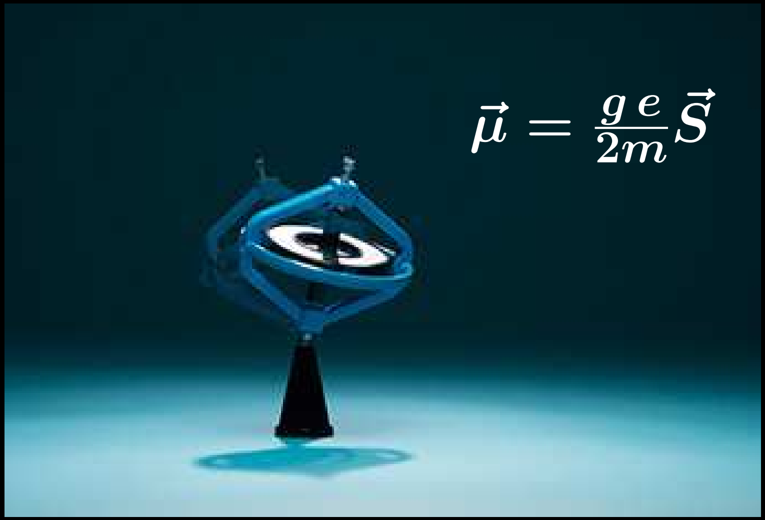
New Physics and the Muon $g-2$

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



$$\vec{\mu} = \frac{g\,e}{2m}\vec{S}$$

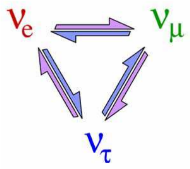
KEK-PH2018/HVP $g_\mu - 2$, February 13-16, 2018, KEK, Tsukuba, Ibaraki, Japan

The Big Picture

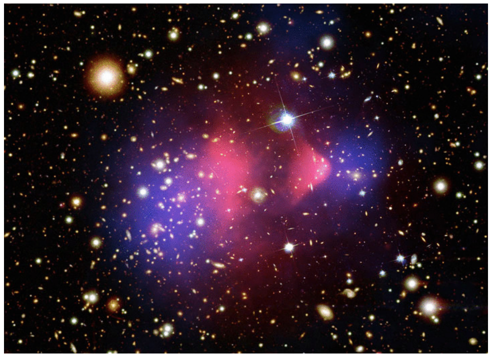
- The Standard Model (SM) a very successful theory
  - Precise description of a large set of microscopic phenomena

- However, SM *incomplete* based on firm evidence

- Neutrino masses: $m_\nu \lesssim 0.1$ eV



  - A large collection of neutrino oscillation data



- Dark matter (DM) ($\sim 27\%$)
  - So far, gravitational evidence only
  - Stable on cosmological time scales
  - Cosmological stability, feeble interactions with ordinary matter

- "Visible" matter: unknown origin ($\sim 5\%$)

- Strong case for new physics

- Yet SM appears well-insulated from new phenomena

- To decouple Beyond SM (BSM) physics:

(A) Large masses or (B) Small couplings

- Option (A): new physics above weak scale (mass $\gtrsim$ 100 GeV)
  - Perhaps associated with EWSB
  - Hierarchy: Why is $m_H \ll \bar{M}_{\rm P}$ (or other large mass scales)?
  - *E.g.* supersymmetry (SUSY), compositeness, extra dimensions, . . .
  - Probed at high energy colliders

- Option (B): possible to have low scale new states (mass $\lesssim$ 1 GeV)
  - Suppressed couplings: hard to detect, requires large statistics, precision
  - *E.g.* axions, sterile neutrinos, dark vector bosons, . . .
  - Intensity physics: fixed target, beam dump, B-facilities, neutrino oscillations, . . .

- Traditionally, BSM has been assumed to be type (A)

- Recent years: a surge of interest in BSM of type (B)
  - Often a phenomenological approach taken
  - Models are typically simple, may not have a relation to type (A)

- Lack of evidence for BSM at LHC so far
  - Perhaps hierarchy (“natural” m_H) not a straightforward BSM guide

- One long-standing $\sim 3.5\sigma$ deviation from SM: $g_\mu - 2$

$$\boxed{\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268\,\overbrace{(63)}^{\text{Ex.}}\,\overbrace{(43)}^{\text{Th.}} \times 10^{-11}}$$ (PDG)

  - We will briefly mention some type (A) resolutions
  - The rest of the talk a survey of some type (B) models

Type (A) Models

- Over the years, many possibilities have been considered:

Supersymmetry, large extra dimensions, warped extra dimensions, . . .

- Motivated mainly from hierarchy

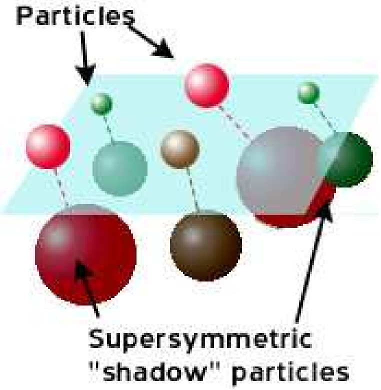
- Here we will only cover some key ideas and focus on the most typical predictions for $g_\mu - 2$

- One often finds that the simplest explanations do not work, as LHC searches push these models well above the weak scale

- No completely general statement can be made, but as naturalness gets less compelling, so do these solutions

MSSM:

- SM super partners cancel quadratic Higgs mass quantum corrections
- Typical dominant one-loop process mediated by (muon sneutrino, chargino)
- Many variations possible
- For typical super partner mass $\tilde{M}$, $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$

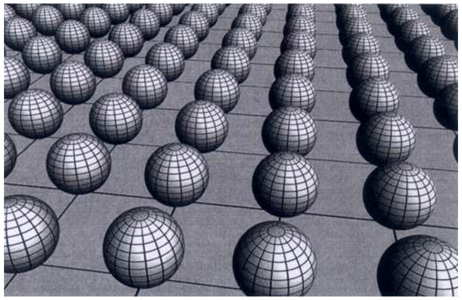


$$\delta a_\mu \sim \frac{g^2}{8\pi^2}\frac{m_\mu^2}{\tilde{M}^2}\tan\beta \;\Rightarrow\; \text{Need } \tilde{M} \lesssim 1 \text{ TeV and } \tan\beta \gg 1$$

- Large parts of parameter space disfavored by LHC null results

E.g., Hagiwara, Ma, Mukhopadhyay, 1706.09313

Large extra dimensions: Arkani-Hamed, Dimopoulos, Dvali, 1998



- Quantum gravity at $M_F \gtrsim 1$ TeV scale
- $n \geq 2$ large ($\gg 1/\text{TeV}$) extra dimensions
- 4d gravity: $\bar{M}_\text{P}^2 \sim M_F^{2+n} V_n$
- Large number of light graviton Kaluza Klein (KK) states
- For $2 \leq n \leq 6$: Graesser, 1999

$$\delta a_\mu \sim (2-3) \times 10^{-9} \left(\frac{\text{TeV}}{M_F}\right)^2$$

(Cutoff sensitive estimate)

- LHC: $M_F \gg 1$ TeV and hence this solution does not appear viable

Warped 5D Randall-Sundrum models:

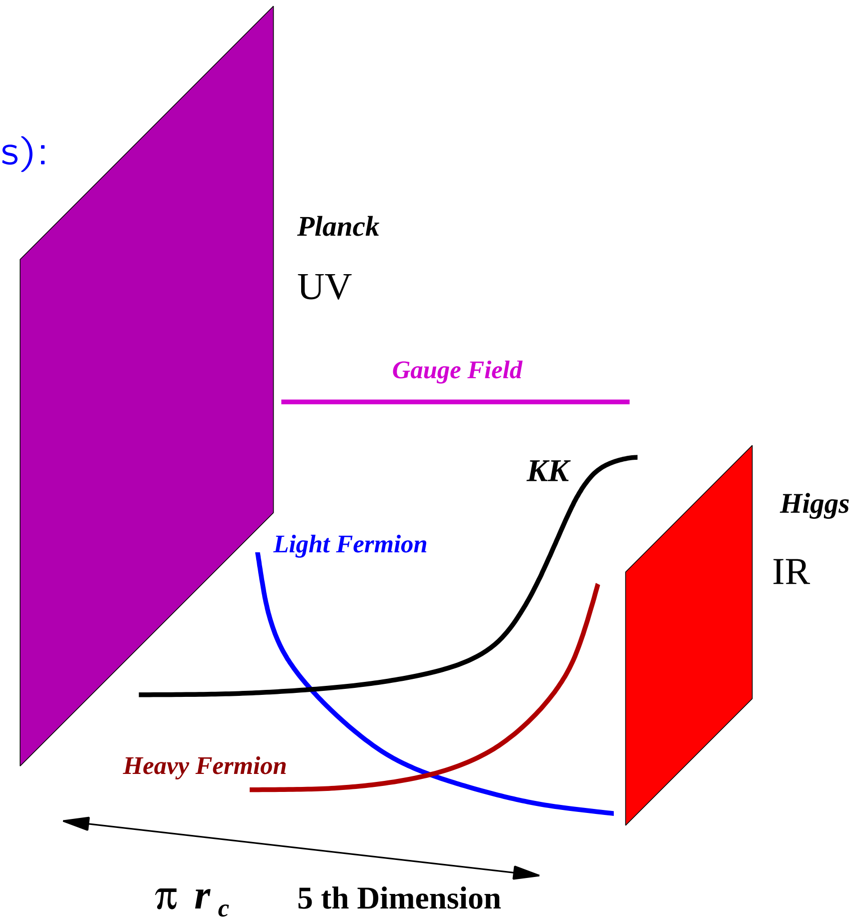
Randall, Sundrum, 1999

- Based on a slice of AdS_5, bounded by 4D Minkowski boundary (branes)
- Planck (UV) and TeV (IR) boundaries
- Hierarchy addressed by gravitational redshift along 5^{th} D
- TeV $\sim e^{-k\pi r_c}k$ with $k \sim \bar{M}_{\mathrm{P}}$ the 5D curvature scale, $\pi r_c \sim 30/k$ size of 5D interval
- The bulk can have SM (and other) fields
- KK gauge modes $m_{\mathrm{KK}} \approx 2.5\, k e^{-k\pi r_c}$:

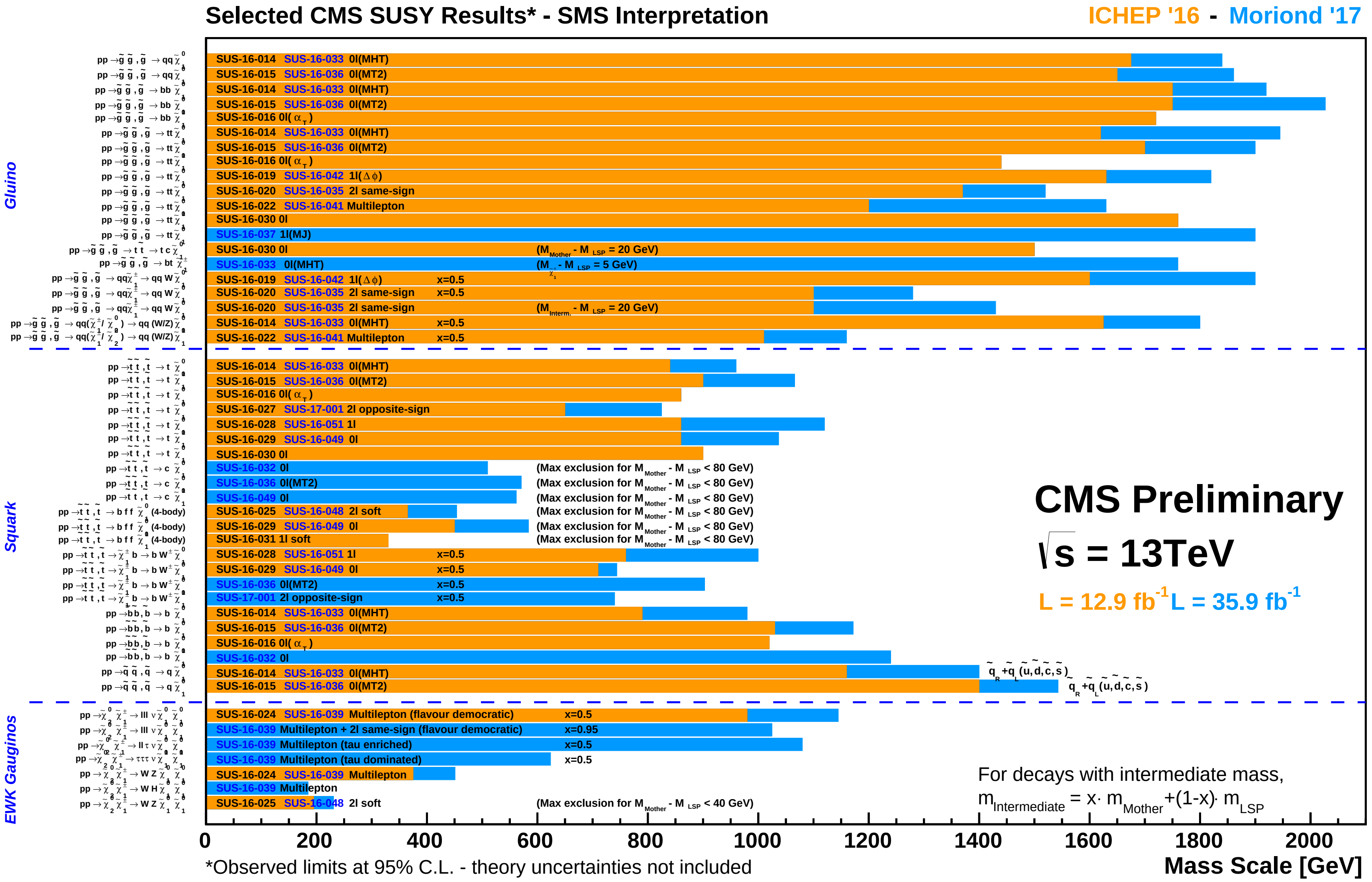
$$\delta a_\mu \sim (9 - 27) \times 10^{-11} \left(\frac{2.5 \ \mathrm{TeV}}{m_{\mathrm{KK}}}\right)^2$$

Latest detailed treatment (corrections to earlier works):
Beneke, Dey, Rohrwild, 2012;
Beneke, Moch, Rohrwild, 2014

- Requires $m_{\mathrm{KK}} \lesssim 1$ TeV, typically ruled out



Selected CMS SUSY Results* - SMS Interpretation



*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

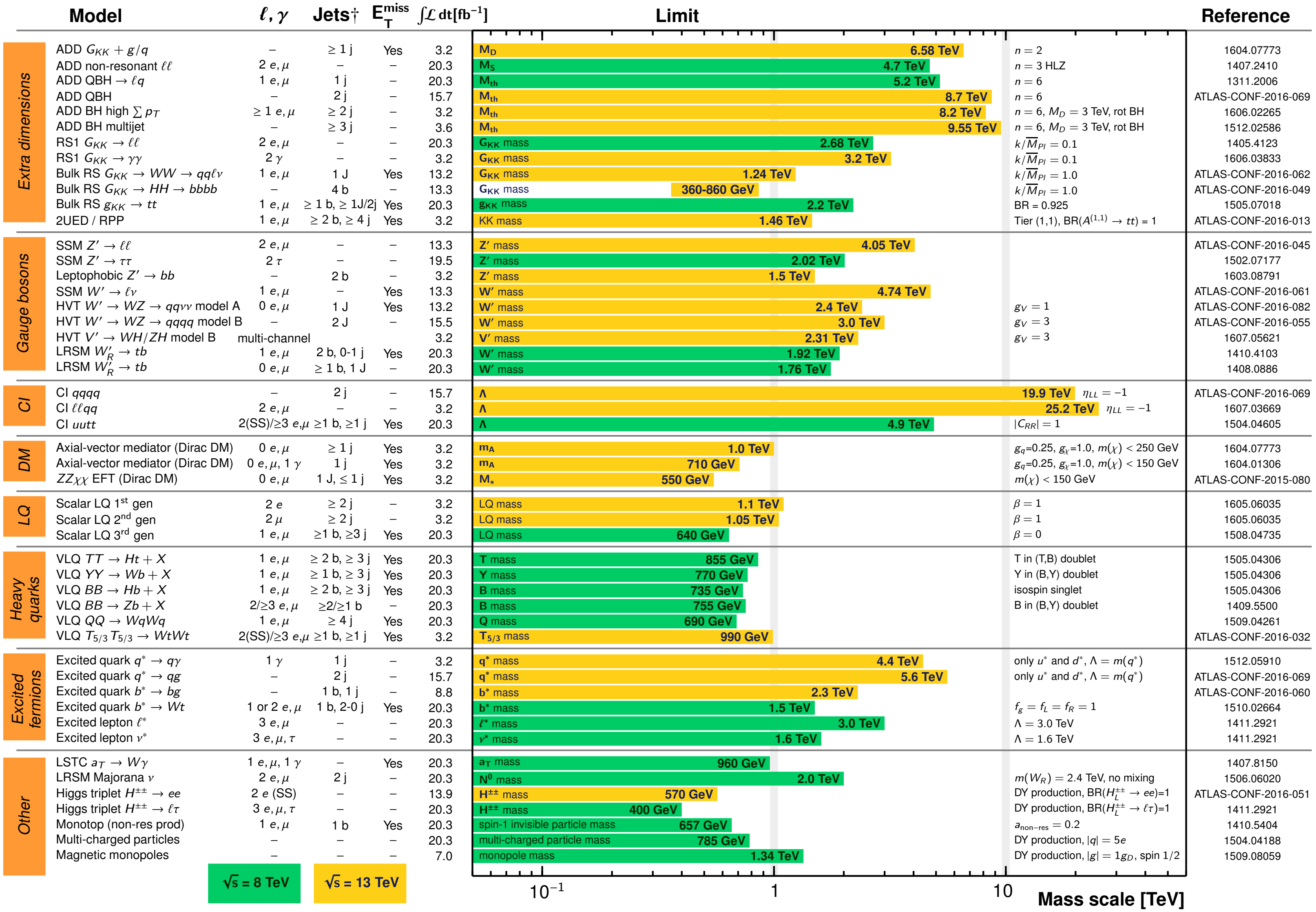
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (3.2 - 20.3) fb^{-1}

$\sqrt{s}$ = 8, 13 TeV



	Model	**ℓ,γ**	**Jets†**	**E_T^{miss}**	**$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$**	**Limit**			**Reference**
Extra dimensions	ADD $G_{KK}+g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D	6.58 TeV	$n=2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e,μ	–	–	20.3	🟩 M_S	4.7 TeV	$n=3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e,μ	1 j	–	20.3	🟩 M_{th}	5.2 TeV	$n=6$	1311.2006
	ADD QBH	–	2 j	–	15.7	🟨 M_{th}	8.7 TeV	$n=6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\rightarrow \ell\ell$	2 e,μ	–	–	20.3	🟩 G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl}=0.1$	1405.4123
	RS1 $G_{KK}\rightarrow \gamma\gamma$	2 γ	–	–	3.2	🟨 G_{KK} mass	3.2 TeV	$k/\overline{M}_{Pl}=0.1$	1606.03833
	Bulk RS $G_{KK}\rightarrow WW\rightarrow qq\ell\nu$	1 e,μ	1 J	Yes	13.2	🟨 G_{KK} mass	1.24 TeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK}\rightarrow HH\rightarrow bbbb$	–	4 b	–	13.3	🟨 G_{KK} mass	360-860 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK}\rightarrow tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	🟩 g_{KK} mass	2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass	1.46 TeV	Tier (1,1), BR($A^{(1,1)}\rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z'\rightarrow \ell\ell$	2 e,μ	–	–	13.3	🟨 Z' mass	4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z'\rightarrow \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass	2.02 TeV		1502.07177
	Leptophobic $Z'\rightarrow bb$	–	2 b	–	3.2	🟨 Z' mass	1.5 TeV		1603.08791
	SSM $W'\rightarrow \ell\nu$	1 e,μ	–	Yes	13.3	🟨 W' mass	4.74 TeV		ATLAS-CONF-2016-061
	HVT $W'\rightarrow WZ\rightarrow qq\nu\nu$ model A	0 e,μ	1 J	Yes	13.2	🟨 W' mass	2.4 TeV	$g_V=1$	ATLAS-CONF-2016-082
	HVT $W'\rightarrow WZ\rightarrow qqqq$ model B	–	2 J	–	15.5	🟨 W' mass	3.0 TeV	$g_V=3$	ATLAS-CONF-2016-055
	HVT $V'\rightarrow WH/ZH$ model B	multi-channel			3.2	🟨 V' mass	2.31 TeV	$g_V=3$	1607.05621
	LRSM $W'_R\rightarrow tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass	1.92 TeV		1410.4103
	LRSM $W'_R\rightarrow tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass	1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	🟨 Λ	19.9 TeV	$\eta_{LL}=-1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e,μ	–	–	3.2	🟨 Λ	25.2 TeV	$\eta_{LL}=-1$	1607.03669
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ	4.9 TeV	$\lvert C_{RR}\rvert=1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e,μ	≥ 1 j	Yes	3.2	🟨 m_A	1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 250 GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e,μ, 1 γ	1 j	Yes	3.2	🟨 m_A	710 GeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 150 GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	550 GeV	$m(\chi)$ < 150 GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass	1.1 TeV	$\beta=1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass	1.05 TeV	$\beta=1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass	640 GeV	$\beta=0$	1508.04735
Heavy quarks	VLQ $TT\rightarrow Ht+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass	855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY\rightarrow Wb+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass	770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB\rightarrow Hb+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass	735 GeV	isospin singlet	1505.04306
	VLQ $BB\rightarrow Zb+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass	755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ\rightarrow WqWq$	1 e,μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
	VLQ $T_{5/3}T_{5/3}\rightarrow WtWt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	3.2	🟨 $T_{5/3}$ mass	990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^*\rightarrow q\gamma$	1 γ	1 j	–	3.2	🟨 q^* mass	4.4 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1512.05910
	Excited quark $q^*\rightarrow qg$	–	2 j	–	15.7	🟨 q^* mass	5.6 TeV	only u^* and d^*, $\Lambda=m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^*\rightarrow bg$	–	1 b, 1 j	–	8.8	🟨 b^* mass	2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^*\rightarrow Wt$	1 or 2 e,μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass	1.5 TeV	$f_g=f_L=f_R=1$	1510.02664
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	LSTC $a_T\rightarrow W\gamma$	1 e,μ, 1 γ	–	Yes	20.3	🟩 a_T mass	960 GeV		1407.8150
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	🟩 N^0 mass	2.0 TeV	$m(W_R)=2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm}\rightarrow ee$	2 e (SS)	–	–	13.9	🟨 $H^{\pm\pm}$ mass	570 GeV	DY production, BR($H_L^{\pm\pm}\rightarrow ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm}\rightarrow \ell\tau$	3 e,μ,τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, BR($H_L^{\pm\pm}\rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass	657 GeV	$a_{\mathrm{non-res}}=0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert=5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass	1.34 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

**Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

Type (B) Models

- A revival of interest in the past several years

- Models mostly phenomenological, addressing possible anomalies
- Astrophysical hints for DM, $g_\mu - 2$, . . .

- Models largely independent of hierarchy
- Low scale ($\lesssim$ 1 GeV) "dark" phenomena

- We will go over some of the main ideas and their status

Dark Forces

- Assume a "dark" sector $U(1)_d$

- Minimal extension that captures key physics
- Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- Interaction with SM: dim-4 operator (portal) via *mixing*

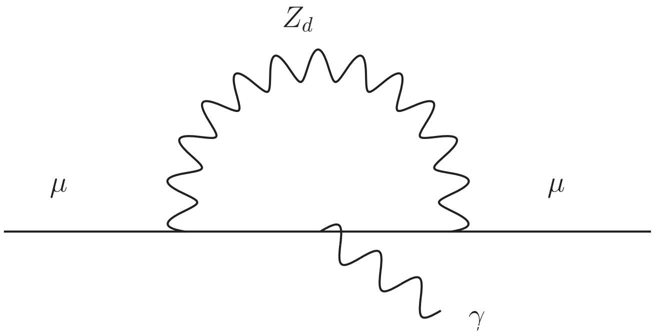
- $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts

- DM interpretation of astrophysical data

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- Explaining $\sim 3.5\sigma$ $g_\mu - 2$ anomaly

Fayet, 2007 (direct coupling)
Pospelov, 2008 (kinetic mixing)



- Model building (Asymmetric DM models,. . .)

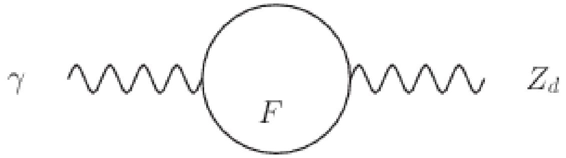
Dark Photon

- Kinetic mixing: Z_d of $U(1)_d$ and B of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_\mathbf{W}}\mathbf{B}_{\mu\nu}\mathbf{Z}_\mathbf{d}^{\mu\nu} - \frac{1}{4}\mathbf{Z}_{\mathbf{d}\mu\nu}\mathbf{Z}_\mathbf{d}^{\mu\nu}$$

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$

  - May be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$



- Remove cross term, via field redefinition
  - $B_\mu \to B_\mu + \frac{\varepsilon}{\cos\theta_W} Z_{d\mu}$; Z-Z_d mass matrix digonalization

$\Rightarrow$ Z_d couples to EM current: $\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$ $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

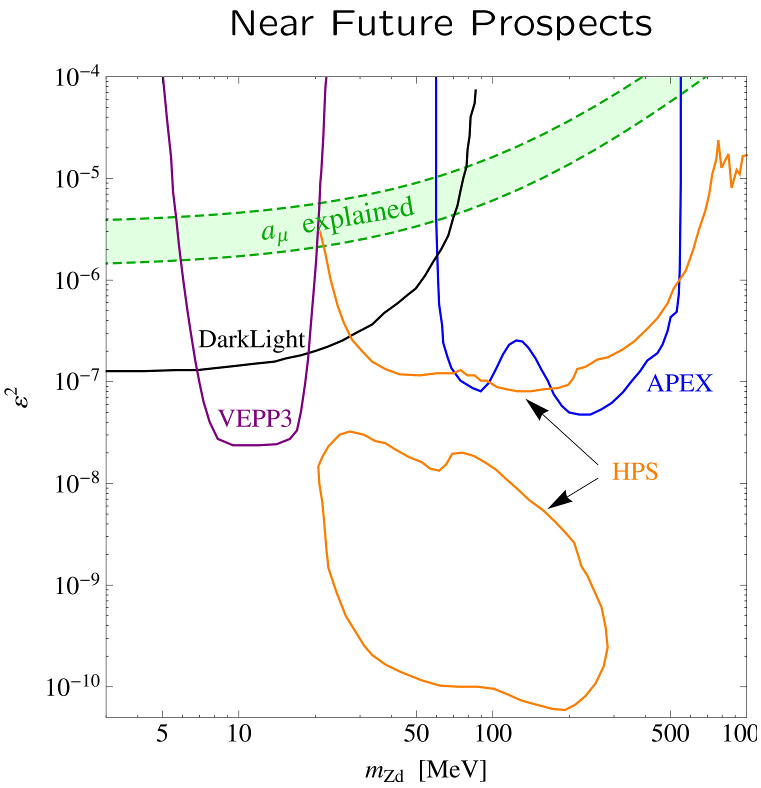
  - Like a photon, but ε-suppressed couplings: "dark" photon
  - Neutral current coupling suppressed by $m^2_{Z_d}/m^2_Z \ll 1$

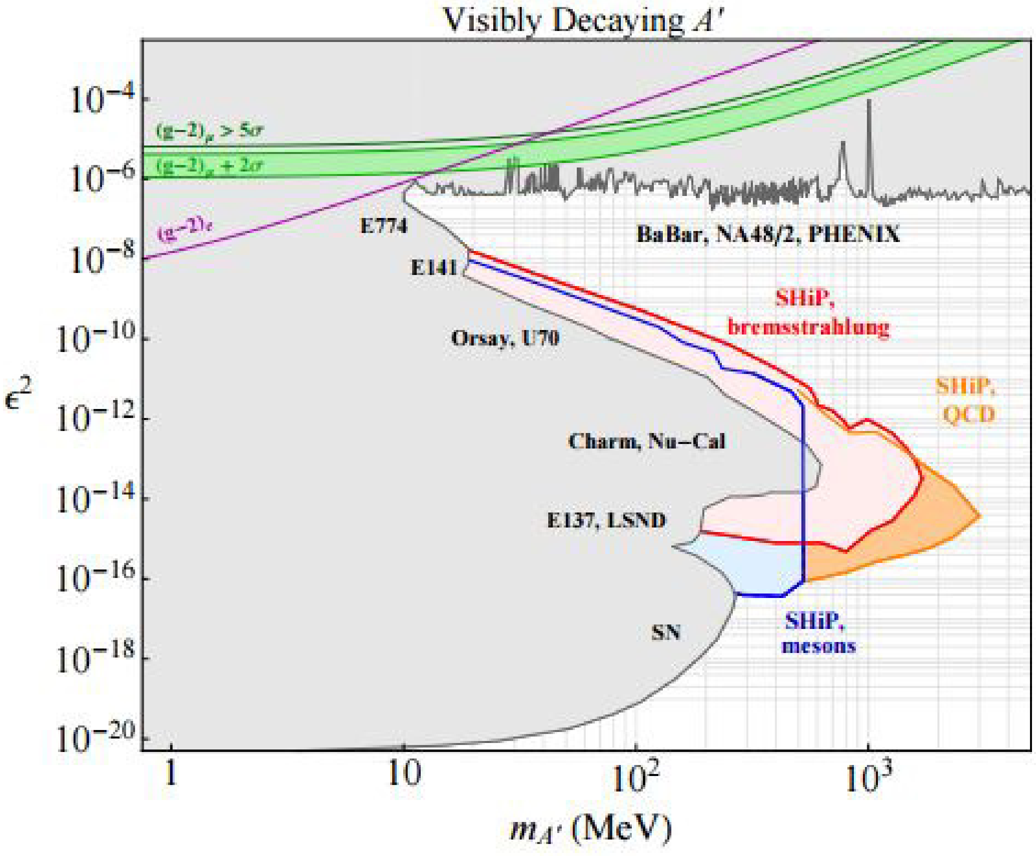
- Add Z-Z_d mass mixing → Z_d as "dark" Z HD, Marciano, Lee, 2012
  - "Dark" parity violation, rare meson and Higgs decays, . . .

- Active experimental program to search for dark photon

Pioneering work by Bjorken, Essig, Schuster, Toro, 2009

- An early experimental target: $g_\mu - 2$ parameter space



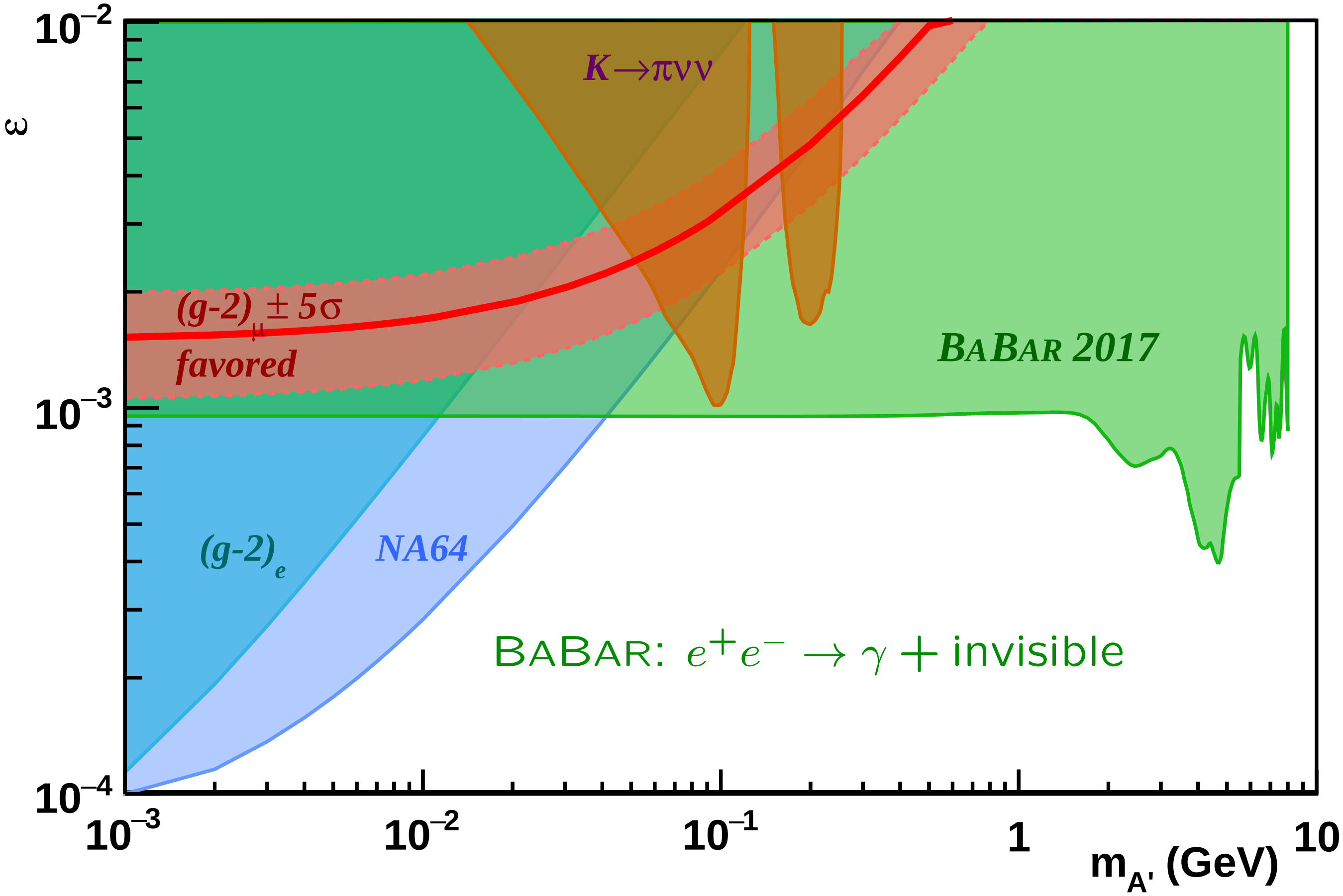


S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

GeV-scale visibly decaying Z_d basically excluded as $g_\mu - 2$ explanation

“Invisible” Dark Photon

- $\exists$ dark X with $m_X < m_{Z_d}/2$ and $Q_d g_d \gg e\varepsilon \Rightarrow \mathrm{Br}(Z_d \to X\bar{X}) \simeq 1$



90% CL bound from BaBar Collaboration, arXiv:1702.03327 [hep-ex]

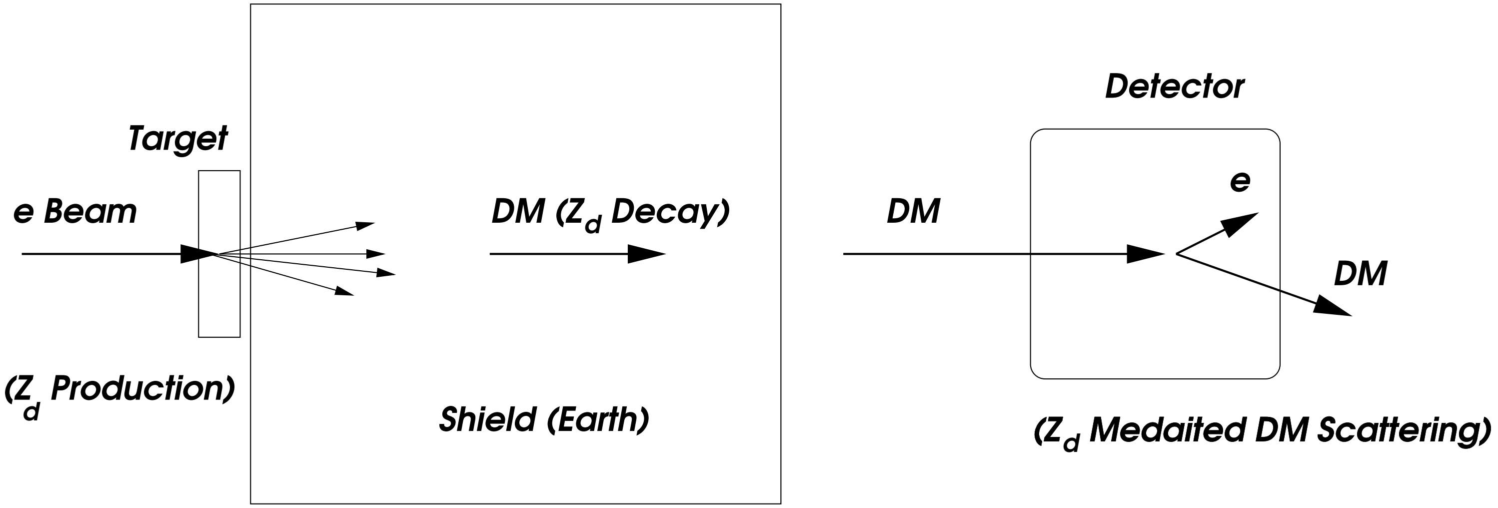
GeV-scale “invisible” dark photon $g_\mu - 2$ solution ruled out

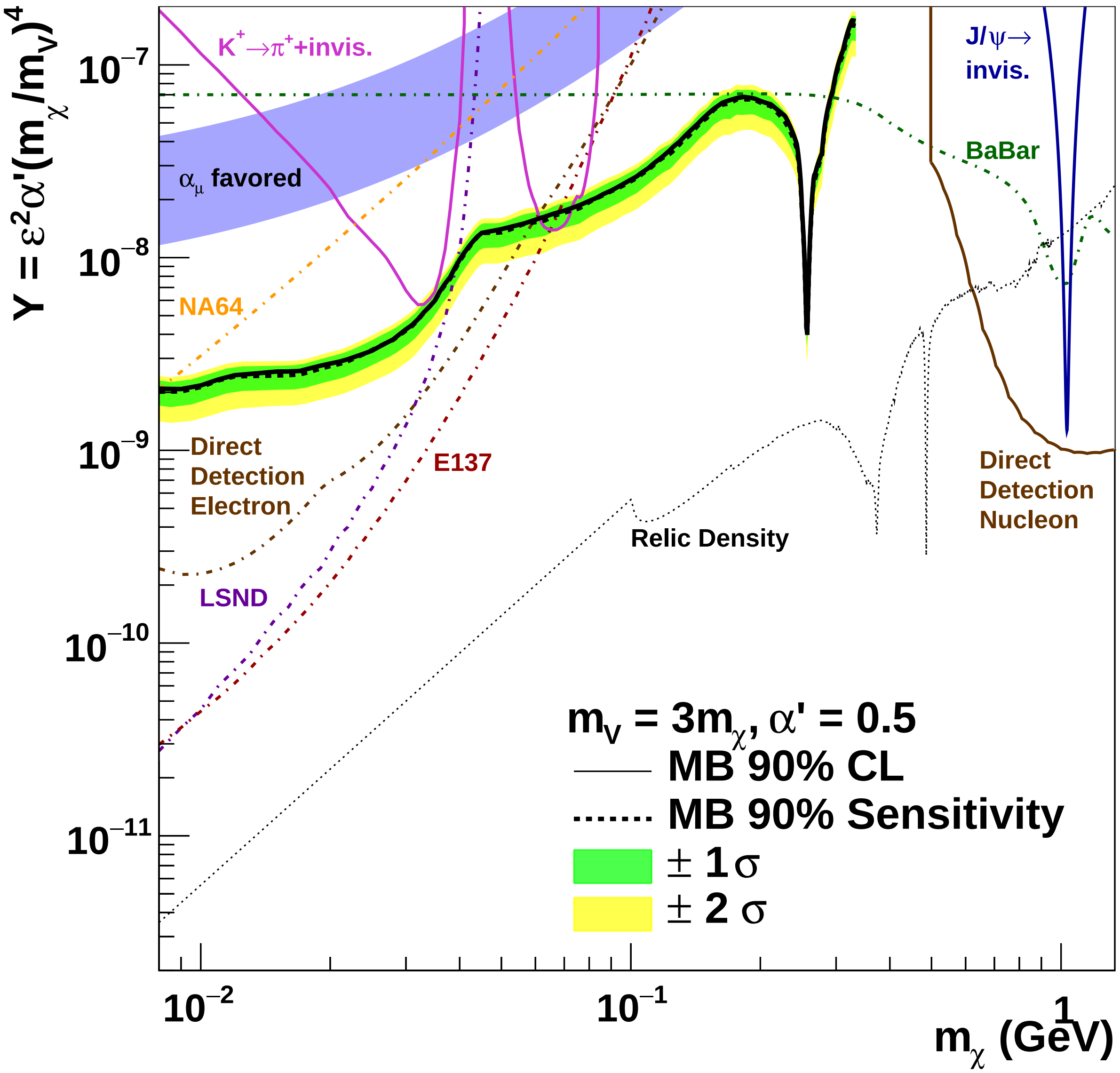
Invisible Z_d and DM Production

- Possible production and detection of *DM beams* in experiments

- p or e on fixed target $\Rightarrow$ production of boosted Z_d (meson decays, bremsstrahlung,. . .)
- Z_d beam decays into DM which can be detected via Z_d exchange
- Event rate depends on $\alpha_d \equiv g_d^2/(4\pi)$ and ε^2

Batell, Pospelov, Ritz, 2009 (p beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (e beam dump)





From arXiv:1702.02688 [hep-ex] (MiniBooNE Collaboration)

“Dark Matter Search in a Proton Beam Dump with MiniBooNE”

- Possible loop hole: “semi-visible” dark photon decay:
- $A' \to \chi_1 \chi_2$ with $\chi_2 \to \chi_1 \, e^+ e^-, \ldots$ Izaguirre, Mohlabeng, work in progress
- May still be relevant to $g_\mu - 2$

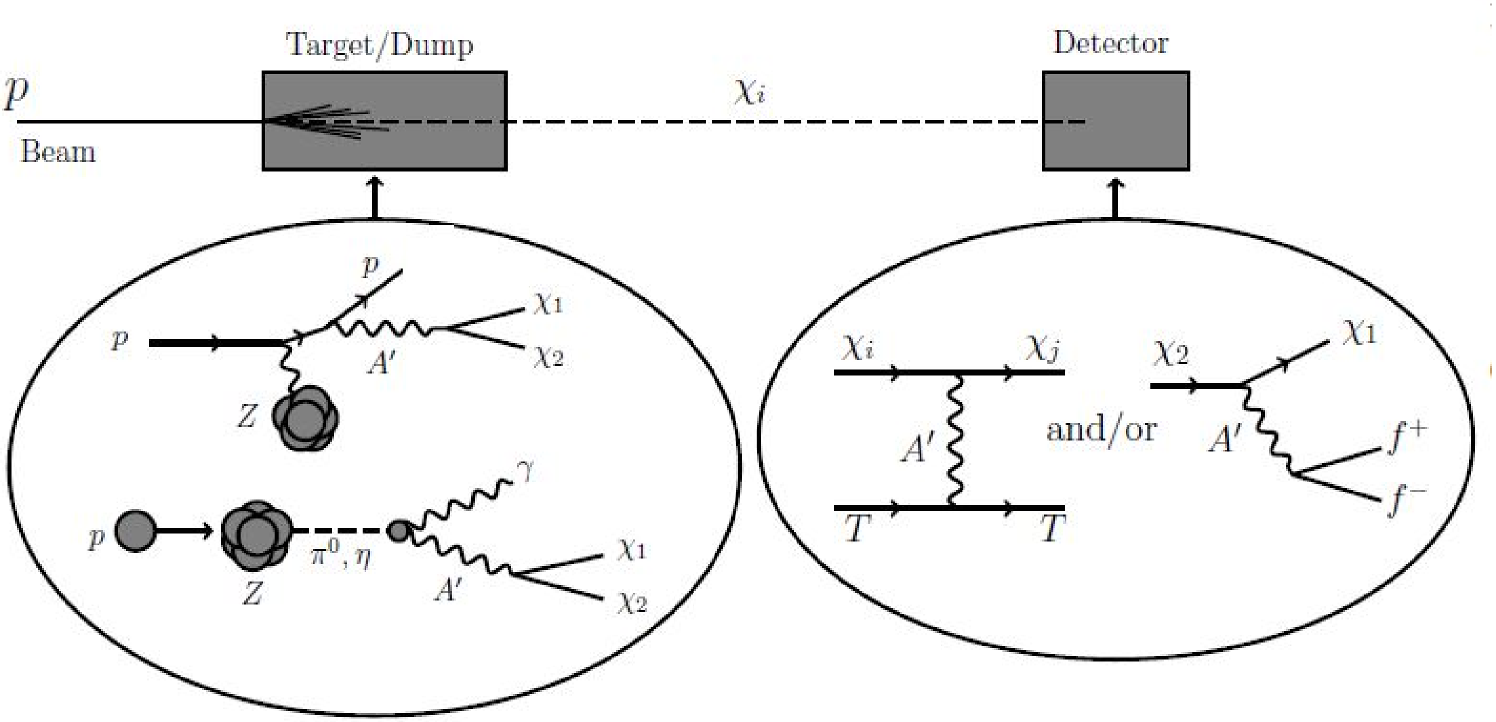


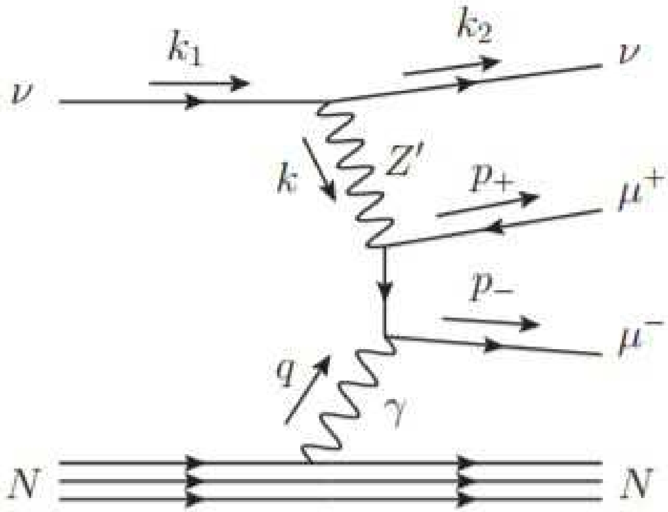
Figure: courtesy of E. Izaguirre

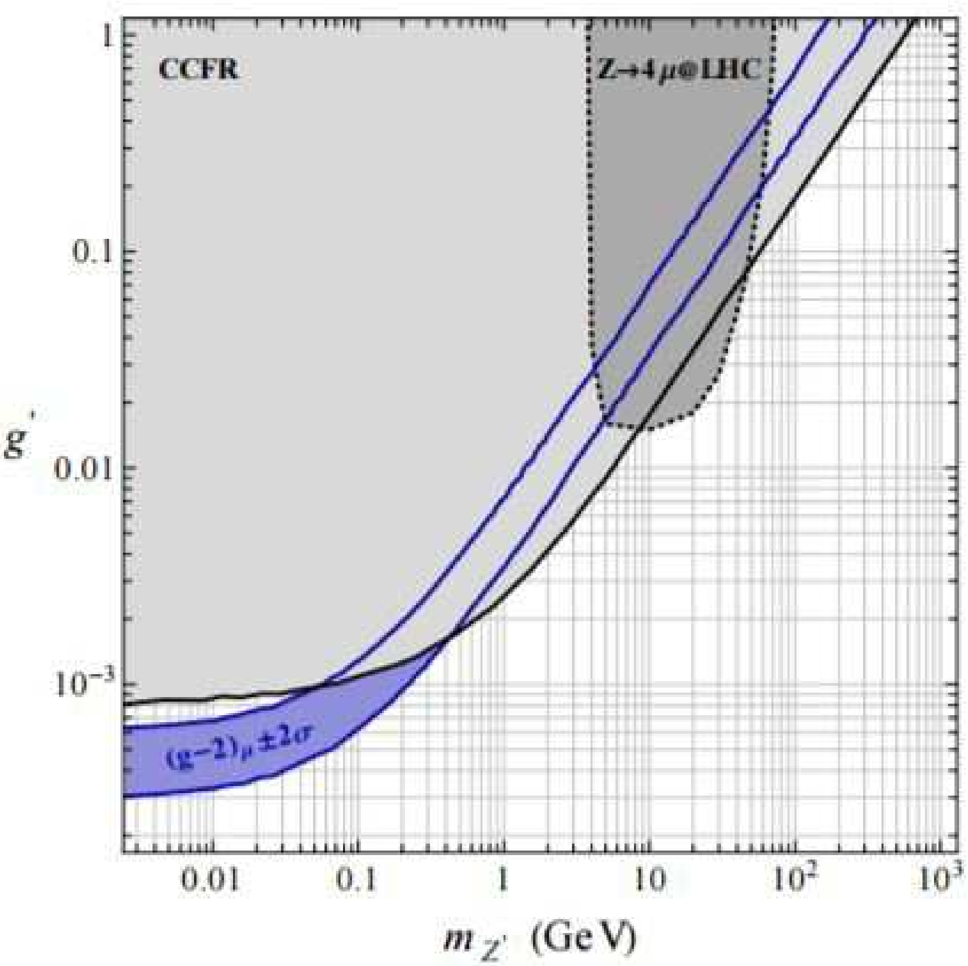
Some Alternative Possibilities for $g_\mu - 2$

- Gauged $L_\mu - L_\tau$: anomaly free

Altmannshofer, Gori, Pospelov, Yavin, 1403.1269, 1406.2332

- Constrained by “trident processes” for low vector masses



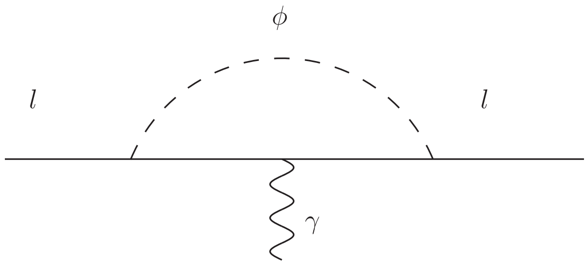


Figures from 1406.2332

- Moments from a Dark Higgs

Chen, HD, Marciano, Zhang, 2015

- Consider a GeV scale "dark" Higgs ϕ as main source of $g_\mu - 2$



- Potentially associated with $U(1)_d$ breaking
- Effective coupling of ϕ with leptons:

$$\mathcal{L}_{\phi\ell\ell} = -\phi\bar{\ell}\left(\lambda_S^\ell + i\lambda_P^\ell\gamma_5\right)\ell$$

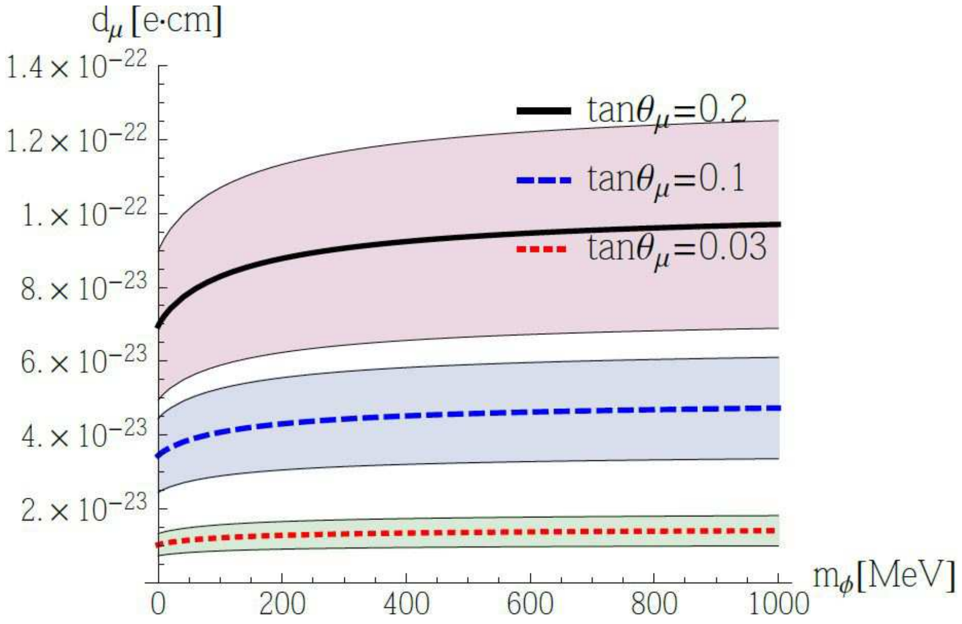
- $\ell = e, \mu, \tau$, and λ_S^ℓ (λ_P^ℓ) CP-even (odd) coupling See also Geng and Ng, 1989

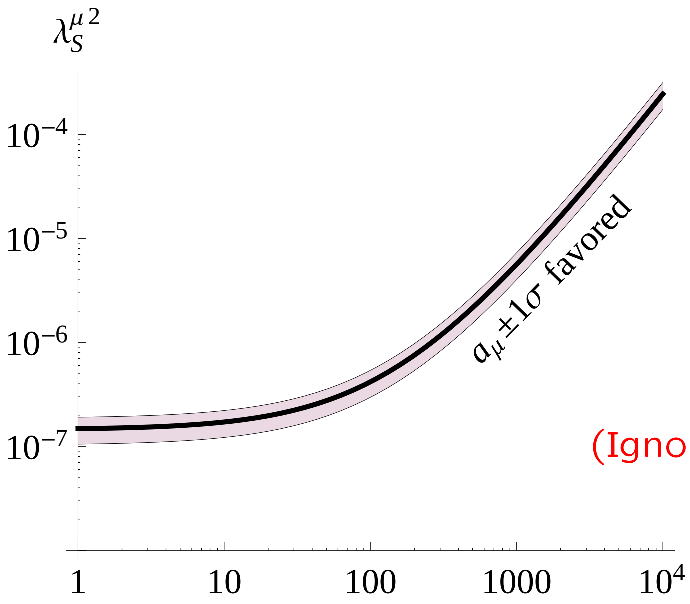
- Induced by heavy vector-like fermions (integrated out at $E \sim m_\mu$)

[Alternate model: ϕ-Higgs mixing (leptonic 2HDM)

Batell, Lange, McKeen, Pospelov, Ritz, 1606.04943]

μ-EDM, assuming $a_\mu \pm 1\sigma$; $\tan\theta_\ell = \lambda_P^\ell/\lambda_S^\ell$





(Ignoring λ_P^ℓ)

Various experimental implications:

- Direct probes: bump hunting in μ decay and capture, K decay including a μ
- Potentially observable muon EDM $\lesssim 10^{-22}$ e cm Semertzidis et al., 2000, 2003
- Current bound $|d_\mu| < 1.8 \times 10^{-19}$ $e \cdot$cm Muon (g-2) Collaboration, 2008
- Possible lepton flavor violating decays, deviation in BR$(H \to \mu^+\mu^-)_{\text{SM}}$

- Axion-Like Particles Marciano, Masiero, Paradisi, Passera, 1607.01022
- Pseudo-scalar a: $\mathcal{L}_a = \frac{1}{4} g_{a\gamma\gamma} a\, F_{\mu\nu} \tilde{F}^{\mu\nu} + i y_{al} a\, \bar{l} \gamma_5 l$

$$[\mathcal{L}_s\text{: } (\tilde{F}, g_{a\gamma\gamma}, i y_{al}) \to (F, g_{s\gamma\gamma}, y_{sl})]$$

- “Barr-Zee” diagram (B) or LBL (C):

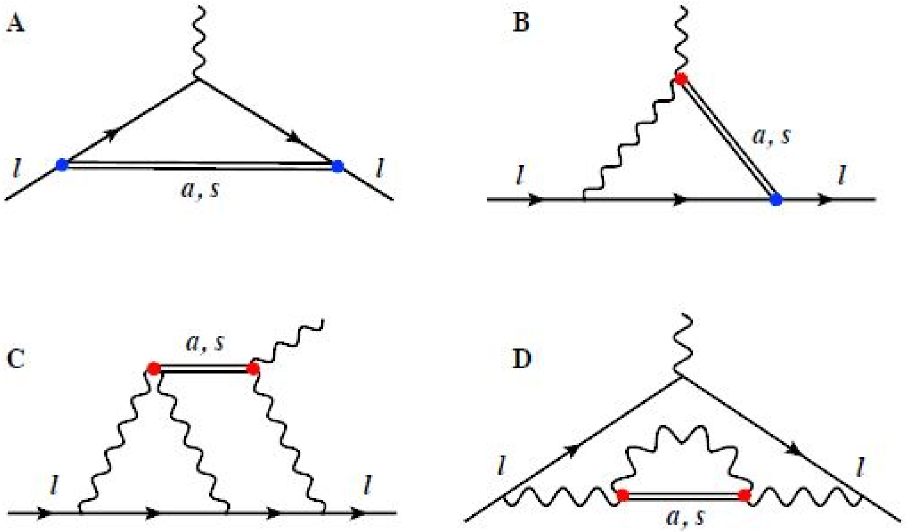
$$a_l^{\text{BZ},a,s} \propto g_{a\gamma\gamma} y_{al} \quad ; \quad a_l^{\text{LBL},a} \propto -a_l^{\text{LBL},s} \propto g_{a\gamma\gamma}^2$$

- $g_\mu - 2$: $y_{al} g_{a\gamma\gamma} > 0$; $g_{a\gamma\gamma} \sim 10^{-(2-4)}$ GeV^{-1}
- $g_{a\gamma\gamma}$ large; can be experimentally allowed

See Bauer, Neubert, Thammm, 1708.00443, for a detailed discussion of constraints

- May require non-trivial model building Marciano, Masiero, Paradisi, Passera, 2016

- VP contribution (D) small



Figures from 1607.01022

Concluding Remarks

- Currently, the long-standing $\sim 3.5\sigma$ deviation of $g_\mu - 2$ one of the most significant potential hints for new physics

- The new E989 experiment at Fermilab underway to settle the status of this anomaly

- A future JPARC experiment will be a valuable confirmation, given its very different experimental approach

- Models with new physics both around weak scale and $\lesssim m_\mu$ have been invoked to address this possible signal of new phenomena

- High scale models (Type A), usually extension of the SM, currently being probed and constrained at the LHC

- Low scale models (Type B) typically more minimal and often invoke a sequestered dark sector with feeble couplings to the SM

- Type B models have been the subject of intense experimental and phenomenological investigations and have been significantly constrained

- Special cases or parameter choices in both Type A and Type B classes could still address the $g_\mu - 2$ deviation

- Overall, it appears that if the anomaly is due to new physics, its character is less generic than some of the typical models accommodate

- Good news: both theory and experiment are moving towards a more decisive conclusion on $g_\mu - 2$ over the next few years