Light New Physics in Precision Lepton Experiments

Martin Bauer

Liverpool, May 3rd 2017

Exciting Times

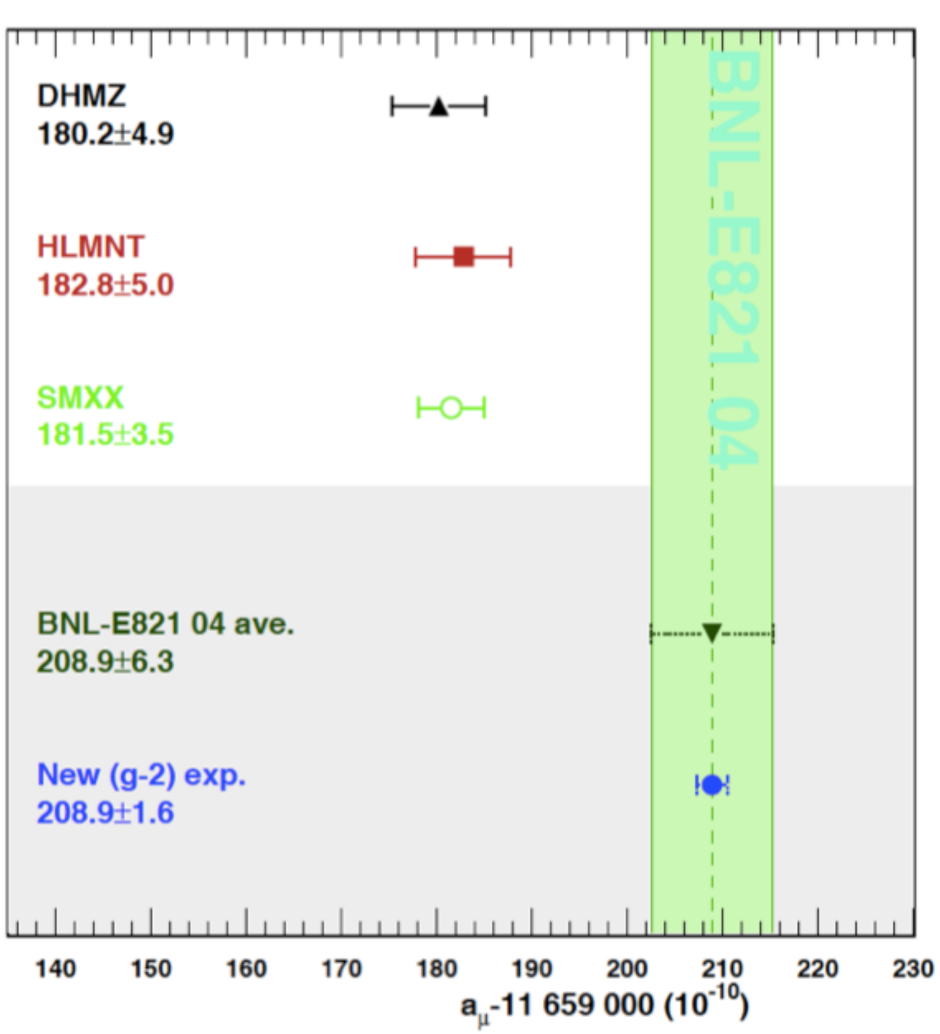
There are several anomalies possibly hinting at physics beyond the SM

- The anomalous magnetic moment of the muon $(g-2)_\mu$

Exciting Times

The anomalous magnetic moment of the muon

$$a_\mu = (g-2)_\mu/2$$

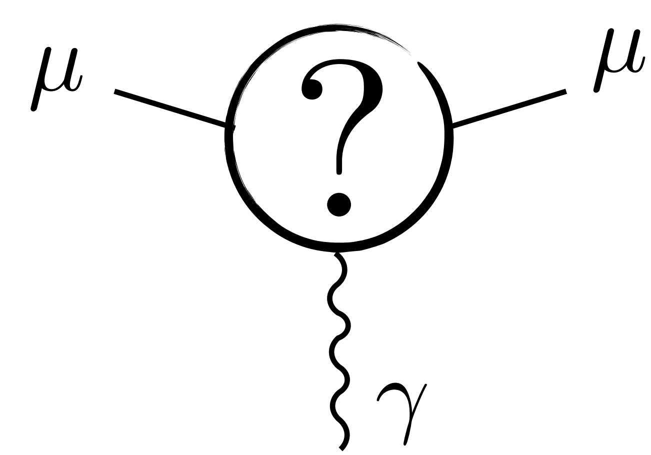


[Gohn 1506.00608]

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49) \cdot 10^{-11}$$

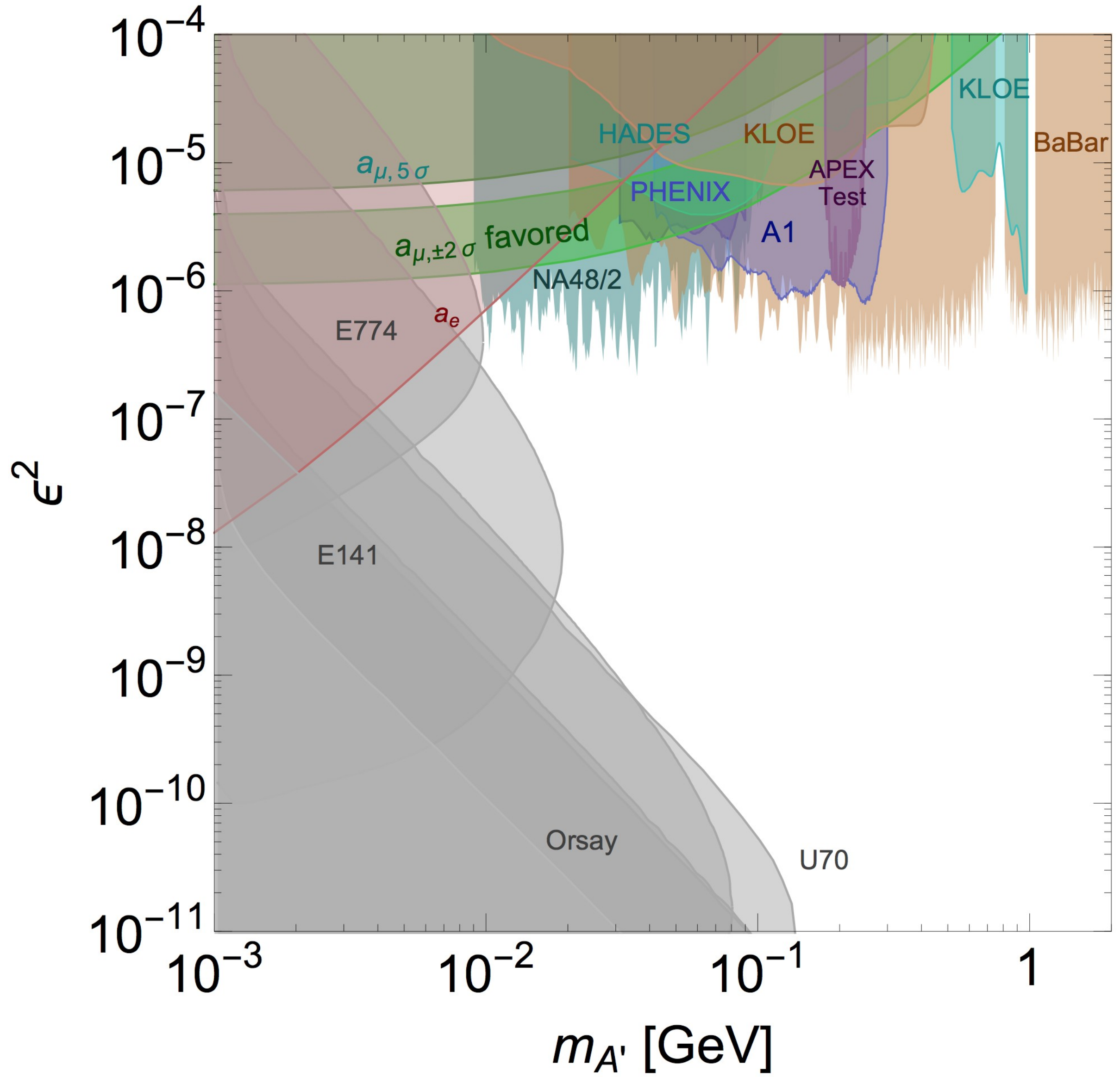
Currently: $3.6\,\sigma$ discrepancy

Future: $\gtrsim 5\,\sigma$?



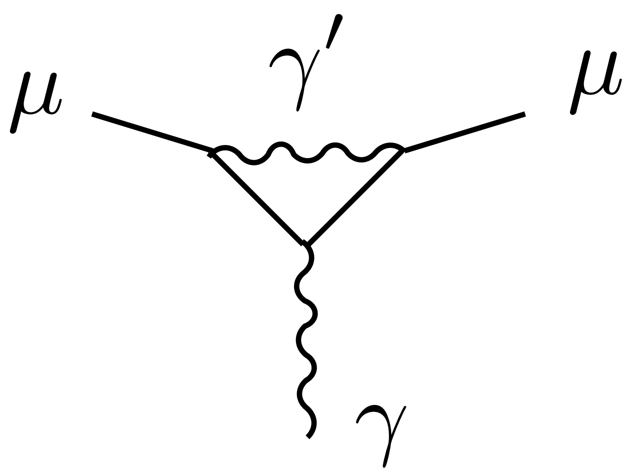
Exciting Times

The anomalous magnetic moment of the muon



[Curtin, Essig et.al.1506.00608]

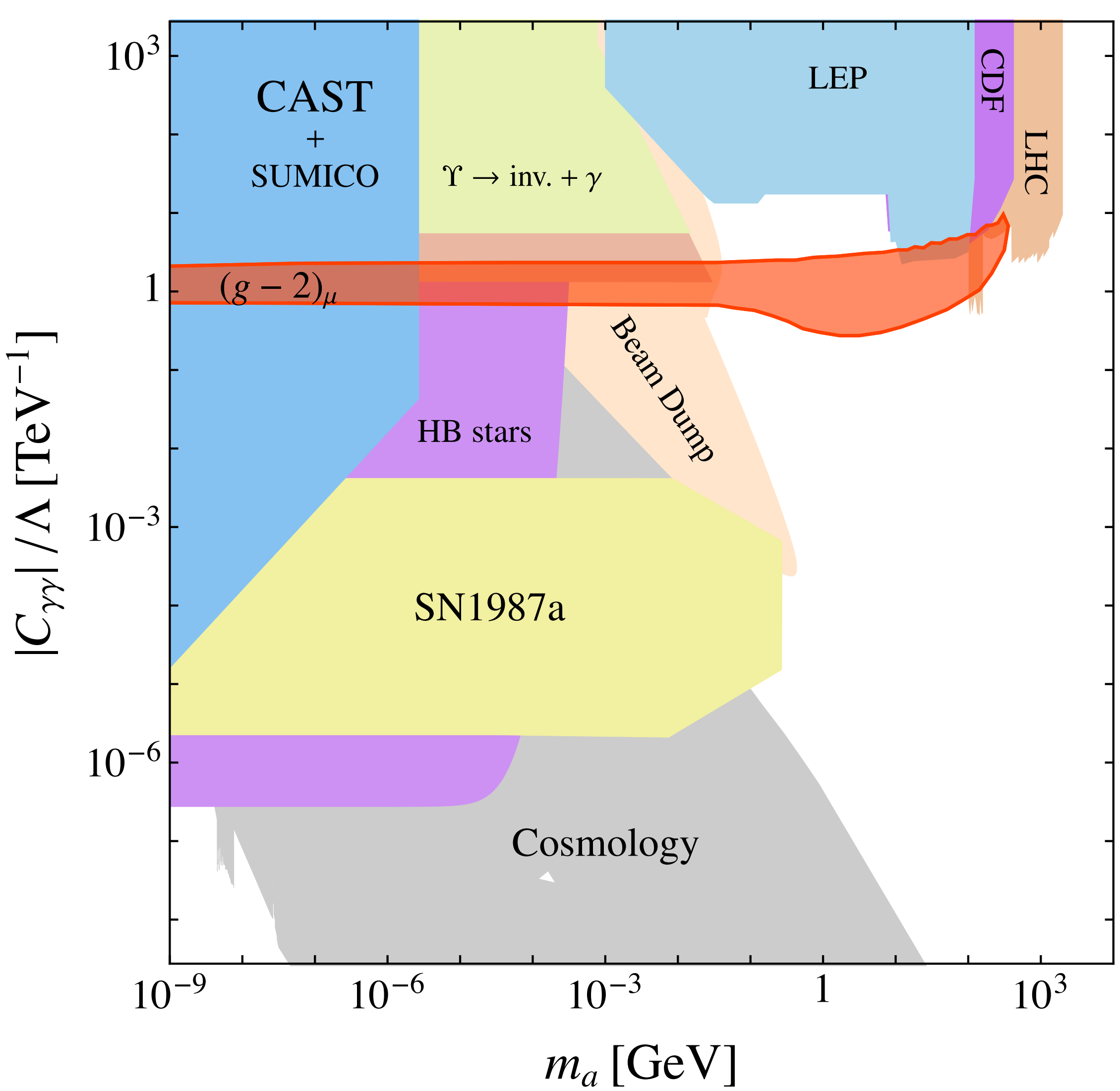
A dark photon/gauge boson



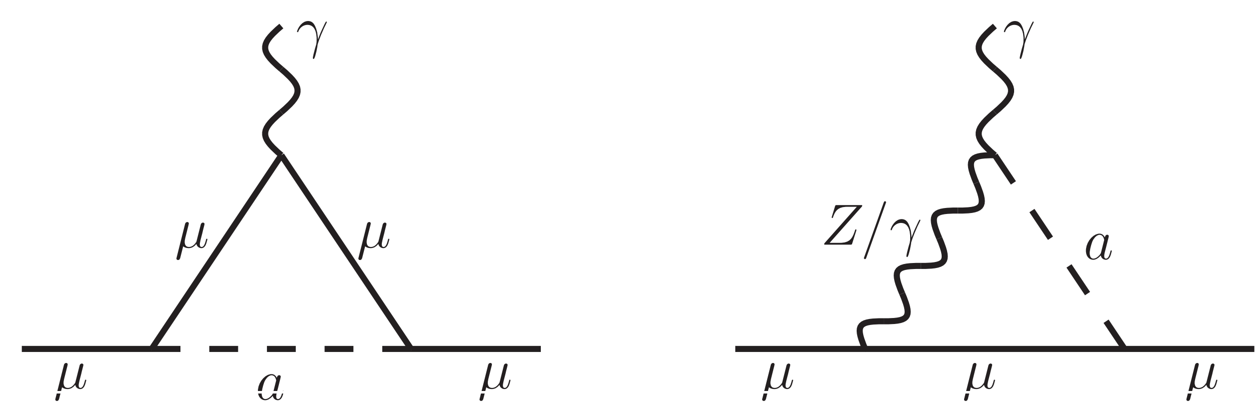
But also more general New Physics

Exciting Times

The anomalous magnetic moment of the muon



A (pseudo)scalar



[MB, et.al.1506.00608]

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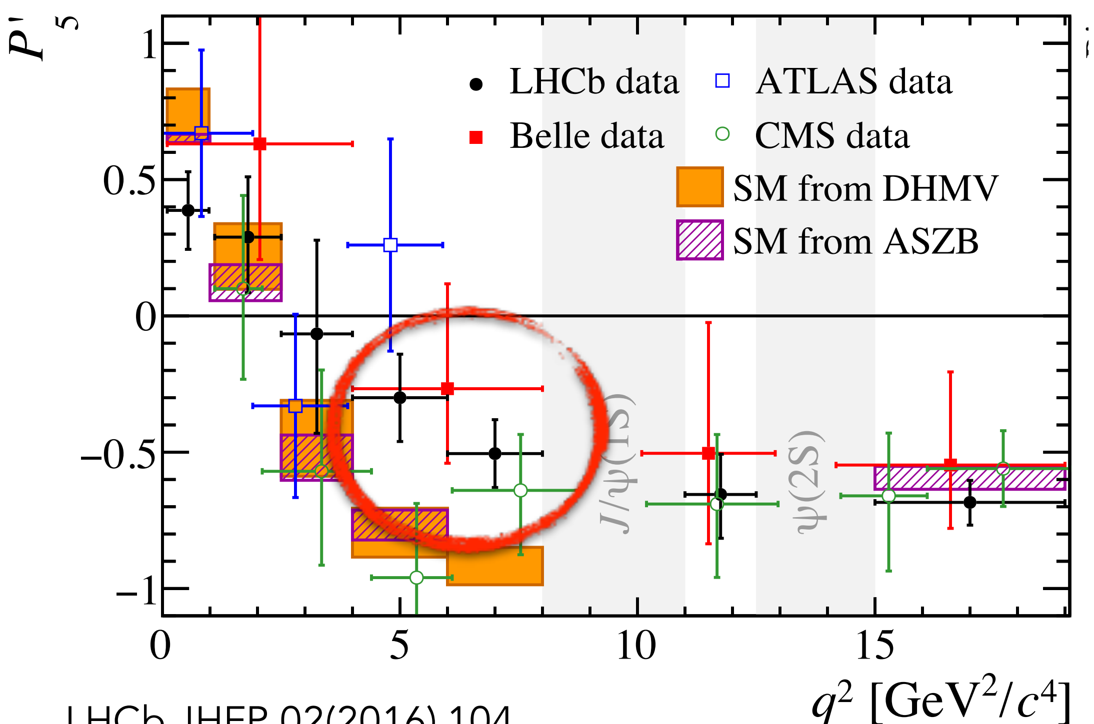


LHCb JHEP 02(2016) 104

Belle PRL118, 111801 (2017)

ATLAS, preliminary Moriond EW

CMS, preliminary Moriond EW

Deviations in several observables

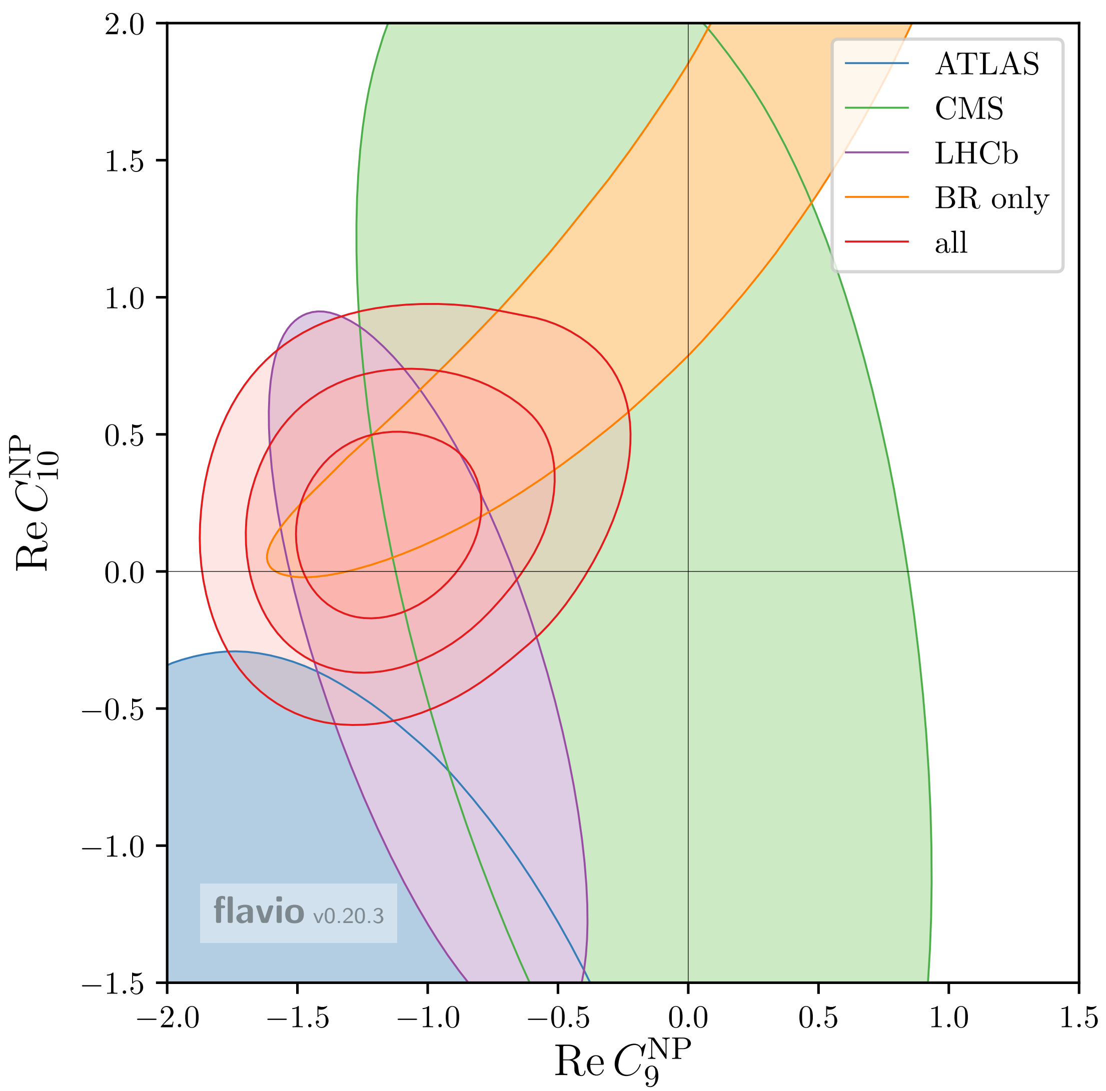
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P'_5	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P'_5	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

Marie-Hélène Schune, Moriond

[Altmannshofer, Straub, 1503.06199]

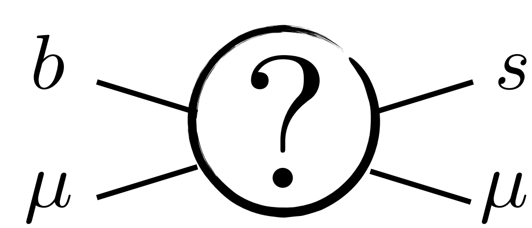
Exciting Times

An intriguing pattern in $b \to s\mu^+\mu^-$ transitions



The global fit shows a $4.6\,\sigma$ deviation.

Doubling Hadronic uncertainties: $3.7\,\sigma$



[Altmannshofer, Straub, 1703.09189]

Exciting Times

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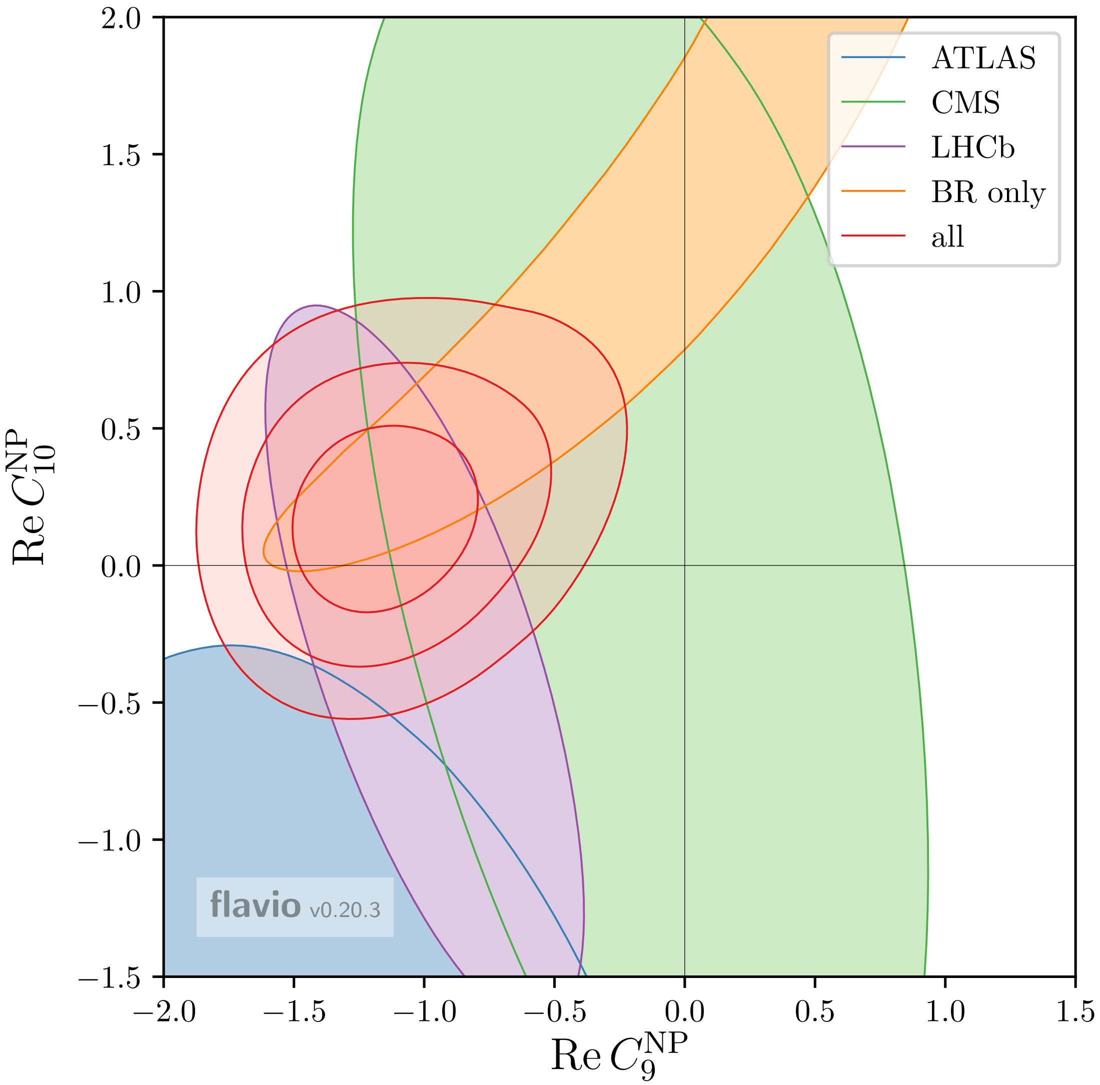

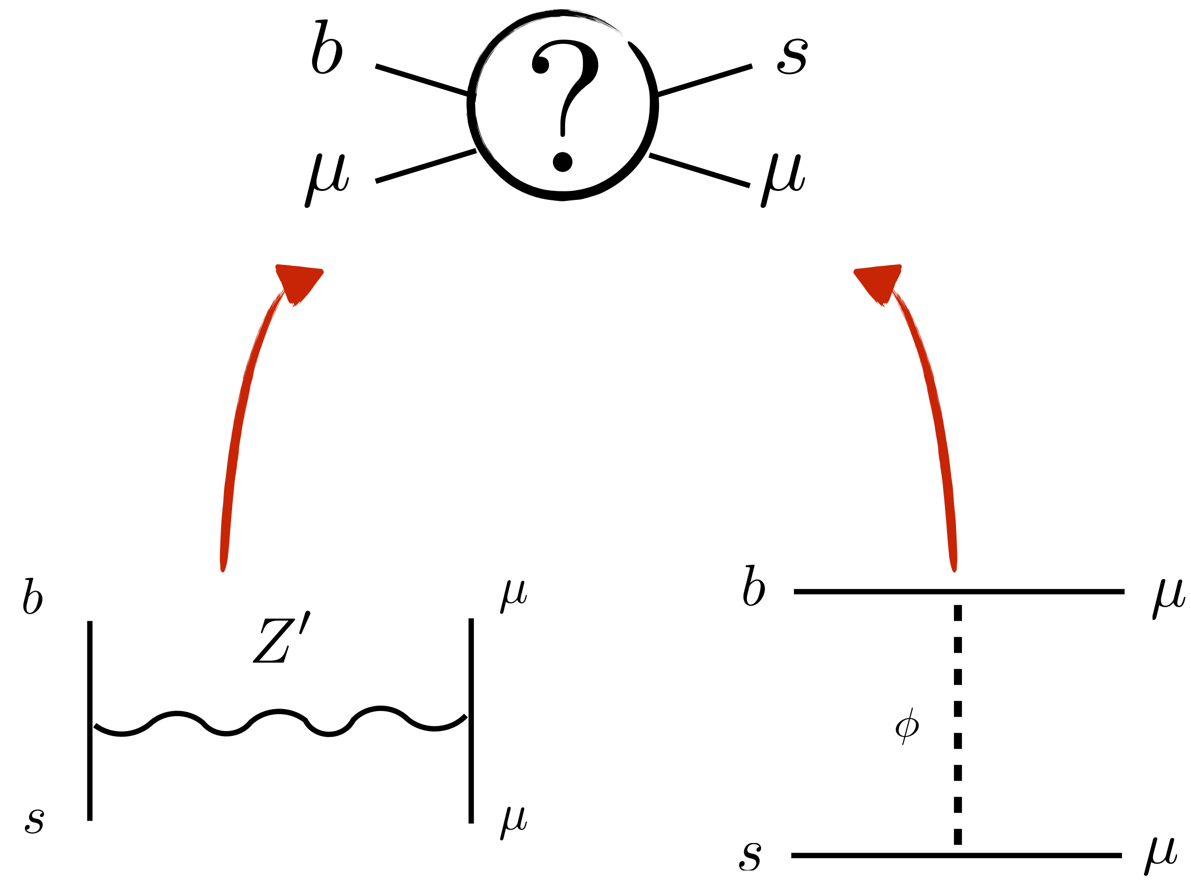

$$C_{9/10}^{\mathrm{NP}} \approx C_{10}^{\mathrm{SM}}/4 \quad \Rightarrow \quad \frac{1}{M^2}\left(\frac{2V_{tb}V_{ts}^*}{v^2}\frac{\alpha_e}{4\pi}\right)^{-1} = \frac{1}{4} \quad \Rightarrow \quad M \approx 35\,\mathrm{TeV}$$

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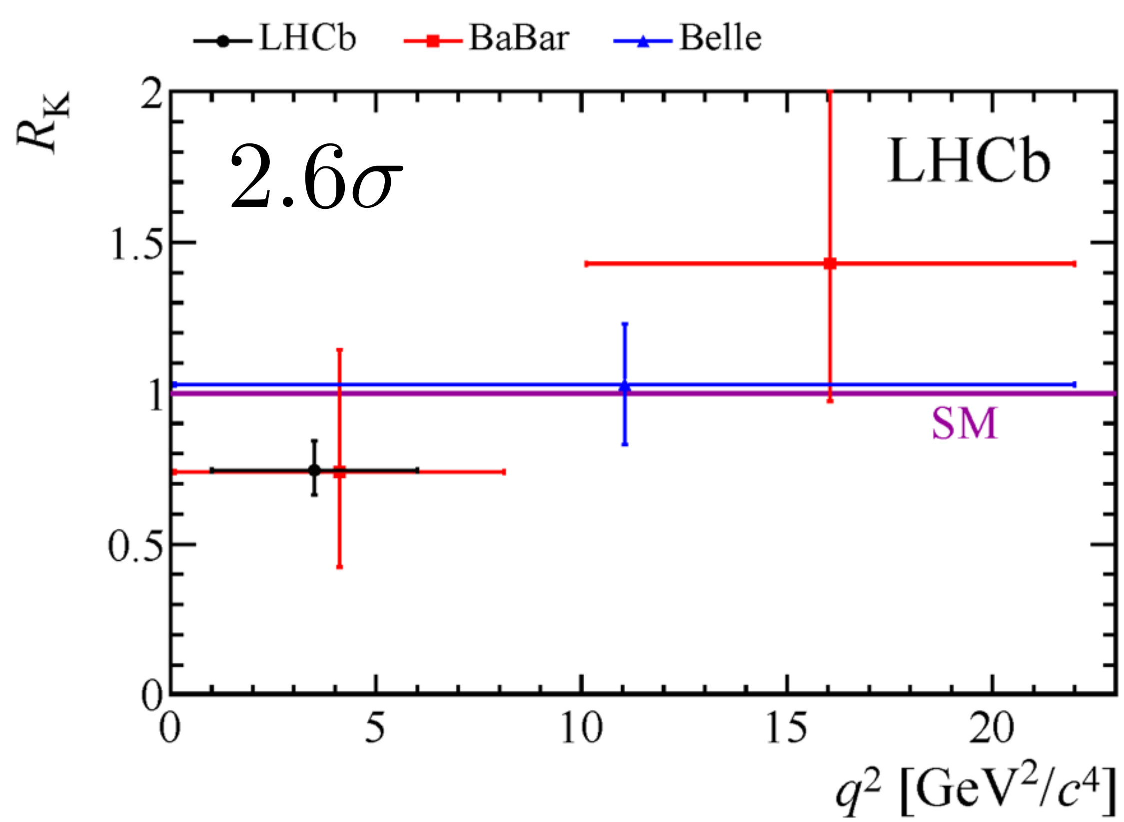
Lepton flavour non-universality in R_K, R_{K^*}

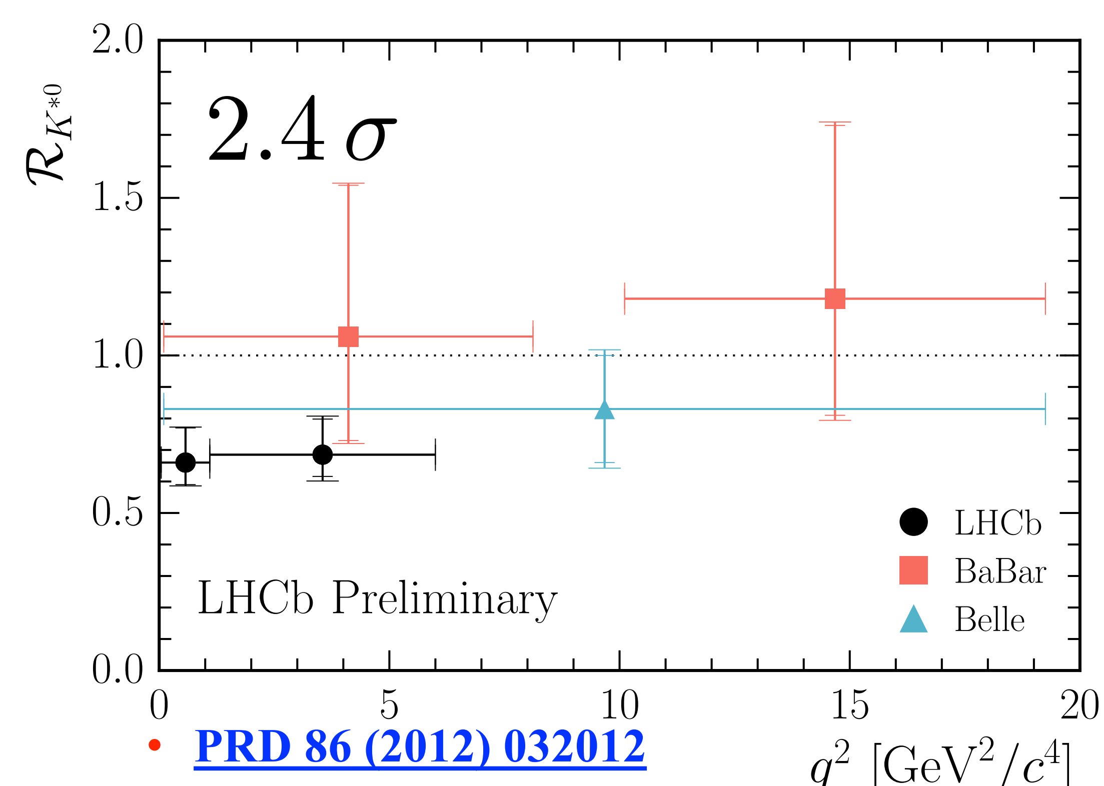
$$R_K = \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

LHCb, arXiv:1406.6482 hep-ex

$$R_{K^*} = \frac{\Gamma(\bar{B} \to \bar{K}^*\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^*e^+e^-)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 \end{cases}$$

[Simone Bifani CERN Seminar]





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

Theoretically clean, QED corrections ~ 1% Bordone, Isidori, Pattori, 1605.07633

Exciting Times

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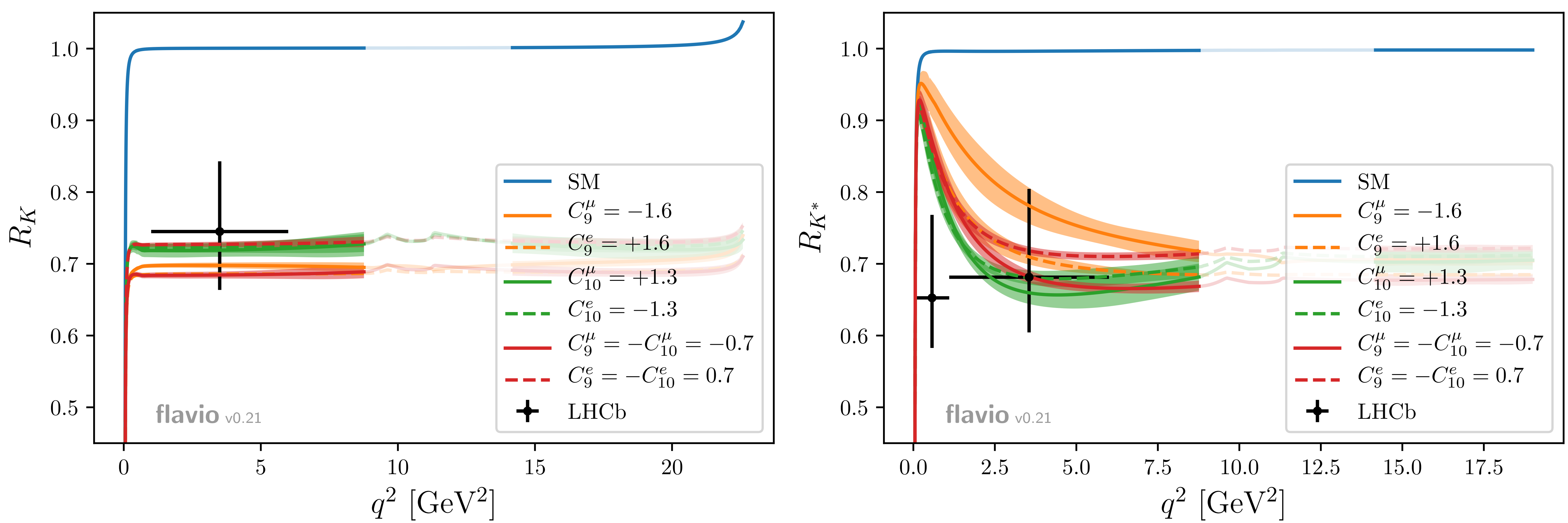

[Altmannshofer et al. 1704.05435]

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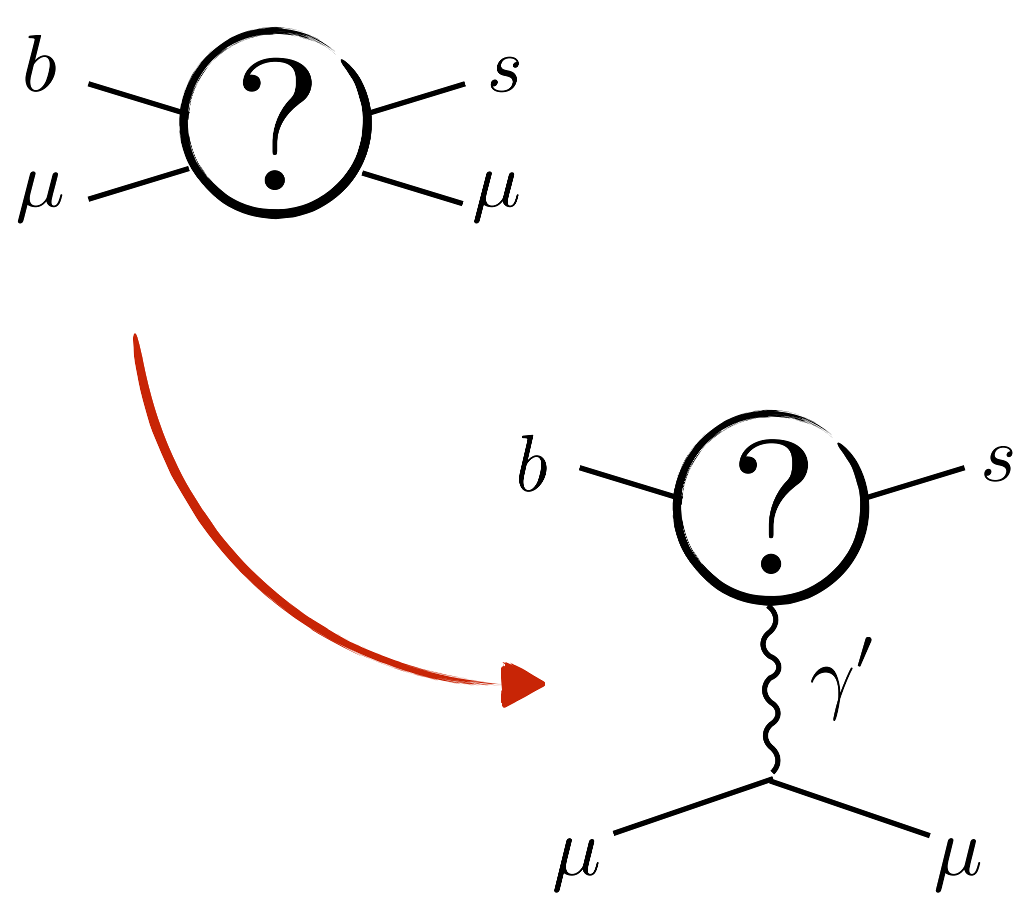

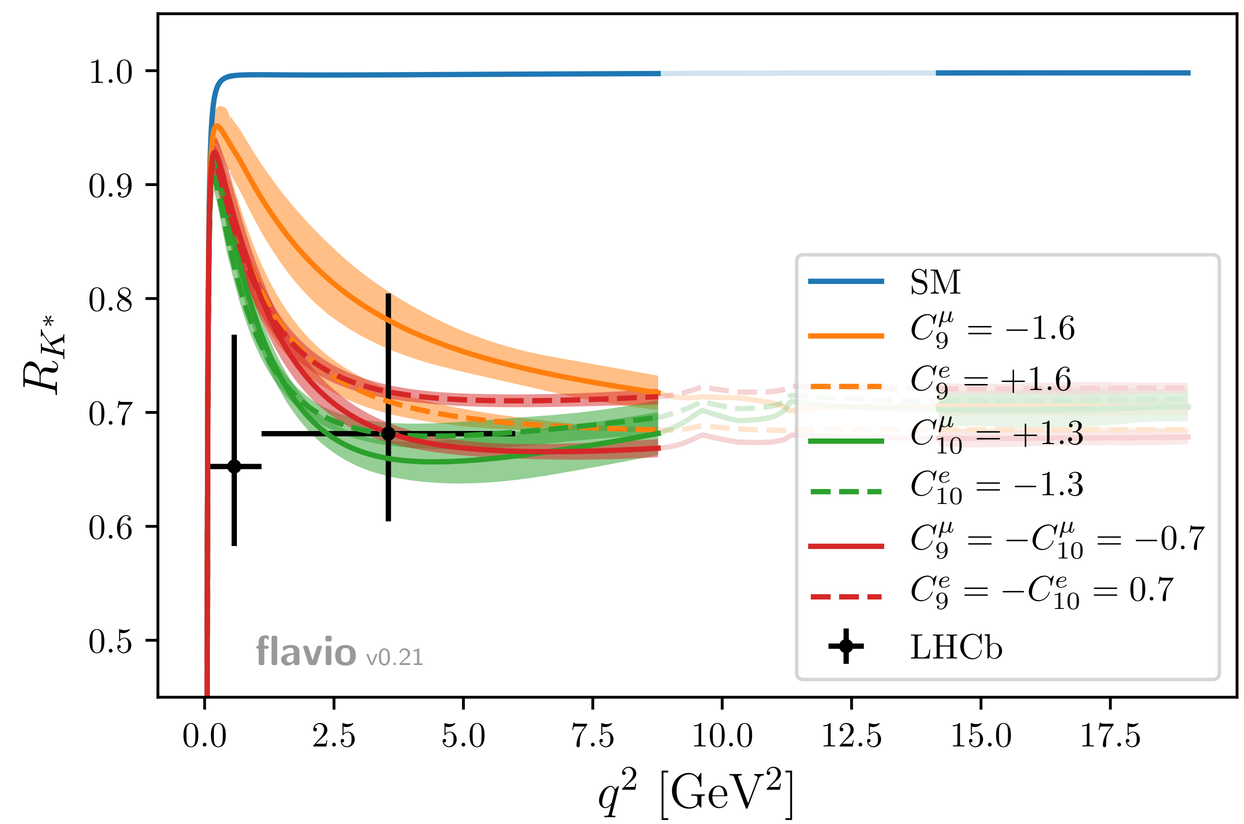

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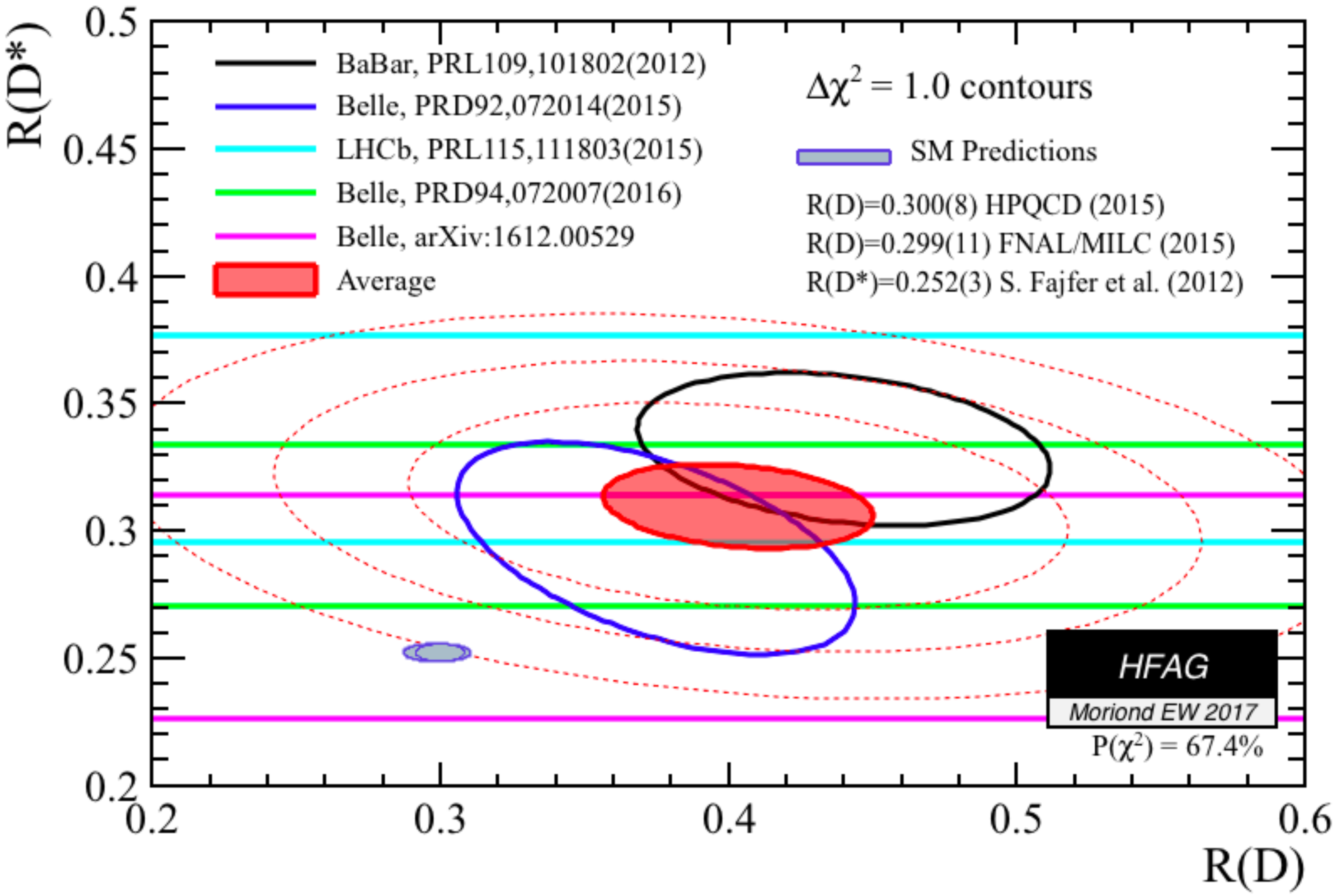
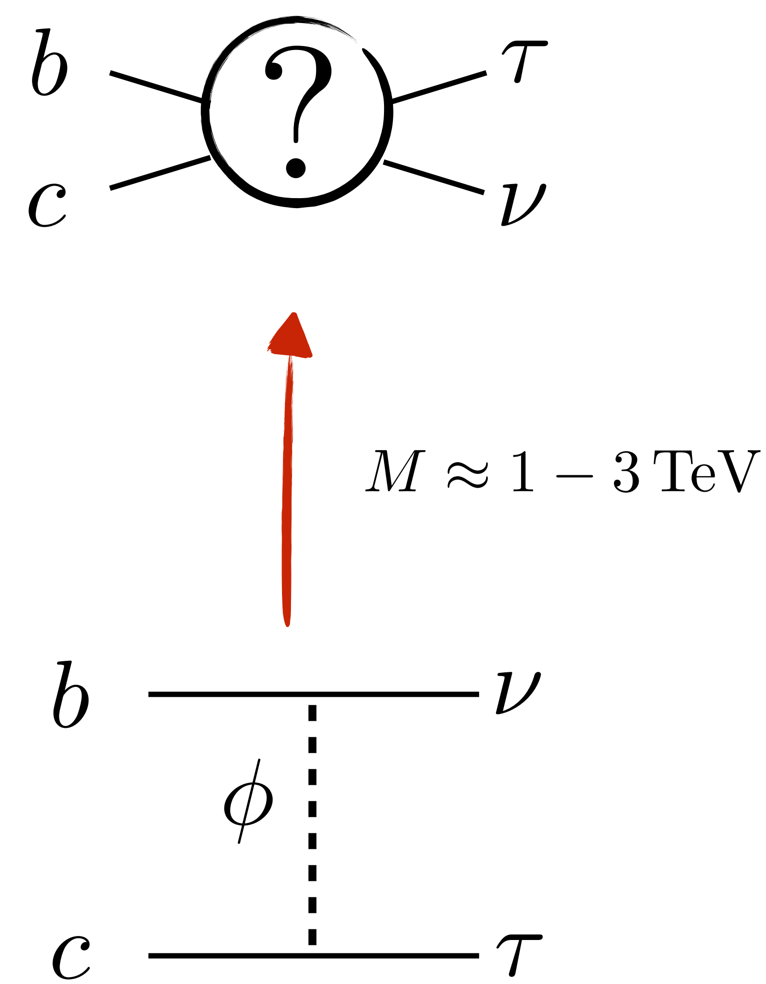
- Lepton flavour non-universality in $R(D^{(*)})$

Exciting Times

$$R(D^{(*)}) = \frac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}$$ deviates by 4σ

- Belle II is expected to improve exp. error by factor ~5 !





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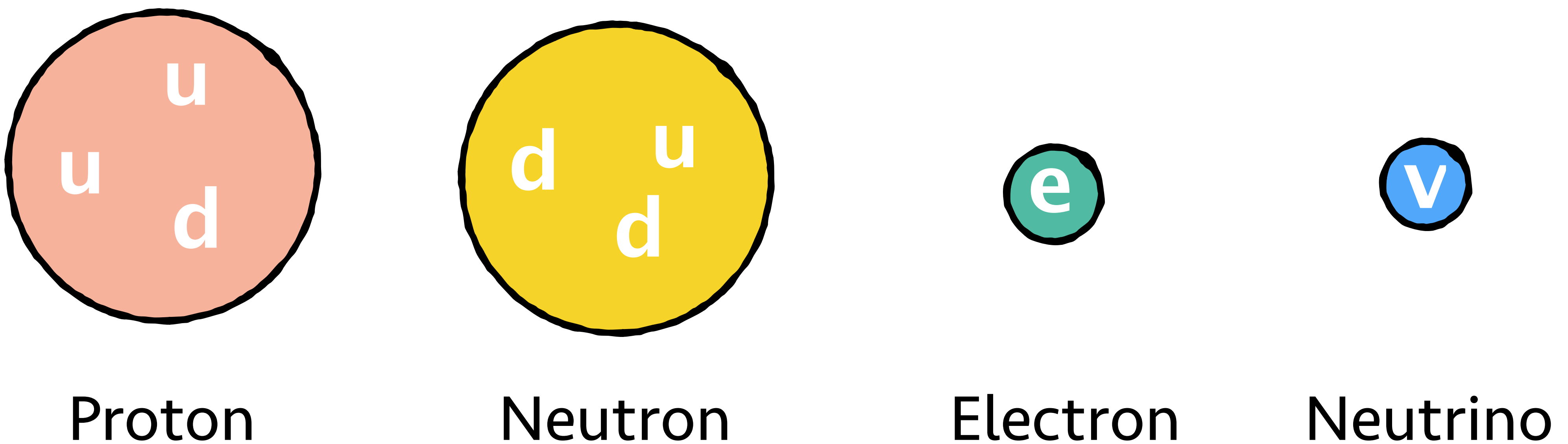
Three of the most remarkable tensions are related to muons!

The Standard Model in the 30s

The known particles were the



This was a very successful model, as it greatly simplified the previous best candidate for a fundamental theory of elementary particles, the periodic table of elements.

Periodic Table of the Elements

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 **H** Hydrogen 1.008																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012											5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007	8 **O** Oxygen 15.999	9 **F** Fluorine 18.998	10 **Ne** Neon 20.180
11 **Na** Sodium 22.990	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.982	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.974	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
19 **K** Potassium 39.098	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.956	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.942	24 **Cr** Chromium 51.996	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933	28 **Ni** Nickel 58.693	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.38	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.631	33 **As** Arsenic 74.922	34 **Se** Selenium 78.971	35 **Br** Bromine 79.904	36 **Kr** Krypton 84.798
37 **Rb** Rubidium 84.468	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.906	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.906	42 **Mo** Molybdenum 95.95	43 **Tc** Technetium 98.907	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.906	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.868	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.711	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.6	53 **I** Iodine 126.904	54 **Xe** Xenon 131.294
55 **Cs** Cesium 132.905	56 **Ba** Barium 137.328	57-71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.948	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.085	79 **Au** Gold 196.967	80 **Hg** Mercury 200.592	81 **Tl** Thallium 204.383	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.980	84 **Po** Polonium [208.982]	85 **At** Astatine 209.987	86 **Rn** Radon 222.018
87 **Fr** Francium 223.020	88 **Ra** Radium 226.025	89-103	104 **Rf** Rutherfordium [261]	105 **Db** Dubnium [262]	106 **Sg** Seaborgium [266]	107 **Bh** Bohrium [264]	108 **Hs** Hassium [269]	109 **Mt** Meitnerium [268]	110 **Ds** Darmstadtium [269]	111 **Rg** Roentgenium [272]	112 **Cn** Copernicium [277]	113 **Uut** Ununtrium unknown	114 **Fl** Flerovium [289]	115 **Uup** Ununpentium unknown	116 **Lv** Livermorium [298]	117 **Uus** Ununseptium unknown	118 **Uuo** Ununoctium unknown

Atomic Number **Symbol** Name Atomic Mass

Series															
Lanthanide Series	57 **La** Lanthanum 138.905	58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.908	60 **Nd** Neodymium 144.243	61 **Pm** Promethium 144.913	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925	66 **Dy** Dysprosium 162.500	67 **Ho** Holmium 164.930	68 **Er** Erbium 167.259	69 **Tm** Thulium 168.934	70 **Yb** Ytterbium 173.055	71 **Lu** Lutetium 174.967
Actinide Series	89 **Ac** Actinium 227.028	90 **Th** Thorium 232.038	91 **Pa** Protactinium 231.036	92 **U** Uranium 238.029	93 **Np** Neptunium 237.048	94 **Pu** Plutonium 244.064	95 **Am** Americium 243.061	96 **Cm** Curium 247.070	97 **Bk** Berkelium 247.070	98 **Cf** Californium 251.080	99 **Es** Einsteinium [254]	100 **Fm** Fermium 257.095	101 **Md** Mendelevium 258.1	102 **No** Nobelium 259.101	103 **Lr** Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

The Standard Model in the 30s

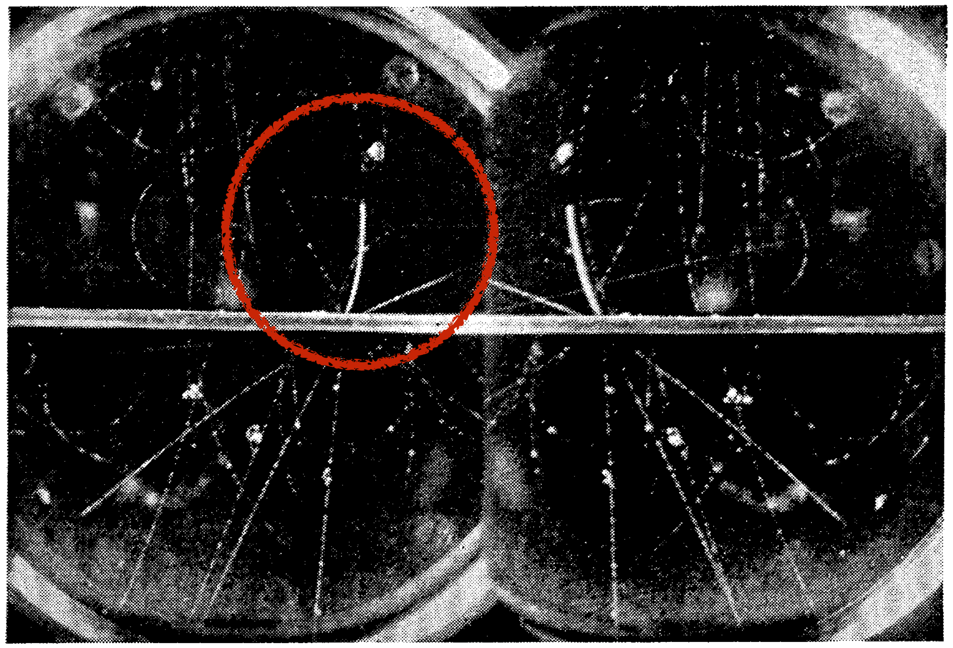
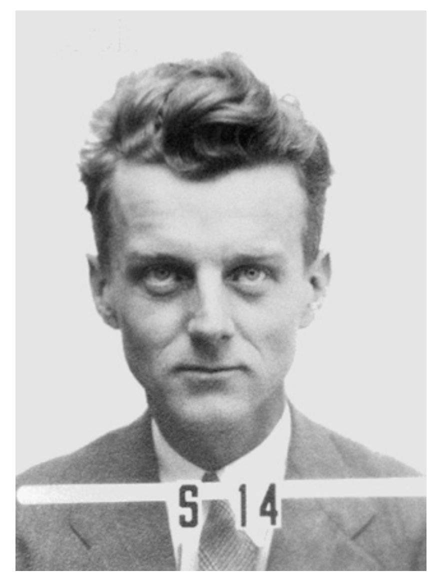


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to estimate to what extent scattering may have modified the curvature in this case. The particle is therefore tentatively interpreted as a proton. The other particle ejected upward

Neddermeyer and Anderson discover a new fermion with

$$m = 106\,\mathrm{MeV}$$



Neddermeyer

Anderson

Who ordered that?

-Rabi

Ultra-High Precision

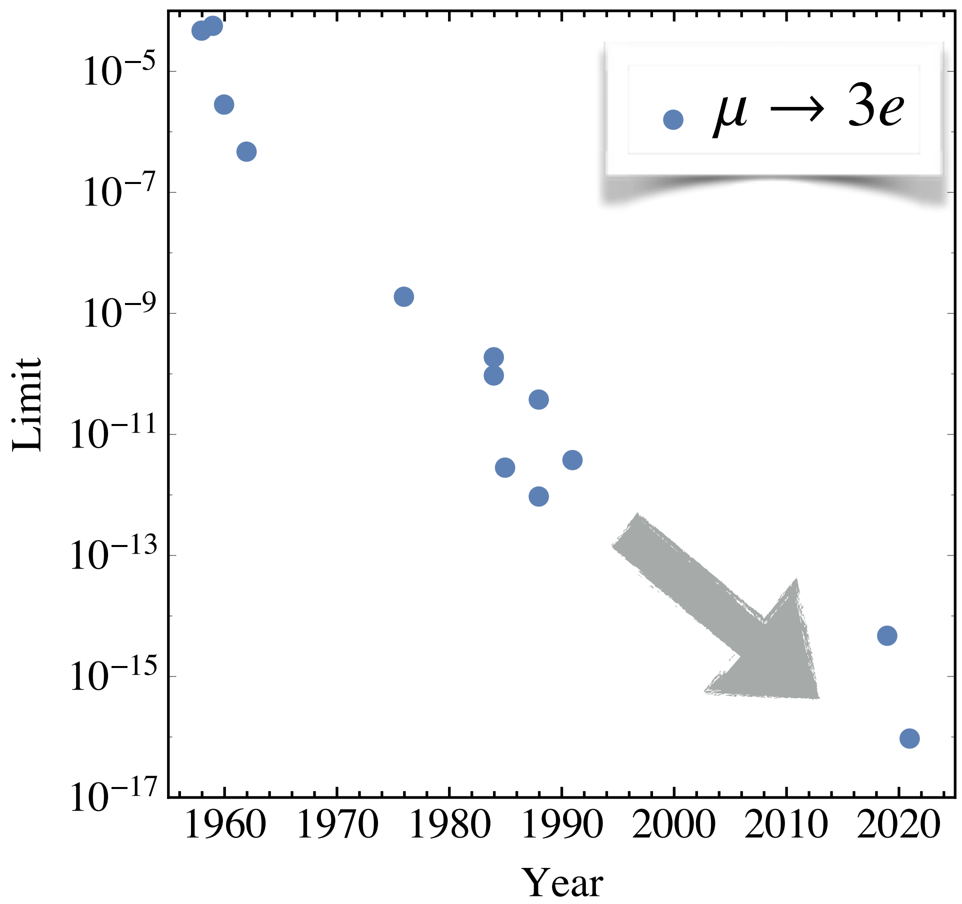
In the next years we will enter a new golden age for high precision lepton experiments

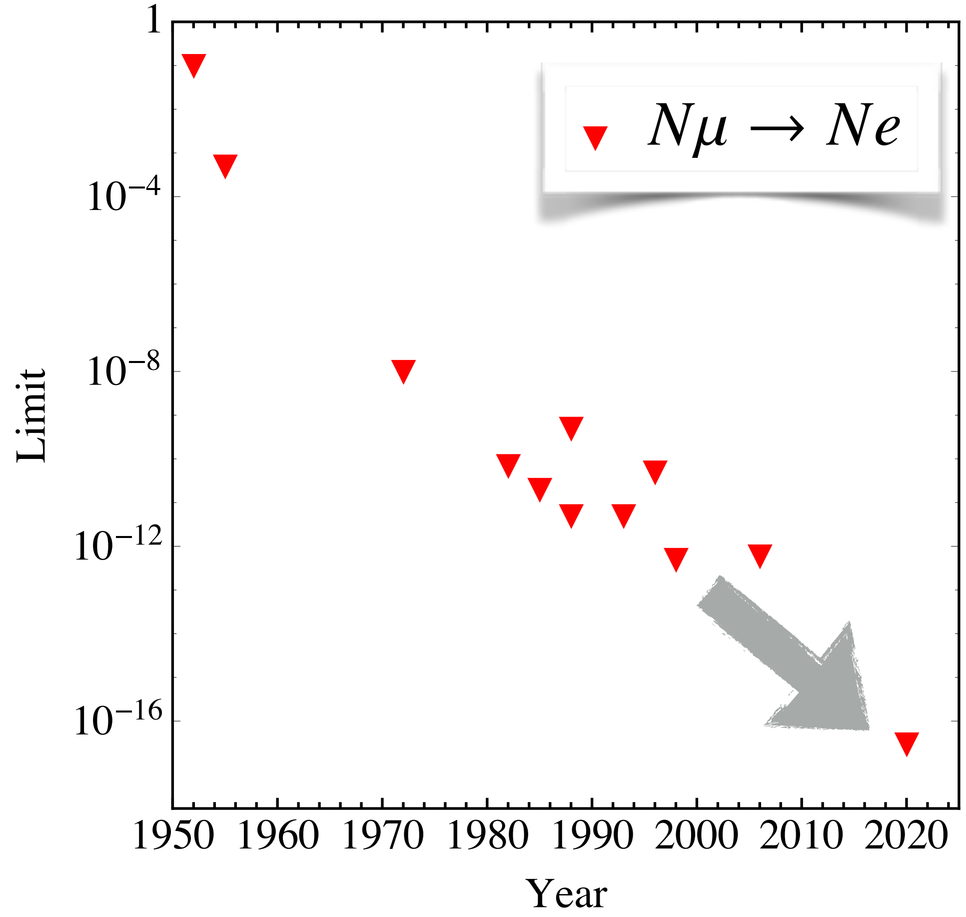
- Electron EDM $d_e \lesssim 10^{-27}\,\mathrm{e\,cm}$ ⟶ $d_e \lesssim 10^{-29}$–$10^{-31}\,\mathrm{e\,cm}$
- Muon g-2 $\delta a_\mu = 7.2 \times 10^{-9}$ ⟶ $\delta a_\mu = 1.4 \times 10^{-9}$
- $\mu \to e\gamma$ $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ ⟶ $BR(\mu \to e\gamma) < 5 \times 10^{-14}$
- $N\mu \to Ne$ $BR(N\mu \to Ne) < 6 \times 10^{-13}$ ⟶ $BR(N\mu \to Ne) < 3 \times 10^{-17}$
- $\mu \to eee$ $BR(\mu \to eee) < 4 \times 10^{-12}$ ⟶ $BR(\mu \to eee) < 1 \times 10^{-16}$

and plans for more…

Ultra-High Precision

This is an improvement hardly found in modern physics…

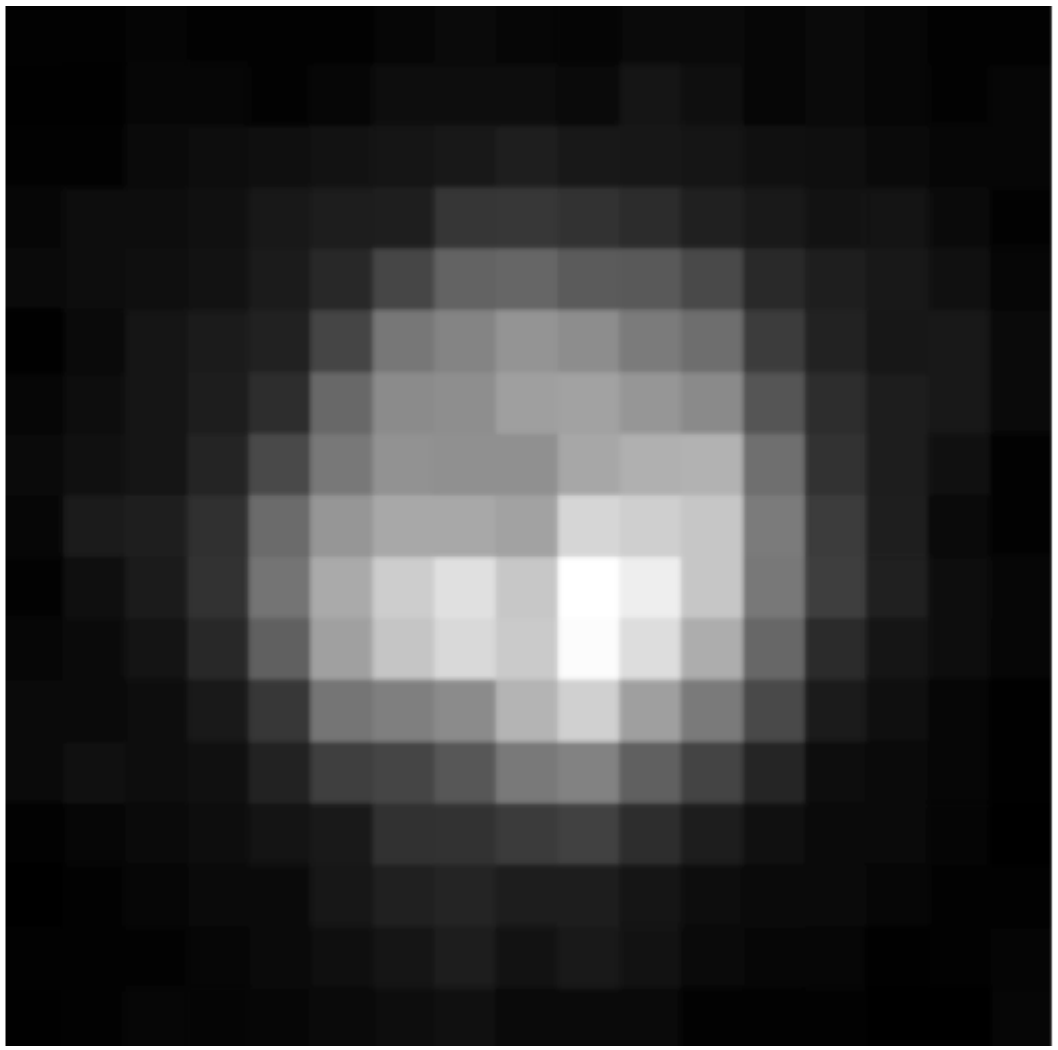


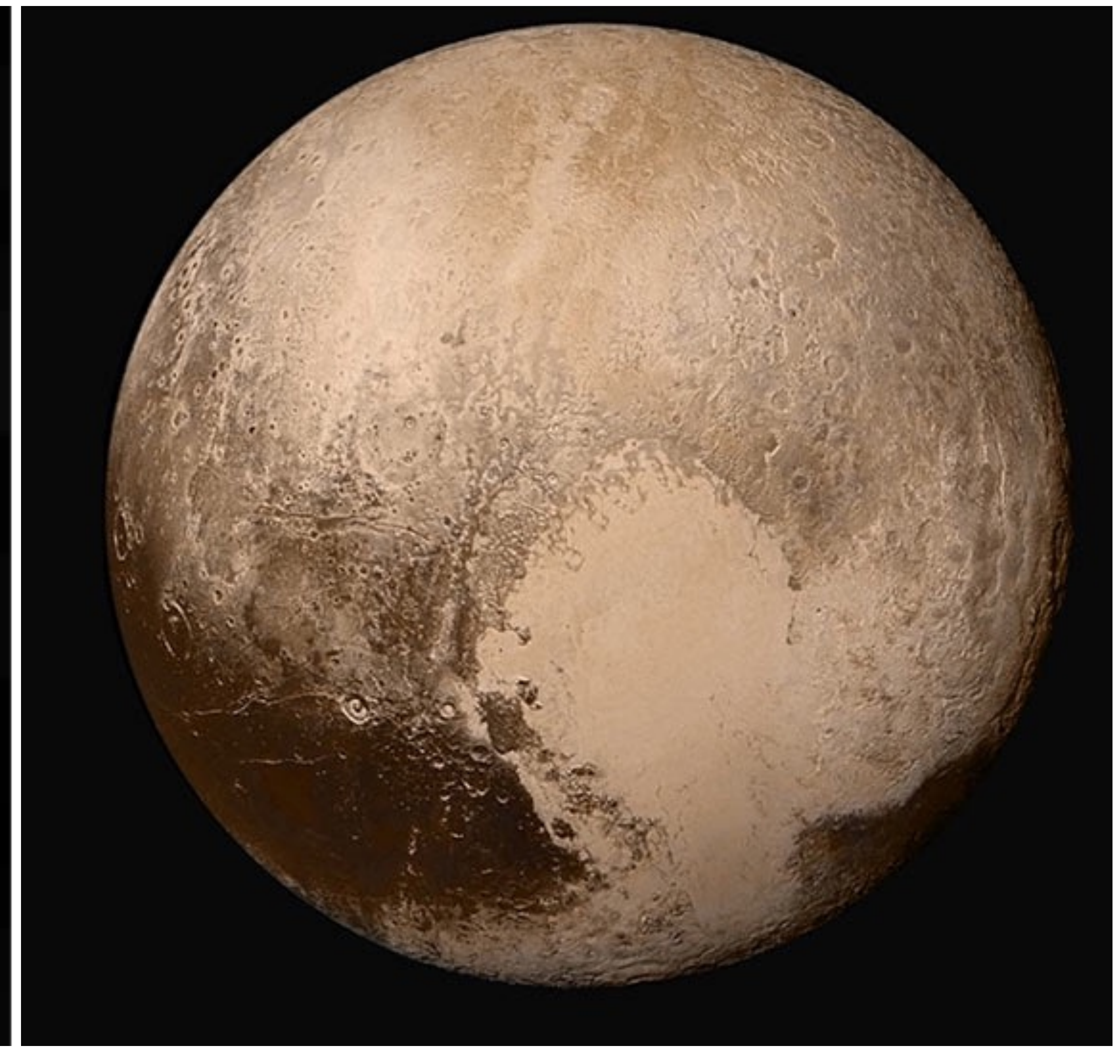


…these experiments will allow us to look at the muon with a resolution ~10 000 times better than ever before.

[Bernstein, P. S. Cooper Phys.Rept. 532 (2013)]

Ultra-High Precision





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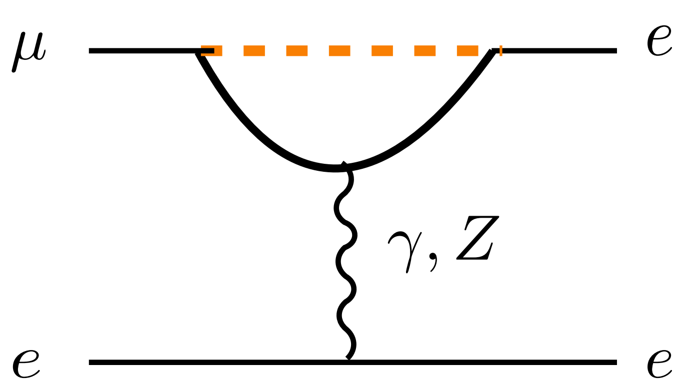
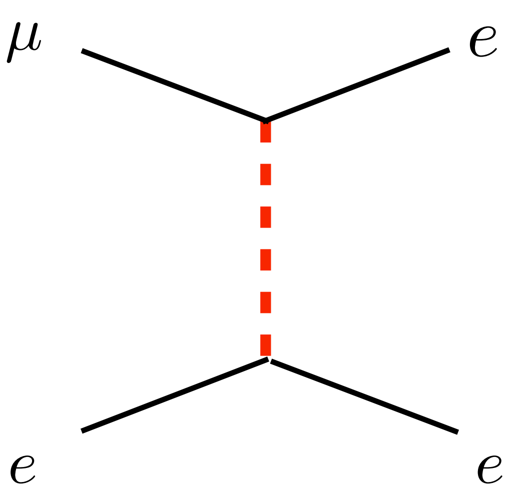
[Bernstein, P. S. Cooper Phys.Rept. 532 (2013)]

What can we learn?

Limits on New Physics

$$\mathcal{L}_{\text{LFV}} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_R\,\sigma^{\mu\nu}e_L\,F_{\mu\nu} + \frac{1}{\Lambda^2}\left(\bar{\mu}_L\gamma^\mu e_L\right)\left(\bar{e}_L\gamma_\mu e_L\right)$$

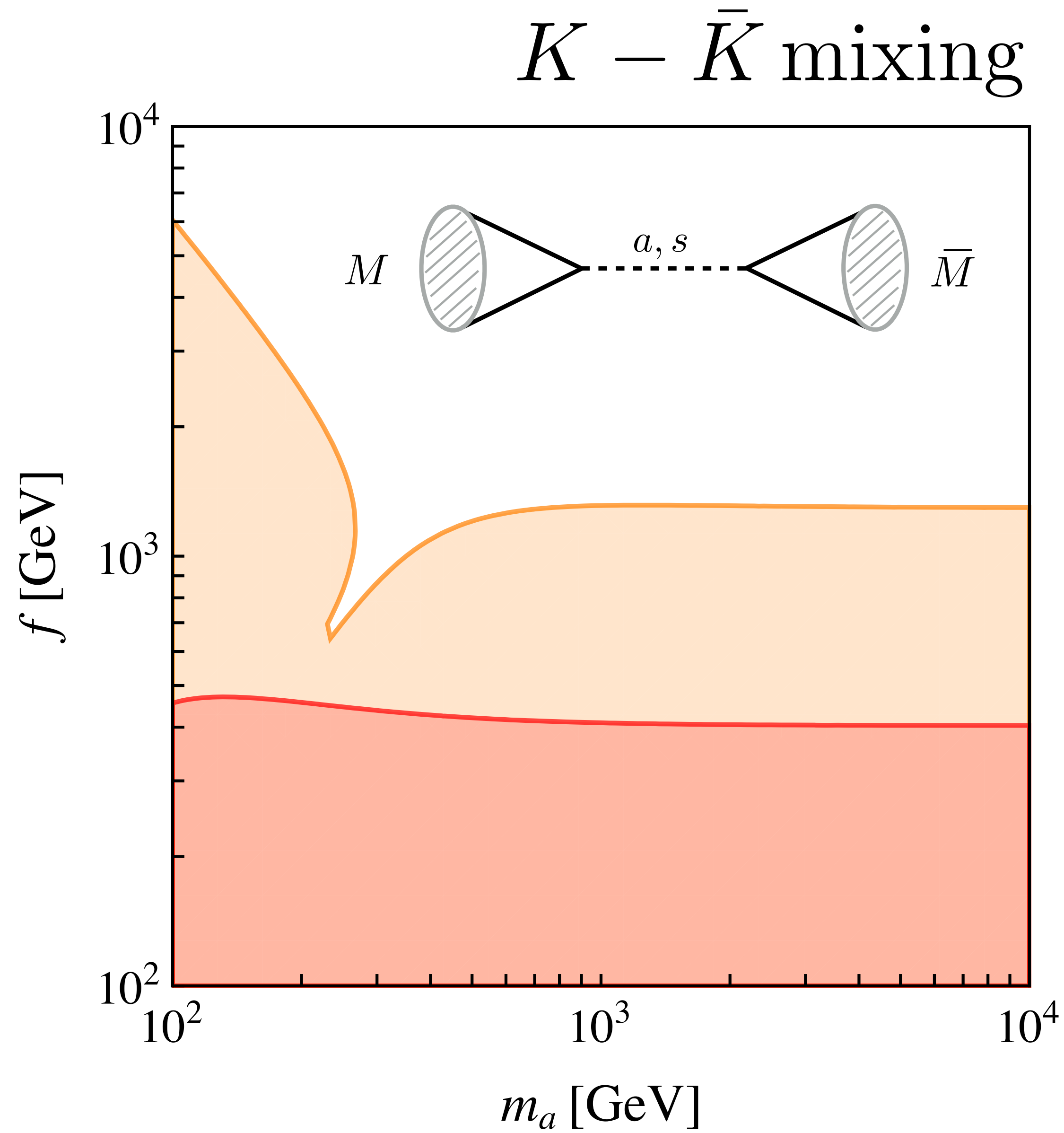


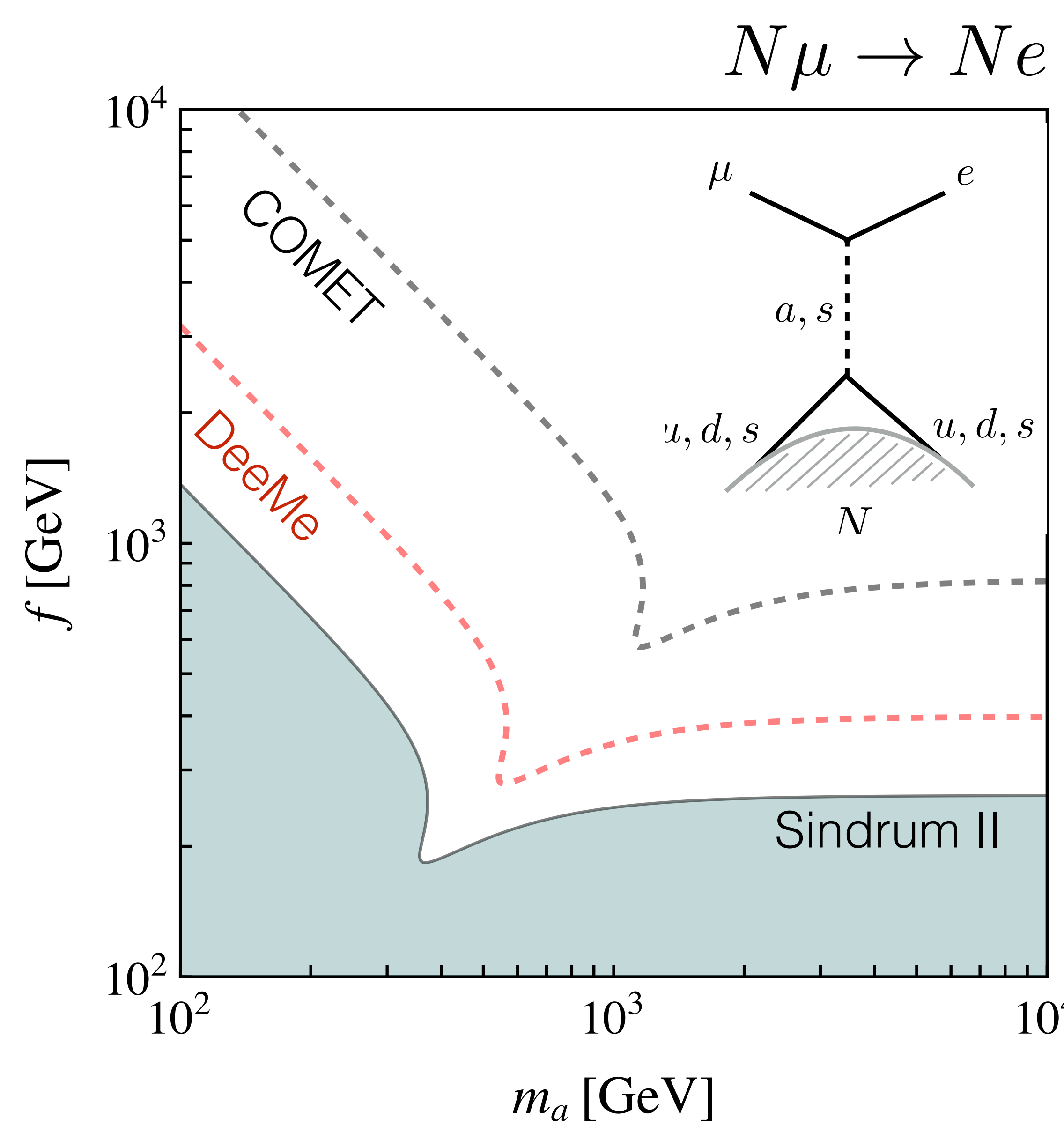


probes scales up to $\Lambda \approx 1000 - 4000\,\text{TeV}$

What can we learn?

This is of course model-dependent, but very impressive

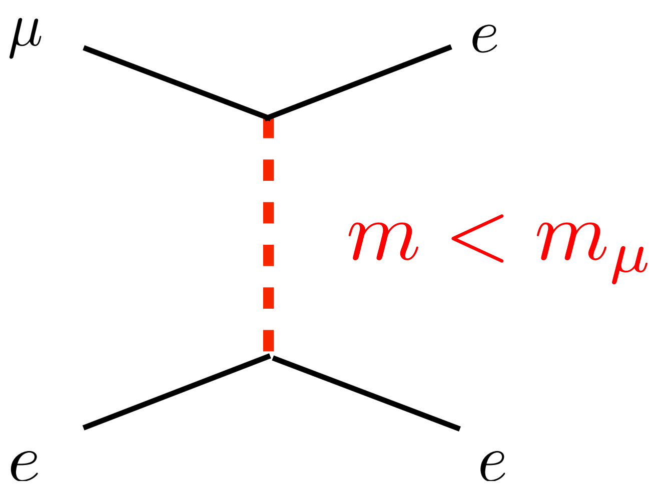




[MB, Schell, Plehn, PRD 94, no. 5, 056003 (2016)]

Light New Physics

What about light New Physics?



In general it needs to be weakly coupled.

There are two theoretically well-motivated categories for light new particles.

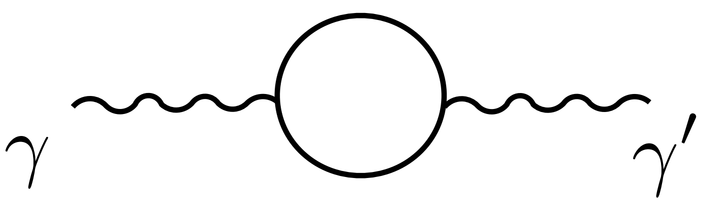
New Gauge Bosons

Goldstone bosons

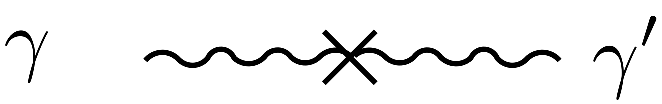
New Gauge Bosons

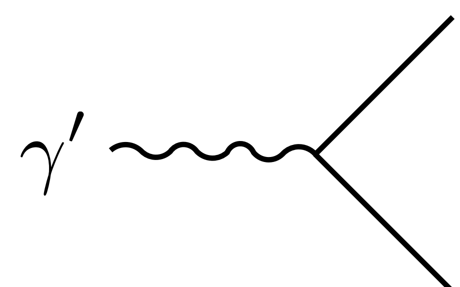
Weak couplings from mixing:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$



Charged matter is milli-charged under $U(1)_X$





$$eA_\mu J^\mu_{\rm EM} - \epsilon\, eX_\mu J^\mu_{\rm EM}$$

Leads to “universal” couplings.

New Gauge Bosons

Light gauge bosons automatically couple weakly!

$$\mathcal{L} = D_\mu S (D^\mu S)^\dagger = (\partial_\mu - igA_\mu)(f+S)(\partial^\mu + igA^\mu)(f+S)$$

$$\ni g^2 f^2 A_\mu A^\mu$$

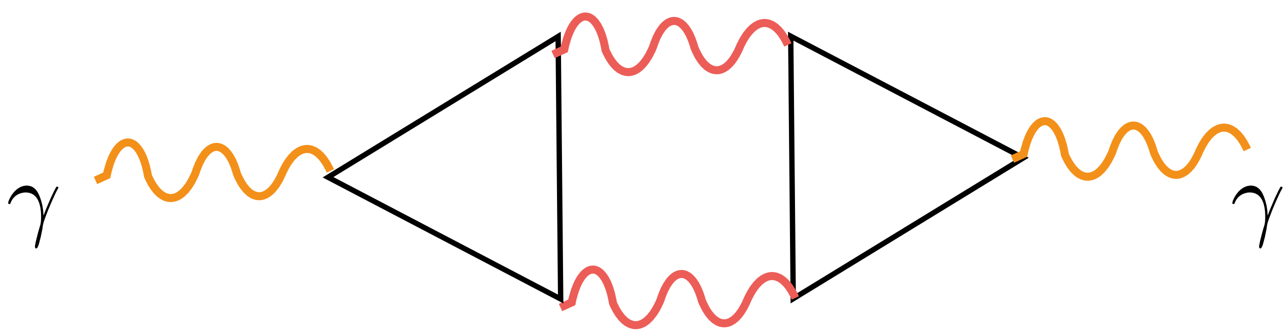
$$\longrightarrow \quad m_A^2 = g^2 f^2$$

If there are no new fermions, not everything can be charged.

Leads to flavor-specific couplings.

New Gauge Bosons

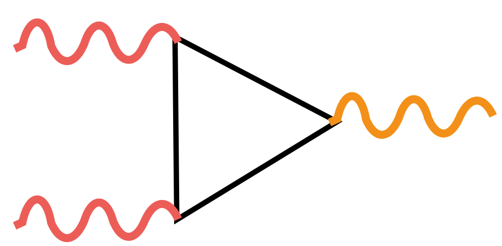
Anomaly cancellation necessary for gauge invariance.



$$\Rightarrow m_\gamma \neq 0$$

All triangle diagrams have to vanish

$$\sum_{\text{Fermions}}$$



$$= 0$$

This fixes the Standard Model hypercharges.

[S. Adler (1969). Physical Review. 177 (5): 2426] [Bell, Jackiw (1969) Il Nuovo Cimento A. 60:47]

Searching all the hidden Photons

There is a limited number of possible new light gauge bosons consistent with the SM (= anomaly free) and flavour safe.

Universal | B - L | $L_\mu - L_e$ | $L_e - L_\tau$ | $L_\mu - L_\tau$

Searching all the hidden Photons

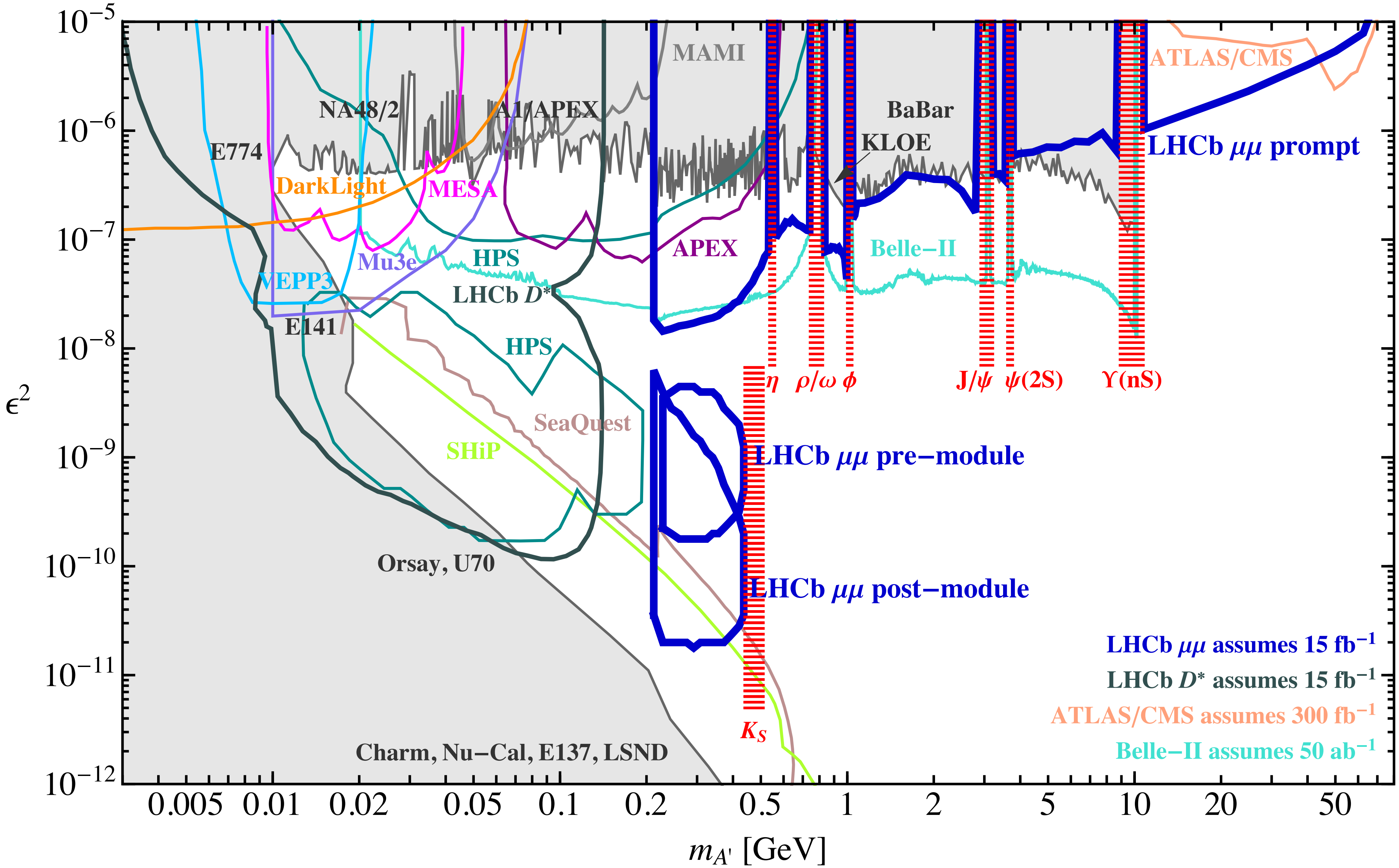
There is a limited number of possible new light gauge bosons consistent with the SM (= anomaly free) and flavour safe.

Universal	B - L	$L_\mu - L_e$	$L_e - L_\tau$	$L_\mu - L_\tau$
• couples to all charged matter	• couples to quarks and leptons	• couples to muons and electrons	• couples to taus and electrons	• couples to taus and muons

usually constraints are put on the most general case.

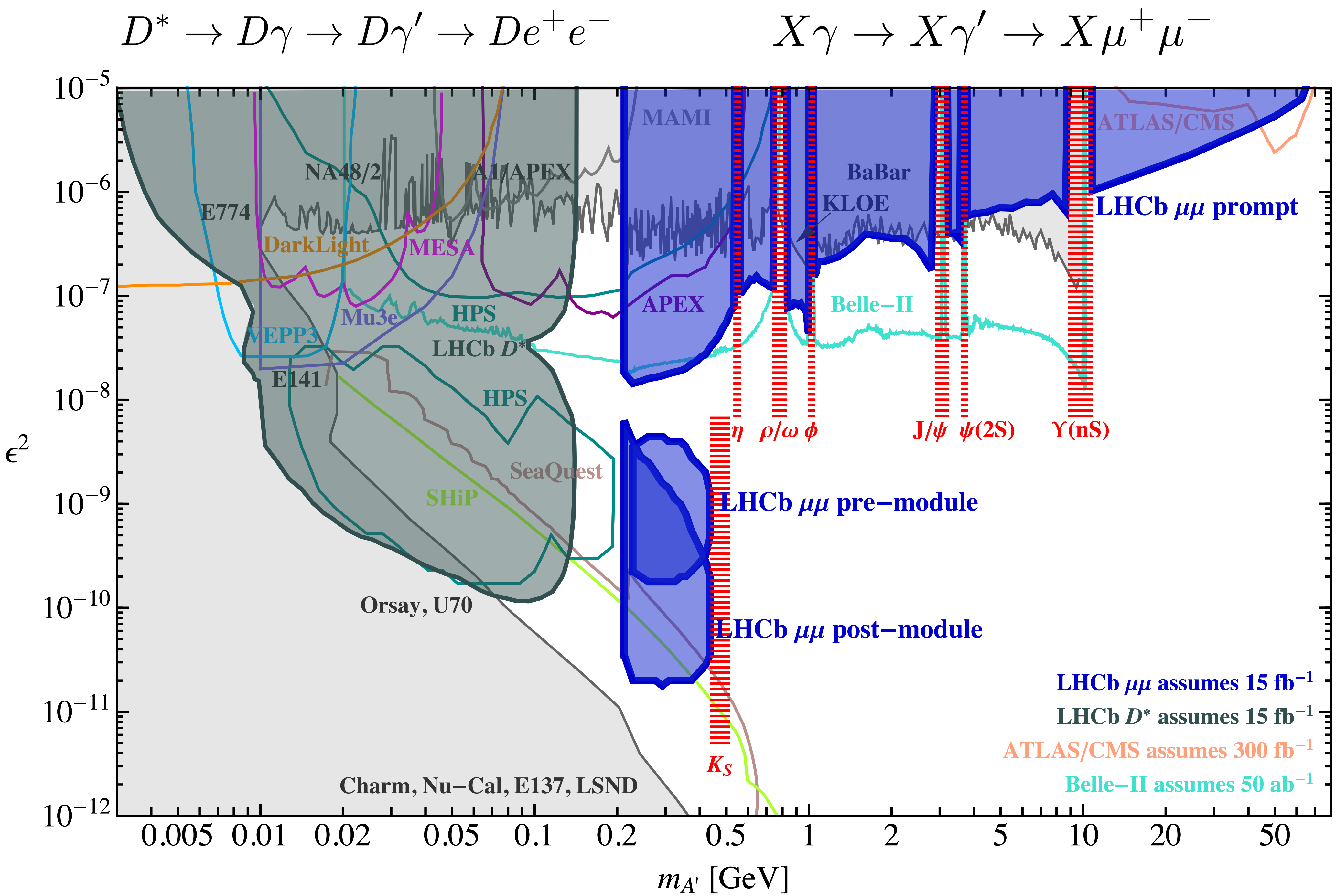
[MB, Foldenauer, Jaeckel, 1705….]

Searching all the hidden Photons



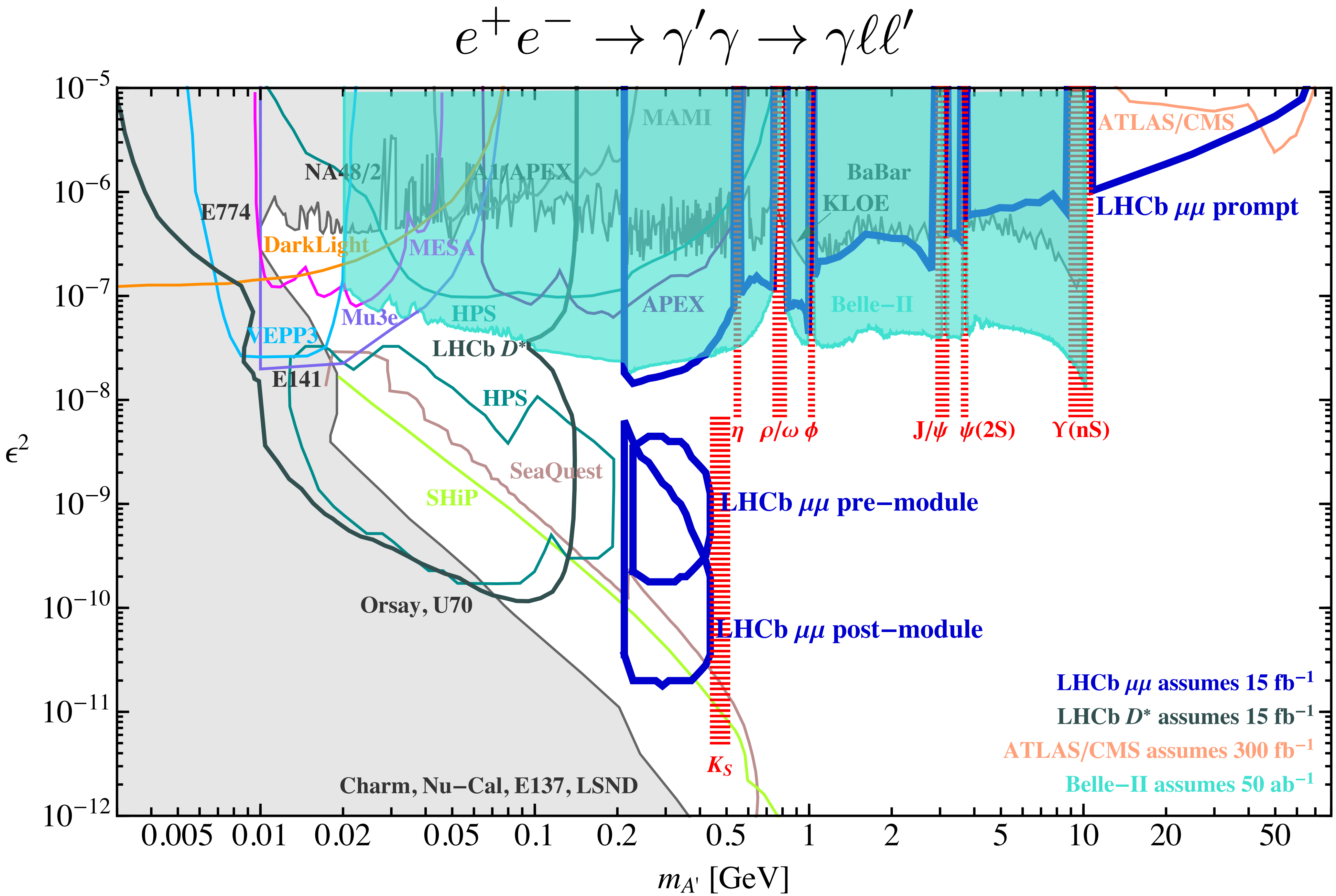
Ilten *et al.* Phys. Rev. Lett. **116**, no. 25, 251803 (2016)

Searching all the hidden Photons



Ilten *et al.* Phys. Rev. Lett. **116**, no. 25, 251803 (2016)

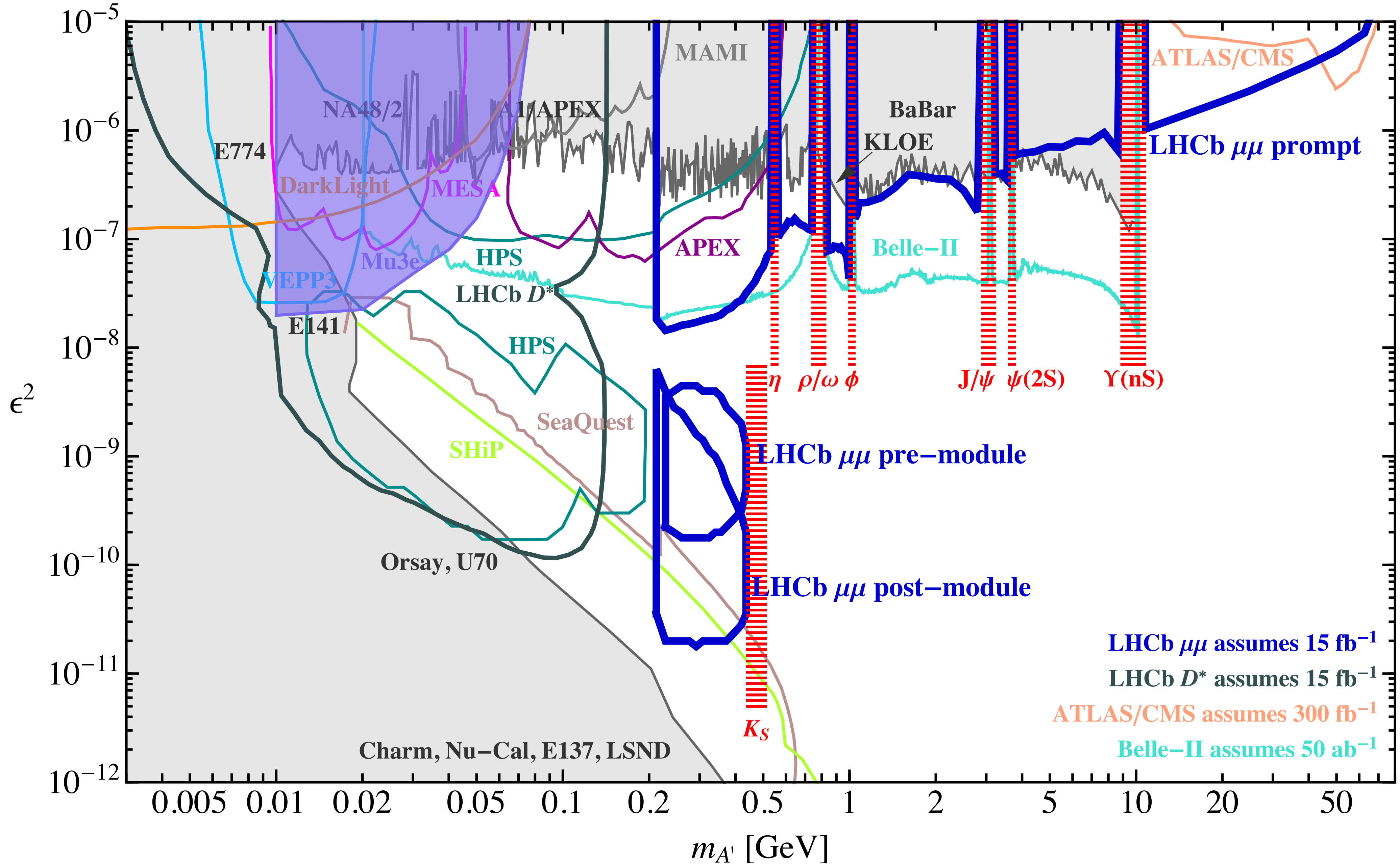
Searching all the hidden Photons



Ilten *et al.* Phys. Rev. Lett. **116**, no. 25, 251803 (2016)

Searching all the hidden Photons

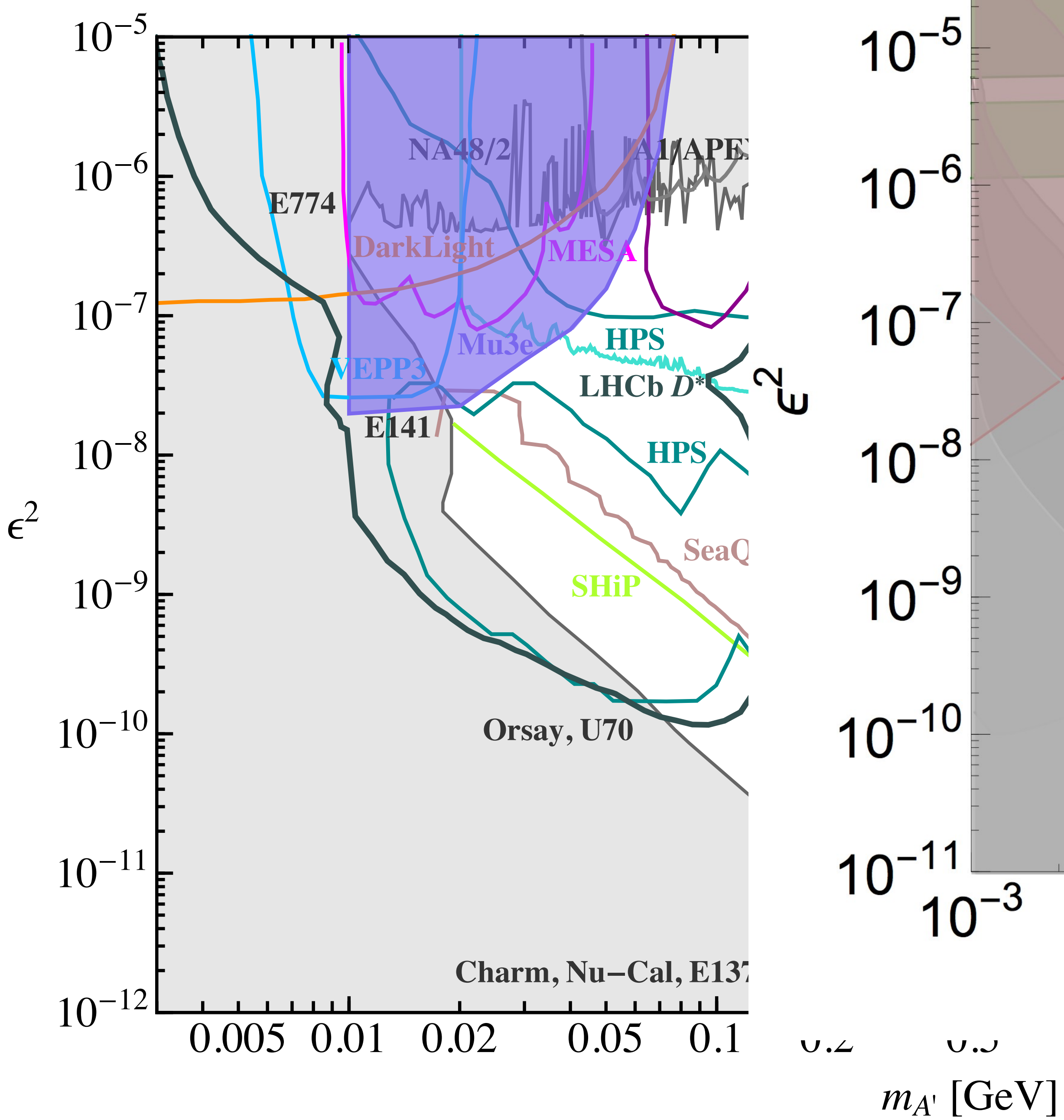
$$\mu^+ \to \gamma' e^+ \nu_e \bar{\nu}_\mu \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$$

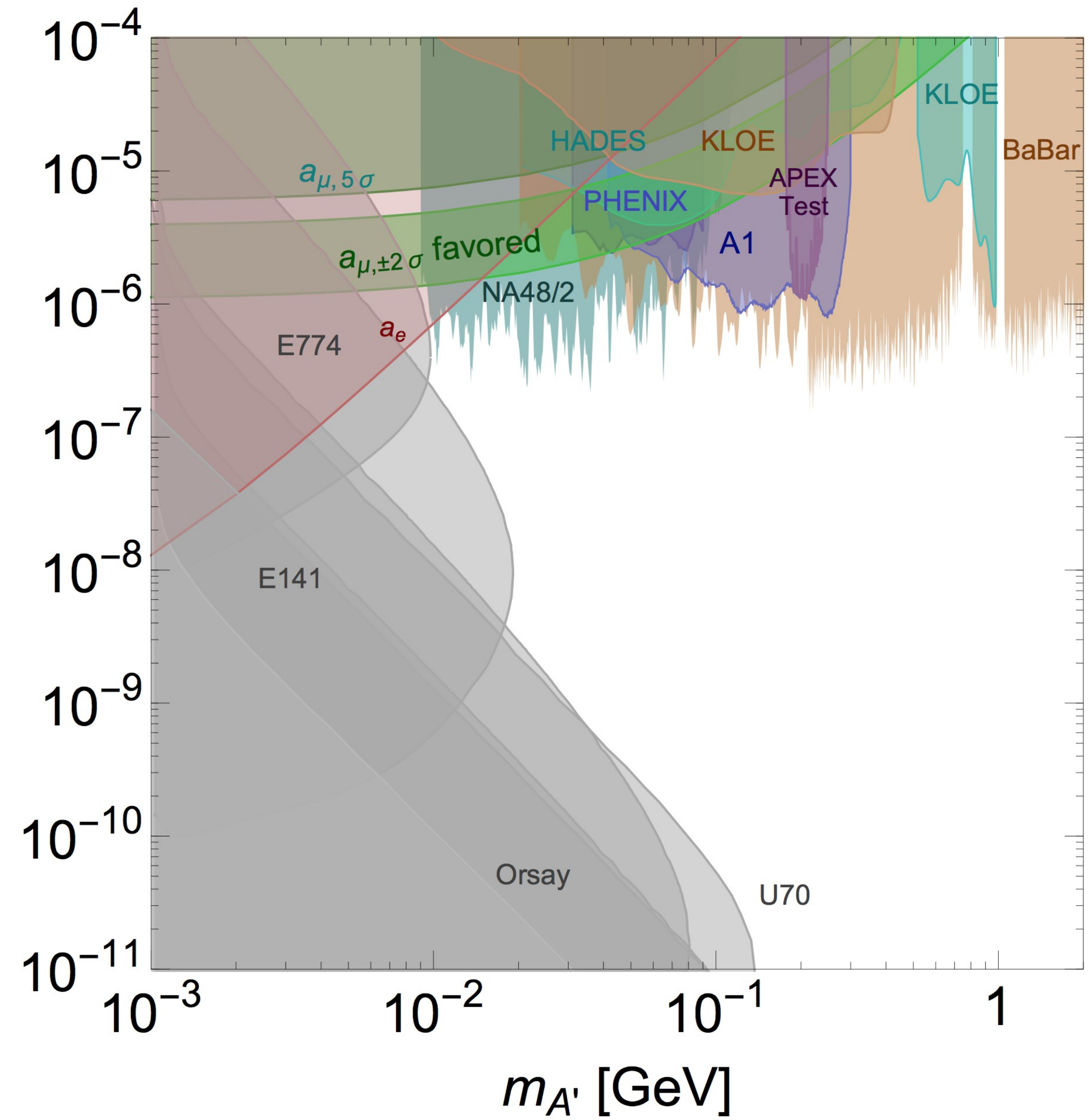


[Echenard, Essig, Zhong, *1411.1770*]

Searching all the hidden Photons

$$\mu^+ \to \gamma' e^+ \nu_e \bar{\nu}_\mu \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$$

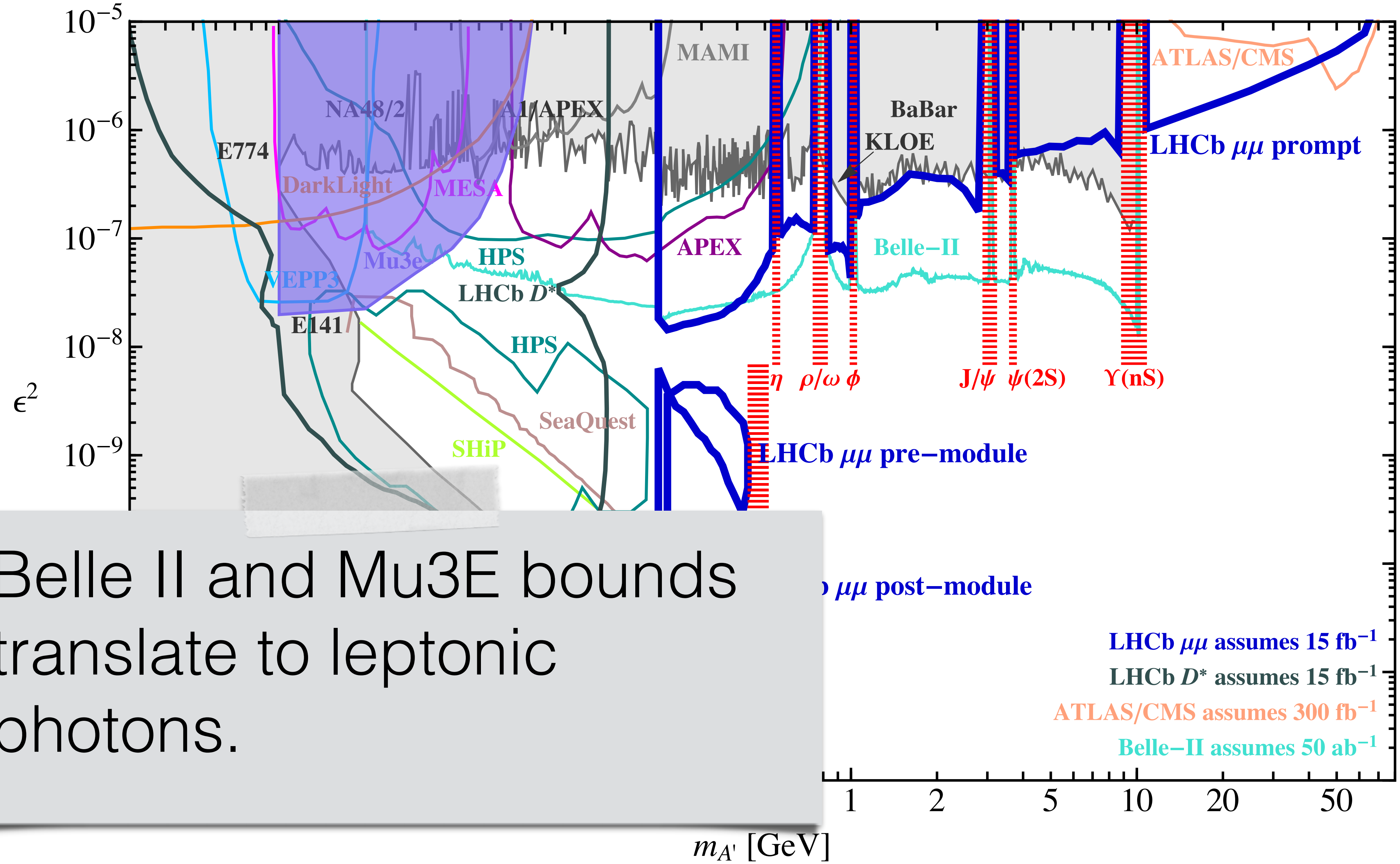




[Echenard, Essig, Zhong, *1411.1770*]

Searching all the hidden Photons

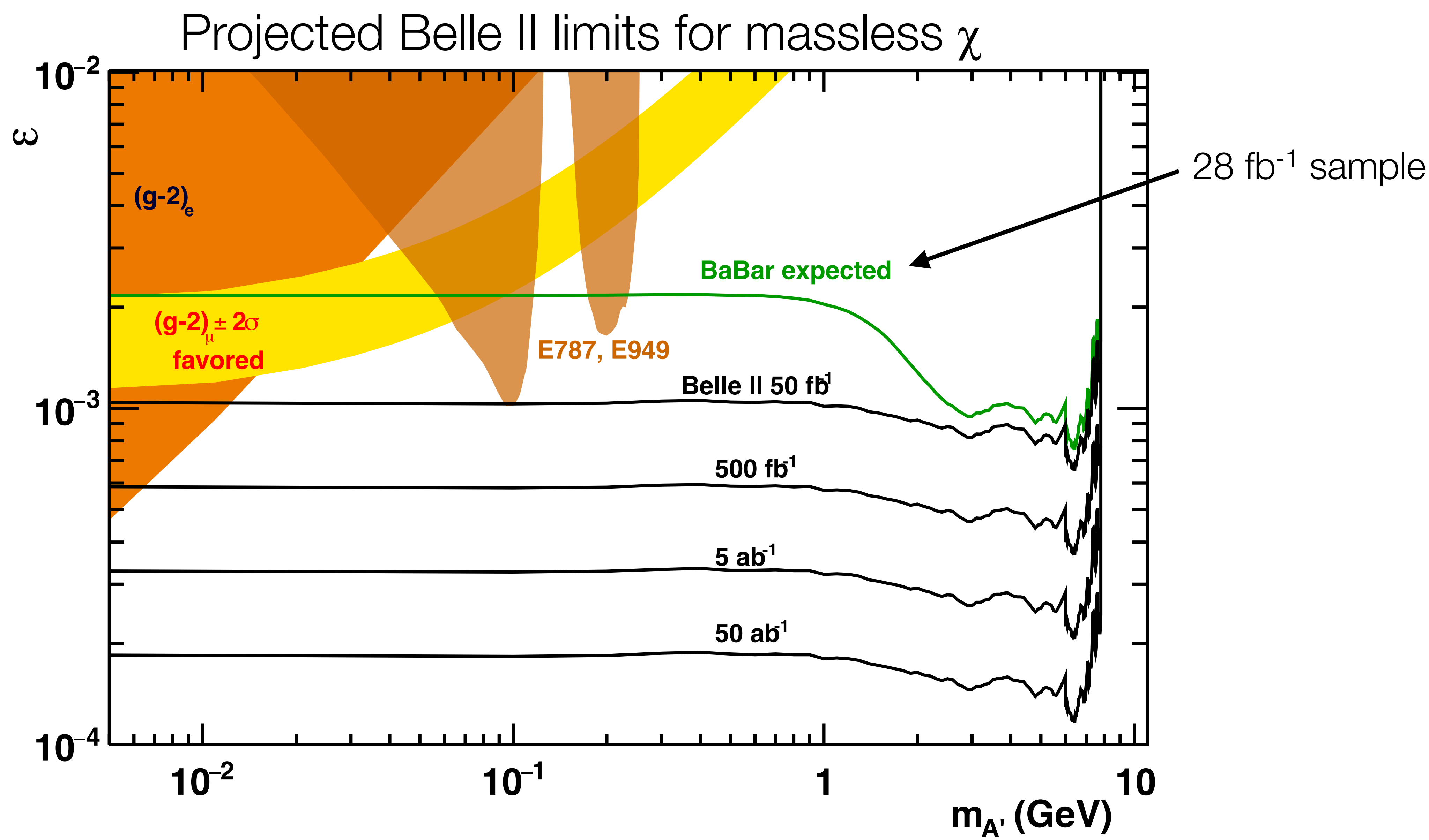
$$\mu^+ \to \gamma' e^+ \nu_e \bar{\nu}_\mu \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$$



Belle II and Mu3E bounds translate to leptonic photons.

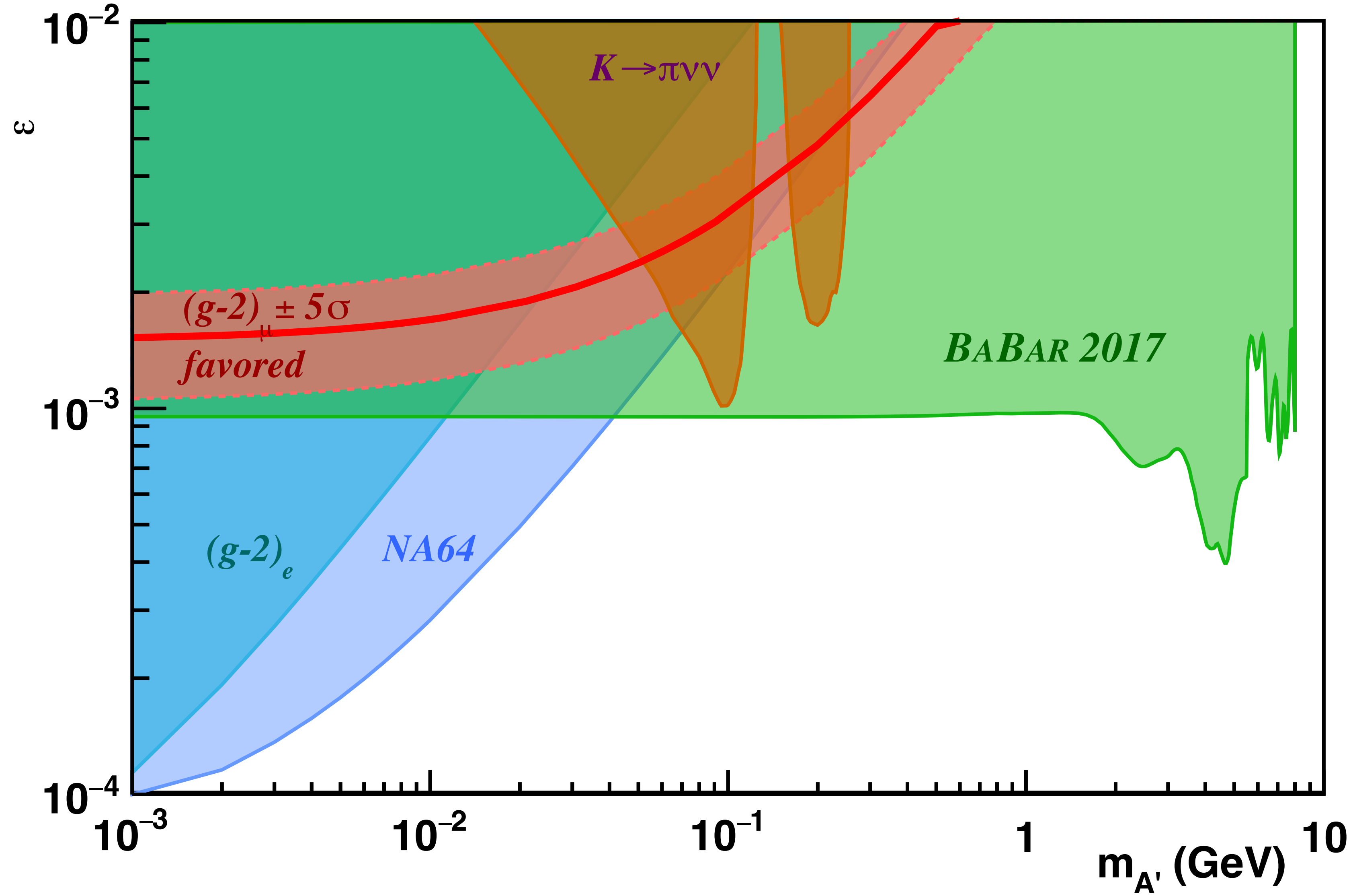
Ilten *et al.* Phys. Rev. Lett. **116**, no. 25, 251803 (2016)

Searching all the hidden Photons



C. Hearty | Dark Photon measurements at Belle II

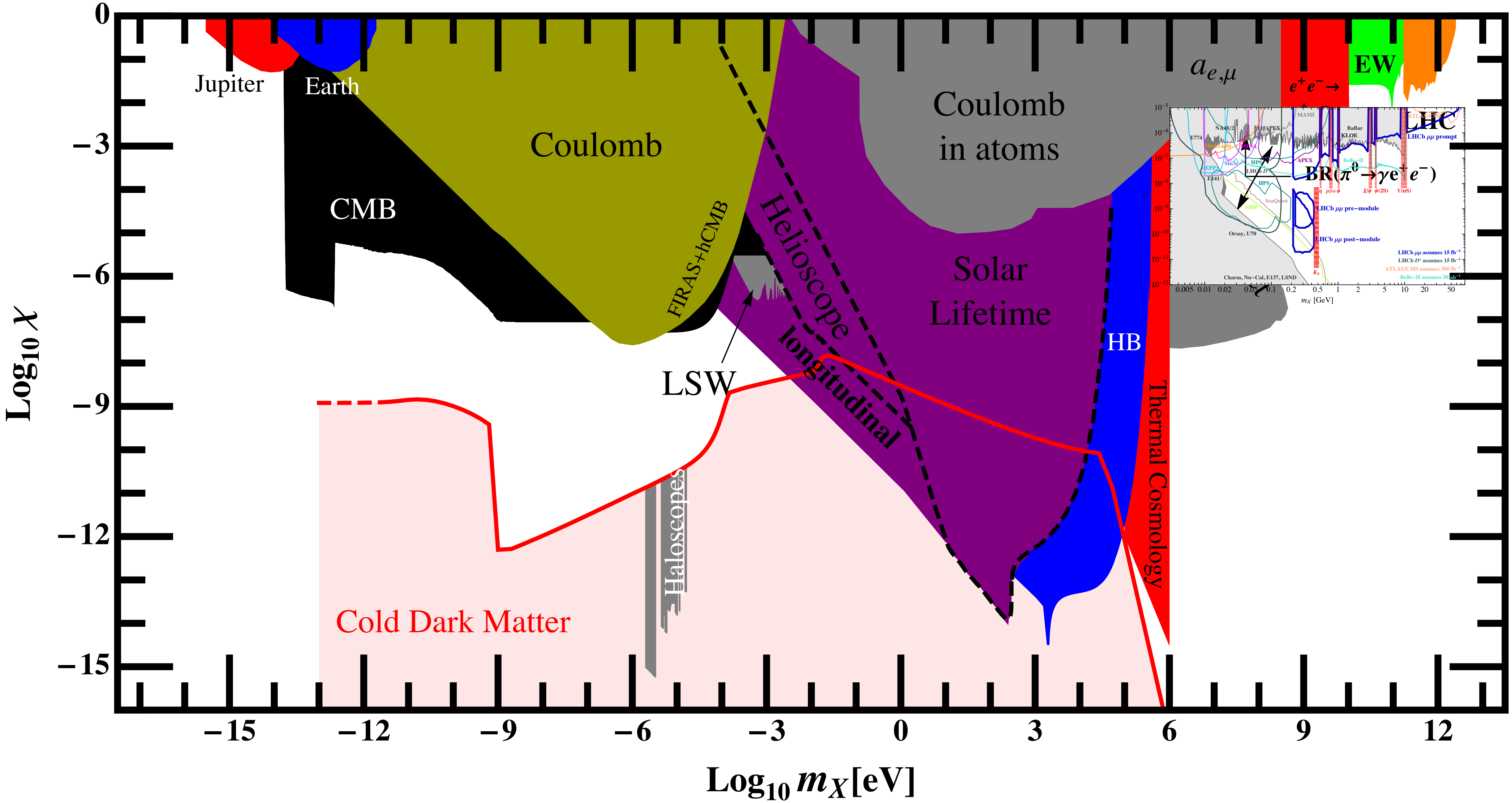
Searching all the hidden Photons



[BaBar 1702.03327]

Hidden Photon Dark Matter

Possible, but only non-thermal…and out of reach.



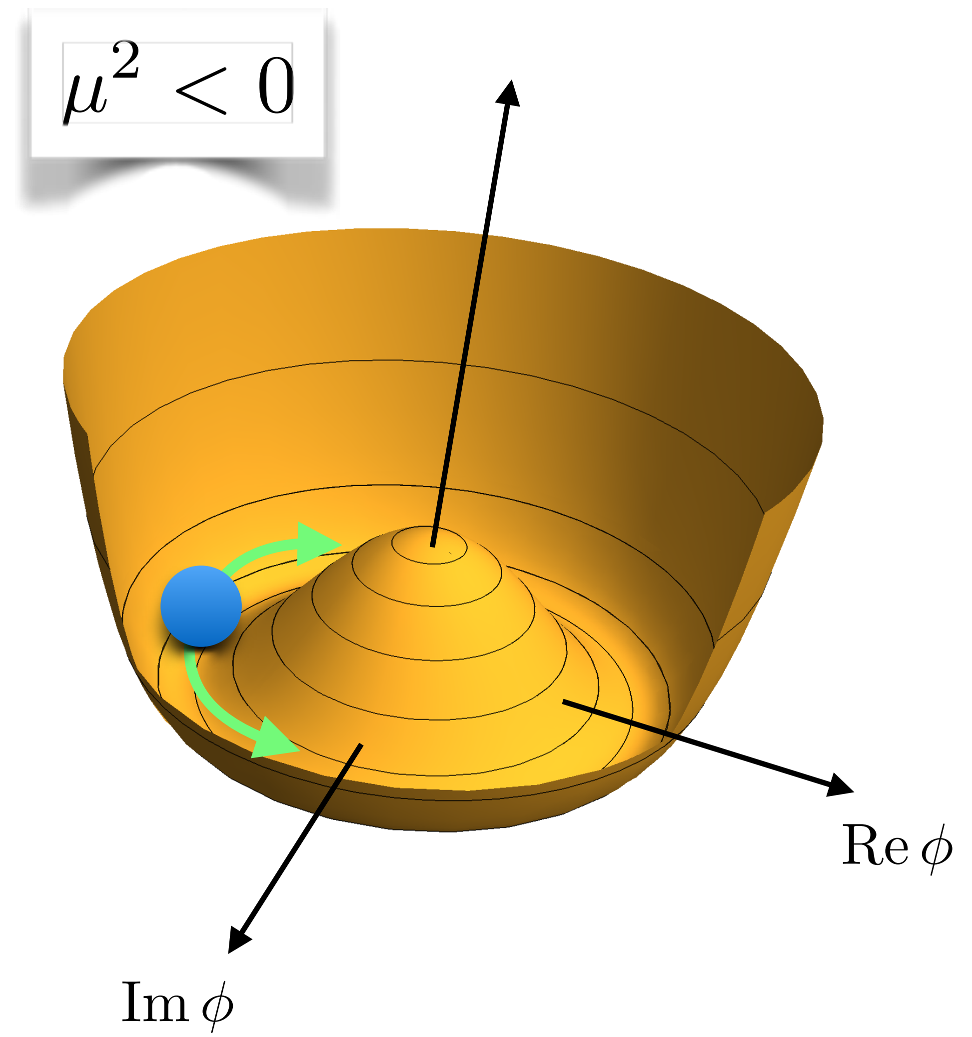
Goldstone Bosons

Goldstone bosons are the phases of symmetry breaking scalars.

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$\phi = \mathrm{Re}\,\phi + i\,\mathrm{Im}\,\phi \;= h\, e^{i\varphi}$$

$$m_h^2 = |\mu^2| \qquad\qquad m_\varphi^2 = 0$$



Goldstone bosons are massless, but can acquire masses due to explicit breaking.

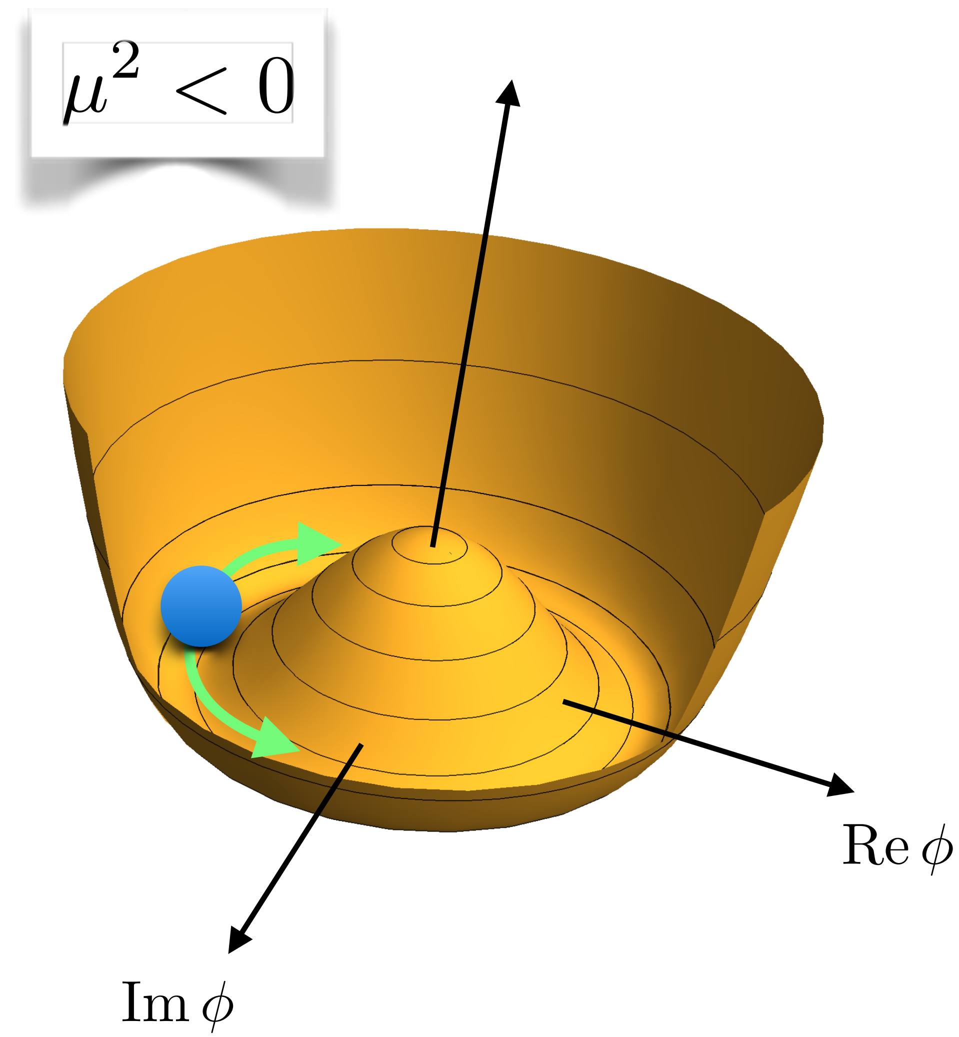
Goldstone Bosons

They are typically lighter than the scale of the UV completion.

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i \not{D}\, q_L + \bar{q}_R i \not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \approx (140\,{\rm MeV})^2$$



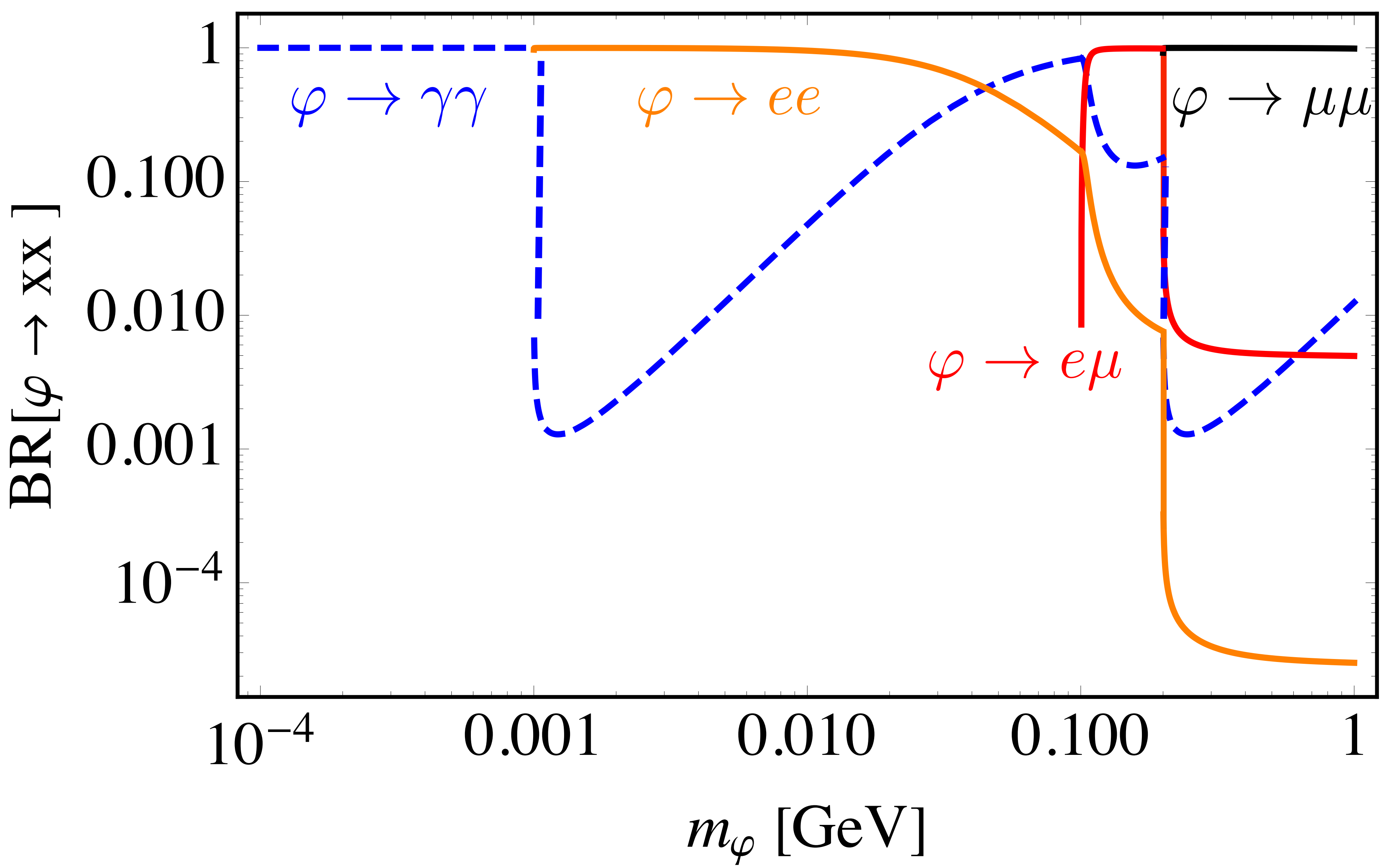
Discovering Pseudo-goldstone bosons reveals non-trivial information about the UV theory.

Familons

Scalar couplings are proportional to masses

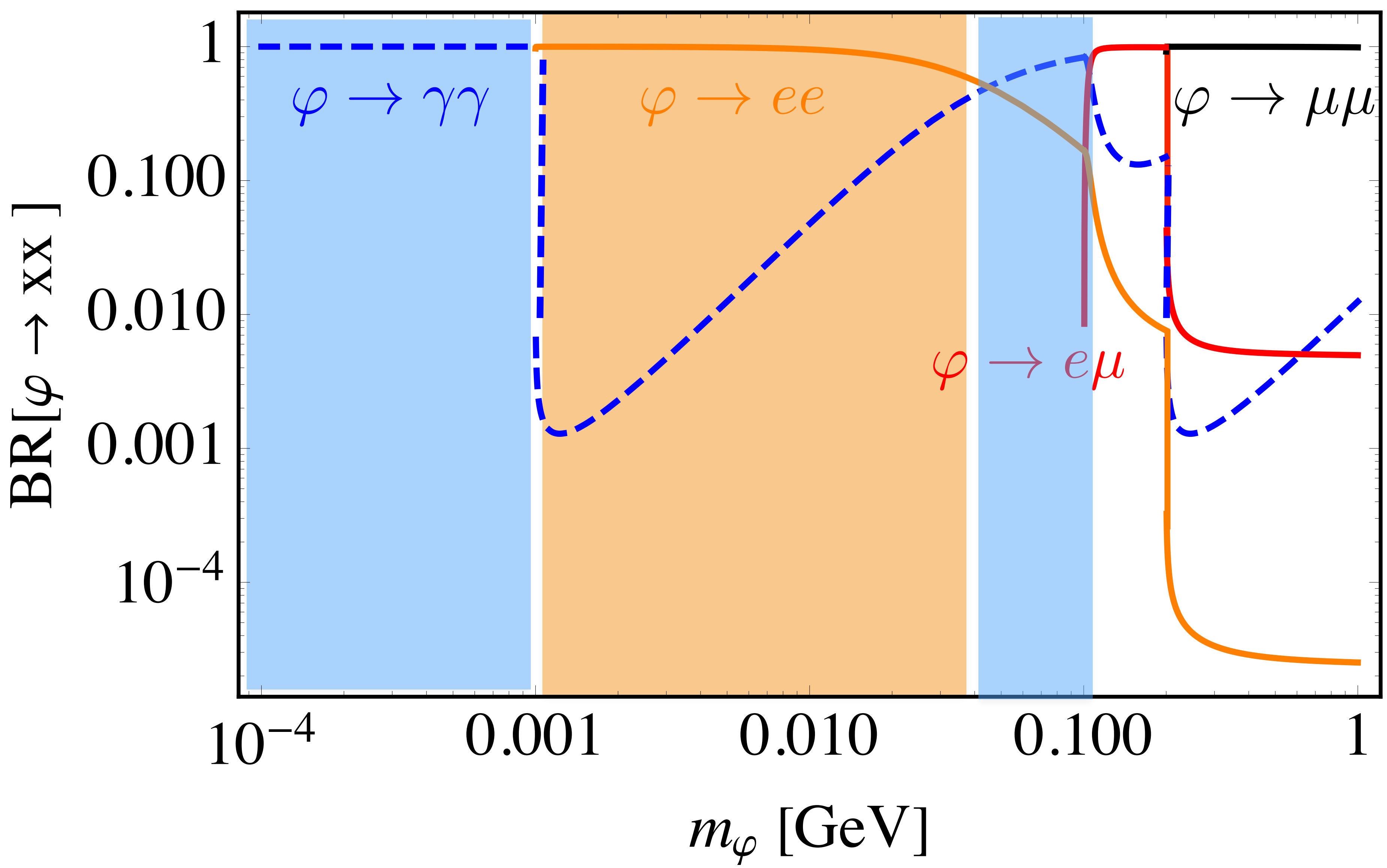
$$\mathcal{L} = A_{ij}\frac{\varphi}{f}\bar{\ell}_i\gamma_5\ell_j + \ldots$$

$$A = (m_i + m_j)\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{\mu e} & a_{\mu\mu} & a_{\mu\tau} \\ a_{\tau e} & a_{\tau\mu} & a_{\tau\tau} \end{pmatrix}$$



Familons

Different Regimes: $\varphi \to ee$ $\varphi \to \gamma\gamma$ φ stable

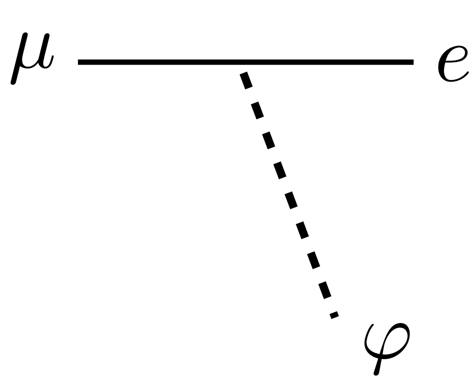


[MB, Jaeckel, Foldenauer, Perrevoort, Schoening]

Familons

Different Regimes:

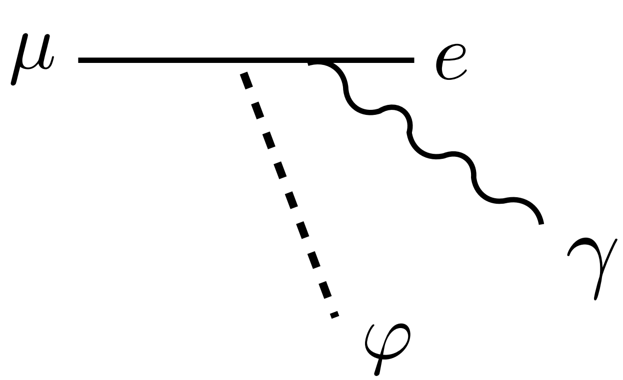
$\varphi \quad \text{stable}$



Distinguishable from Michel decays due to kinematics

$$p_e \propto \sqrt{\left(\frac{m_\mu^2 - m_\varphi^2 + m_e^2}{2m_\mu}\right)^2 - m_e^2}$$

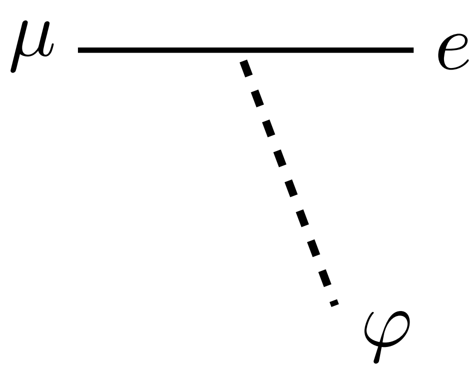
[A. Jodidio et al., Phys. Rev. D 34, 1967 (1986)]



[R. D. Bolton et al., Phys. Rev. D 38, 2077 (1988)]

Familons

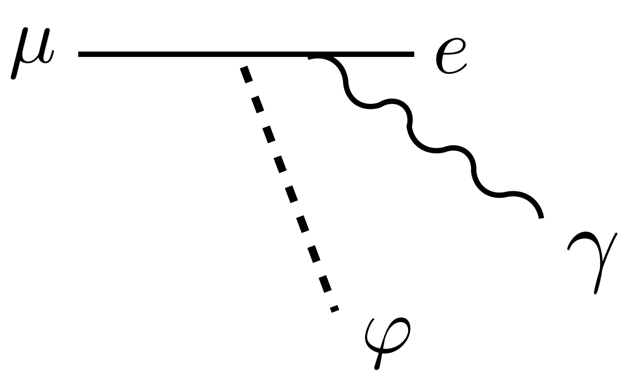
Different Regimes: φ stable



$$\mathrm{BR}(\mu^+ \to e^+\varphi) < 3 \times 10^{-6}$$

$$f > 5.5 \times 10^9 \, a_{\mu e} \mathrm{GeV}$$

[A. Jodidio et al., Phys. Rev. D 34, 1967 (1986)]



$$\mathrm{BR}(\mu^+ \to e^+\varphi\gamma) < 1.1 \times 10^{-9}$$

$$f > 3.1 \times 10^9 \, a_{\mu e} \mathrm{GeV}$$

[R. D. Bolton et al., Phys. Rev. D 38, 2077 (1988)]

Familons

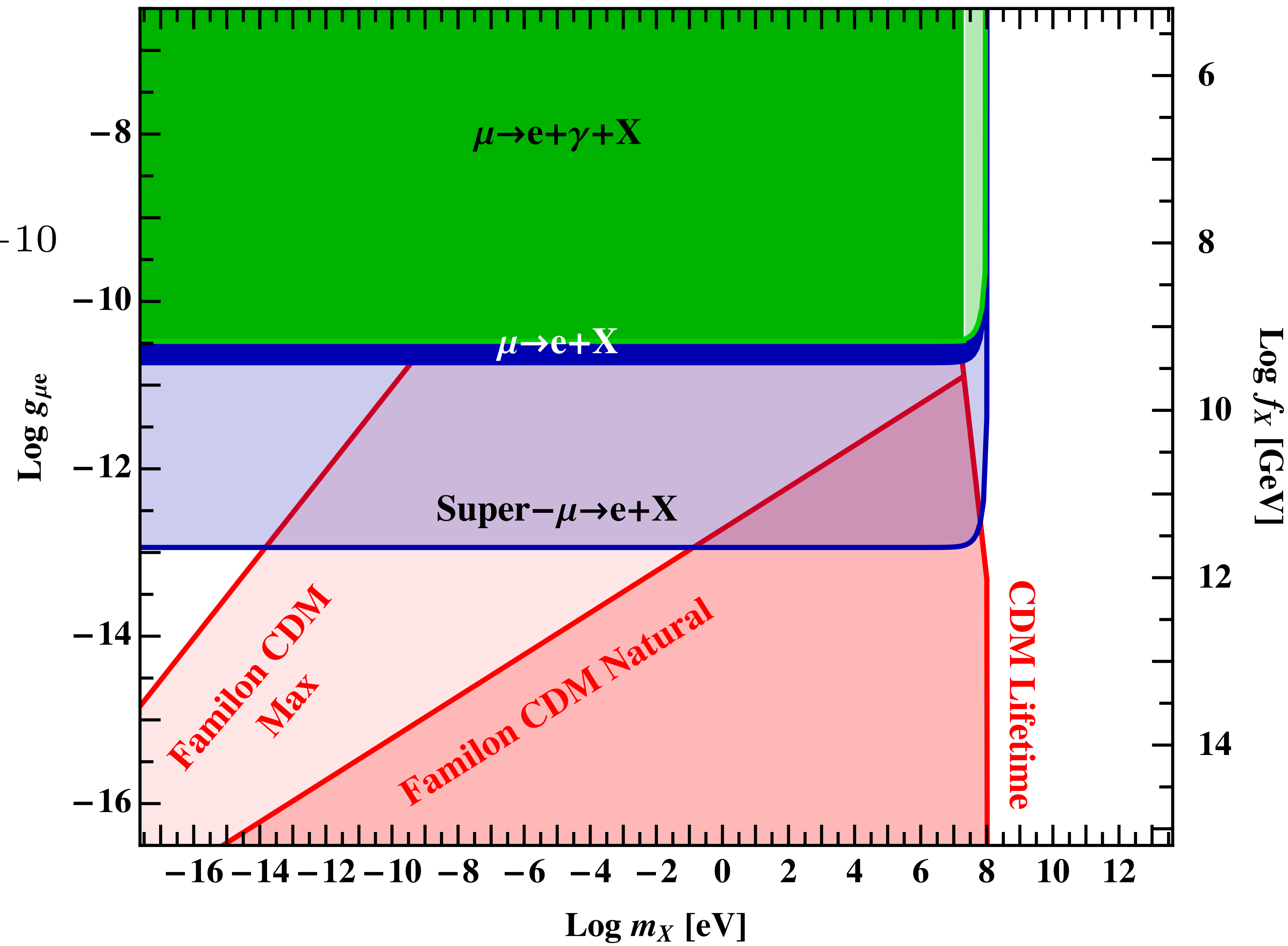
Different Regimes:

φ stable

Projected Limit for

$$\text{BR}(\mu^+ \to e^+\varphi) < 1 \times 10^{-10}$$

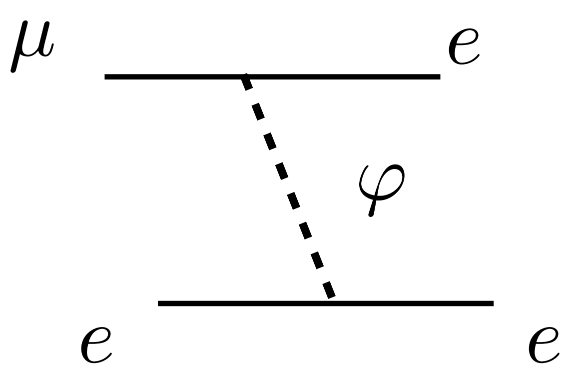
Can probe GB Dark Matter!



[MB, Jaeckel, Foldenauer, Perrevoort, Schoening]

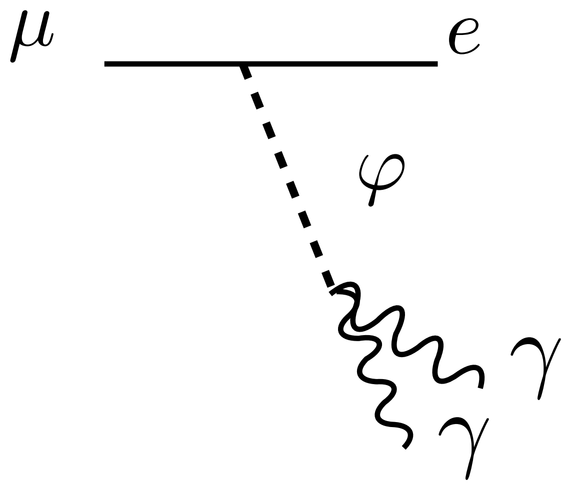
Familons

Different Regimes: $\varphi \to ee$



well…

Different Regimes: $\varphi \to \gamma\gamma$



Can this be measured?

[MB, Jaeckel, Foldenauer, Perrevoort, Schoening]

Familons

What about couplings to taus?

$$A = (m_i + m_j)\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{\mu e} & a_{\mu\mu} & a_{\mu\tau} \\ a_{\tau e} & a_{\tau\mu} & a_{\tau\tau} \end{pmatrix}$$

Constraints are not very strong

ARGUS

$$\mathrm{BR}(\tau^- \to \mu^- \varphi) < 4.6 \times 10^{-3}$$
$$\mathrm{BR}(\tau^- \to \mu^- \varphi) < 2.6 \times 10^{-3}$$

$$f < 3.2 \times 10^6 \, a_{\tau\mu} \, \mathrm{GeV}$$

$$f < 4.4 \times 10^6 \, a_{\tau e} \, \mathrm{GeV}$$

ARGUS Collaboration, H. Albrecht et al., Z. Phys. C 68, 25 (1995).

Familons

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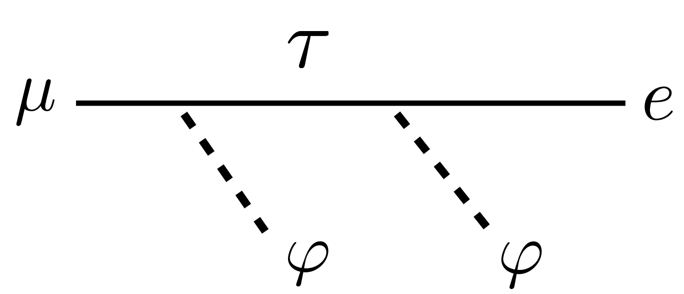
$$A = (m_i + m_j) \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{\mu e} & a_{\mu\mu} & a_{\mu\tau} \\ a_{\tau e} & a_{\tau\mu} & a_{\tau\tau} \end{pmatrix}$$



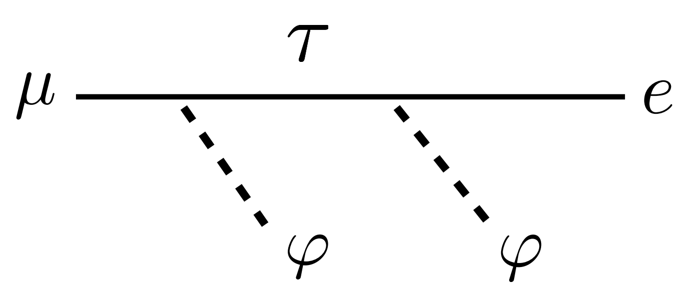
$\mathrm{BR}(\mu^+ \to \varphi\varphi e^+)$ impossible?

[MB, Jaeckel, Foldenauer, Perrevoort, Schoening]

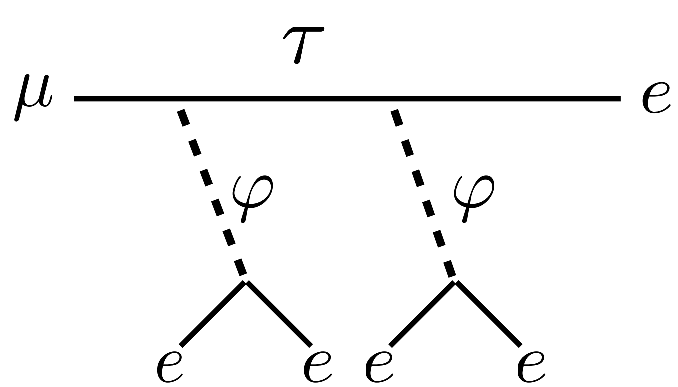
Familons

What about couplings to taus?

$$A = (m_i + m_j) \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{\mu e} & a_{\mu\mu} & a_{\mu\tau} \\ a_{\tau e} & a_{\tau\mu} & a_{\tau\tau} \end{pmatrix}$$



$\mathrm{BR}(\mu^+ \to \varphi\varphi e^+)$ impossible?



$$\mathrm{BR}(\mu^+ \to e^+ e^- e^+ e^- e^+)$$

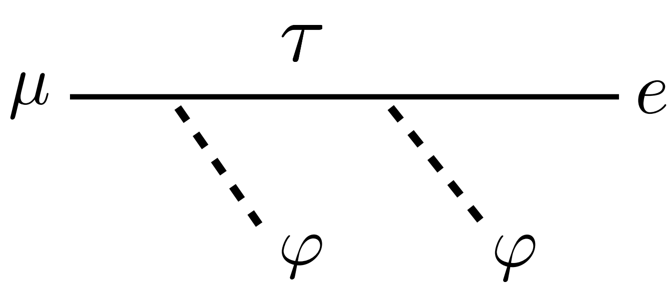
$$p_e \approx 20\,\mathrm{MeV}$$

[MB, Jaeckel, Foldenauer, Perrevoort, Schoening]

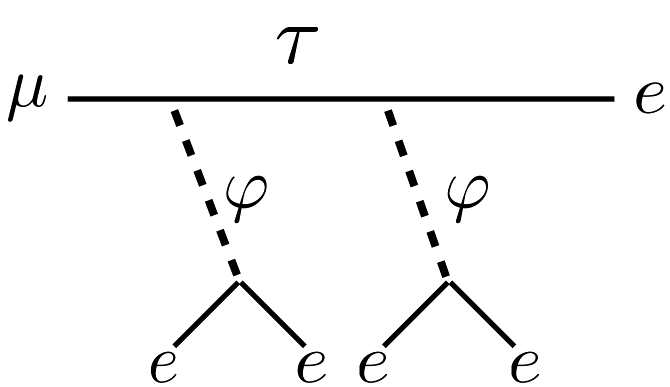
Familons

What about couplings to taus?

$$A = (m_i + m_j) \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{\mu e} & a_{\mu\mu} & a_{\mu\tau} \\ a_{\tau e} & a_{\tau\mu} & a_{\tau\tau} \end{pmatrix}$$

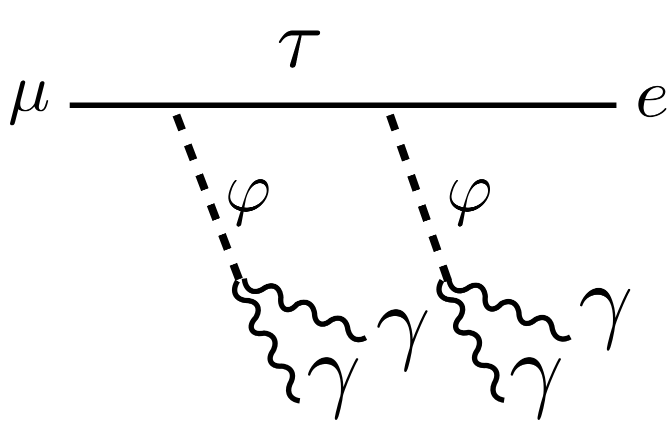


$\mathrm{BR}(\mu^+ \to \varphi\varphi e^+)$ impossible?



$$\mathrm{BR}(\mu^+ \to e^+ e^- e^+ e^- e^+)$$

$$p_e \approx 20\,\mathrm{MeV}$$



$$\mathrm{BR}(\mu^+ \to \gamma\gamma\gamma\gamma e^+)$$

[MB, Jaeckel, Foldenauer, Perrevoort, Schoening]

Conclusions

Signs of New Physics increase in observables related to muons.

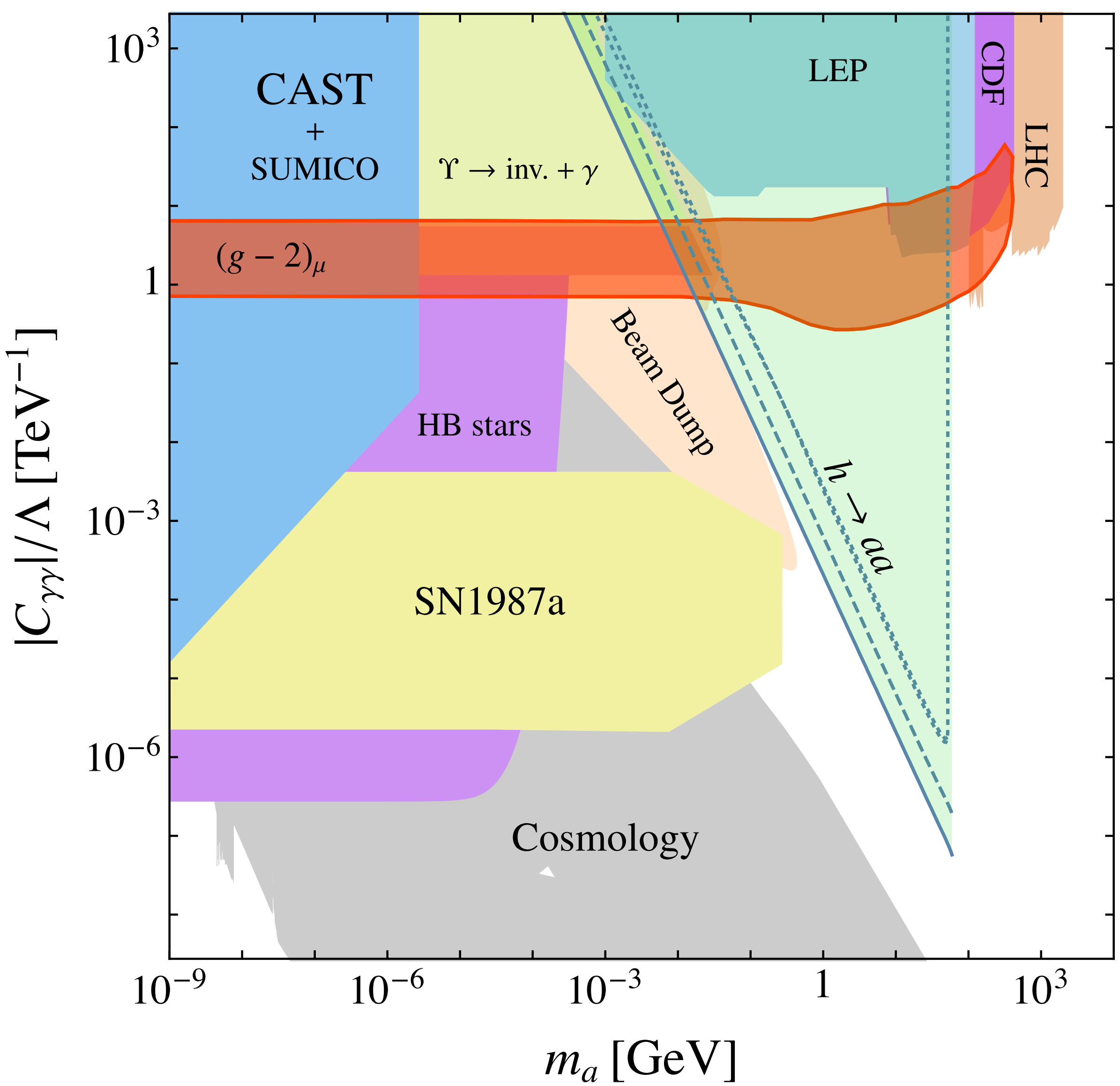
A new golden age of lepton flavour experiments is going to deliver unprecedented precision.

There is a great discovery potential for new light gauge bosons and goldstone bosons.

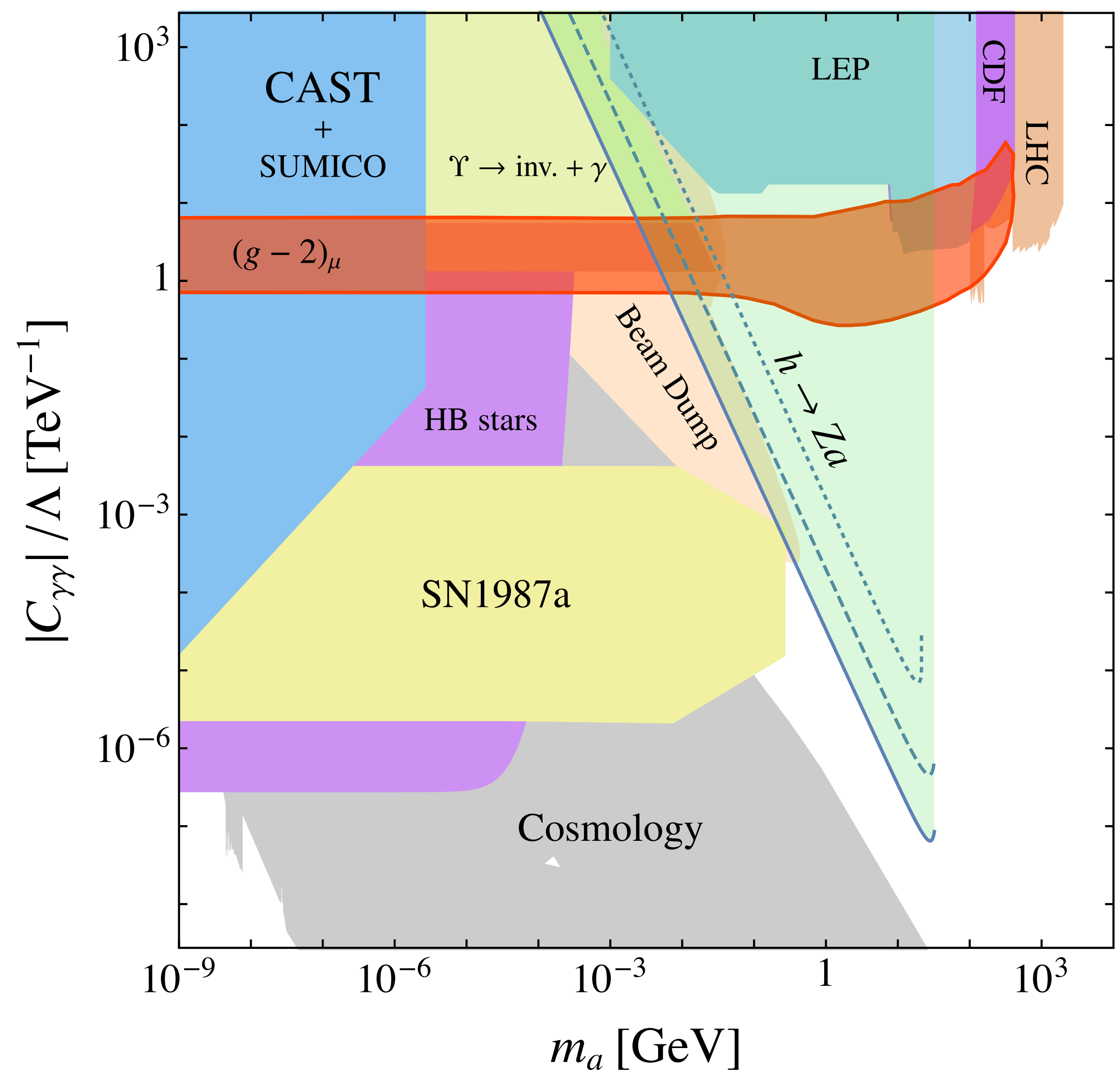
Backup

Searches with Higgs Decays

$$h \to aa \to 4\gamma$$



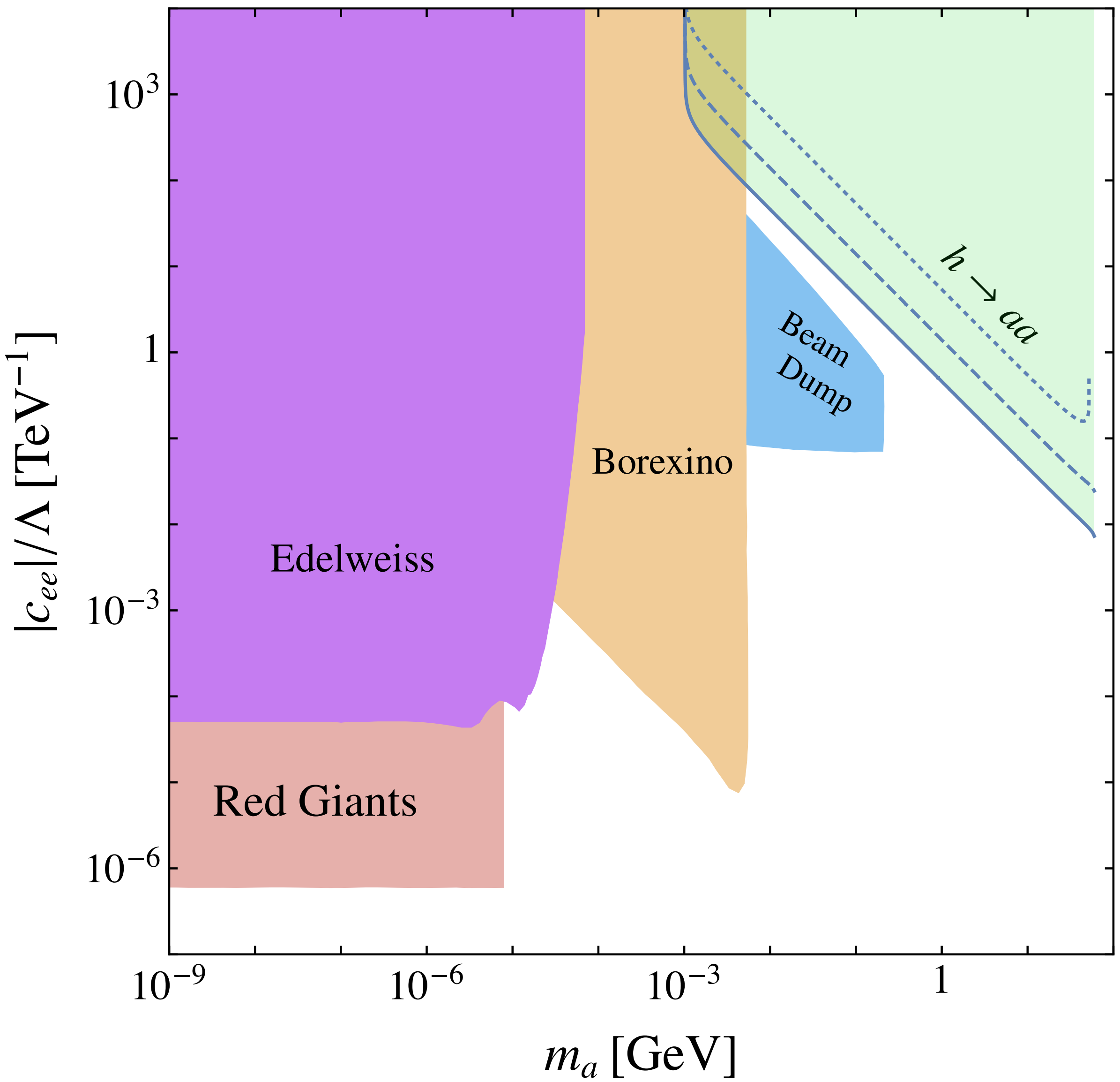
$$h \to Za \to \ell^+\ell^- 2\gamma$$



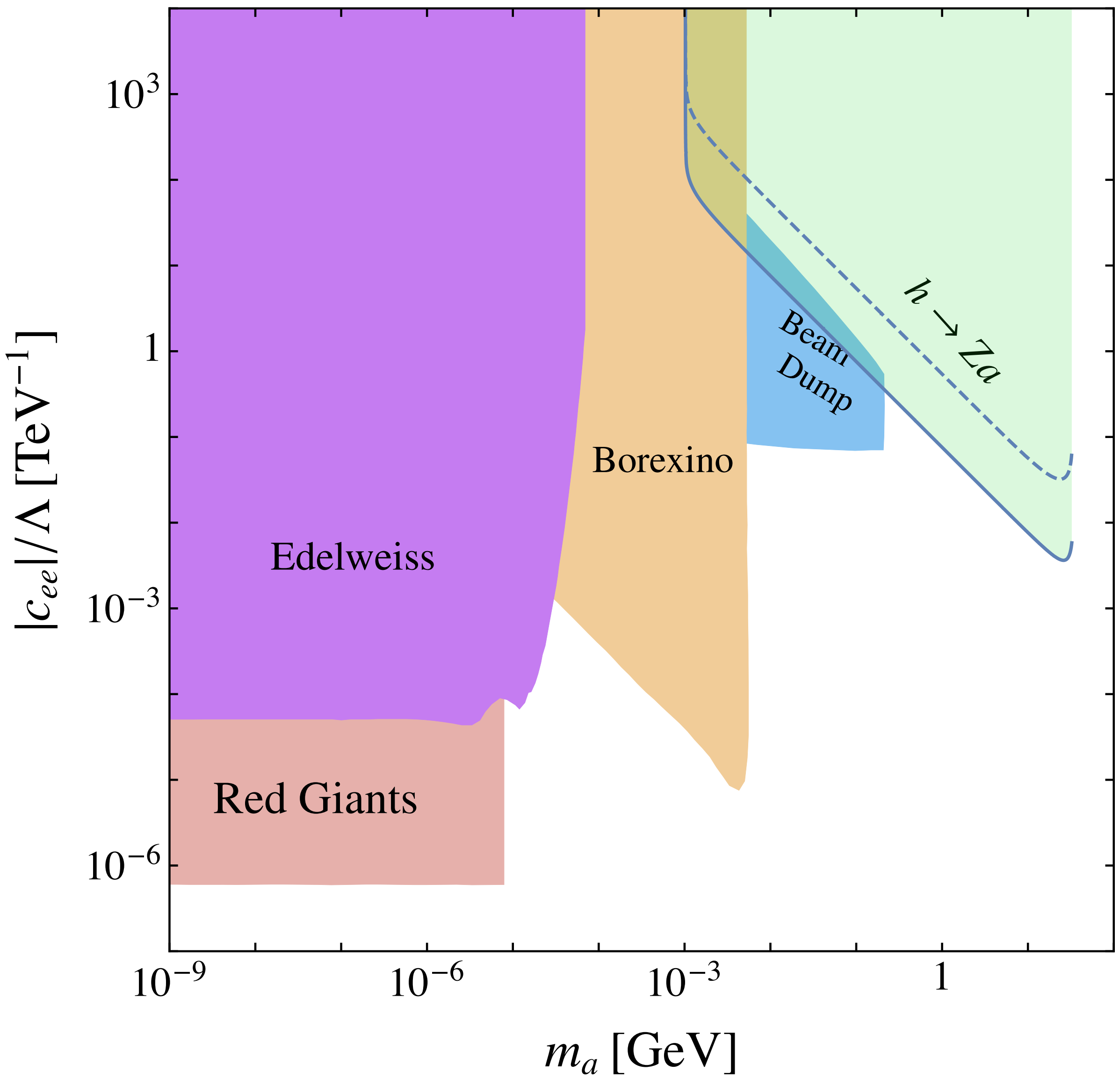
[MB, Neubert,Thamm, 1704.08207]

Searches with Higgs Decays

$$h \to aa \to e^- e^+ e^- e^+$$



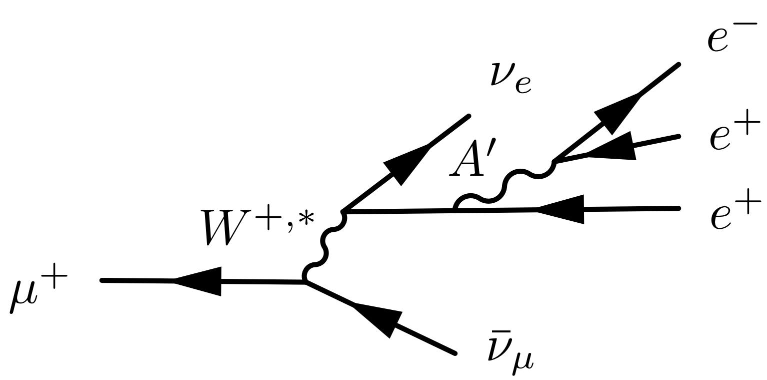
$$h \to Za \to e^- e^+ e^- e^+$$

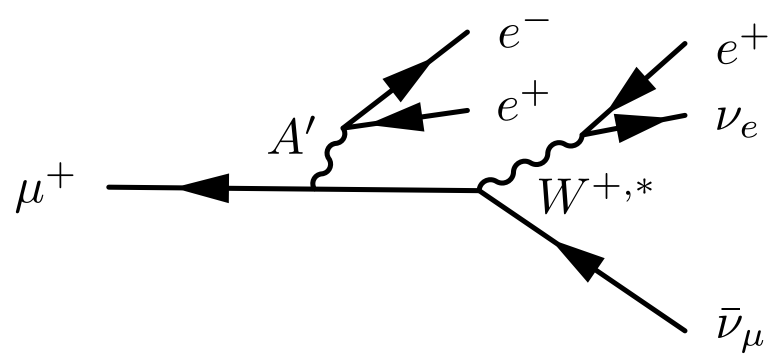


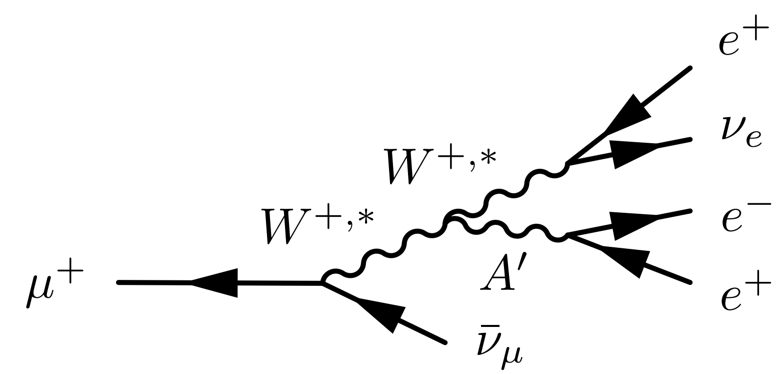
[MB, Neubert,Thamm, 1704.08207]

Searching all the hidden Photons

$$\mu^+ \to \gamma' e^+ \nu_e \bar{\nu}_\mu \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$$







$$\propto \frac{m_\mu^2}{M_W^2} \approx 10^{-6}$$

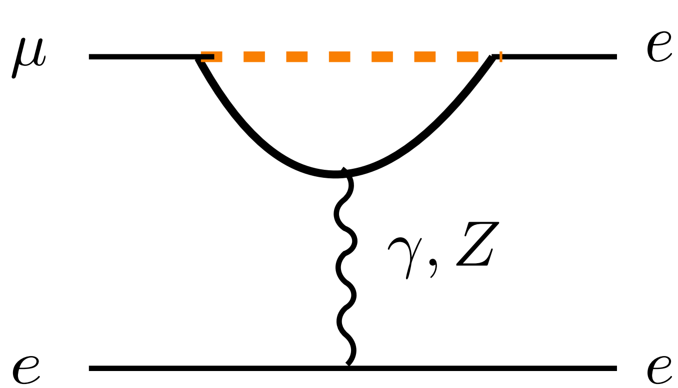
Belle II and Mu3E bounds translate to leptonic photons.

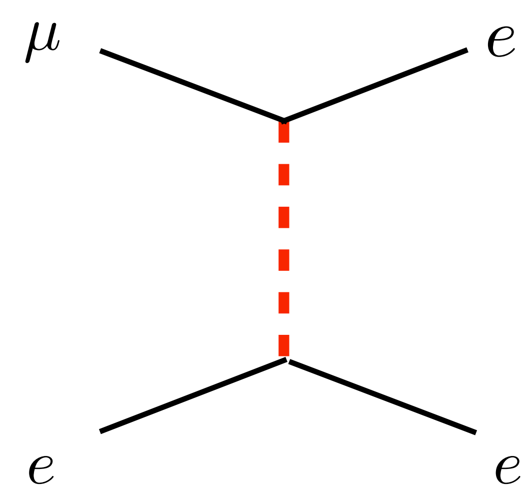
[Echenard, Essig, Zhong, *1411.1770*]

What can we learn?

Limits on New Physics

$$\mathcal{L}_{\rm LFV} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_R\,\sigma^{\mu\nu}e_L\,F_{\mu\nu} + \frac{1}{\Lambda^2}\left(\bar{\mu}_L\gamma^\mu e_L\right)\left(\bar{e}_L\gamma_\mu e_L\right)$$





probes scales up to $\Lambda \approx 1000 - 4000\,\mathrm{TeV}$