any Z' with $\mathcal{L}_{NC} = g\bar{f}\gamma^{\mu}(g_v + g_a\gamma^5)fZ'_{\mu}$.

$$
\begin{aligned}
a_f^{Z'} &= \frac{g^2}{4\pi^2}\left[g_v^2 F_V\left(\frac{m_f^2}{M_{Z'}^2}\right) + g_a^2 F_A\left(\frac{m_f^2}{M_{Z'}^2}\right)\right] \\
F_V(\tau) &= \int_0^1 dx \frac{x^2(1-x)\tau}{1-x+x^2\tau}, \\
F_A(\tau) &= \int_0^1 dx \frac{\tau x(1-x)(x-4)+2x^3\tau^2}{1-x+x^2\tau}
\end{aligned}
$$

- $F_V > 0$, and $F_A < 0$ for $\tau < 1.4488$ and becomes positive for $\tau > 1.4488$.
- A useful limit

$$
a_l^{Z'} = \frac{g^2}{4\pi^2} \times \begin{cases} \frac{1}{3}\tau(g_v^2 - 5g_a^2) & \text{for} \quad \tau \ll 1 \\ \frac{1}{2}g_v^2 + g_a^2\tau & \text{for} \quad \tau \gg 1 \end{cases}
$$

Charged lepton (g-2)-2

- In SM, $g = g_2/c_W$ and $g_a^l(= 1/4) \gg g_v^l(= s_W^2 - 1/4)$. SM Z yields a negative contribution to a_μ and a_e.
- For light shadow Z, its coupling tend to be vector-like with $g_v^l \to \epsilon s_W c_W^2$ and $g_a^l \to -s_W s_\epsilon/(1 + s_W^2 s_\epsilon^2)^{3/2} \times (M_{Z_s}/2M_Z)^2$ and gives a positive contribution to a_μ and a_e.
- Which can explain the a_μ discrepancy

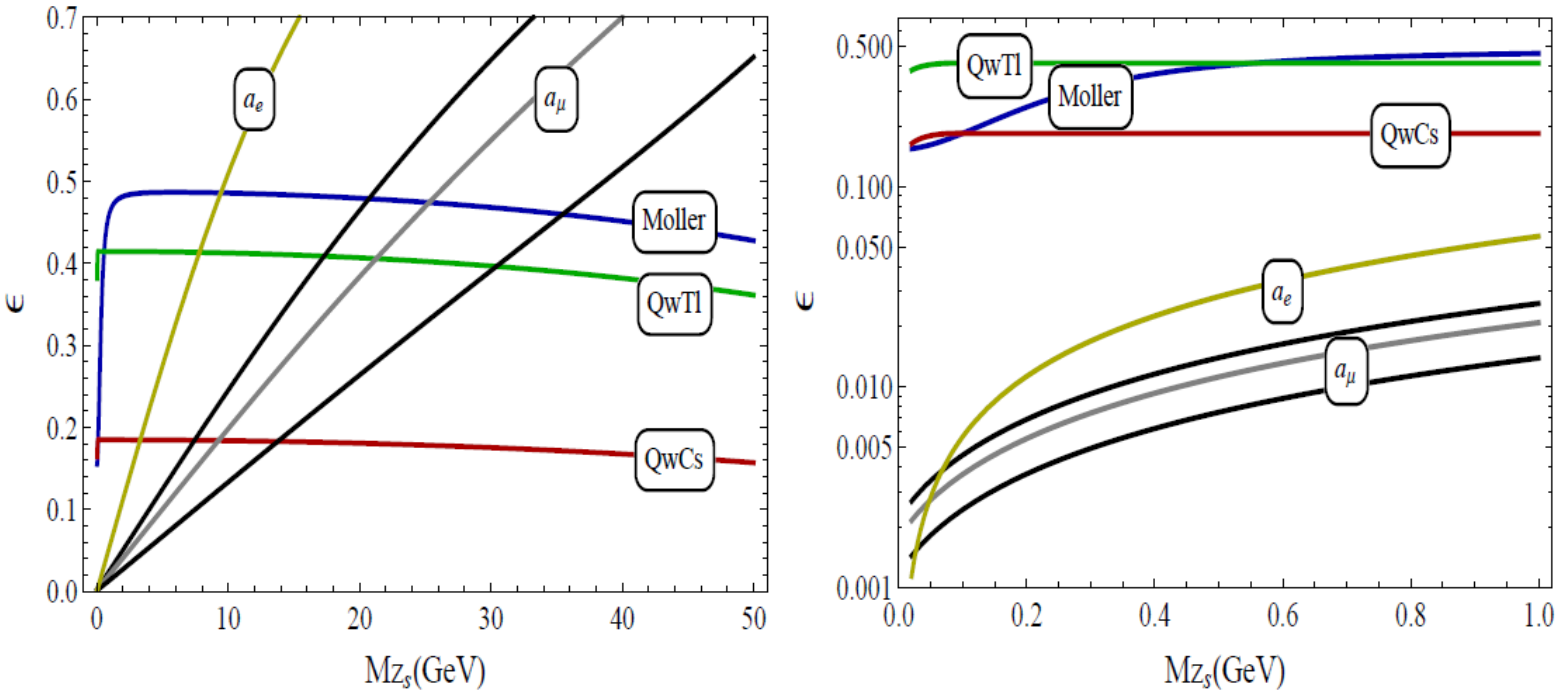
$$a_\mu^{exp} - a_\mu^{SM} = (2.39 \pm 0.79) \times 10^{-9} \tag{2}$$

- but make the situation of a_e worse.

$$a_e^{exp} - a_e^{SM} = (-1.09 \pm 0.83) \times 10^{-12} \tag{3}$$

- For Z_s, $M_{Z_s} \leq m_e$, a universal contribution $\sim +0.98 \times 10^{-3} \times \epsilon^2$ to any charge lepton. And the a_e will weight in to limit ϵ

Various bounds



Asymmetries at Z pole

- SM Z contribution dominates
- PV asymmetry $\propto (g_L^2 - g_R^2)/(g_L^2 + g_R^2)$.
- for $M_{Z_s} \ll M_Z$, and keep the expansion to the ϵ^2,

$$\left(\frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}\right)_{SM} \to \left(\frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}\right)_{SM} \times (1 - \epsilon^2 K_f)$$

$$K_f = 4 s_W^2 \frac{g_L^f g_R^f (g_R^f Y_L^f - g_L^f Y_R^f)}{(g_L^f)^4 - (g_R^f)^4}$$

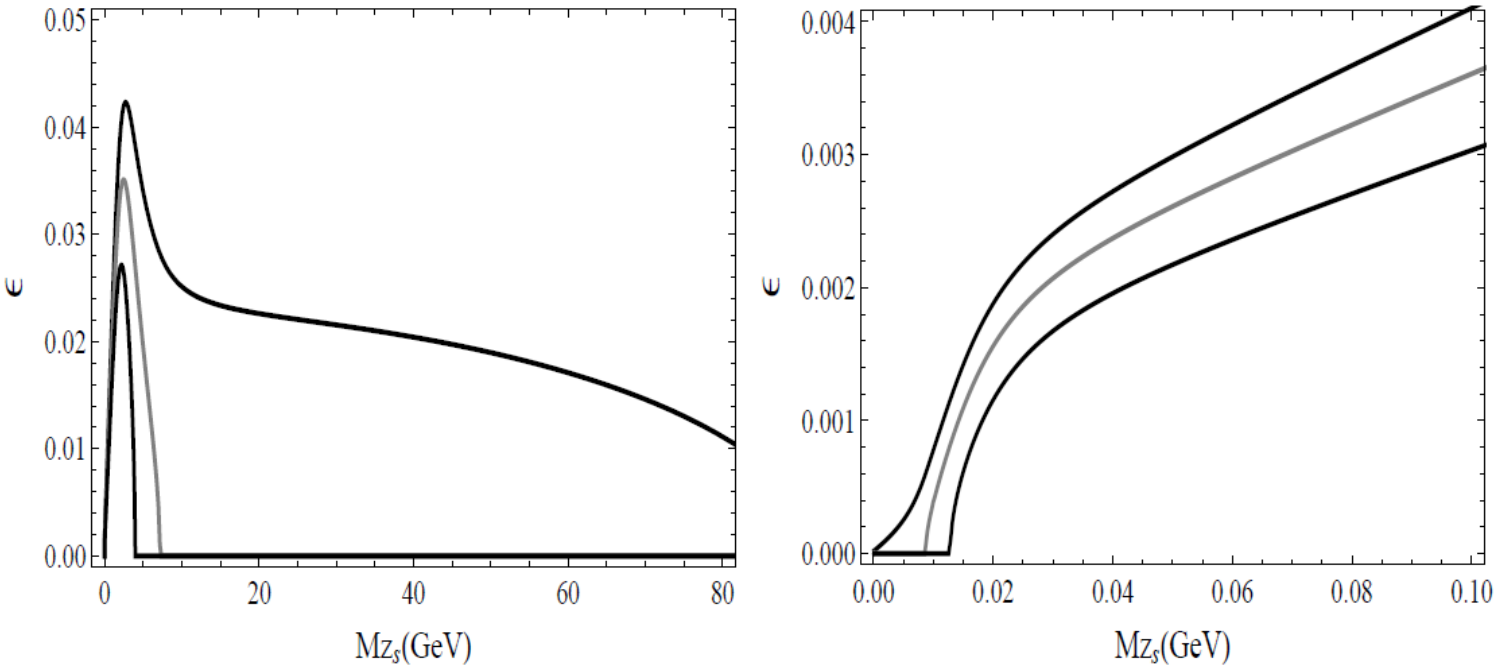
- $K_u = 0.9186$, $K_d = 0.12080$, and $K_e = 9.3268$ by using the $\overline{MS}$ $s_W^2 = 0.23116$ at the Z pole.
- The accuracy of LEP2 PV asymmetries are around percent level $\Rightarrow \epsilon \lesssim \mathcal{O}(0.01)$.

Z pole EW

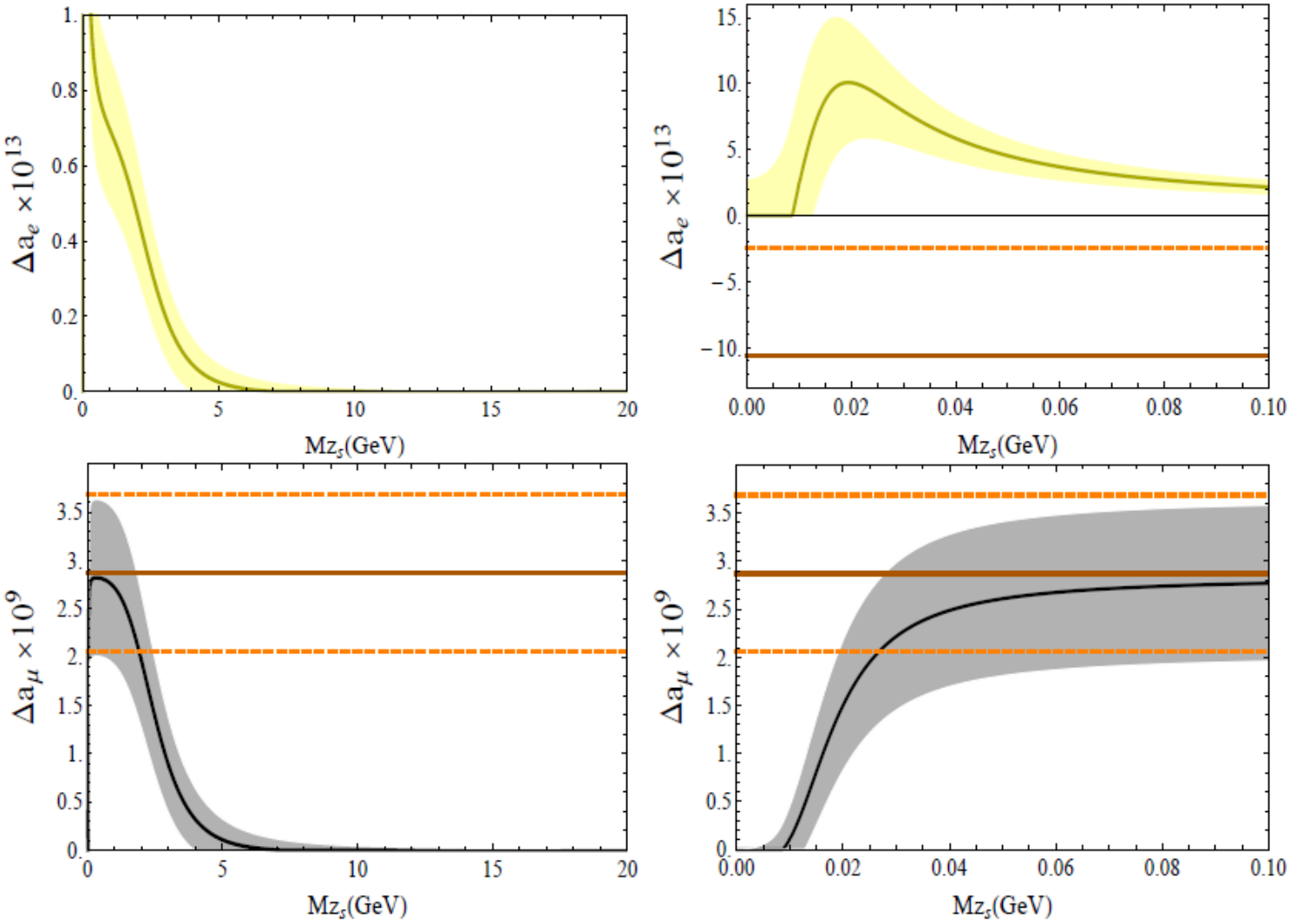
Quanity	$\Delta_{Expt} = (\frac{Expt}{SM}) - 1$	Quanity	$\Delta_{Expt} = (\frac{Expt}{SM}) - 1$
σ_{had}	0.0015(9)	$\overline{s}_l^2(A_{FB}^{(0,q)})$	0.0041(52)
R_e	0.0029(25)		0.0023(33)
R_μ	0.0020(17)		-0.0119(138)
R_τ	-0.0012(22)	A_e	0.0263(110)
R_b	0.0025(31)		0.047(41)
R_c	-0.0010(174)		0.016(34)
$A_{FB}^{(0,e)}$	-0.112(154)	A_μ	-0.037(102)
$A_{FB}^{(0,\mu)}$	0.035(81)	A_τ	-0.078(102)
$A_{FB}^{(0,\tau)}$	0.151(105)		-0.024(30)
$A_{FB}^{(0,b)}$	-0.041(17)	A_b	-0.013(21)
$A_{FB}^{(0,c)}$	-0.043(48)	A_c	0.003(40)
$A_{FB}^{(0,s)}$	-0.057(11)	A_s	-0.043(97)

A similar analysis for $M_{Z_s} \gg M_Z$ was done by WFC, J. Ng, J. Wu, in hep-ph/0608068

Global fitting



$(g-2)$



some future low energy PV exp

- JLAB as example

Measurements	$\delta \sin^2\theta_{\rm W}/\sin^2\theta_{\rm W}$	$\delta \sin^2\theta_{\rm W}$
2.5% Møller Q_w^e	0.1%	0.00025
4% Q_w^p	0.3%	0.00072
0.8% e-D PVDIS	0.45%	0.00011

- e-P scattering

$$A_{PV}^{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left(\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right)\left[Q_w^P + F^p(\theta, Q^2)\right]$$

- $F^p(\theta, Q^2) \propto Q^2$ can be ignored for $Q^2 \simeq 0.03(GeV)^2$
- Large cancelation between 1st (from Z) and 2nd(from Z_s) terms

$$\frac{\delta A_{PV}^{ep}}{A_{PV}^{ep}} \sim \left[-3s_W^2 s_\epsilon^2 + 4\frac{(1-s_W^2)s_W^2 s_\epsilon^2}{(1+s_W^2 s_\epsilon^2)^2}\left(\frac{M_Z^2 c_W^2}{M_W^2}\right)^2\right]/(1-4s_W^2)$$

- $\delta A_{PV}^{ep}/A_{PV}^{ep} \sim -0.48\epsilon^2 \sim \mathcal{O}(10^{-4})$

some future low energy PV exp

- For Moller scattering, the asymmetry is proportional to $(g_L^e - g_R^e)(g_L^e + g_R^e)$.
- In low energy e-p scattering, the proton responses coherently with an isospin $+1/2 = -T_3^e$ and a charge $-Q^e$ which make proton react as a positron
- Roughly, Moller asymmetry $\propto -Q_w^p$, and always reduces the PV asymmetry from the SM prediction.
- For the proposed 2.5% and 4% accuracies for Moller scattering and Q_W^p measurements at JLab, only the $\epsilon \gtrsim 0.2 - 0.3$ can be probed.

some future low energy PV exp

- In SM the e-D scattering asymmetry is given by

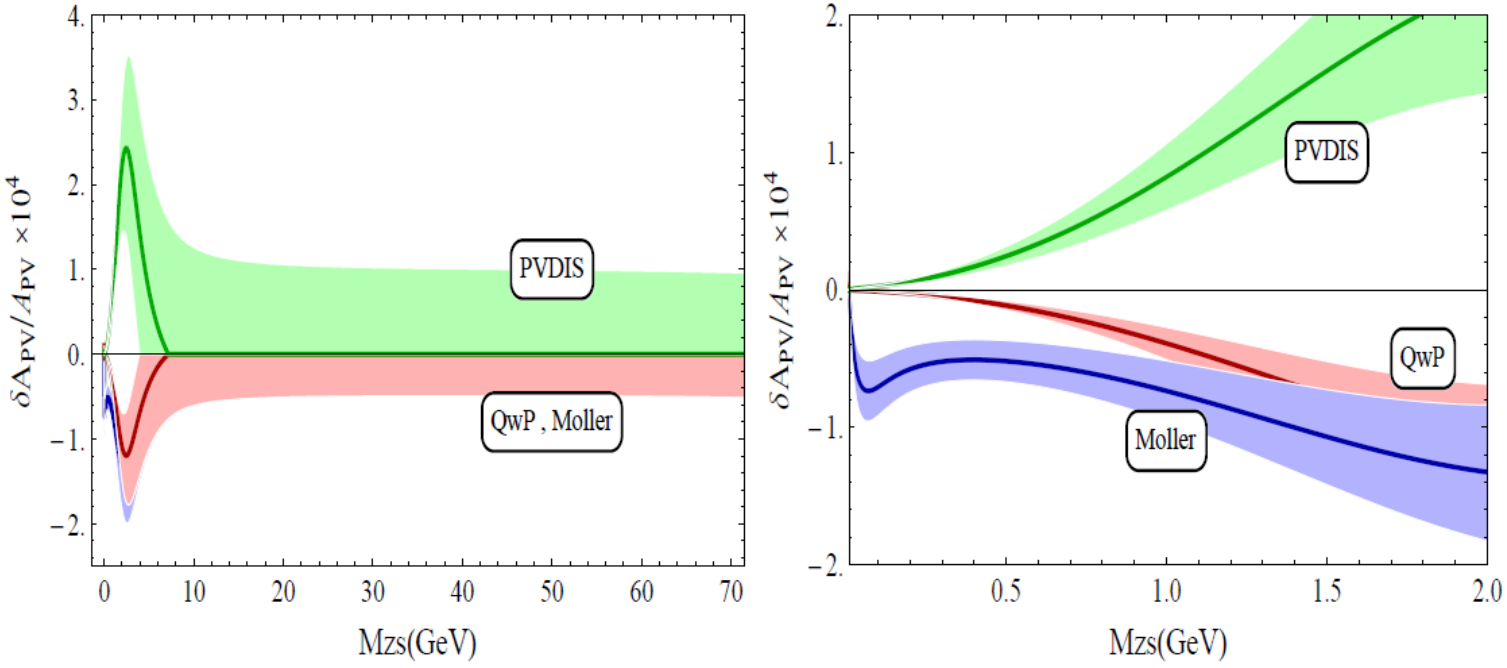
$$A_{PV}^{DIS} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Y_1 a_1 + Y_3 a_3\right]$$

$a_1 \sim 2(\sum_q Q_q C_{1q})/\sum_q Q_q^2$, $a_3 \sim 2(\sum_q Q_q C_{2q})/\sum_q Q_q^2$,

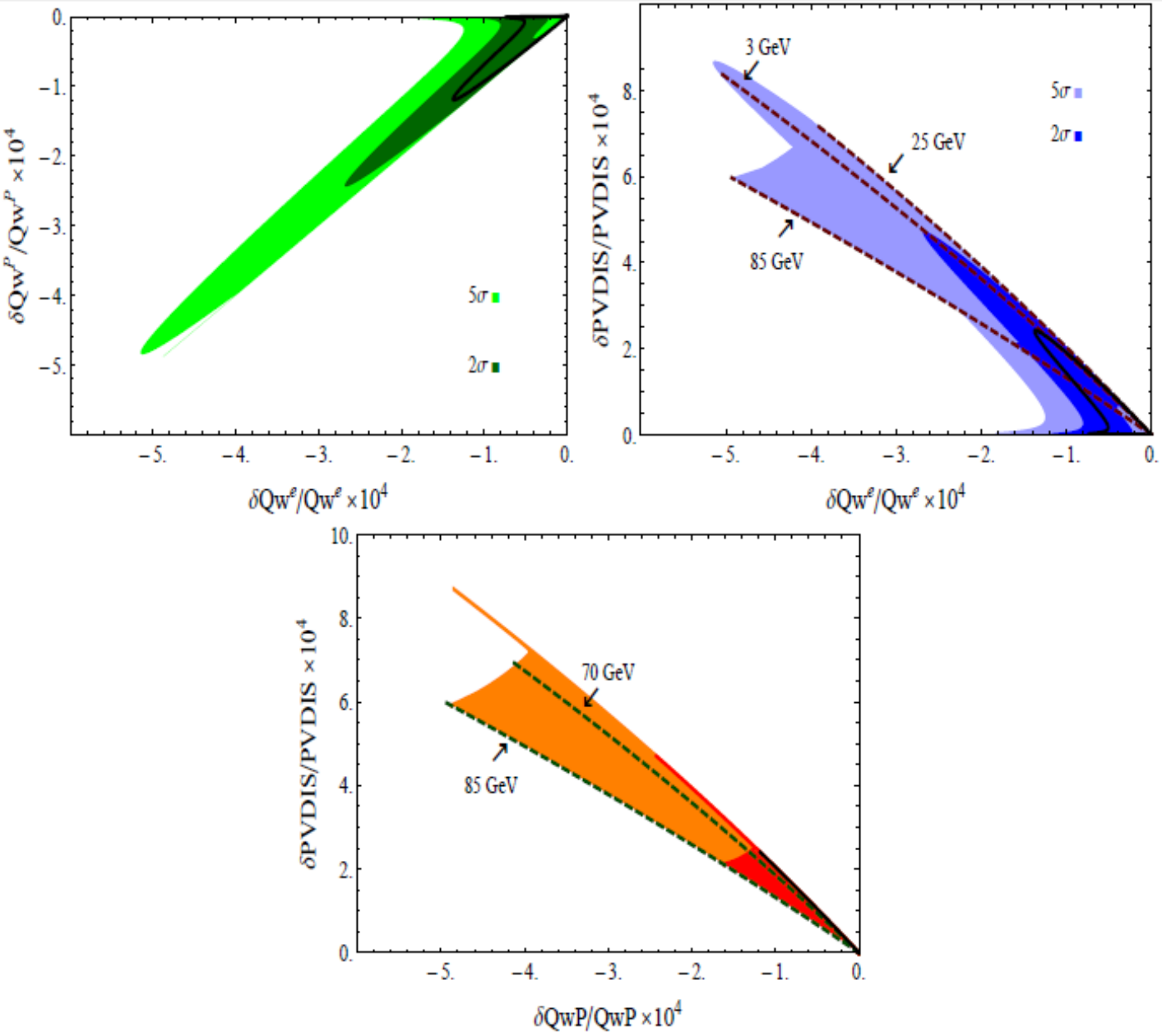
- at JLAB $Y_1 \sim 1$, $Y_3 \sim 0.84$
- $\delta A_{PV}^{PVDIS}/A_{PV}^{PVDIS} \sim$

$$\left[\left(-\frac{11}{6} - \frac{9}{2}Y_3\right) s_W^2 s_\epsilon^2 + \left(\frac{10}{3} + 6Y_3\right)\frac{(1-s_W^2)s_W^2 s_\epsilon^2}{(1+s_W^2 s_\epsilon^2)^2}\left(\frac{M_Z^2 c_W^2}{M_W^2}\right)^2\right]$$
$$\times\left[\frac{3}{2} - \frac{10}{3}s_W^2 + Y_3\left(\frac{3}{2} - 6s_W^2\right)\right]^{-1} \sim +0.748\epsilon^2$$

predictions for JLAB



Correlation for JLAB

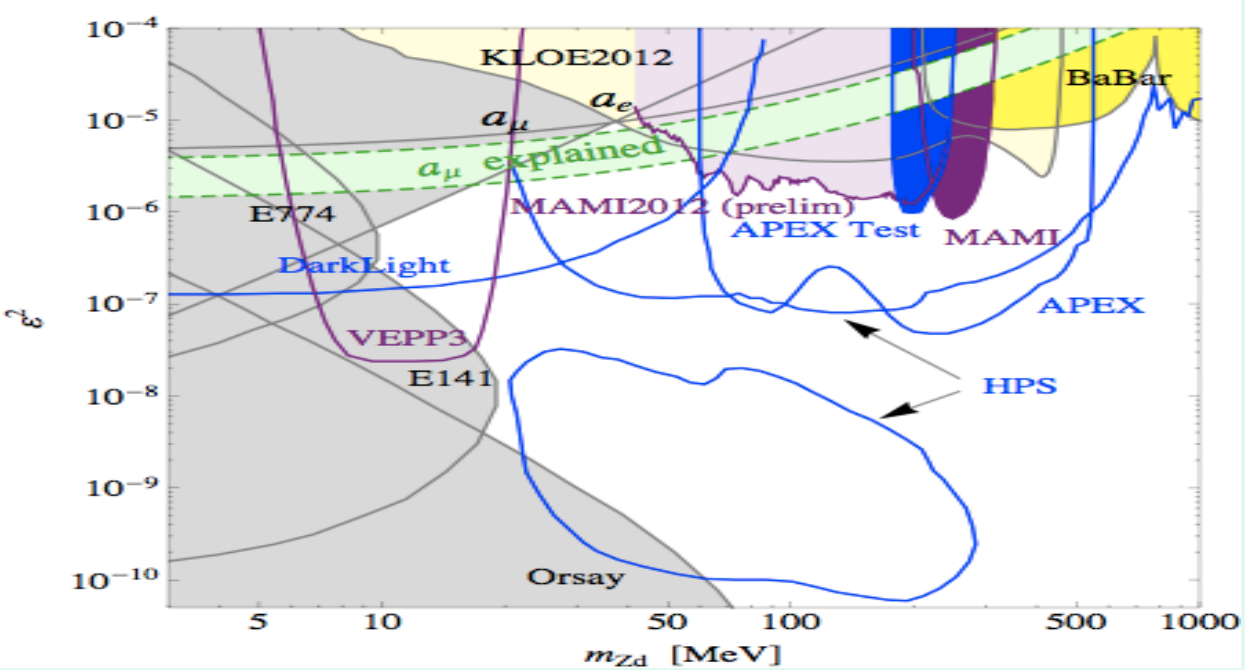


For extremely light Z_s

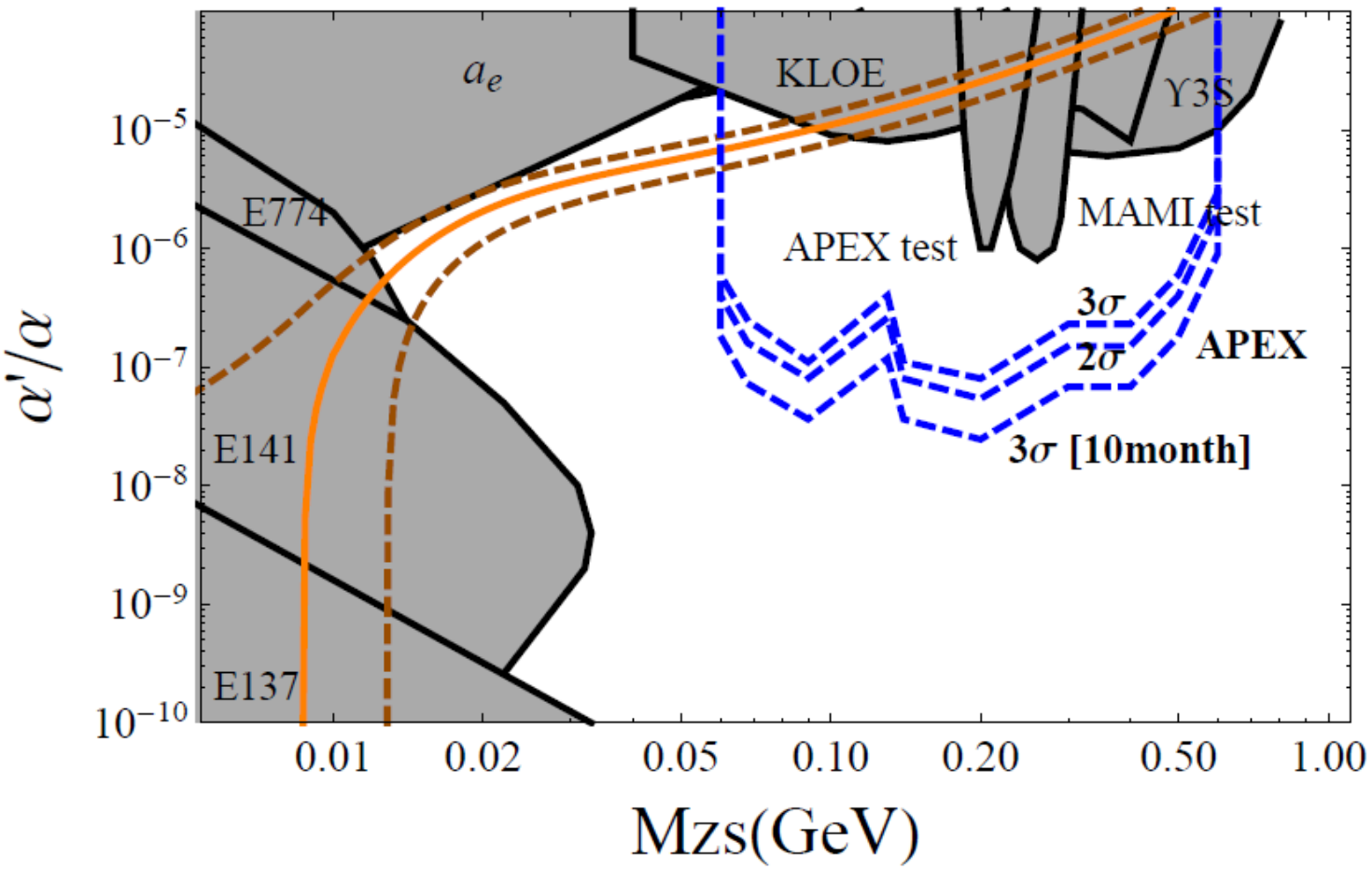
The plot is very busy. (From Prof.Marciano's MITP talk)

Current Bounds & Future Dark Photon Sensitivity

Assumes Br($Z_d \rightarrow e^+e^-$)=1 What if $Z_d \rightarrow$ missing energy?



For extremely light Z_s



Conclusion

- A minimal hidden sector with gauge portal is discussed
- shadow Z introduces new PV interaction, but becomes vector-like and photon-like when being light.
- global analysis for $M_{Z_s} < M_Z$ includes PV at Z pole, (g-2), atomic Q_W, and SLAC Moller.
- PV contribution from Z and Z_s largely cancel and make the future PV experiment very challenging (for this simplest model, but NOT for more complicated versions).
- However, the window $\sim (10 - 50)$ MeV still open for this model.