Aspects of Charged Lepton Flavor Violation in High Energy Physics

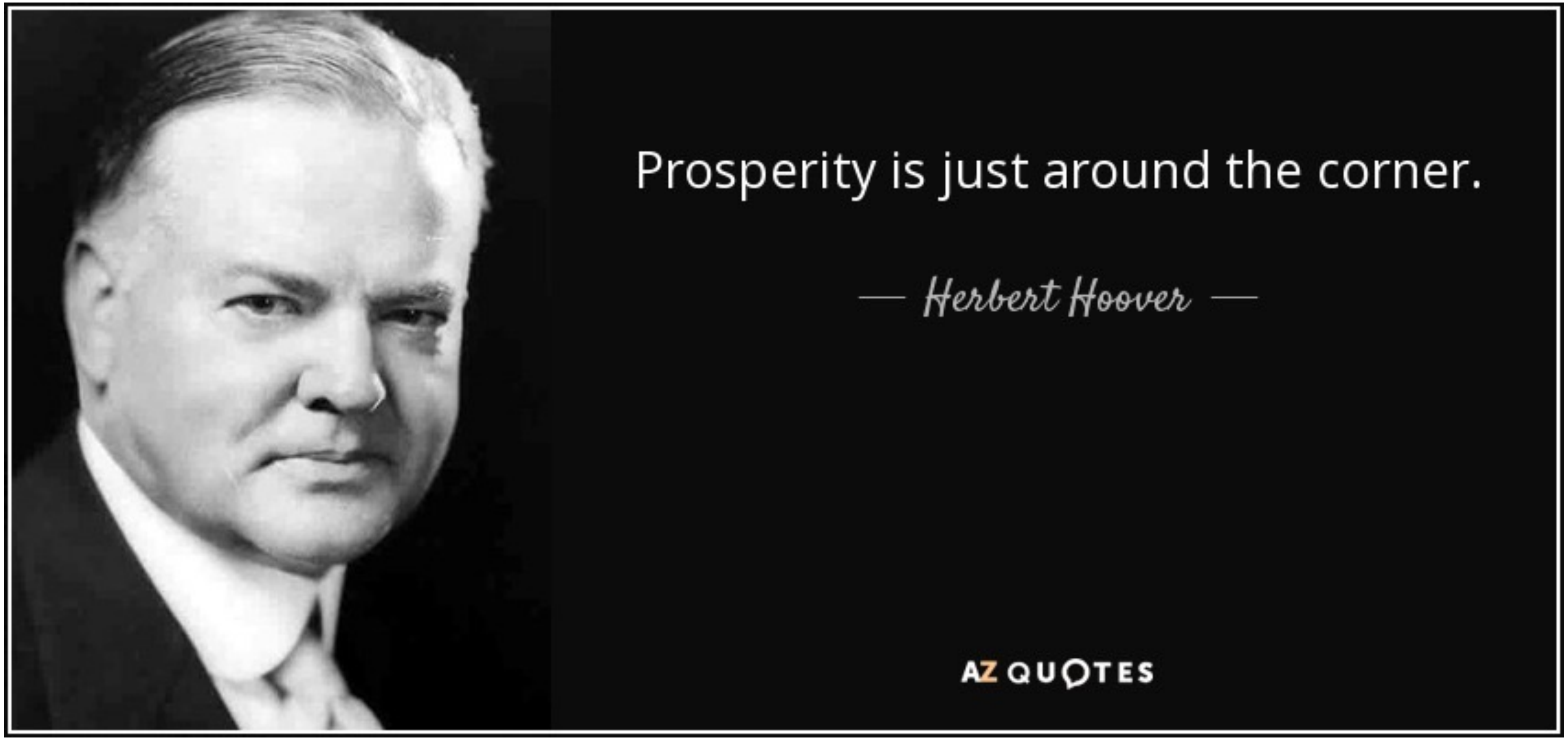
Roman Marcarelli

Advisor: Ethan Neil

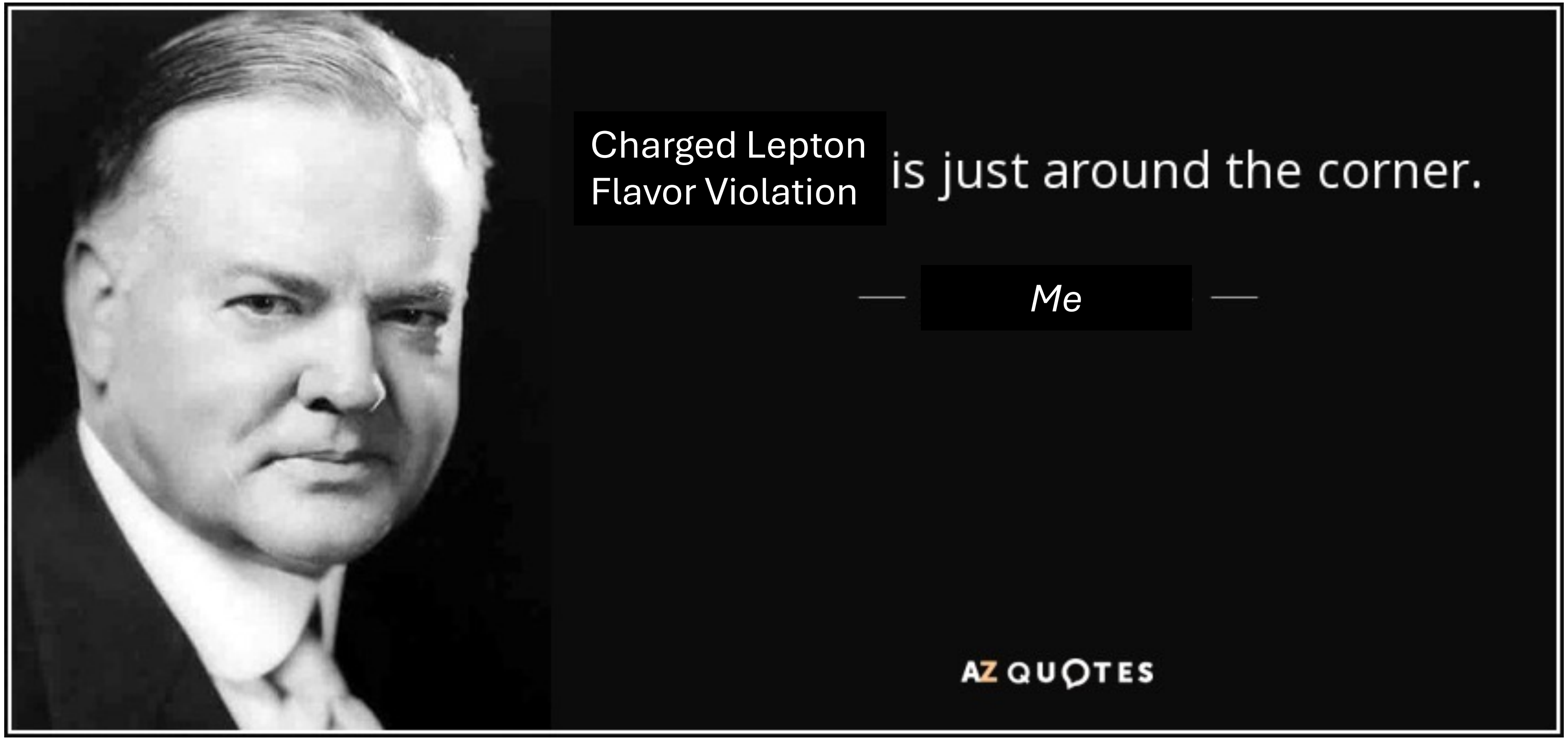
Committee: Oliver DeWolfe, Andrew Hamilton, Anna Hasenfratz, Keith Ulmer, Jamie Nagle

Why study CLFV?

Why study CLFV?



Why study CLFV?



Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*

Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d} \quad \boldsymbol{s} \quad \boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u} \quad \boldsymbol{c} \quad \boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e} \quad \boldsymbol{\mu} \quad \boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e} \quad \boldsymbol{\nu_\mu} \quad \boldsymbol{\nu_\tau}$

Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d} \quad \boldsymbol{s} \quad \boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u} \quad \boldsymbol{c} \quad \boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e} \quad \boldsymbol{\mu} \quad \boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e} \quad \boldsymbol{\nu_\mu} \quad \boldsymbol{\nu_\tau}$

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*

Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d} \quad \boldsymbol{s} \quad \boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u} \quad \boldsymbol{c} \quad \boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e} \quad \boldsymbol{\mu} \quad \boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e} \quad \boldsymbol{\nu_\mu} \quad \boldsymbol{\nu_\tau}$

Flavor-changing

Flavor-violating

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*

Flavor-Violation in the SM

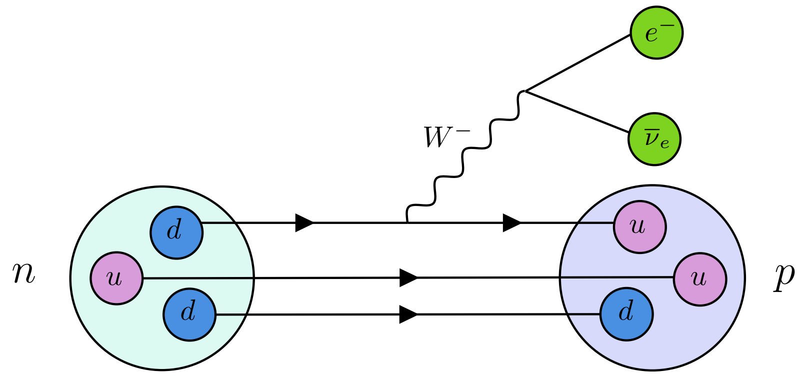
- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*

Down-type quarks:	$\boldsymbol{d}$	$\boldsymbol{s}$	$\boldsymbol{b}$
Up-type quarks:	$\boldsymbol{u}$	$\boldsymbol{c}$	$\boldsymbol{t}$
Charged leptons:	$\boldsymbol{e}$	$\boldsymbol{\mu}$	$\boldsymbol{\tau}$
Neutrinos:	$\boldsymbol{\nu_e}$	$\boldsymbol{\nu_\mu}$	$\boldsymbol{\nu_\tau}$

Flavor-changing

Flavor-violating

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*



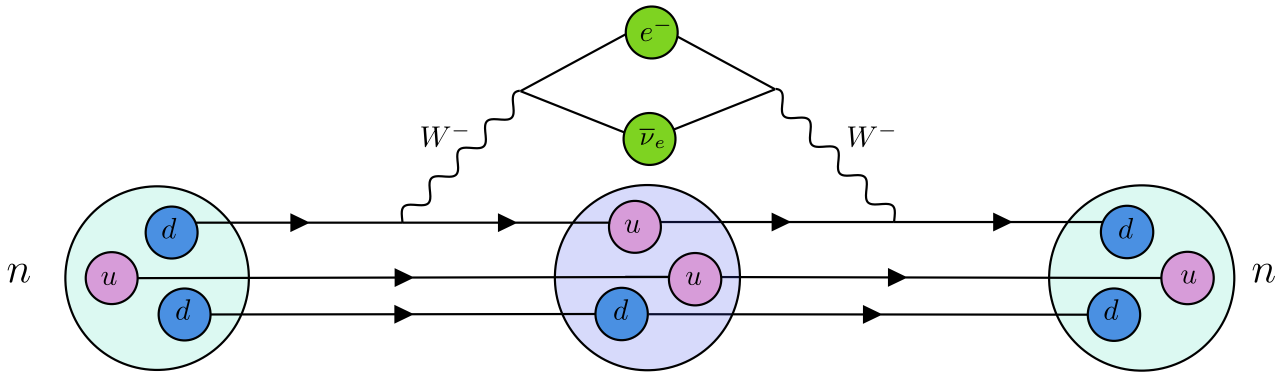
Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$

Flavor-changing

Flavor-violating

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*



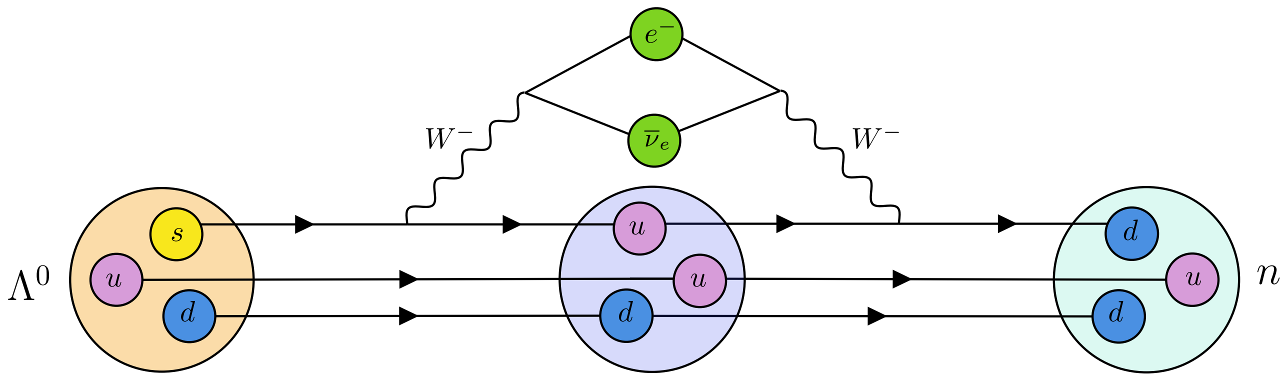
Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$

Flavor-changing

Flavor-violating

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*



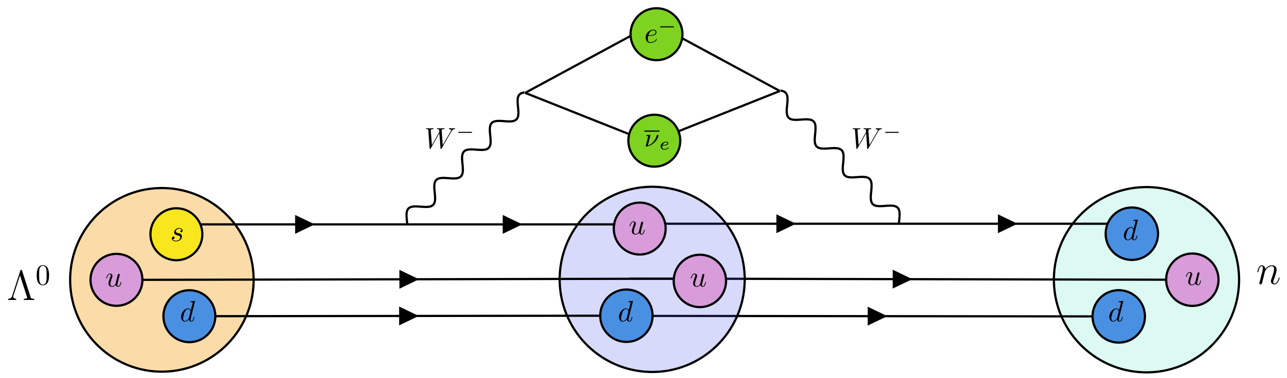
Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$

Flavor-changing

Flavor-violating

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*



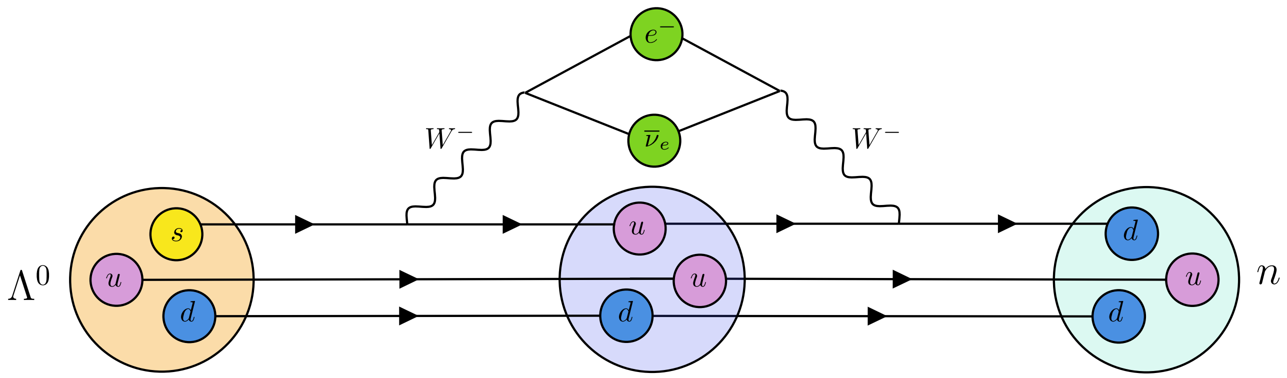
Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$

Flavor-violating

Source: mismatch between W-boson interaction and Yukawa interactions

- Flavor violating: *Interaction that contributes to flavor-changing **neutral** currents*



Flavor-Violation in the SM

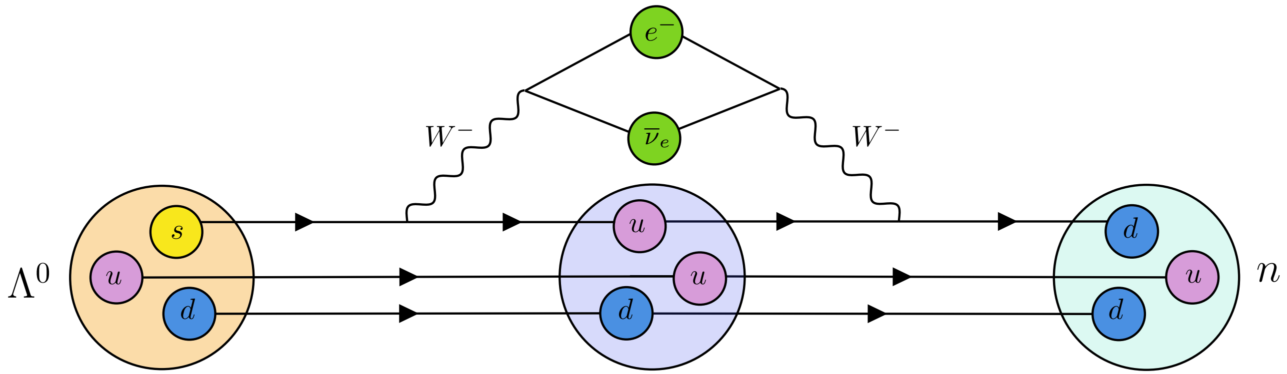
- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$

Flavor-violating

Source: mismatch between W-boson interaction and Yukawa interactions

Absence: no neutrino masses in SM

- Flavor violating: *Interaction that contributes to flavor-changing **neutral** currents*



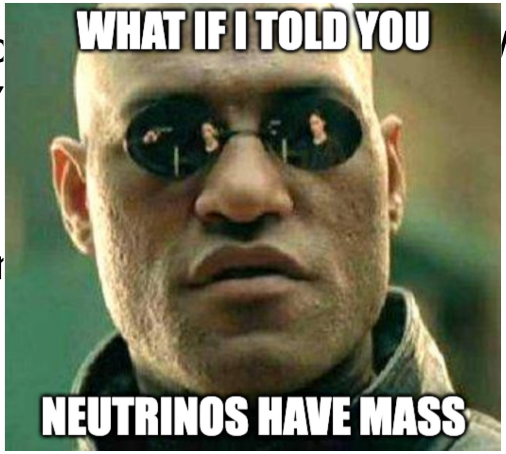
Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$

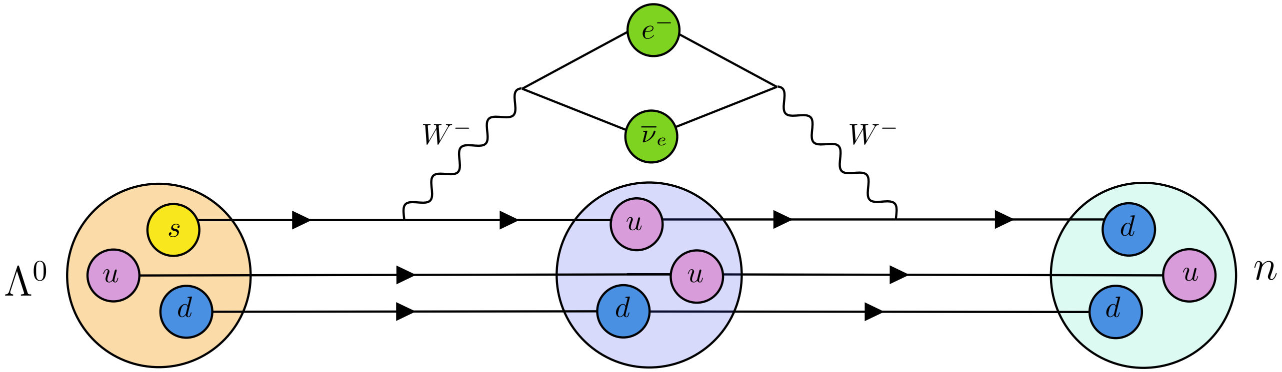
Flavor-violating

Sourc -boson interaction
and Y

Abser in SM



- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*



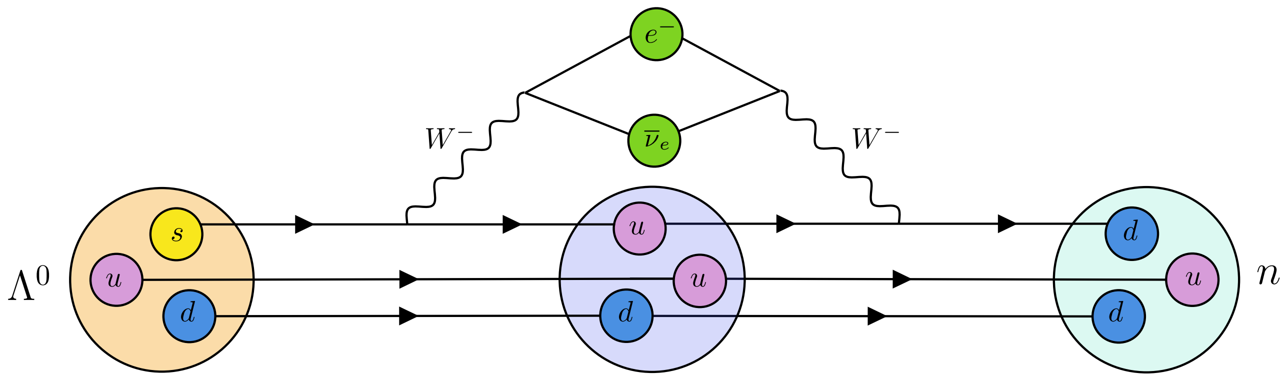
Flavor-Violation in the SM

- Flavor: *The names we give to the mass eigenstates of the fields in the SM.*
  - Down-type quarks: $\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$
  - Up-type quarks: $\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$
  - Charged leptons: $\boldsymbol{e}$ $\boldsymbol{\mu}$ $\boldsymbol{\tau}$
  - Neutrinos: $\boldsymbol{\nu_e}$ $\boldsymbol{\nu_\mu}$ $\boldsymbol{\nu_\tau}$ $\longrightarrow$ $\boldsymbol{\nu_1}$ $\boldsymbol{\nu_2}$ $\boldsymbol{\nu_3}$

Source: mismatch between W-boson interaction and Yukawa interactions

Flavor-violating

- Flavor violating: *Interaction that contributes to flavor-changing* ***neutral*** *currents*



Neutrino oscillations

- Homestake experiment, 1963
  - 30% less ν_e than expected!

- Solution: neutrinos oscillate!

$$\nu_e \to \nu_\mu \to \nu_e \to \nu_\mu \to \cdots$$

- Neutrinos have mass
  - *Type I see-saw (RH neutrino)*
  - *Type II see-saw (triplet scalar)*
  - *Type III see-saw (triplet fermion)*

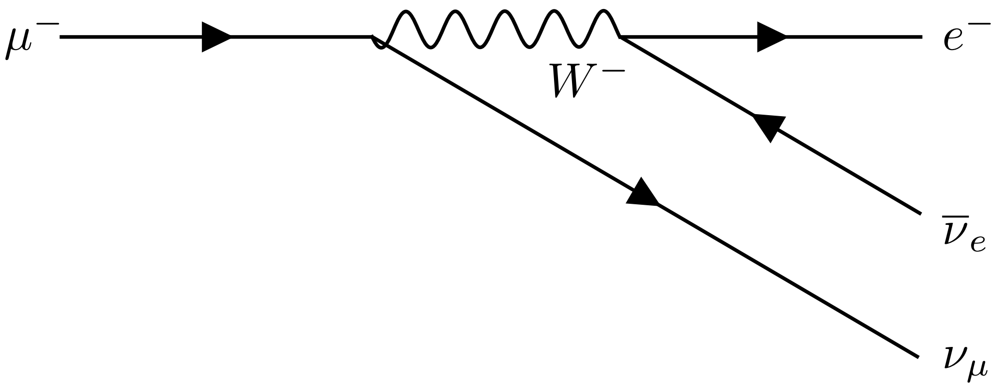
- What about charged leptons?

What about the charged leptons?

- Consider a muon

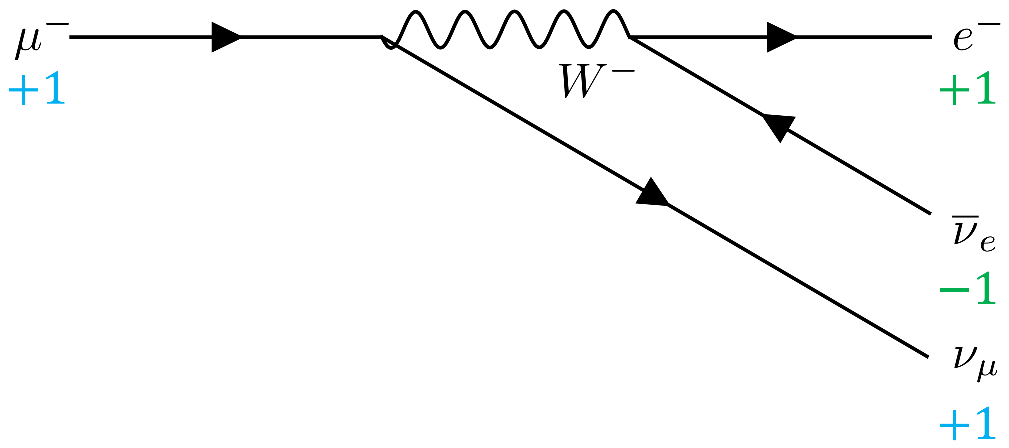
What about the charged leptons?

- Consider a muon



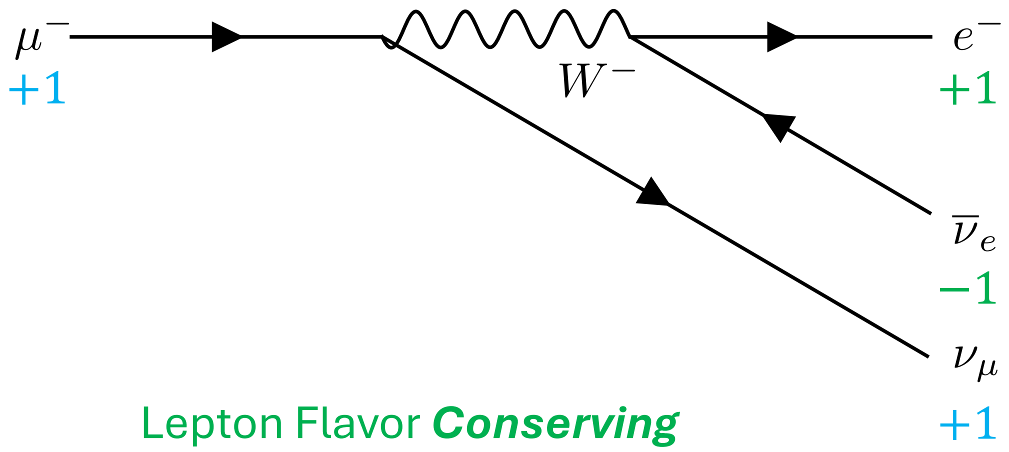
What about the charged leptons?

- Consider a muon



What about the charged leptons?

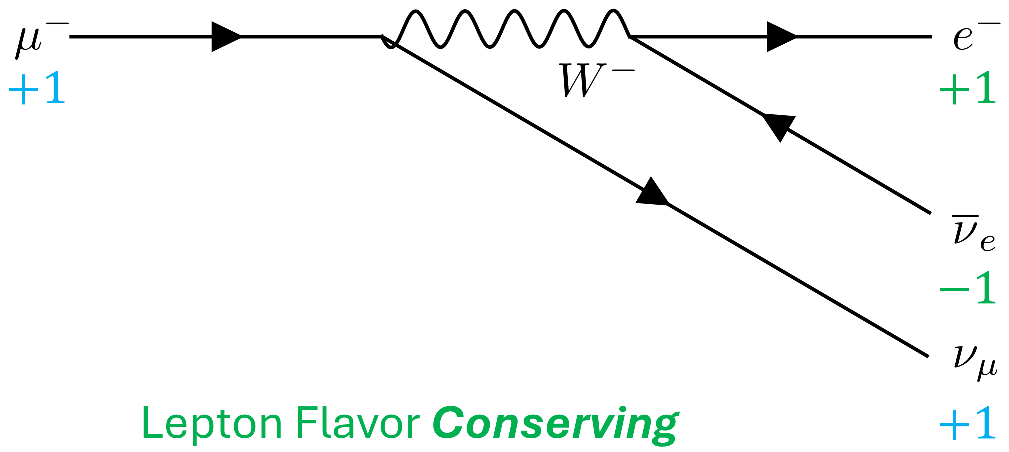
- Consider a muon

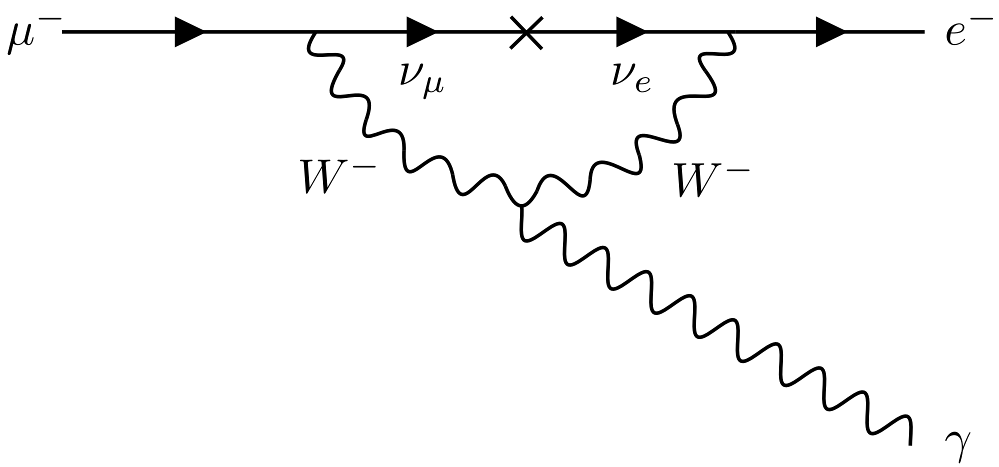


Lepton Flavor ***Conserving***

What about the charged leptons?

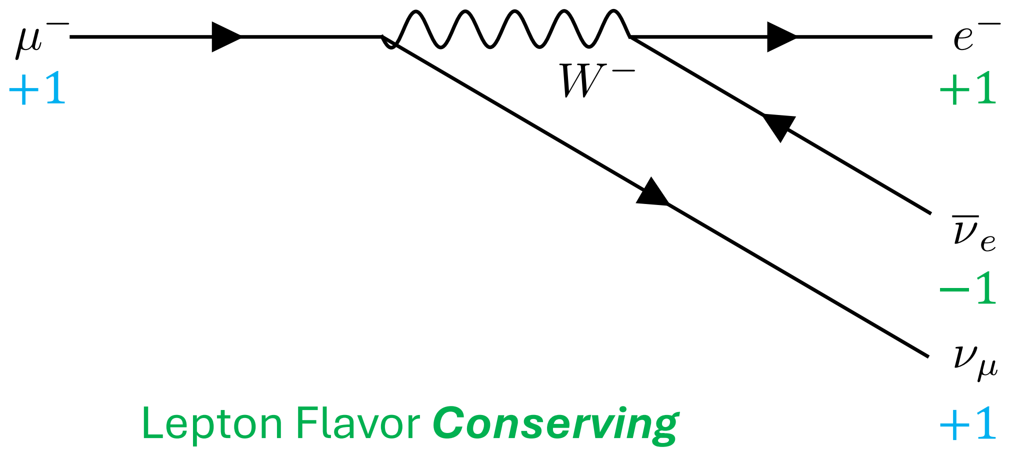
- Consider a muon

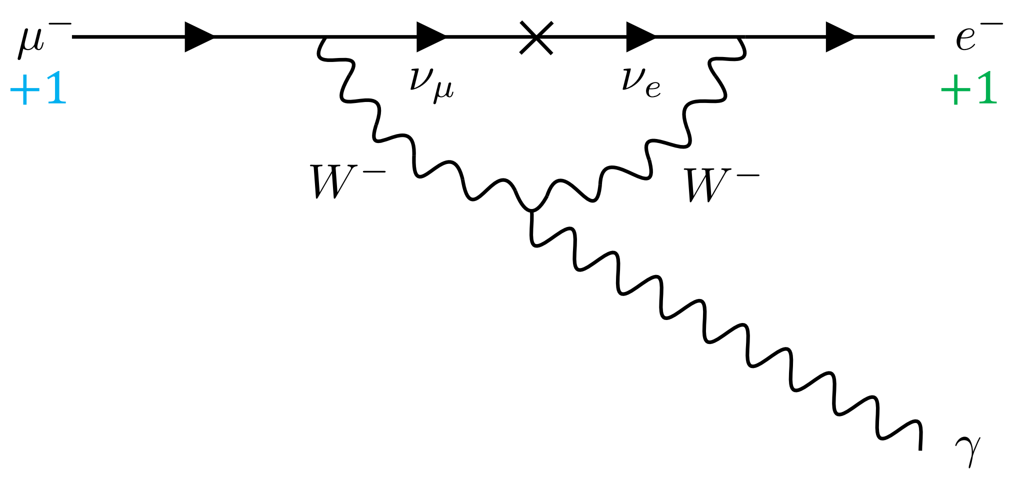




What about the charged leptons?

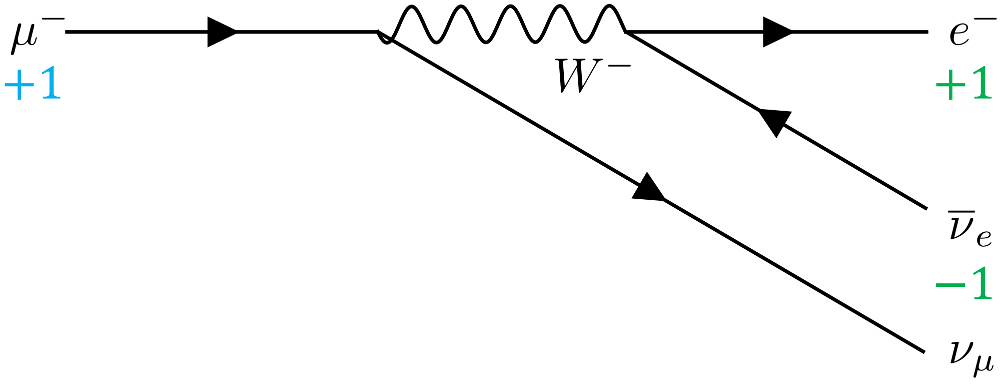
- Consider a muon



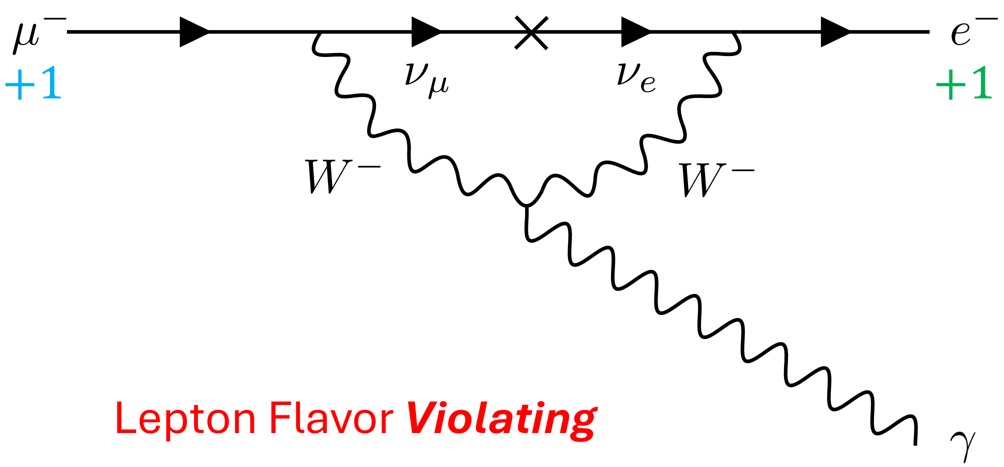


What about the charged leptons?

- Consider a muon



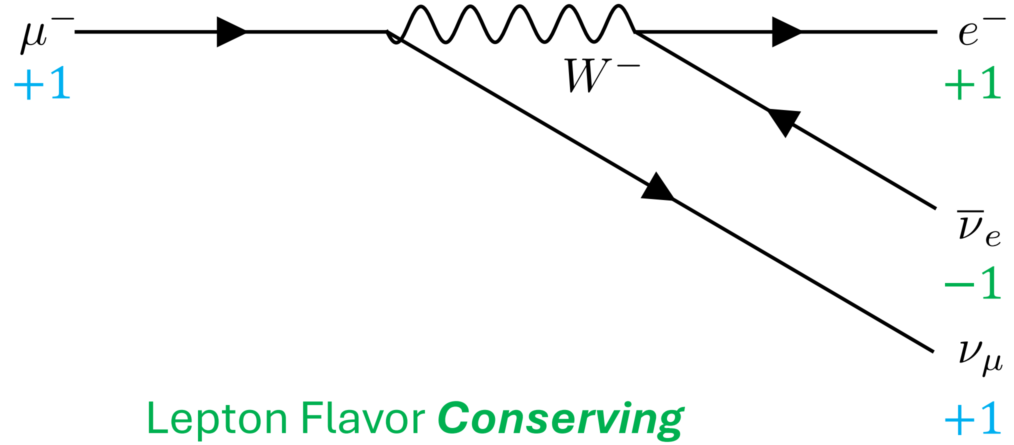
Lepton Flavor ***Conserving***



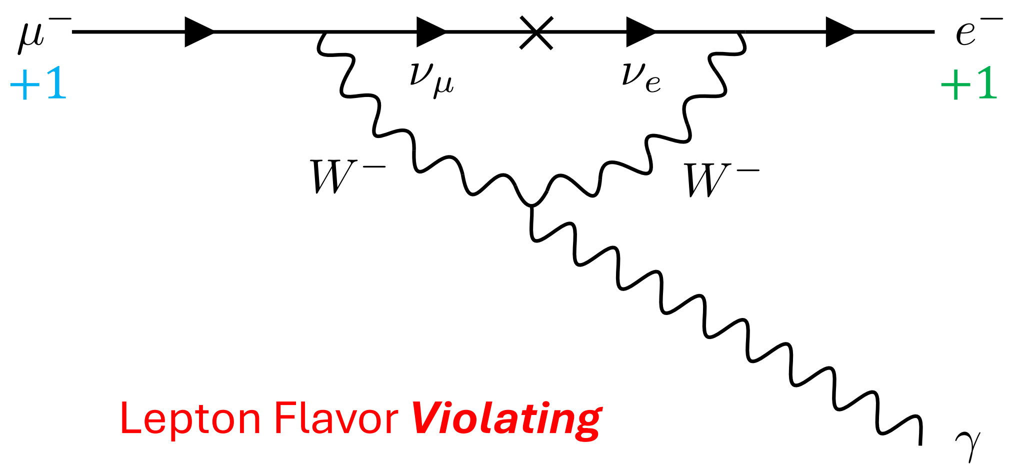
Lepton Flavor ***Violating***

What about the charged leptons?

- Consider a muon



Lepton Flavor ***Conserving***

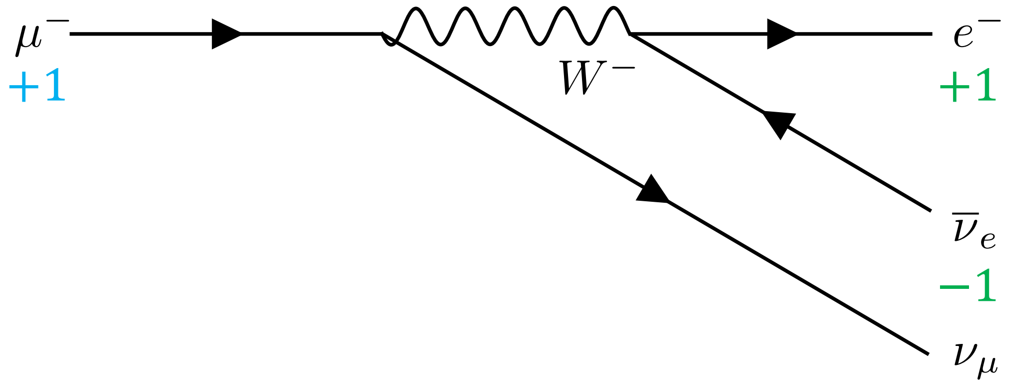


Lepton Flavor ***Violating***

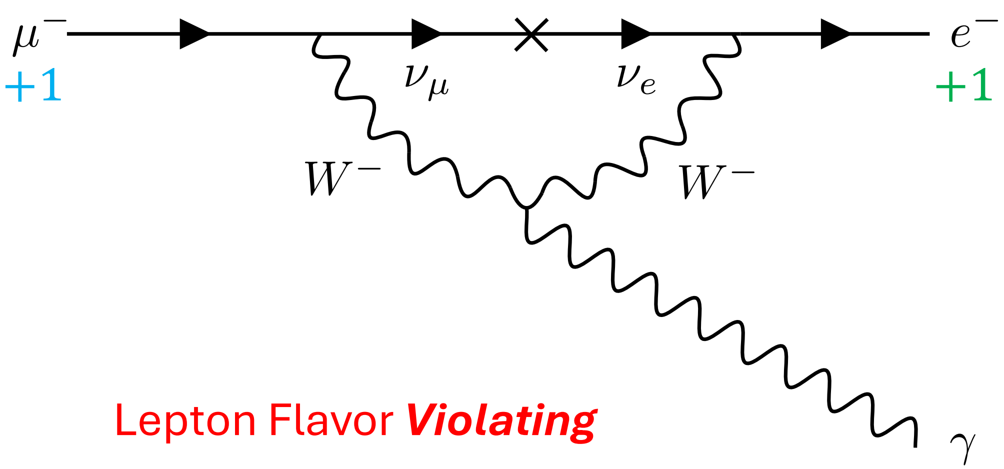
- Charged lepton flavor is *not* a good symmetry of the universe.

What about the charged leptons?

- Consider a muon



Lepton Flavor ***Conserving***



Lepton Flavor ***Violating***

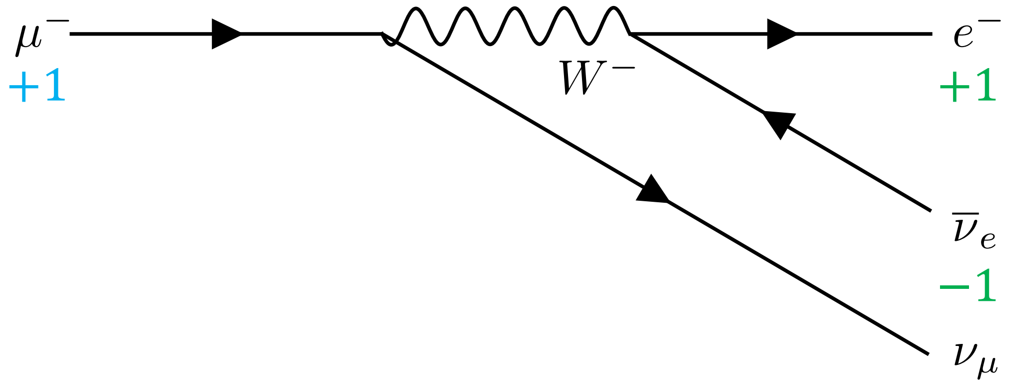
$$\mathcal{B}\left(\mu^- \to e^- + \overline{\nu_e} + \nu_\mu\right) \approx 0.999966$$

$$\mathcal{B}(\mu^- \to e^- + \gamma) \approx 10^{-54}$$

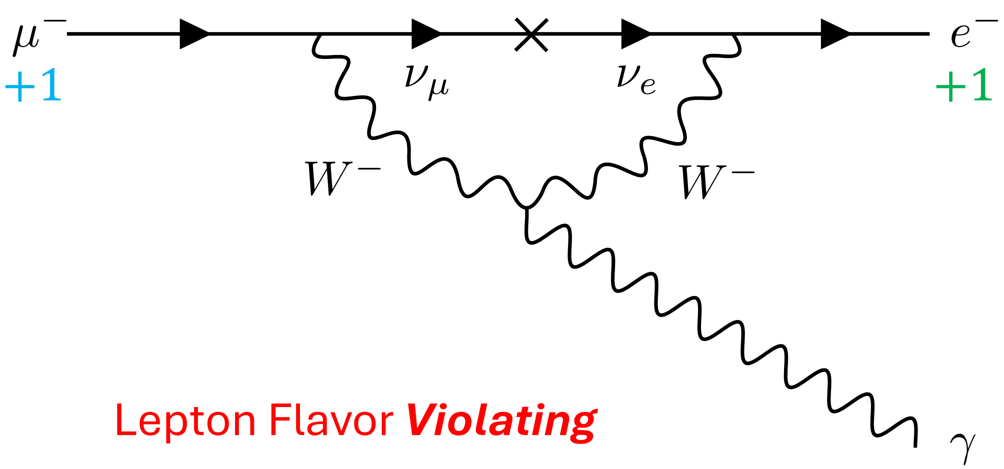
- Charged lepton flavor is *not* a good symmetry of the universe.

What about the charged leptons?

- Consider a muon



Lepton Flavor ***Conserving***



Lepton Flavor ***Violating***

$$\mathcal{B}\left(\mu^- \to e^- + \overline{\nu_e} + \nu_\mu\right) \approx 0.999966$$

$$\mathcal{B}(\mu^- \to e^- + \gamma) \approx 10^{-54}$$

- Charged lepton flavor is *not* a good symmetry of the universe.
- We shouldn't expect new physics to obey it!

Dark matter?

Fermion Hierarchy problem?

Higgs Hierarchy problem?

Strong-CP problem?

Baryogenesis?

Flavor structure of SM?

Origin of SM symmetry group?

Quantization of Gravity?

Dark matter?

Sterile neutrinos
Axion
SIMPs
WIMPs
MACHOS
MoND

Fermion Hierarchy problem?

Froggatt-Nielsen models
Extra dimensions
Partial compositeness
Radiative mass generation
Flavor textures
Anthropic principle

Higgs Hierarchy problem?

Supersymmetry
Extra dimensions
Composite Higgs
Little Higgs
Twin Higgs
Anthropic principle

Strong-CP problem?

DFSZ axion
KSVZ axion

Baryogenesis?

Leptogenesis
GUT Baryogenesis
Electroweak Baryogenesis
Anthropic principle

Flavor structure of SM?

Froggatt-Nielsen models
Extra dimensions
Partial compositeness
Grand unified theories

Origin of SM symmetry group?

Grand unified theories
String theory
Extra dimensions
Anthropic principle

Quantization of Gravity?

Supersymmetry from string theory
Asymptotic safety
Loop quantum gravity

Flavor-violating scalar interactions

FV scalar terminology: couplings

$$\mathcal{L}_{\varphi\psi\psi} = \sum_{ij} \varphi\bar{\psi}_i\left[g_{ij}^S + i g_{ij}^{PS}\gamma^5\right]\psi_j$$

- Hermiticity requires $g_{ij}^S = g_{ji}^{S*}, g_{ij}^{PS} = g_{ji}^{PS*}$
- If $g_{ij}^{PS} = 0$, we say φ a *pure* scalar.
- If $g_{ij}^S = 0$, we say a φ is a *pseudo*scalar.
- If $g_{ij}^{PS} = \pm i g_{ij}^S$, we say φ is a *chiral* scalar. ($P_{L,R} = \frac{1}{2}(1 \pm \gamma^5)$)

FV scalar terminology: angles and phases

$$\mathcal{L}_{\varphi\psi\psi} = \sum_{ij} \varphi \bar{\psi}_i \left[g_{ij}^{S} + i g_{ij}^{PS} \gamma^5\right] \psi_j$$

- Define $g_{ij}^{S} \equiv g_{ij} e^{i\phi_{ij}^{S}} \cos\theta_{ij}$, $g_{ij}^{PS} \equiv g_{ij} e^{i\phi_{ij}^{PS}} \sin\theta_{ij}$
- Define $\delta_{ij} \equiv \phi_{ij}^{PS} - \phi_{ij}^{S}$

$$\mathcal{L}_{\varphi\psi\psi} = \sum_{ij} \varphi g_{ij} e^{i\phi_{ij}^{S}} \bar{\psi}_i \left[\cos\theta_{ij} + i e^{i\delta_{ij}} \sin\theta_{ij}\right] \psi_j$$

FV scalar terminology: angles and phases

$$\mathcal{L}_{\varphi\psi\psi} = \sum_{ij} \varphi g_{ij} e^{i\phi_{ij}^S} \bar{\psi}_i \left[\cos\theta_{ij} + i e^{i\delta_{ij}} \sin\theta_{ij}\right] \psi_j$$

- Hermiticity requires $g_{ij} = g_{ji}, \theta_{ij} = \theta_{ji}, \phi_{ij} = -\phi_{ji}, \delta_{ij} = -\delta_{ji}$
- θ_{ij} characterizes *parity violation* (PV)
- δ_{ij} characterizes *charge-parity* (CP) *violation*
- $\theta_{ij} = 0$: pure scalar
- $\theta_{ij} = \pi/2$: pseudoscalar
- $\theta_{ij} = \pi/4, \delta_{ij} = \pm\pi/2$: chiral scalar

FV ALP terminology: background

- ALP: *axion-like particle*
  - pseudo-Nambu-Goldstone boson of spontaneously broken *approximate* global symmetry
  - axion (hypothetical), pion (real)
- For our purposes: obeys approximate shift symmetry $a \to a + f$, so only couples via a derivative interaction:

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} \bar{\psi}_i \gamma^\mu \left[g_{ij}^V + g_{ij}^A \gamma^5 \right] \psi_j$$

- Hermiticity requires $g_{ij}^V = g_{ji}^{V*}, g_{ij}^A = g_{ji}^{A*}$

FV ALP terminology: angles and phases

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} \bar{\psi}_i \gamma^\mu [g_{ij}^V + g_{ij}^A \gamma^5] \psi_j$$

- Define $g_{ij}^V \equiv C_{ij} e^{i\Phi_{ij}^V} \sin\Theta_{ij}$, $g_{ij}^V \equiv C_{ij} e^{i\Phi_{ij}^A} \cos\Theta_{ij}$
- Define $\Delta_{ij} = \Phi_{ij}^V - \Phi_{ij}^A$

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} C_{ij} e^{i\Phi_{ij}^A} \bar{\psi}_i \gamma^\mu [e^{i\Delta_{ij}} \sin\Theta_{ij} - \cos\Theta_{ij}\, \gamma^5] \psi_j$$

FV ALP terminology: effective scalar interaction

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} \bar{\psi}_i \gamma^\mu [g_{ij}^V + g_{ij}^A \gamma^5] \psi_j$$

- Integrate by parts and apply equations of motion:

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} ia\bar{\psi}_i \left[\frac{m_j - m_i}{\Lambda} g_{ij}^V - \frac{m_j + m_i}{\Lambda} g_{ij}^A \gamma^5\right] \psi_j$$

FV ALP terminology: effective scalar interaction

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} \bar{\psi}_i \gamma^\mu [g_{ij}^V + g_{ij}^A \gamma^5] \psi_j$$

- Integrate by parts and apply equations of motion:

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} i a \bar{\psi}_i \left[\frac{m_j - m_i}{\Lambda} g_{ij}^V - \frac{m_j + m_i}{\Lambda} g_{ij}^A \gamma^5 \right] \psi_j$$

(extra gauge coupling from chiral anomaly)

$$+ \frac{a}{\Lambda} \sum_f \sum_i \frac{N_c^f Q_f^2}{8\pi^2} g_{ii}^A F_{\mu\nu} \tilde{F}^{\mu\nu} + \cdots$$

FV ALP terminology: effective scalar interaction

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} \bar{\psi}_i \gamma^\mu [g_{ij}^V + g_{ij}^A \gamma^5] \psi_j$$

- Integrate by parts and apply equations of motion:

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} ia\bar{\psi}_i \left[\frac{m_j - m_i}{\Lambda} g_{ij}^V - \frac{m_j + m_i}{\Lambda} g_{ij}^A \gamma^5 \right] \psi_j$$

FV ALP terminology: effective scalar interaction

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} \bar{\psi}_i \gamma^\mu [g_{ij}^V + g_{ij}^A \gamma^5] \psi_j$$

- Integrate by parts and apply equations of motion:

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} i a \bar{\psi}_i \left[\frac{m_j - m_i}{\Lambda} g_{ij}^V - \frac{m_j + m_i}{\Lambda} g_{ij}^A \gamma^5\right] \psi_j$$

- ALPs couple to fermions according to mass hierarchy
- Coupling to scalar current vanishes for $i = j$
- Can write as a scalar interaction $g_{ij}^S = i \frac{m_j - m_i}{\Lambda} g_{ij}^V, g_{ij}^{PS} = -i \frac{m_j + m_i}{\Lambda} g_{ij}^A$

FV ALP terminology: scalar-ALP conversion

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} C_{ij} e^{i\Phi_{ij}^V} \bar{\psi}_i \gamma^\mu \left[e^{i\Delta_{ij}} \sin\Theta_{ij} - \cos\Theta_{ij}\,\gamma^5 \right] \psi_j + \mathrm{H.c.}$$

- Can write in terms of scalar coupling, angle, phases:

$$g_{ij} = \frac{C_{ij}}{\Lambda} \sqrt{m_i^2 + m_j^2 + 2m_i m_j \cos 2\Theta_{ij}}, \quad \tan\theta_{ij} = \frac{m_i + m_j}{m_i - m_j} \cot\Theta_{ij}$$

$$\frac{C_{ij}}{\Lambda} = \frac{g_{ij}}{\left|m_i^2 - m_j^2\right|} \sqrt{m_i^2 + m_j^2 + 2m_i m_j \cos 2\theta_{ij}}, \quad \tan\Theta_{ij} = \frac{m_i + m_j}{m_i - m_j} \cot\theta_{ij}$$

$$\sqrt{m_i^2 + m_j^2 + 2m_i m_j \cos 2\theta_{ij}}\,\sqrt{m_i^2 + m_j^2 + 2m_i m_j \cos 2\Theta_{ij}} = \left|m_i^2 - m_j^2\right|$$

FV ALP terminology: scalar-ALP conversion

$$\mathcal{L}_{a\psi\psi} = \sum_{ij} \frac{\partial_\mu a}{\Lambda} C_{ij} e^{i\Phi^V_{ij}} \bar{\psi}_i \gamma^\mu \left[e^{i\Delta_{ij}} \sin\Theta_{ij} - \cos\Theta_{ij}\, \gamma^5 \right] \psi_j + \mathrm{H.c.}$$

- Can write in terms of scalar coupling, angle, phases:

Law of cosines?

Law of tangents?

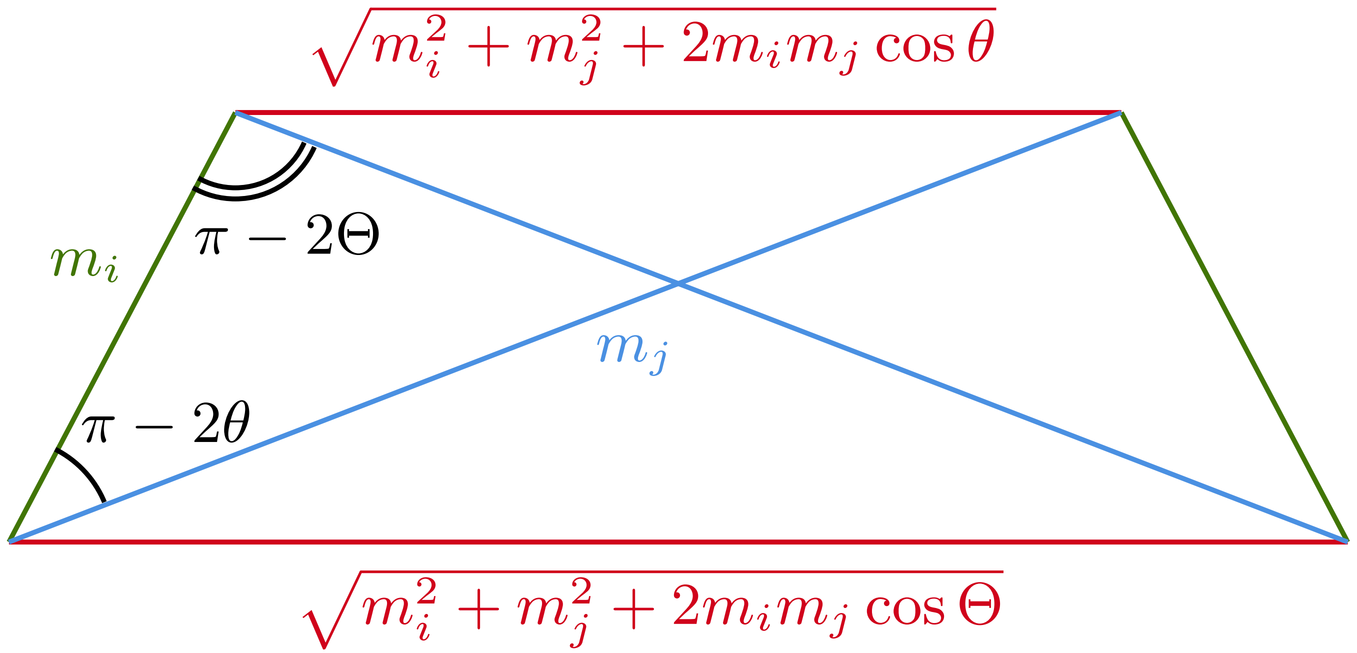
$$g_{ij} = \frac{C_{ij}}{\Lambda} \boxed{\sqrt{m_i^2 + m_j^2 + 2 m_i m_j \cos 2\Theta_{ij}},} \quad \boxed{\tan\theta_{ij} = \frac{m_i + m_j}{m_i - m_j} \cot\Theta_{ij}}$$

$$\frac{C_{ij}}{\Lambda} = \frac{g_{ij}}{|m_i^2 - m_j^2|} \boxed{\sqrt{m_i^2 + m_j^2 + 2 m_i m_j \cos 2\theta_{ij}},} \quad \boxed{\tan\Theta_{ij} = \frac{m_i + m_j}{m_i - m_j} \cot\theta_{ij}}$$

Isosceles trapezoid side length-diagonal relationship?

$$\boxed{\sqrt{m_i^2 + m_j^2 + 2 m_i m_j \cos 2\theta_{ij}}\, \sqrt{m_i^2 + m_j^2 + 2 m_i m_j \cos 2\Theta_{ij}} = |m_i^2 - m_j^2|}$$

FV ALP terminology: scalar-ALP trapezoid



- Deeper interpretation?

- At the very least, useful for converting scalar expressions to ALP expressions.

CLFV in Lepton Observables

CLFV in Lepton Observables: leptophilic models

Leptophilic scalar:

$$\mathcal{L}_\varphi = \varphi \sum_{ij} g_{ij} e^{i\phi_{ij}} \overline{\ell}_i \left(\cos\theta_{ij} + i e^{i\delta_{ij}} \sin\theta_{ij} \gamma^5 \right) \ell'_j)$$

Leptophilic ALP:

$$\mathcal{L}_a = \frac{\partial_\mu a}{\Lambda} \sum_{ij} C_{ij} e^{i\Phi_{ij}} \overline{\ell}_i \gamma^\mu \left(e^{i\Delta_{ij}} \sin\Theta_{ij} + \cos\Theta_{ij} \gamma^5 \right) \ell'_j)$$

CLFV in Lepton Observables: leptophilic models

Leptophilic scalar:

$$\mathcal{L}_\varphi = \varphi \sum_{ij} g_{ij} e^{i\phi_{ij}} \bar{\ell}_i \left(\cos\theta_{ij} + i e^{i\delta_{ij}} \sin\theta_{ij}\, \gamma^5\right) \ell'_j)$$

Leptophilic ALP (as scalar):

$$\mathcal{L}_a = \mathcal{L}_\varphi(\varphi \to a) + \frac{a}{\Lambda} C_{\gamma\gamma}^{\text{eff}} F_{\mu\nu}\, \tilde{F}^{\mu\nu}, \quad C_{\gamma\gamma}^{\text{eff}} = \sum_i \frac{N_c^f\, Q_f^2}{8\pi^2} g_{ii}^A F_{\mu\nu}$$

CLFV in Lepton Observables: observables

- LFV lepton decays:

$\mu \to e\gamma$ | $\mu \to 3e$

$\tau \to e\gamma$ | $\tau \to 3e$ | $\tau \to ee\bar{\mu}$ | $\tau \to e\mu\bar{e}$

$\tau \to \mu\gamma$ | $\tau \to 3\mu$ | $\tau \to \mu\mu\bar{e}$ | $\tau \to e\mu\bar{\mu}$

- Lepton dipole moments:

e^- electric dipole moment (EDM)

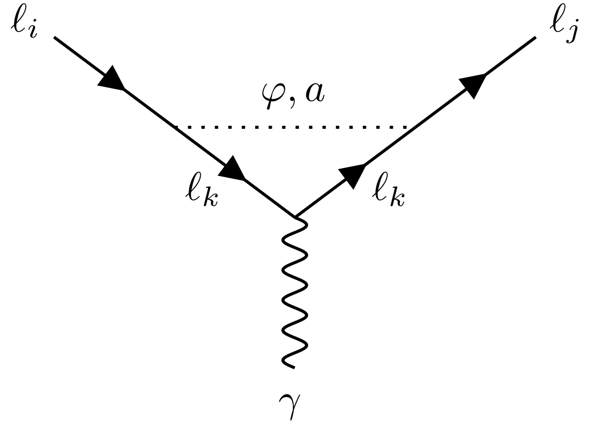
$$\boldsymbol{d_e}$$

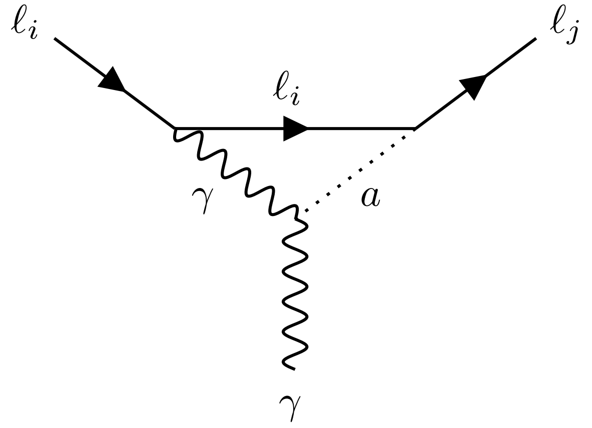
e^- and μ^- magnetic dipole moment (MDM)

$$\mu_\ell = \frac{1}{2} g_\ell \frac{e}{2m_\ell}$$

Anomalous magnetic moment: $\boldsymbol{a_\ell = \frac{g_\ell - 2}{2}}$

CLFV in Lepton Observables: dipole form factors

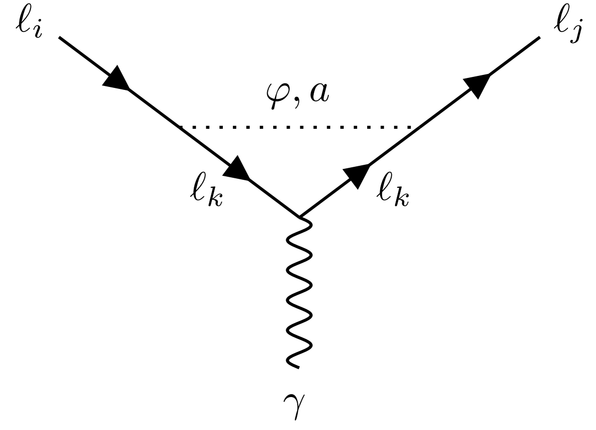


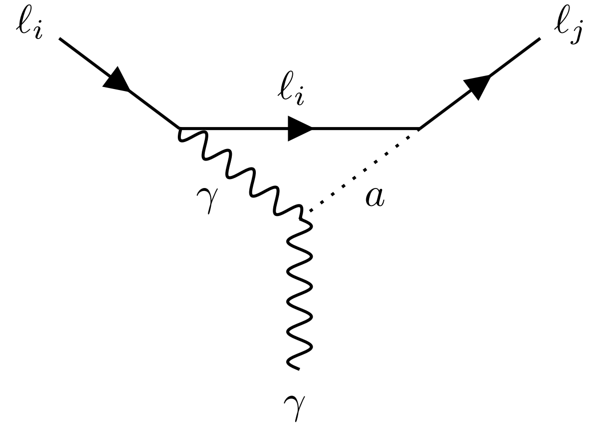


CLFV in Lepton Observables: dipole form factors

- Transition dipole form-factors ($i \neq j$):

$$\bar{u}_j \Gamma_\mu^{ij} u_i = e\bar{u}_j \left[\left(q_\mu + \frac{q^2}{m_i - m_j} \gamma_\mu \right) F_1^{ij} + \frac{i\sigma^{\mu\nu}}{m_i + m_j} q_\nu F_2^{ij} \right.$$
$$\left. + \frac{i\sigma^{\mu\nu}}{m_i - m_j} q_\nu \gamma^5 F_3^{ij} + \left(q_\mu - \frac{q^2}{m_i + m_j} \gamma_\mu \right) \gamma^5 F_4^{ij} \right] u_j$$



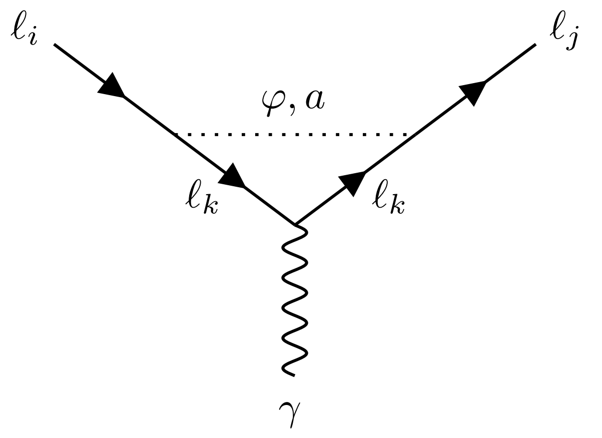


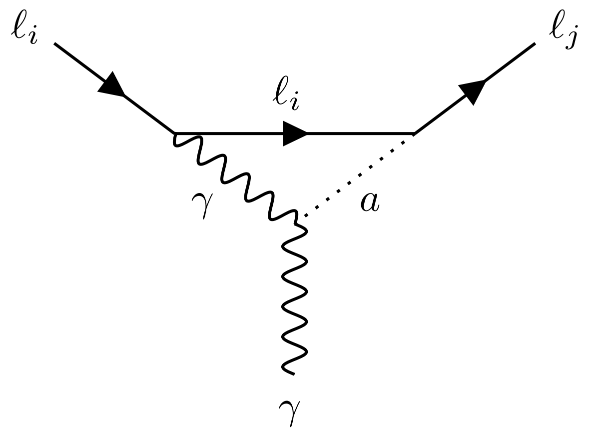
CLFV in Lepton Observables: dipole form factors

- Transition dipole form-factors ($i \neq j$):

$$\bar{u}_j \Gamma_\mu^{ij} u_i = e\bar{u}_j \left[\left(q_\mu + \frac{q^2}{m_i - m_j} \gamma_\mu \right) F_1^{ij} + \frac{i\sigma^{\mu\nu}}{m_i + m_j} q_\nu F_2^{ij} + \frac{i\sigma^{\mu\nu}}{m_i - m_j} q_\nu \gamma^5 F_3^{ij} + \left(q_\mu - \frac{q^2}{m_i + m_j} \gamma_\mu \right) \gamma^5 F_4^{ij} \right] u_j$$

$$\Gamma(\ell_i \to \ell_j \gamma) \propto \left| F_2^{ij}(0) \right|^2 + \left| F_3^{ij}(0) \right|^2$$



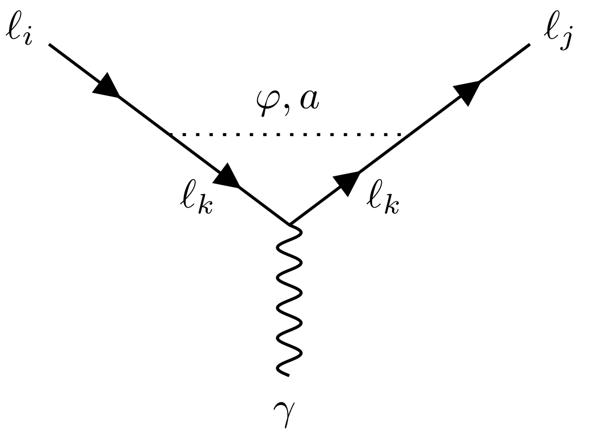


CLFV in Lepton Observables: dipole form factors

- Transition dipole form-factors ($i \neq j$):

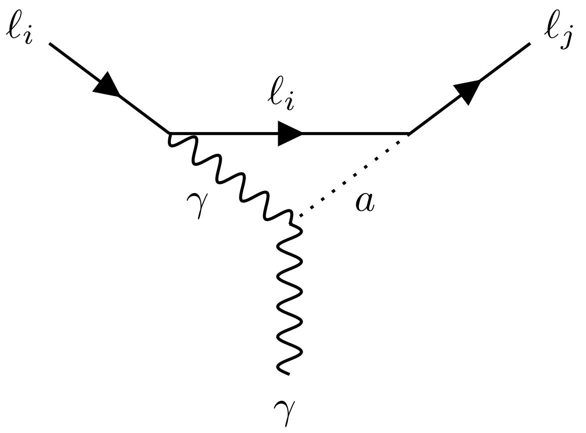
$$\bar{u}_j \Gamma_\mu^{ij} u_i = e \bar{u}_j \left[\left(q_\mu + \frac{q^2}{m_i - m_j} \gamma_\mu \right) F_1^{ij} + \frac{i\sigma^{\mu\nu}}{m_i + m_j} q_\nu F_2^{ij} + \frac{i\sigma^{\mu\nu}}{m_i - m_j} q_\nu \gamma^5 F_3^{ij} + \left(q_\mu - \frac{q^2}{m_i + m_j} \gamma_\mu \right) \gamma^5 F_4^{ij} \right] u_j$$

$$\Gamma(\ell_i \to \ell_j \gamma) \propto \left| F_2^{ij}(0) \right|^2 + \left| F_3^{ij}(0) \right|^2$$



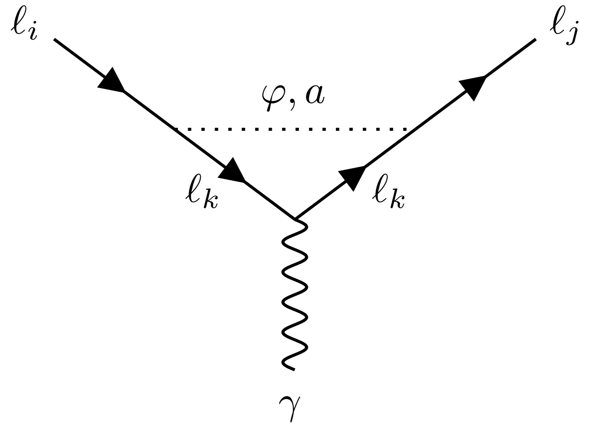
- Diagonal dipole form-factors ($i = j$):

$$\bar{u}_j \Gamma_\mu^{i} u_i = e \bar{u}_i \left[\gamma^\mu F_1^i + \frac{i\sigma^{\mu\nu}}{2m_i} q_\nu F_2^i + \frac{i\sigma^{\mu\nu}}{2m_i} q_\nu \gamma^5 F_3^i + \left(q_\mu - \frac{q^2}{2m_i} \gamma_\mu \right) \gamma^5 F_4^i \right] u_i$$



CLFV in Lepton Observables: dipole form factors

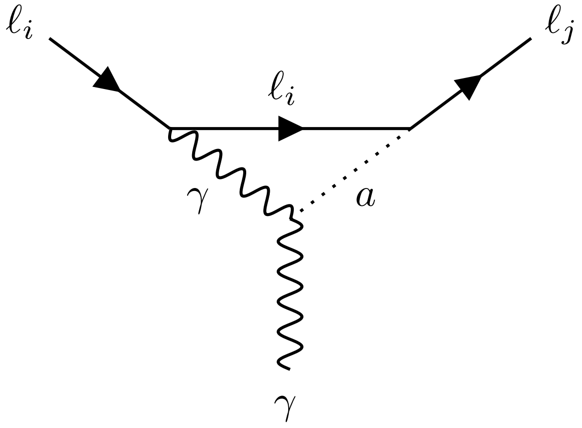
- Transition dipole form-factors ($i \neq j$):



$$\bar{u}_j \Gamma_\mu^{ij} u_i = e\bar{u}_j \left[\left(q_\mu + \frac{q^2}{m_i - m_j} \gamma_\mu \right) F_1^{ij} + \frac{i\sigma^{\mu\nu}}{m_i + m_j} q_\nu F_2^{ij} + \frac{i\sigma^{\mu\nu}}{m_i - m_j} q_\nu \gamma^5 F_3^{ij} + \left(q_\mu - \frac{q^2}{m_i + m_j} \gamma_\mu \right) \gamma^5 F_4^{ij} \right] u_j$$

$$\Gamma(\ell_i \to \ell_j \gamma) \propto \left| F_2^{ij}(0) \right|^2 + \left| F_3^{ij}(0) \right|^2$$

- Diagonal dipole form-factors ($i = j$):



$$\bar{u}_j \Gamma_\mu^{i} u_i = e\bar{u}_i \left[\gamma^\mu F_1^i + \frac{i\sigma^{\mu\nu}}{2m_i} q_\nu F_2^i + \frac{i\sigma^{\mu\nu}}{2m_i} q_\nu \gamma^5 F_3^i + \left(q_\mu - \frac{q^2}{2m_i} \gamma_\mu \right) \gamma^5 F_4^i \right] u_i$$

MDM EDM

$$a \equiv F_2^i(0) \qquad d \equiv \frac{e}{2m_i} F_3^i(0)$$

CLFV in Lepton Observables: role of chirality

- Expand form-factors in lepton mass ratios:

$$F\left(0; m_e, m_\mu, m_\tau\right) \equiv F_0(0) + \mathcal{O}\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}\right) F_1(0) + \cdots$$

CLFV in Lepton Observables: role of chirality

- Expand form-factors in lepton mass ratios:

small

$$F(0; m_e, m_\mu, m_\tau) \equiv F_0(0) + \cancel{\mathcal{O}\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}\right)} F_1(0) + \cdots$$

CLFV in Lepton Observables: role of chirality

- Expand form-factors in lepton mass ratios:

$$F(0; m_e, m_\mu, m_\tau) \equiv F_0(0) + \mathcal{O}\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}\right) F_1(0) + \cdots$$

- In terms of chiral angles:

$$F(0; m_e, m_\mu, m_\tau) \equiv F_0(0)\cos(\theta_{ik} + \theta_{jk}) + \mathcal{O}\left(\frac{m_e}{m_\mu}, \frac{m_\mu}{m_\tau}, \frac{m_e}{m_\tau}\right) F_1(0)\sin(\theta_{ik} + \theta_{jk}) + \cdots$$

CLFV in Lepton Observables: role of chirality

- Expand form-factors in lepton mass ratios:

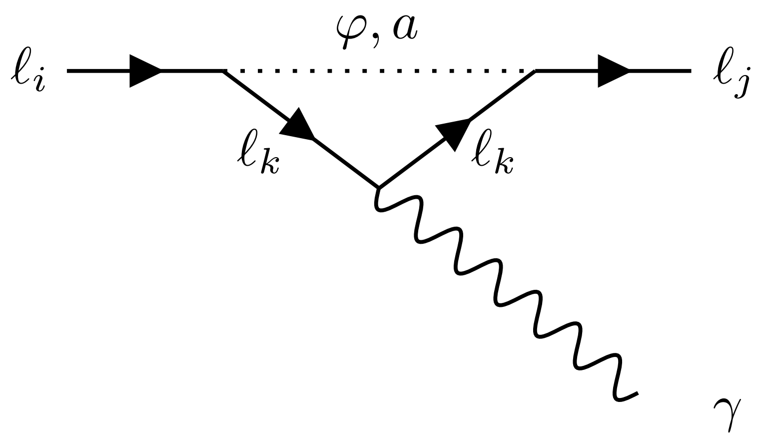
$$F(0; m_e, m_\mu, m_\tau) \equiv F_0(0) + \mathcal{O}\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}\right) F_1(0) + \cdots$$

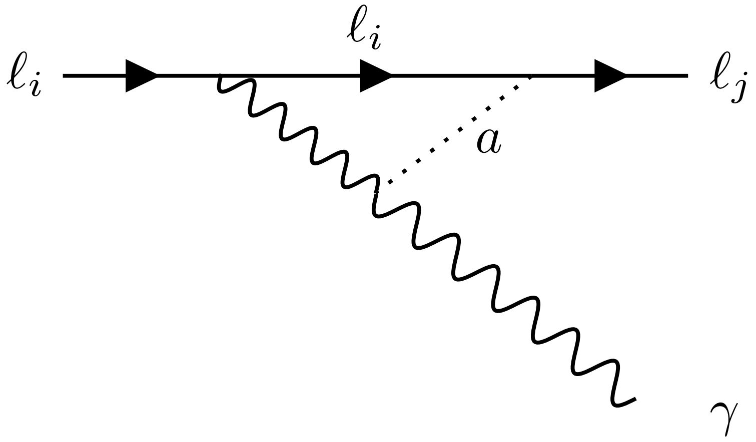
- In terms of chiral angles:

$$F(0; m_e, m_\mu, m_\tau) \equiv F_0(0) \cos(\theta_{ik} + \theta_{jk}) + \mathcal{O}\left(\frac{m_e}{m_\mu}, \frac{m_\mu}{m_\tau}, \frac{m_e}{m_\tau}\right) F_1(0) \sin(\theta_{ik} + \theta_{jk}) + \cdots$$

- Chiral suppression (first term is zero for $\theta_{ik} = \theta_{jk} = \pm\pi/4$).

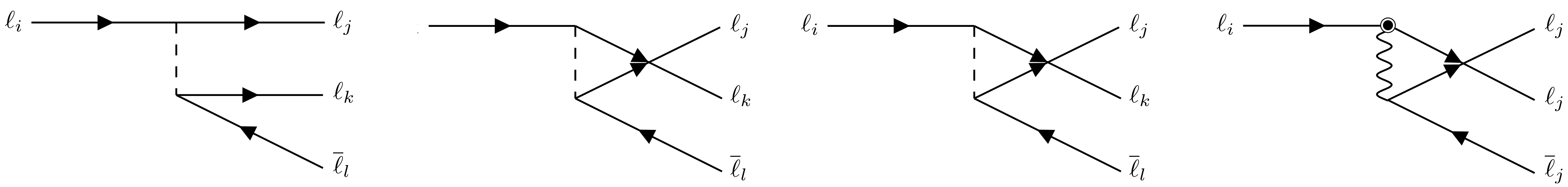
CLFV in Lepton Observables: $\ell_i \to \ell_j \gamma$





Process	Constraints		Projections	
	Experiment	$\mathcal{B}$ limit (90% CL)	Experiment	$\mathcal{B}$ limit (90% CL)
$\mu \to e\gamma$	MEG, MEG II	$< 3.1 \times 10^{-13}$ [76]	MEG II	$\lesssim 6 \times 10^{-14}$ [77]
$\tau \to e\gamma$	BaBar	$< 3.3 \times 10^{-8}$ [78]	Belle II	$\lesssim 9 \times 10^{-9}$ [79]
$\tau \to \mu\gamma$	Belle	$< 4.2 \times 10^{-8}$ [80]	Belle II	$\lesssim 7 \times 10^{-9}$ [79]

CLFV in Lepton Observables: $\ell_i \to \ell_j \ell_k \bar{\ell}_l$



Process	Constraints		Projections	
	Experiment	$\mathcal{B}$ limit (90% CL)	Experiment	$\mathcal{B}$ limit (90% CL)
$\mu \to ee\bar{e}$	SINDRUM	$< 1.0 \times 10^{-12}$ [81]	Mu3e	$\lesssim 2 \times 10^{-15}$ [82]
$\tau \to ee\bar{e}$	Belle	$< 2.7 \times 10^{-8}$ [83]	Belle II	$\lesssim 5 \times 10^{-10}$ [79]
$\tau \to ee\bar{\mu}$	Belle	$< 1.5 \times 10^{-8}$ [83]	Belle II	$\lesssim 3 \times 10^{-10}$ [79]
$\tau \to e\mu\bar{e}$	Belle	$< 1.8 \times 10^{-8}$ [83]	Belle II	$\lesssim 3 \times 10^{-10}$ [79]
$\tau \to \mu\mu\bar{\mu}$	Belle	$< 2.1 \times 10^{-8}$ [83]	Belle II	$\lesssim 4 \times 10^{-10}$ [79]
$\tau \to \mu e\bar{\mu}$	Belle	$< 2.7 \times 10^{-8}$ [83]	Belle II	$\lesssim 5 \times 10^{-10}$ [79]
$\tau \to \mu\mu\bar{e}$	Belle	$< 1.7 \times 10^{-8}$ [83]	Belle II	$\lesssim 3 \times 10^{-10}$ [79]

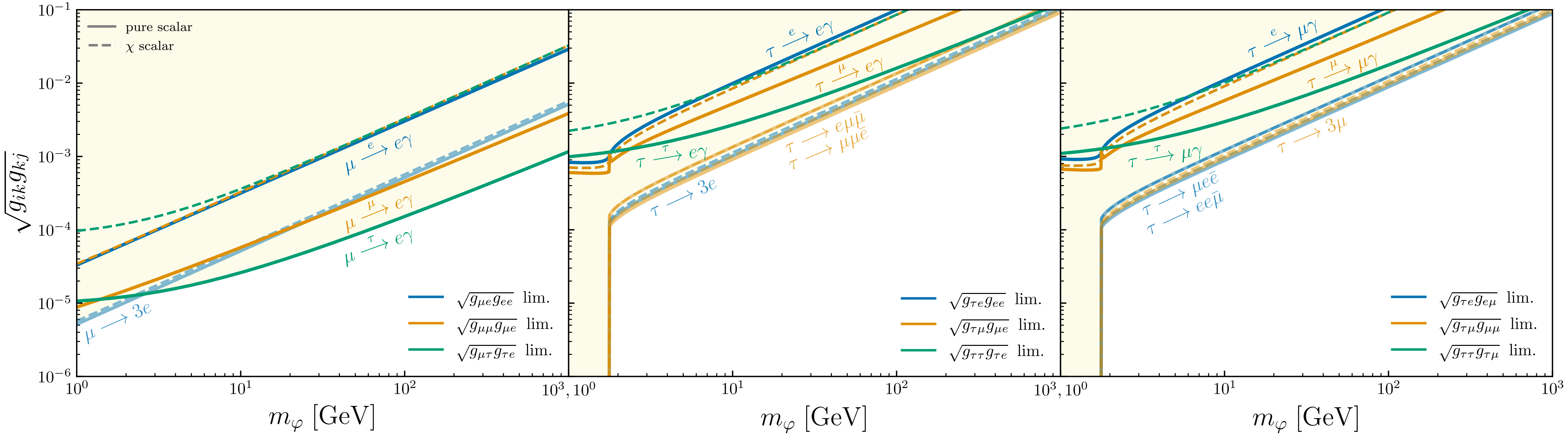
CLFV in Lepton Observables: coupling hierarchies

Process	$g_{ee}g_{e\mu}$	$g_{\mu\mu}g_{e\mu}$	$g_{\tau\tau}g_{e\mu}$	$g_{e\tau}g_{\mu\tau}$	$g_{ee}g_{e\tau}$	$g_{\mu\mu}g_{e\tau}$	$g_{\tau\tau}g_{e\tau}$	$g_{e\mu}g_{\mu\tau}$	$g_{ee}g_{\mu\tau}$	$g_{\mu\mu}g_{\mu\tau}$	$g_{\tau\tau}g_{\mu\tau}$	$g_{e\mu}g_{e\tau}$
$\mu \to e\gamma$	✓	✓	!	✓	✗	✗	✗	✗	✗	✗	✗	✗
$\mu \to ee\bar{e}$	✓	✓	!	✓	✗	✗	✗	✗	✗	✗	✗	✗
$\tau \to e\gamma$	✗	✗	✗	✗	✓	!	✓	✓	✗	✗	✗	✗
$\tau \to ee\bar{e}$	✗	✗	✗	✗	✓	!	✓	✓	✗	✗	✗	✗
$\tau \to e\mu\bar{\mu}$	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗
$\tau \to \mu\gamma$	✗	✗	✗	✗	✗	✗	✗	✗	!	✓	✓	✓
$\tau \to \mu e\bar{e}$	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓
$\tau \to \mu\mu\bar{\mu}$	✗	✗	✗	✗	✗	✗	✗	✗	!	✓	✓	✓
$\tau \to ee\bar{\mu}$	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
$\tau \to \mu\mu\bar{e}$	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗

✓ : contributes ✗ : doesn't contribute ! : ALP contributes (through photon)

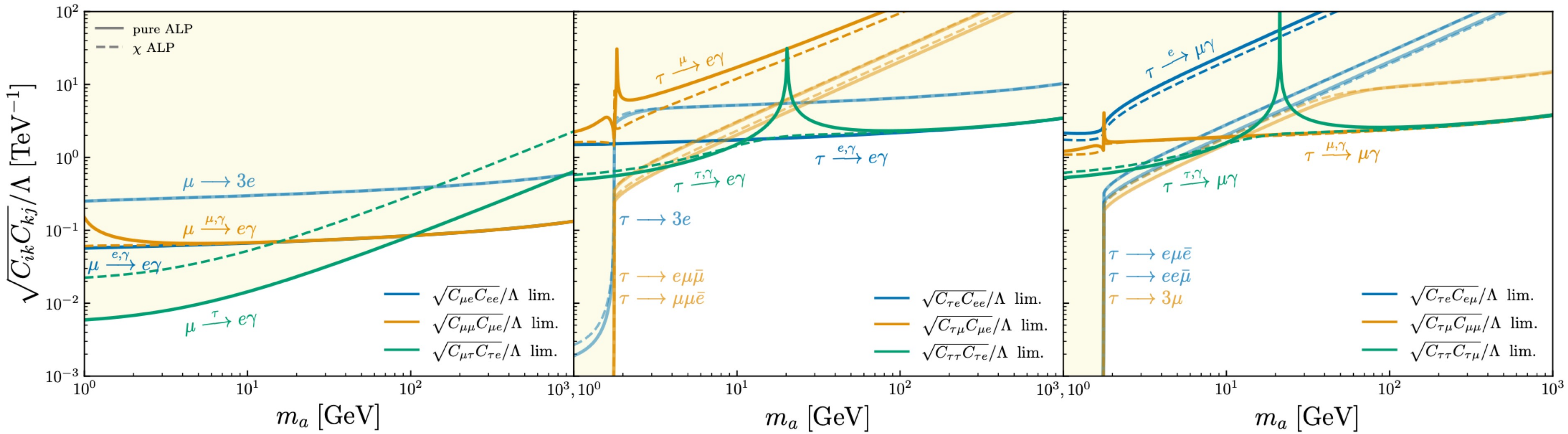
✓ ! : contribution from $\ell_i \to \ell_j \gamma^*$

CLFV in Lepton Observables: scalar limits



- Limits down to $|g_{ij}| < 10^{-5}$ at low masses
- Many $\ell_i \to \ell_j\gamma$ channels suppressed for chiral scalars
- $\mathcal{B}(\mu \xrightarrow{\tau} e\gamma)_\chi \approx 10^{-4}\mathcal{B}(\mu \xrightarrow{\tau} e\gamma)_{\text{PC}}$!

CLFV in Lepton Observables: ALP limits



- Limits down to $|C_{ij}| < 10^{-2}$ at low masses
- Only $\mu \xrightarrow{\tau} e\gamma$ channel is substantially suppressed
- $\mathcal{B}(\mu \xrightarrow{\tau} e\gamma)_\chi \approx 5\times10^{-3} \cdot \mathcal{B}(\mu \xrightarrow{\tau} e\gamma)_{\text{PC}}$

CLFV in Lepton Observables: eEDM

- d_e is most precisely constrained observable in modern physics

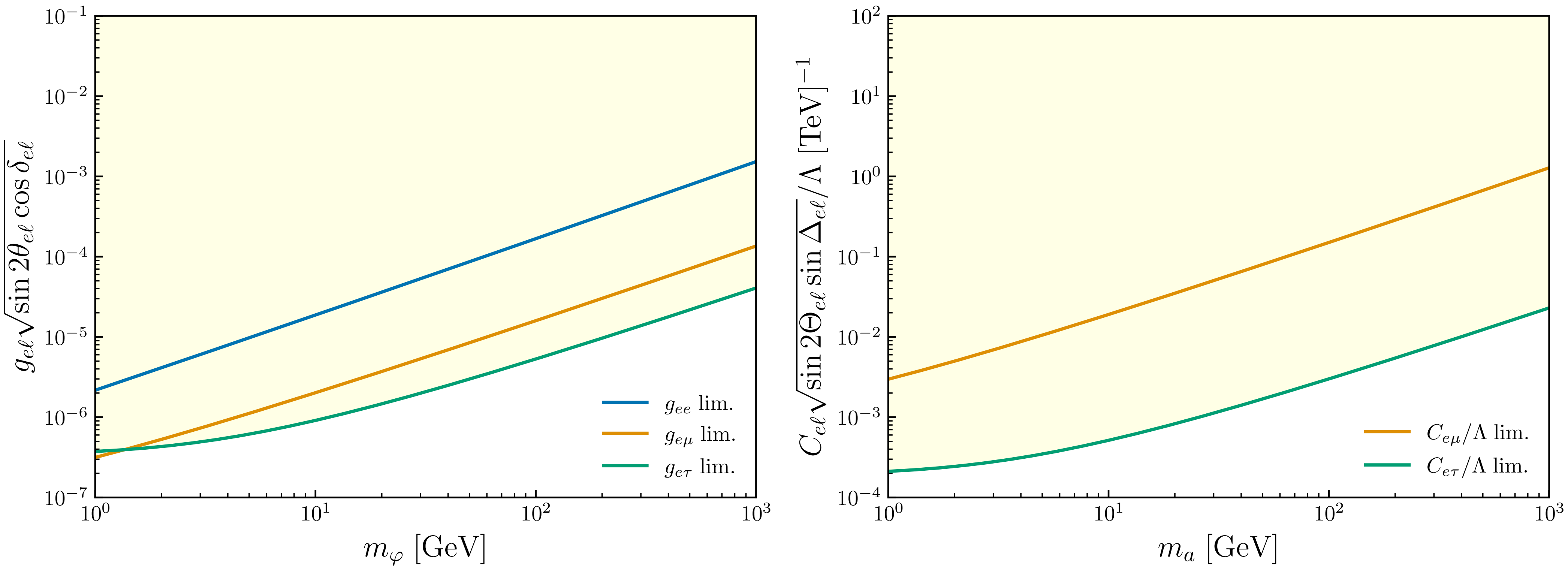
- Leading limits from Eric Cornell's group in JILA!

$$|d_e| < 4.1\times10^{-30}\ e\cdot\mathrm{cm}$$

- Still five orders of magnitude above SM value:

$$|d_e| \sim 10^{-35} e\cdot\mathrm{cm}$$

CLFV in Lepton Observables: eEDM



- Limits down to $|g_{e\ell}| < 10^{-6}$, $|C_{e\ell}| < 2\times10^{-4}$ at low masses
- Requires CP violation (zero in parity-conserving and chiral scenarios)

CLFV in Lepton Observables: $(g-2)_e$

- a_e is most precisely measured observable in modern physics

$$a_e = 1\,159\,652\,180.59(13)\times10^{-12}$$

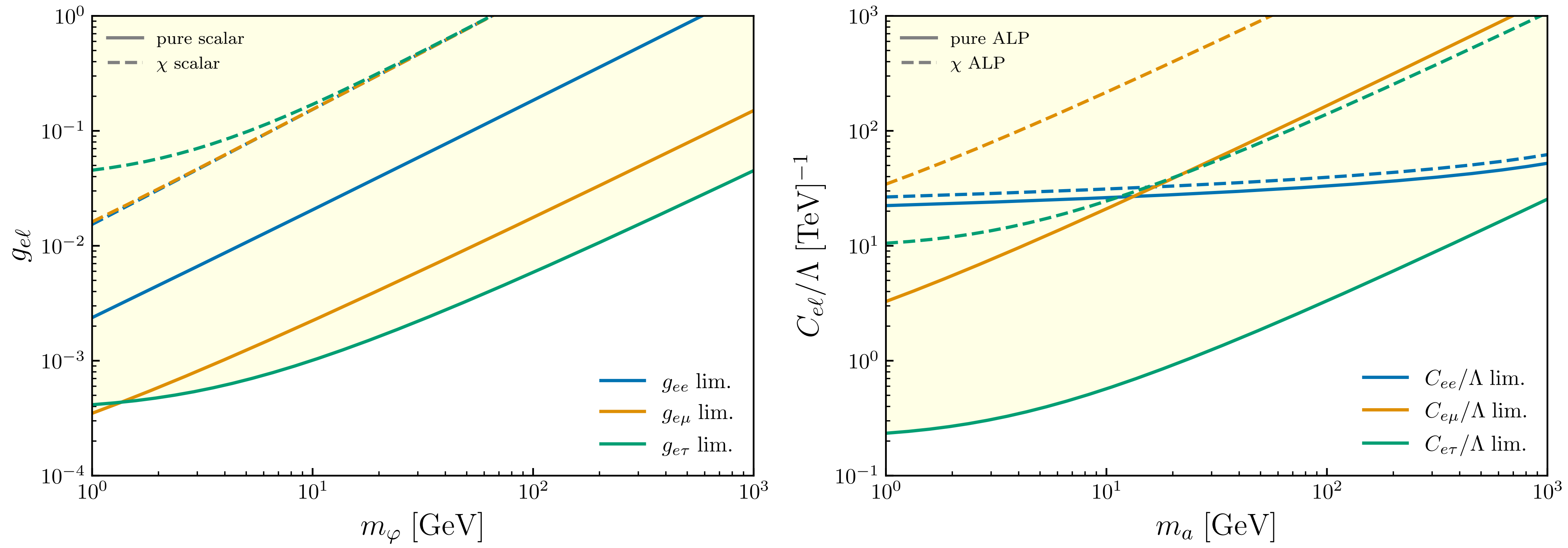
- SM value is anomalous with theory, and dependent on which measurement of α (fine-structure constant) is used:

$$a_e(\mathrm{Cs}) = 1\,159\,652\,181.61(23)\times10^{-12}$$

$$a_e(\mathrm{Rb}) = 1\,159\,652\,180.252(95)\times10^{-12}$$

- Corresponding anomalies $\Delta a_e(\mathrm{Rb}) = -3.7\sigma, \Delta a_e(\mathrm{Cs}) = +2.1\sigma.$

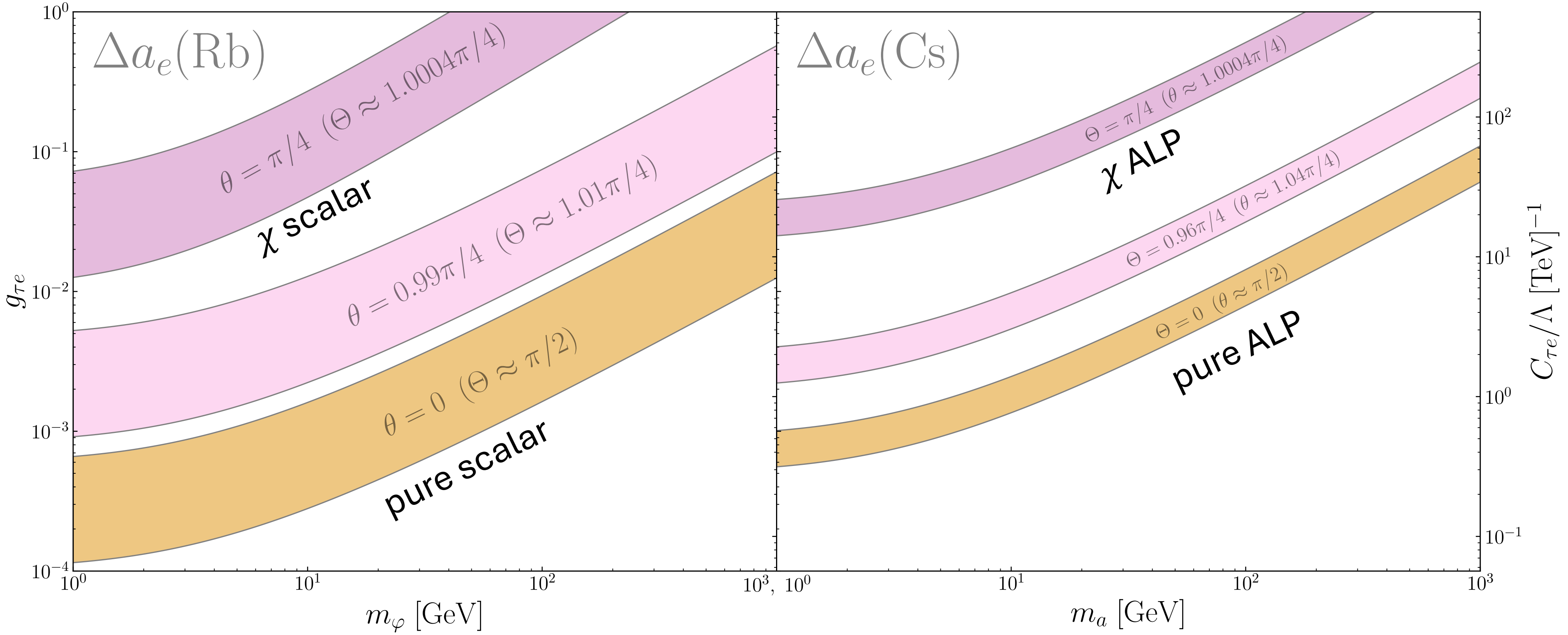
CLFV in Lepton Observables: $(g-2)_e$ limits



- Limits down to $|g_{e\ell}| < 10^{-3}$, $|C_{e\ell}| < 2\times10^{-1}$ at low masses
- 1-2 orders of magnitude weaker than lepton decays, but constrain a single coupling.
- Chiral scalars/ALPs are much less constrained than their PC counterparts.

CLFV in Lepton Observables: $(g-2)_e$ explanations

- Assume discrepancy between $\alpha(\mathrm{Rb})$ and $\alpha(\mathrm{Cs})$ is resolved
- LFV, PV scalar solutions to Δa_e: $\mathcal{L} = g_{\tau e}\varphi\bar{\tau}(\cos\theta + \sin\theta\,\gamma^5)e$



CLFV in Lepton Observables: $(g-2)_\mu$ limits

- a_μ leading measurement from Fermilab (as of June 3):

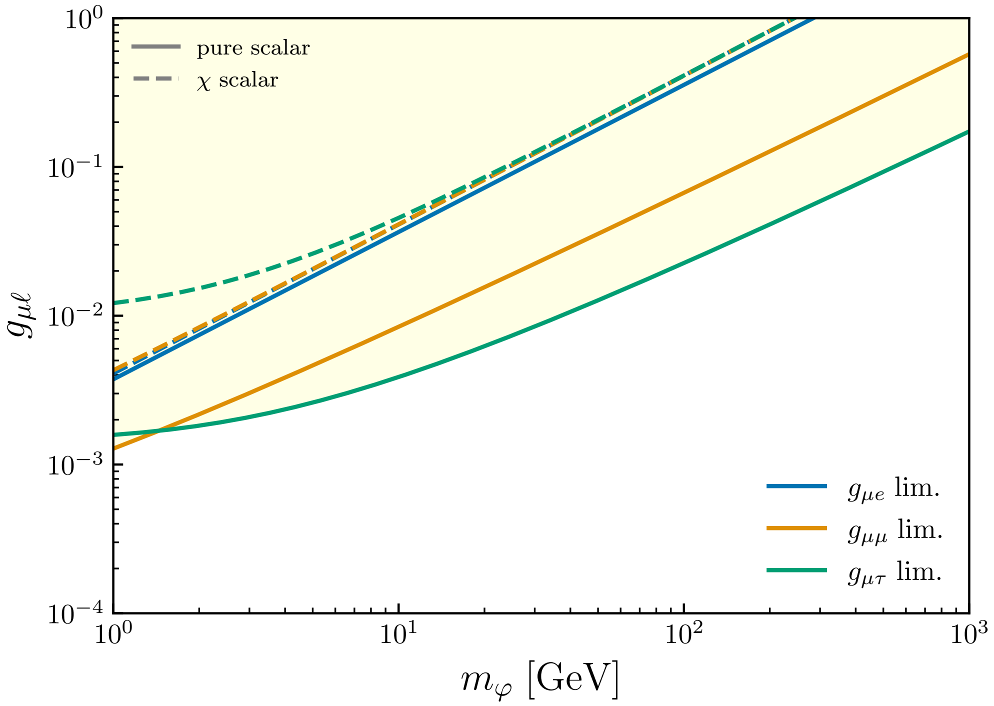
$$a_\mu^{\mathrm{exp}} = 1\,165\,920\,705(145)\times 10^{-12}$$

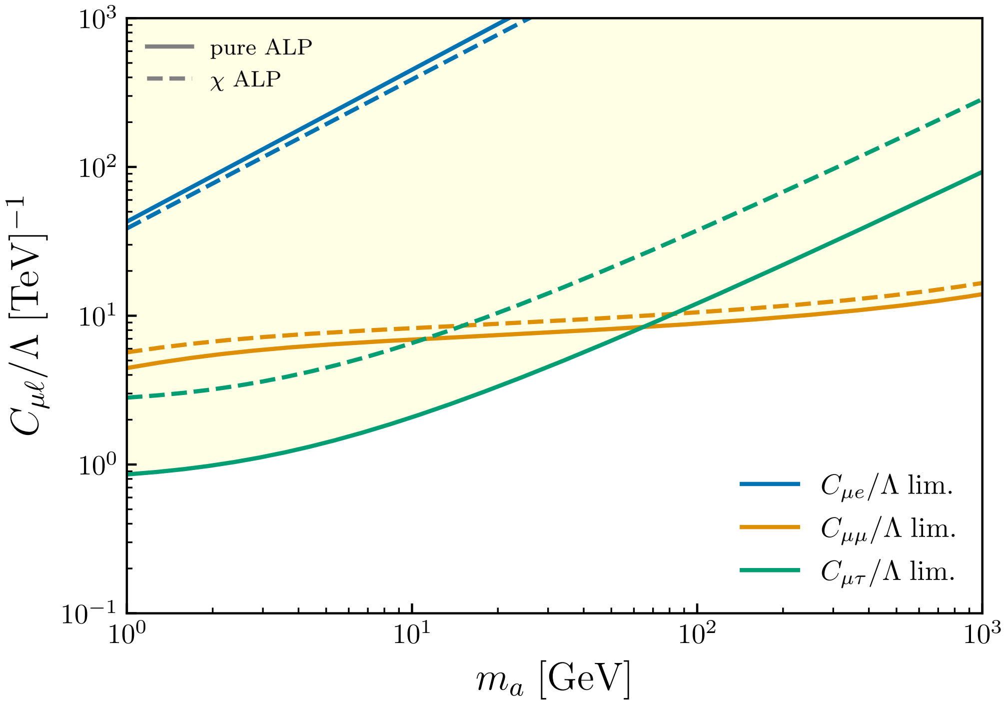
- Theory value using lattice determination of HVP:

$$a_\mu^{\mathrm{th}} = 1\,165\,920\,330(620)\times 10^{-12}$$

- 4.7σ deviation when using data-driven determination of HVP

CLFV in Lepton Observables: $(g-2)_\mu$ limits





- Limits down to $|g_{e\ell}| < 10^{-3}$, $|C_{e\ell}| < 2\times 10^{-1}$ at low masses
- Chiral scalars/ALPs are less constrained than their PC counterparts.

Boson Production in Lepton-Nucleus Collisions

Boson Production in Lepton-Nucleus Collisions

The picture can't be displayed.

$$t = -q^2$$

- $\sigma \propto Z^2 F(t)^2$, $F(t) \approx 1$ for $\sqrt{t} < 1/r \sim 10 \text{ MeV}$
- For a given t, can produce particles $\left(m_\varphi + m'_\ell\right)^2 \leq 2|\mathbf{p}|\sqrt{t}$, ($\mathbf{p}$ = momentum of lepton in nuc frame)
- Single coupling: $\sigma \propto |g_{\ell\ell'}|^2$
- Often studied in beam dump experiments.
- What about lepton-nucleus collision experiments?

Boson Production: Interaction

- Consider (pseudo) scalar interaction of the form:

$$\mathcal{L}_{\varphi\ell\ell'} = g_{\ell\ell'}\varphi e^{i\phi}\bar{\ell}\left(\cos\theta + ie^{i\delta}\gamma^5\sin\theta\right)\ell'$$

- Consider (axial) vector interaction of the form:

$$\mathcal{L}_{\varphi\ell\ell'} = g_{\ell\ell'}\varphi_\mu e^{i\phi}\bar{\ell}\gamma^\mu\left(\cos\theta + e^{i\delta}\gamma^5\sin\theta\right)\ell'$$

Lepton-Nucleus Colliders

	Electron beam	Muon beam
Beam Dump		
Collider		

Lepton-Nucleus Colliders

	Electron beam	Muon beam
Beam Dump	**E137** • SLAC E137 Beam Dump • Some of the earliest bounds on LLPs • 20 GeV electron beam on Al • Pseudo-rapidity coverage $\eta > 5$ • Integrated luminosity of $200\ \mathrm{fb}^{-1}$	
Collider		

Lepton-Nucleus Colliders

<table>
<tr><th></th><th>Electron beam</th><th>Muon beam</th></tr>
<tr><td>Beam Dump</td><td>E137
• SLAC E137 Beam Dump
• Some of the earliest bounds on LLPs
• 20 GeV electron beam on Al
• Pseudo-rapidity coverage $\eta > 5$
• Integrated luminosity of $200\ \mathrm{fb}^{-1}$</td><td></td></tr>
<tr><td>Collider</td><td>EIC
• Electron Ion Collider at Brookhaven
• Excellent probe for PDFs of nucleons and heavy nuclei.
• 18 GeV electron beam, 110 GeV/nuc Au beam
• $E_e \approx 4\ \mathrm{TeV}$ in ion frame
• Pseudo-rapidity coverage $|\eta| < 3.5$
• Integrated luminosity of $\mathcal{L} \approx (100/A)\mathrm{fb}^{-1} \approx 0.5\ \mathrm{fb}^{-1}$</td><td></td></tr>
</table>

Lepton-Nucleus Colliders

	Electron beam	Muon beam
Beam Dump	**E137** • SLAC E137 Beam Dump • Some of the earliest bounds on LLPs • 20 GeV electron beam on Al • Pseudo-rapidity coverage $\eta > 5$ • Integrated luminosity of $200\ \mathrm{fb}^{-1}$	**MuBeD** • TeV Muon Beam Dump • Can provide excellent bounds on LLPs (Cesarotti,) • 1 TeV muon beam on Pb • Pseudo-rapidity coverage $\eta > 0, \eta > 5$ • 10^{16}-10^{20} muons on target (MAP)
Collider	**EIC** • Electron Ion Collider at Brookhaven • Excellent probe for PDFs of nucleons and heavy nuclei. • 18 GeV electron beam, 110 GeV/nuc Au beam • $E_e \approx 4$ TeV in ion frame • Pseudo-rapidity coverage $\|\eta\| < 3.5$ • Integrated luminosity of $\mathcal{L} \approx (100/A)\mathrm{fb}^{-1} \approx 0.5\ \mathrm{fb}^{-1}$	

Lepton-Nucleus Colliders

	Electron beam	Muon beam
Beam Dump	**E137** • SLAC E137 Beam Dump • Some of the earliest bounds on LLPs • 20 GeV electron beam on Al • Pseudo-rapidity coverage $\eta > 5$ • Integrated luminosity of $200\ \mathrm{fb}^{-1}$	**MuBeD** • TeV Muon Beam Dump • Can provide excellent bounds on LLPs (Cesarotti,) • 1 TeV muon beam on Pb • Pseudo-rapidity coverage $\eta > 0, \eta > 5$ • 10^{16}-10^{20} muons on target (MAP)
Collider	**EIC** • Electron Ion Collider at Brookhaven • Excellent probe for PDFs of nucleons and heavy nuclei. • 18 GeV electron beam, 110 GeV/nuc Au beam • $E_e \approx 4\ \mathrm{TeV}$ in ion frame • Pseudo-rapidity coverage $\|\eta\| < 3.5$ • Integrated luminosity of $\mathcal{L} \approx (100/A)\mathrm{fb}^{-1} \approx 0.5\ \mathrm{fb}^{-1}$	**MuSIC** • Muon (Synchrotron)-Ion Collider • Promising nuclear physics applications. (Acosta,) • 1 TeV muon beam, 110 GeV/nuc Au beam • $E_e \approx \mathbf{20}\ \mathrm{TeV}$ in ion frame • Pseudo-rapidity coverage $\|\eta\| < 6$ • Integrated luminosity $\mathcal{L} \approx (400/A)\mathrm{fb}^{-1} \approx 2\ \mathrm{fb}^{-1}$

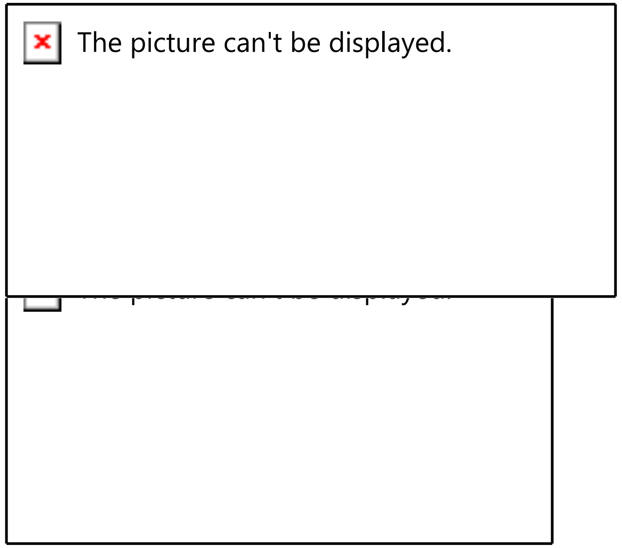
X Differential Production Cross-Section

- Can be written in the form (in the ion frame)

$$\frac{d\sigma}{dE_k\, d\theta_k} = \frac{\sin\theta_k}{64\pi^3}\frac{|\mathbf{k}|}{|\mathbf{p}|V}\int_{t_-}^{t_+} dt\,\frac{1}{8M^2}\int d\phi_q |\mathcal{M}|^2$$

- Weizsacker-Williams Approximation (effective photon approximation):

$$\frac{1}{8M^2}\int d\phi_q |\mathcal{M}|^2 \approx \frac{t-t_-}{2t_-}\frac{F(t)^2}{t^2}|\mathcal{M}^{2\to 2}|^2_{t=t_-}$$



- Instead, can compute $\int d\phi_q |\mathcal{M}|^2$ analytically
- Compute $\int_{t_-}^{t_+} dt$ numerically

Total Production Cross-Section

- Can be found by integrating over differential cross-section:

$$\sigma = \int dE_k \, d\theta_k \cdot \frac{d\sigma}{dE_k d\theta_k}$$

- Simple dependence on the PV angle θ:

$$\sigma = \sigma_0 + \sin^2 \theta \, \sigma_{PV}$$

- No dependence on δ or ϕ, $\sigma_{PV} \ll \sigma_0$

Total Production Cross-Section

- Cross-section similar for beam dump and collider experiments for low m_φ
- Collider experiments have more reach for large m_φ
- Fill in plots between σ_0 and $\sigma_0 + \sigma_{PV}$
- PV only important for *diagonal* production $(\ell A_Z \to \ell A_Z \varphi)$ and $m_\varphi < m_\ell$

Final-state Kinematical Distributions

- In ion/nucleus frame, energy-angle distribution of φ is given by

$$\rho\left(E^{\text{ion}}, \theta^{\text{ion}}\right) = \frac{1}{\sigma} \frac{d\sigma}{dE^{\text{ion}}\, d\theta^{\text{ion}}}$$

- This works for fixed-target/beam dump, but for lepton-ion colliders:

$$\rho_{\text{lab}}\left(E^{\text{lab}}, \theta^{\text{lab}}\right) = \left|\frac{\partial\left(E^{\text{ion}}, \theta^{\text{ion}}\right)}{\partial\left(E^{\text{lab}}, \theta^{\text{lab}}\right)}\right| \rho_{\text{ion}}\left(E^{\text{ion}}, \theta^{\text{ion}}\right)$$

- It turns out $\left|\frac{\partial\left(E^{\text{ion}},\theta^{\text{ion}}\right)}{\partial\left(E^{\text{lab}},\theta^{\text{lab}}\right)}\right| = 1$! In other words: $dE\ d\theta$ is a boost-invariant measure.

Final-state Kinematical Distributions: boson η

- More useful than angle for describing kinematics of forward-produced particles

Final-state Kinematical Distributions: boson η

- More useful than angle for describing kinematics of forward-produced particles

- Angle-pseudorapidity ($\theta - \eta$) relationship:

$\theta = 140°$, $\eta = -1$ $\theta = 90°$, $\eta = 0$ $\theta = 40°$, $\eta = 1$

$\theta = 15°$, $\eta = 2$

$\theta = 0°$, $\eta = \infty$

Final-state Kinematical Distributions: boson η

- More useful than angle for describing kinematics of forward-produced particles

- Angle-pseudorapidity ($\theta - \eta$) relationship:

$$\eta = -\log\tan\left(\frac{\theta}{2}\right), \quad \theta = 2\arctan(e^{-\eta})$$

$$\frac{\mathrm{d}\eta}{d\theta} = \csc\theta\,, \qquad \frac{\mathrm{d}\theta}{d\eta} = \operatorname{sech}\eta$$

$\theta = 140^\circ$ $\eta = -1$

$\theta = 90^\circ$ $\eta = 0$

$\theta = 40^\circ$ $\eta = 1$

$\theta = 15^\circ$ $\eta = 2$

$\theta = 0^\circ$ $\eta = \infty$

The picture can't be displayed.

Final-state Kinematical Distributions: boson η

- More useful than angle for describing kinematics of forward-produced particles

- Angle-pseudorapidity ($\theta - \eta$) relationship:

$$\eta = -\log\tan\left(\frac{\theta}{2}\right), \quad \theta = 2\arctan(e^{-\eta})$$

$$\frac{\mathrm{d}\eta}{d\theta} = \csc\theta\,, \qquad \frac{\mathrm{d}\theta}{d\eta} = \operatorname{sech}\eta$$

- Pseudorapidity distribution:

$$\rho_\eta(\eta) = \int dE\,\operatorname{sech}\eta\,\rho_{\text{lab}}\big(E, \theta(\eta)\big)$$

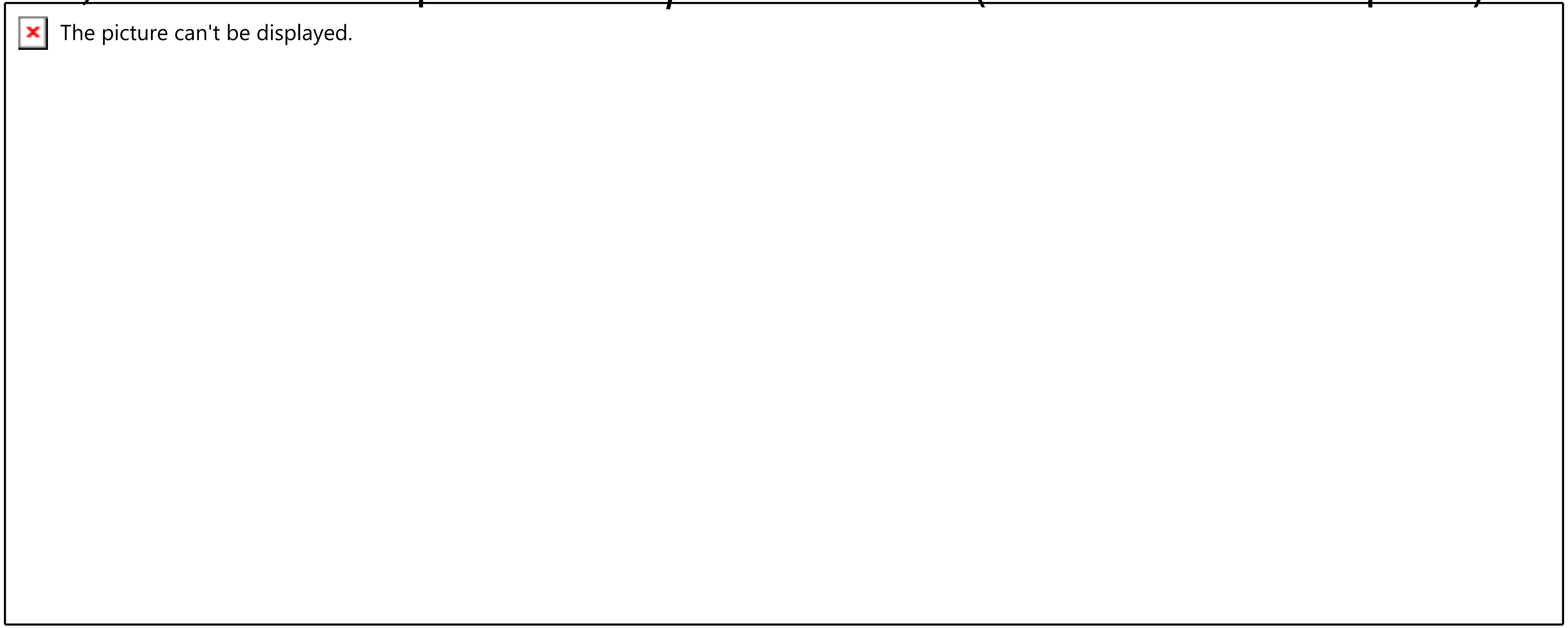
Final-state Kinematical Distributions: boson η

- Envelope of η distributions from $m_\varphi = 1\ \mathrm{MeV}$ to $m_\varphi = 5\ (40)\ \mathrm{GeV}$.

The picture can't be displayed.

Final-state Kinematical Distributions: boson η

- Median, first and third quartiles of η distributions ("box and whisker plot"):



Final-state Kinematical Distributions: boson η

- Median, first and third quartiles of η distributions (“box and whisker plot”):

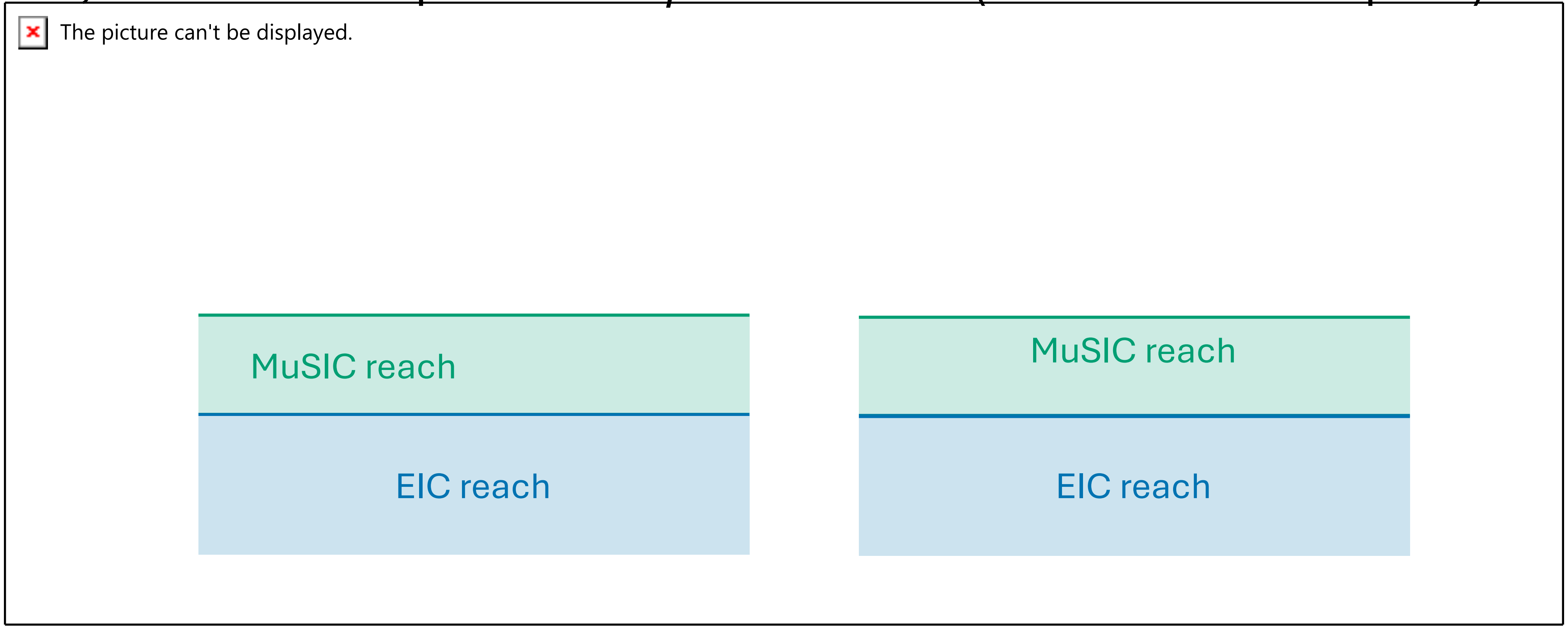
The picture can't be displayed.

EIC reach

EIC reach

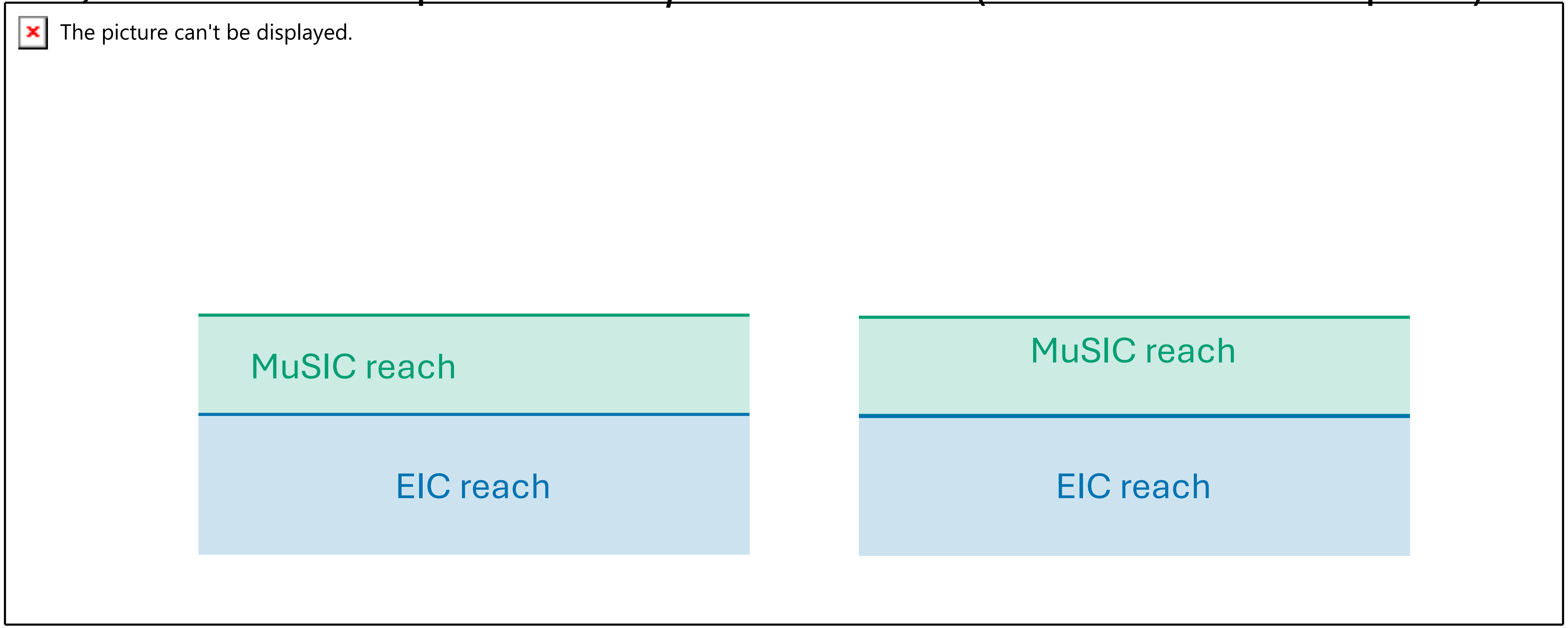
Final-state Kinematical Distributions: boson η

- Median, first and third quartiles of η distributions (“box and whisker plot”):



Final-state Kinematical Distributions: boson η

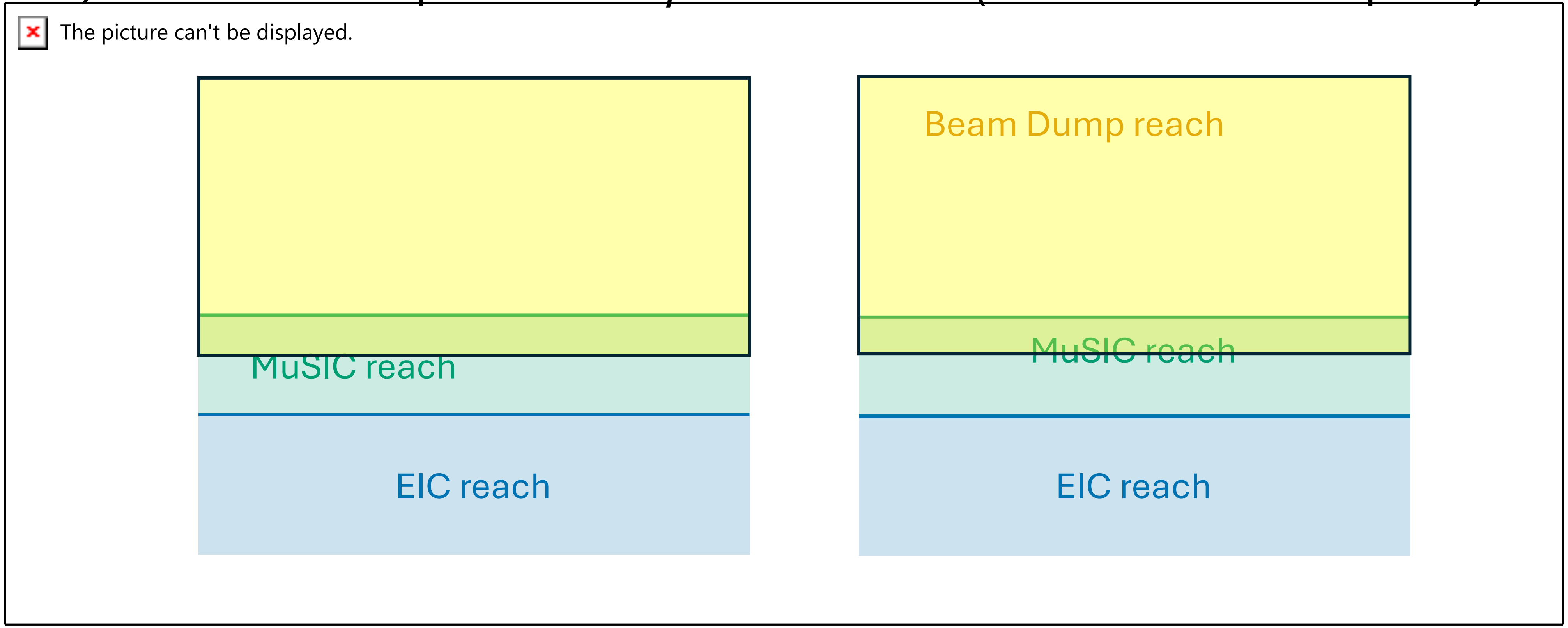
- Median, first and third quartiles of η distributions (“box and whisker plot”):



- Lighter particles are very forward produced at collision experiments, but heavier (GeV-scale) particles are within reach.

Final-state Kinematical Distributions: boson η

- Median, first and third quartiles of η distributions ("box and whisker plot"):



- Lighter particles are very forward produced at collision experiments, but heavier (GeV-scale) particles are within reach.

Final-state Kinematical Distributions: boson γ

- More useful than energy for studying long-lived particles (decay length $d \approx \gamma c \tau_0$)
- Energy-boost $(E - \gamma)$ relationship:

$$\gamma = E/m_\varphi, \qquad E = \gamma m_\varphi$$
$$\frac{\mathrm{d}\gamma}{dE} = 1/m_\varphi, \qquad \frac{\mathrm{d}E}{d\gamma} = m_\varphi$$

- Boost distribution:

$$\rho_\gamma(\gamma) = \int d\theta \; m_\varphi \rho_{\mathrm{lab}}(E(\gamma), \theta)$$

Final-state Kinematical Distributions: boson γ

- Envelope of γ distributions from $m_\varphi = 1\ \mathrm{MeV}$ to $m_\varphi = 5\ (40)\ \mathrm{GeV}$.

The picture can't be displayed.

Final-state Kinematical Distributions: boson γ

- Median, first and third quartiles of γ distributions (“box and whisker plot”):

The picture can't be displayed.

- Distribution is very sharp, most particles have $\gamma \sim E_\ell / m_\varphi$

Lepton-Flavor Violating ALPs

LFV ALPs: Lagrangian

$$\mathcal{L} = \sum_{\ell} \frac{\partial_\mu a}{\Lambda} C_{\ell\ell'} \bar{\ell} \gamma^\mu [\cos\Theta_{\ell\ell'} + \gamma^5 \sin\Theta_{\ell\ell'}] \ell' + \cdots$$

$$+ C_{ah} \frac{(\partial_\mu a)^2}{\Lambda^2} v h + C'_{ah} a^2 \frac{m_a^2}{\Lambda^2} v h + \cdots$$

- C_{ah} preserves the global symmetry
- C'_{ah} present if Higgs coupling is source of explicit breaking of global symmetry

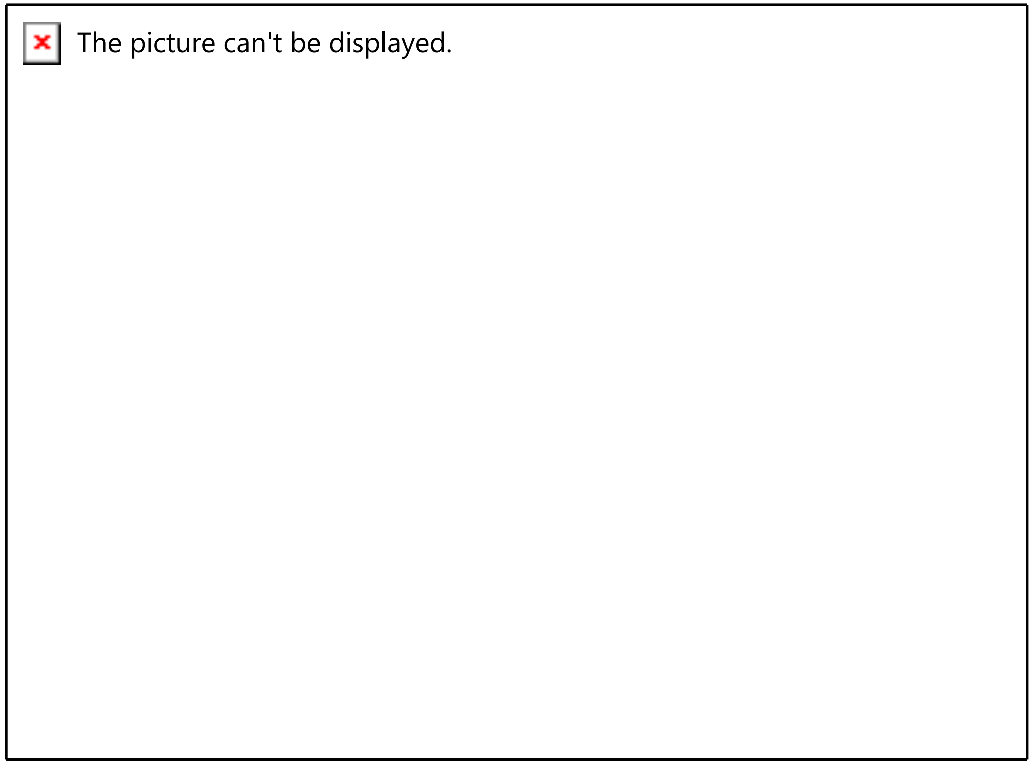
LFV ALPs: examples

- Froggatt-Nielsen models ()
  - Introduces scalar field (the flavon) to solve fermion hierarchy problem
  - Radial mode of the flavon acts as an ALP (*flaxion* or *axiflavon*)
  - Flaxion/axiflavon light in models with $U(1)_H$ flavor symmetry, but can be GeV-scale in theories discrete $\mathbb{Z}_N$ symmetry

- ALP as dark pion from composite dark sectors (Davoudiasl, Neil, Rinaldi)
  - Strongly-coupled dark quarks with Higgs portal interaction
  - "Dark neutrons" are RH neutrinos, "dark kaon" is dark matter
  - Spectrum of LFV pions (ALPs from spontaneous breaking of chiral symmetry)
  - (personally) original motivation for studying LFV ALPs.
  - Benchmark scenario has $C_{\ell\ell'}/\Lambda \sim 10^{-7}\mathrm{TeV}^{-1}$, $C'_{ah}/\Lambda^2 \sim 10\ \mathrm{TeV}^{-2}$

LFV ALPs: branching fraction

- Assuming democratic ALP-lepton couplings (all $C_{\ell\ell'}$ the same)



- a decays to at least one τ 99.7% of the time.

LFV ALPs: Higgs decays

- Higgs ALP decay rate:

$$\Gamma(h \to aa) = \frac{1}{32\pi}\frac{v^2 m_h^3}{\Lambda^4}\left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}\overbrace{\left(C_{ah} + C'_{ah}\frac{2m_a^2}{m_h^2 - 2m_a^2}\right)}^{\bar{C}_{ah}}{}^2$$

- Similar search in the past for LFV scalars: (Evans,)
  - Different parameter space of interest due to predominant τ coupling of ALPs.

- Given mass hierarchy, look for decay mode $h \to (\tau\ell)(\tau\ell')$

LFV ALPs: CMS prompt analysis

- Recast limits from 1911.04968 (CMS Collaboration)
  - Searched for proton-proton collisions which resulted in multilepton final-states at CMS

- Focus on events with *zero* opposite-sign, same-flavor ("**OSSF0**") lepton pairs (i.e. $\boldsymbol{\mu^+\mu^+e^-e^-}$ or $\boldsymbol{e^+e^+\mu^-\mu^-}$)

- Corresponds to $h \to aa \to (\tau\ell)(\tau\ell') \to \ell^+\ell^+\ell'^-\ell'^- + \text{invis.}$

- Reproduced the analysis in MadGraph+Pythia+Delphes

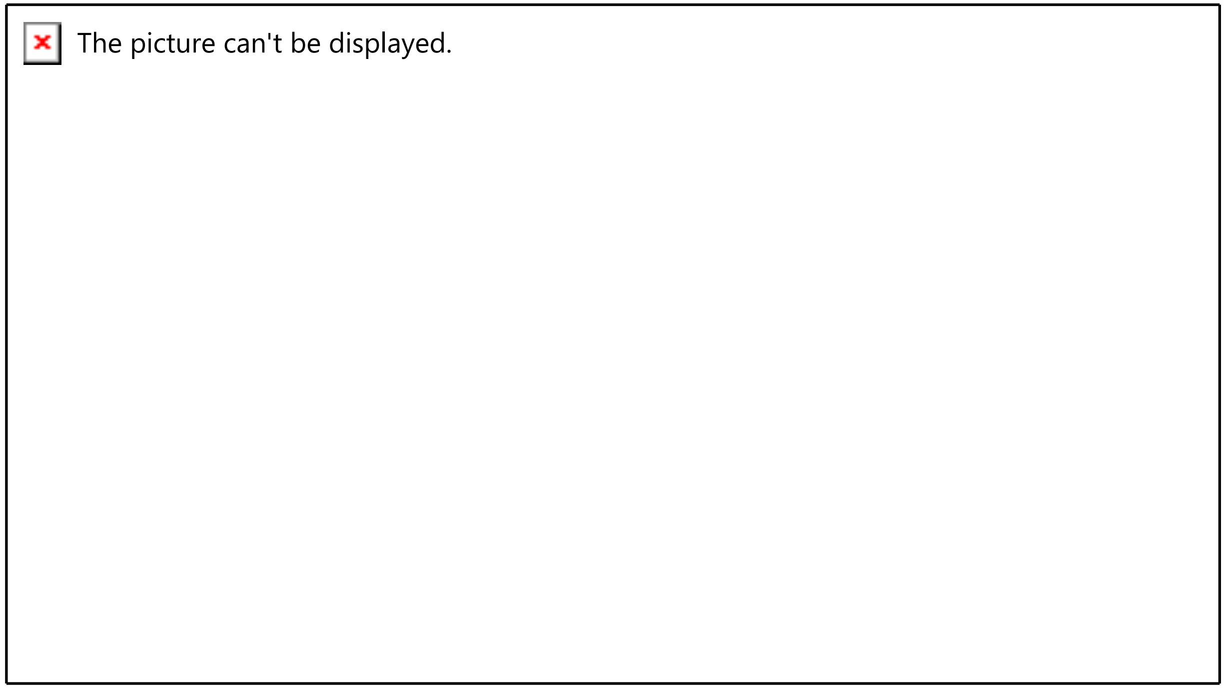
LFV ALPs: ATLAS displaced analysis

- Recast limits from 1911.12575 (ATLAS Collaboration)
  - Searched for pairs of displaced jets in ATLAS inner-detector and muon spectrometer.
  - Placed limits on long-lived hidden scalars between $8 - 400\ \mathrm{GeV}$ produced in Higgs decays.

- Consider displaced decays $a \to \tau\ell$ after Higgs production $h \to aa$, with τ decaying hadronically.

- Reproduce the analysis in MadGraph+Pythia+Delphes

LFV ALPs: MATHUSLA



- Projections from MATHUSLA
  - Proposed experiment to search for long-lived particles.
  - Operations planned to start in late 2020s.

- Look for $h \to aa$, with long-lived a decaying to any final-state in the MATHUSLA detector.

- Recast limits on Higgs decay of LLPs from 1806.07396.
  - Caveat: limits based on earlier iteration of MATHUSLA
  - 200m x 200m x 20m detector 100m away from the CMS detector

Lepton-flavor-violating ALPs: C_{ah} vs. $C_{\tau\ell}$

The picture can't be displayed.

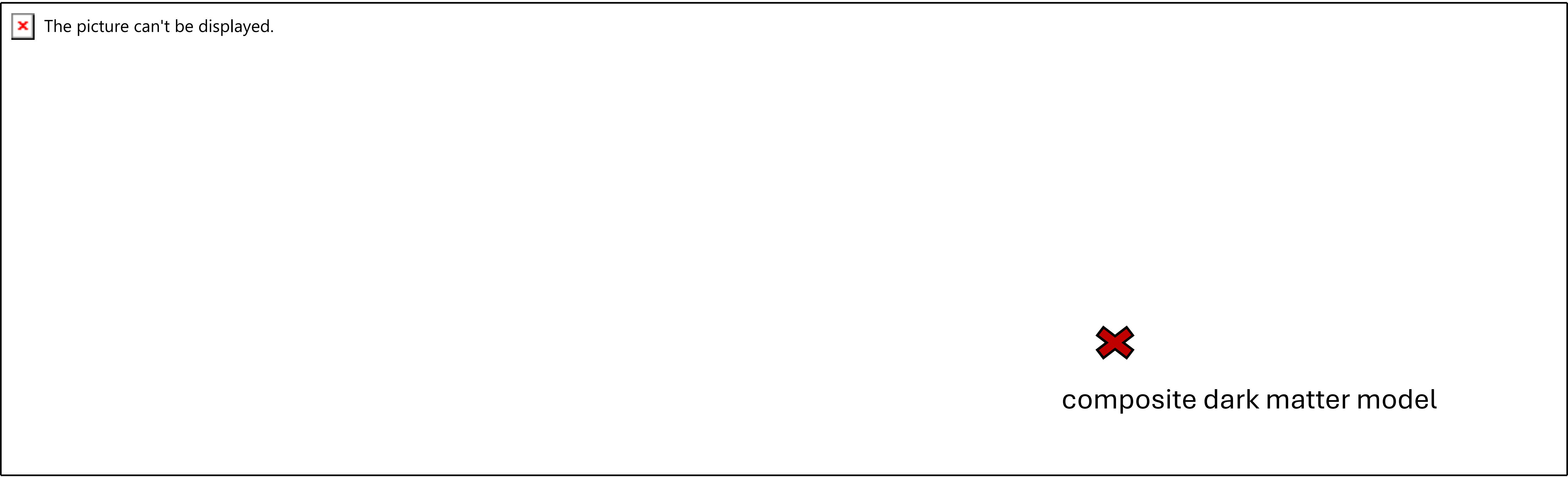
- For substantial C_{ah}, LHC can probe $C_{\tau\ell}$ far beyond LFV decay limits
- Factor of $\mathcal{O}(10^3)$ improvement in coupling limits at high-lumi LHC

Lepton-flavor-violating ALPs: C'_{ah} vs. $C_{\tau\ell}$

The picture can't be displayed.

- Larger C'_{ah} required to place strong limits on $C_{\tau\ell}$
- Benchmark for composite scenario within reach at high-lumi LHC

Lepton-flavor-violating ALPs: C'_{ah} vs. $C_{\tau\ell}$



- Larger C'_{ah} required to place strong limits on $C_{\tau\ell}$
- Benchmark for composite scenario within reach at high-lumi LHC

What about lepton-nucleus collisions?

- Focus on ALP with single coupling:

$$\mathcal{L} = \frac{\partial_\mu a}{\Lambda} C_{\tau\ell} \bar{\tau}(\cos\theta + \gamma^5 \sin\theta)\ell + \mathrm{H.c.}$$

- $\ell = e$ for EIC and $\ell = \mu$ for MuBeD and MuSIC

- Production via $\ell^- A_Z \to \tau^- A_Z a$, ALP decays via $a \to \tau^- \ell^+$

- Perturbatively protected by $\mathbb{Z}_4$ symmetry ($Q(a) = -1, Q(\ell) = i,, Q(\tau) = -i$)

- Two reasons for considering this:
  1. Represents a region of parameter space which is untouched by many other LFV experiments ☺
  2. (spoiler alert) limits from LFV decays are too strong otherwise ☹

Lepton-flavor-violating ALPs: EIC

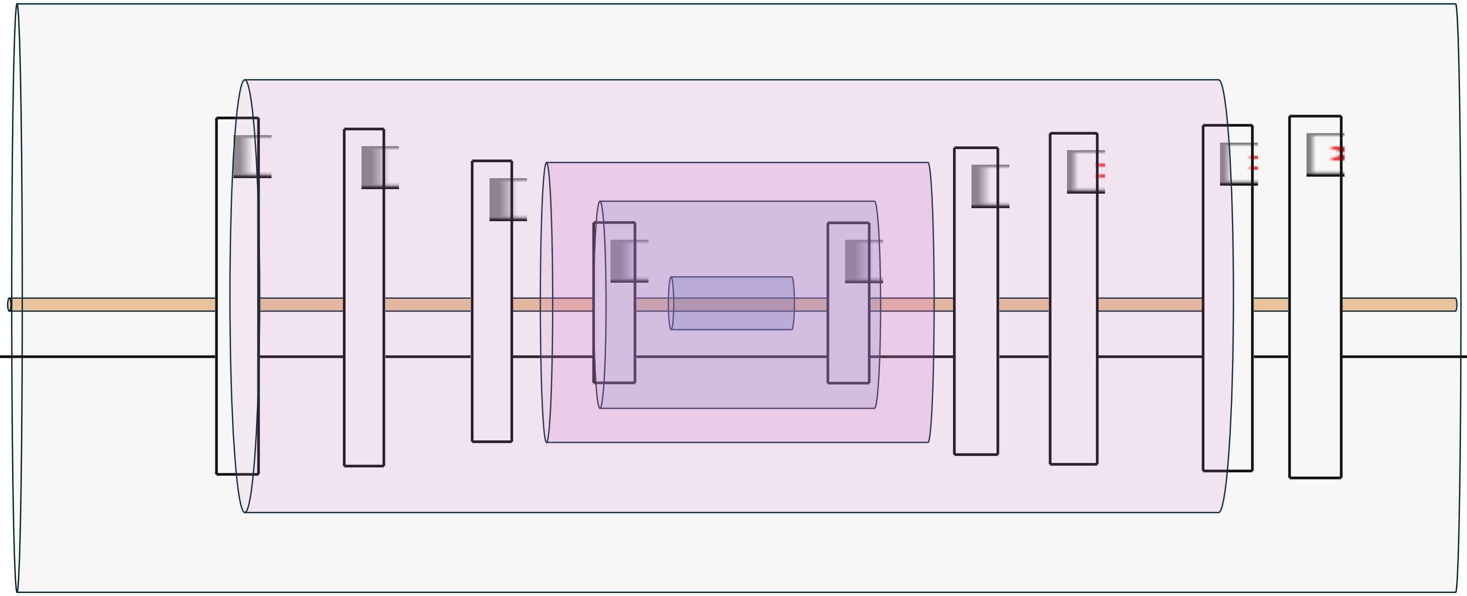
Lepton-flavor-violating ALPs: EIC

The picture can't be displayed.

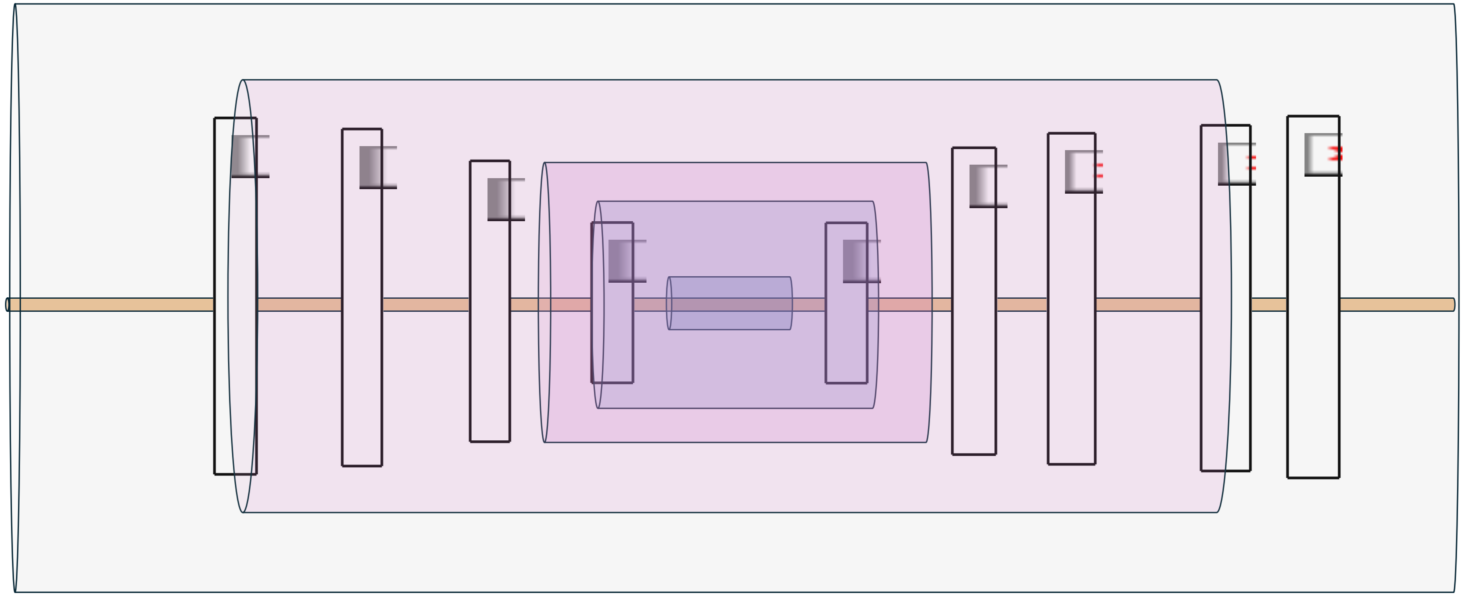
(2209.02580)

Lepton-flavor-violating ALPs: EIC

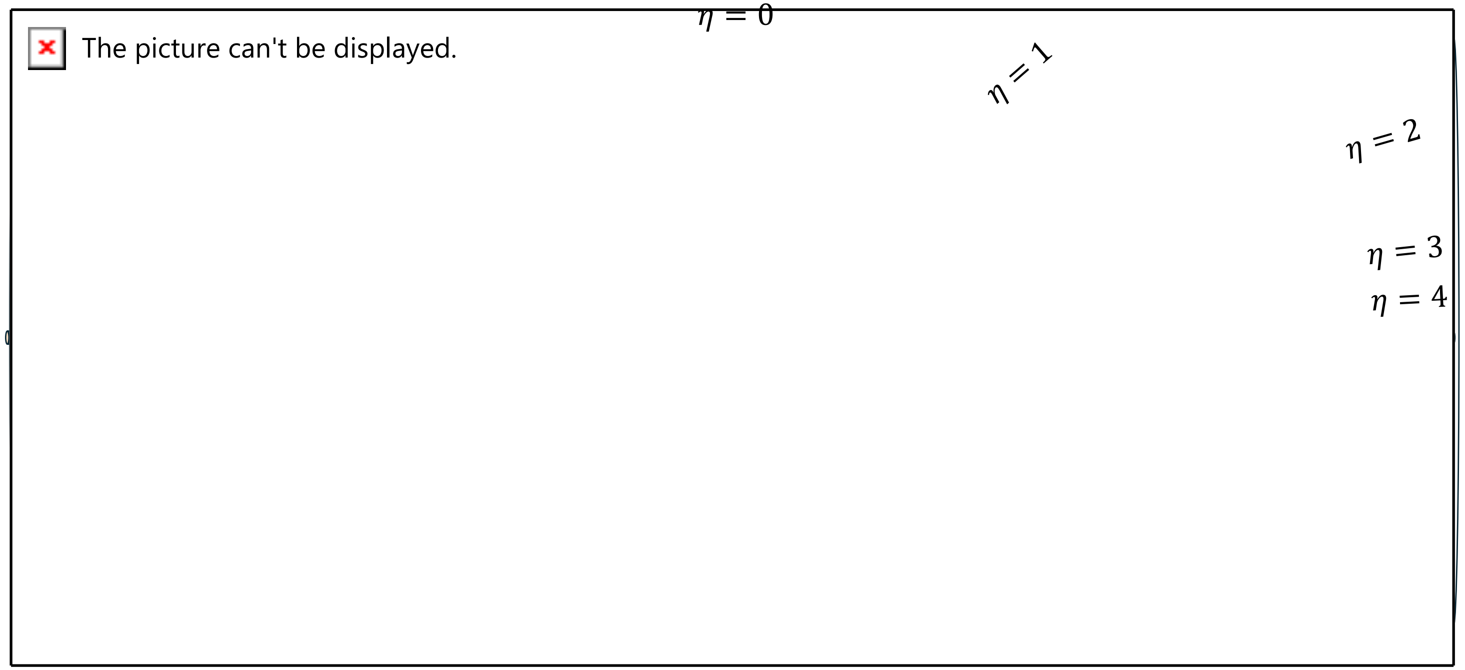
The picture can't be displayed.



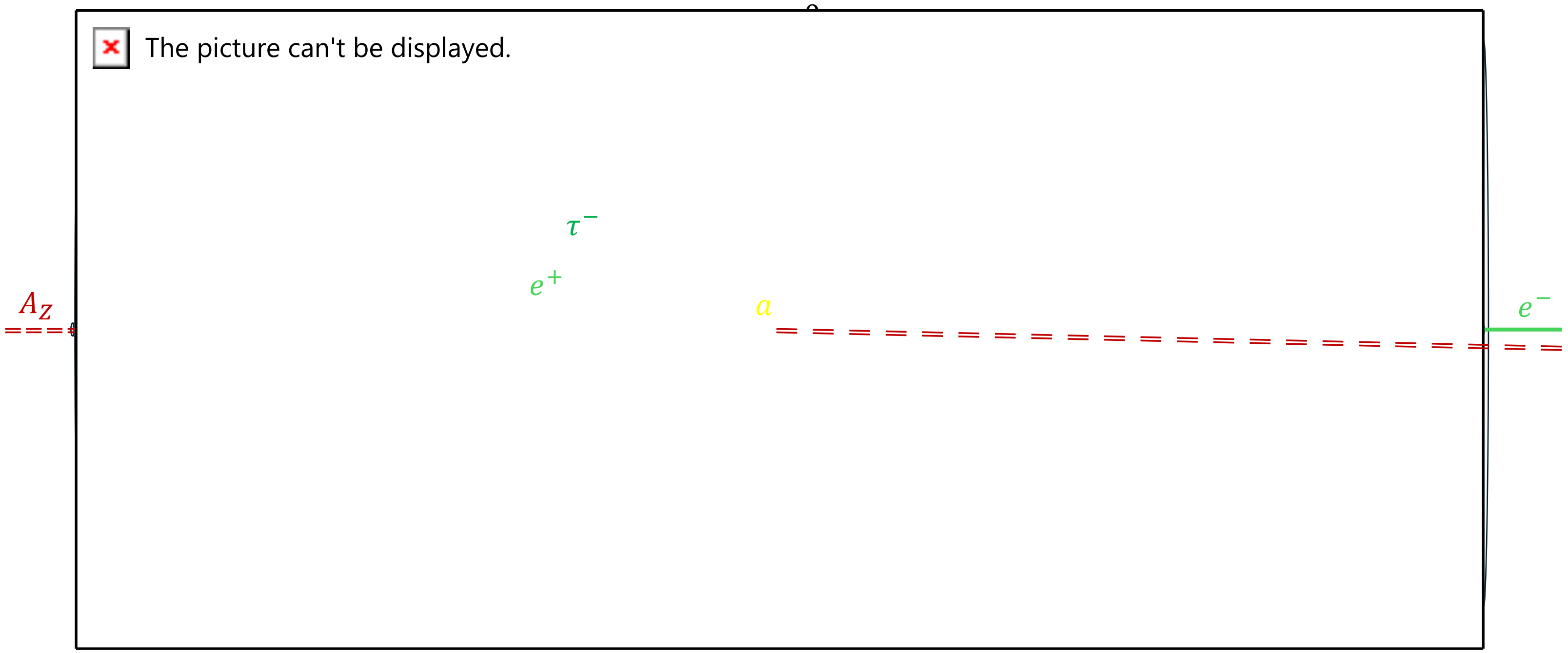
Lepton-flavor-violating ALPs: EIC



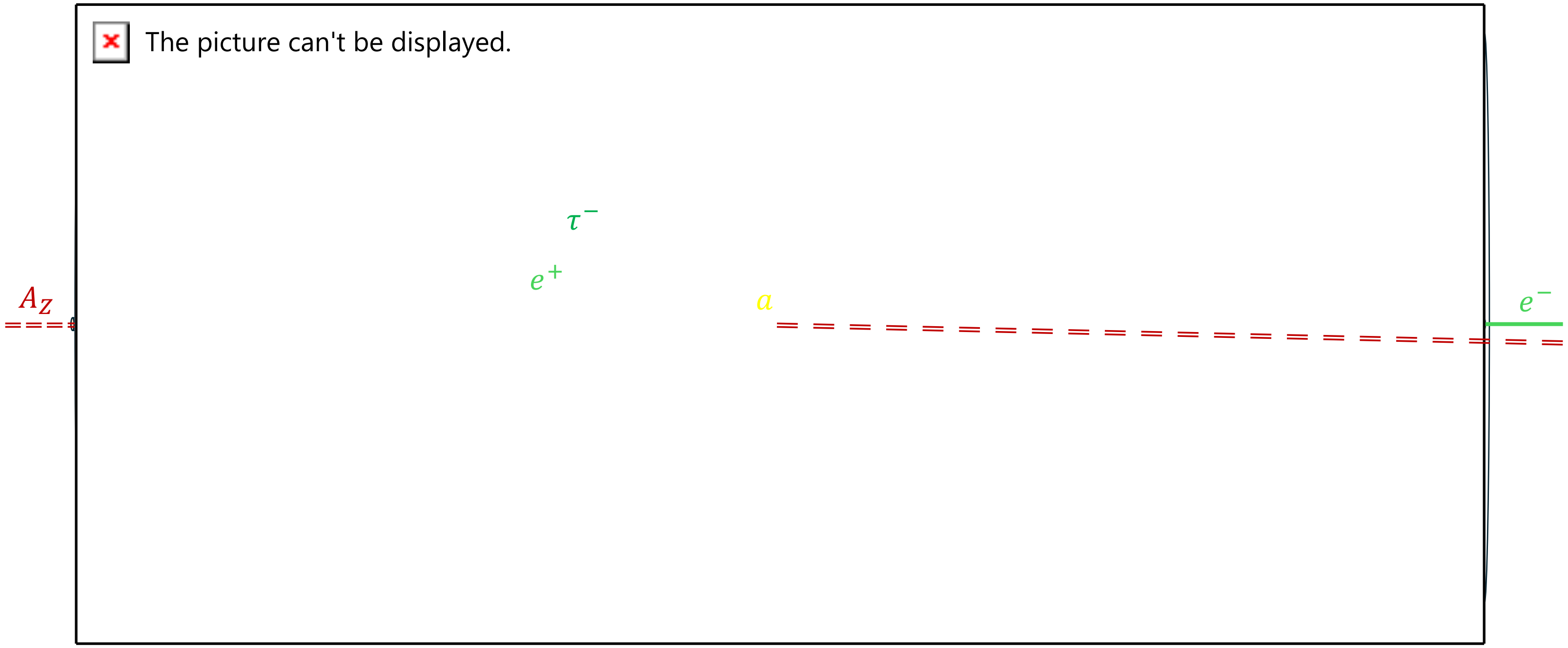
Lepton-flavor-violating ALPs: EIC



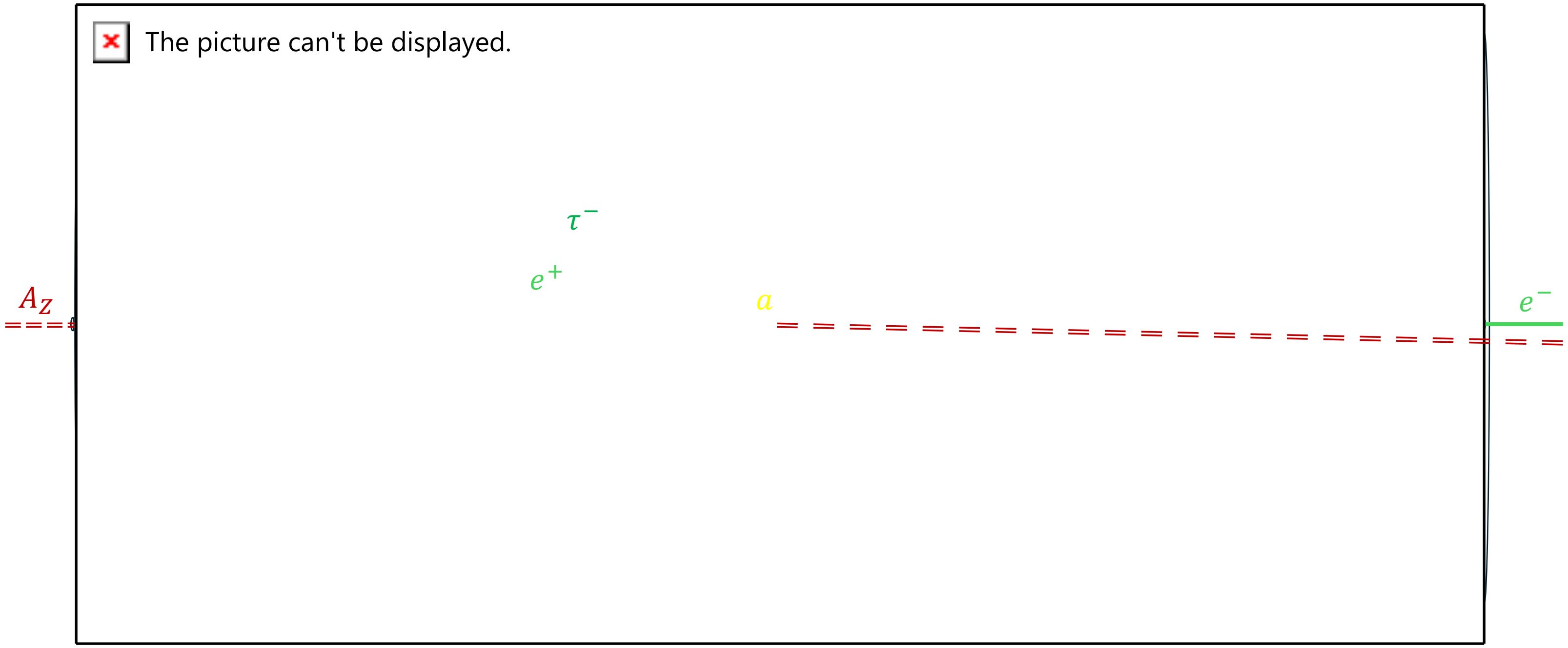
Lepton-flavor-violating ALPs: EIC



Lepton-flavor-violating ALPs: EIC



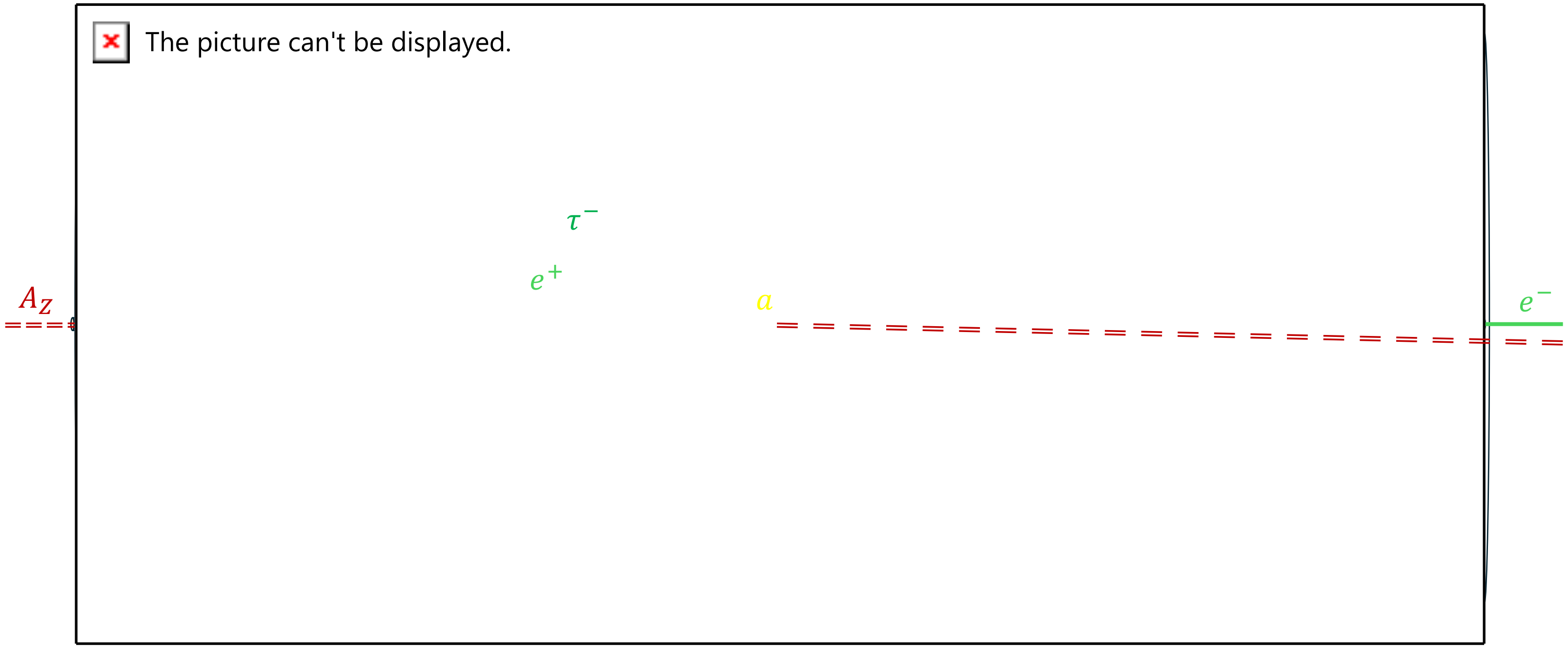
Lepton-flavor-violating ALPs: EIC



SIGNAL

- Purely LFV final-state ($e^- \to \tau^-(e^+\tau^-)$)
- Require ID of e^+ one τ^-, **veto on $\boldsymbol{e^-}$**
- Signal efficiency $\epsilon_{\mathrm{sig}} \approx 0.82\epsilon_\tau$
- No SM background

Lepton-flavor-violating ALPs: EIC



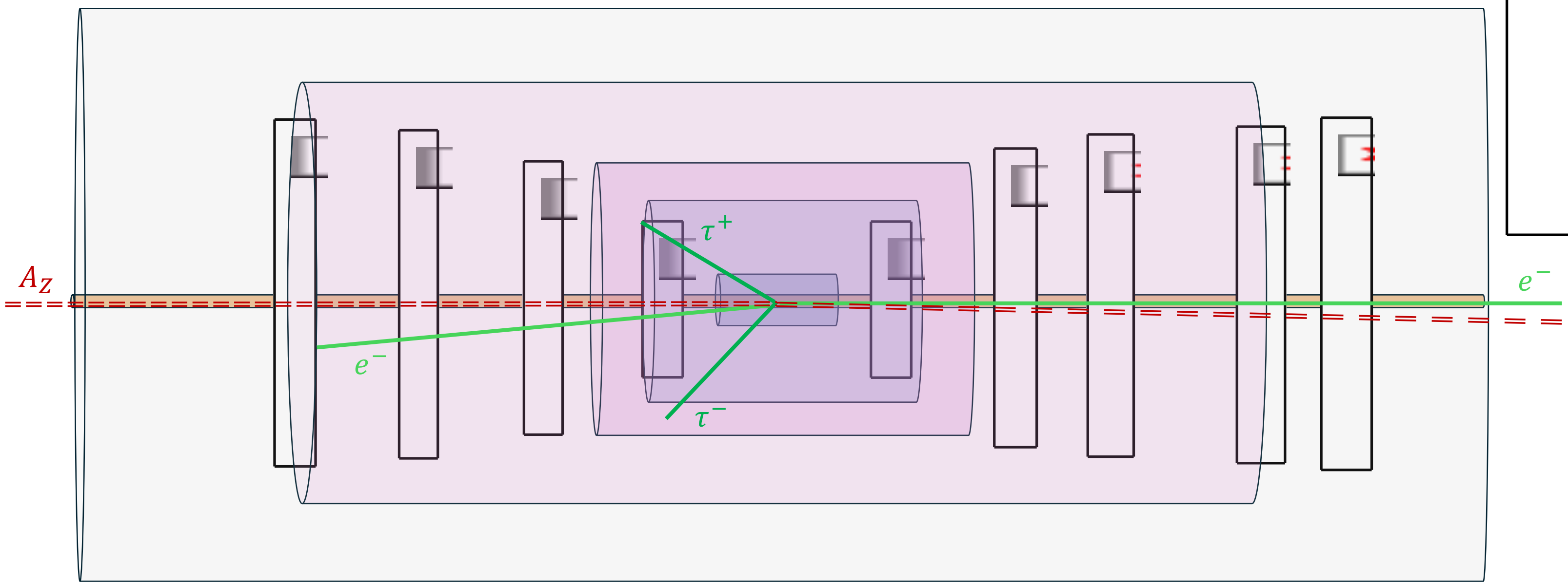
SIGNAL

- Purely LFV final-state ($e^- \to \tau^-(e^+\tau^-)$)
- Require ID of e^+ one τ^-, **veto on e^-**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- No SM background…?

Lepton-flavor-violating ALPs: EIC

The picture can't be displayed.

The picture can't be displayed.



SIGNAL

- Purely LFV final-state ($e^- \to \tau^-(e^+\tau^-)$)
- Require ID of e^+ one τ^-, **veto on $\boldsymbol{e^-}$**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- No SM background…?

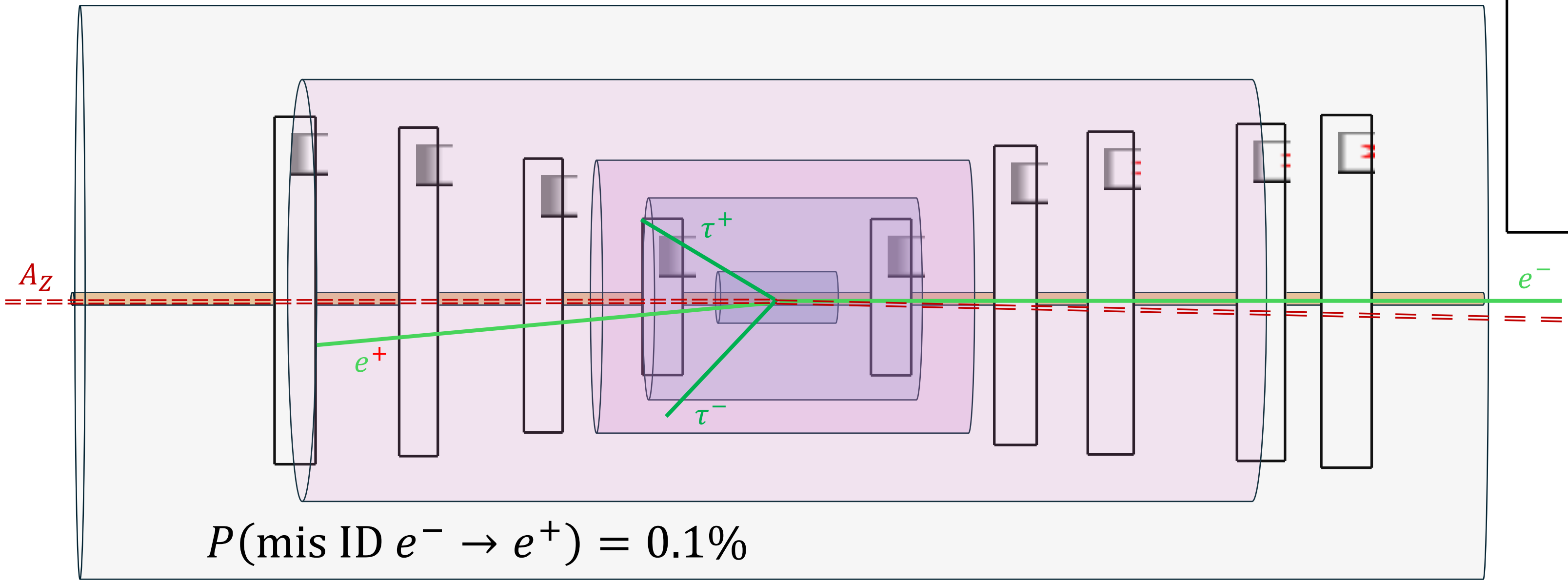
BACKGROUND

- ditau production
- $\sigma \approx 26$ nb

The picture can't be displayed.

The picture can't be displayed.

Lepton-flavor-violating ALPs: EIC



SIGNAL

- Purely LFV final-state ($e^- \to \tau^-(e^+\tau^-)$)
- Require ID of e^+ one τ^-, **veto on e^-**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- No SM background...?

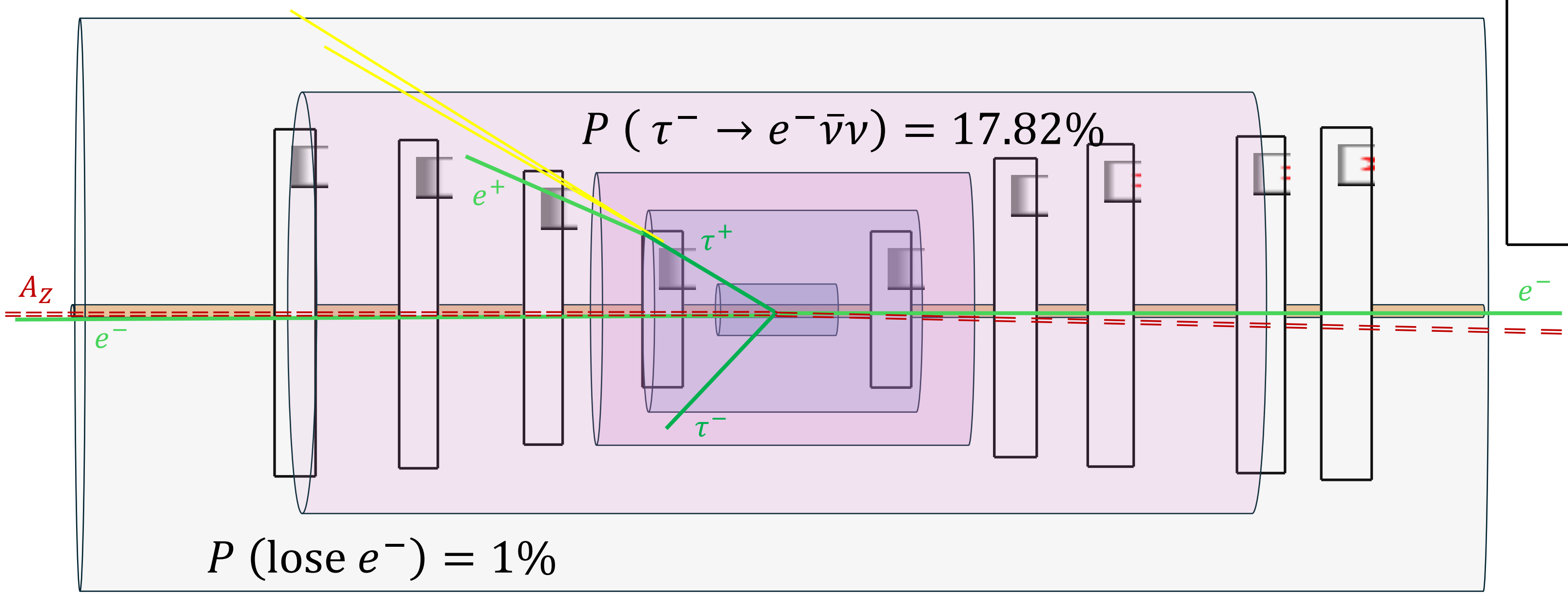
BACKGROUND

- ditau production
- $\sigma \approx 26$ nb

The picture can't be displayed.

The picture can't be displayed.

Lepton-flavor-violating ALPs: EIC



SIGNAL

- Purely LFV final-state $(e^- \to \tau^-(e^+\tau^-))$
- Require ID of e^+ one τ^-, **veto on $\boldsymbol{e^-}$**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- No SM background…?

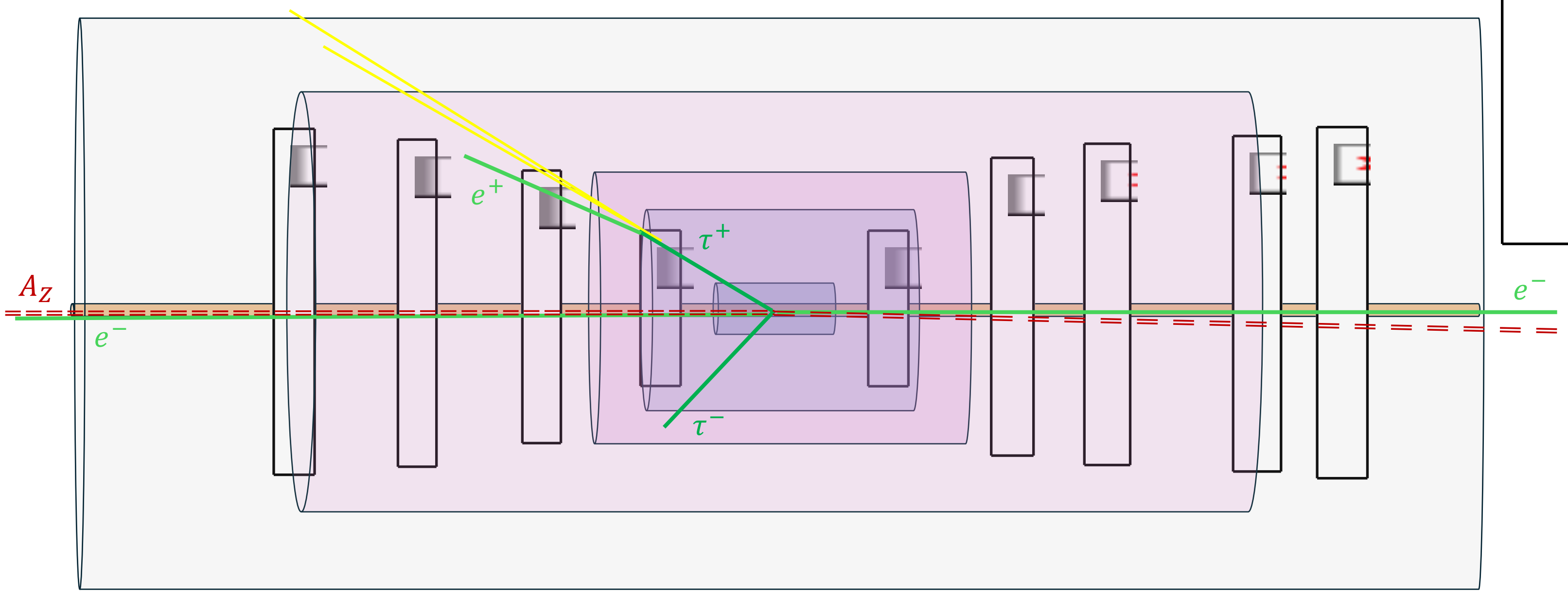
BACKGROUND

- ditau production
- $\sigma \approx 26$ nb

Lepton-flavor-violating ALPs: EIC

The picture can't be displayed.

The picture can't be displayed.



SIGNAL

- Purely LFV final-state ($e^- \to \tau^-(e^+\tau^-)$)
- Require ID of e^+ one τ^-, **veto on e^-**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- No SM background…?

BACKGROUND

- ditau production
- $\sigma \approx 26$ nb
- B.G. efficiency: $\epsilon_{\text{b.g.}} \approx 0.0036\epsilon_\tau$
- $N_{\text{b.g.}} \approx 47\,000\epsilon_\tau$ (at $\mathcal{L} \approx (100/A)$ fb^{-1})

Lepton-flavor-violating ALPs: EIC projected limits

The picture can't be displayed.

LFV ALPs: EIC+LHC limits (only C nonzero)

The picture can't be displayed.

LFV ALPs: EIC+LHC limits (only $C_{\tau e}$ non-zero)

The picture can't be displayed.

LFV ALPs: EIC+LHC limits (democratic couplings)

The picture can't be displayed.

(assuming $C_{\tau\mu} = C_{\tau e}$)

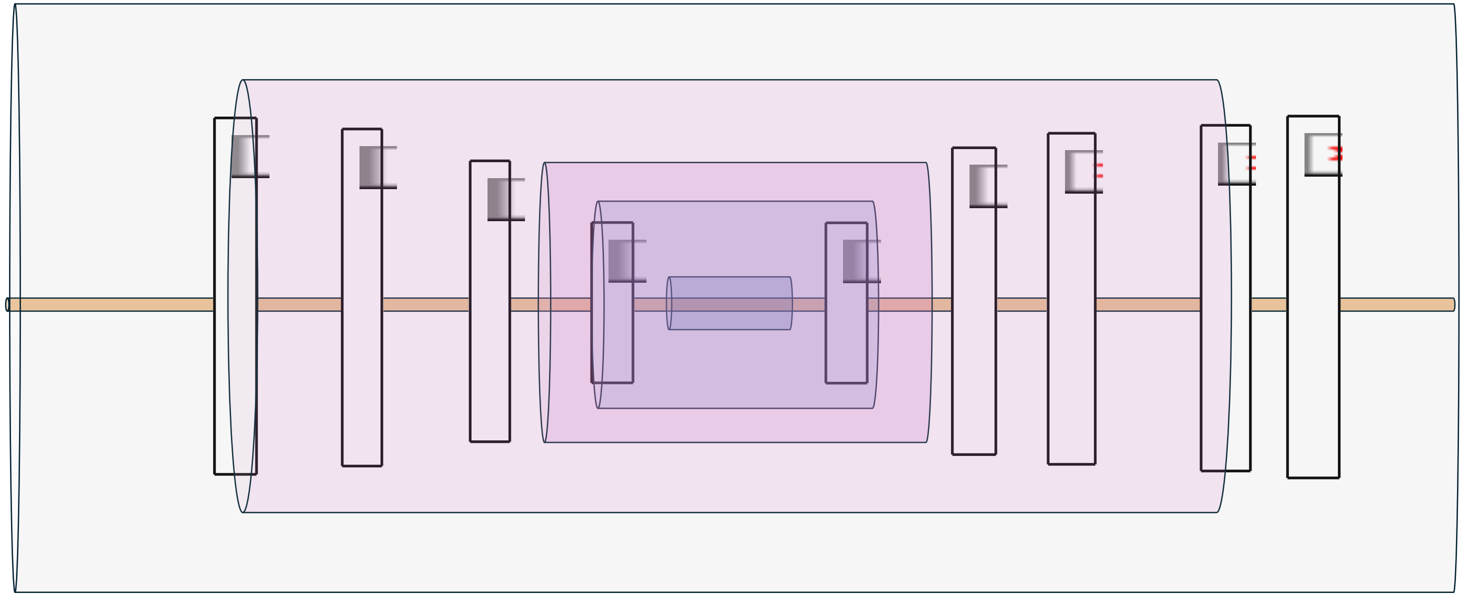
LFV ALPs: EIC +$(g-2)_e$

The picture can't be displayed.

LFV ALPs: EIC $+(g-2)_e$

The picture can't be displayed.

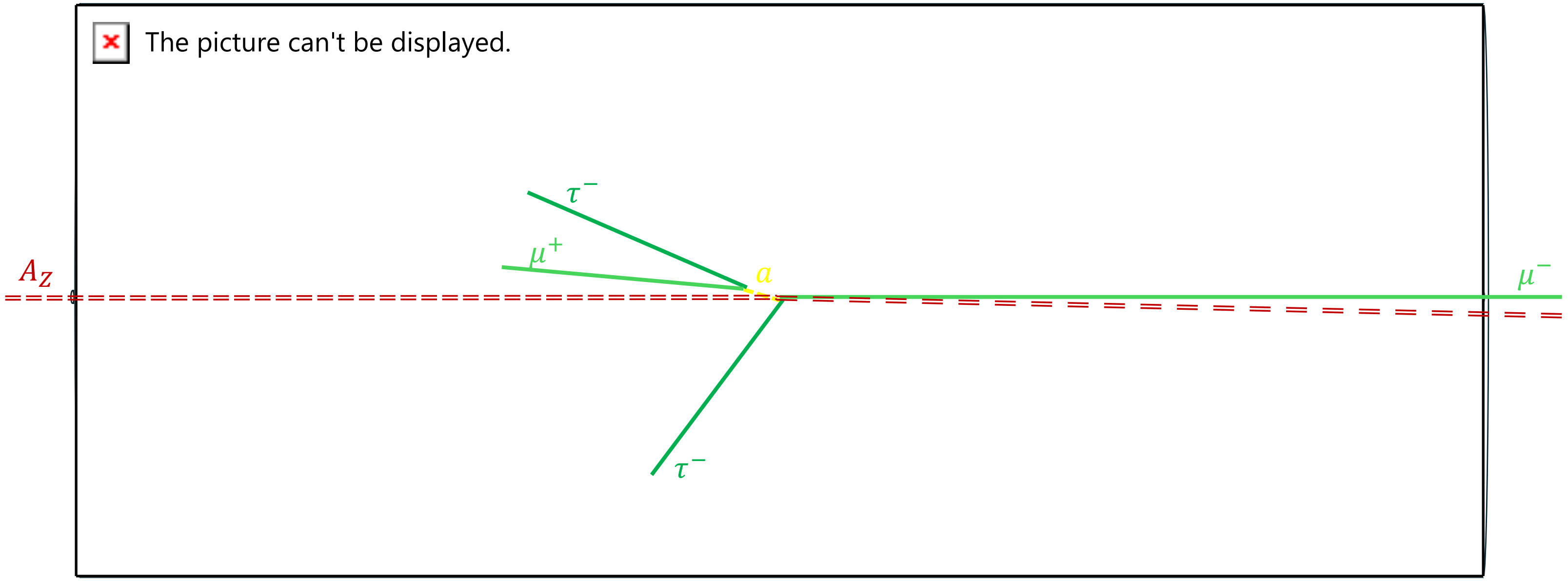
LFV ALPs: MuSIC



LFV ALPs: MuSIC

The picture can't be displayed.

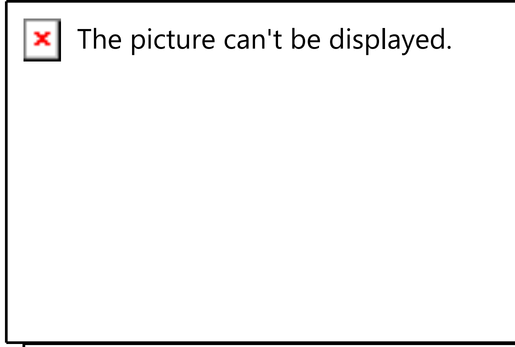
LFV ALPs: MuSIC

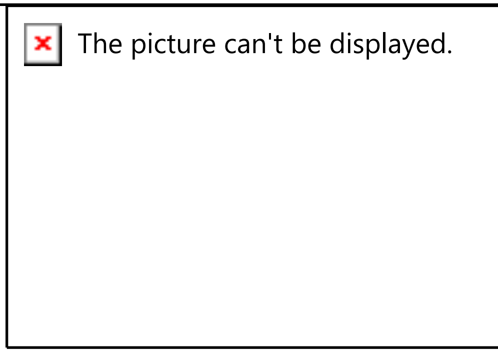


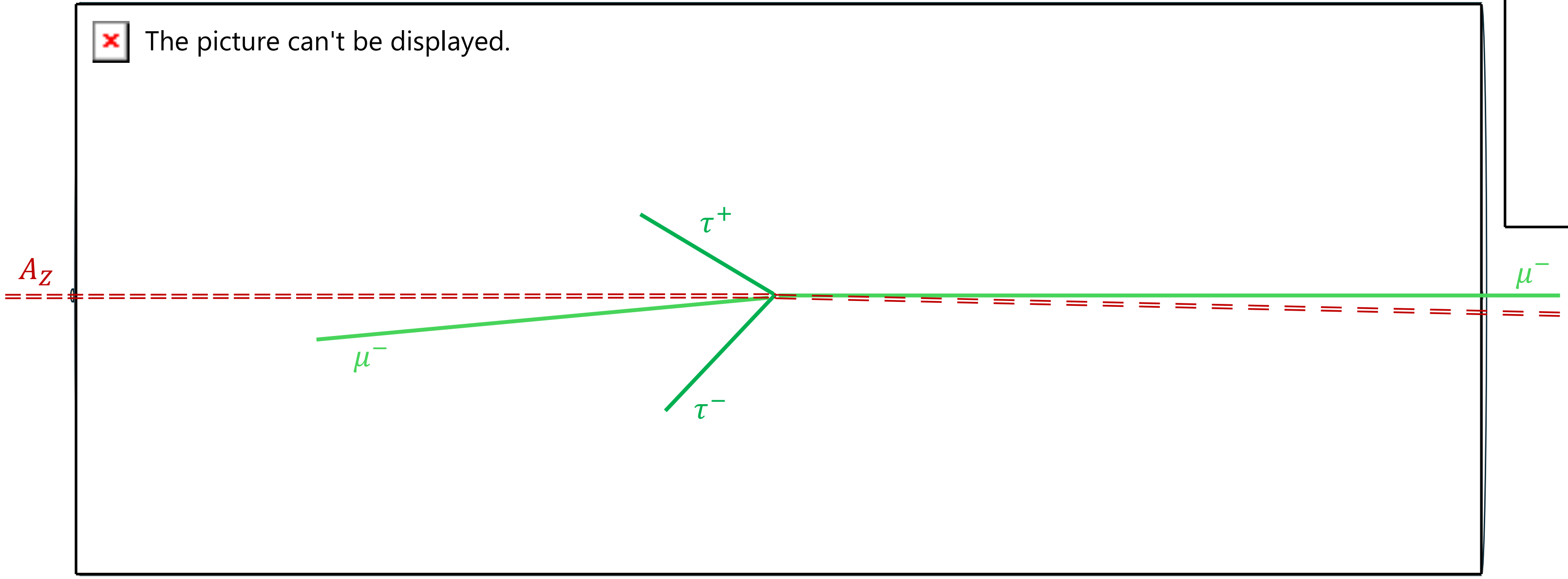
SIGNAL

- Purely LFV final-state ($\mu^- \to \tau^-(\mu^+\tau^-)$)
- Require ID of μ^+ one τ^-, **veto on $\boldsymbol{\mu^-}$**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- $\boldsymbol{|\eta| < 6}$

LFV ALPs: MuSIC







SIGNAL

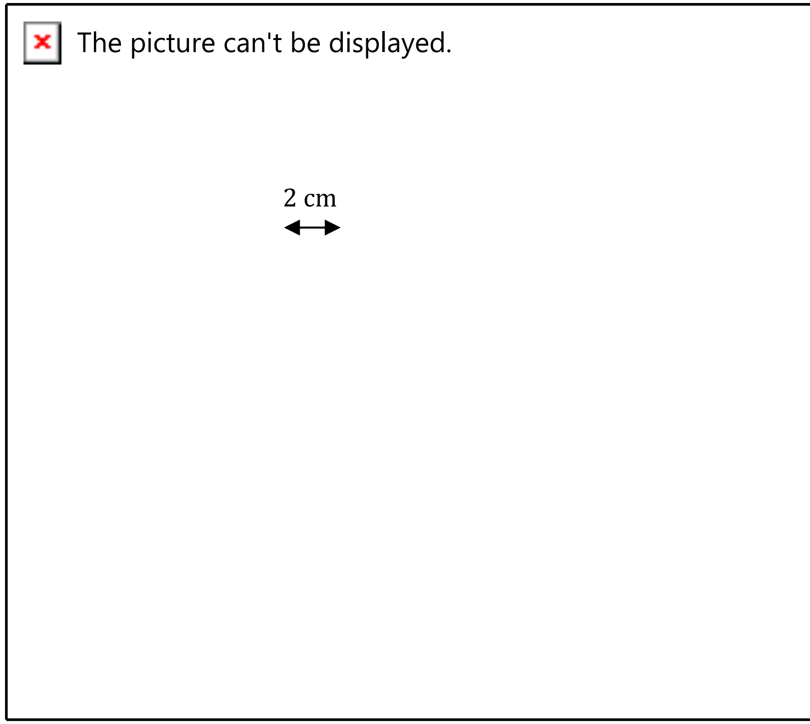
- Purely LFV final-state ($\mu^- \to \tau^-(\mu^+\tau^-)$)
- Require ID of μ^+ one τ^-, **veto on $\boldsymbol{\mu^-}$**
- Signal efficiency $\epsilon_{\text{sig}} \approx 0.82\epsilon_\tau$
- $\boldsymbol{|\eta| < 6}$

BACKGROUND

- ditau production
- $\sigma \approx 100$ nb
- B.G. efficiency: $\epsilon_{\text{b.g.}} \approx 0.0036\epsilon_\tau$
- $N_{\text{b.g.}} \approx 180\,000\epsilon_\tau$

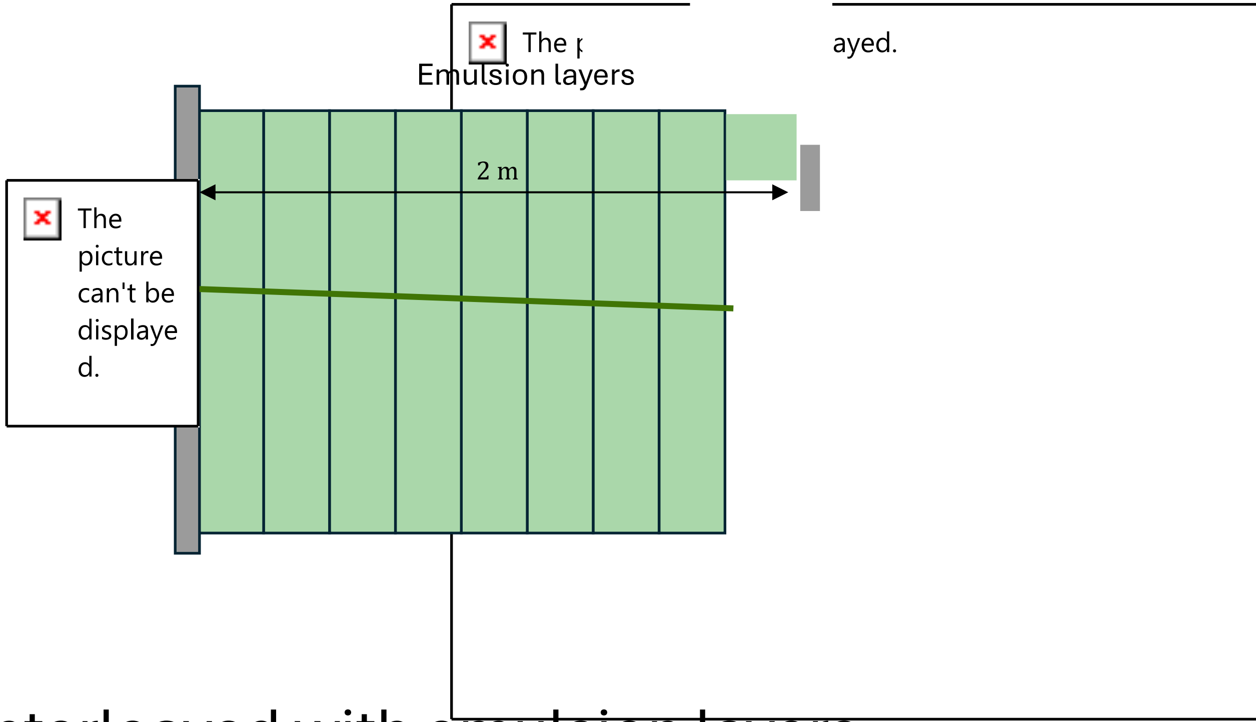
LFV ALPs: MuBeD

- Muon fixed target experiment
  - 2cm lead target bookended by veto/tracking layers
  - Followed by spectrometer
- Focus on $\tau^-\tau^-\mu^+$ final-state
- Identify μ^+ and *both* τ^-
- Assume 100% reconstruction of hadronic τ with $\sim 2\ \mathrm{cm}$ track.
- 10^{16}-10^{18} muons on target (MOT)



LFV ALPs: MuBeD

- Muon fixed target experiment
  - 2cm lead target bookended by veto/tracking layers
  - Followed by spectrometer
- Focus on $\tau^-\tau^-\mu^+$ final-state
- Identify μ^+ and *both* τ^-
- Assume 100% reconstruction of hadronic τ with ~ 2 cm track.
- 10^{16}-10^{18} muons on target (MOT)
- Optimistic: 10^{20} MOT, 2 m lead target interleaved with emulsion layers.



LFV ALPs: MuSIC+MuBeD ($C_{\tau\mu}$ only non-zero)

The picture can't be displayed.

LFV ALPs: MuSIC+MuBeD (democratic)

The picture can't be displayed.

Hidden Gauge Bosons

Hidden Gauge Bosons: Dark photons

- Dark matter: 85% of gravitational mass in the universe
- May have its own abelian gauge theory $U(1)_X$ with gauge field A'

Hidden Gauge Bosons: Dark photons

- Dark matter: 85% of gravitational mass in the universe
- May have its own abelian gauge theory $U(1)_X$ with gauge field A'
- Totalitarian principle allows a mixing term with SM photon $\mathcal{L}_{\text{mix}} = \epsilon F_{\mu\nu} F'^{\mu\nu}$
- Resulting $U(1)$ Lagrangian:

$$\mathcal{L} = F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu} + \epsilon F_{\mu\nu} F'^{\mu\nu} - e A'_\mu j_X^\mu - e A_\mu j_{\text{EM}}^\mu, \qquad F_{\mu\nu}^{(\prime)} \equiv \partial_\mu A_\nu^{(\prime)} - \partial_\nu A_\mu^{(\prime)}$$

ϵ is kinetic mixing, j_{EM}^μ the SM electromagnetic current, and j_X^μ the dark current

Hidden Gauge Bosons: Dark photons

- Dark matter: 85% of gravitational mass in the universe
- May have its own abelian gauge theory $U(1)_X$ with gauge field A'
- Totalitarian principle allows a mixing term with SM photon $\mathcal{L}_{\text{mix}} = \epsilon F_{\mu\nu}F'^{\mu\nu}$
- Resulting $U(1)$ Lagrangian:

$$\mathcal{L} = F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu} + \epsilon F_{\mu\nu}F'^{\mu\nu} - eA'_\mu j^\mu_X - eA_\mu j^\mu_{\text{EM}}, \qquad F^{(\prime)}_{\mu\nu} \equiv \partial_\mu A^{(\prime)}_\nu - \partial_\nu A^{(\prime)}_\mu$$

ϵ is kinetic mixing, j^μ_{EM} the SM electromagnetic current, and j^μ_X the dark current

- Diagonalize the kinetic term:

$$\mathcal{L} = F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu} - eA'_\mu j^\mu_X + \epsilon e A'_\mu j^\mu_{\text{EM}} - eA_\mu j^\mu_{\text{EM}} + \epsilon e A_\mu j^\mu_{\text{EM}}$$

- $U(1)_X$ is typically taken to be broken, so A' is taken to be massive.

Hidden Gauge Bosons: Dark photons

- Dark matter: 85% of gravitational mass in the universe
- May have its own abelian gauge theory $U(1)_X$ with gauge field A'
- Totalitarian principle allows a mixing term with SM photon $\mathcal{L}_{\mathrm{mix}} = \epsilon F_{\mu\nu} F'^{\mu\nu}$
- Resulting $U(1)$ Lagrangian:

$$\mathcal{L} = F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu} + \epsilon F_{\mu\nu} F'^{\mu\nu} - e A'_\mu j^\mu_X - e A_\mu j^\mu_{\mathrm{EM}}, \qquad F^{(\prime)}_{\mu\nu} \equiv \partial_\mu A^{(\prime)}_\nu - \partial_\nu A^{(\prime)}_\mu$$

ϵ is kinetic mixing, j^μ_{EM} the SM electromagnetic current, and j^μ_X the dark current

- Diagonalize the kinetic term:

millicharged coupling to
SM electromagnetic current

$$\mathcal{L} = F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu} - e A'_\mu j^\mu_X + \boxed{\epsilon e A'_\mu j^\mu_{\mathrm{EM}}} - e A_\mu j^\mu_{\mathrm{EM}} + \epsilon e A_\mu j^\mu_{\mathrm{EM}}$$

- $U(1)_X$ is typically taken to be broken, so A' is taken to be massive.

Hidden Gauge Bosons: Anomaly-free theories

- SM can also be charged under $U(1)_X$
- Without appending additional fermions to the SM, there are three anomaly-free gauge theories:

$$U(1)_{L_\mu - L_e} \qquad U(1)_{L_\tau - L_e} \qquad U(1)_{L_\tau - L_\mu}$$

Hidden Gauge Bosons: Anomaly-free theories

- SM can also be charged under $U(1)_X$
- Without appending additional fermions to the SM, there are three anomaly-free gauge theories:

$$U(1)_{L_\mu - L_e} \qquad U(1)_{L_\tau - L_e} \qquad U(1)_{L_\tau - L_\mu}$$

- Coupling to the SM leptons:

$$\mathcal{L}_{\text{int}} = -g' A'_\mu \left(\bar{\ell} \mathbf{Q} \ell + \bar{\boldsymbol{\nu}}_L \mathbf{Q} \boldsymbol{\nu}_L \right)$$

$$\boldsymbol{Q}_{\boldsymbol{\mu}-\boldsymbol{e}} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\boldsymbol{Q}_{\boldsymbol{\tau}-\boldsymbol{e}} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\boldsymbol{Q}_{\boldsymbol{\tau}-\boldsymbol{\mu}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Hidden Gauge Bosons: Anomaly-free theories

- SM can also be charged under $U(1)_X$
- Without appending additional fermions to the SM, there are three anomaly-free gauge theories:

$$U(1)_{L_\mu - L_e} \qquad U(1)_{L_\tau - L_e} \qquad U(1)_{L_\tau - L_\mu}$$

- Coupling to the SM leptons (mass rotation):

$$\mathcal{L}_{\text{int}} = -g' A'_\mu \left(\bar{\ell}' \boldsymbol{V}_\ell \mathbf{Q} \boldsymbol{V}_\ell^\dagger \ell' + \bar{\boldsymbol{\nu}}' \boldsymbol{V}_\nu \mathbf{Q} \boldsymbol{V}_\nu^\dagger \boldsymbol{\nu}' \right)$$

- Charge matrices not $\propto$ identity: $[\boldsymbol{Q}, \boldsymbol{V}] \neq 0 \implies$ LFV A' couplings.

- Scalar sector has LFV couplings as well.

$$\boldsymbol{Q}_{\mu-e} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\boldsymbol{Q}_{\tau-e} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\boldsymbol{Q}_{\tau-\mu} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Hidden Gauge Bosons: Anomaly-free theories

- SM can also be charged under $U(1)_X$
- Append three right-handed neutrinos ν_R, there is an additional anomaly-free gauge theory:

$$U(1)_{B-L}$$

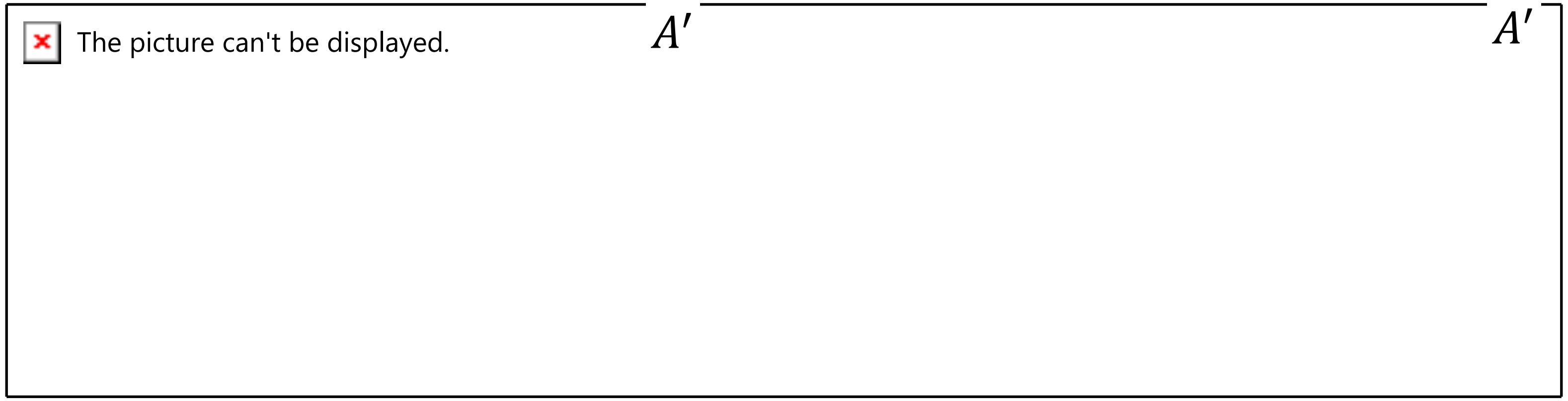
- Prevalent in GUTs and LR-symmetric models; can give neutrino mass.
- Coupling to the fermions:

$$\mathcal{L}_{\text{int}} = -g' A'_\mu \left(\frac{1}{3} \bar{\boldsymbol{q}} \gamma^\mu \boldsymbol{q} - \bar{\ell} \gamma^\mu \ell - \bar{\boldsymbol{\nu}} \gamma^\mu \boldsymbol{\nu} \right)$$

- Typically requires symmetry breaking of the $U(1)_{B-L}$, which gives Majorana neutrino masses.

Hidden Gauge Bosons: Displaced signal

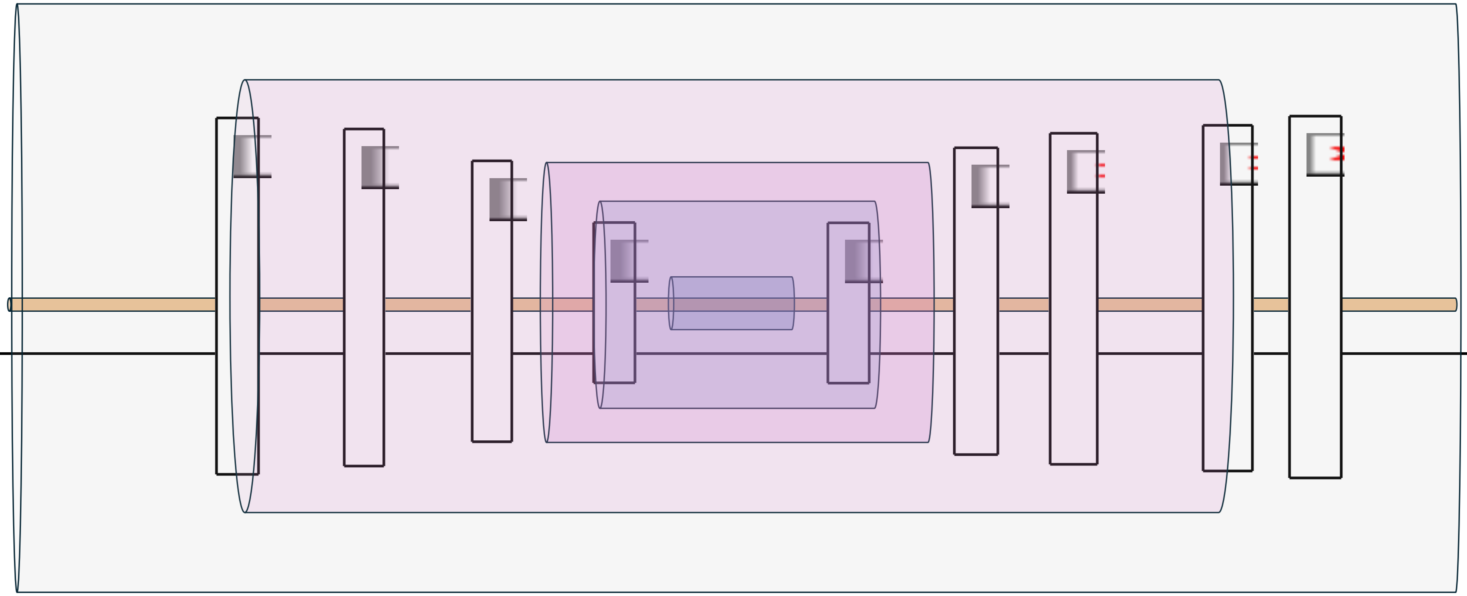
- Won’t focus explicitly on LFV
- Instead, diagonal production of gauge bosons in lepton-nucleus collisions:



- For MeV-GeV $m_{A'}$:
  - A' is long-lived: focus on **displaced decay** signals ($\ell^+\ell^-$ far from interaction point)
  - A' is produced very forward: Consider **detector geometry** carefully

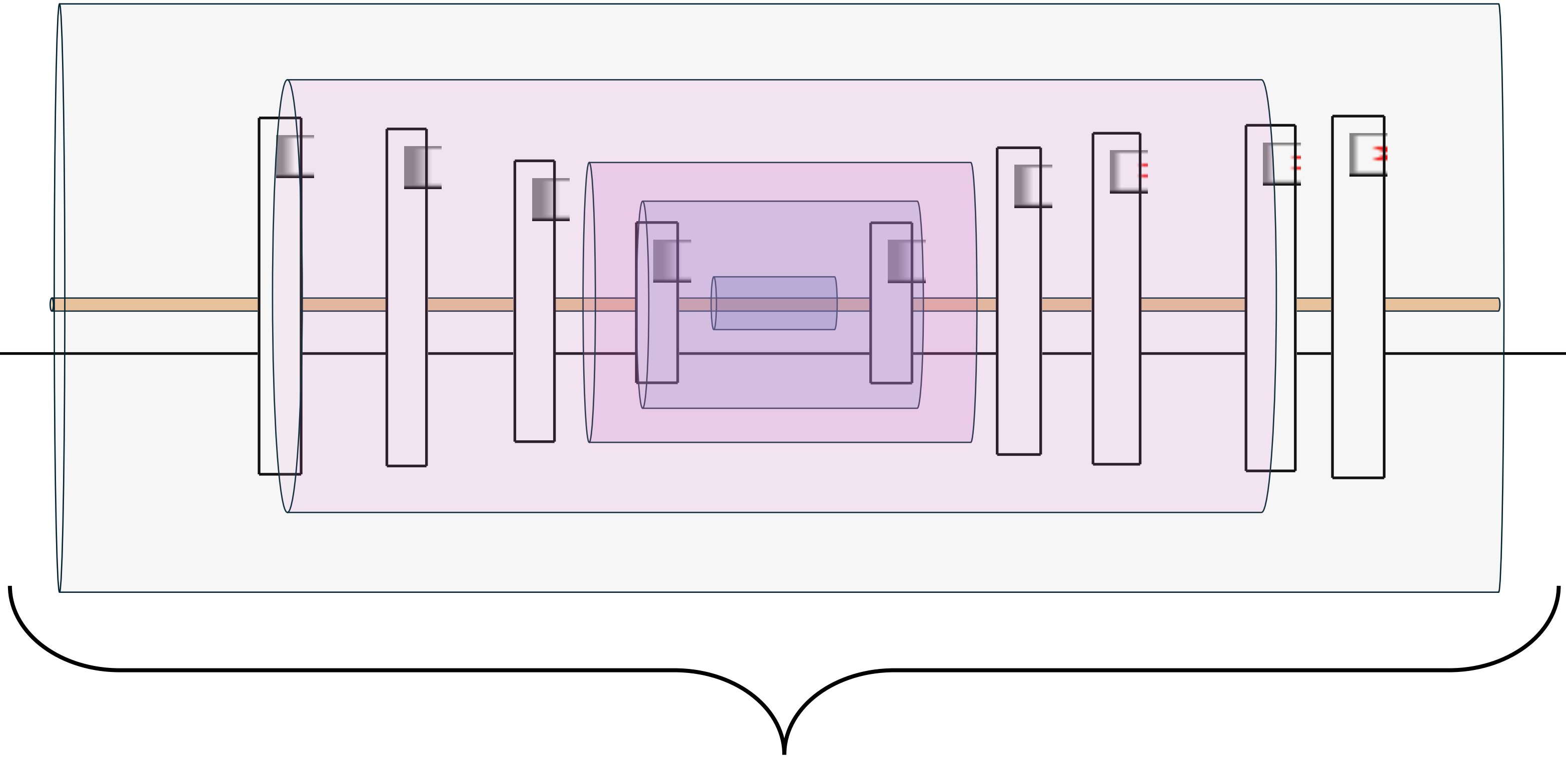
Hidden Gauge Bosons: EIC Signal

The picture can't be displayed.



Hidden Gauge Bosons: EIC Signal

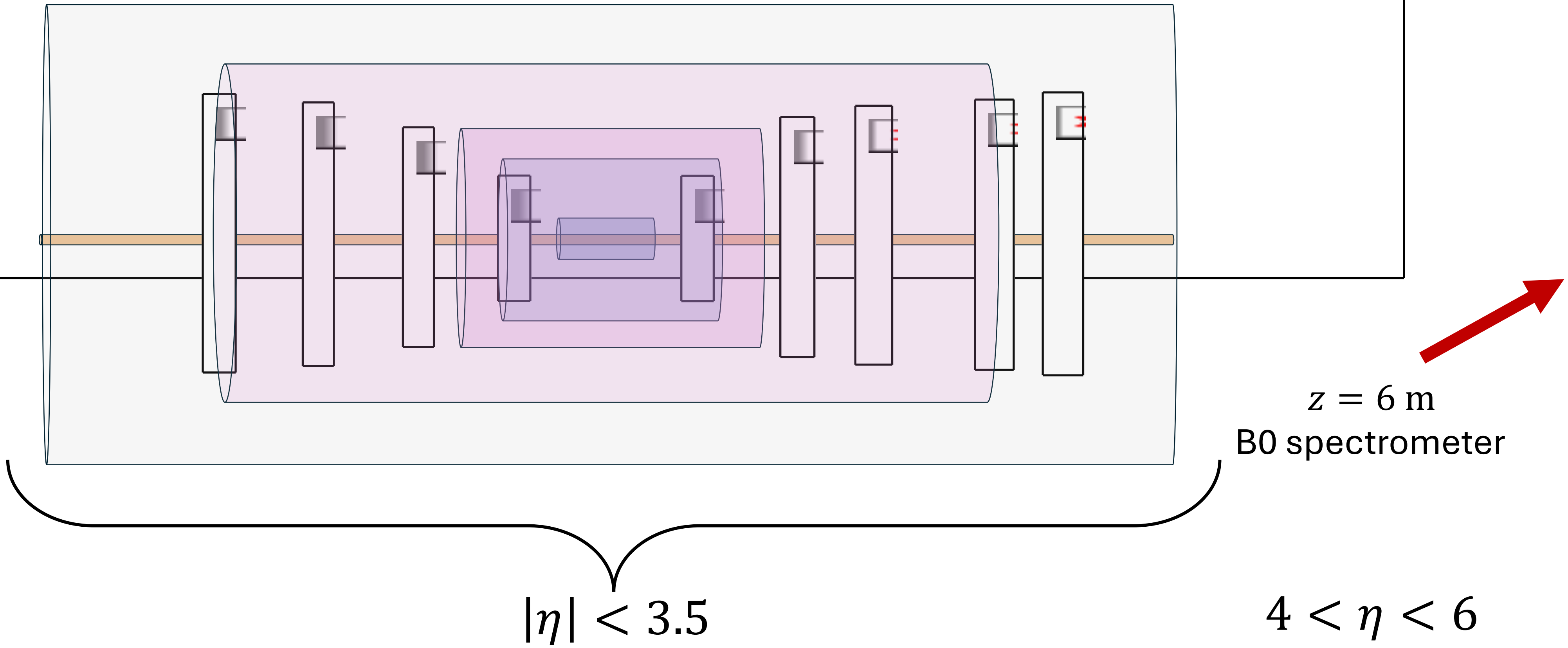
The picture can't be displayed.



$|\eta| < 3.5$

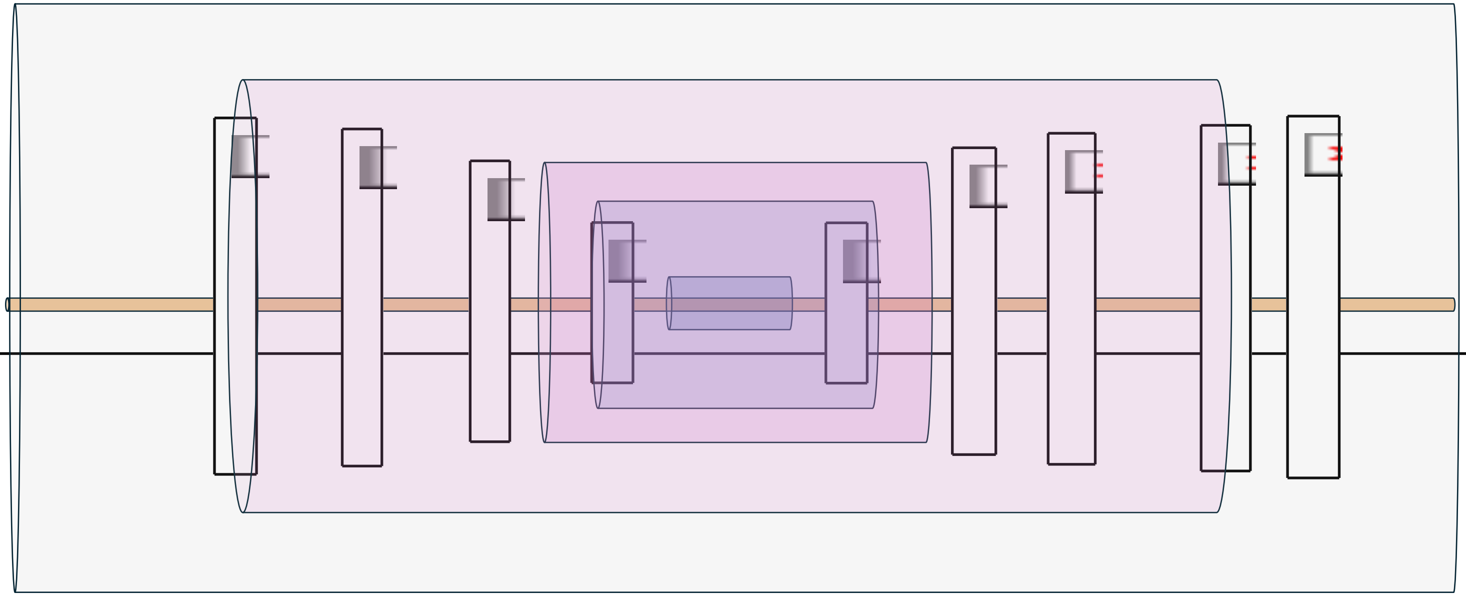
Hidden Gauge Bosons: EIC Signal

The picture can't be displayed.



Hidden Gauge Bosons: EIC Signal

The picture can't be displayed.



$z = -6$ m
Hypothetical far-backward detector "EIC (FB)"

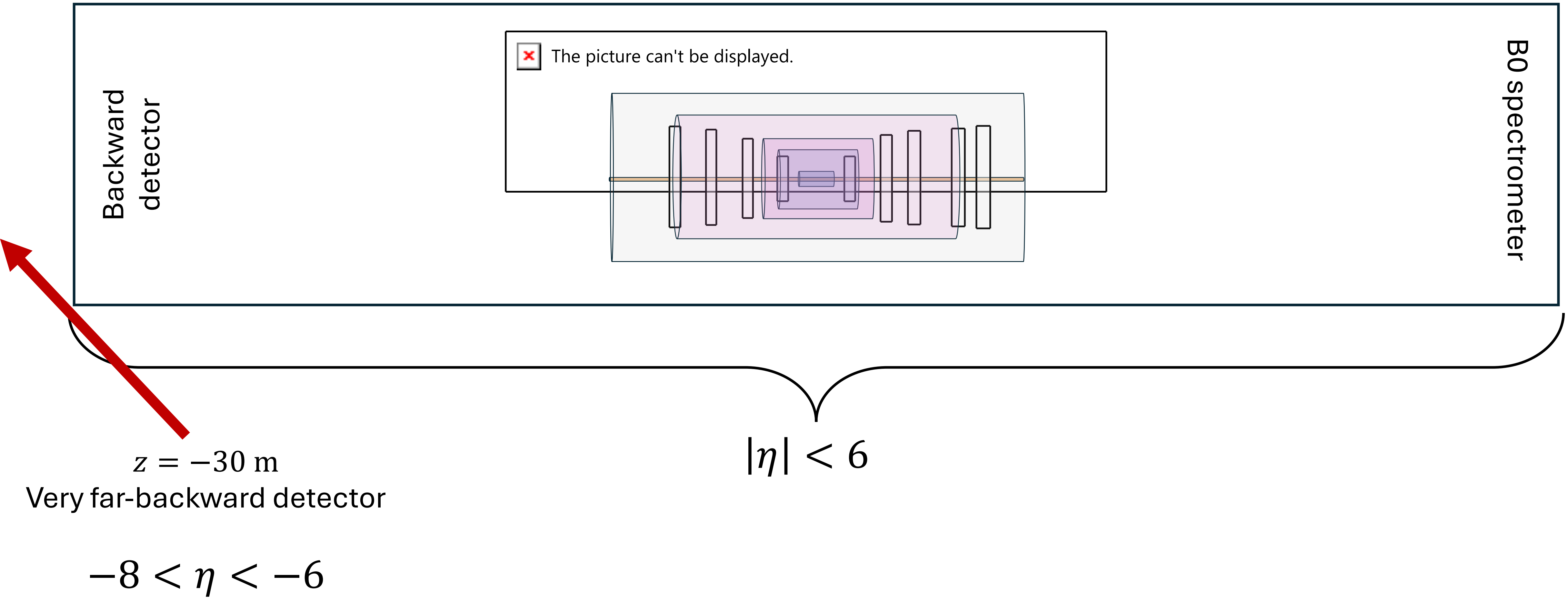
$-6 < \eta < -4$

$|\eta| < 3.5$

$z = 6$ m
B0 spectrometer

$4 < \eta < 6$

Hidden Gauge Bosons: MuSIC Signal



Hidden Gauge Bosons: MuBeD

The picture can't be displayed.

- Reproduced analysis from (Cesarotti and Gambhir 2310.16110)
- Look at scenario $L_{\mathrm{tar}} = 5\ \mathrm{m}$, $L_{\mathrm{sh}} = 10\ \mathrm{m}$, $L_{\mathrm{dec}} = 100\ \mathrm{m}$
- Take $E_\mu = 1\ \mathrm{TeV}$, and $N_\mu = 10^{18}$ or 10^{20}.
- Pseudo-rapidity coverage $\eta > 5$

Hidden Gauge Bosons: Experimental Parameters

Experiment	Pseudorapidity range	Transverse DCA resolution	Comments
EIC	$\lvert\eta\rvert < 3.5$	$100\mu\mathrm{m}$	
EIC (FB)	$\lvert\eta\rvert < 6$	$200\mu\mathrm{m}$	Requires detector at $z \sim -6\mathrm{m}$
MuSIC	$\lvert\eta\rvert < 6$	$200\mu\mathrm{m}$	Requires detector at $z \sim -6\mathrm{m}$
MuSIC (FB)	$\lvert\eta\rvert < 8$	$1\ \mathrm{mm}$	Requires detector at $z \sim -30\mathrm{m}$
MuBeD (10^{18})	$\lvert\eta\rvert > 5$	N/A	
MuBeD (10^{20})	$\lvert\eta\rvert > 5$	N/A	

Hidden Gauge Bosons: EIC projected limits

- EIC can reach novel parameter space in the mass coupling-plane, with masses of $\mathcal{O}(100\ \mathrm{MeV})$ and couplings of $\mathcal{O}(10^{-5}) - \mathcal{O}(10^{-4})$.

- Far-backward detector can reach $m_{A'}$ of a few hundred MeV.

Hidden Gauge Bosons: EIC, MuBeD and MuSIC

- MuSIC struggles to compete with EIC, due to very “backward” bosons

- MuSIC and EIC could both be improved with better DCA resolution

- MuBeD competitive with current and future experiments, probing masses beyond a GeV

The picture can't be displayed.

Concluding Remarks

Concluding Remarks

- CLFV is prevalent in BSM physics

- Leading constraints come from LFV lepton decays, and lepton electric and magnetic dipole moments:
  - LFV decays: dependent on PV and relative couplings
  - eEDM: requires substantial CP violation to be competitive
  - $g-2$: limit single coupling, dependent on PV
  - $(g-2)_e$ currently has anomalies between theory and experiment

- Production of bosons in lepton-nucleus collisions
  - Only dependent on single coupling, largely independent of PV angle
  - At low masses, beam-dump experiments superior due to pseudorapidity reach
  - Lepton-ion colliders (EIC and MuSIC) outperform at higher masses

Concluding Remarks

- Lepton-Flavor-Violating ALPs
  - Parameter-space of long-lived LFV ALPs with Higgs couplings will be probed substantially at the high-luminosity LHC.
  - EIC fills in some gaps of the parameter space for which $C_{\tau e}$ is the only coupling.
  - Even for $C_{\tau\mu}$-only scenario, MuSIC not very competitive in light of new (g-2) result
  - Best-case scenario for MuBeD outperforms limits on $C_{\tau\mu}$ from LFV decays

- Hidden gauge bosons
  - EIC can probe a new parameter space for $U(1)_{\mathrm{EM}}$, $U(1)_{B-L}$, $U(1)_{L_e-L_\mu}$ and $U(1)_{L_\tau-L_e}$
  - MuBeD covers a wide range of parameters for $U(1)_{\mathrm{EM}}$, $U(1)_{B-L}$, $U(1)_{L_e-L_\mu}$ and $U(1)_{L_\tau-L_\mu}$ that are not probed by current experiments.

Flavor-Violation in the SM: Quark sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U}_R, \boldsymbol{D}_R, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Quark-*W* boson interaction:

$$\mathcal{L}_{QW} = -g' W_\mu^- \overline{\boldsymbol{U}}_L \gamma^\mu \boldsymbol{D}_L + \mathrm{H.c.}$$

- Diagonal by convention
- Invariant under $\boldsymbol{U}_L' = \boldsymbol{V}\,\boldsymbol{U}_L, \boldsymbol{D}_L' = \boldsymbol{V}\,\boldsymbol{D}_L$

- Quark-Higgs Yukawa interaction:

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{U}}_L \mathbf{Y}^u \boldsymbol{U}_R + \varphi \overline{\boldsymbol{D}}_L \mathbf{Y}^d \boldsymbol{D}_R + \mathrm{H.c.}$$

- Non-diagonal ($\mathbf{Y}^f$ complex matrices)
- Couples to left and right-handed quarks

Flavor-Violation in the SM: Quark sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U}_R, \boldsymbol{D}_R, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Quark W-boson interaction:

$$\mathcal{L}_{QW} = -g' W_\mu^- \overline{\boldsymbol{U}}_L \gamma^\mu \boldsymbol{D}_L + \mathrm{H.c.}$$

- Quark-Higgs Yukawa interaction:

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{U}}_L \mathbf{Y}^u \boldsymbol{U}_R + \varphi \overline{\boldsymbol{D}}_L \mathbf{Y}^d \boldsymbol{D}_R + \mathrm{H.c.}$$

$$\mathbf{Y}^d = \boldsymbol{V}_{dL} \mathbf{y}^d \boldsymbol{V}_{dR}^\dagger$$

$$\boldsymbol{D}_L \equiv \boldsymbol{V}_{dL} \boldsymbol{d}_L$$

$$\boldsymbol{D}_R \equiv \boldsymbol{V}_{dR} \boldsymbol{d}_R$$

$$\mathbf{Y}^u = \boldsymbol{V}_{uL} \mathbf{y}^u \boldsymbol{V}_{uR}^\dagger$$

$$\boldsymbol{U}_L \equiv \boldsymbol{V}_{uL} \boldsymbol{u}_L$$

$$\boldsymbol{U}_R \equiv \boldsymbol{V}_{uR} \boldsymbol{u}_R$$

Flavor-Violation in the SM: Quark sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U}_R, \boldsymbol{D}_R, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Quark W-boson interaction:

$$\mathbf{Y}^d = \boldsymbol{V}_{dL}\mathbf{y}^d\boldsymbol{V}_{dR}^\dagger$$

$$\boldsymbol{D}_L \equiv \boldsymbol{V}_{dL}\boldsymbol{d}_L$$

$$\boldsymbol{D}_R \equiv \boldsymbol{V}_{dR}\boldsymbol{d}_R$$

$$\mathcal{L}_{QW} = -g' W_\mu^- \overline{\boldsymbol{U}}_L \gamma^\mu \boldsymbol{D}_L + \mathrm{H.c.}$$

- Quark-Higgs Yukawa interaction:

$$\mathbf{Y}^u = \boldsymbol{V}_{uL}\mathbf{y}^u\boldsymbol{V}_{uR}^\dagger$$

$$\boldsymbol{U}_L \equiv \boldsymbol{V}_{uL}\boldsymbol{u}_L$$

$$\boldsymbol{U}_R \equiv \boldsymbol{V}_{uR}\boldsymbol{u}_R$$

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{u}}_L \boldsymbol{y}^u \boldsymbol{u}_R + \varphi \overline{\boldsymbol{d}}_L \boldsymbol{y}^d \boldsymbol{d}_R + \mathrm{H.c.}$$

Flavor-Violation in the SM: Quark sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U}_R, \boldsymbol{D}_R, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Quark W-boson interaction:

$$\mathbf{Y}^d = \boldsymbol{V}_{dL}\mathbf{y}^d\boldsymbol{V}_{dR}^\dagger$$

$$\mathcal{L}_{QW} = -g' W_\mu^- \overline{\boldsymbol{u}}_L \gamma^\mu \left[\boldsymbol{V}_{uL}^\dagger \boldsymbol{V}_{dL}\right] \boldsymbol{d}_L + \mathrm{H.c.}$$

$$\boldsymbol{D}_L \equiv \boldsymbol{V}_{dL}\boldsymbol{d}_L$$

$$\boldsymbol{D}_R \equiv \boldsymbol{V}_{dR}\boldsymbol{d}_R$$

- Quark-Higgs Yukawa interaction:

$$\mathbf{Y}^u = \boldsymbol{V}_{uL}\mathbf{y}^u\boldsymbol{V}_{uR}^\dagger$$

$$\boldsymbol{U}_L \equiv \boldsymbol{V}_{uL}\boldsymbol{u}_L$$

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{u}}_L \boldsymbol{y}^u \boldsymbol{u}_R + \varphi \overline{\boldsymbol{d}}_L \boldsymbol{y}^d \boldsymbol{d}_R + \mathrm{H.c.}$$

$$\boldsymbol{U}_R \equiv \boldsymbol{V}_{uR}\boldsymbol{u}_R$$

Flavor-Violation in the SM: Quark sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U}_R, \boldsymbol{D}_R, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Quark W-boson interaction:

$$\mathcal{L}_{QW} = -g' W_\mu^- \overline{\boldsymbol{u}}_L \gamma^\mu [\boldsymbol{V}_{\mathrm{CKM}}] \boldsymbol{d}_L + \mathrm{H.c.}$$

$$\mathbf{Y}^d = \boldsymbol{V}_{dL} \mathbf{y}^d \boldsymbol{V}_{dR}^\dagger$$

$$\boldsymbol{D}_L \equiv \boldsymbol{V}_{dL} \boldsymbol{d}_L$$

$$\boldsymbol{D}_R \equiv \boldsymbol{V}_{dR} \boldsymbol{d}_R$$

- Quark-Higgs Yukawa interaction:

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{u}}_L \boldsymbol{y}^u \boldsymbol{u}_R + \varphi \overline{\boldsymbol{d}}_L \boldsymbol{y}^d \boldsymbol{d}_R + \mathrm{H.c.}$$

$$\mathbf{Y}^u = \boldsymbol{V}_{uL} \mathbf{y}^u \boldsymbol{V}_{uR}^\dagger$$

$$\boldsymbol{U}_L \equiv \boldsymbol{V}_{uL} \boldsymbol{u}_L$$

$$\boldsymbol{U}_R \equiv \boldsymbol{V}_{uR} \boldsymbol{u}_R$$

Flavor-Violation in the SM: Lepton sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U}_R, \boldsymbol{D}_R, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Lepton W-boson interaction:

$$\mathcal{L}_{LW} = -g' W_\mu^- \overline{\boldsymbol{E}}_L \gamma^\mu \boldsymbol{N}_L + \mathrm{H.c.}$$

- Diagonal by convention
- Only couples to left-handed leptons

- Lepton-Higgs Yukawa interaction:

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{E}}_L \mathbf{Y}^\ell \boldsymbol{E}_R + \mathrm{H.c.}$$

- Non-diagonal **(**$\boldsymbol{Y}^f$ complex matrices**)**
- No neutrino ($\boldsymbol{N}_L$) mass term

Flavor-Violation in the SM: Lepton sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Lepton W-boson interaction:

$$\mathbf{Y}^\ell = \boldsymbol{V}_{\ell L}\mathbf{y}^\ell \boldsymbol{V}_{\ell R}^\dagger$$

$$\mathcal{L}_{LW} = -g' W_\mu^- \overline{\boldsymbol{E}}_L \gamma^\mu \boldsymbol{N}_L + \mathrm{H.c.}$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L}\boldsymbol{\ell}_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R}\boldsymbol{\ell}_R$$

- Lepton-Higgs Yukawa interaction:

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\ell L}\boldsymbol{\nu}_L$$

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\boldsymbol{E}}_L \mathbf{Y}^\ell \boldsymbol{E}_R + \mathrm{H.c.}$$

Flavor-Violation in the SM: Lepton sector

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad \boldsymbol{F} = (F_1, F_2, F_3), \qquad \boldsymbol{F}' = \boldsymbol{V}\boldsymbol{F}$$

- Lepton W-boson interaction:

$$\mathbf{Y}^\ell = \boldsymbol{V}_{\ell L}\mathbf{y}^\ell \boldsymbol{V}_{\ell R}^\dagger$$

$$\mathcal{L}_{LW} = -g' W_\mu^- \overline{\ell}_L \gamma^\mu \boldsymbol{\nu}_L + \mathrm{H.c.}$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L}\boldsymbol{\ell}_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R}\boldsymbol{\ell}_R$$

- Lepton-Higgs Yukawa interaction:

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\ell L}\boldsymbol{\nu}_L$$

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\ell}_L \boldsymbol{y}^\ell \ell_R + \mathrm{H.c.}$$

Flavor-Violation in the SM: New singlet fermion

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad + \qquad \boldsymbol{N}_R \text{ (singlet)}$$

- Lepton W-boson interaction:

$$\mathbf{Y}^\ell = \boldsymbol{V}_{\ell L} \mathbf{y}^\ell \boldsymbol{V}_{\ell R}^\dagger$$

$$\mathcal{L}_{LW} = -g' W_\mu^- \overline{\ell}_L \gamma^\mu \boldsymbol{\nu}_L + \mathrm{H.c.}$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L} \ell_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R} \ell_R$$

- Lepton-Higgs Yukawa interaction:

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\ell L} \boldsymbol{\nu}_L$$

$$\mathcal{L}_{\varphi Q} = \varphi \overline{\ell}_L \boldsymbol{y}^\ell \ell_R + \mathrm{H.c.}$$

Flavor-Violation in the SM: New singlet fermion

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad + \qquad \boldsymbol{N}_R \text{ (singlet)}$$

- Lepton W-boson interaction:

$$\mathbf{Y}^{\ell} = \boldsymbol{V}_{\ell L}\mathbf{y}^{\ell}\boldsymbol{V}_{\ell R}^{\dagger}$$

$$\mathcal{L}_{LW} = -g' W_{\mu}^{-} \bar{\ell}_L \gamma^{\mu} \boldsymbol{\nu}_L + \mathrm{H.c.}$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L}\ell_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R}\ell_R$$

- Lepton-Higgs Yukawa interaction:

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\ell L}\boldsymbol{\nu}_L$$

$$\mathcal{L}_{\varphi Q} = \varphi \bar{\ell}_L \boldsymbol{y}^{\ell} \ell_R + \varphi \bar{\boldsymbol{N}}_L \boldsymbol{Y}^{\nu} \boldsymbol{N}_R + \mathrm{H.c.}$$

Flavor-Violation in the SM: New singlet fermion

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad + \qquad \boldsymbol{N}_R \text{ (singlet)}$$

- Lepton W-boson interaction:

$$\mathbf{Y}^{\ell} = \boldsymbol{V}_{\ell L}\mathbf{y}^{\ell}\boldsymbol{V}_{\ell R}^{\dagger}$$

$$\mathcal{L}_{LW} = -g' W_{\mu}^{-} \bar{\boldsymbol{\ell}}_L \gamma^{\mu} \boldsymbol{\nu}_L + \mathrm{H.c.}$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L}\boldsymbol{\ell}_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R}\boldsymbol{\ell}_R$$

- Lepton-Higgs Yukawa interaction:

$$\mathbf{Y}^{\boldsymbol{\nu}} = \boldsymbol{V}_{\nu L}\mathbf{y}^{\nu}\boldsymbol{V}_{\nu R}^{\dagger}$$

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\nu L}\boldsymbol{\nu}_L$$

$$\mathcal{L}_{\varphi Q} = \varphi \bar{\boldsymbol{\ell}}_L \boldsymbol{y}^{\ell} \boldsymbol{\ell}_R + \varphi \bar{\boldsymbol{N}}_L \boldsymbol{Y}^{\nu} \boldsymbol{N}_R + \mathrm{H.c.}$$

$$\boldsymbol{N}_R \equiv \boldsymbol{V}_{\nu R}\boldsymbol{\nu}_R$$

Flavor-Violation in the SM: New singlet fermion

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad + \qquad \boldsymbol{N}_R \text{ (singlet)}$$

- Lepton W-boson interaction:

$$\mathcal{L}_{LW} = -g' W_\mu^- \bar{\ell}_L \gamma^\mu \left[\boldsymbol{V}_{\ell L}^\dagger \boldsymbol{V}_{\nu L}\right] \boldsymbol{\nu}_L + \mathrm{H.c.}$$

$$\mathbf{Y}^\ell = \boldsymbol{V}_{\ell L} \mathbf{y}^\ell \boldsymbol{V}_{\ell R}^\dagger$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L} \boldsymbol{\ell}_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R} \boldsymbol{\ell}_R$$

- Lepton-Higgs Yukawa interaction:

$$\mathcal{L}_{\varphi Q} = \varphi \bar{\boldsymbol{\ell}}_L \boldsymbol{y}^\ell \boldsymbol{\ell}_R + \varphi \bar{\boldsymbol{\nu}}_L \boldsymbol{y}^\nu \boldsymbol{\nu}_R + \mathrm{H.c.}$$

$$\mathbf{Y}^\nu = \boldsymbol{V}_{\nu L} \mathbf{y}^\nu \boldsymbol{V}_{\nu R}^\dagger$$

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\nu L} \boldsymbol{\nu}_L$$

$$\boldsymbol{N}_R \equiv \boldsymbol{V}_{\nu R} \boldsymbol{\nu}_R$$

Flavor-Violation in the SM: New singlet fermion

$$\mathbf{Q} = \begin{pmatrix} \boldsymbol{U}_L \\ \boldsymbol{D}_L \end{pmatrix}, \boldsymbol{U_R}, \boldsymbol{D_R}, \mathbf{L} = \begin{pmatrix} \boldsymbol{N}_L \\ \boldsymbol{E}_L \end{pmatrix}, \boldsymbol{E}_R \qquad + \qquad \boldsymbol{N}_R \text{ (singlet)}$$

- Lepton W-boson interaction:

$$\mathcal{L}_{LW} = -g' W_\mu^- \bar{\ell}_L \gamma^\mu [\boldsymbol{V}_{PMNS}] \boldsymbol{\nu}_L + \mathrm{H.c.}$$

$$\mathbf{Y}^\ell = \boldsymbol{V}_{\ell L} \mathbf{y}^\ell \boldsymbol{V}_{\ell R}^\dagger$$

$$\boldsymbol{E}_L \equiv \boldsymbol{V}_{\ell L} \ell_L$$

$$\boldsymbol{E}_R \equiv \boldsymbol{V}_{\ell R} \ell_R$$

- Lepton-Higgs Yukawa interaction:

$$\mathcal{L}_{\varphi Q} = \varphi \bar{\ell}_L \boldsymbol{y}^\ell \ell_R + \varphi \bar{\boldsymbol{\nu}}_L \boldsymbol{y}^\nu \boldsymbol{\nu}_R + \mathrm{H.c.}$$

$$\mathbf{Y}^{\boldsymbol{\nu}} = \boldsymbol{V}_{\nu L} \mathbf{y}^\nu \boldsymbol{V}_{\nu R}^\dagger$$

$$\boldsymbol{N}_L \equiv \boldsymbol{V}_{\nu L} \boldsymbol{\nu}_L$$

$$\boldsymbol{N}_R \equiv \boldsymbol{V}_{\nu R} \boldsymbol{\nu}_R$$

Flavor-Violation in the SM: New singlet fermion

- All it takes to dismantle LFV in SM is a new singlet (right-handed ν)

- Singlet has no charge, so has a Majorana mass term:

$$\mathcal{L}_{\nu\ \mathrm{mass}} = \frac{v}{\sqrt{2}}\overline{\boldsymbol{N}}_L \mathbf{Y}^\nu \boldsymbol{N}_R + \frac{v}{\sqrt{2}}\overline{\boldsymbol{N}}_R \mathbf{Y}^{\nu\dagger} \boldsymbol{N}_L + \overline{\boldsymbol{N}}_R \mathbf{M} \boldsymbol{N}_R^c$$

- $m_\nu \sim y^2 v^2/M$: large $M \Longrightarrow$ small m_ν

- Can choose y and M to solve dark matter problem and give neutrinos mass!

- Values for y and M required to keep $\boldsymbol{\nu}_R$ stable on cosmological time-scales are “unnaturally” small.

FV *Beyond* the SM: 2-Higgs Doublet Model

- Prevalent in BSM theories, notably including supersymmetry
- Can provide an explanation for the Higgs hierarchy problem
- Call the Higgs doublets Φ_1 and Φ_2
- Yukawa interaction:

$$\begin{aligned}\mathcal{L} = {} & Y_{ij}^{\ell}\bar{L}_i\Phi_1 E_{Rj} + Y_{ij}^{u}\bar{Q}_i\Phi_1 U_{Rj} + Y_{ij}^{d}\bar{Q}_i\widetilde{\Phi}_1 D_{Rj} \\ & + Y_{ij}^{\ell}\bar{L}_i\Phi_2 E_{Rj} + Y_{ij}^{u}\bar{Q}_i\Phi_2 U_{Rj} + Y_{ij}^{d}\bar{Q}_i\widetilde{\Phi}_2 D_{Rj}\end{aligned}$$

FV *Beyond* the SM: 2-Higgs Doublet Model

- Prevalent in BSM theories, notably including supersymmetry
- Can provide an explanation for the Higgs hierarchy problem
- Call the Higgs doublets Φ_1 and Φ_2
- Yukawa interaction:

$$\begin{gathered}\mathcal{L} = v_1 Y_{ij}^{\ell} \bar{E}_{Li} E_{Rj} + v_1 Y_{ij}^{u} \bar{Q}_i U_{Rj} + v_1 Y_{ij}^{d} \bar{D}_{Li} D_{Rj} \\ + v_2 Y_{ij}^{\ell} \bar{E}_{Li} E_{Rj} + v_2 Y_{ij}^{u} \bar{Q}_i U_{Rj} + v_2 Y_{ij}^{d} \bar{D}_{Li} D_{Rj} \\ + \cdots\end{gathered}$$

FV *Beyond* the SM: Froggatt-Nielsen models

- Solution to the fermion Hierarchy problem
- Introduce a global $U(1)_H$ symmetry under which the SM fermions are charged, and a scalar with charge 1.
- Forbids usual Yukawa couplings, replacing them with

FV *Beyond* the SM: Axion-Like Particles

- Strong CP-problem:

- Axion:

- Axion-like Particle (ALP):

FV *Beyond* the SM: ALP Effective Field Theory

- Lagrangian:

FV *Beyond* the SM: FN ALPs

- Fermion coupling:

FV *Beyond* the SM: Composite ALPs

- Fermion coupling:

FV *Beyond* the SM: Anomaly free $U(1)_{L_i - L_j}$

- Will come back to these at the end of the talk…

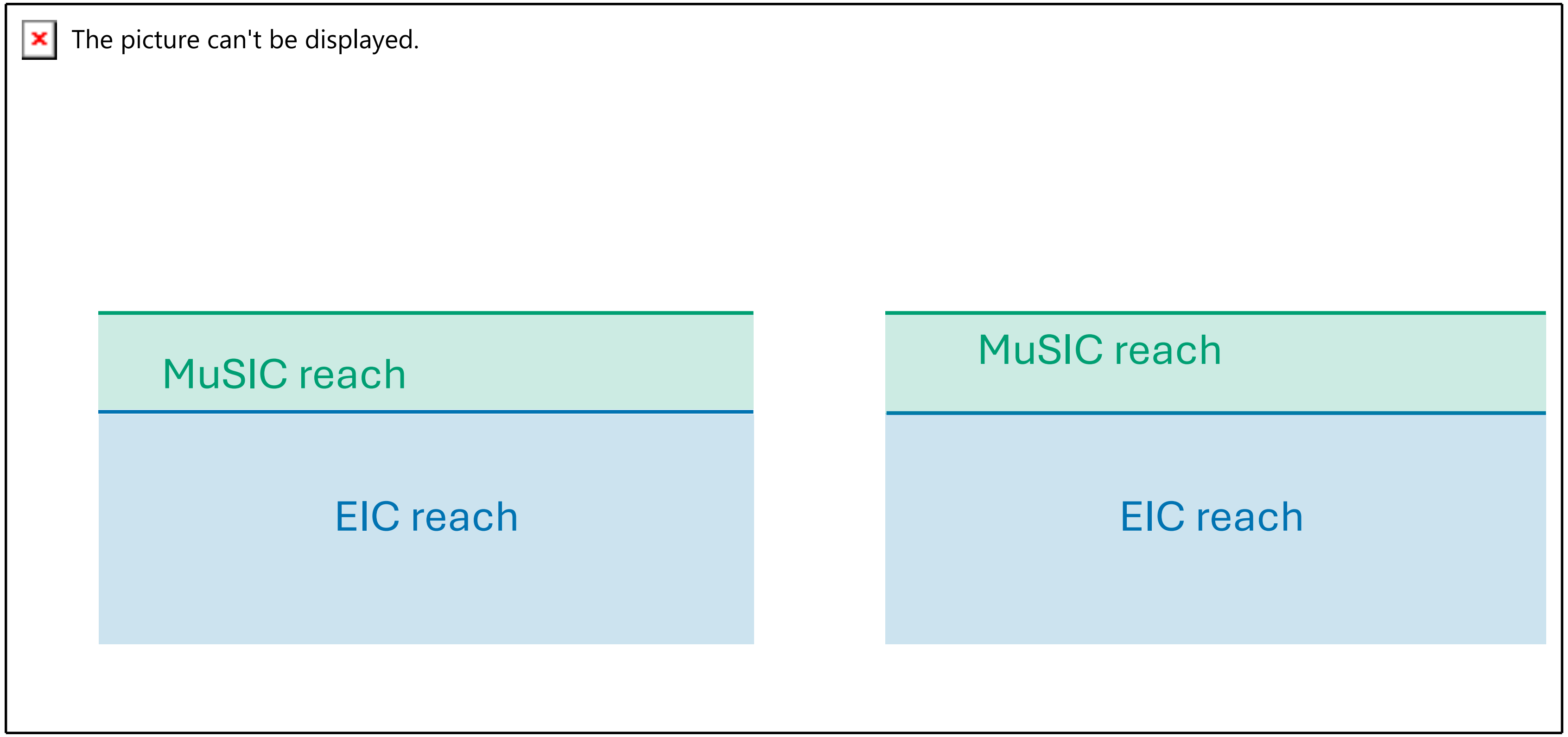
Final-State kinematic distributions: lepton η

- Median, first and third quartiles of lepton η distributions ("box and whisker plot"):

The picture can't be displayed.

Final-State kinematic distributions: lepton η

- Median, first and third quartiles of lepton η distributions (“box and whisker plot”):



Final-State kinematic distributions: lepton γ

- Median, first and third quartiles of lepton γ distributions ("box and whisker plot"):

The picture can't be displayed.

- γ_ℓ relatively flat over a wide range of masses

LFV ALPs: CMS prompt analysis efficiency

The picture can't be displayed.

LFV ALPs: CMS prompt limits

The picture can't be displayed.

- For promptly decaying ALPs, $|\overline{C}_{ah}| > 0.2$ excluded.

LFV ALPs: CMS long-lived limits

The picture can't be displayed.

- For promptly decaying ALPs, $\left|\overline{C}_{ah}\right| > 0.2$ excluded.
- For long-lived ALPs, limits weaken

X Lepton-flavor-violating ALPs: $\bar{C}_{ah}$ vs. $C_{\tau\ell}$

The picture can't be displayed.

X Lepton-flavor-violating ALPs: $\bar{C}_{ah}$ vs. $C_{\tau\ell}$

The picture can't be displayed.

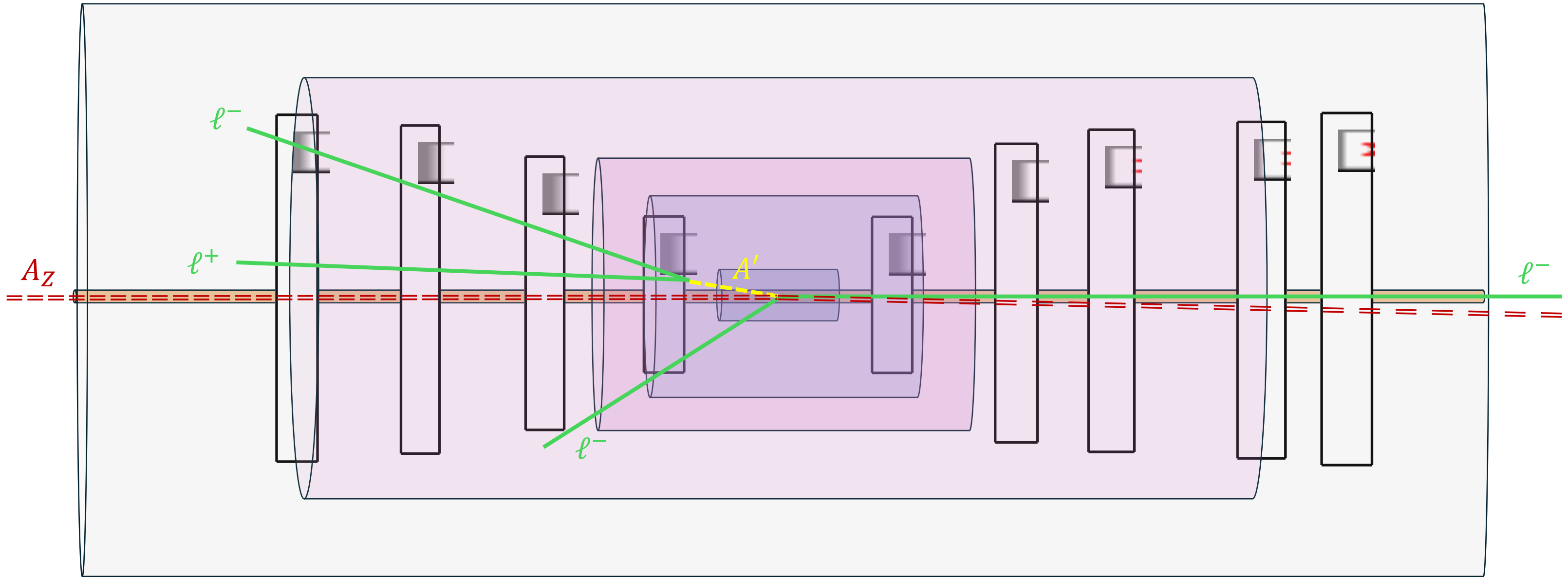
X Lepton-flavor-violating ALPs: $\bar{C}_{ah}$ vs. $C_{\tau\ell}$

The picture can't be displayed.

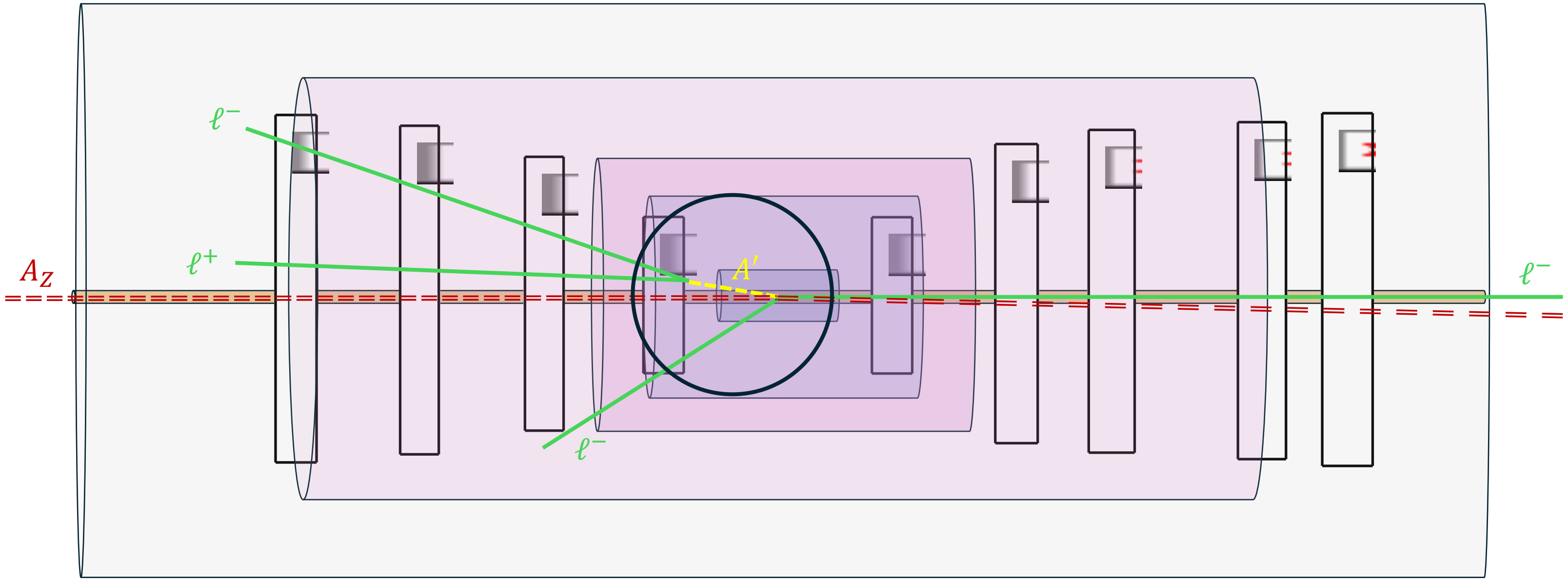
X Lepton-flavor-violating ALPs: $\bar{C}_{ah}$ vs. $C_{\tau\ell}$

The picture can't be displayed.

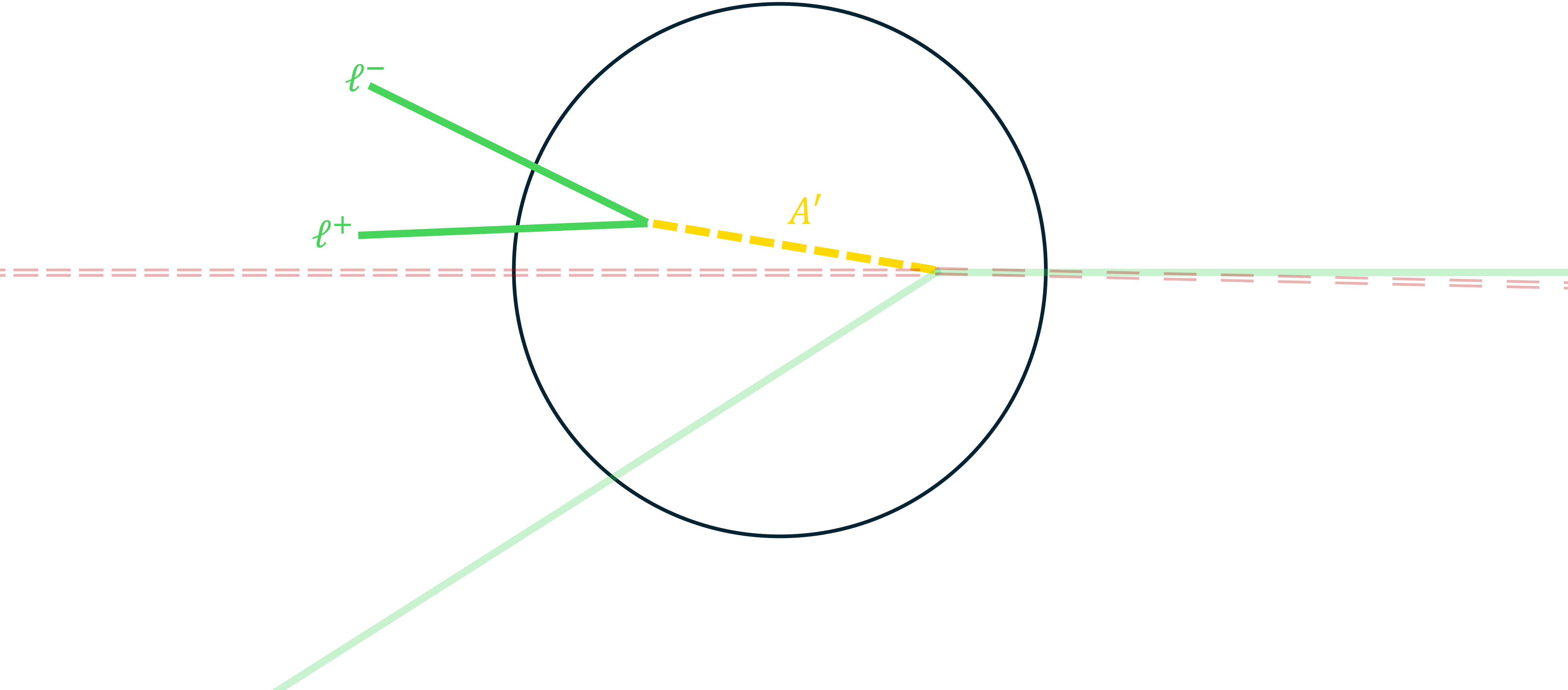
Hidden Gauge Bosons: Lepton-Ion colliders



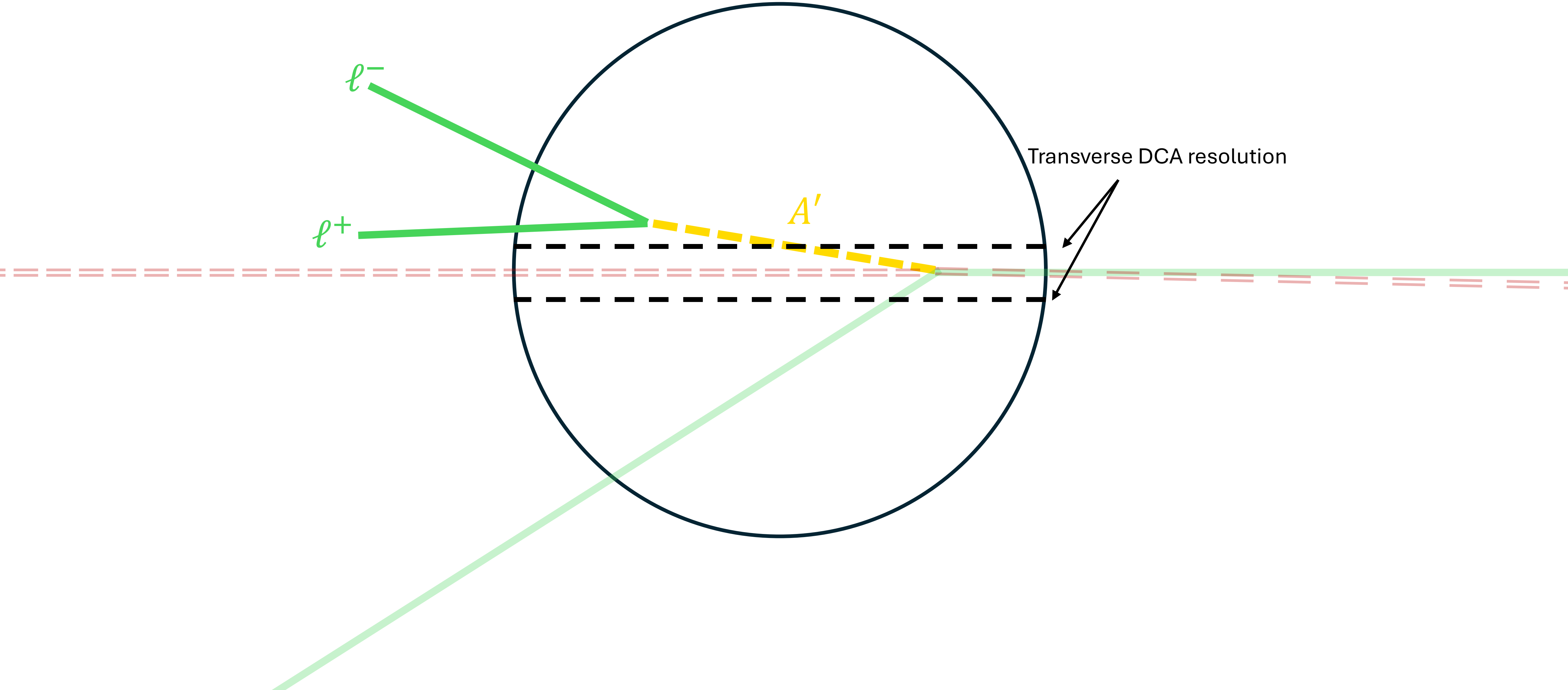
Hidden Gauge Bosons: Lepton-Ion colliders



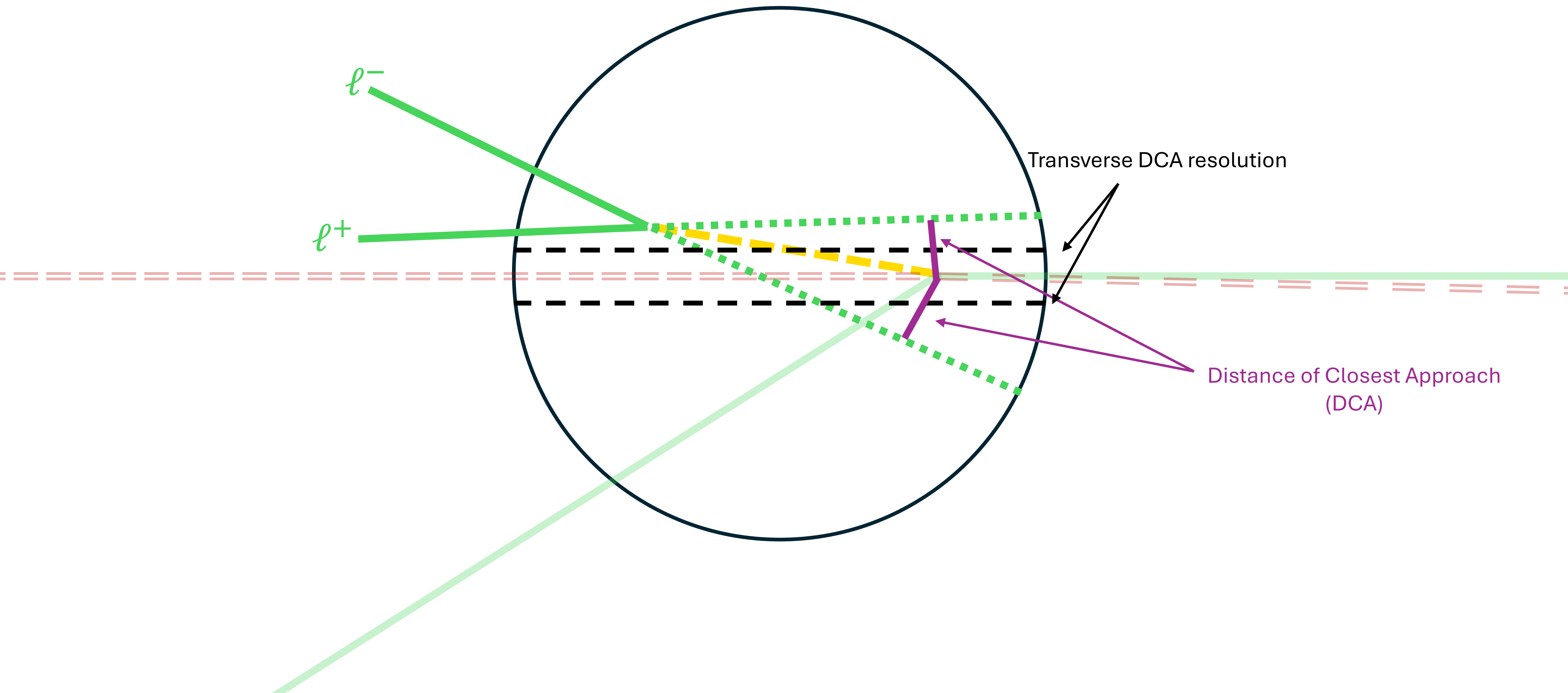
Hidden Gauge Bosons: Transverse DCA



Hidden Gauge Bosons: Transverse DCA



Hidden Gauge Bosons: Transverse DCA



Hidden Gauge Bosons: Transverse DCA