Title: Effective Theories and Applications of StÃ¼ckelberg Vector Bosons

Speakers: Graham Kribs

Series: Particle Physics

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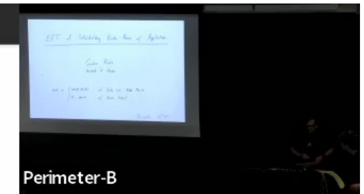
Abstract: New massive "dark" vector bosons are ubiquitous in BSM physics. I'll discuss the effective theories, interactions, and applications of theories with a (single) massive vector boson with a Stückelberg mass, with the goal of providing a clear and self-consistent approach to the (sometimes confusing) subject. The critical role of possible couplings of the longitudinal mode will be emphasized, demarcating when theories have amplitudes that grow with energy. In such theories, I'll identify the cutoff scale, as well as show the potential of longitudinally-enhanced observables given specific couplings of the vector boson. The Stückelbergian approach to massive vectors also provides insight into generalized dark vector boson theories; I'll demonstrate a specific application to an "electrophobic" vector field that can evade many terrestrial experiment constraints that would otherwise apply to a dark photon.

Zoom Link: https://pitp.zoom.us/j/96937794653?pwd=cjIvM0hxQmo2ZEhuamhxeWx3cVdoZz09



EFT of Stückelberg Vector Bosons w/ Applications

Graham Kribs

University of Oregon

based on
- 2204.01755 w/ Gabe Lee, Adam Martin
- to appear w/ Haider Esseili

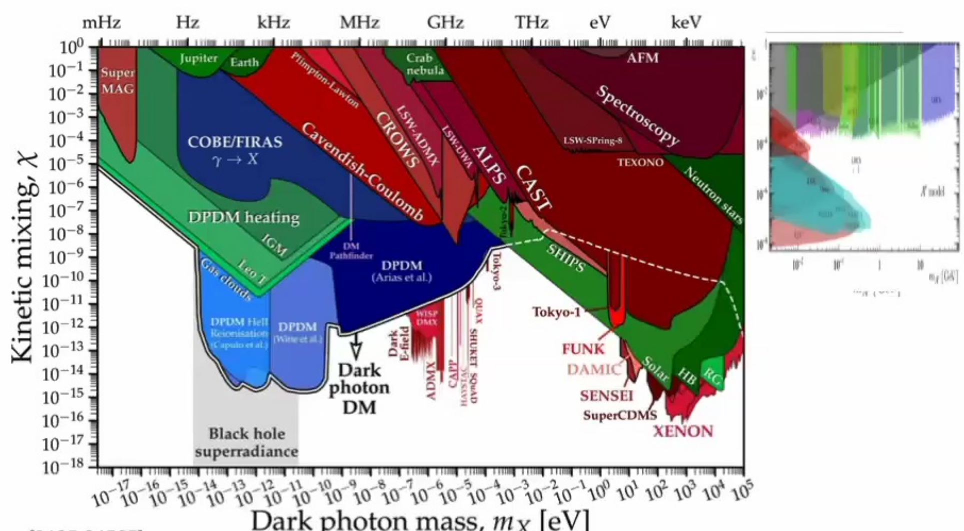
Perimeter 6/2022

Motivation

- Massive vector bosons ubiquitous in SM & beyond.
- Wide range of BSM uses:
  - mediator of light DM
  - DM itself
  - g-2 of muon

  ⋮

Light (but massive) vectors are EVERYWHERE!



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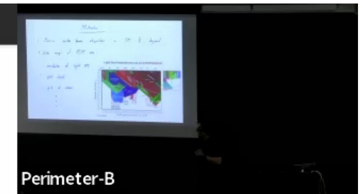
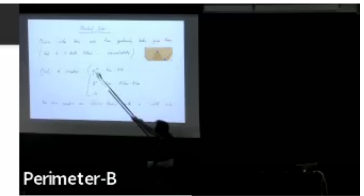
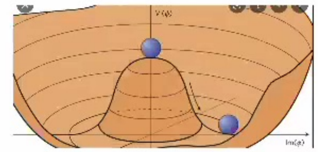




Standard Lore

Massive vector bosons arise from spontaneously broken gauge theory

(back to 't Hooft - Veltman .... renormalizability)



Plenty of exceptions :

- ρ_a^μ from QCD
- A^μ from Kaluza - Klein
- etc.

But these exceptions are effective theories with a cutoff scale.

Stückelberg Vector Boson

Seemingly different:

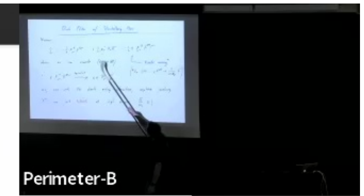
$$\mathcal{L} = -\frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu$$

$F^X_{\mu\nu}$ utilized for kinetic term simply to ensure 3 propagating d.of f. Nothing to do with gauge invariance.

Mass m_X^2 does not arise from spontaneous symmetry breaking.

No cutoff scale needed.

Dark Photon w/ Stückelberg Mass



Moreover,

$$\mathcal{L} = -\frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu - \frac{1}{2} \varepsilon F^X_{\mu\nu} F^{EM\,\mu\nu}$$

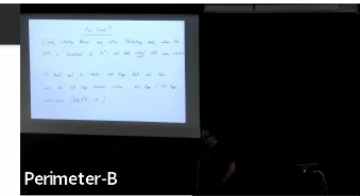
Kinetic mixing*

(* In SM: $\varepsilon F^{EM} \to \frac{\varepsilon}{\cos\theta_W} F^Y$)

where we can rewrite (EOM + IBP)

$$\varepsilon F^X_{\mu\nu} F^{EM\,\mu\nu} \xrightarrow{\text{equivalent}} \varepsilon e X_\mu J^\mu_{EM}$$

and, even with the kinetic mixing interaction, amplitudes involving X^μ are well behaved at high energies $\frac{\sqrt{s}}{m_X} \gg 1$.

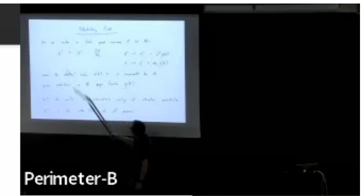


Free Lunch?

Clearly, interesting theories may utilize Stückelberg mass, where the EFT is characterized by X^μ: vector field without $U(1)$ gauge invariance.

$\Rightarrow$ Avoid need to introduce dark Higgs field, and thus avoid the dark Higgs hierarchy problem, dark Higgs / SM Higgs destabilization ($\phi_D^\dagger \phi_D H^\dagger H$, etc.)

Stückelberg Trick



We can restore a "fake" gauge invariance if we like:

$$X^\mu \equiv A^\mu - \frac{\partial^\mu \pi}{m_X} \qquad\qquad A^\mu \to A^\mu + \partial^\mu g(x^\mu)$$

$$\pi \to \pi + m_X\, g(x^\mu)$$

when the additional scalar d.o.f. π is compensated by the gauge redundancy in the gauge function $g(x^\mu)$.

Will be useful to characterize scaling of interactions, nevertheless X^μ is the vector field for all purposes.

EFT for Massive Vectors

Given X^μ can be written with impunity, what is the dynamics of X^μ and what are the possible interactions?

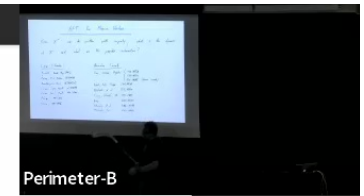
Large Literature!

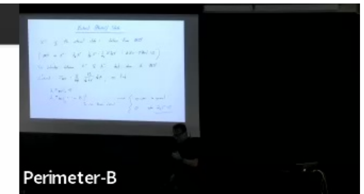
Preskill, Annals Phys (1991)
Ruegg, Ruiz-Altaba th/0304245
Anastasopoulos et al th/0605225
Coriano, Irges, Morelli ph/0701010
Coriano, Guzzi, Morelli 0801.2949
Racioppi, 0907.1534
Reece 1808.09966

Anomalous Currents

Dror, Lasenby, Pospelov $\begin{cases} \text{1705.06726} \\ \text{1707.01503} \\ \text{1811.00595 (bosonic currents)} \end{cases}$

Ismail, Katz, Racco 1707.00709
Ekstedt et. al 1712.03410
Craig, $(\text{Garcia})^2$, GK 1912.10054
Dror 2004.04750
Allanach et al 2006.03588
Michaels, Yu 2010.00021





External (Physical) State

X^μ is the external state: follows from BRST.

(BRST on X^μ: $\delta_\theta X^\mu = \delta_\theta A^\mu - \frac{1}{m_X} \partial^\mu \delta_\theta \pi = \theta \partial^\mu \omega - \partial^\mu(\theta\omega) = 0$)

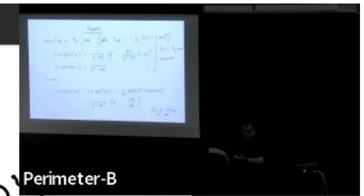
The distinction between X^μ & A^μ boils down to BRST.

Construct $J^\mu_{BRST} = \sum_{\text{fields}} \frac{\delta \mathcal{L}}{\delta_\theta \partial_\mu \phi} \delta_\theta \phi$, one finds:

$$\partial_\mu J^\mu_{BRST}\Big|_X = 0$$

$$\partial_\mu J^\mu_{BRST}\Big|_A = -\omega\, \partial_\mu j^\mu \longrightarrow \begin{cases} \text{non-zero, in general} \\ 0 \quad \text{when } \underline{\partial_\mu j^\mu = 0}. \end{cases}$$

e.g. fermion current



Propagator

Gauge-fixing in R_ξ gauge [adding $\mathcal{L}_{gf} = -\frac{1}{2\xi}\left(\partial_\mu A^\mu + \xi m_X \pi\right)^2$]

$$\langle A^\mu(p)\, A^\nu(-p)\rangle = \frac{-i}{p^2 - m_X^2}\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2 - \xi m_X^2}(1-\xi)\right)$$

$$\langle \pi(p)\, \pi(-p)\rangle = \frac{i}{p^2 - \xi m_X^2}$$

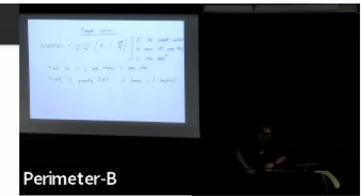
Usual R_ξ-gauge propagators.

Combine:

$$\langle X^\mu(p)\, X^\nu(-p)\rangle = \langle A^\mu(p)\, A^\nu(-p)\rangle + \frac{1}{m_X^2}(ip^\mu)(-ip^\nu)\langle \pi(p)\, \pi(-p)\rangle$$

$$= \frac{-i}{p^2 - m_X^2}\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{m_X^2}\right)$$

[See also Weinberg QFT book!]



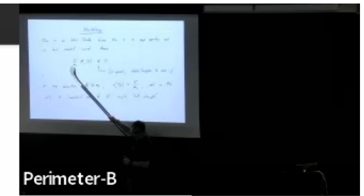
Propagator continued ...

$$\langle X^\mu(p)\, X^\nu(-p)\rangle = \frac{-i}{p^2 - m_X^2}\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{m_X^2}\right)$$

X^μ has propagator equivalent to massive U(1) gauge theory in unitary gauge*.

* But, there is $\underline{\underline{\text{no}}}$ gauge redundancy or gauge choice.

Manifestly 3 propagating d.o.f.: 2 transverse + 1 longitudinal.



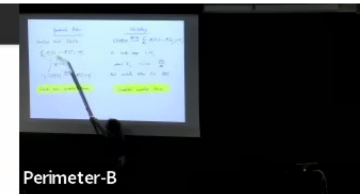
Stückelberg

There is no Ward Identity because there is no gauge symmetry and no local conserved current. Hence

$$\frac{k^\mu}{m_X}\mathcal{M}_\mu(X) \neq 0$$

(in general; details/exceptions to come ...)

At large momentum, $|\underline{k}| \gg m_X$, $\varepsilon_L^\mu(X) \approx \frac{k^\mu}{m_X}$, and so this implies the longitudinal mode of X^μ couples "full strength".



Spontaneously Broken

Generalized Ward Identity:

$$\frac{k^\mu}{m_X}\mathcal{M}_\mu(A) = i\mathcal{M}(G^0;\ \xi=0)$$

$$\Big\downarrow\ |k| \gg m_X$$

$$\epsilon_L^\mu(A)\mathcal{M}_\mu(A) \xrightarrow{|k|\gg m_X} i\mathcal{M}(G^0;\ \xi=0)$$

Goldstone boson equivalence theorem.

Stückelberg

$$\epsilon_L^\mu(X)\mathcal{M}_\mu(X) \xrightarrow{|k|\gg m_X} \frac{k^\mu}{m_X}\mathcal{M}_\mu(X) = i\mathcal{M}(\pi;\ \xi=0)$$

In Landau gauge $\xi=0$,

external $X^\mu_L \longrightarrow \frac{\partial^\mu \pi}{m_X}$.

that essentially follows from BRST.

"Longitudinal equivalence theorem".

Interactions

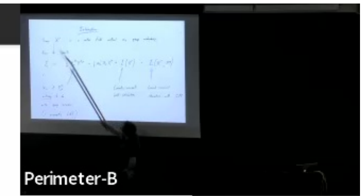
Since X^μ is a vector field without any gauge redundancy, free to write

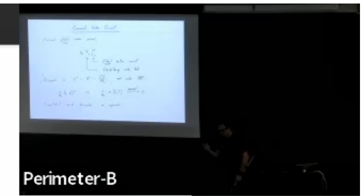
$$\mathcal{L} = -\frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu + \mathcal{L}(X^\mu) + \mathcal{L}(X^\mu, SM)$$

Use of $F^X_{\mu\nu}$ nothing to do with gauge invariance (3 propagating d.o.f.).

Lorentz-invariant self-interactions

Lorentz-invariant interactions with SM





Conserved Vector Current

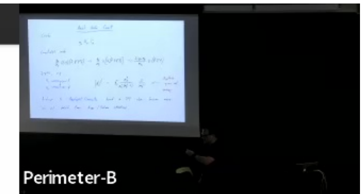
Conserved global vector current:

$$g_X \underbrace{X_\mu}_{\text{Stückelberg vector field}} \underbrace{j^\mu}_{\text{Global vector current}}$$

Decompose as $X^\mu = A^\mu - \frac{\partial^\mu \pi}{m_X}$, and under IBP:

$$-\frac{1}{m_X}(\partial_\mu \pi) j^\mu \to \frac{1}{m_X}\pi(\partial_\mu j^\mu) \xrightarrow{\text{conserved}} 0$$

Longitudinal mode decouples, as expected.



Axial Vector Current

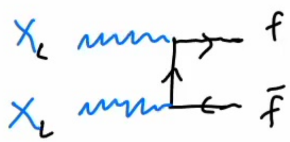
Consider

$$g_X \, X_\mu \, j^\mu_A$$

Longitudinal mode

$$-\frac{g_X}{m_X}(\partial_\mu \pi)(\bar f \gamma^\mu \gamma^5 f) \to \frac{g_X}{m_X}\pi\left[\partial_\mu(\bar f \gamma^\mu \gamma^5 f)\right] \to \frac{2 i g_X m_f}{m_X}\pi(\bar f \gamma^5 f)$$

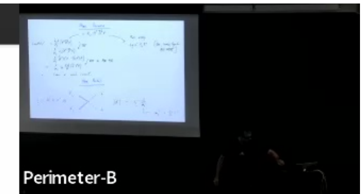
Implies, e.g.



$$|A|^2 \sim g_X^4 \frac{m_f^4}{m_X^2(m_f^2 - t)} \cdot \frac{s}{m_X^2} \leftarrow$$

Amplitude grows w/ energy

Analogous to Appelquist-Chanowitz bound in SM when fermion masses are not obtained from Higgs / Yukawa interactions.



Higgs Derivative

$$\lambda\, X_\mu\, i H^\dagger \overleftrightarrow{D}^\mu H$$

Longitudinal: $-i \frac{\partial_\mu \pi}{m_X}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)$

IBP

$$i \frac{\pi}{m_X}\, \partial_\mu \left(H^\dagger \overleftrightarrow{D}^\mu H\right)$$

$$i \frac{\pi}{m_X}\left[H^\dagger D^2 H - (D^2 H^\dagger) H\right]$$

EOM on Higgs field

$$\to -i \frac{\pi}{m_X}\, y_f \frac{v+h}{\sqrt{2}}\left(\bar{f} \gamma^5 f\right)$$

Same as axial current.

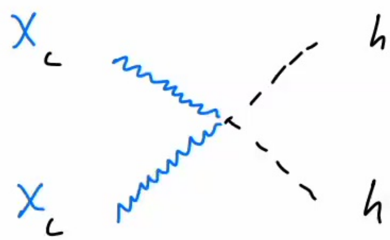
Mass mixing

$$\lambda g v^2 X_\mu Z^\mu$$

[Dror, Lasenby, Pospelov 1811.00595]

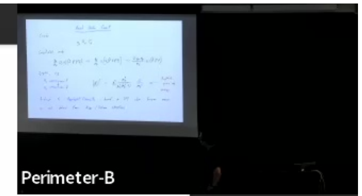
Higgs Portal

$$\frac{1}{2}\lambda_2 |H|^2 X_\mu X^\mu \Rightarrow$$



$$|A| \sim \lambda_2 \cdot \frac{s}{\tilde{m}_X^2}$$

$$\tilde{m}_X^2 = m_X^2 + \frac{\lambda_2}{2} v^2$$



Axial Vector Current

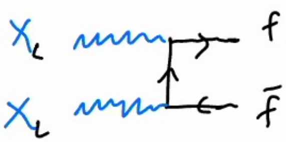
Consider

$$g_X \, X_\mu \, j^\mu_A$$

Longitudinal mode

$$-\frac{g_X}{m_X}(\partial_\mu \pi)(\bar f \gamma^\mu \gamma^5 f) \to \frac{g_X}{m_X}\pi\left[\partial_\mu(\bar f \gamma^\mu \gamma^5 f)\right] \to \frac{2 i g_X m_f}{m_X}\pi(\bar f \gamma^5 f)$$

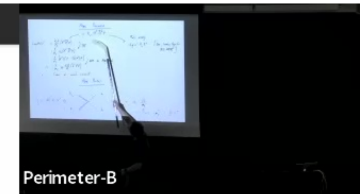
Implies, e.g.



$$|A|^2 \sim g_X^4 \frac{m_f^4}{m_X^2(m_f^2 - t)} \cdot \frac{s}{m_X^2} \longleftarrow$$

Amplitude grows w/ energy

Analogous to Appelquist-Chanowitz bound in SM when fermion masses are not obtained from Higgs / Yukawa interactions.



Higgs Derivative

$$\lambda X_\mu \, i H^\dagger \overleftrightarrow{D}^\mu H$$

Longitudinal: $-i \frac{\partial_\mu \pi}{m_X} (H^\dagger \overleftrightarrow{D}^\mu H)$ IBP

$i \frac{\pi}{m_X} \partial_\mu (H^\dagger \overleftrightarrow{D}^\mu H)$

$i \frac{\pi}{m_X} \left[H^\dagger D^2 H - (D^2 H^\dagger) H \right]$ EOM on Higgs field

$\to -i \frac{\pi}{m_X} y_f \frac{v+h}{\sqrt{2}} (\bar{f} \gamma^5 f)$

Same as axial current.

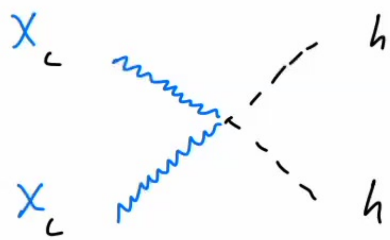
Mass mixing

$\lambda g v^2 X_\mu Z^\mu$

[Dror, Lasenby, Pospelov 1811.00595]

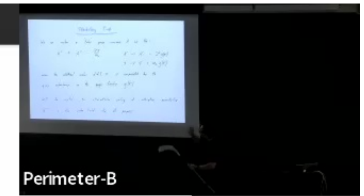
Higgs Portal

$\frac{1}{2} \lambda_2 |H|^2 X_\mu X^\mu \Rightarrow$



$|A| \sim \lambda_2 \cdot \frac{s}{\tilde{m}_X^2}$

$m_X^2 + \frac{\lambda_2}{2} v^2$



Stückelberg Trick

We can restore a "fake" gauge invariance if we like:

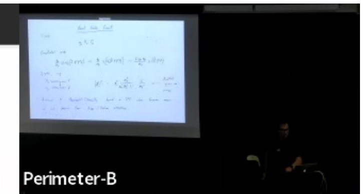
$$X^\mu \equiv A^\mu - \frac{\partial^\mu \pi}{m_X}$$

$$A^\mu \to A^\mu + \partial^\mu g(x^\mu)$$

$$\pi \to \pi + m_X\, g(x^\mu)$$

when the additional scalar d.o.f. π is compensated by the gauge redundancy in the gauge function $g(x^\mu)$.

Will be useful to characterize scaling of interactions, nevertheless X^μ is the vector field for all purposes.



Axial Vector Current

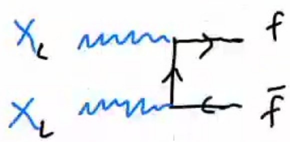
Consider

$$g_X X_\mu j^\mu_A$$

Longitudinal mode

$$-\frac{g_X}{m_X}(\partial_\mu \pi)(\bar{f}\gamma^\mu\gamma^5 f) \to \frac{g_X}{m_X}\pi\left[\partial_\mu(\bar{f}\gamma^\mu\gamma^5 f)\right] \to \frac{2 i g_X m_f}{m_X}\pi(\bar{f}\gamma^5 f)$$

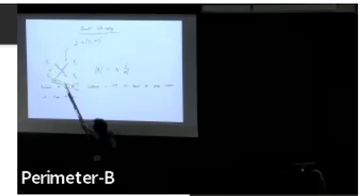
Implies, e.g.



$$|A|^2 \sim g_X^4 \frac{m_f^4}{m_X^2(m_f^2 - t)} \cdot \frac{s}{m_X^2}$$

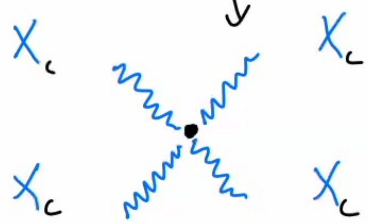
← Amplitude grows w/ energy

Analogous to Appelquist-Chanowitz bound in SM when fermion masses are not obtained from Higgs / Yukawa interactions.



Quartic Self-coupling

$$\frac{1}{4!}\lambda_4\left(X_\mu X^\mu\right)^2$$



$$|A| \sim \lambda_4 \frac{s^2}{m_X^4}$$

Analogous to $W_L W_L \to W_L W_L$ scattering in SM $\Rightarrow$ tamed by gauge invariance and Higgs exchange.

Anomalous Vector Current

(Motivated by
Dror, Lasenby, Pospelov '17

One of the most interesting & puzzling interactions is

$$g_X X_\mu j^\mu_{anom}$$

← Globally anomalous vector current.

This interaction appears to gauge a globally anomalous U(1) current,

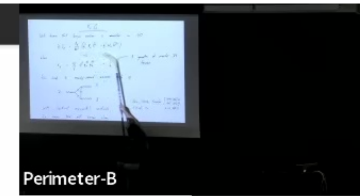
yet we know X^μ is not a gauge field.

For the purposes of illustration, let's take $\boxed{j^\mu_{anom} = j^\mu_B}$

← baryon number

Perimeter-B

$X_\mu \, j^\mu_B$



Well known that baryon number is anomalous in SM:

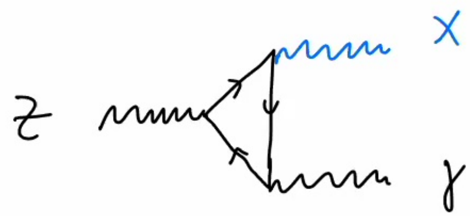
$$\partial_\mu j^\mu_B = \frac{A_B}{8\pi^2}\left(g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu} - g^2 W_{\mu\nu}\tilde{W}^{\mu\nu}\right)$$

where

$$A_B = \sum_f Q^f \, q_X^{V,f} \, q_Z^{A,f} = \frac{3}{4}$$

3 generations of massless SM fermions.

This leads to anomaly-induced processes such as

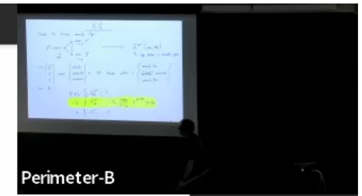


Dror, Lasenby, Pospelov $\begin{cases} 1705.06726 \\ 1707.01503 \end{cases}$

Michaels, Yu 2010.00021

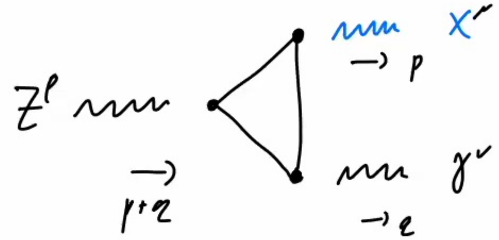
With significant experimental constraints,

for reasons that will become clear.



$X_\mu \, j^\mu_B$

Consider the fermion anomaly loop:



$$\longrightarrow \quad \tilde{\Delta}^{\rho\mu\nu}(p, q, m_\psi)$$

↑ loop function in momentum space

$$\Rightarrow \left\{ \begin{array}{c} Z^\rho \\ X^\mu \\ \gamma^\nu \end{array} \right\} \text{ couples } \left\{ \begin{array}{c} \text{chirally} \\ \text{vectorially} \\ \text{vectorially} \end{array} \right\} \text{ to SM fermion which is } \left\{ \begin{array}{c} \text{anomaly-free} \\ \text{(globally) anomalous} \\ \text{anomaly-free} \end{array} \right\}$$

And thus:

$$-(p+q)_\rho \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = 0$$

$$-p_\mu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = -\mathcal{A}_B \frac{e g g_X}{2\pi^2 c_W} \varepsilon^{\rho\nu\alpha\beta} p_\alpha q_\beta$$

$$-q_\nu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = 0$$

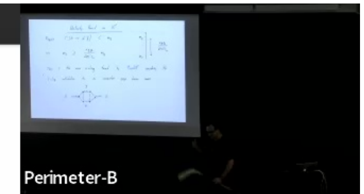
Stückelberg X^μ

$$-p_\mu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = -A_B \frac{e g g_X}{2\pi^2 c_W} \varepsilon^{\rho\nu\alpha\beta} p_\alpha q_\beta$$

This is the end of the story. The "momentum-contracted vertex" (would-be Ward Identity) is non-vanishing. One can use this result to directly calculate (the leading)

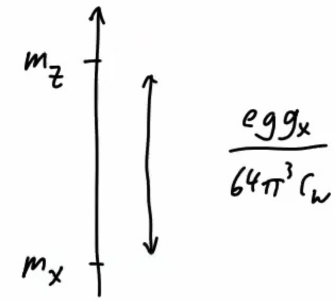
$$\Gamma(Z \to X_L \gamma) \sim \frac{1}{24\pi^2} A_B^2 \frac{\alpha_{em}^2 \alpha_X}{c_W^2 s_W^2} \left(\frac{m_Z}{m_X}\right)^2 m_Z$$

Longitudinal enhancement



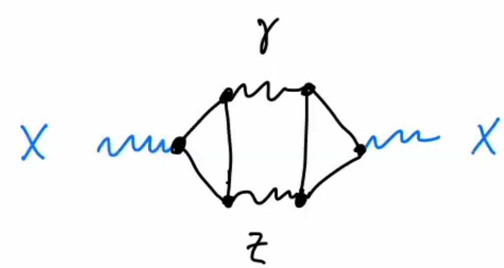
Unitarity Bound on X^μ

Require $\Gamma(Z \to X\gamma) < m_Z$



$$\Rightarrow \quad m_X \gtrsim \frac{e g g_x}{64\pi^3 c_w} m_Z$$

This is the same scaling found by Preskill considering the 3-loop contribution to an anomalous gauge boson mass



Stückelberg X^μ

$$-p_\mu \sum_f \tilde{\Delta}^{\rho\mu}_{SM} = - A_B \frac{e g g_X}{2\pi^2 c_W} \varepsilon^{\rho\nu\alpha\beta} p_\alpha q_\beta$$

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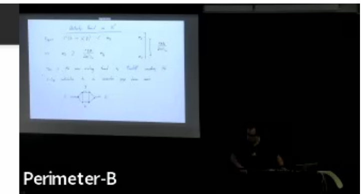

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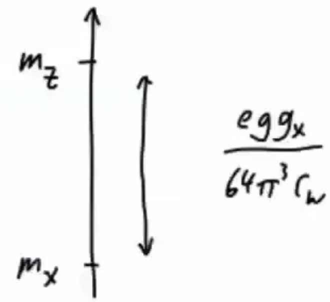

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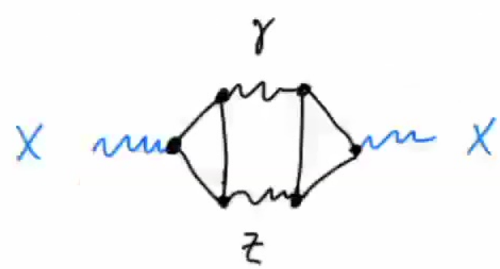
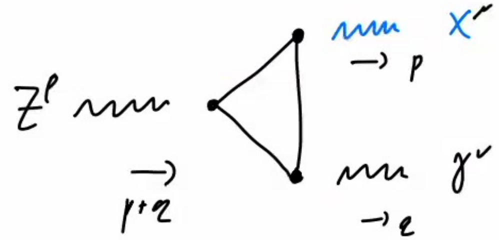


$X_\mu j^\mu_B$

Consider the fermion anomaly loop:



$$\longrightarrow \tilde{\Delta}^{\rho\mu\nu}(p,q,m_\psi)$$

↑ loop function in momentum space

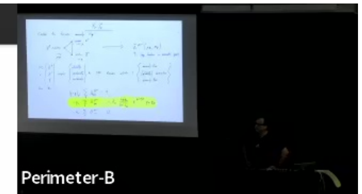
$$\Rightarrow \begin{Bmatrix} Z^\rho \\ X^\mu \\ \gamma^\nu \end{Bmatrix} \text{ couples } \begin{Bmatrix}\text{chirally}\\ \text{vectorially}\\ \text{vectorially}\end{Bmatrix} \text{ to SM fermion which is } \begin{Bmatrix}\text{anomaly-free}\\ \text{(globally) anomalous} \\ \text{anomaly-free}\end{Bmatrix}$$

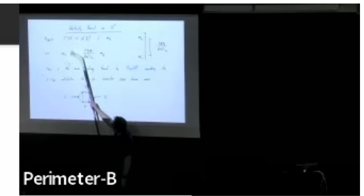
And thus:

$$-(p+q)_\rho \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = 0$$

$$-p_\mu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = -\mathcal{A}_B \frac{e g g_X}{2\pi^2 c_W} \varepsilon^{\rho\nu\alpha\beta} p_\alpha q_\beta$$

$$-q_\nu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM} = 0$$

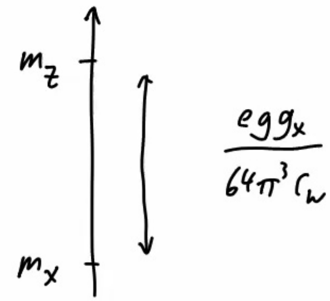




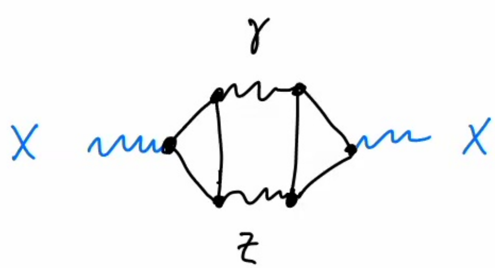
Unitarity Bound on X^μ

Require $\quad \Gamma(Z \to X\gamma) < m_Z$

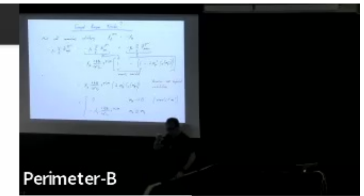
$$\Rightarrow \quad m_X \gtrsim \frac{e\, g\, g_X}{64\pi^3 c_W}\, m_Z$$



This is the same scaling found by Preskill considering the 3-loop contribution to an anomalous gauge boson mass



Gauged Baryon Number?



Must add anomalons satisfying: $A_B^{anom} = -A_B$

$$-p_\mu \sum_f \tilde{\mathcal{O}}^{\rho\mu\nu}_{total} = \underbrace{-p_\mu \sum_f \tilde{\mathcal{O}}^{\rho\mu\nu}_{SM}} + \underbrace{-p_\mu \sum_f \tilde{\mathcal{O}}^{\rho\mu\nu}_{ANOM}}$$

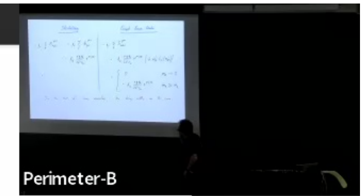
$$= -A_B \frac{e g g_x}{2\pi^2 c_W} \epsilon^{\rho\nu;pq} \left[1 - \left(1 + 2 m_\psi^2 C_0(m_\psi^2) \right) \right]$$

anomaly canceled

$$= A_B \frac{e g g_x}{2\pi^2 c_W} \epsilon^{\rho\nu;pq} \left(2 m_\psi^2 C_0(m_\psi^2) \right)$$

Anomalon mass-dependent contribution.

$$= \begin{cases} 0 & m_\psi \to 0 \quad \text{(anomaly-free!)} \\ -A_B \frac{e g g_x}{2\pi^2 c_W} \epsilon^{\rho\nu;pq} & m_\psi \gg m_Z \end{cases}$$



Stückelberg

$$-p_\mu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{total} = -p_\mu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{SM}$$

$$= -A_B \frac{e\, g\, g_x}{2\pi^2 c_W}\, \epsilon^{\rho\nu; p q}$$

Gauged Baryon Number

$$-p_\mu \sum_f \tilde{\Delta}^{\rho\mu\nu}_{total}$$

$$= A_B \frac{e\, g\, g_x}{2\pi^2 c_W}\, \epsilon^{\rho\nu; p q} \left(2\, m_\psi^2\, C_0(m_\psi^2) \right)$$

$$= \begin{cases} 0 & m_\psi \to 0 \\ -A_B \dfrac{e\, g\, g_x}{2\pi^2 c_W}\, \epsilon^{\rho\nu; p q} & m_\psi \gg m_Z \end{cases}$$

In the limit of heavy anomalons, the decay widths are the same.

$$X^\mu = A^\mu - \frac{\partial^\mu \pi}{m_X} \,?$$

Now, $g_X A^\mu j_B^\mu$ really gauges baryon number, giving

$$-p_\mu \sum_f \tilde{\Delta}_{SM}^{\rho\mu\nu} = - \mathcal{A}_B \frac{e g g_X}{2\pi^2 c_W} \varepsilon^{\rho\nu;\rho q}$$

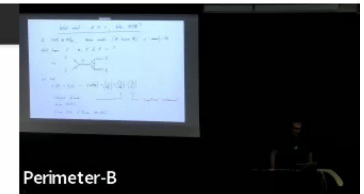
But we also have

$$-\frac{g_X}{m_X}(\partial_\mu \pi) j^\mu_B \longrightarrow \frac{g_X}{m_X}\pi(\partial_\mu j_B^\mu) \longrightarrow \mathcal{A}_B \frac{e g g_X}{4\pi^2}\frac{\pi}{m_X} F_{Z\mu\nu}\tilde{F}^{\gamma\mu\nu}$$

This dimension-5 interaction can be combined with the gauge interaction:

$$p_\mu \sum_f \tilde{\Delta}_{SM}^{\rho\mu\nu}(A) - i m_X \sum_f \tilde{\Delta}^{\rho\nu}(\pi) = 0$$

Satisfying a generalized Ward Identity. This is more commonly known as 4-d Green-Schwarz anomaly cancellation.

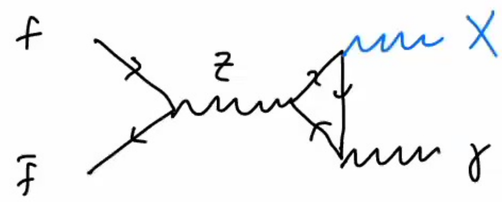


What about $\sqrt{s} \ll v$, below EWSB?

In $SU(3)_c \otimes U(1)_{EM}$, baryon number (all fermion #s) is anomaly-free.

What happens if $m_X \ll \sqrt{s} \ll v$?

e.g.

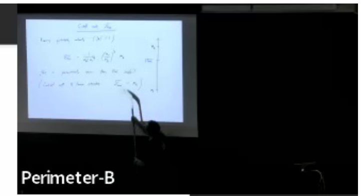


We find:

$$\sigma(f\bar{f} \to X_L \gamma) \sim (\text{couplings}) \times \left(\frac{1}{m_Z^2}\right) \times \left(\frac{s}{m_Z^2}\right) \times \left(\frac{s}{m_X^2}\right)$$

Standard behavior below EWSB (e.g. think 4-fermion interaction)

Longitudinal enhancement



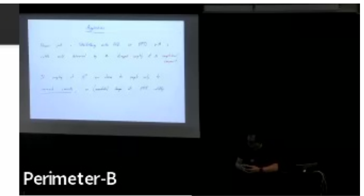
Cutoff scale $\sqrt{s_{max}}$

Requiring perturbative unitarity $\left(|A|^2 < 1 \right)$,

$$\sqrt{s_{max}} \sim \frac{1}{\alpha_{em}^{1/2}\,\alpha_X^{1/2}} \left(\frac{m_X}{m_Z}\right)^{1/3} \cdot m_Z$$

This is parametrically lower than EW scale !

(Contrast with 4-fermion interaction : $\sqrt{s_{max}} \sim m_Z$)



Applications

Theories with a Stückelberg vector field are EFTs with a cutoff scale determined by the strongest coupling of its longitudinal component.

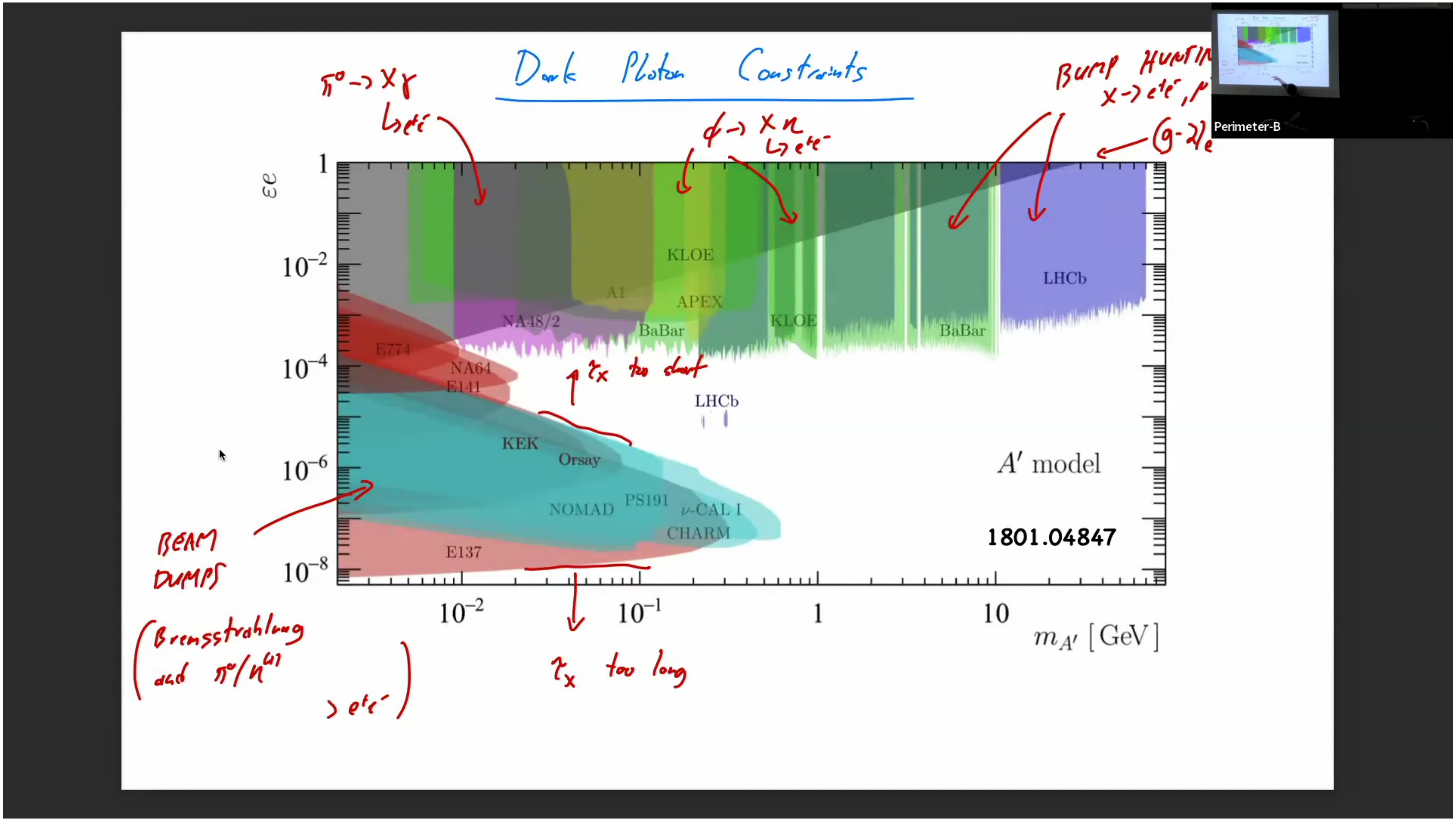
If couplings of X^μ are chosen to couple only to conserved currents, no (immediate) danger of EFT validity.

X^μ Couplings to Conserved Currents

$$g_X X_\mu \cdot \begin{cases} j^\mu_Y \\ j^\mu_{B-L} \\ j^\mu_{L_\mu - L_\tau} \\ \vdots \end{cases}$$

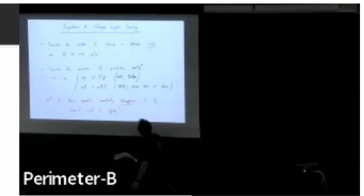
Flavor universal (j^μ_Y, j^μ_{B-L})

Flavor dependent ($j^\mu_{L_\mu - L_\tau}$, …)



Dark Photon Constraints
$\pi^0 \to X\gamma$
$\hookrightarrow e^+e^-$
$\phi \to X\eta$
$\hookrightarrow e^+e^-$
Bump Huntin
$X \to e^+e^-, \mu$
$(g-2)_e$
Perimeter-B
εe
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
KLOE
A1
APEX
NA48/2
BaBar
KLOE
BaBar
LHCb
E774
NA64
E141
τ_X too short
LHCb
KEK
Orsay
A' model
NOMAD
PS191
ν-CAL I
CHARM
1801.04847
E137
10^{-2}
10^{-1}
1
10
$m_{A'}$ [GeV]
BEAM DUMPS
(Bremsstrahlung and $\pi^0/\eta^{(\prime)}$ $\to e^+e^-$)
τ_X too long

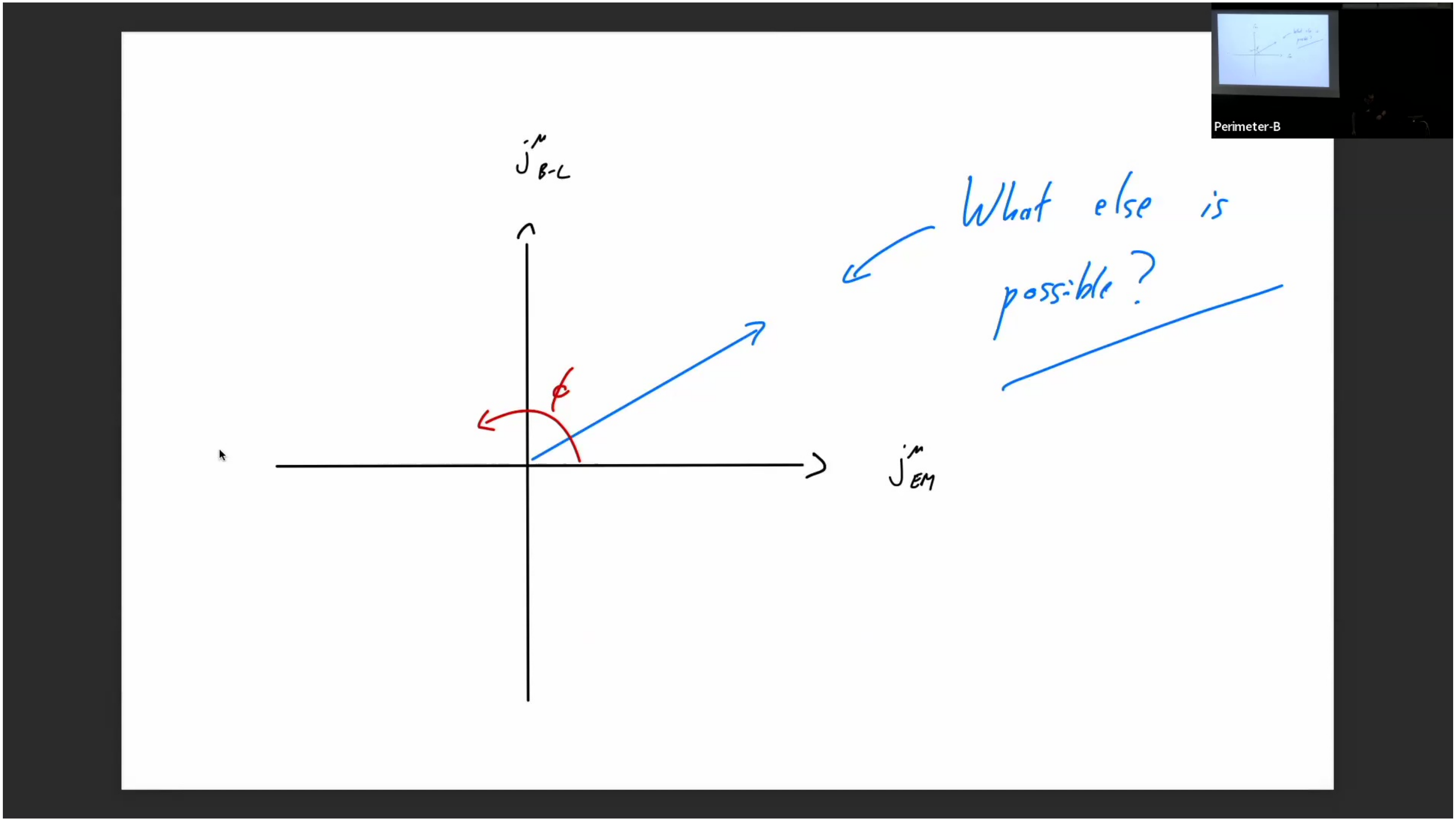
Importance of Charged Lepton Coupling



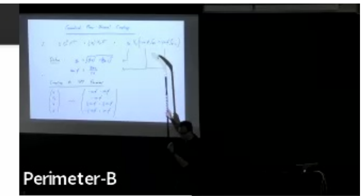
- Searches for visible X decays in detectors rely on $X \to e^+e^-, \mu^+\mu^-$

- Searches for invisible X production mostly* rely on
$$\begin{cases} e^+e^- \to X\gamma & (\text{LEP, BaBar}) \\ eZ \to eZX & (\text{NA64; brem from } e^- \text{ beam}) \end{cases}$$

All* of these searches' sensitivity disappears if X doesn't couple to leptons!



j^μ_{B-L}
j^μ_{EM}
ϕ
What else is possible?
Perimeter-B



Generalized Flavor-Universal Couplings

$$\mathcal{L} = -\frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu + g_X X_\mu \left(-\cos\phi \, j^\mu_{EM} + \sin\phi \, j^\mu_{B-L} \right)$$

Define:

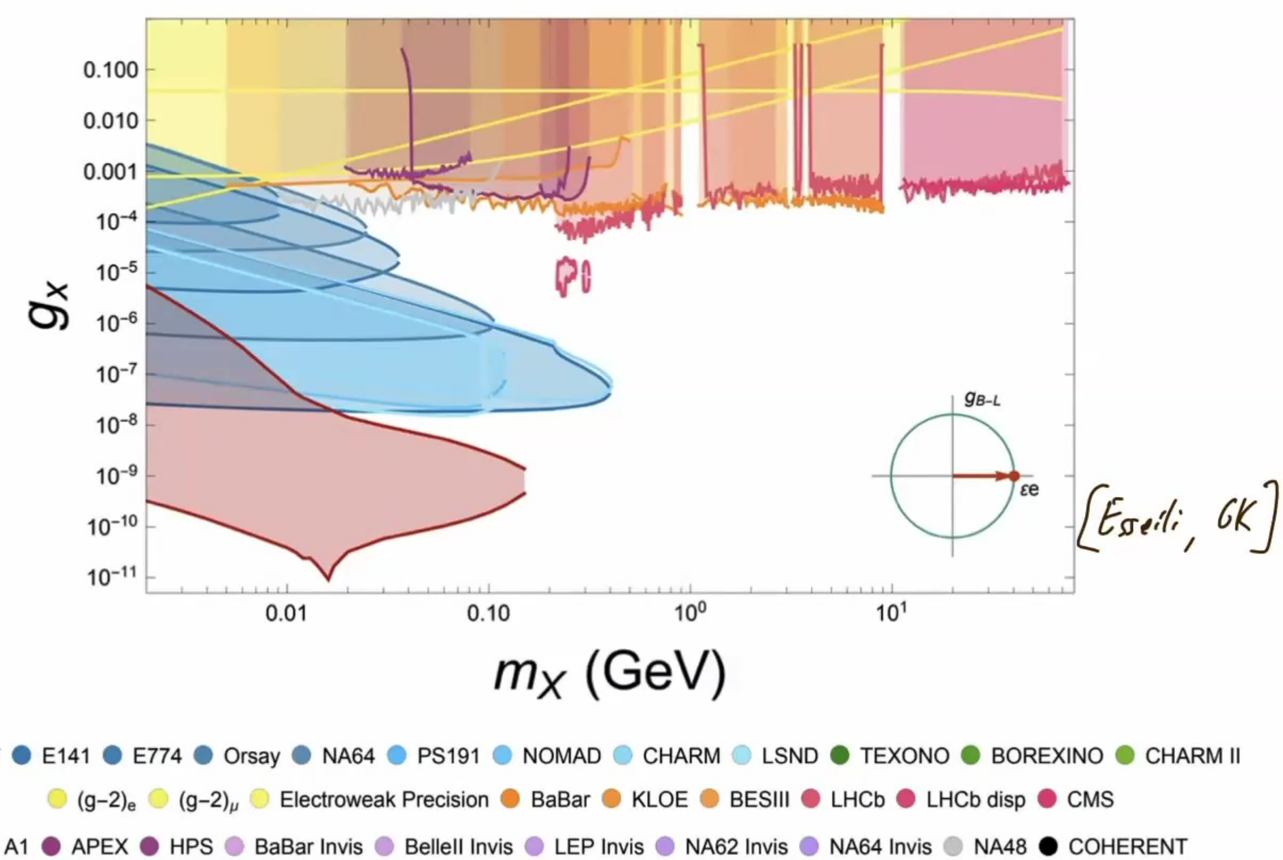
$$g_X \equiv \sqrt{(\varepsilon e)^2 + (g_{B-L})^2}$$

$$\tan\phi \equiv \frac{g_{B-L}}{\varepsilon e}$$

Couplings to SM fermions:

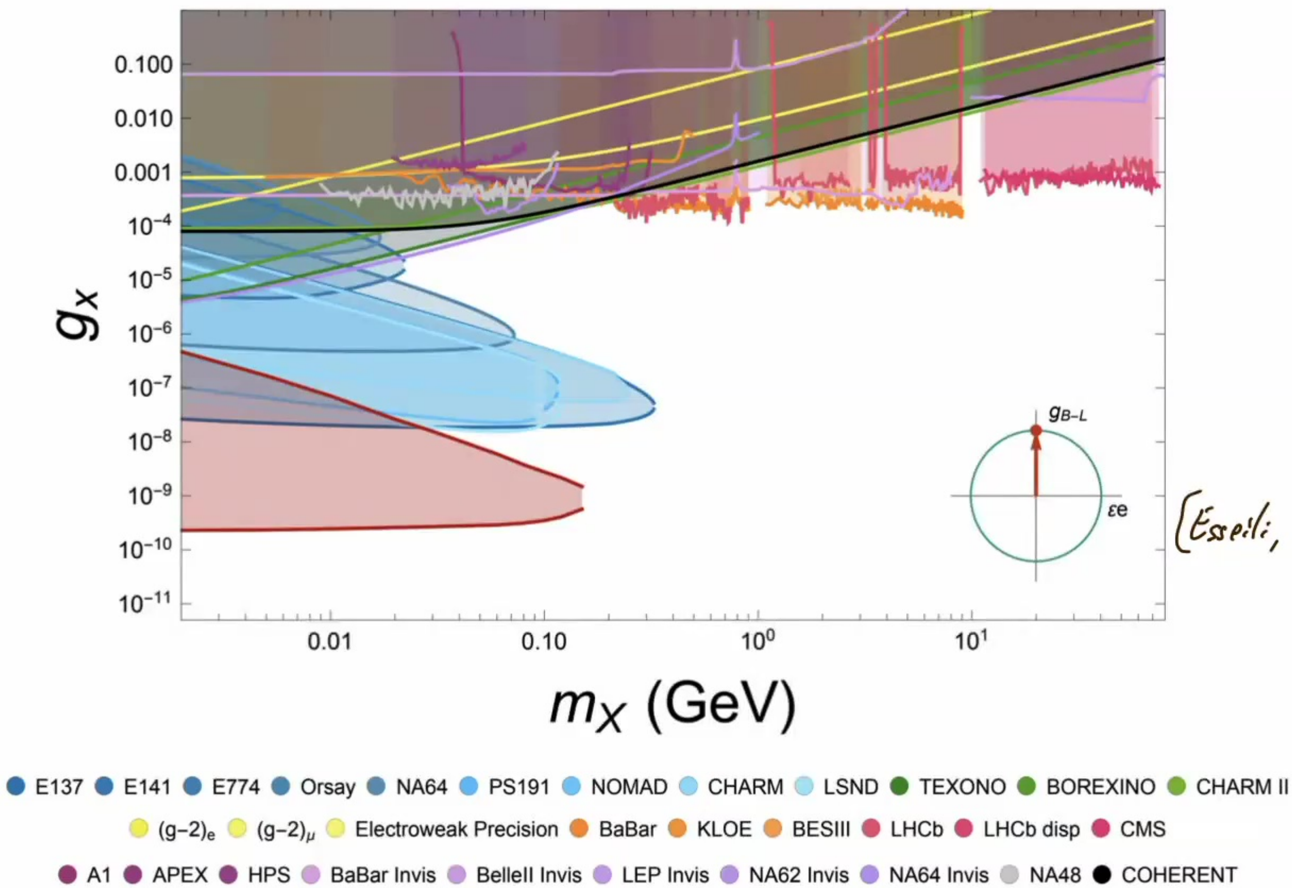
$$\begin{pmatrix} e \\ \nu_e \\ u \\ d \end{pmatrix} \longrightarrow \begin{pmatrix} -\cos\phi - \sin\phi \\ -\sin\phi \\ \frac{2}{3}\cos\phi + \frac{1}{3}\sin\phi \\ -\frac{1}{3}\cos\phi + \sin\phi \end{pmatrix}$$

$X_\mu J^\mu_{EM}$



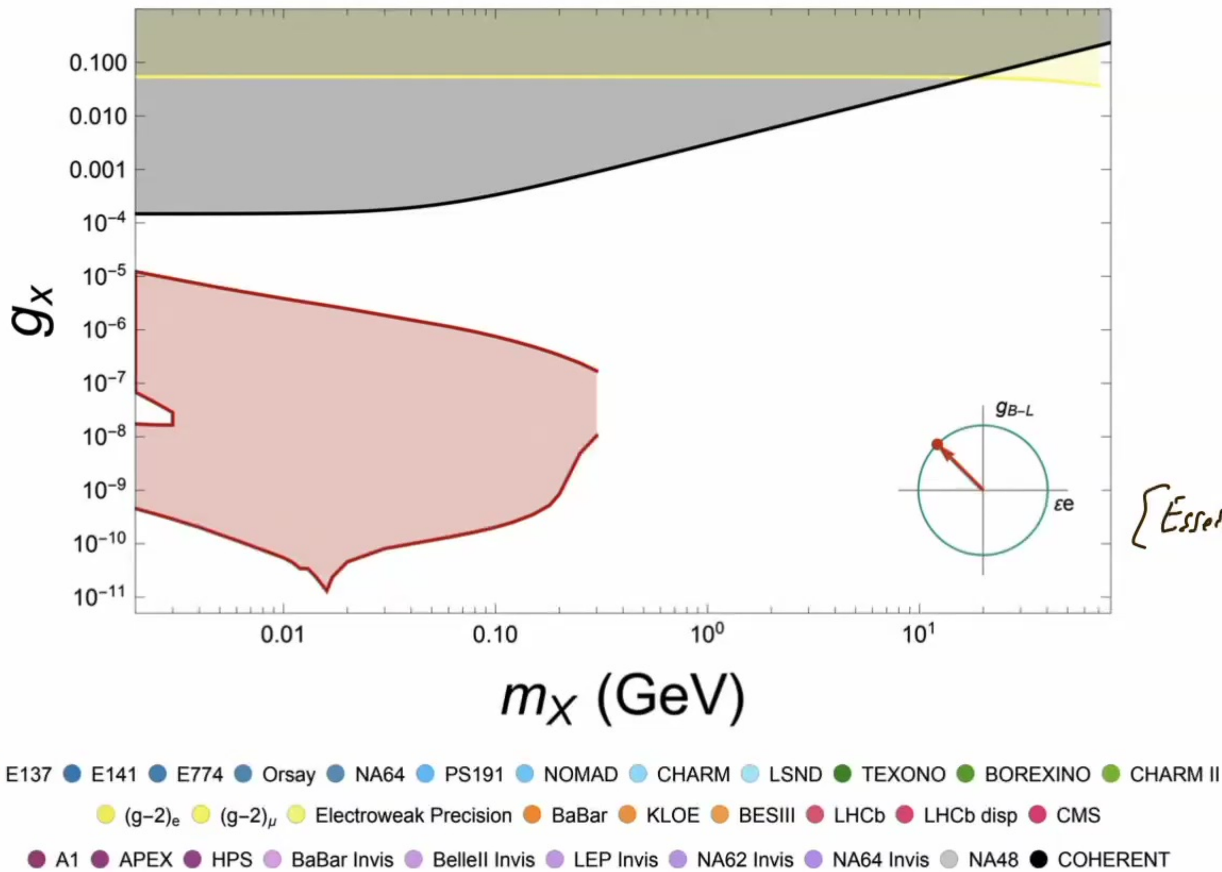
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
g_X
0.01
0.10
10^0
10^1
m_X (GeV)
g_{B-L}
εe
[Essili, GK]
E137 E141 E774 Orsay NA64 PS191 NOMAD CHARM LSND TEXONO BOREXINO CHARM II
$(g-2)_e$ $(g-2)_\mu$ Electroweak Precision BaBar KLOE BESIII LHCb LHCb disp CMS
A1 APEX HPS BaBar Invis BelleII Invis LEP Invis NA62 Invis NA64 Invis NA48 COHERENT
Perimeter-B

$X \sim j^{\mu}_{B-L}$

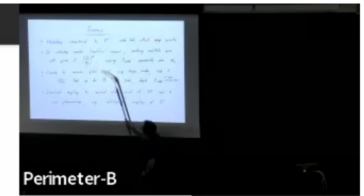


[Esseili, GK]

Electrophobic



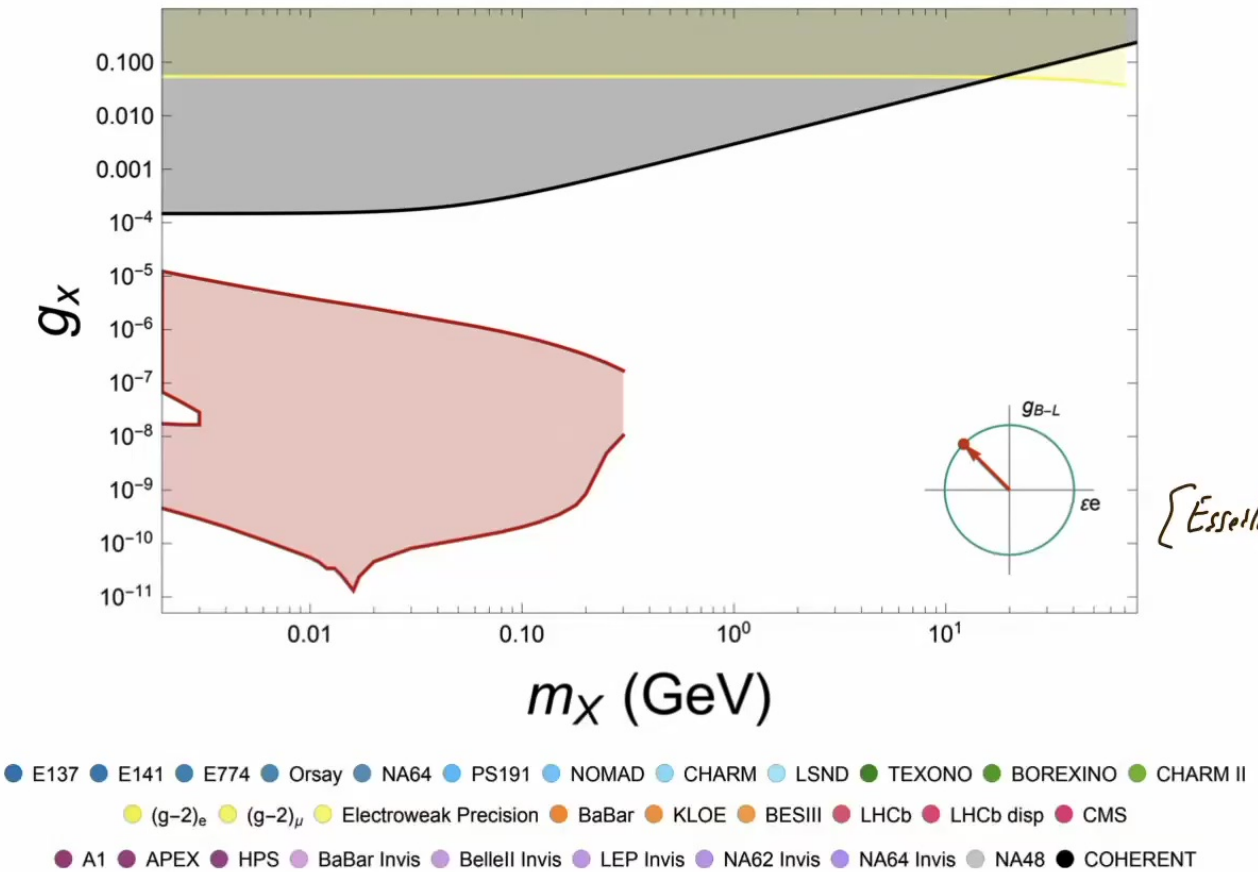
[Esseili, GK]



Summary

- Stückelberg characterized by X^μ : vector field without gauge symmetry.
- If interactions involve longitudinal component, scattering amplitudes grow with powers of $\left(\frac{\sqrt{s}}{m_X}\right)^{\#}$, implying Λ_{cutoff} parametrically above m_X.
- Coupling to anomalous global current, e.g. baryon number, leads to $\sqrt{s_{max}}$ that can be $\ll$ EW scale, despite $\Lambda_{cutoff} \xrightarrow{v\to\infty} \infty$.
- Generalized couplings to conserved global currents of SM lead to rich phenomenology, e.g. "electrophobic" couplings of X^μ

Electrophobic



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