SUPERWEAK FORCE

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FFK-2019, Tihany, 11 June 2019

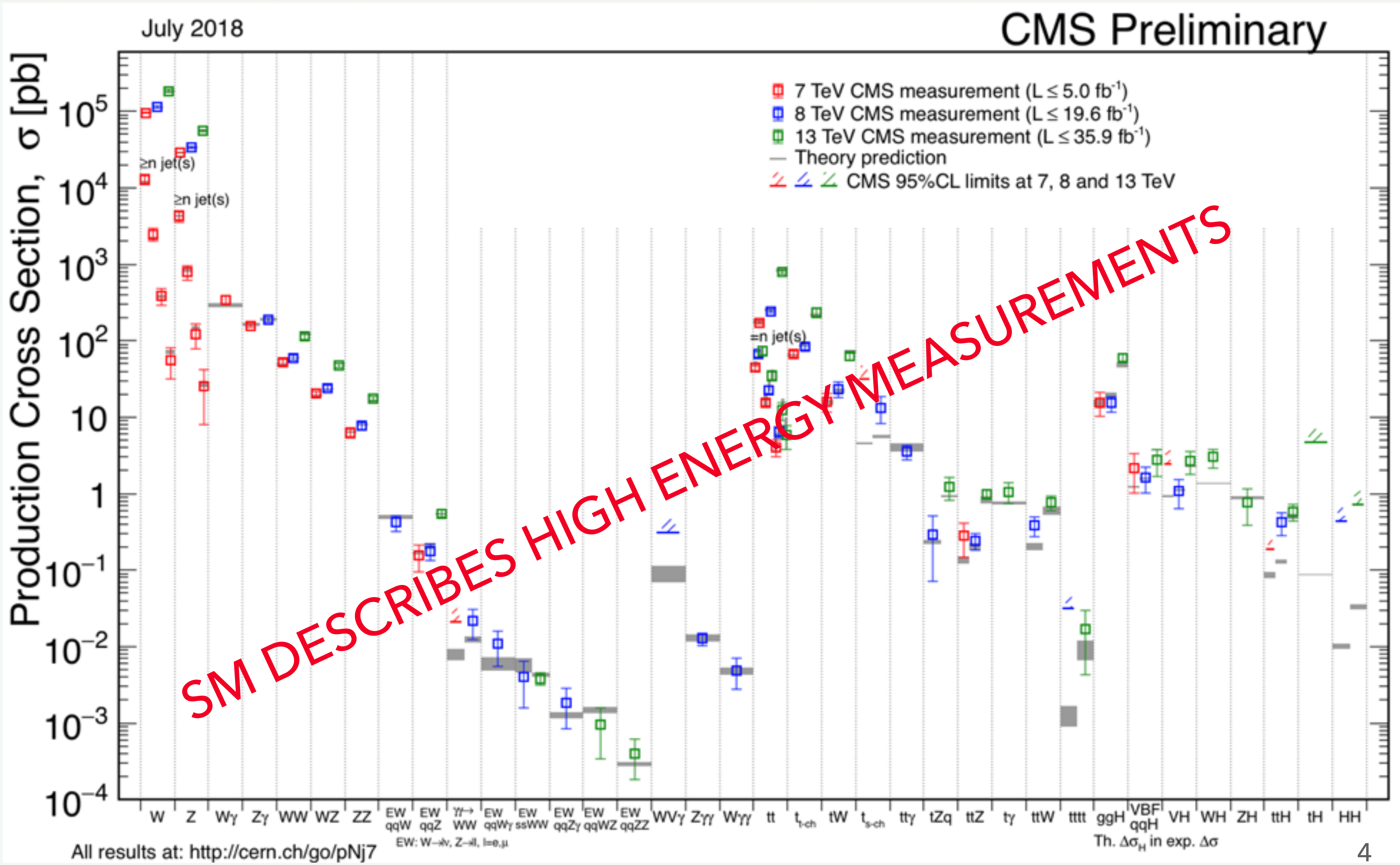
OUTLINE

1. Status of particle physics
2. $U(1)_Z$ extension of SM
3. Constraints on the parameter space

Status of particle physics: energy frontier

- LEP, LHC: SM describes final states of particle collisions precisely [remember talks of Monday afternoon]

SM@LHC: theory vs. 36 measurements at CMS



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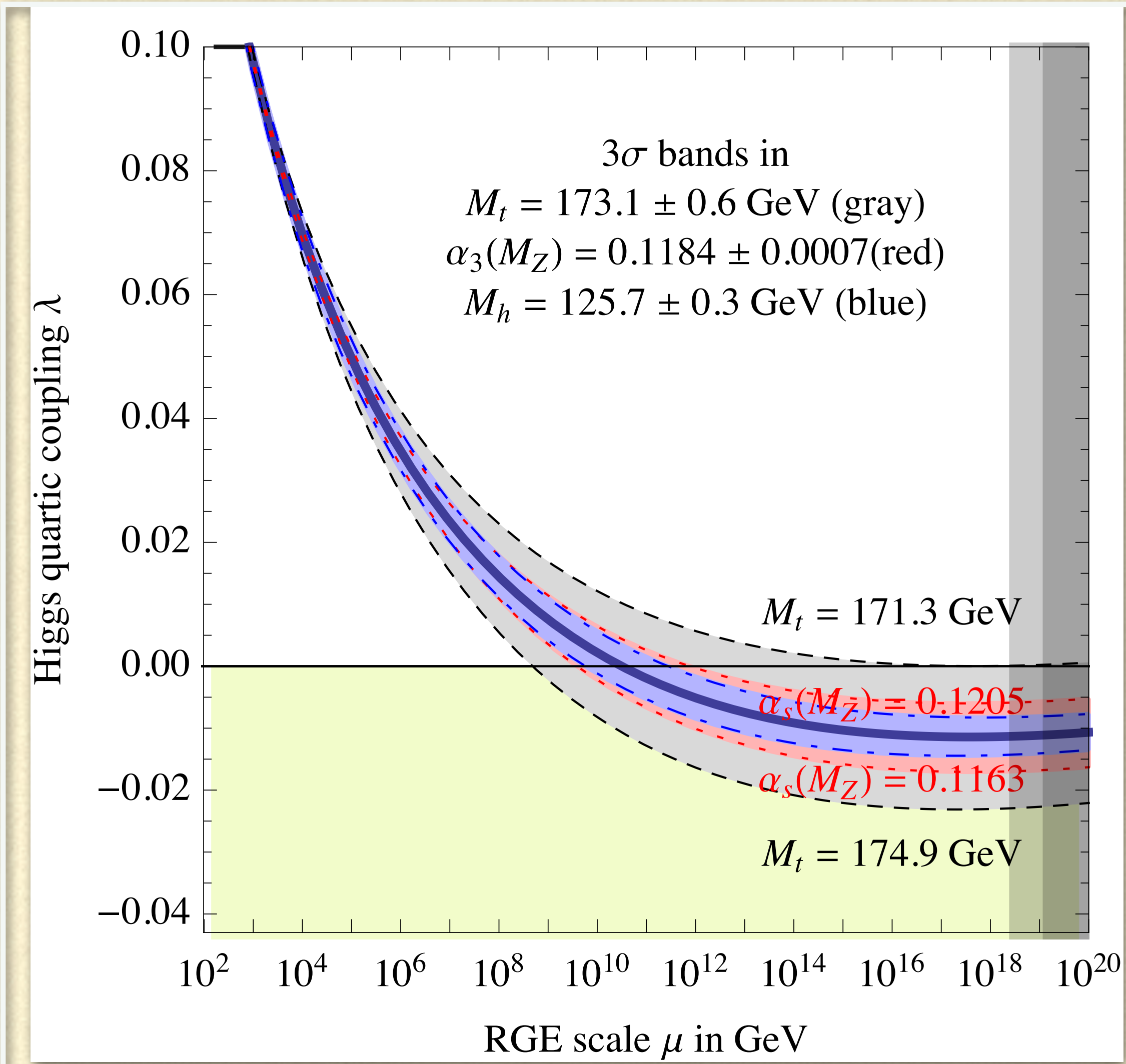

Degrassi et al., arXiv:1205.6497

Status of particle physics: energy frontier

- LEP, LHC: SM describes final states of particle collisions precisely
- SM is unstable
- No proven sign of new physics beyond SM at colliders*

*There are some indications below discovery significance (such as muon anomalous magnetic moment, lepton flavor non-universality in meson decays)

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- Universe at large scale described precisely by cosmological SM: ΛCDM ($\Omega_m = 0.3$)

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- Neutrino flavours oscillate
- Existing baryon asymmetry cannot be explained by CP asymmetry in SM
- Inflation of the early, accelerated expansion of the present Universe

Extension of SM

- There are many extensions proposed, mostly with the aim of predicting some observable effect at the LHC – but there are none so far, so may give up

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- SM is highly efficient – let us stick to efficiency

the only exception of economical description is the relatively large number of Yukawa couplings

Extension of SM

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  with non-zero masses they must feel another force apart from the weak one, such as Yukawa coupling to a scalar, which requires the existence of right-handed neutrinos

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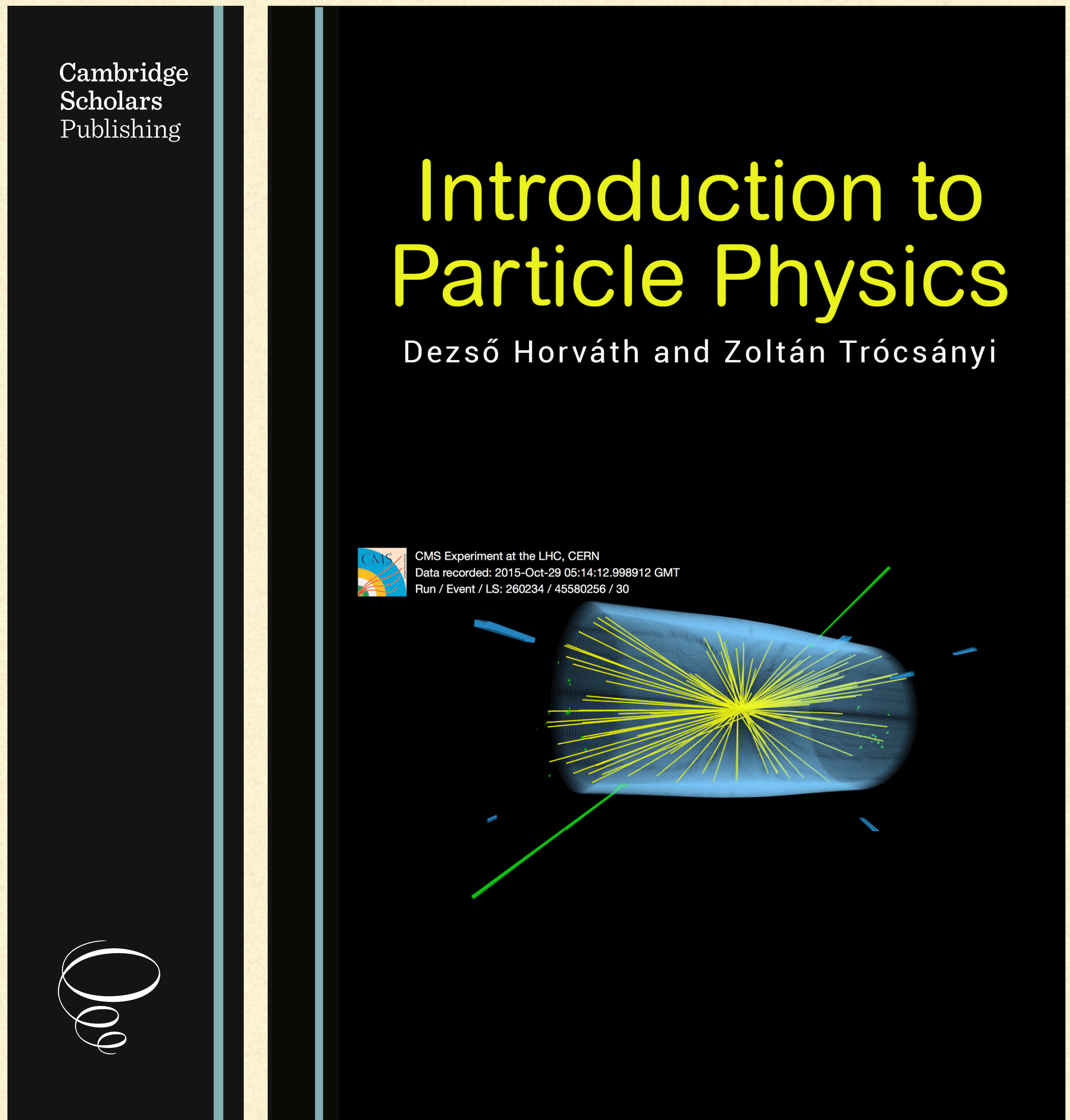
- Fix Z-charges by requirement of
  - gauge and gravity anomaly cancellation and
  - gauge invariant Yukawa terms for neutrino mass generation

Focus only on addition to the SM, find SM in this new book:



Fermions

- fermion fields:

$$\psi^f_{q,1} = \begin{pmatrix} U^f \\ D^f \end{pmatrix}_{\rm L} \qquad \psi^f_{q,2} = U^f_{\rm R}\,, \qquad \psi^f_{q,3} = D^f_{\rm R}$$

$$\psi^f_{l,1} = \begin{pmatrix} \nu^f \\ \ell^f \end{pmatrix}_{\rm L} \qquad \psi^f_{l,2} = \nu^f_{\rm R}\,, \qquad \psi^f_{l,3} = \ell^f_{\rm R}$$

where

$$\psi_{\rm L/R} \equiv \psi_{\mp} = \frac{1}{2}\,(1 \mp \gamma_5)\,\psi \equiv P_{\rm L/R}\psi$$

($\nu_{\rm L}$ can $\nu_{\rm R}$ can also be Majorana neutrinos, embedded into *different* Dirac spinors)

- covariant derivatives:

$$D^\mu_j = \partial^\mu + {\rm i}g_{\rm L}\,\boldsymbol{T}\cdot\boldsymbol{W}^\mu + {\rm i}g_Y\,y_j B'^\mu + {\rm i}(g'_Z\,z_j - g'_Y\,y_j)Z'^\mu$$

Anomaly free charge assignment

field	$SU(3)_c$	$SU(2)_L$	y_j	z_j	z_j	$r_j = z_j/z_\phi - y_j$
$U_L,\ D_L$	3	2	$\frac{1}{6}$	z_1	$\frac{1}{6}$	0
U_R	3	1	$\frac{2}{3}$	z_2	$\frac{7}{6}$	$\frac{1}{2}$
D_R	3	1	$-\frac{1}{3}$	$2z_1 - z_2$	$-\frac{5}{6}$	$-\frac{1}{2}$
$\nu_L,\ \ell_L$	1	2	$-\frac{1}{2}$	$-3z_1$	$-\frac{1}{2}$	0
ν_R	1	1	0	$z_2 - 4z_1$	$\frac{1}{2}$	$\frac{1}{2}$
ℓ_R	1	1	-1	$-2z_1 - z_2$	$-\frac{3}{2}$	$-\frac{1}{2}$
ϕ	1	2	$\frac{1}{2}$	z_ϕ	1	$\frac{1}{2}$
χ	1	1	0	z_χ	-1	-1

essentially from neutrino-scalar interactions

Anomaly free charge assignment

re-parametrization

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χ	1	1	0	z_χ	-1	-1

$$D_j^\mu = \partial^\mu + \mathrm{i} g_L \boldsymbol{T} \cdot \boldsymbol{W}^\mu + \mathrm{i}\, y_j g_Y B'^\mu + \mathrm{i}\,(r_j g'_Z + y_j g'_{ZY})\, Z'^\mu$$

Scalars

- Standard Φ complex $SU(2)_L$ doublet and new χ complex singlet:

$$\mathcal{L}_{\phi,\chi} = [D_\mu^{(\phi)}\phi]^* D^{(\phi)\,\mu}\phi + [D_\mu^{(\chi)}\chi]^* D^{(\chi)\,\mu}\chi - V(\phi,\chi)$$

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- with scalar potential

$$V(\phi,\chi) = V_0 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 + \left(|\phi|^2, |\chi|^2\right)\begin{pmatrix}\lambda_\phi & \frac{\lambda}{2} \\ \frac{\lambda}{2} & \lambda_\chi\end{pmatrix}\begin{pmatrix}|\phi|^2 \\ |\chi|^2\end{pmatrix}$$

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- After SSB, G → SU(3)$_c$×U(1)$_{QED}$:

$$\phi = \frac{1}{\sqrt{2}}\,e^{i\boldsymbol{T}\cdot\boldsymbol{\xi}(x)/v}\begin{pmatrix}0\\ v + h'(x)\end{pmatrix} \;\&\; \chi(x) = \frac{1}{\sqrt{2}}\,e^{i\eta(x)/w}\left(w + s'(x)\right)$$

Fermion-scalar interactions

- Standard Yukawa terms:

$$\mathcal{L}_{\rm Y} = -\left[c_D\,(\bar{U},\,\bar{D})_{\rm L}\begin{pmatrix}\phi^{(+)}\\ \phi^{(0)}\end{pmatrix} D_{\rm R} + c_U\,(\bar{U},\,\bar{D})_{\rm L}\begin{pmatrix}\phi^{(0)\,*}\\ -\phi^{(+)\,*}\end{pmatrix} U_{\rm R} + c_\ell\,(\bar{\nu}_\ell,\,\bar{\ell})_{\rm L}\begin{pmatrix}\phi^{(+)}\\ \phi^{(0)}\end{pmatrix}\ell_{\rm R}\right] + {\rm h.c.}$$

- lead to fermion masses after SSB:

$$\mathcal{L}_{\rm Y} = -\left(1+\frac{h(x)}{v}\right)\left[\bar{D}_{\rm L}\,M_D\,D_{\rm R} + \bar{U}_{\rm L}\,M_U\,U_{\rm R} + \bar{\ell}_{\rm L}\,M_\ell\,\ell_{\rm R}\right] + {\rm h.c.}$$

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- Neutrino Yukawa terms $(z_\chi = -2z_{\nu_{\mathrm{R}}})$:

$$\mathcal{L}_{\mathrm{Y}}^{\nu} = -\sum_{i,j}\left((c_\nu)_{ij}\bar{L}_{i,\mathrm{L}}\cdot\tilde{\phi}\,\nu_{j,\mathrm{R}} + \frac{1}{2}(c_{\mathrm{R}})_{ij}\,\overline{\nu^c_{i,\mathrm{R}}}\nu_{j,\mathrm{R}}\,\chi\right) + \mathrm{h.c.}$$

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$$\mathcal{L}_{\mathrm{Y}}^{\nu} = -\frac{1}{2}\sum_{i,j}\left[\left(\overline{\nu_{\mathrm{L}}},\, \overline{\nu_{\mathrm{R}}^{c}}\right)_i M(h,s)_{ij} \begin{pmatrix} \nu_{\mathrm{L}}^{c} \\ \nu_{\mathrm{R}} \end{pmatrix}_j + \mathrm{h.c.}\right]$$

where

$$M(h,s)_{ij} = \begin{pmatrix} 0 & m_{\mathrm{D}}\left(1+\frac{h}{v}\right) \\ m_{\mathrm{D}}\left(1+\frac{h}{v}\right) & M_{\mathrm{M}}\left(1+\frac{s}{w}\right) \end{pmatrix}_{ij}$$

6x6 symmetric matrix (m_{D} complex, M_{M} real)

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but ν_{L} and ν_{R} have the same q-numbers,
can mix, leading to type-I see-saw

Effective light neutrino masses

If m_i << M_j , can integrate out the heavy neutrinos

$$\mathcal{L}^{\nu}_{\mathrm{dim}-5} = -\frac{1}{2}\sum_i m_{\mathrm{M},i}\left(1+\frac{h}{v}\right)^2\left(\overline{\nu'^{c}_{i,\mathrm{L}}}\nu'_{i,\mathrm{L}} + \mathrm{h.c.}\right)$$

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if m_i ~ O(100keV) and M_j ~ O(100GeV), then

$m_{M,i}$ ~ O(0.1eV)

Mixing in the neutral gauge sector

$$\begin{pmatrix} W^3_\mu \\ B'_\mu \\ Z'_\mu \end{pmatrix} = \underline{M}(\sin\theta_\mathrm{W}, \sin\theta_\mathrm{T}) \begin{pmatrix} Z^0_\mu \\ T_\mu \\ A_\mu \end{pmatrix}$$

- QED current remains unchanged:

$$\mathcal{L}_\mathrm{QED} = -eA_\mu J^\mu_\mathrm{em}\,, \quad J^\mu_\mathrm{em} = \sum_{f=1}^{3}\sum_{j=1}^{3} e_j \Big(\overline{\psi}^f_{q,j}(x)\gamma^\mu\psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu\psi^f_{l,j}(x)\Big)$$

Neutral current interactions

$$\mathcal{L}_{\mathrm{Z}^0} = -eZ^0_\mu\Big(\cos\theta_T J^\mu_{\mathrm{Z}^0} + \sin\theta_T J^\mu_{\mathrm{T}}\Big) = -eZ^0_\mu J^\mu_{\mathrm{Z}^0} + \mathrm{O}(\theta_T)$$

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$$J^\mu_{\mathrm{Z}^0} = \sum_{f=1}^{3}\sum_{j=1}^{3} \frac{T_3 - \sin^2\theta_{\mathrm{W}}\, e_j}{\sin\theta_{\mathrm{W}}\cos\theta_{\mathrm{W}}}\Big(\overline{\psi}^f_{q,j}(x)\gamma^\mu\psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu\psi^f_{l,j}(x)\Big)$$

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- but mixes with new current of new couplings:

$$J^\mu_{\mathrm{T}} = \sum_{f=1}^{3}\sum_{j=1}^{3} \frac{\gamma'_Z r_j + \gamma'_{ZY} y_j}{\sin\theta_{\mathrm{W}}} \Big(\overline{\psi}^f_{q,j}(x)\gamma^\mu\psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu\psi^f_{l,j}(x) \Big)$$

Possible consequences with 5 new parameters

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- The second scalar together with the established BEH field may be the source of hybrid inflation.

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Is there any region of the parameter space of the model that is not excluded by experimental results, both established in standard model phenomenology and elsewhere?

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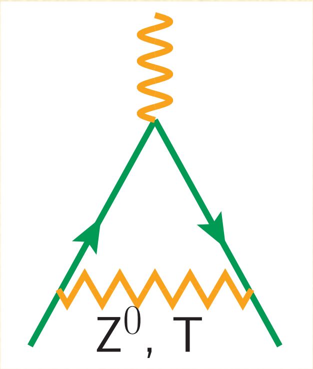
Answer is not immediate, extensive studies are needed

Contribution of the new gauge boson to the anomalous magnetic moment of the muon

using the new neutral currents:

$$\Delta a_\mu = a_\mu^{(\mathrm{T+SM})} - a_\mu^{(\mathrm{SM})} = a_\mu^{(\mathrm{Z}^0)}(h_f,\theta_T) - a_\mu^{(\mathrm{Z}^0)}(0,0) + a_\mu^{(\mathrm{T}^0)}(h_f,\theta_T)$$



where

$$a_\mu^{(X)}(h_f,\theta_T) = \frac{G_{\mathrm{F}} m_\mu^2}{6\sqrt{2}\pi^2}\left[3C_X^+C_X^- - (C_X^+)^2 - (C_X^-)^2\right]$$

with chiral couplings:

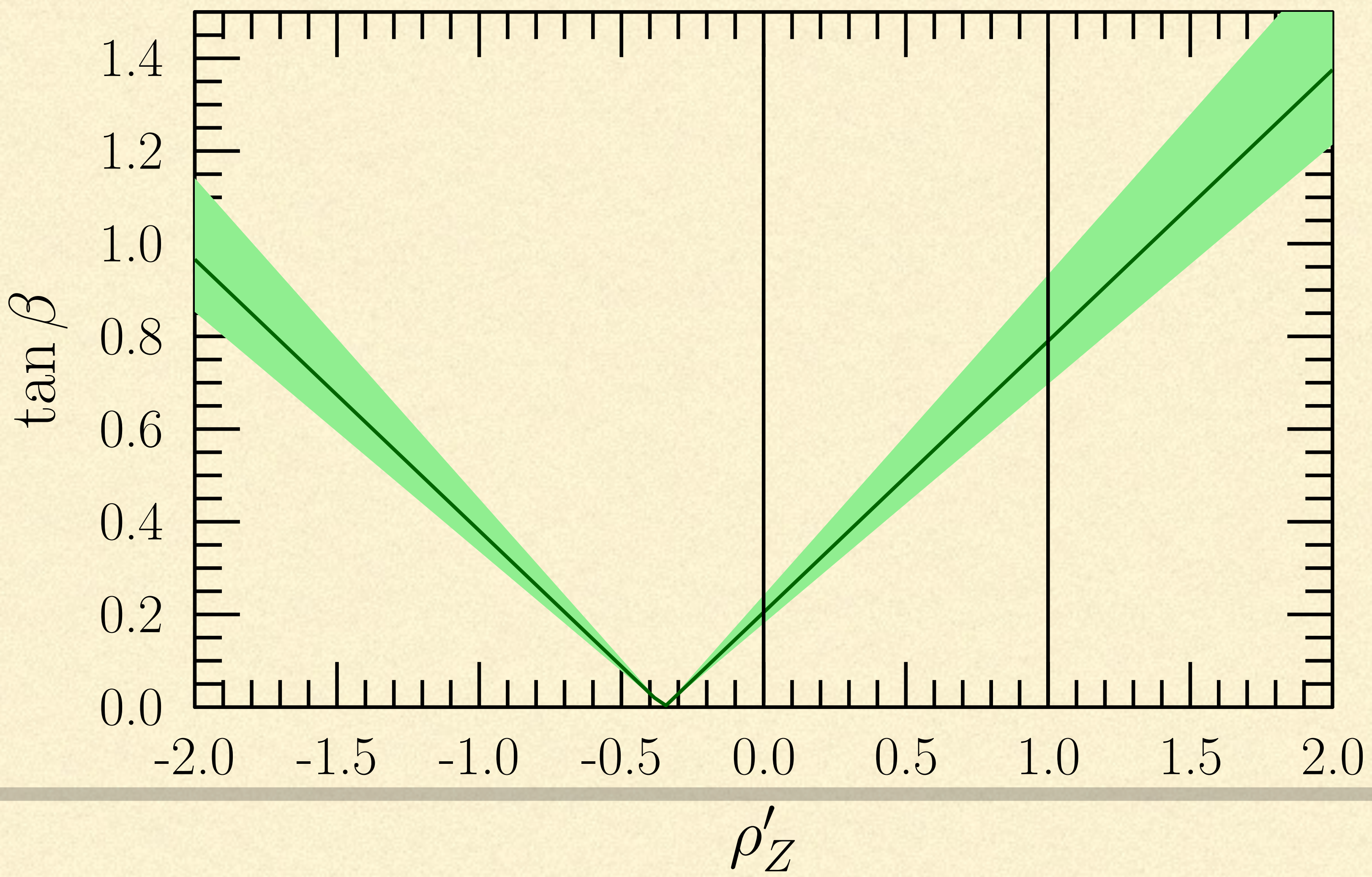
$$V_\alpha \bar{f}_i f_j\colon\ -\mathrm{i}e\gamma_\alpha(C^- P_- + C^+ P_+)$$

$V\bar{f}_i f_j$	C^+	C^-
$\gamma \bar{f}_i f_j$	$e_f\delta_{ij}$	$e_f\delta_{ij}$
$Z\bar{f}_i f_j$	$(g_f^+\cos\theta_T - h_f^+\sin\theta_T)\delta_{ij}$	$(g_f^-\cos\theta_T - h_f^-\sin\theta_T)\delta_{ij}$
$T\bar{f}_i f_j$	$(g_f^+\sin\theta_T + h_f^+\cos\theta_T)\delta_{ij}$	$(g_f^-\sin\theta_T + h_f^-\cos\theta_T)\delta_{ij}$

Contribution of the new gauge boson to a_μ

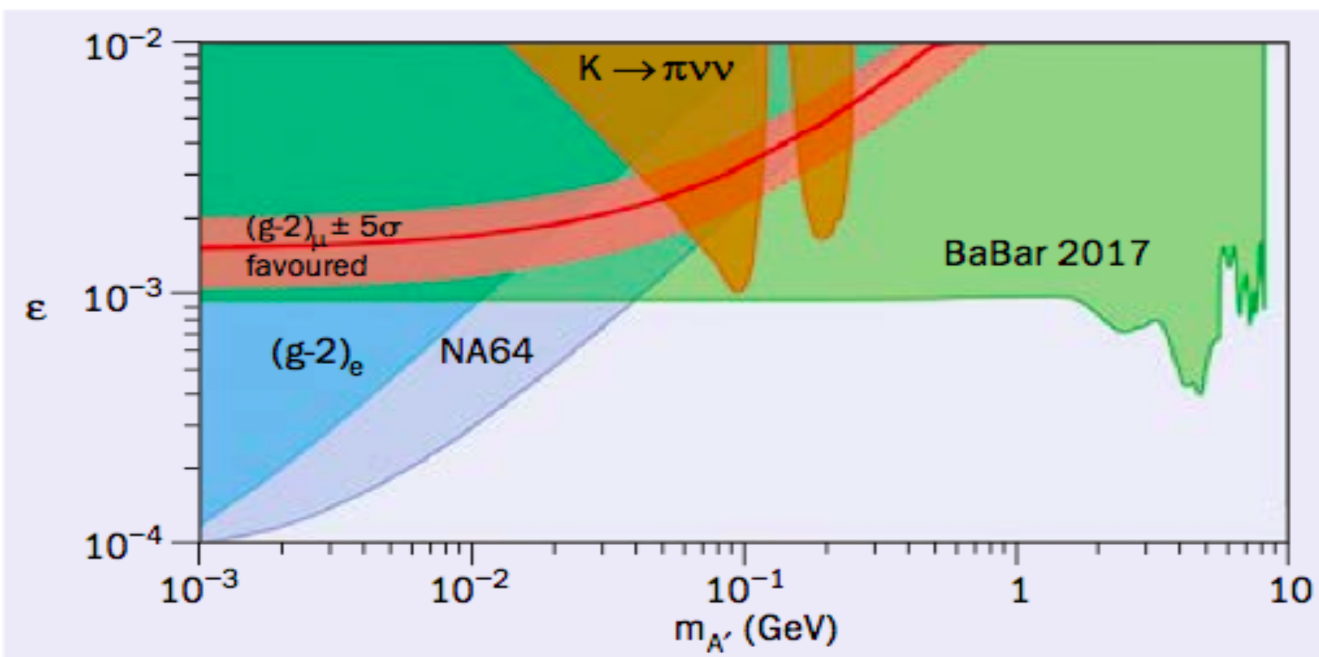
$$a_\mu^{(\mathrm{T+SM})} - a_\mu^{(\mathrm{SM})} = \frac{G_\mathrm{F} m_\mu^2}{6\sqrt{2}\pi^2}\left(\frac{(1+\rho'_Z)\cos^2\theta_\mathrm{W} - \frac{1}{2}}{\tan\beta} + \mathrm{O}(\theta_T,\, \gamma'_Z)\right)^2 \quad \rho'_Z = \frac{\gamma'_{ZY}}{\gamma'_Z}$$

experimentally: $a_\mu^{(\exp)} - a_\mu^{(\mathrm{SM})} = 268(76)\cdot 10^{-11}$



A′ explanation of the anomaly ruled out?

CERN Courier April 2017



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

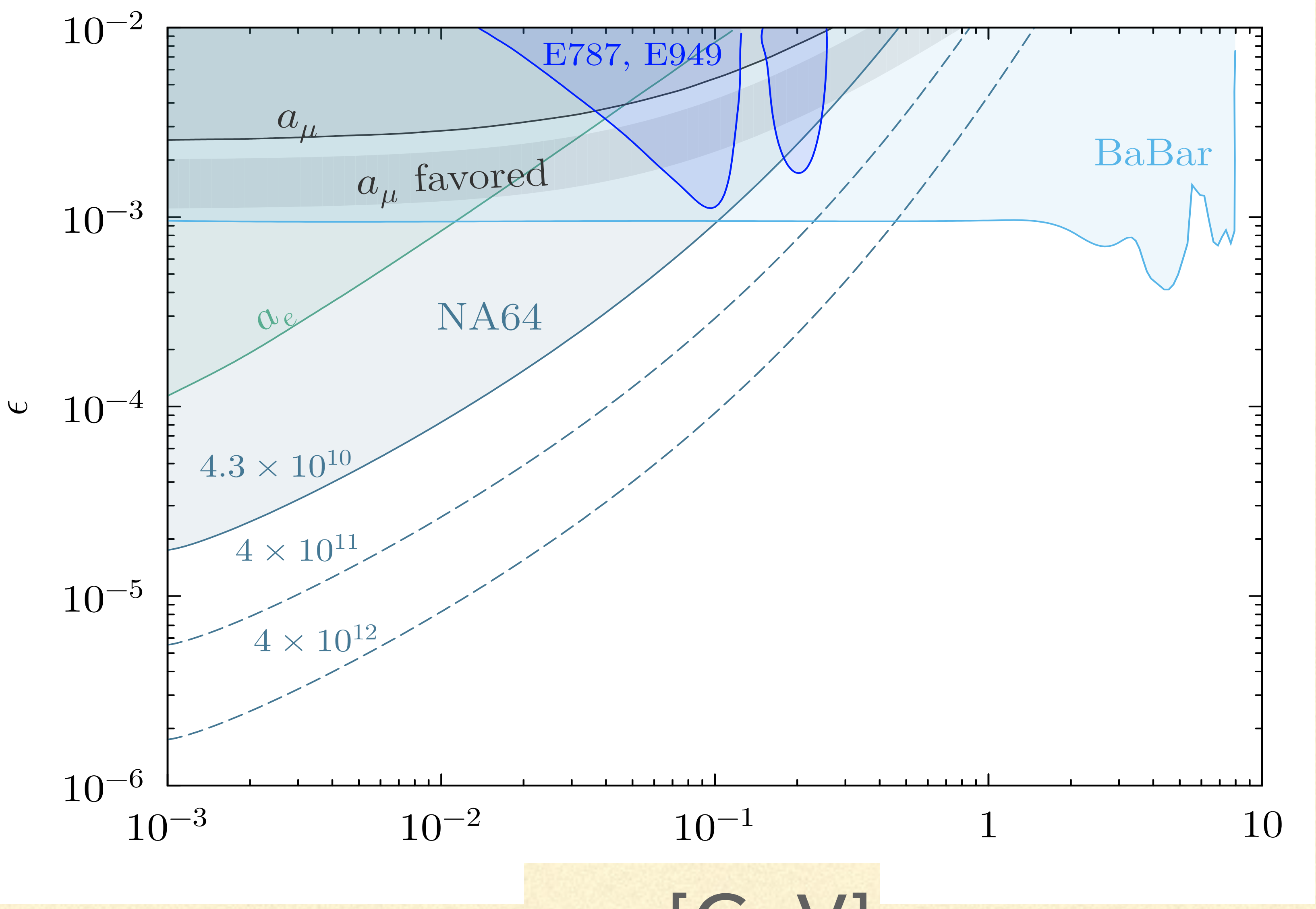
- **Further reading**

BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

Searches for invisibly decaying, light, neutral gauge bosons

best exclusion limits by BaBar and NA64

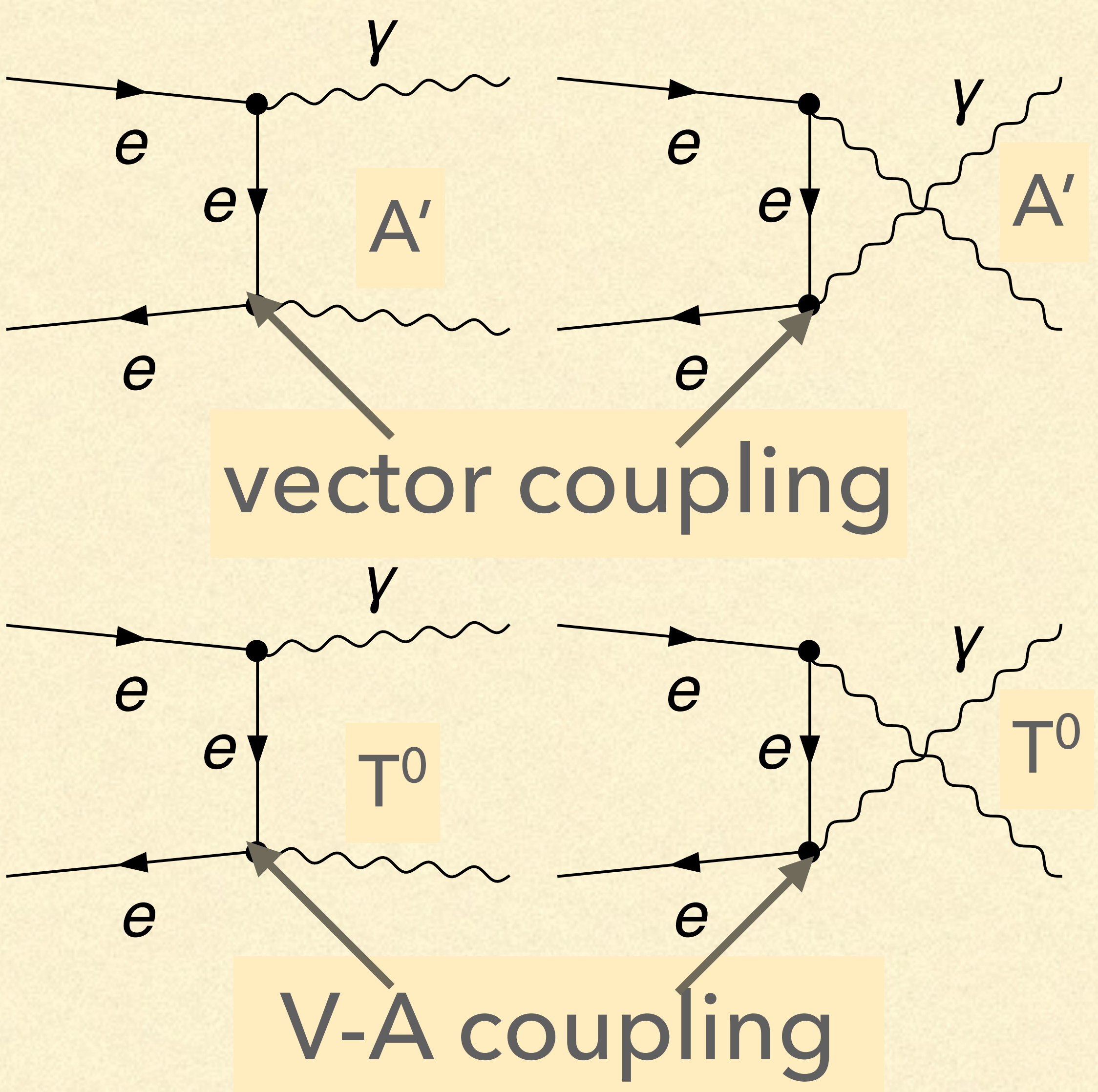
kinetic mixing parameter → (with vector coupling of new boson to fermions)



$m_{A'}$ [GeV]

Effective kinetic mixing for BaBar production

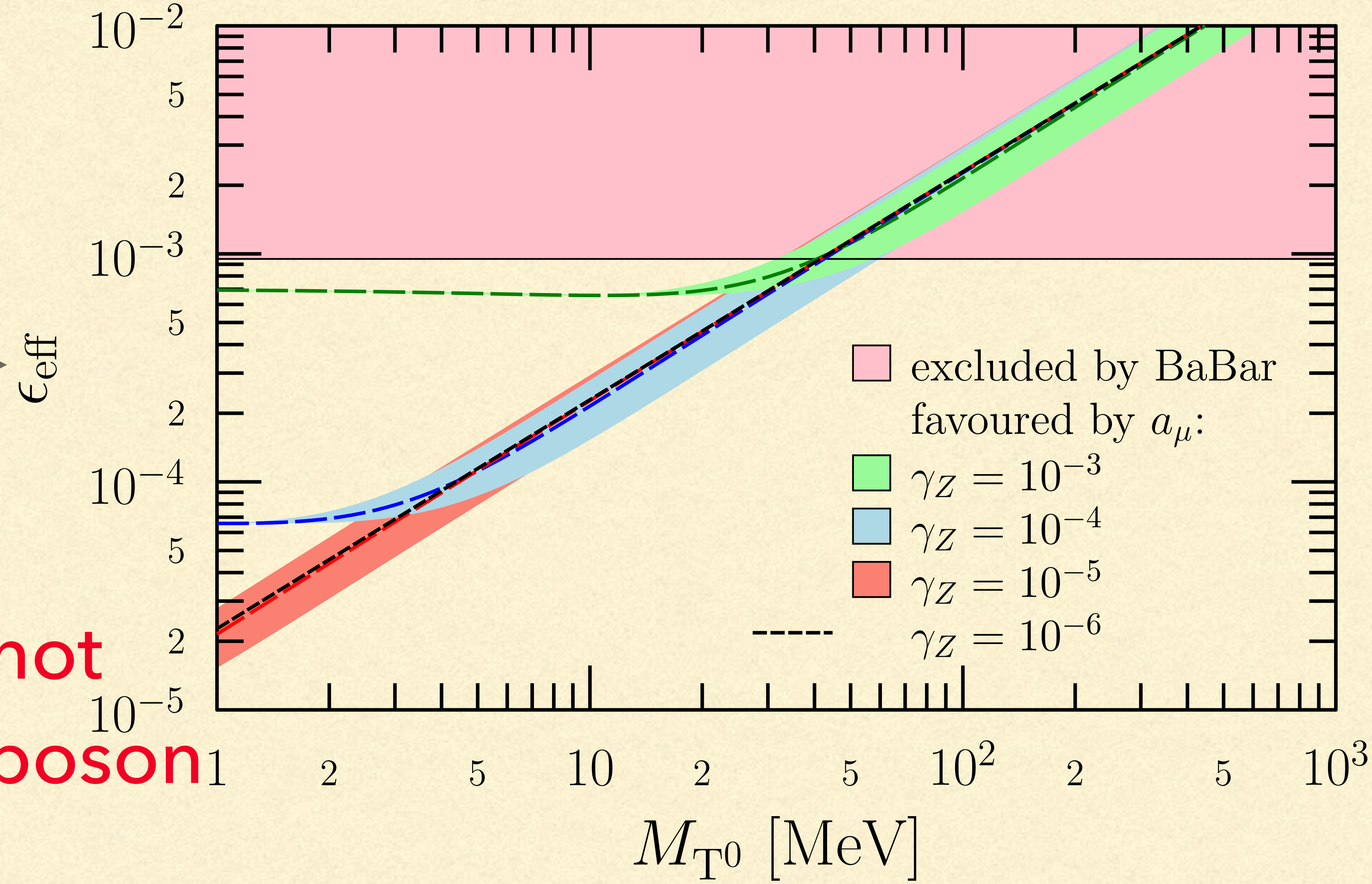
Production channel:



Favoured region by a_μ vs. BaBar exclusion limit

$$\epsilon_{\rm eff} = \sqrt{\frac{\sigma(e^+e^- \to \gamma T^0)}{\sigma(e^+e^- \to \gamma A')/\epsilon^2}} = \sqrt{\left(v_e^{(T)}\right)^2 + \left(a_e^{(T)}\right)^2} = \frac{\gamma'_Z}{2\sin\theta_W}\sqrt{\frac{5}{2}{\rho'_Z}^2 + \rho'_Z + \frac{1}{2}}$$

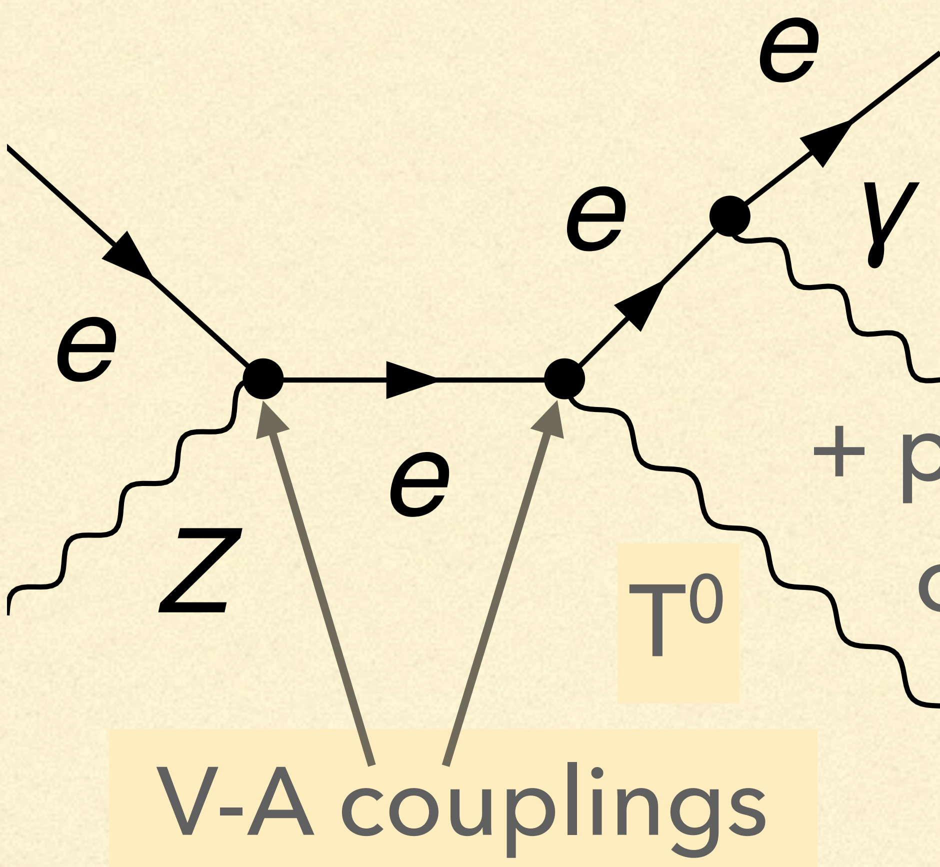
effective kinetic mixing parameter →



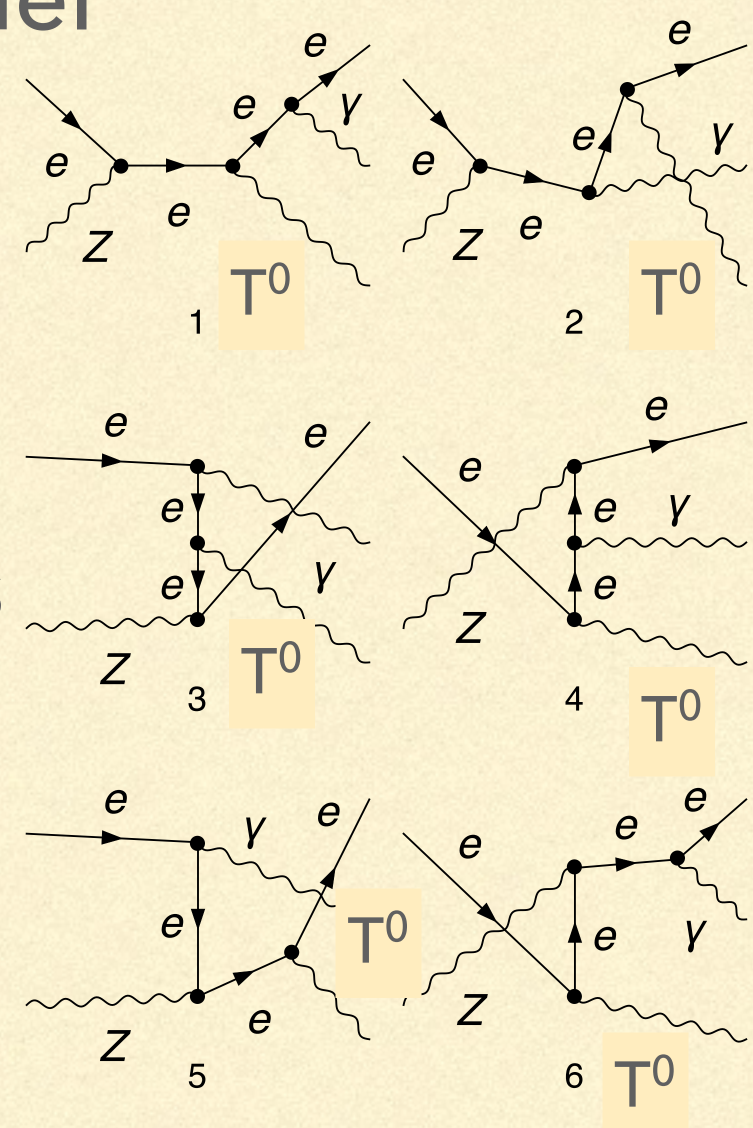
BaBar does not exclude the T^0 boson

Searches for invisibly decaying, light, neutral gauge bosons, NA64 limit

Production channel



+ permutations of bosons:



Expect result at the EPSHEP 2019

Conclusions

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- $U(1)_Z$ extension has the potential of explaining all known results
- Anomaly cancellation and neutrino mass generation mechanism are used to fix the Z-charges up to reasonable assumptions
- Parameter space can be constrained from existing experimental results

UV behavior

with Zoltán Péli