Beyond Standard Model from Flavor Physics.

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OUTLINE

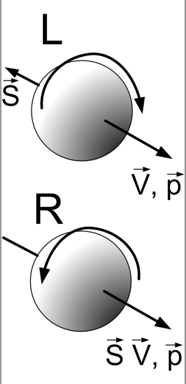
- Basic idea of talk: what is the SM, why BSM, how to look for BSM physics in experiments like Belle 2.
- Start with :What is a fundamental particle?
- How do fundamental particles interact- Standard Model.
- Why Beyond Standard Model (BSM) is needed.
- Some BSM models and their signatures.

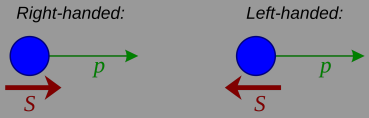
Particle Types

- Particles come in two types: Bosons and Fermions
- A collection of bosons and fermions will fill up a given set of energy levels differently
- Bosons satisfy Bose-Einstein Statistics. Fermions satisfy the Fermi-Dirac Statistics.
- Bosons have integral spin (measured in terms of $\hbar$) and are responsible for forces between particles
- Bosons: Spin 0 (Higgs), Spin 1 (Photon), Spin 2 (Graviton)
- Fermions have half integral spin and are the matter particles: E.g.: Spin 1/2 (electron), Spin 1/2 (neutrino- ν)

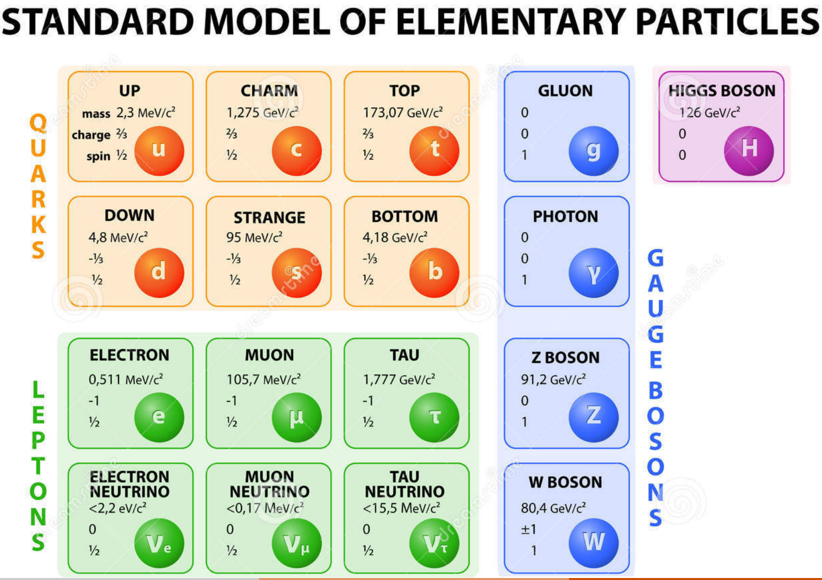
Fundamental matter particle

- Generally, a fundamental particle is characterized by its spin and charge.
- Spin: Intrinsic angular momentum of a particle- intrinsic property just like mass and charge.





A purely left-handed(LH) or a right- handed (RH) particle is massless.



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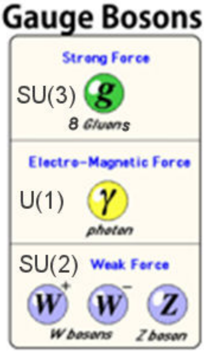
Forces

Standard Model

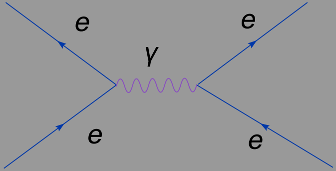
- SM has a gauge sector: Coupling of the matter field with the gauge bosons: 3 parameters, g_W, g_S and g_{EM}.



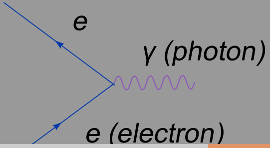
Language of PP- Feynman Diagrams

- Particles and their interactions are described by Feynman Diagrams

Feynman Diagrams



Coulomb Force

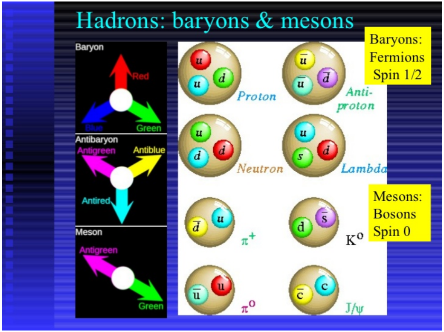


Electron in EM Field

Strong Force

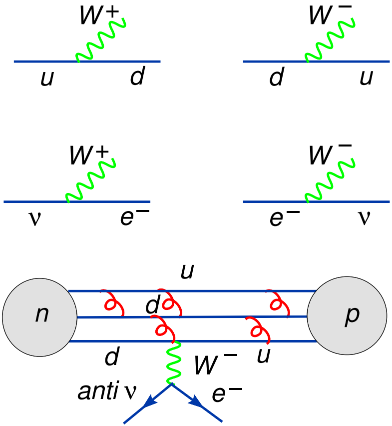
QCD

QCD binds quarks in mesons, baryons, tetraquarks, pentaquarks ....



Weak Force - Charged

Weak Force: Changes Flavor e.g. Beta Decay



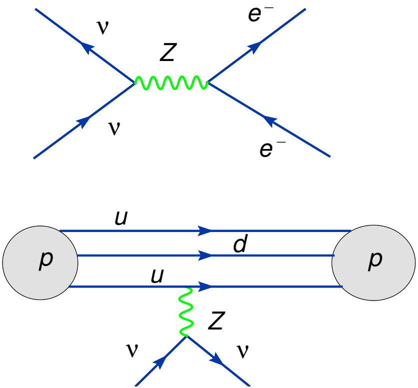
$n \rightarrow p e^- \bar{\nu}$: beta decay

Weak force - Neutral

Neutral Current Interactions

Neutral Current Interaction are mediated through the exchange of Z^0.

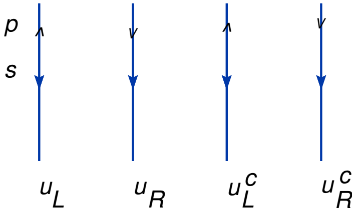
e – ν and p – ν scattering



Weak Interactions are Different

• Any quark (u and d) and lepton (e and ν_e) can split up into a left handed (LH) and a right handed (RH) piece.

$$u \equiv u_L + u_R$$



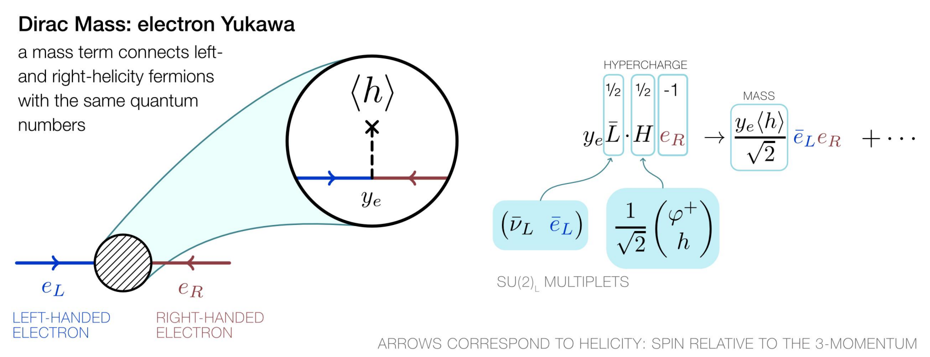
• $W^{\pm}$ couple only to LH particles and RH antiparticles.

Basic Forces and the SM

- Electromagnetic force couple equally to the LH and RH particles if they are electrically charged.
- Strong Force couple equally to the LH and RH particles if they are color charged.
- Weak Interactions only couple to LH particles.
- Neutrino only has weak interactions. In the SM there is only a LH neutrino, ν_L, and no RH neutrino, ν_R, and neutrinos are massless.

Higgs Force- mass generation

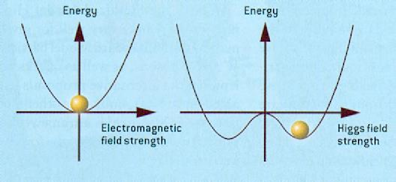
- A purely left-handed(LH) or a right- handed (RH) particle is massless.
- However certain particles can change from LH to RH via interacting with a Higgs boson. In that case the particle is sum of the LH and RH particles: $e = e_L + e_R$.
- Such particles can become massive.



The Higgs Mechanism- Flavor sector

We are aware of phase change- for example steam to water to ice.

When the universe was very hot at a temperature equivalent to 100 GeV (300 K $\equiv 10^{-2}$ eV) there was a phase change when the Higgs, W, Z, the quarks and leptons went from being massless to having masses.



$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda_H}{4}\phi^4$$

$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda_H}{4}\phi^4$$

$$m_{q.l} \sim Y_{q,l}\langle 0|\phi|0\rangle$$

$$m_{W,Z} \sim g\langle 0|\phi|0\rangle$$

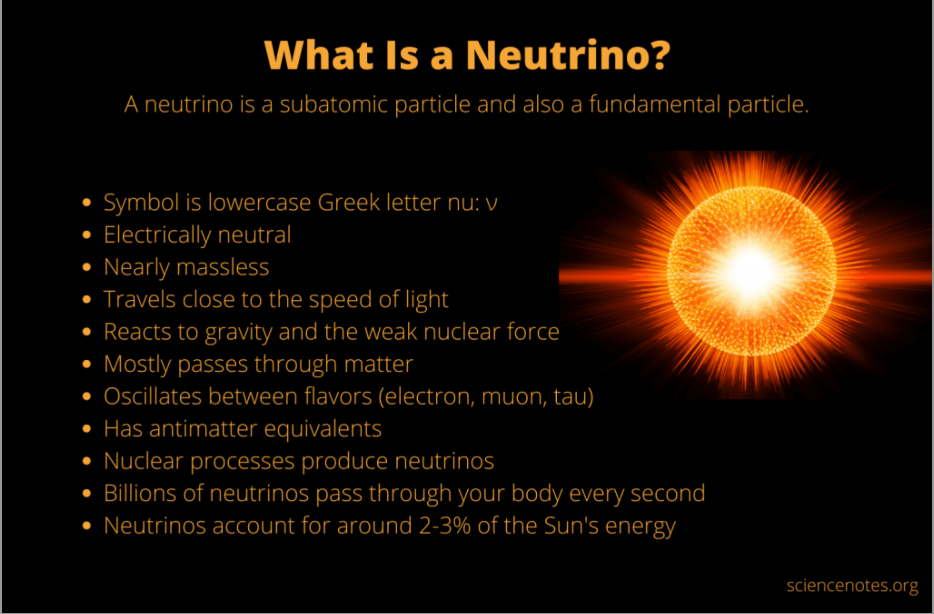
Evidence of BSM physics

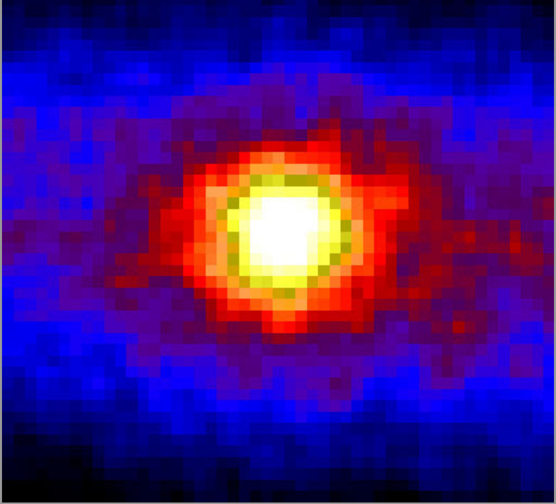
Clearly Established

- Neutrino Masses.
- Dark matter.

Several Hints

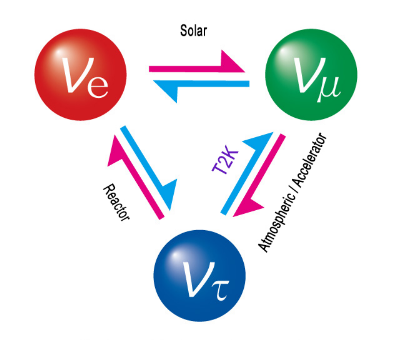
- Anomalies in semileptonic B decays.
- Neutrino anomalies.
- Hints of new scalar bosons.


What Is a Neutrino?
A neutrino is a subatomic particle and also a fundamental particle.
Symbol is lowercase Greek letter nu: ν
Electrically neutral
Nearly massless
Travels close to the speed of light
Reacts to gravity and the weak nuclear force
Mostly passes through matter
Oscillates between flavors (electron, muon, tau)
Has antimatter equivalents
Nuclear processes produce neutrinos
Billions of neutrinos pass through your body every second
Neutrinos account for around 2-3% of the Sun's energy
sciencenotes.org



The image has been obtained with a 503 days exposure, by registering neutrinos emitted from the solar core and detected in a 50 000-ton water pool located 1 km underground. At night, neutrinos were transparently traversing the whole earth before being registered in this image

Neutrinos Oscillate



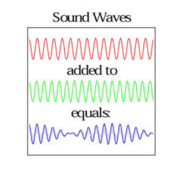
Neutrino oscillation between three generations

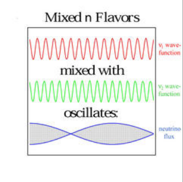
A particle has wave like behavior with $E = \sqrt{p^2c^2 + m^2c^4} = \hbar\omega$ and $p = \frac{h}{\lambda}$.

$$
\begin{aligned}
|\nu_e\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \\
|\nu_\mu\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle
\end{aligned}
$$

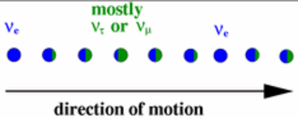
$|\nu_1\rangle$ and $|\nu_2\rangle$ have different masses (or frequencies)

Neutrino Oscillation Model

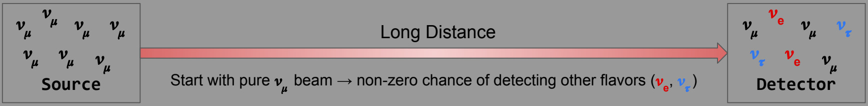




$$
\begin{aligned}
|\nu_e\rangle &= \cos\theta\,|\nu_1\rangle\, e^{-i\omega_1 t} + \sin\theta\,|\nu_2\rangle\, e^{-i\omega_2 t} \\
|\nu_\mu\rangle &= -\sin\theta\,|\nu_1\rangle\, e^{-i\omega_1 t} + \cos\theta\,|\nu_2\rangle\, e^{-i\omega_2 t}
\end{aligned}
$$



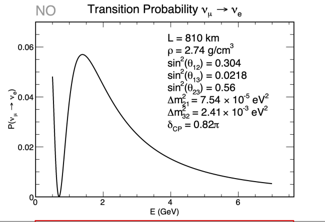
Neutrino Oscillations



flavor basis **mass basis**

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} \doteq \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$P_{\nu_\mu \to \nu_e} \approx 4\cos^2(\theta_{13})\sin^2(\theta_{13})\sin^2(\theta_{23})\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$



$\nu_\mu \longrightarrow \nu_e$ on NOvA

3

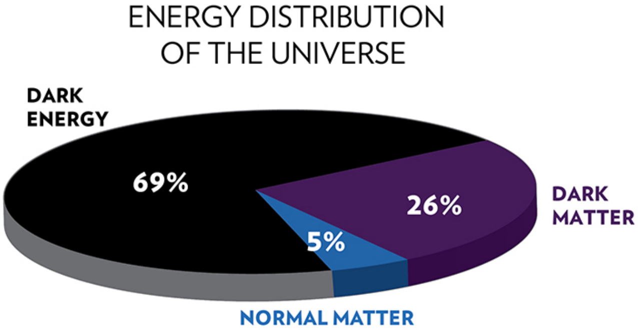
$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle\, e^{-i\omega_1 t} + \sin\theta\,|\nu_2\rangle\, e^{-i\omega_2 t}$$
$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle\, e^{-i\omega_1 t} + \cos\theta\,|\nu_2\rangle\, e^{-i\omega_2 t}$$

Sterile Neutrino

- Neutrino Oscillation indicate that neutrinos have mass.
- In general this means that there must be something more than just a LH, ν_L, which is massless.

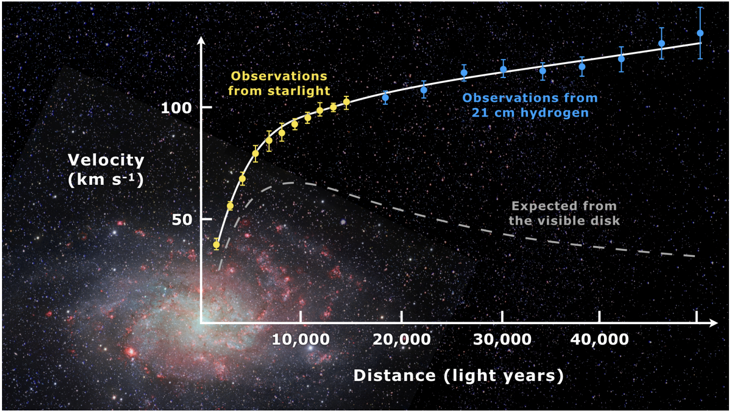
  A possibility is there are new RH ν_R states. This RH neutrino, ν_R, is called the sterile neutrino.
- Weak Interactions only couple to LH neutrinos. Hence the sterile neutrino has no known interactions except for gravitational interaction.
- How can we detect the sterile neutrino. Can it be dark matter?

Energy Distribution of the Universe



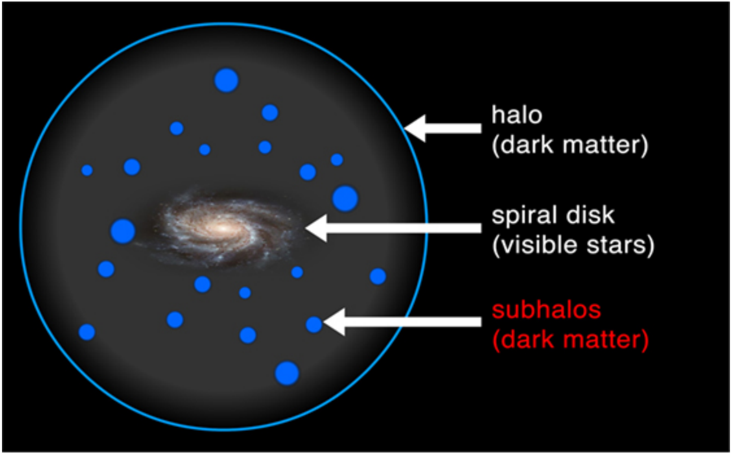
- Normal Matter: Radiation + Matter.
- Dark Energy is the vacuum energy- Cosmological constant.
- DM is like very weakly interacting non- relativistic (moving slowly)

Evidence for Dark Matter



$$v^2 = \frac{GM}{r}$$

Evidence for Dark Matter



$$v^2 \neq \frac{GM}{r}$$

Evidence for Dark Matter- Bullet Cluster

DM is very weakly interaction and can go through each other.
https://www.youtube.com/watch?v=eC5LwjsgI4I

SM problems - Many

- To many particles: For first generation: $(u_L, d_L) \times 3 + (u_R, d_R) \times 3 + (\nu_L, e_L) + e_R = 15$ states. For 3 generations 45 particles. Cannot be a fundamental theory!

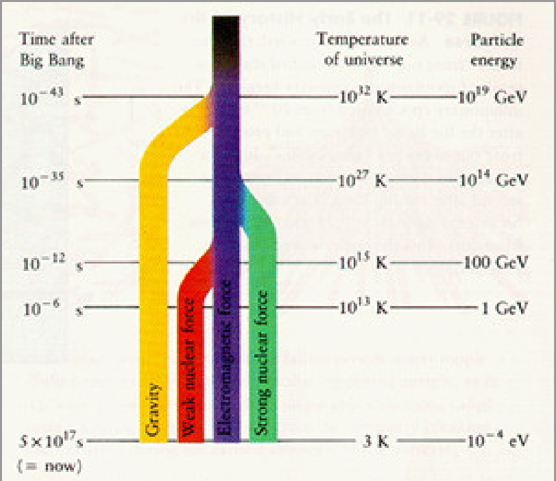
- There is no theory to explain the masses of the fermions and the mixing.

- There is no dark matter candidate.

- Mechanism for neutrino mass.

- Does not include gravity.

Possible BSM: Grand Unification

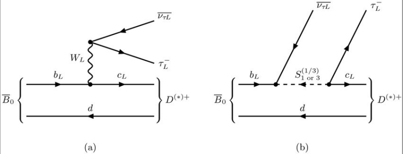


If forces are unified then new particles should exist such as Leptoquarks and diquarks

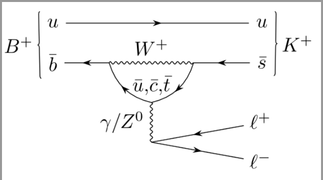
LQ signatures

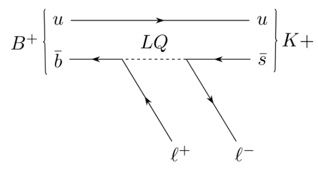
LQ's can change the rates and distributions of many processes. eg: B anomalies

In charged current processes such as $B \to D^* \tau \nu_\tau$



In neutral current processes such as $B \to K \ell^+ \ell^-$





Sterile Neutrino Detection

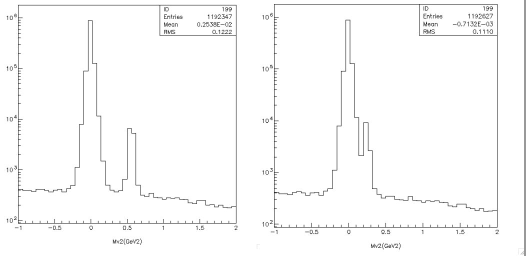
- In general sterile neutrino is a neutrino that does not have any interactions of the the standard model.
- The sterile neutrino can mix with the ordinary neutrino and so $\nu \leftrightarrow \nu_S$.
- Can be detected in beta decay type reactions: $n \to p + e^- + \bar{\nu}_s$ where ν_s has a mass.
- Sterile neutrino can have interact through new forces with the usual SM particles.

Sterile Neutrino Signatures

For semileptonic $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$, N can be produced.

$$B \to D^{(*)}\ell\nu_\ell \to D^{(*)}\ell(\nu_1 \cos\theta + N \sin\theta)$$

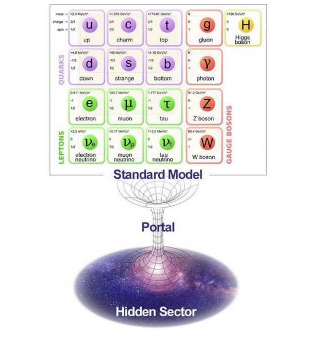
Missing mass : $p_M^2 = (p_B - p_{D^{(*)}} - p_\ell)^2$

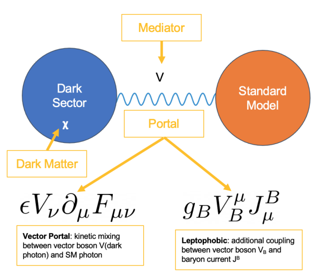


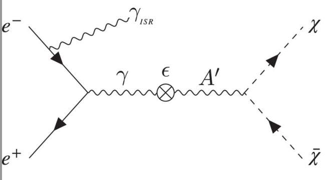
Mhv=0.75 GeV
5% SM d*lv
Phase space

Mhv=0.50 GeV
5% d*lv
Phase space

Dark Matter Signature



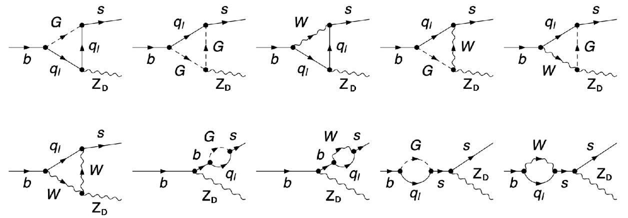




$$e^+ + e^- \to \gamma + \text{inv}$$

Dark Matter Signature

Decays to invisible states. Penguin Flavor Changing Neutral Current (FCNC)



Look for rare decays $B \to K + \mathrm{inv}$, $D \to \pi + \mathrm{inv}$, $K \to \pi + \mathrm{inv}$

Eg: $b \to sZ_D \to s + \chi\bar{\chi}$

Evidence for enhancement in $B \to K + \mathrm{inv}$ by Belle 2.

Summary

- SM is a very successful theory.
- Clear evidence and various hints of BSM physics.
- Many ways to probe various BSM models in Belle 2 and Flavor experiments.
- Exciting results may be revealed in the near future.