

Acknowledgements:
Numerous physics colleagues who have educated me over the years

Parity Violation at Jefferson Lab and Beyond



Electroweak Interactions ***Lecture I***

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CNUGS26, Jefferson Lab
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Introductory Comments

- ❖ **Student background and preparation varies..**
 - ❖ **Some of you perhaps already have been introduced to nuclear and particle physics at an advanced level but not all of you...**
 - ❖ **You are getting an excellent set of pedagogical lectures on QCD topics**
- ❖ **As you complete doctoral research and move on, you will learn to cope with imperfect knowledge on things unrelated to your own projects**
- ❖ **Qualitative understanding (at a minimum) of the breadth of nuclear and particle physics is critical to help select interesting problems to work on**
- ❖ **I am an experimentalist! I will focus on measurements, but theory is critical!**
- ❖ **I will concentrate on the “big picture” in the BSM search subfield**
 - ❖ **Necessary “general knowledge” when focused on other subfields (e.g. QCD)**

Rationale for Lecture Flow

- ❖ Friday's lectures are primarily focused on how Jefferson Lab is uniquely capable of parity-violating electron scattering (PVES) measurements.
- ❖ In order to put the PVES physics potential in context, it is important to know enough about the foundations of electroweak unification in the Standard Model in general and weak neutral current interactions in particular.
- ❖ In addition, to understand PVES potential for Beyond the Standard Model (BSM) searches, one must have general knowledge about worldwide BSM efforts, especially as it relates to violations of fundamental symmetries.

Outline of Lectures

- 1) Introduction to electroweak (EW) interactions, precision EW physics, EW radiative corrections, BSM Motivation
- 2) Introduction to discrete symmetries, historical discoveries, modern searches for violation of “accidental” symmetries
- 3) PVES for BSM searches, E158, PVDIS, Qweak, MOLLER, P2, SoLID
- 4) PVES for nuclear/nucleon structure studies: Strange quarks, Neutron skins, neutral current structure functions at the EIC

Outline of Lecture 1

- **Introduction to Symmetries (review)**
- **Electroweak Interactions in the Standard Model (review)**
- **Electroweak Radiative Corrections (start with QED review)**
- **Open Questions: Beyond Standard Model Physics**

Introduction to Symmetries

Symmetries and Conservation Laws

Noether's Theorem:

If the Euler-Lagrange equation is invariant under any coordinate transformation, $\exists$ an integral of motion

Symmetry		conservation law	
translation		momentum	$\exists$
time		energy	
rotation		angular momentum	

Symmetries and Conservation Laws

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translation	$\longleftrightarrow$	momentum	$\exists$
time	$\longleftrightarrow$	energy	
rotation	$\longleftrightarrow$	angular momentum	

Not just space-time symmetries: Invariance of Lagrangian/Hamiltonian

e.g. Charge
Conservation

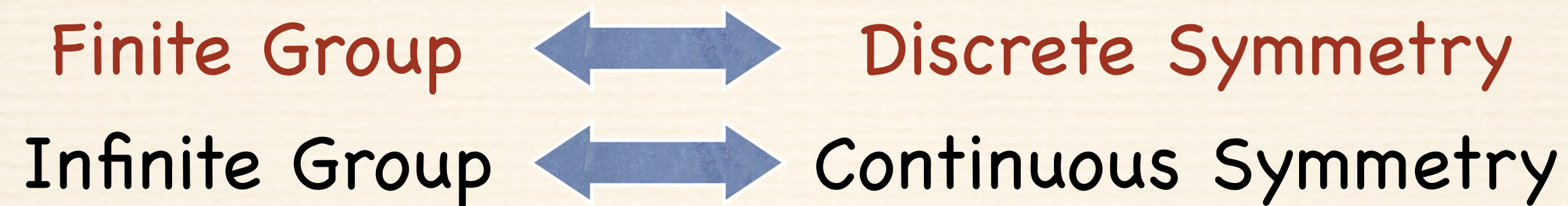
$$[Q, H] = 0 \rightarrow \frac{d\langle Q \rangle}{dt} = 0 \quad Q|\Psi\rangle = q|\Psi\rangle$$

Conserved Quantities/Quantum Numbers

Symmetries and Groups

Symmetry operations:

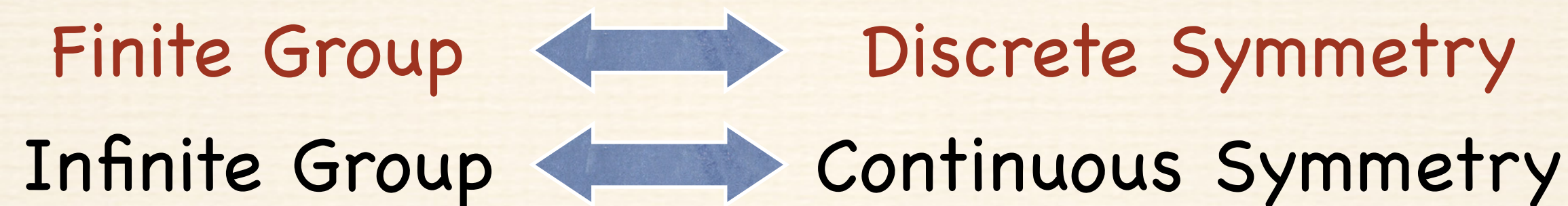
Group of all operations: display closure & Associativity and have identity and inverse



Symmetries and Groups

Symmetry operations:

Group of all operations: display closure & Associativity and have identity and inverse



In Physics, group operations can be represented by matrices

$SO(n)$: n-D rotations $SO(3) \longleftrightarrow SU(2)$

Invariance under $SU(2)$: Angular Momentum Conservation

Continuous Symmetries

Dirac free particle
Lagrangian

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

U(1) Invariance: conserved current

Local U(1) Invariance: $A_\mu J^\mu$ Electromagnetic Interactions

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Rotation in $\begin{pmatrix} p \\ n \end{pmatrix}$
"Isospin Space" $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$

nucleon-nucleon interaction Hamiltonian invariant
under SU(2) transformations in Isospin Space

the "massless" left-handed electron and electron-
neutrino are part of a similar "weak isospin" doublet

SU(2) invariance yields 3
independent conserved currents

(there are 3 independent 2x2
Pauli spin matrices)

Symmetries of the EW Lagrangian

$SU(2)_L \times U(1)_Y$ 4 conserved currents
local gauge invariance yields 4 bosons: W^+ , W^- , W^0 , B^0

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After spontaneous symmetry breaking via Higgs Mechanism:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{EM}}$$

two weak charged currents

$W^\pm$

electromagnetic current

γ

weak neutral current

Z^0

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$SU(3)_c$ and gluons $\longleftrightarrow$ Quantum Chromodynamics

Exact symmetries of nature: fully manifest in the early universe

Unbroken exact symmetries: massless mediator & infinite range force

Electroweak Interactions in the Standard Model

Inspired by lectures by Chris Quigg (Fermilab)

Quantum Electrodynamics

Free fermions fields are solutions to the Dirac equation $(i\gamma_\mu \partial^\mu - m)\psi = 0$

Corresponding Lagrangian: $\mathcal{L} \sim \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi$

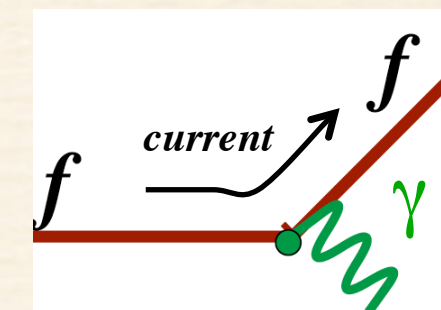
Local gauge invariance gives rise to interaction with photon field:

$$-J_\mu A^\mu$$

Conserved electromagnetic current

$$J^\mu = q\bar{\psi}\gamma^\mu\psi \quad \text{4-vector}$$

Feynman Rules: emission and absorption of virtual photons by fermion electromagnetic current



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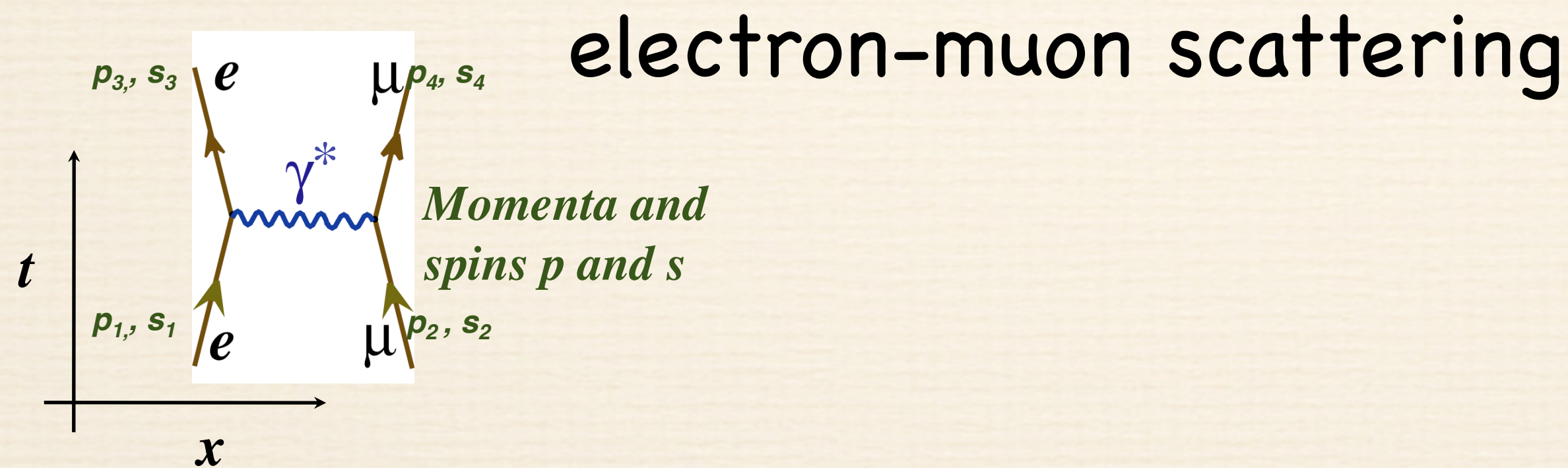
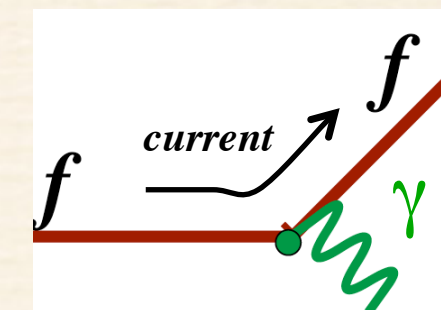
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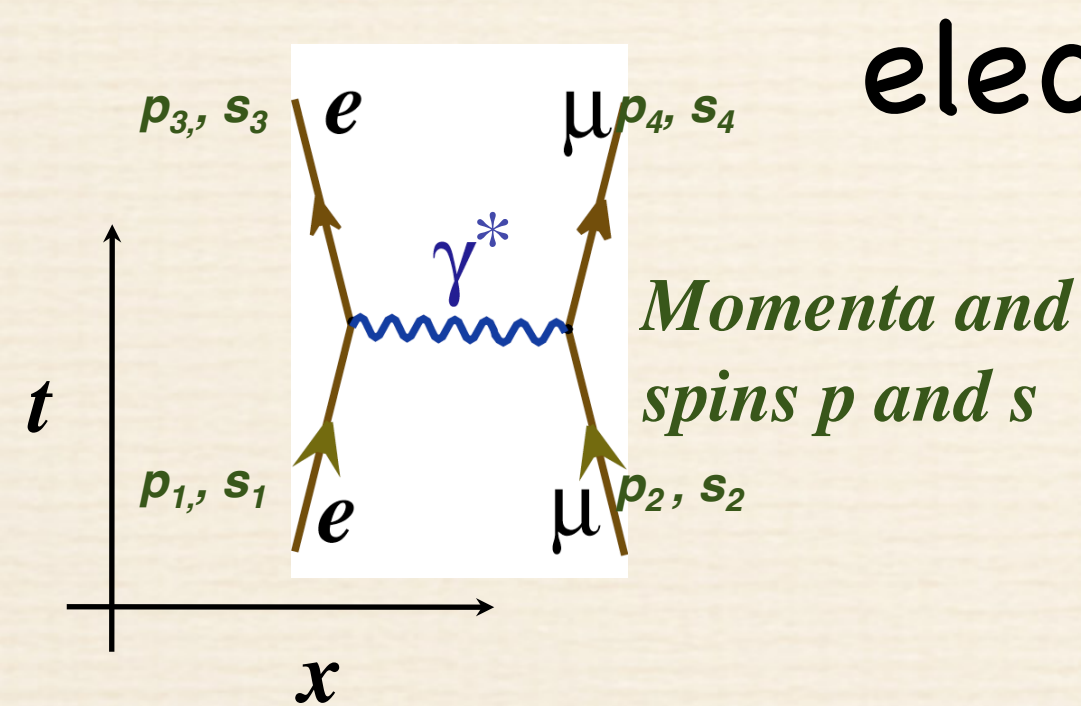
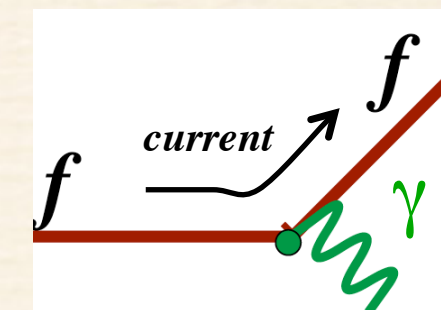
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electron-muon scattering

$$\mathcal{M} \sim -\frac{g_e^2}{(p_1 - p_3)^2} [\bar{u}^{s_3}(p_3)\gamma_\mu u^{s_1}(p_1)] [\bar{u}^{s_4}(p_4)\gamma^\mu u^{s_2}(p_2)]$$

Momenta and spins p and s

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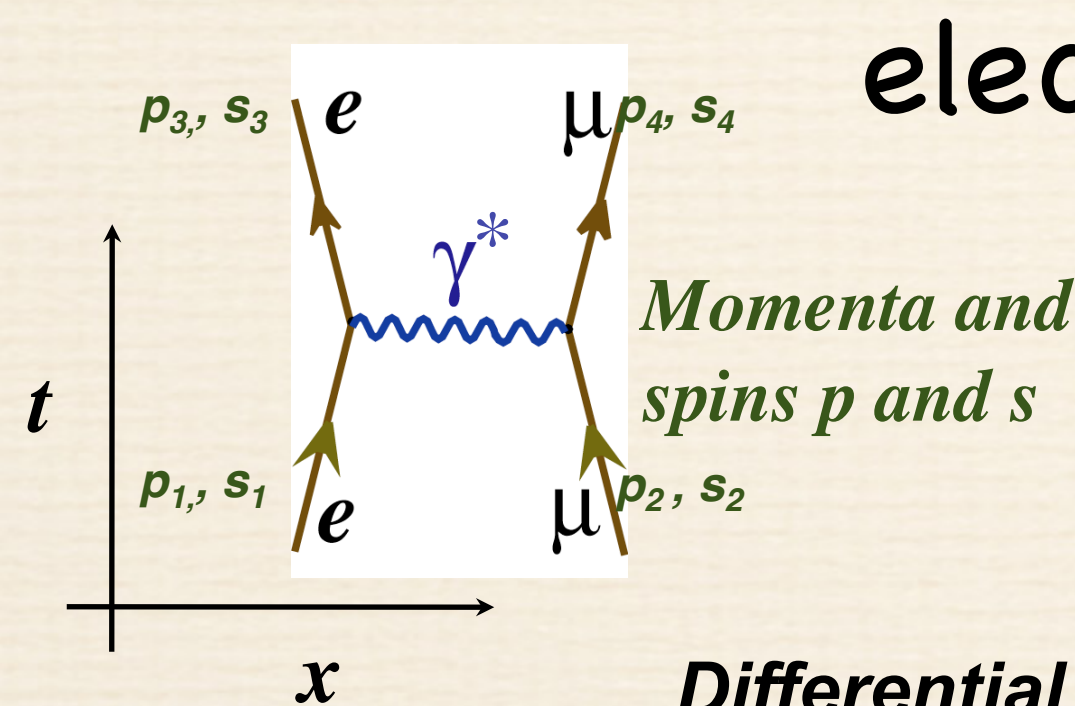
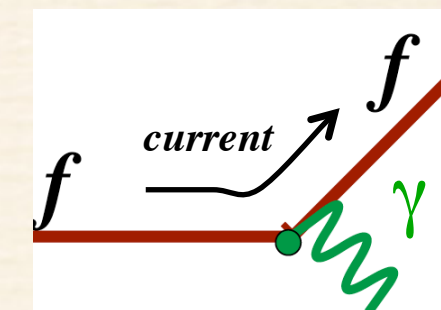
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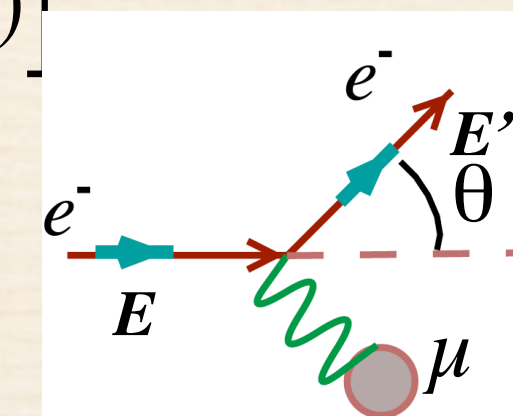


electron-muon scattering

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Differential Cross Section

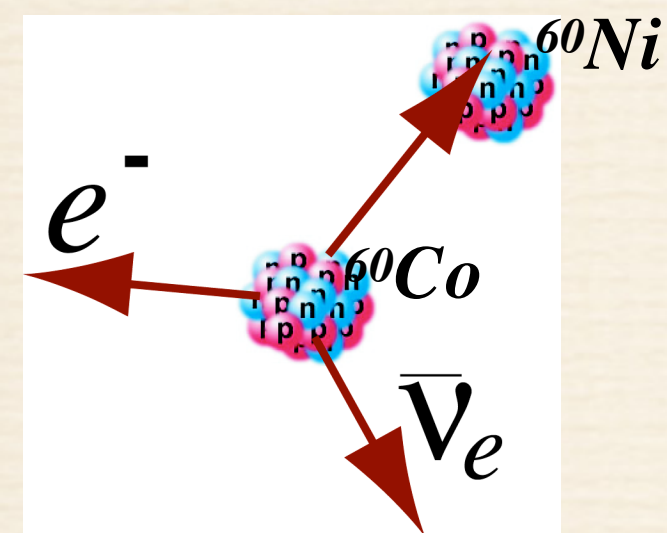
$$\frac{d\sigma}{d\Omega} = \frac{4\alpha^2 E'^2}{q^4} \cos^2 \frac{\theta}{2}$$



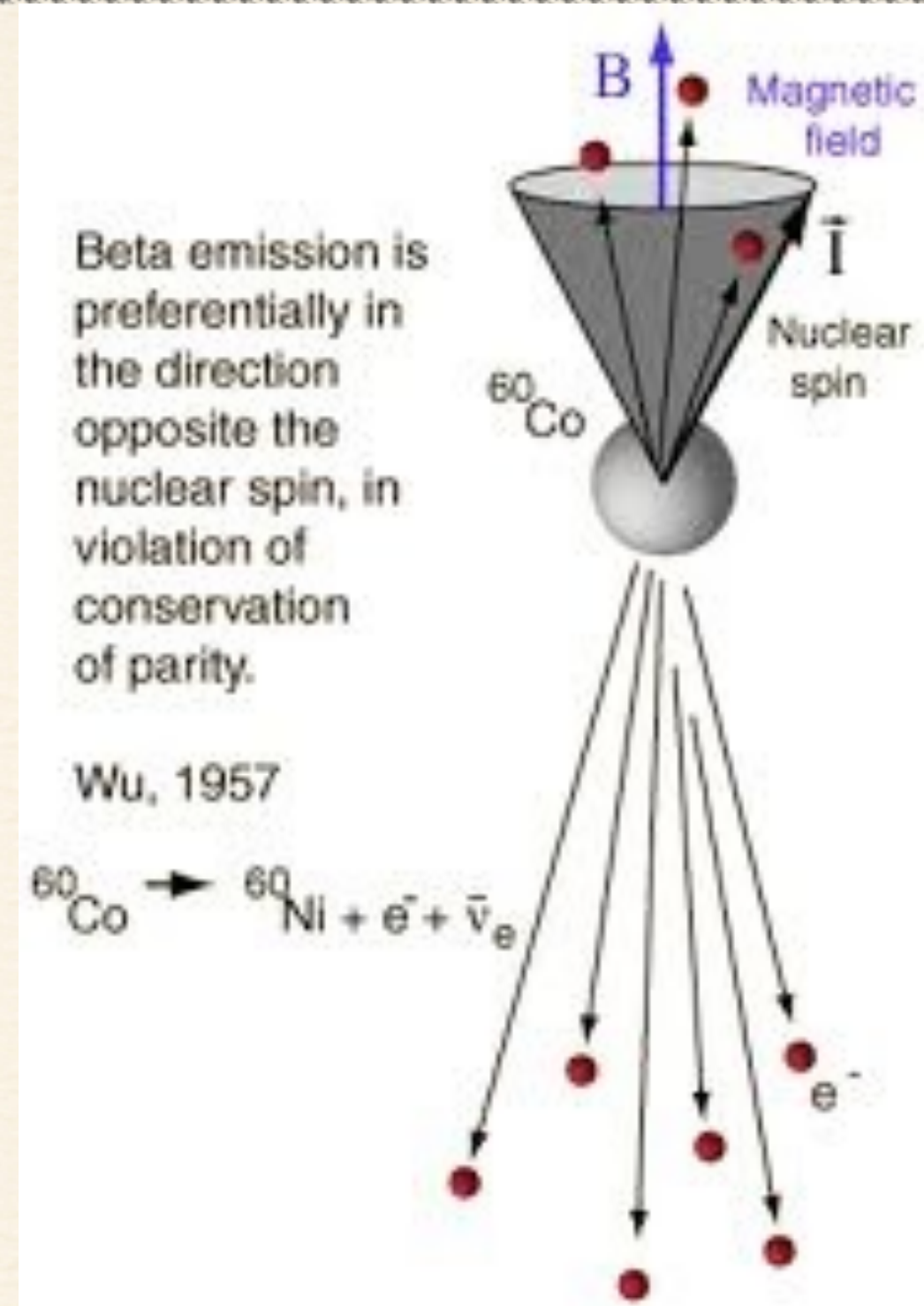
4-momentum transfer

$$q^2 = -4EE' \sin^2 \frac{\theta}{2}$$

Weak Interactions: Parity Violation



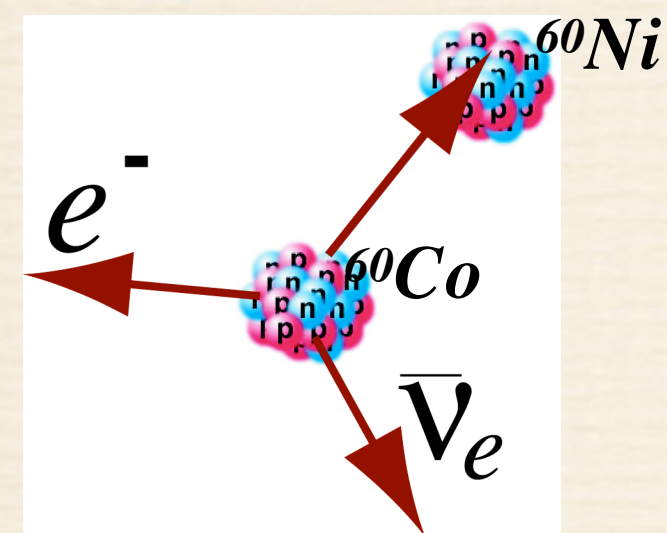
Weak decay of ^{60}Co Nucleus



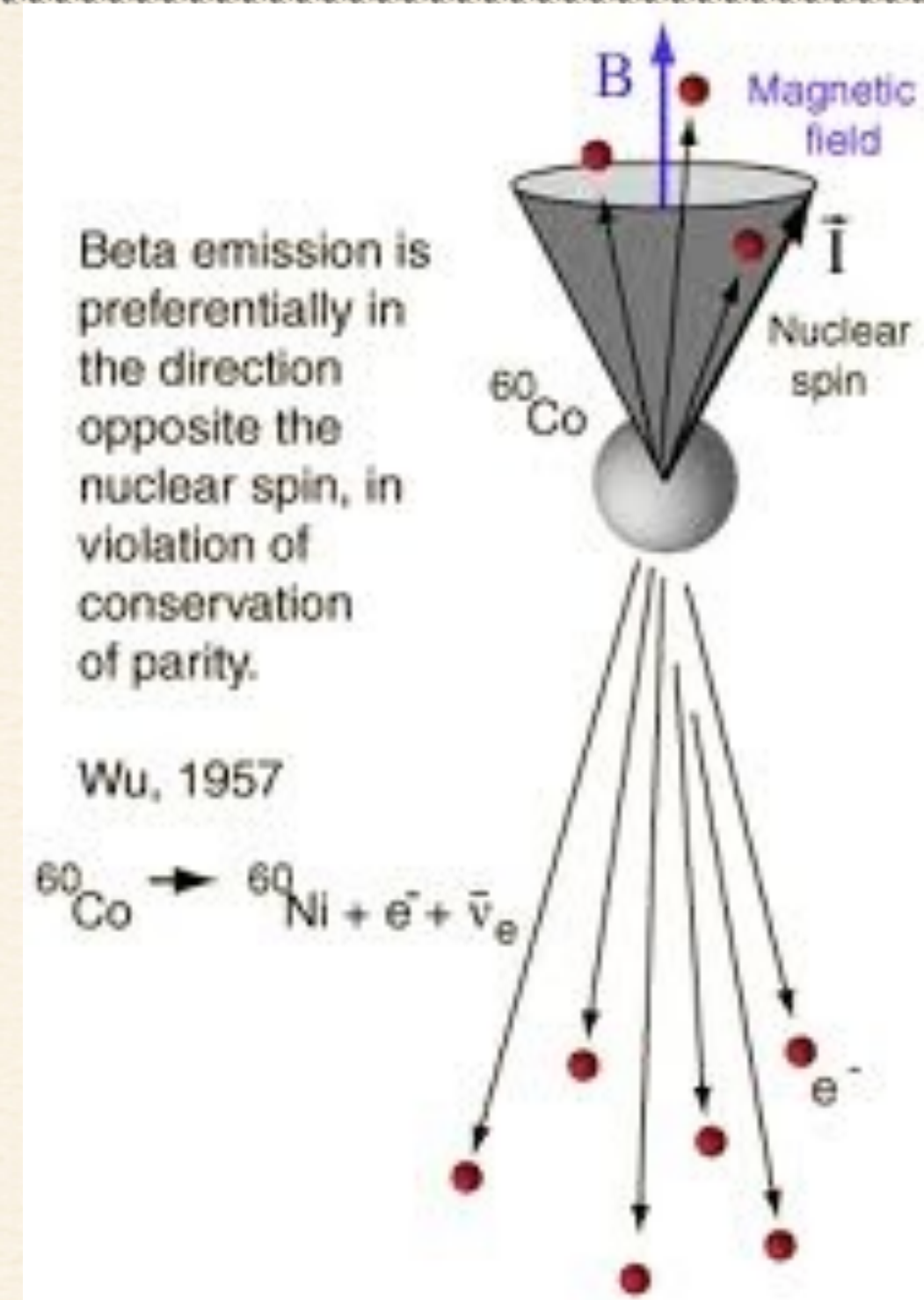
Weak Interactions: Parity Violation

*parity transformation
(reflection)*

$$x, y, z \rightarrow -x, -y, -z$$



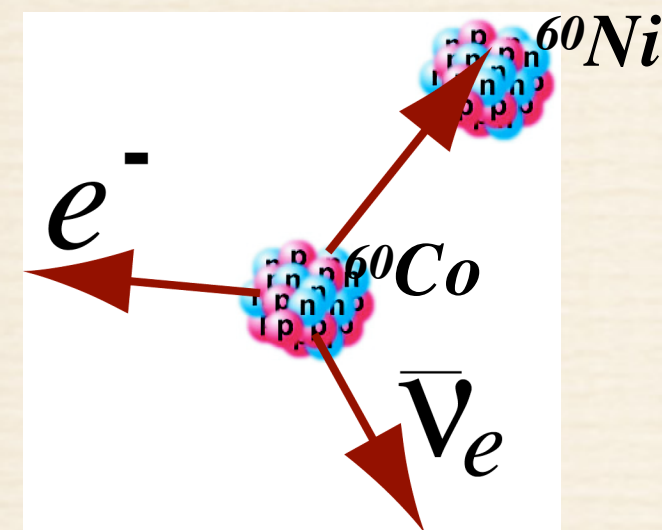
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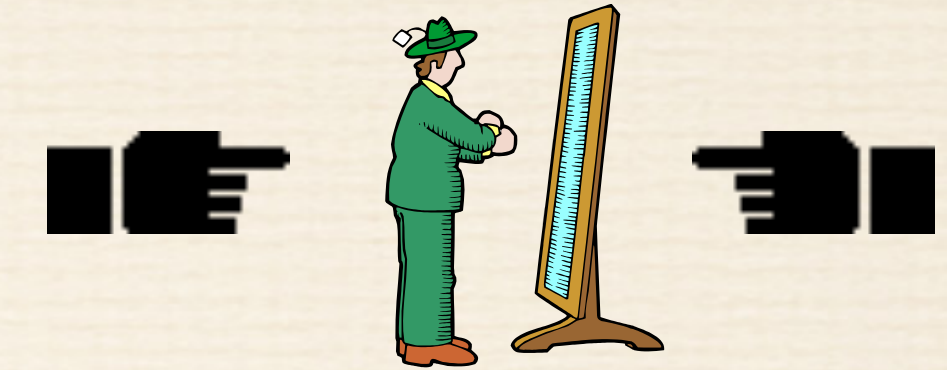
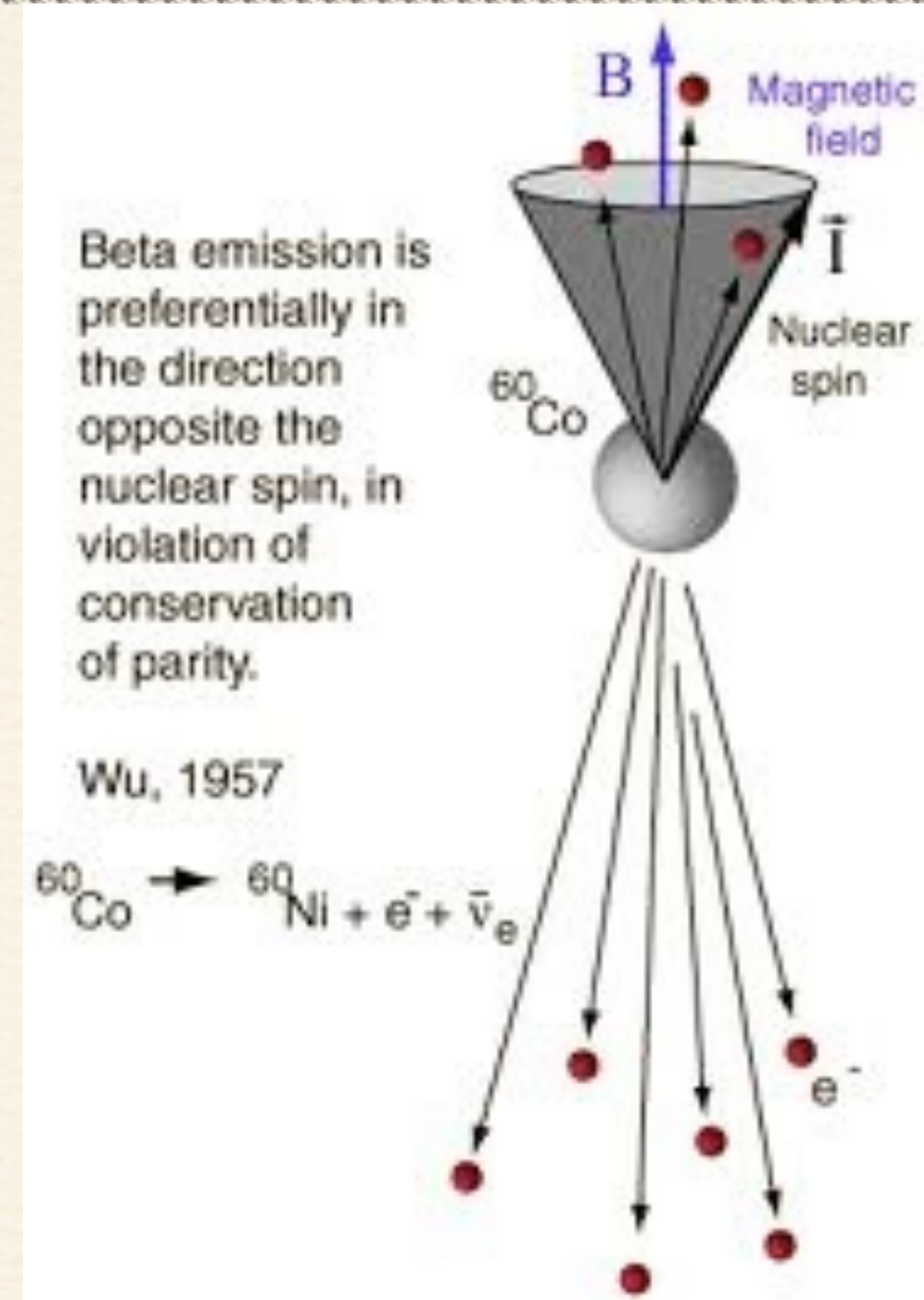
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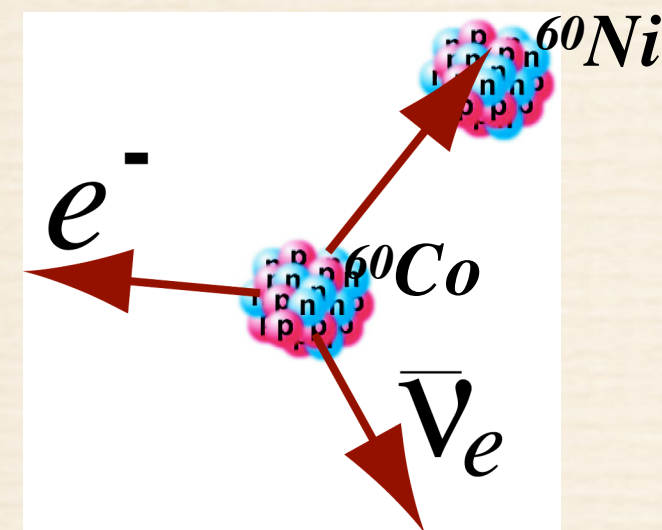


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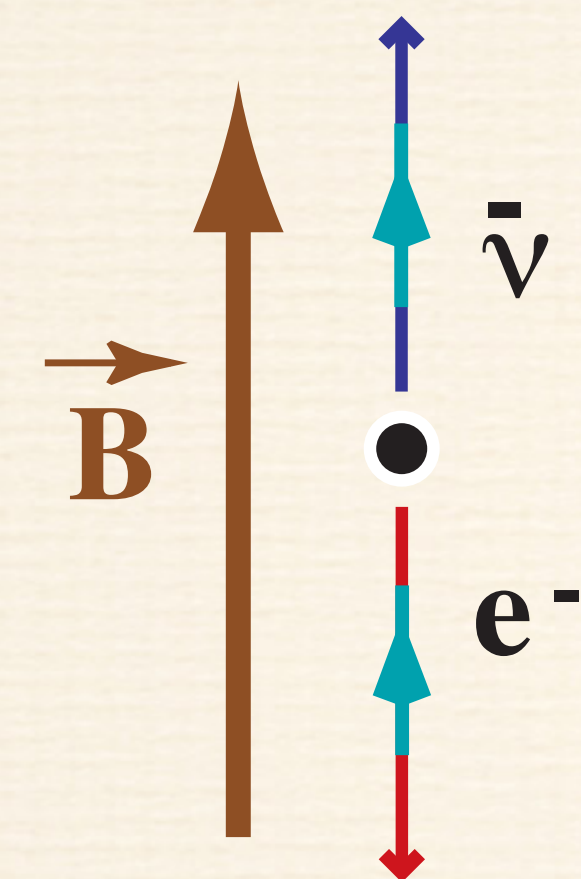
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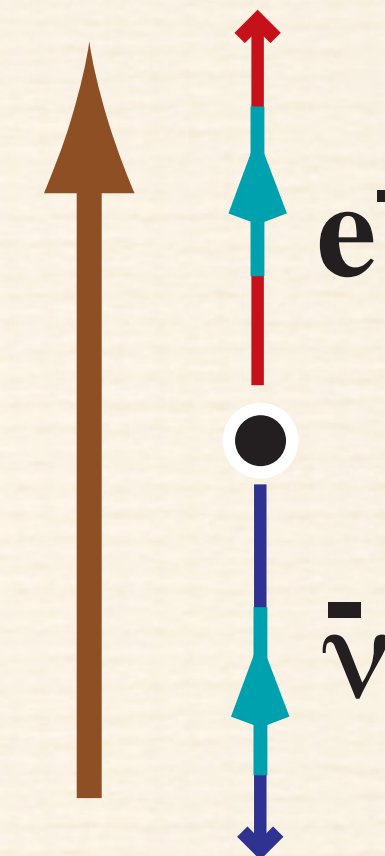


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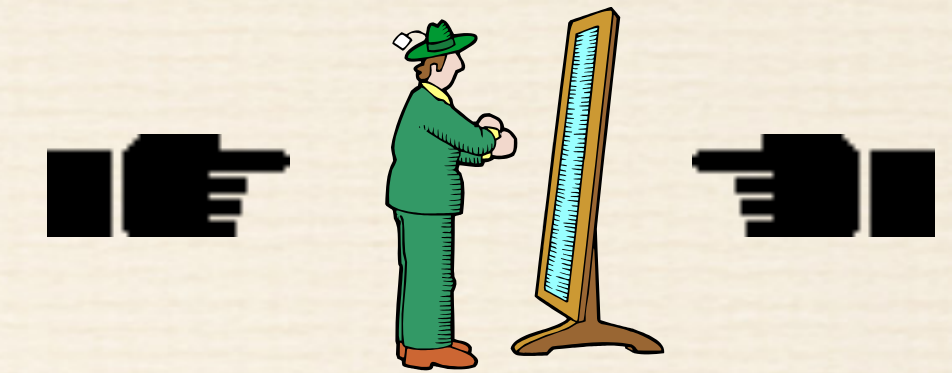


observed

reflection



not observed

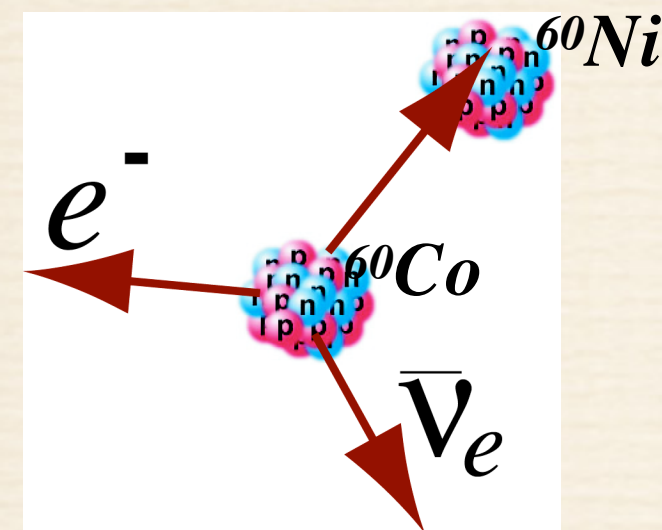


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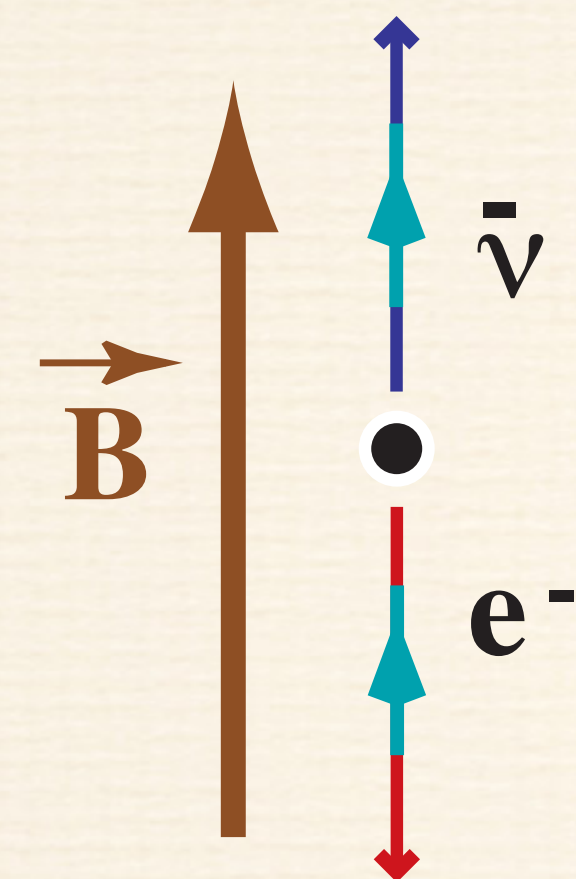
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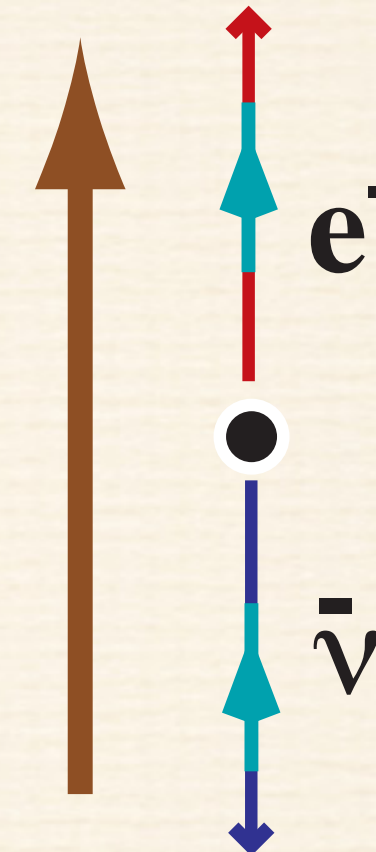


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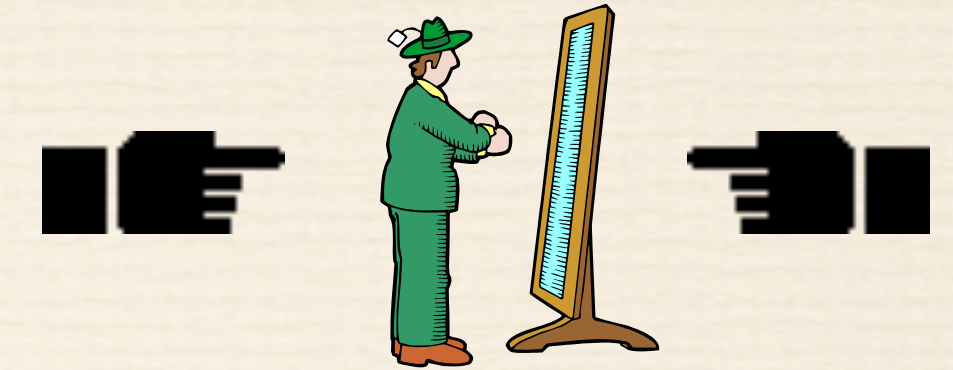


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*matter particles
have spin = 1/2*

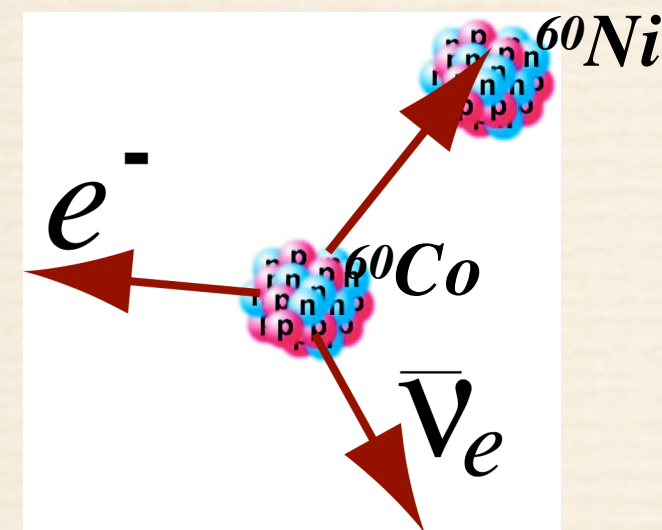
$$h = \frac{\vec{s} \cdot \vec{p}}{|\vec{s}| |\vec{p}|} = \pm 1$$

*handedness or
helicity/chirality*

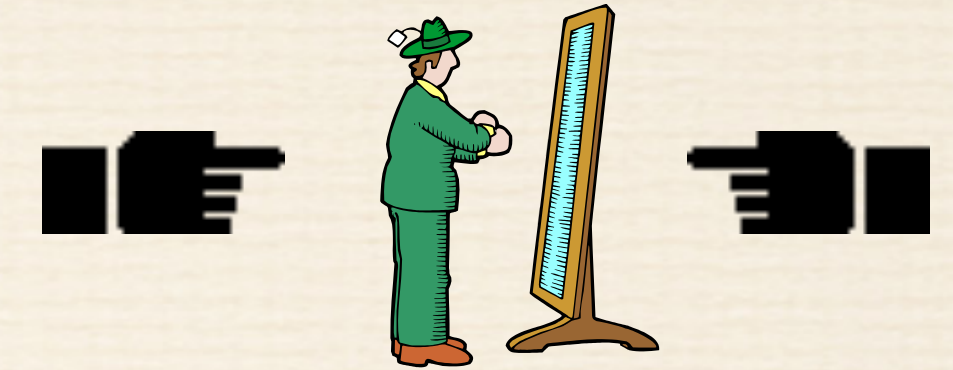
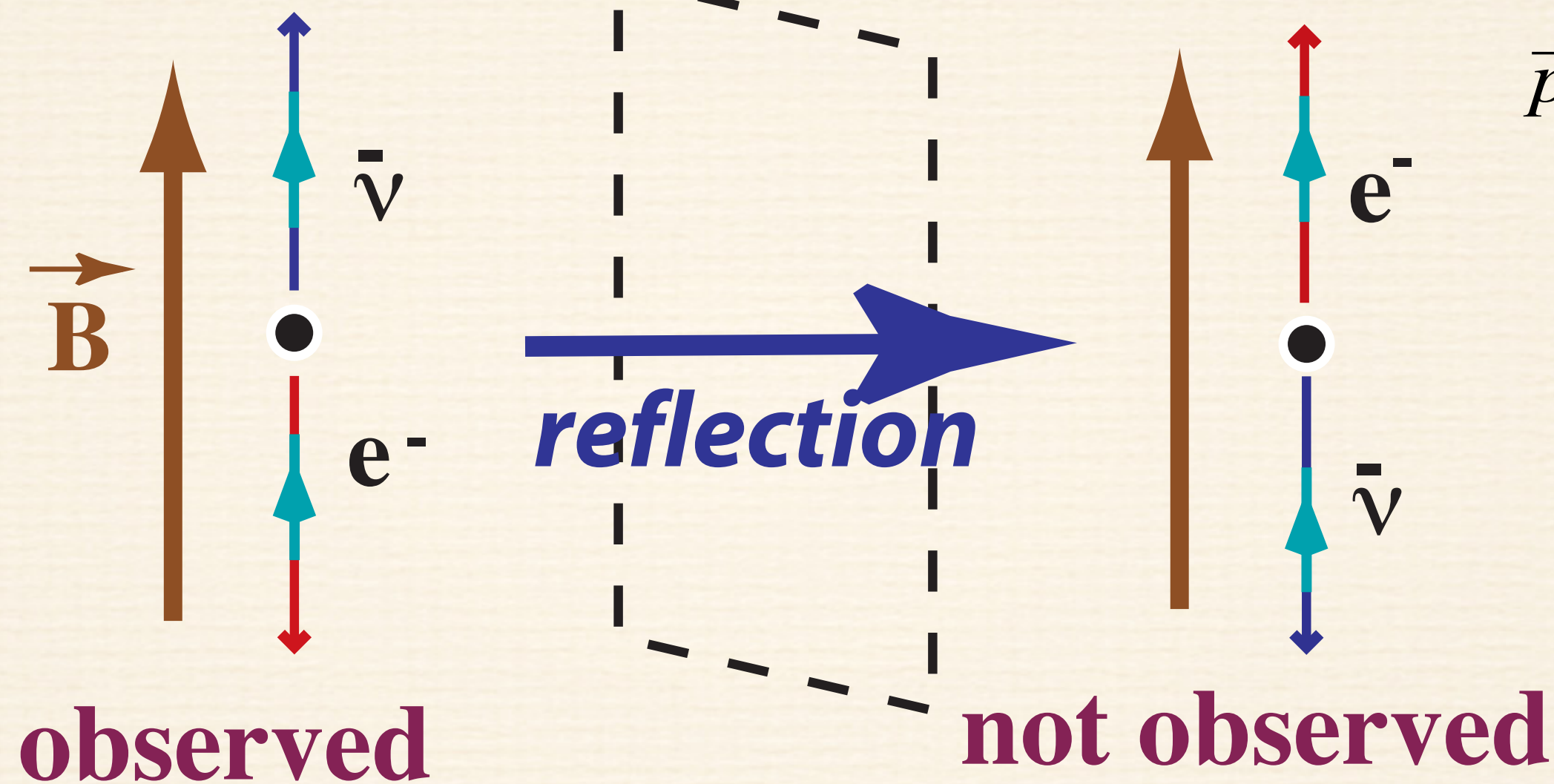
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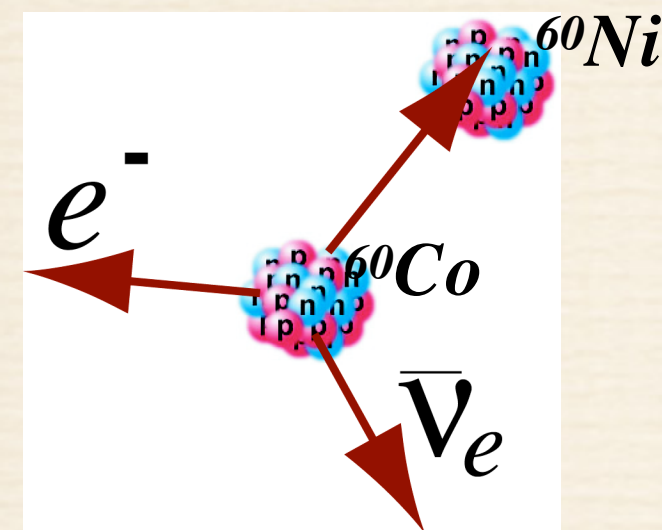
***Feynman and Gell-Mann proposed the
the “V-A” form of the weak interaction***

Vector and and Axial-Vector components to
the “current” that describes the interaction

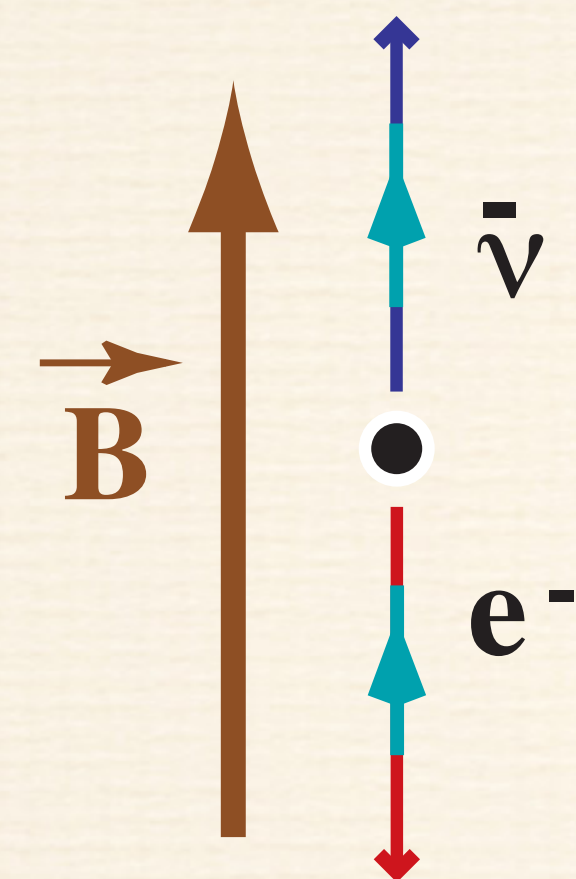
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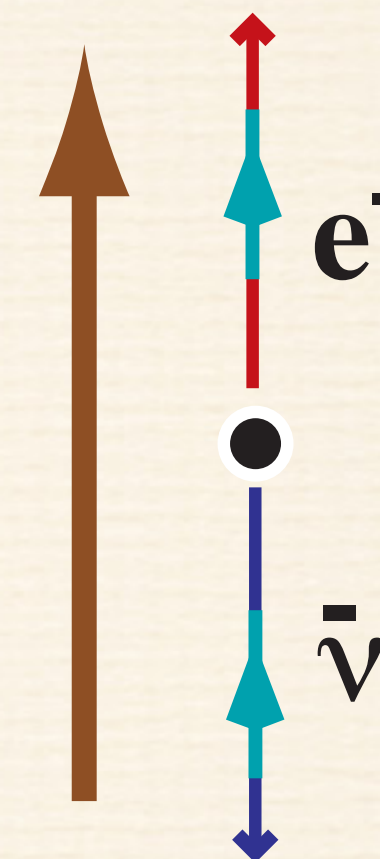


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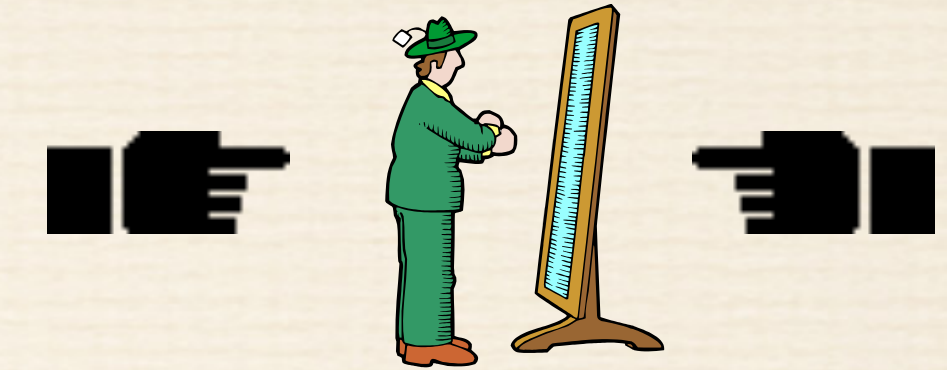


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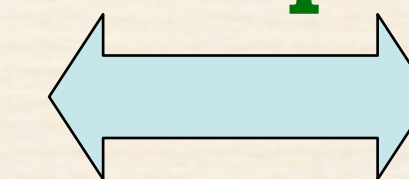
*handedness or
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***Feynman and Gell-Mann proposed the
the “V-A” form of the weak interaction***

Vector and and Axial-Vector components to
the “current” that describes the interaction

Mirror reflection flips sign of helicity

Left-handed



right-handed

**Only left-handed particles can mediate W bosons
(right-handed anti-particles)**

Weak Interactions

$$J^\mu \sim \bar{\psi} \gamma^\mu \psi \quad \text{vector}$$

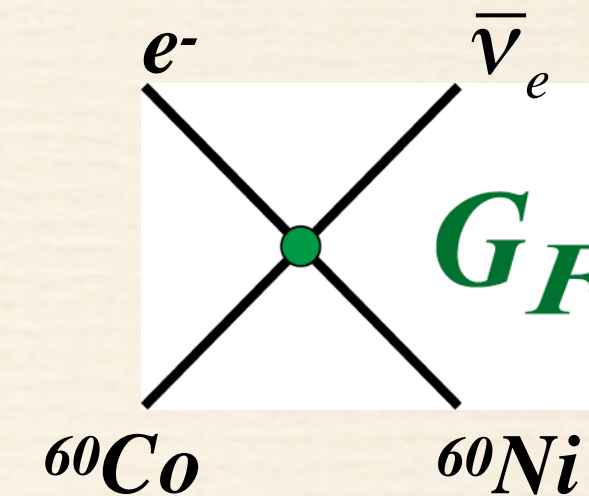
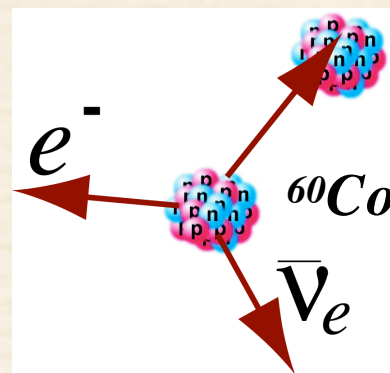
$$J^\mu \sim \bar{\psi} \gamma^\mu \gamma^5 \psi \quad \text{axial-vector}$$

V-A Interaction

V X A gives rise to pseudo-scalars

$$\mathcal{M} \sim -\frac{G_F}{\sqrt{2}} \left[\bar{u}(Co) \gamma_\mu (1 - \gamma^5) u(Ni) \right] \left[\bar{u}(e) \gamma^\mu (1 - \gamma^5) v(\bar{\nu}) \right]$$

4-Fermi Contact interaction with maximal parity violation

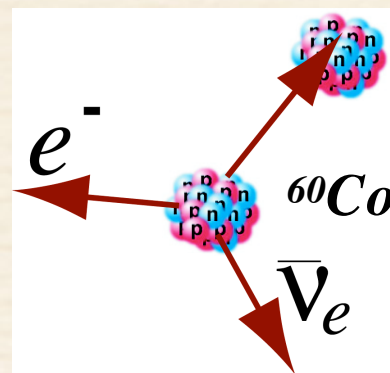


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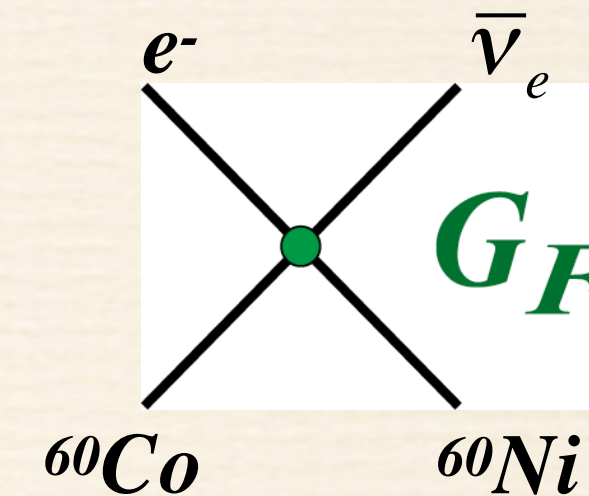
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4-Fermi Contact interaction with maximal parity violation



For massless particles:

$$\gamma^5 u = (\vec{p} \cdot \vec{\Sigma}) u$$

$$\vec{\Sigma} \equiv \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$$\vec{p} \cdot \vec{\Sigma} \equiv h$$

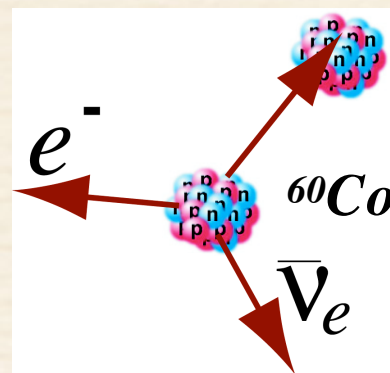
helicity operator

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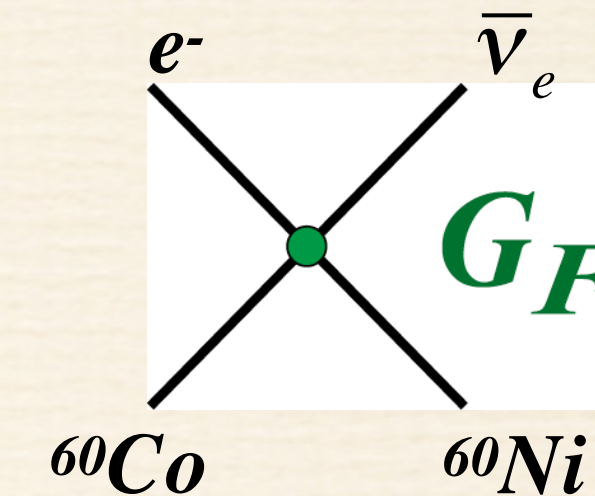
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helicity operator

$$\Sigma u = +u \quad \Rightarrow \quad \frac{(1 - \gamma^5)}{2} u = 0$$

$$\Sigma u = -u \quad \Rightarrow \quad \frac{(1 - \gamma^5)}{2} u = u$$

$$P_L \equiv \frac{(1 - \gamma^5)}{2} \quad P_R \equiv \frac{(1 + \gamma^5)}{2}$$

Left- and right-handed projections

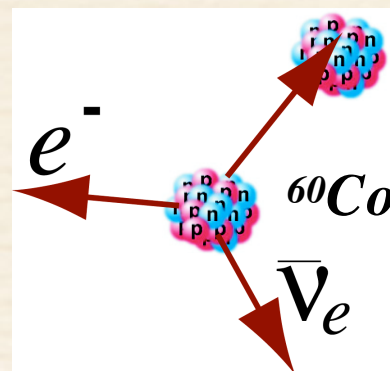
$$P_{L,R} u \equiv u_{L,R} \quad P_i P_j = \delta_{ij} P_j \quad \sum_i P_i = I$$

Weak Interactions

$$J^\mu \sim \bar{\psi} \gamma^\mu \psi \quad \text{vector}$$

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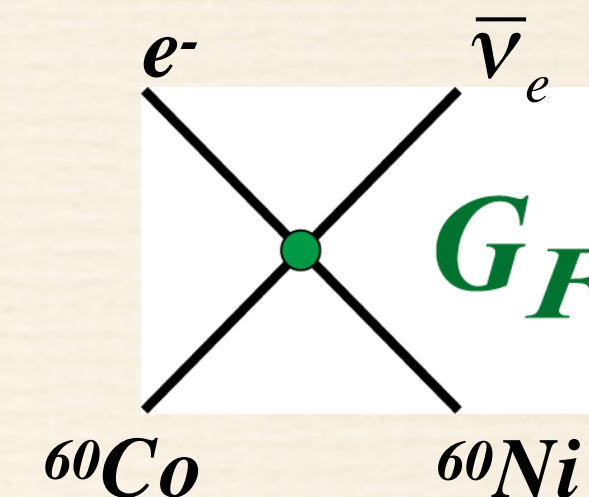
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V X A gives rise to pseudo-scalars

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4-Fermi Contact interaction with maximal parity violation



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helicity operator

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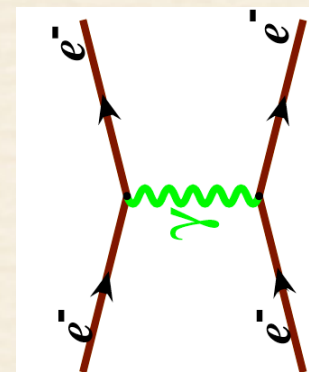
$$-\frac{G_F}{\sqrt{2}} \left[\bar{u}_L(Co) \gamma_\mu u_L(Ni) \right] \left[\bar{u}_L(e) \gamma^\mu v_R(\bar{\nu}) \right]$$

Only left-handed projections participate in charged weak interactions

Charge and Handedness

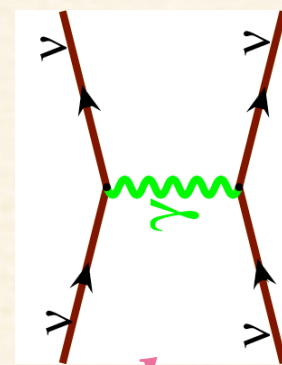
Electric charge determines strength of electric force

Electrons and protons have same charge magnitude: same strength



observed

Neutrinos are "charge neutral": do not feel the electric force

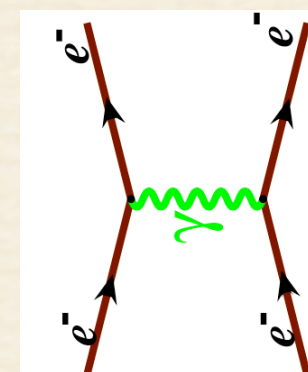


not observed

Charge and Handedness

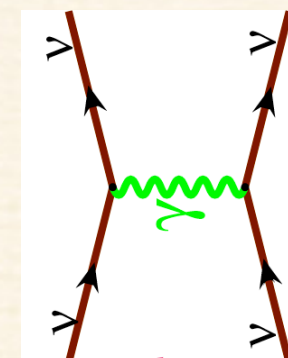
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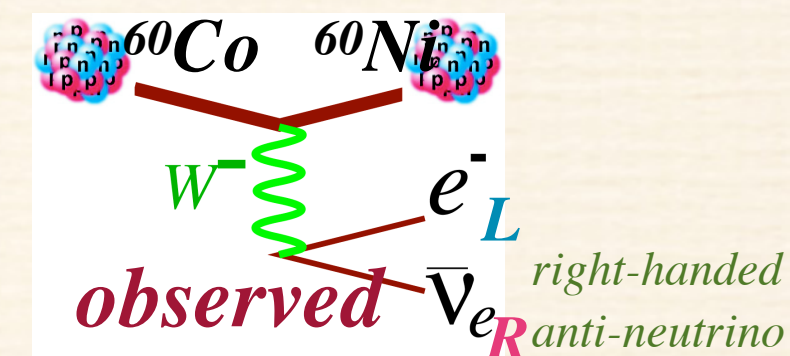
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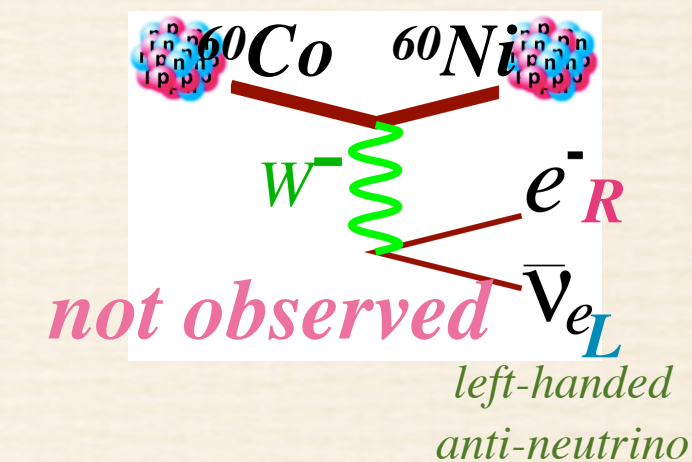
not observed

Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge



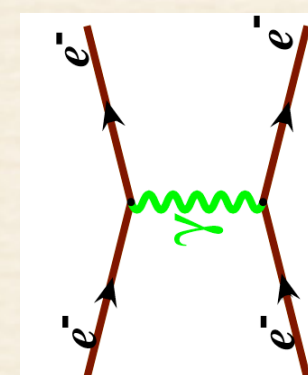
Right-handed particles (left-handed antiparticles) are “weak charge neutral”



Charge and Handedness

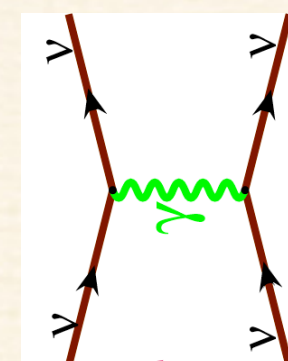
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observed

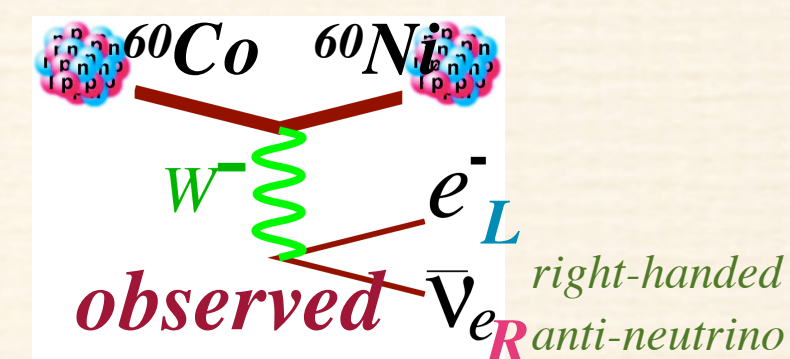
Neutrinos are “charge neutral”: do not feel the electric force



not observed

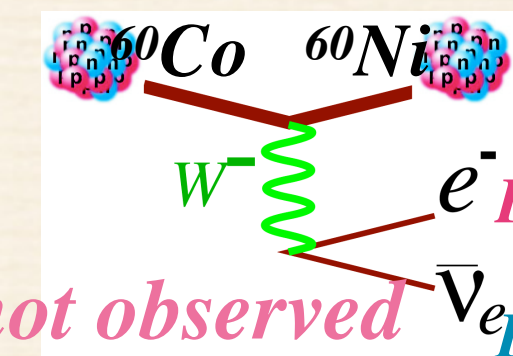
Weak charge determines strength of weak force

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not observed

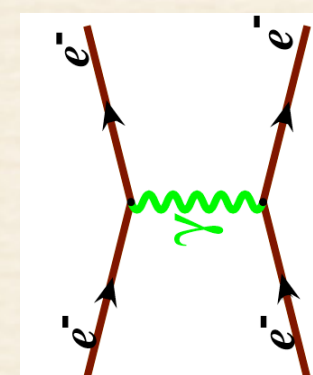
left-handed anti-neutrino

Important: Helicity $\neq$ Chirality if $m \neq 0$!

Charge and Handedness

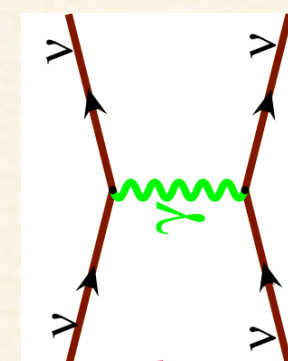
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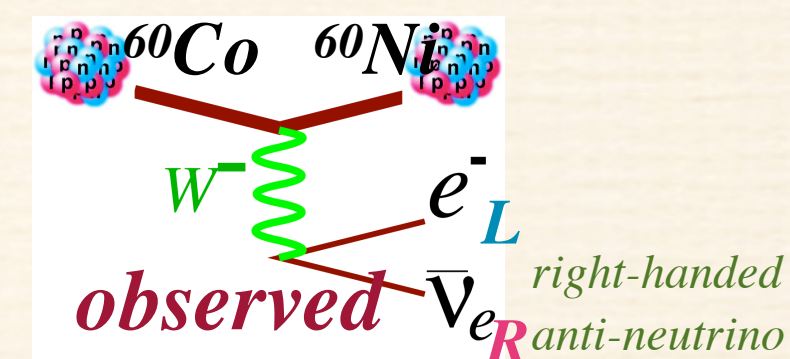
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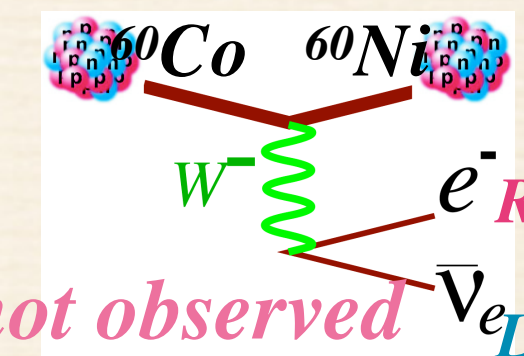
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Helicity operator commutes with free-particle Hamiltonian

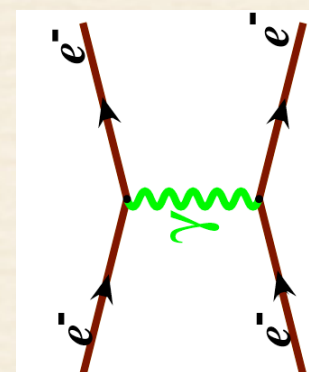
Conserved but not Lorentz invariant!

(Can race past a massive particle and observe it spinning the other way)

Charge and Handedness

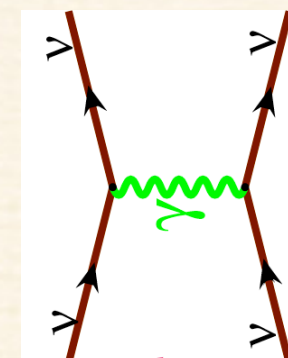
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Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge



observed e^-_L $\bar{\nu}_{eR}$ right-handed anti-neutrino

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



not observed e^-_R $\bar{\nu}_{eL}$ left-handed anti-neutrino

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Helicity operator commutes with free-particle Hamiltonian

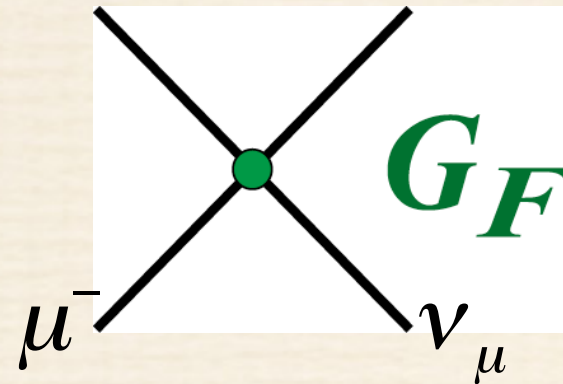
Conserved but not Lorentz invariant!

(Can race past a massive particle and observe it spinning the other way)

Chirality operator not conserved, but Lorentz invariant!

Freely propagating left-chiral projection will develop a right-chiral component

Weak Decays and Scattering



$$\mathcal{M} \sim -\frac{G_F}{\sqrt{2}} \left[\bar{u}(\nu_\mu) \gamma_\mu (1 - \gamma^5) u(\mu) \right] \left[\bar{u}(e) \gamma^\mu (1 - \gamma^5) v(\bar{\nu}_e) \right]$$

Each decay mode provides a partial width Γ_i

$$\tau = \frac{1}{\sum_i \Gamma_i}$$

Partial width has units of energy

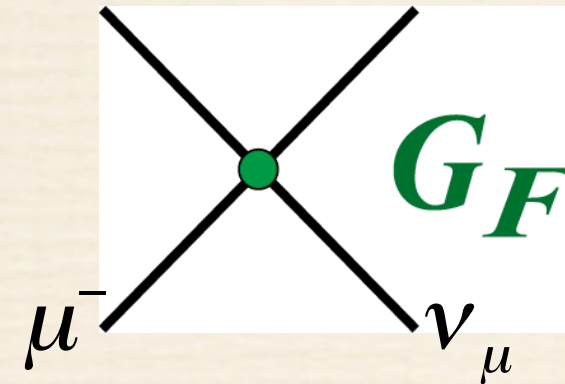
$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi}$$



Conversion factor: 197 MeV-fm

Muon lifetime in vacuum: 2.2 μs

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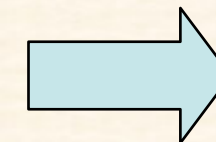
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Gedanken Experiments: The luxury of being a theorist

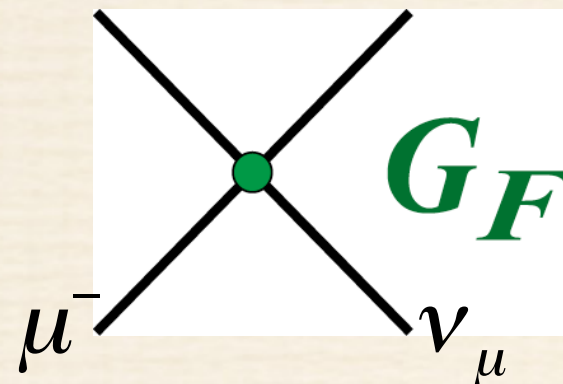
Consider

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

Can use same $\mathcal{M}$

$$\sigma = \frac{G_F^2 E^2}{3\pi^2}$$

Weak Decays and Scattering



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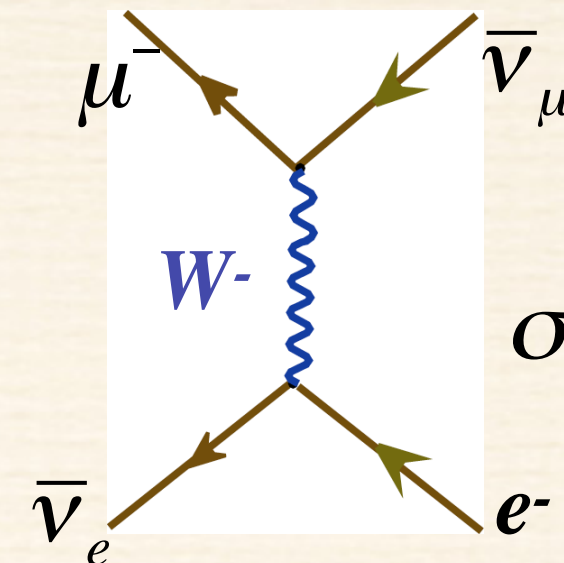
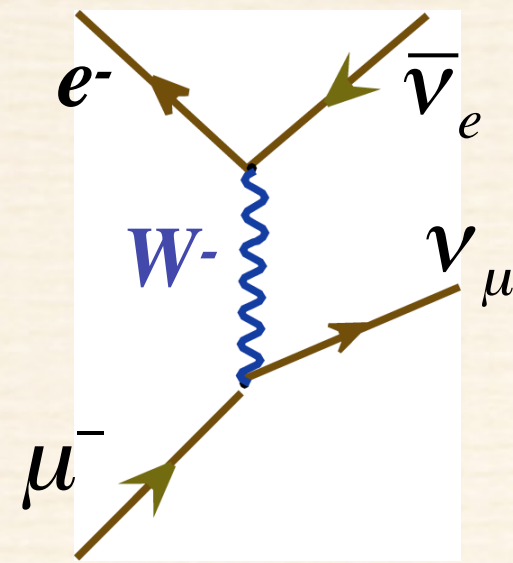
For $E \sim 1$ TeV, probability > 1 !

More particles going out than coming in!

Massive Vector Bosons

$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$



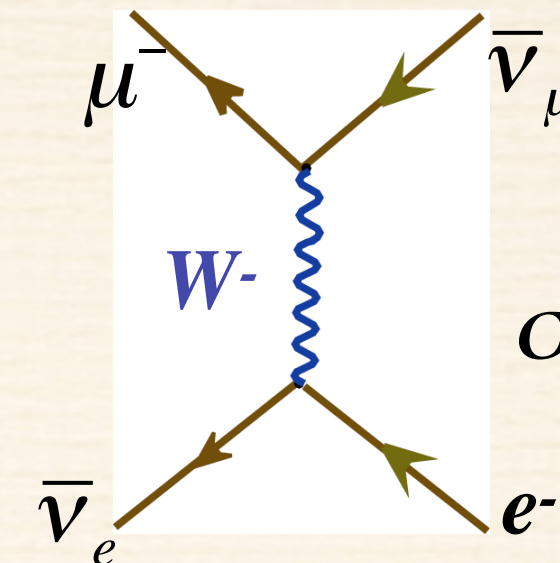
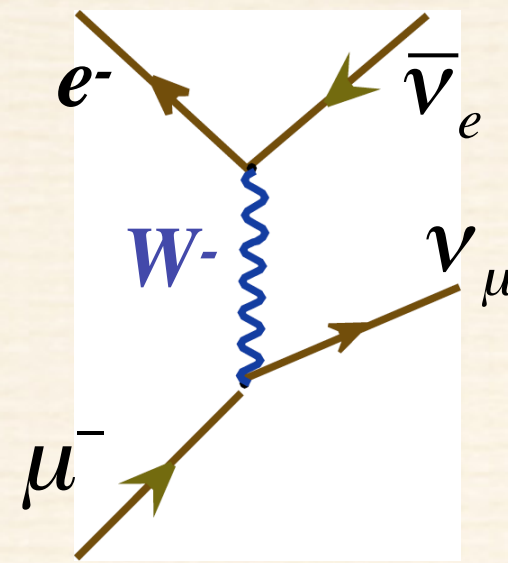
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma \approx \frac{2g_W^4}{3\pi} \frac{4E^2}{4(E^2 - m_W^2)^2}$$

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$$V = \frac{1}{4\pi\epsilon_0} \frac{q}{r} e^{-\left[\frac{mc}{\hbar}\right]r} \text{ Short range}$$

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Real W production

Fixed target: $M_{new}^2 \sim 2ME$

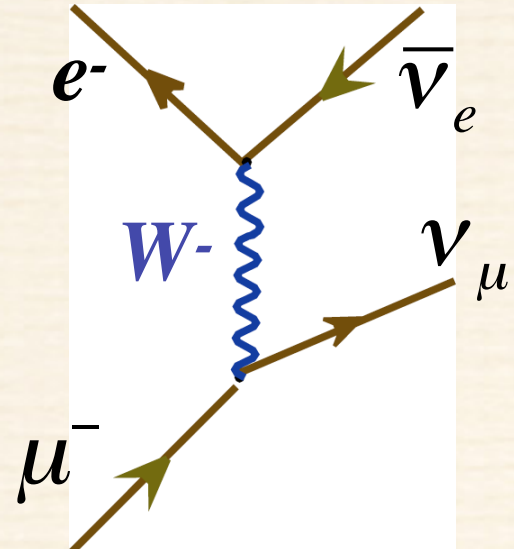
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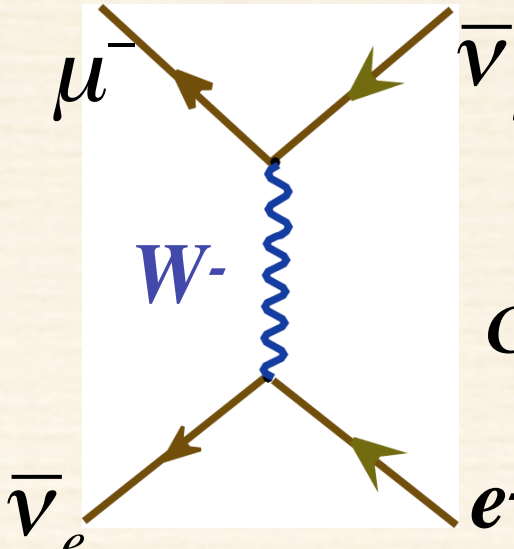
Collider: $M_{new}^2 \sim 4E^2$

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Very short lifetime



Large width

$$p(E) = \frac{\Gamma}{2\pi} \frac{1}{(E - m_W)^2 + (\Gamma/2)^2}$$

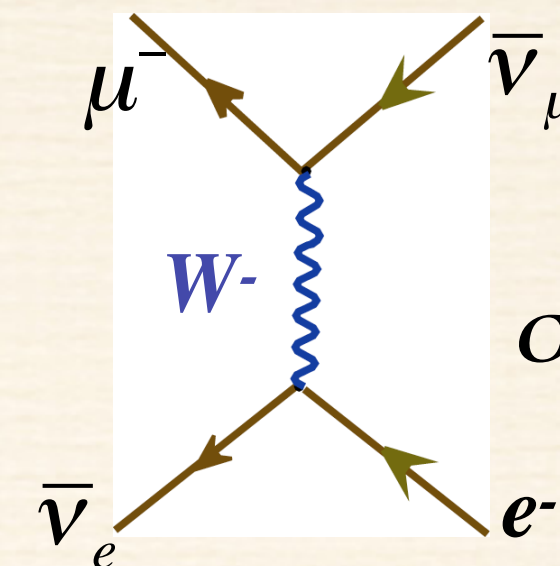
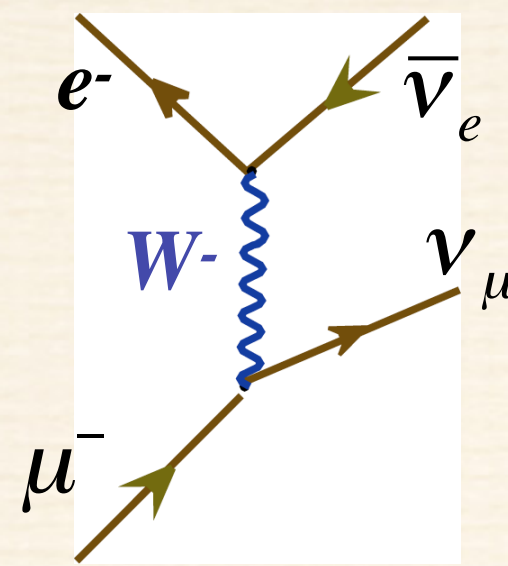
$$A + B \rightarrow W^+ \rightarrow C + D$$

$$\sigma_{peak} \approx \frac{4\pi}{3m_W^2} \frac{\Gamma_{AB}}{\Gamma_{tot}} \frac{\Gamma_{CD}}{\Gamma_{tot}}$$

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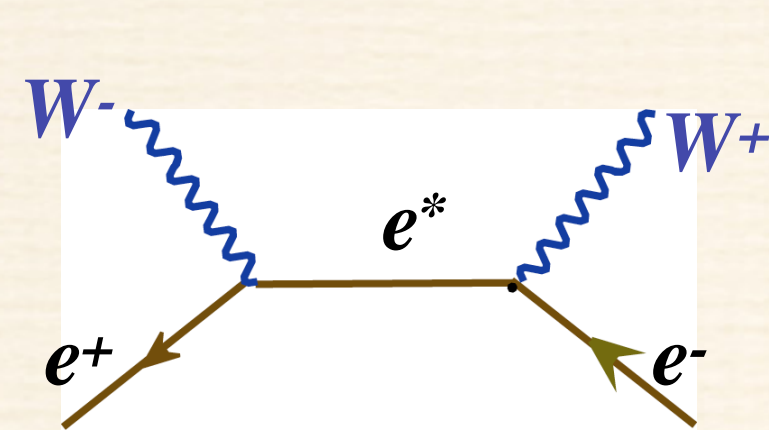
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W Boson discovered by the CERN UA1 experiment in 1983

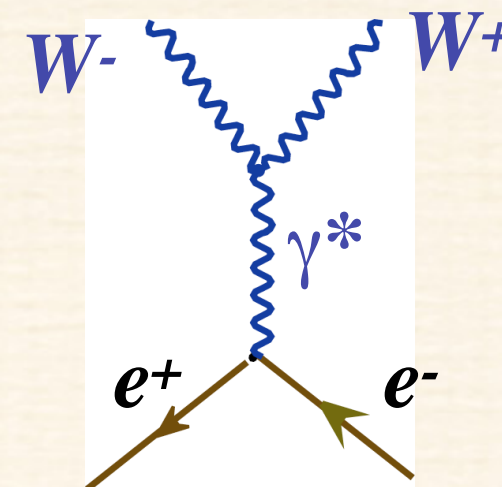
Z Bosons and EW Unification

More gedanken experiments

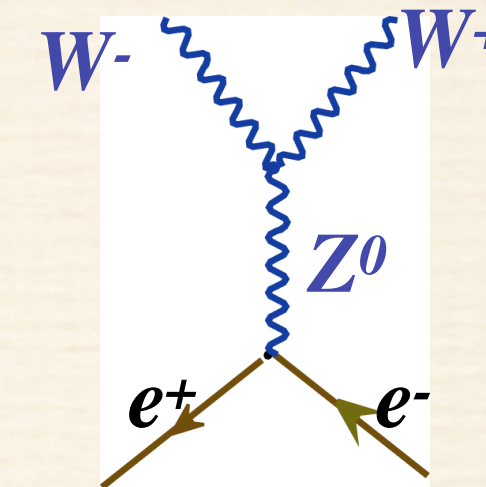
$$e^+ \nu_e \rightarrow W^+ \gamma$$



+



+



Electron-positron collisions

$$e^+ e^- \rightarrow W^+ W^-$$

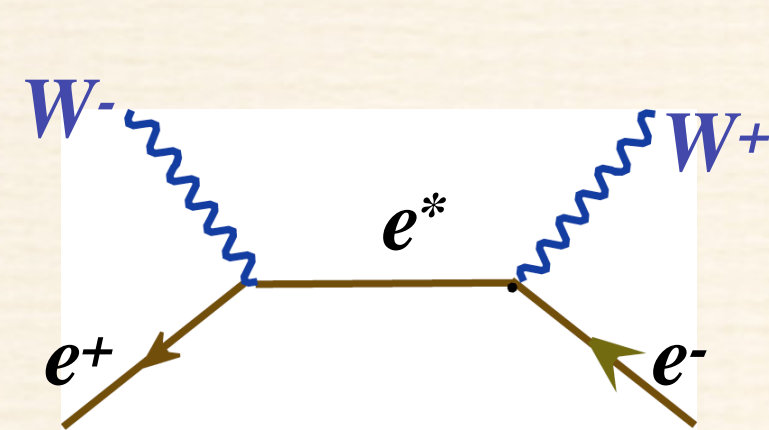
Unitarity violation forces important constraints

- Need $WW\gamma$ vertex: same charge as electron!
- Need a new, neutral massive weak boson: the Z^0
- One free parameter: θ_w , the weak mixing angle

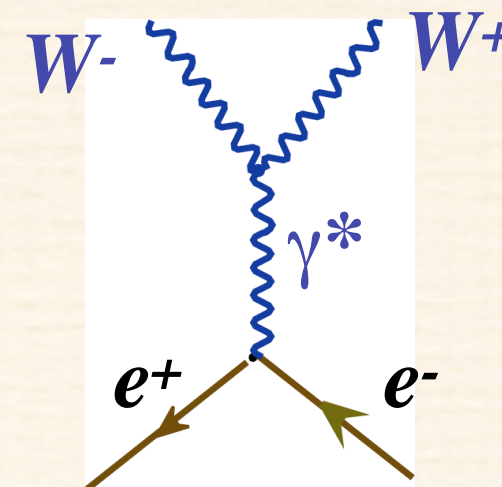
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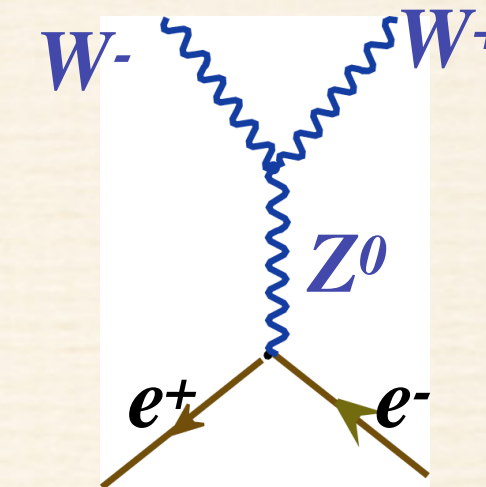
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+



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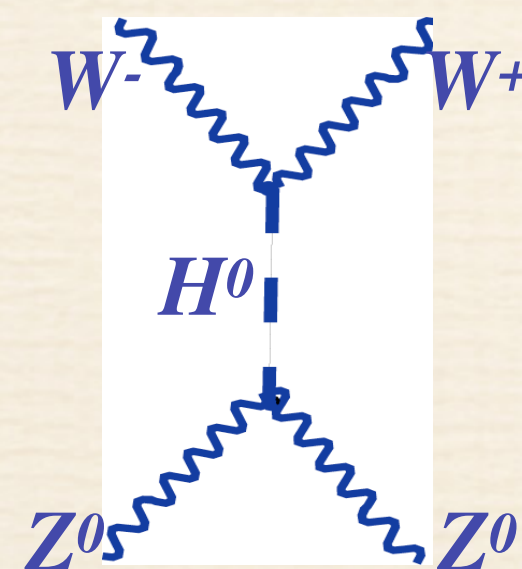


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Scattering of longitudinal vector bosons ($m=0$)

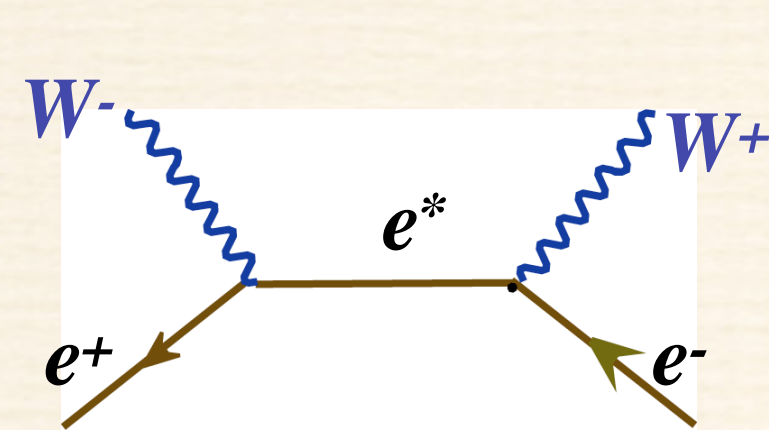
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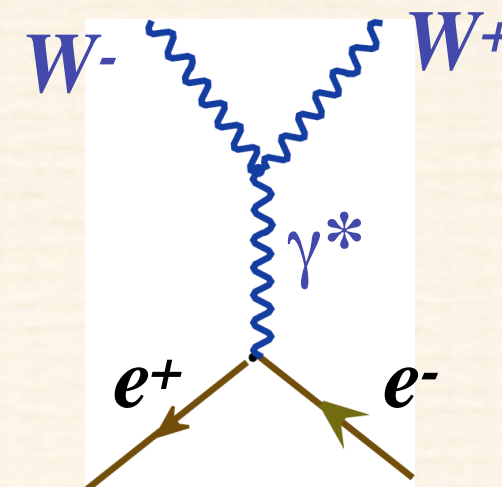
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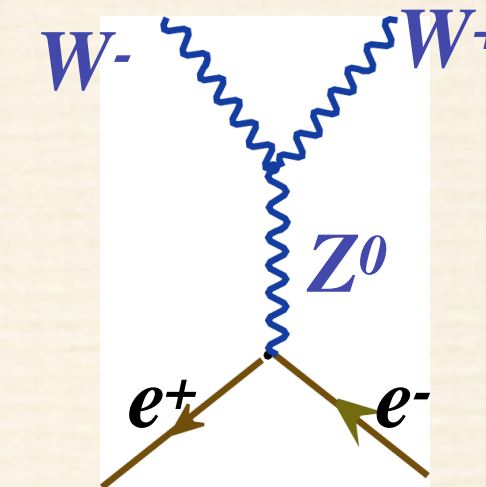
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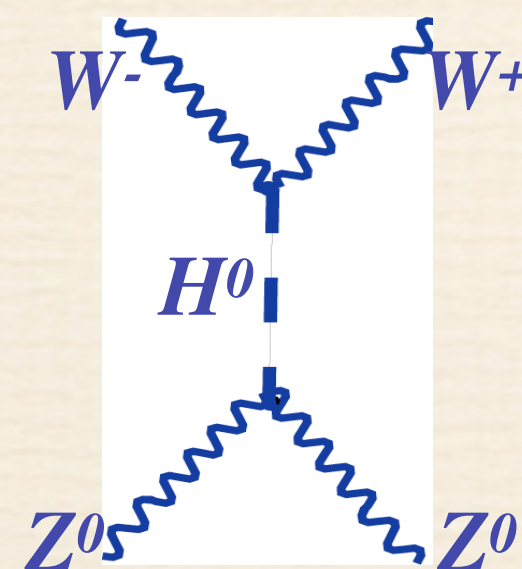
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Something
like this
must occur

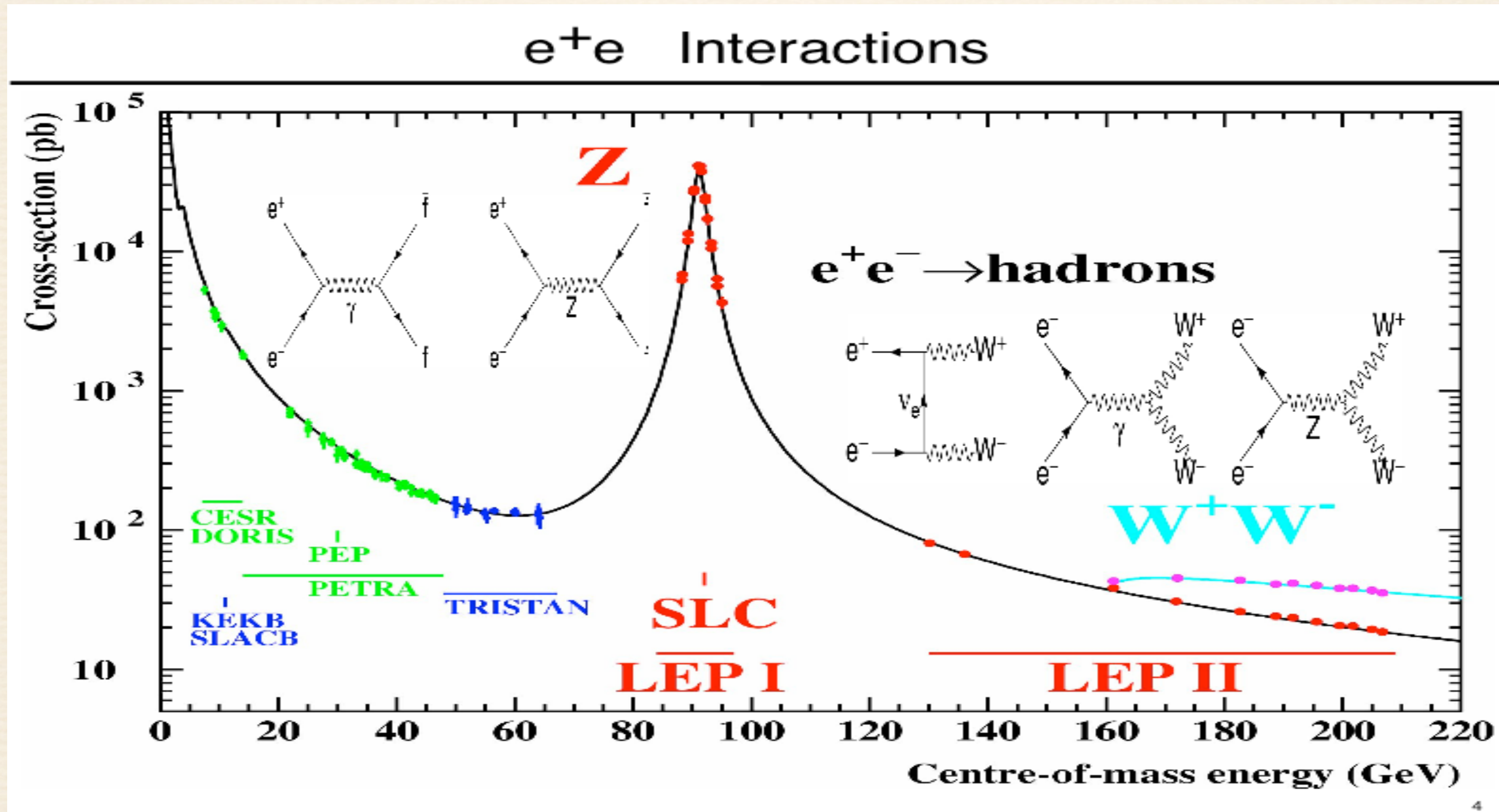


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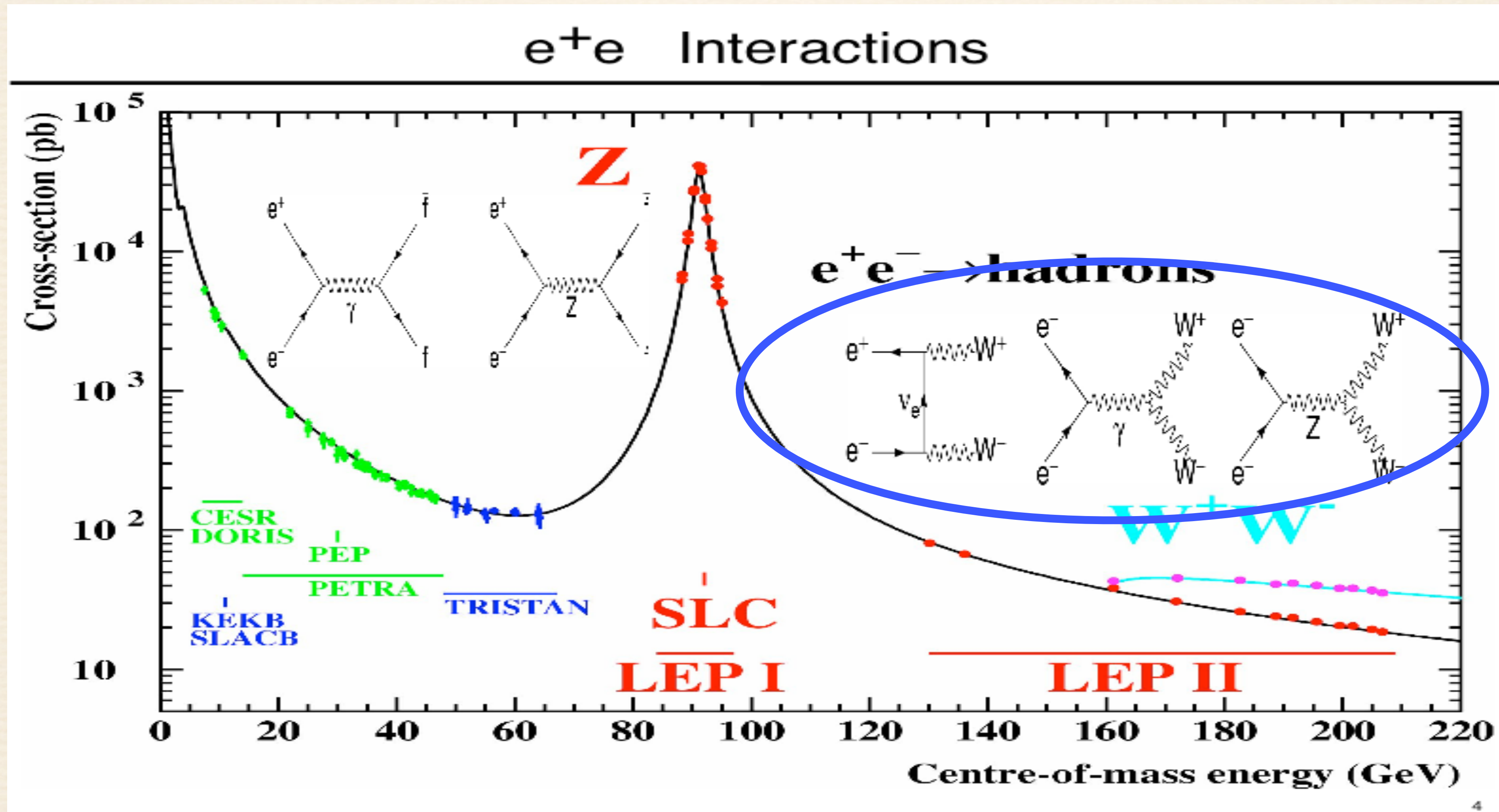
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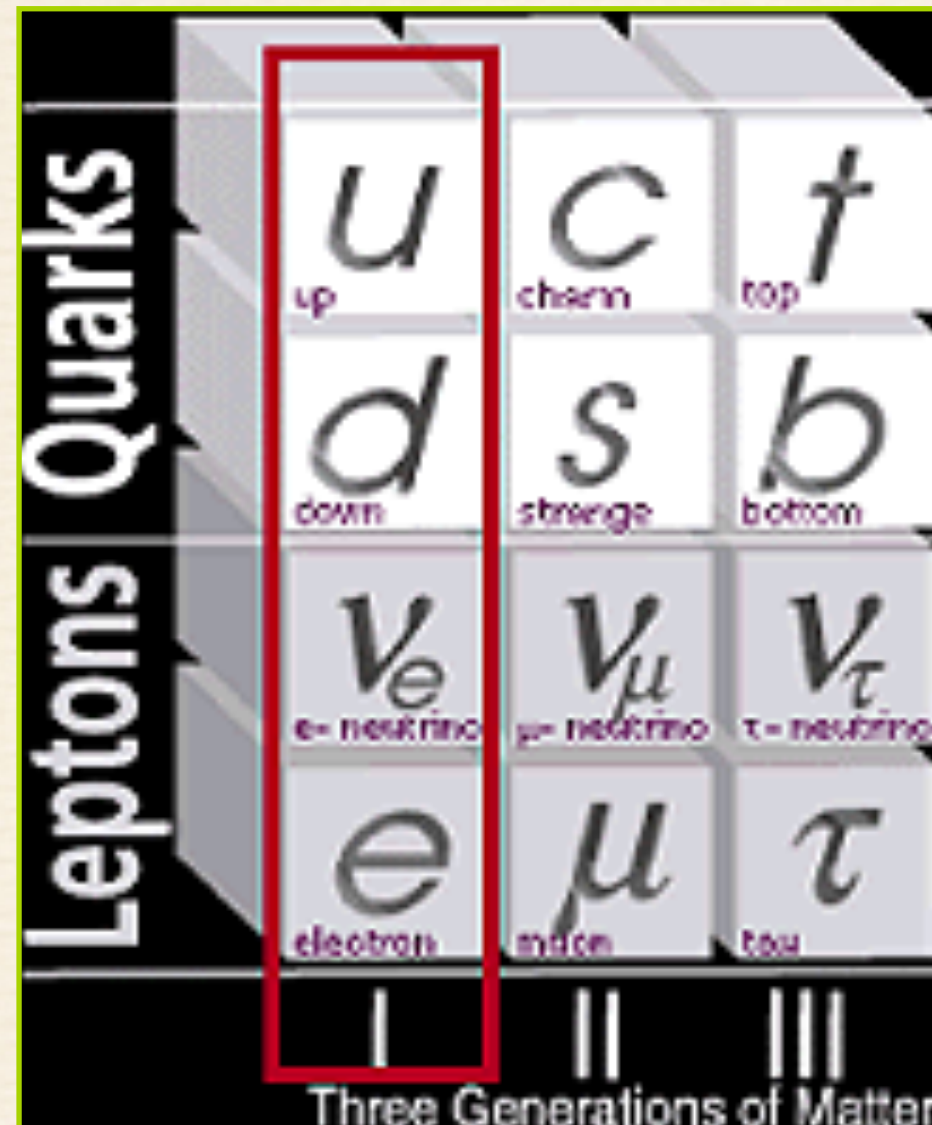
e^+e^- Collider Data



e^+e^- Collider Data



W and Z Charges



- Left-handed particles in isodoublets
- Right-handed particles iso-singlets
- Including neutrinos!

	Left-	Right-
γ Charge	$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$	$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$
W Charge	$T = \pm \frac{1}{2}$	$T = 0$
Z Charge	$T - q \sin^2 \theta_w$	$-q \sin^2 \theta_w$

- *Ws have no couplings to right-handed projections*
- *Zs couple to both (provided the particles are charged): introduce g_L and g_R*

Also use g_V and g_A :

$$g_V = g_L + g_R$$

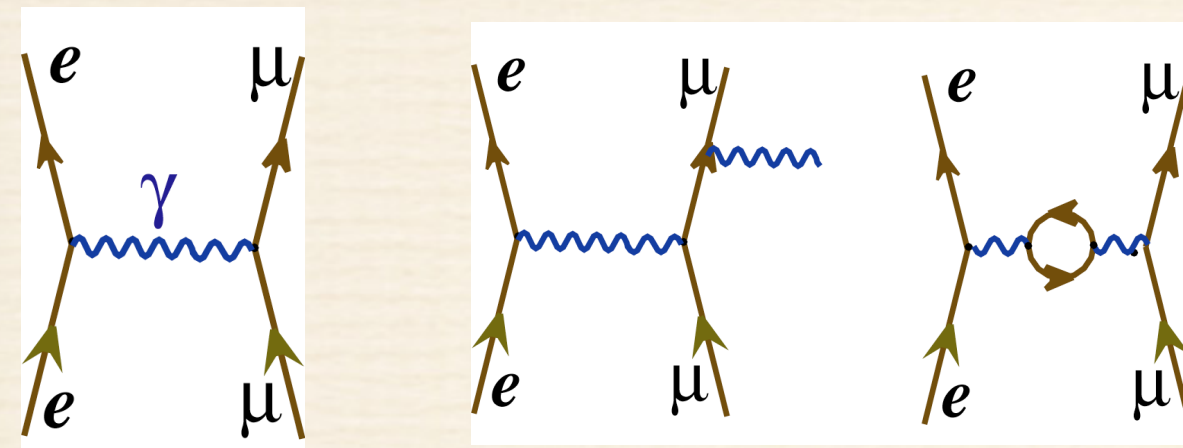
$$g_A = g_L - g_R$$

Vector and Axial-vector couplings

Electroweak Radiative Corrections

Perturbation Theory and Renormalization

From Feynman rules: Construct all possible diagrams consistent with known conservation laws

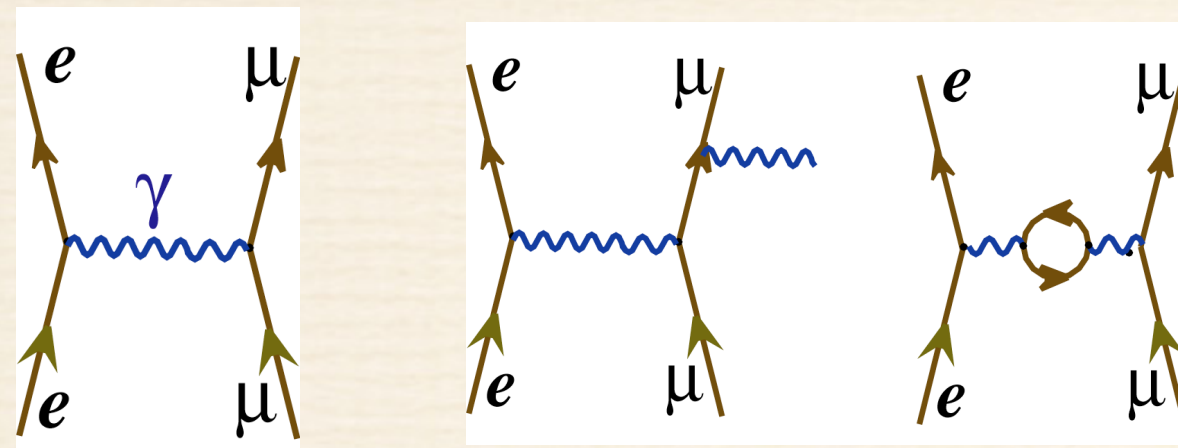


Amplitude is sum of all possible states: Feynman's path integral formulation of QM

Problem: Total amplitude diverges

Perturbation Theory and Renormalization

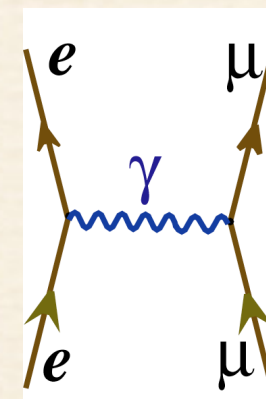
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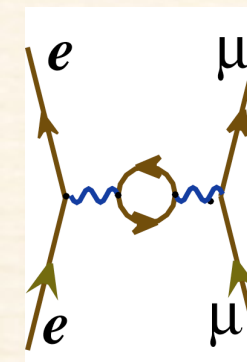
Problem: Total amplitude diverges

Start with



$$M_1 \sim \frac{e^2}{q^2}$$

Add



$$M_1 \sim i \frac{e^2}{q^2} + i \frac{e^2}{q^2} \frac{i \Sigma_{\gamma\gamma}(q^2)}{q^2}$$

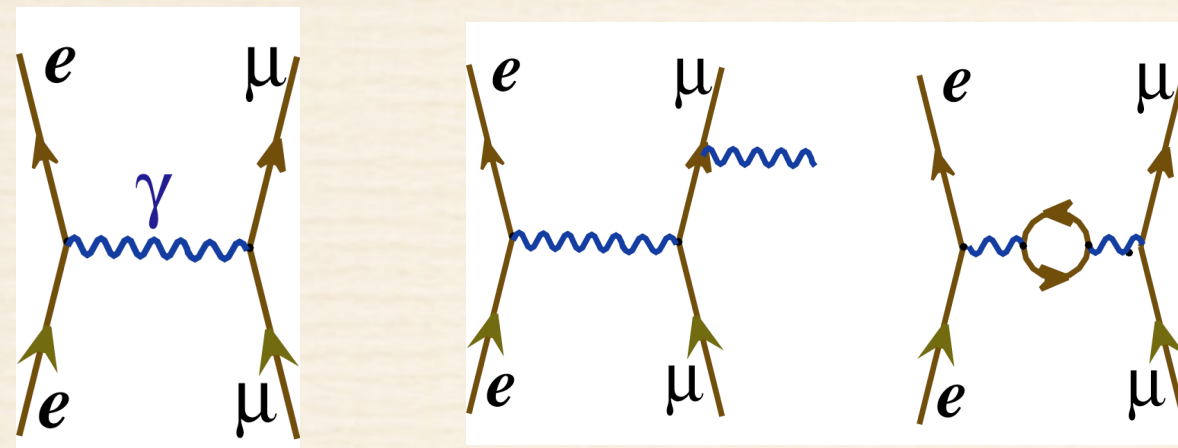
Introduce parameter

$\Sigma_{\gamma\gamma}(q^2)$ **(It is infinite)**

$$e^2 \Rightarrow e^2(1 + \Sigma_{\gamma\gamma}(q^2))$$

Perturbation Theory and Renormalization

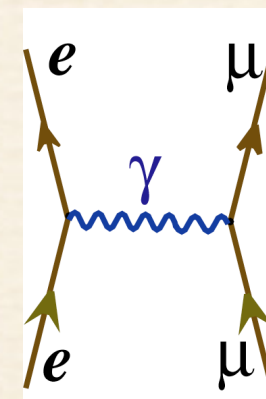
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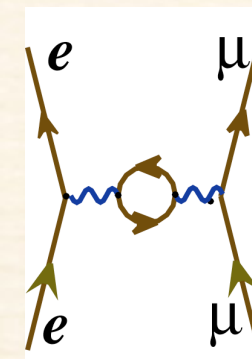
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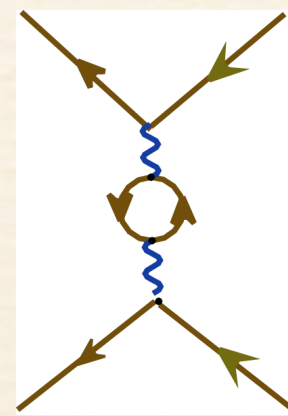
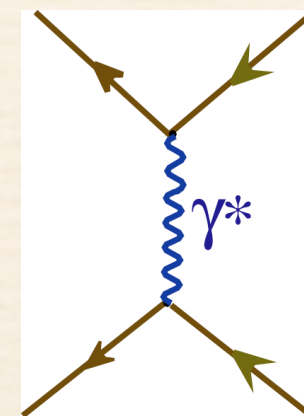
Introduce parameter

$$M_1 \sim i \frac{e^2}{q^2} + i \frac{e^2}{q^2} \frac{i \Sigma_{\gamma\gamma}(q^2)}{q^2}$$

$\Sigma_{\gamma\gamma}(q^2)$ **(It is infinite)**

$$e^2 \Rightarrow e^2(1 + \Sigma_{\gamma\gamma}(q^2))$$

Now consider



Introduce parameter $\Pi_{\gamma\gamma}(p^2)$

(Also infinite)

$$M_2 \sim \frac{e^2}{p^2} (1 - \Pi_{\gamma\gamma}(p^2))$$

$$M_2 \sim \frac{e^2}{p^2} (1 - [\Pi_{\gamma\gamma}(p^2) - \Pi_{\gamma\gamma}(q^2)])$$

Finite!

Running Couplings

- *Feynman rules with electric charge*
- *Calculate $\sigma_1(e)$ for a test process*
- *Measure $\sigma_1(e)$ and extract e*
- *Calculate $\sigma_2(e)$ for another process*

Not all Quantum Field Theories behave this way:

The ones that do are renormalizable theories

Electroweak theory: t'Hooft and Veltman
QCD: Gross, Politzer and Wilzcek

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- *Measure $\sigma_1(e)$ and extract e*
- *Calculate $\sigma_2(e)$ for another process*

Not all Quantum Field Theories behave this way:

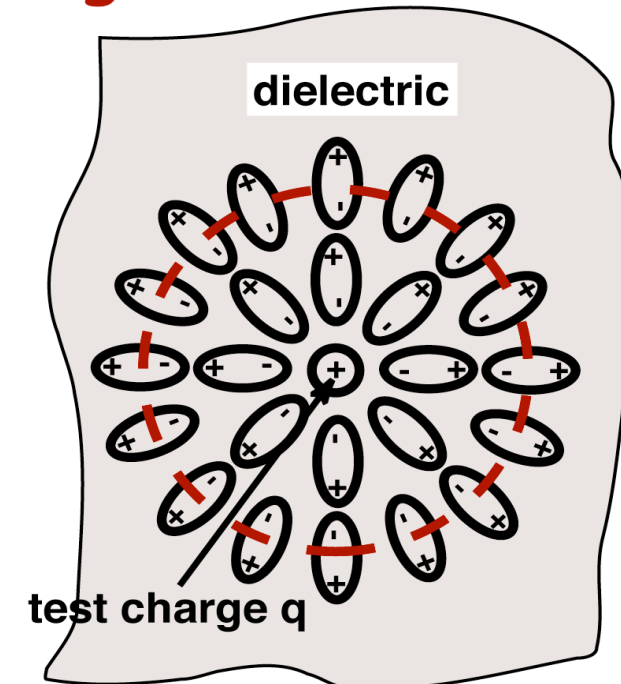
The ones that do are renormalizable theories

Electroweak theory: t'Hooft and Veltman

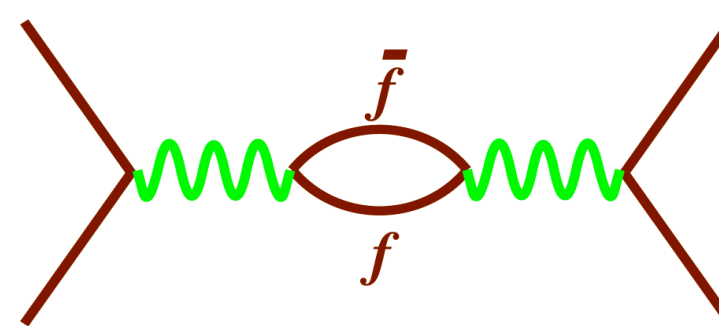
QCD: Gross, Politzer and Wilzcek

**Fine structure constant: 1/137 at low energy,
1/128 at Z pole**

total charge enclosed is less than q



total charge depends on relative distance



*effective charge increases
with decreasing distance:*

***higher order terms in
perturbative expansion***

Running Couplings

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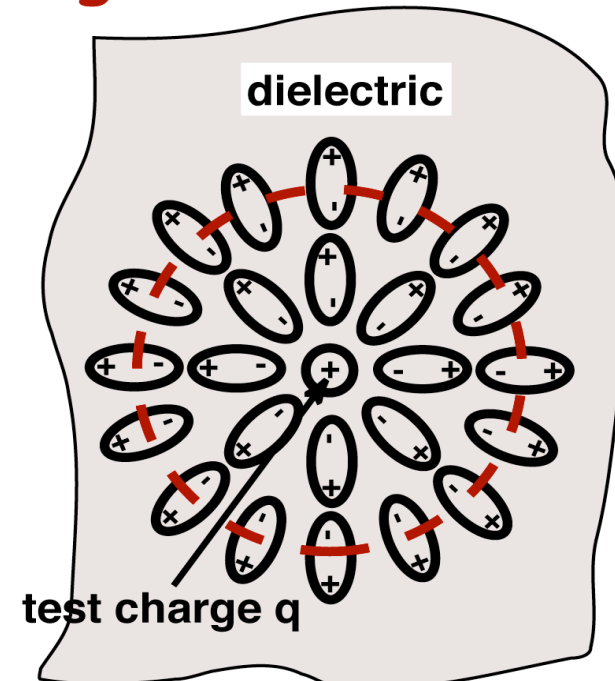
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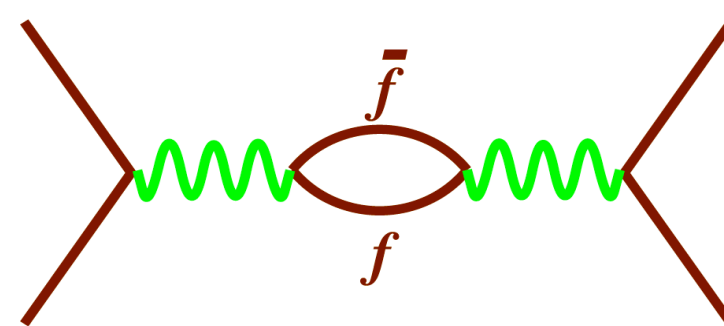
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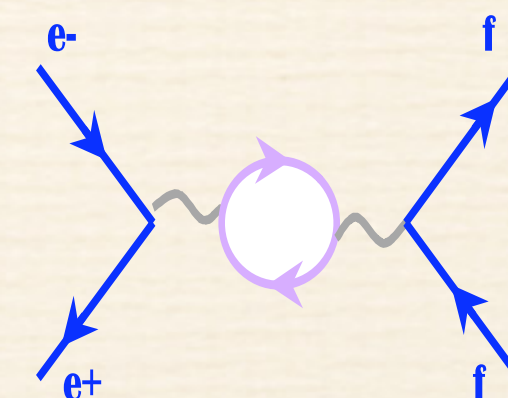


effective charge increases with decreasing distance:

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Fine structure constant: 1/137 at low energy, 1/128 at Z pole

The shift $\Delta\alpha$ can be determined analytically for lepton loops and by a dispersion integral over the e^+e^- annihilation cross section for light quarks (u,d,s,c,b)



$$\alpha(m_Z^2) = \alpha / (1 - \Delta\alpha)$$

Optical theorem

$$\Delta\alpha_{\text{lepton}} = \sum_{l=e,\mu,\tau} \frac{\alpha}{3\pi} \left(\log \frac{m_Z^2}{m_l^2} - \frac{5}{3} \right) + \dots$$

$$\Delta\alpha_{\text{hadron}} = -\frac{\alpha}{3\pi} \int_{4m_\pi^2}^{\infty} \frac{m_Z^2 ds}{s[s - m_Z^2]} \frac{\sigma(e^+e^- \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

Electroweak Theory

$$\tan \theta_W = \frac{g'}{g}$$

$$A_\mu = B_\mu^0 \cos \theta_W + W_\mu^0 \sin \theta_W$$

$$Z_\mu = W_\mu^0 \cos \theta_W - B_\mu^0 \sin \theta_W.$$

The Z boson incorporated

*One free parameter:
weak mixing angle θ_W*

	Left-	Right-
γ Charge	$0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$	$0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$
W Charge	$T = \pm \frac{1}{2}$	zero
Z Charge	$T - q \sin^2 \theta_W$	$-q \sin^2 \theta_W$

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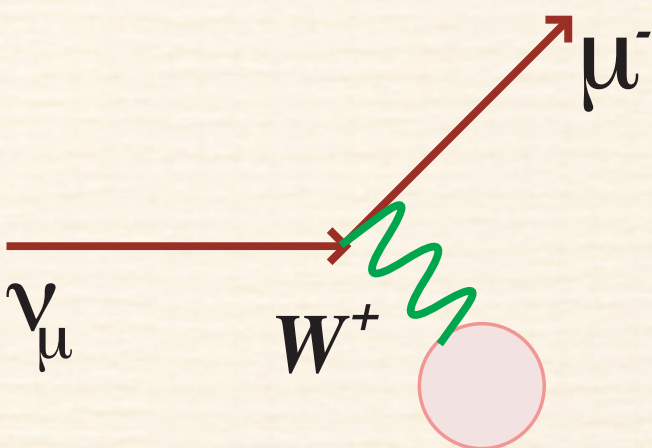
γ Charge

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Left- g_L	Right- g_R
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Charged Current

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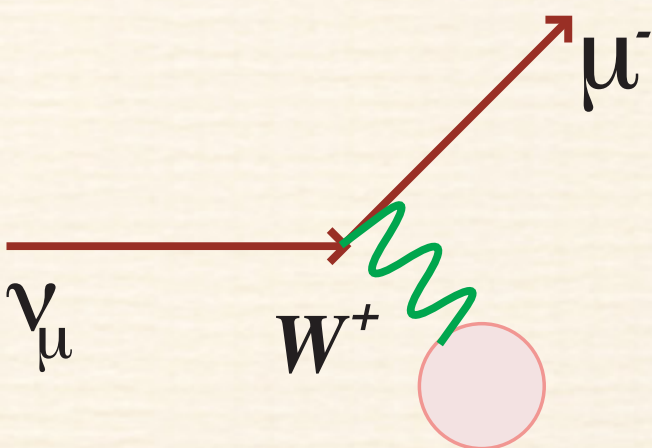
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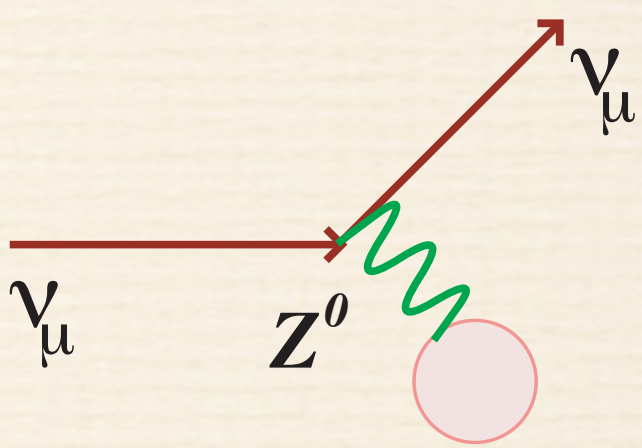
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Charged Current



Neutral Current

Electroweak Theory

$$\tan \theta_W = \frac{g'}{g}$$

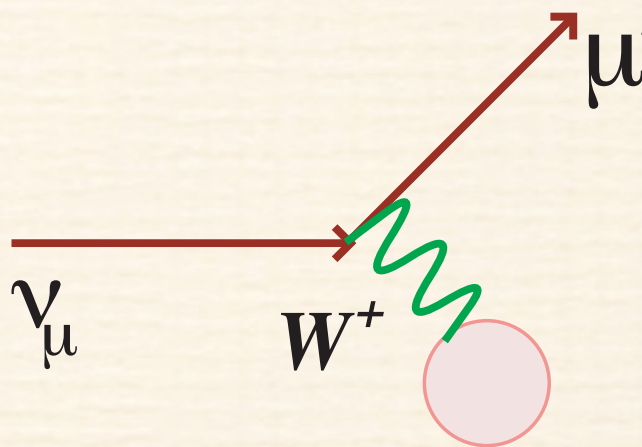
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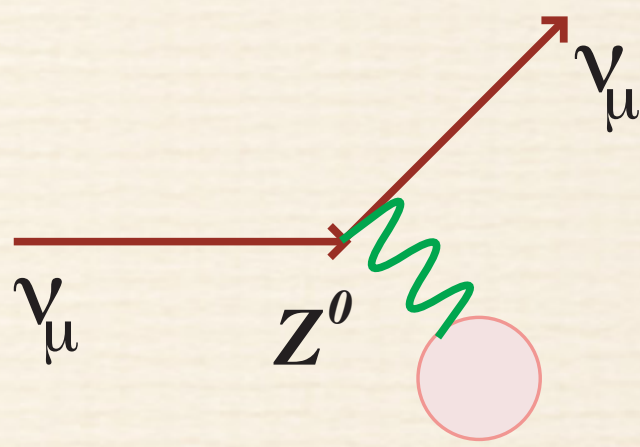
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Charged Current



Neutral Current

Higgs Mechanism + Renormalizability

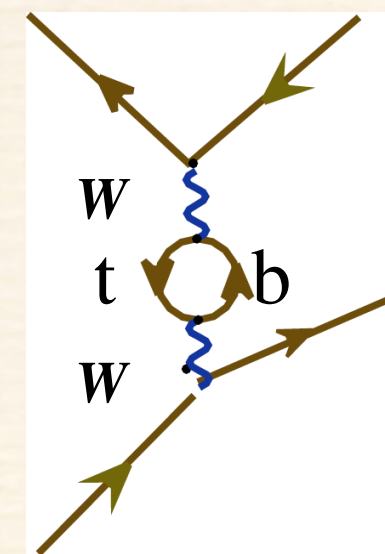
$$\sin^2 \theta_W^0 = \left(\frac{e^0}{g^0} \right)^2 = 1 - \left(\frac{M_W^0}{M_Z^0} \right)^2$$

EW Theory at 1-Loop

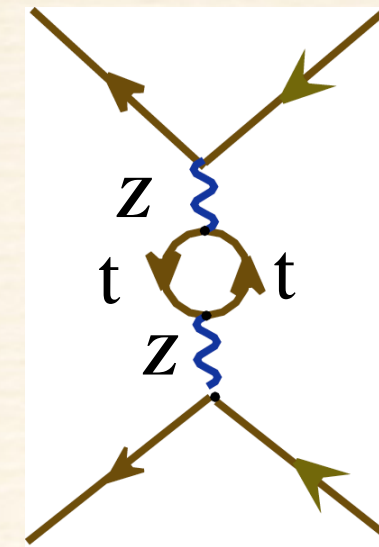
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2. The muon lifetime
3. The Z line shape

Effectively α_{QED} G_F M_Z



Muon decay



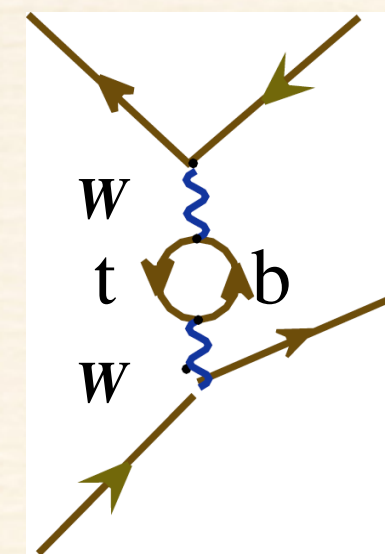
Z production

4th and 5th best
measured parameters:
 M_W and $\sin^2\theta_W$

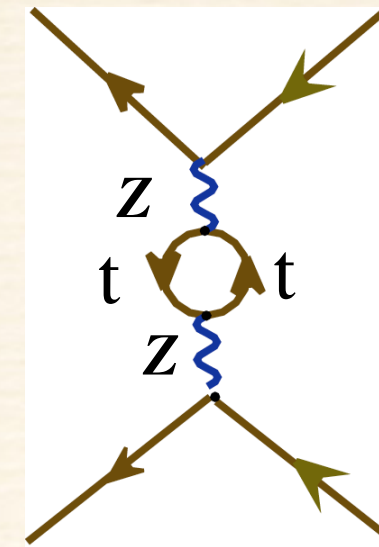
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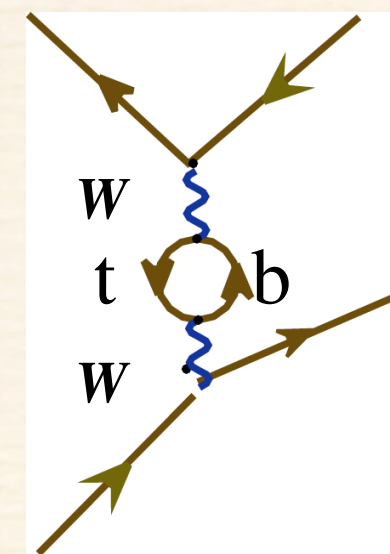
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simple definition; disfavored due to heavy m_t

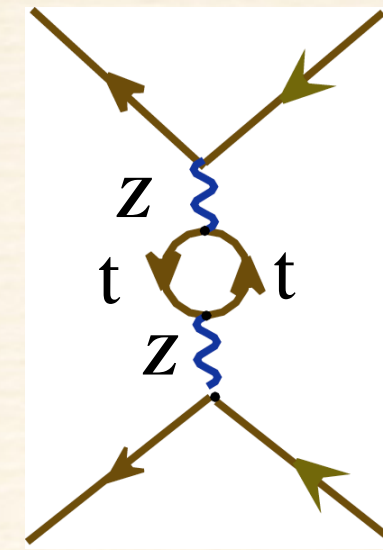
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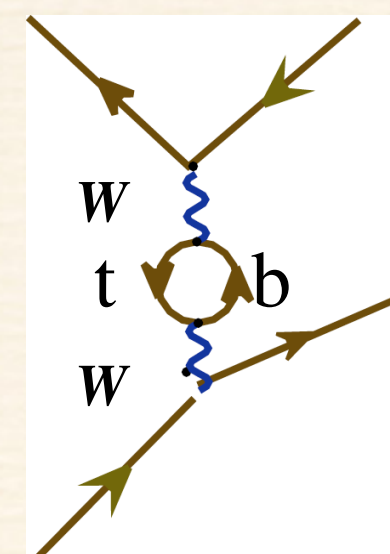
$$\sin^2 \theta_W^{\text{eff}} \equiv (1 - g_{\mu\mu Z})/4$$

good at Z-pole; nasty counterterms at other scales

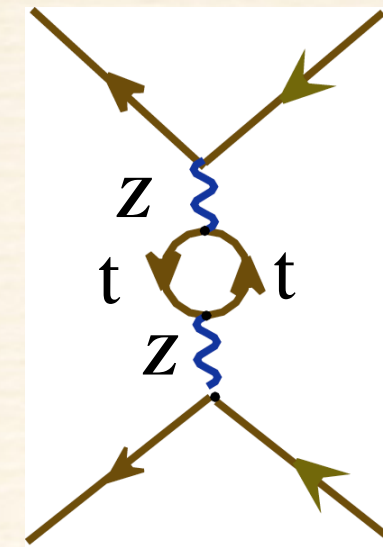
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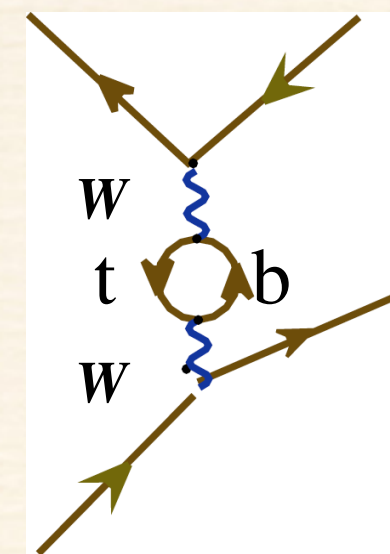
$$\sin^2 \theta_W(\mu)_{\overline{\text{MS}}} \equiv e^2(\mu)_{\overline{\text{MS}}}/g^2(\mu)_{\overline{\text{MS}}}$$

theoretically motivated; but not physical

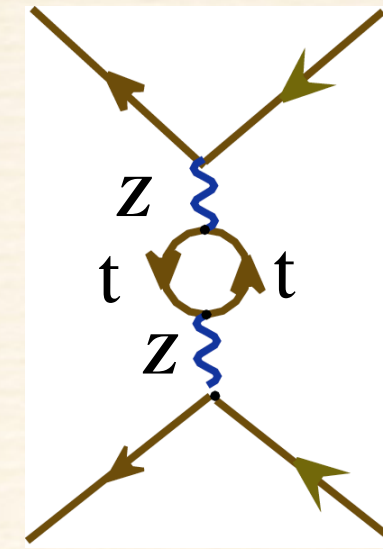
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$$\sin^2 \theta_W(M_Z)_{\overline{\text{MS}}} = \sin^2 \theta_W^{\text{eff}} - 0.00028$$

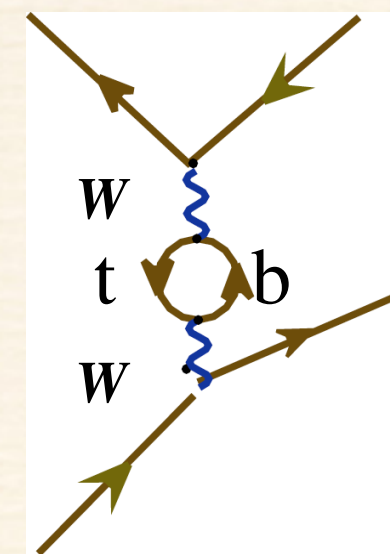
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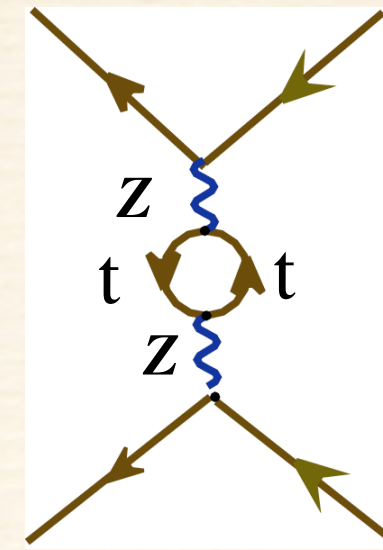
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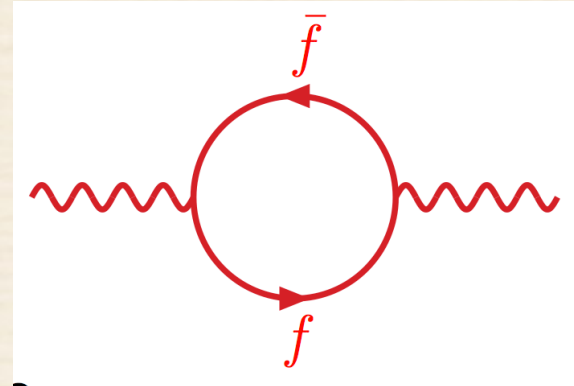
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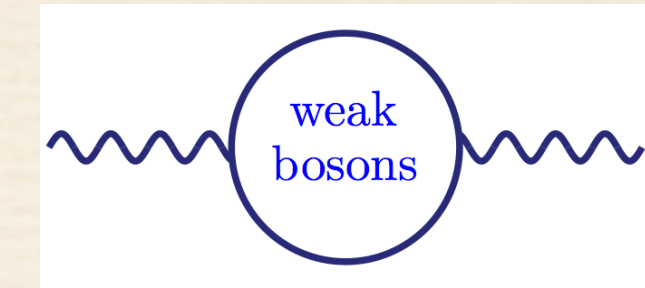
Important note for experimentalists: do not worry too much about the exact definition of $\sin^2 \theta_W$. When designing experiments, all that matters is the projected uncertainty; the actual value does not matter. When the experiment is fully designed, then work with theorists to extract $\sin^2 \theta_W(\mu)_{\overline{\text{MS}}}$ and properly account for radiative corrections.

Heroic efforts of phenomenologists and experimentalists!



Precision Relations

The Electroweak Theory and Measurements at 1-Loop



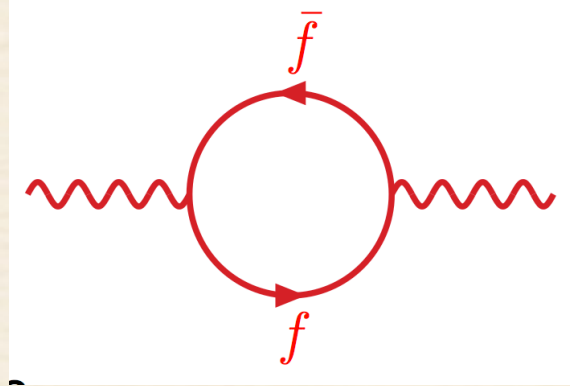
Thanks to Bill
Marciano for
the education!

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

$$e^2 = 4\pi\alpha$$

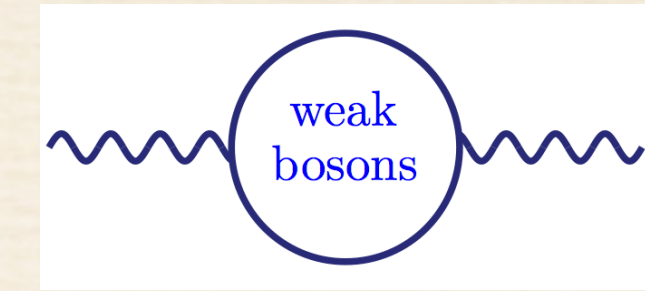
$$\sin^2 \theta_W \approx \left(\frac{e}{g}\right)^2 \approx 1 - \left(\frac{M_W}{M_Z}\right)^2$$

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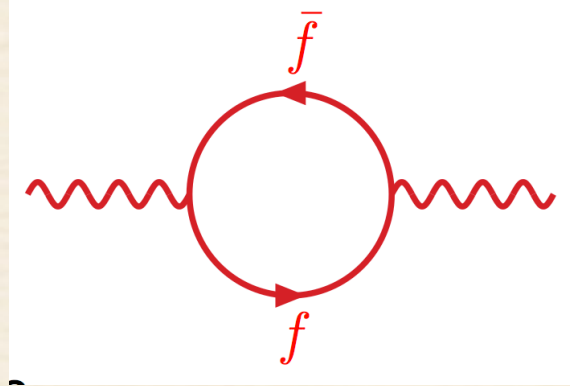
$$(\Delta r)^{\text{expt}} = 1 - \left[\pi\alpha / \{ \sqrt{2} G_F m_W^2 (1 - m_W^2/m_Z^2) \} \right] = 0.0355(7)$$

$$(\Delta r)^{\text{SM}} = 0.0366(3) + 3.4 \times 10^{-3} \ln [m_H/126 \text{ GeV}]$$

m_t, α_s uncertainty

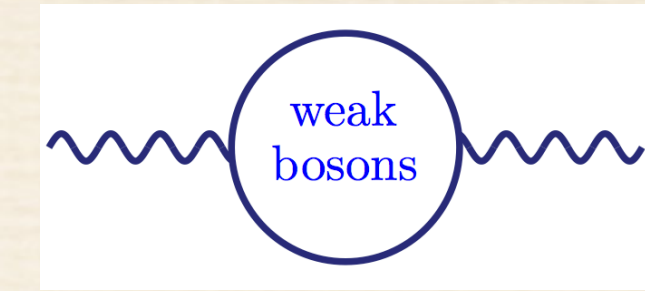
PDG 2022

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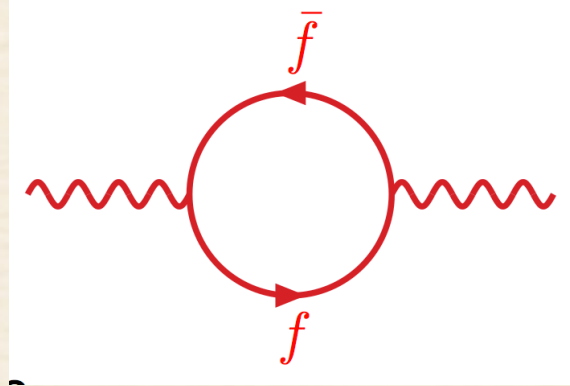
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$$(\Delta \hat{r})^{\text{expt}} = 1 - \left[2\sqrt{2}\pi\alpha / \{ G_F m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{\text{MS}}} \} \right] = 0.0595(4)$$

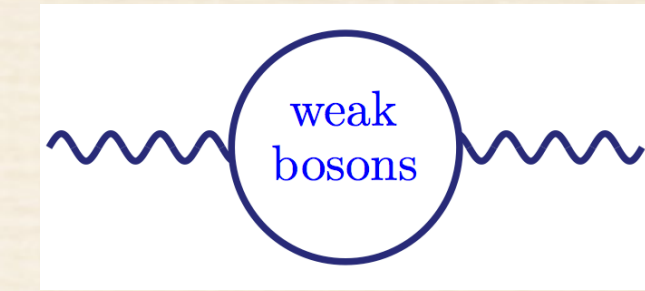
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PDG 2022

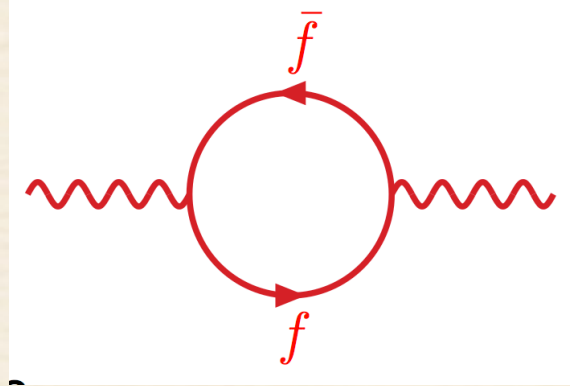
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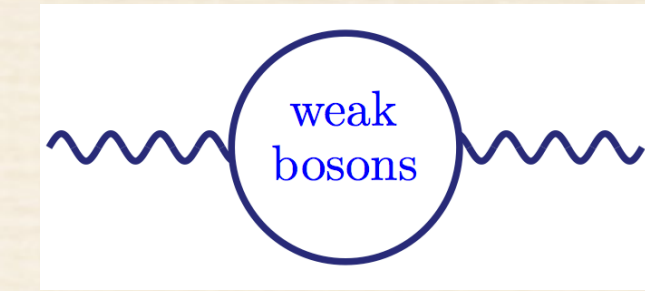
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Precision Relations

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theory $m_W = 80.360(6) \text{ GeV}$

expt. $m_W = 80.377(12) \text{ GeV}$

PDG 2022

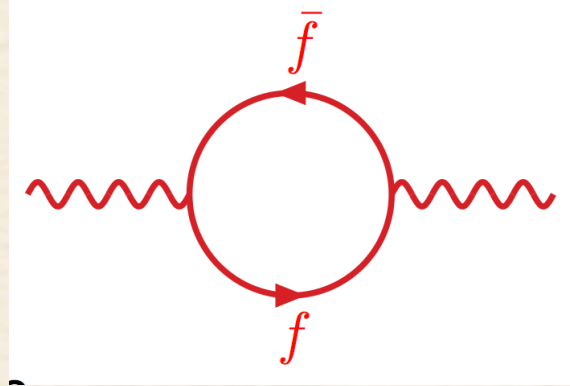
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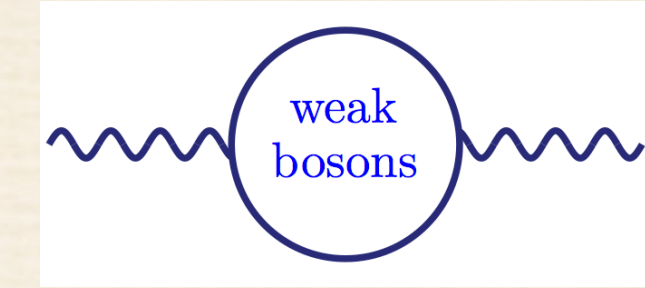
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Precision Relations

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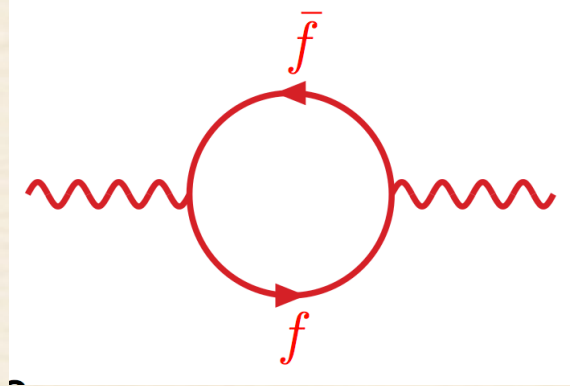
theory $\sin^2 \theta_W(m_Z)_{\overline{\text{MS}}} = 0.23122(4)$

expt. $\sin^2 \theta_W(m_Z)_{\overline{\text{MS}}} = 0.23116(13)$

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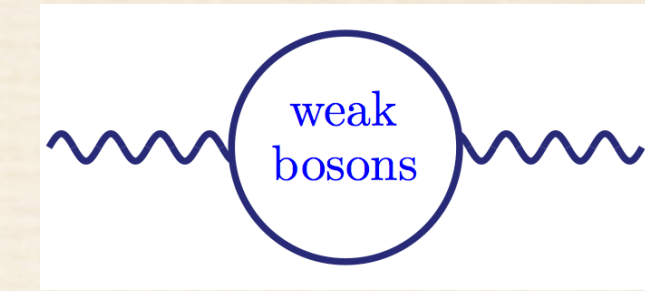
$$(\Delta r_{\overline{\text{MS}}})^{\text{SM}} = 0.0692(1) + 6.5 \times 10^{-4} \ln [m_H/126 \text{ GeV}]$$

Heroic efforts of phenomenologists and experimentalists!



Precision Relations

The Electroweak Theory and Measurements at 1-Loop



Thanks to Bill
Marciano for
the education!

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

$$e^2 = 4\pi\alpha$$

$$\sin^2 \theta_W \approx \left(\frac{e}{g}\right)^2 \approx 1 - \left(\frac{M_W}{M_Z}\right)^2$$

$$(\Delta r)^{\text{expt}} = 1 - \left[\pi\alpha / \{ \sqrt{2} G_F m_W^2 (1 - m_W^2/m_Z^2) \} \right] = 0.0355(7)$$

$$(\Delta r)^{\text{SM}} = 0.0366(3) + 3.4 \times 10^{-3} \ln [m_H/126 \text{ GeV}]$$

m_t, α_s uncertainty

theory $m_W = 80.360(6) \text{ GeV}$

expt. $m_W = 80.377(12) \text{ GeV}$

PDG 2022

$$(\Delta \hat{r})^{\text{expt}} = 1 - \left[2\sqrt{2}\pi\alpha / \{ G_F m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{\text{MS}}} \} \right] = 0.0595(4)$$

$$(\Delta \hat{r})^{\text{SM}} = 0.0597(1) + 1.4 \times 10^{-3} \ln [m_H/126 \text{ GeV}]$$

theory $\sin^2 \theta_W(m_Z)_{\overline{\text{MS}}} = 0.23122(4)$

expt. $\sin^2 \theta_W(m_Z)_{\overline{\text{MS}}} = 0.23116(13)$

$$(\Delta r_{\overline{\text{MS}}})^{\text{expt}} = 1 - \left[\pi\alpha / \{ \sqrt{2} G_F m_W^2 \sin^2 \theta_W(m_Z)_{\overline{\text{MS}}} \} \right] = 0.0694(3)(5)$$

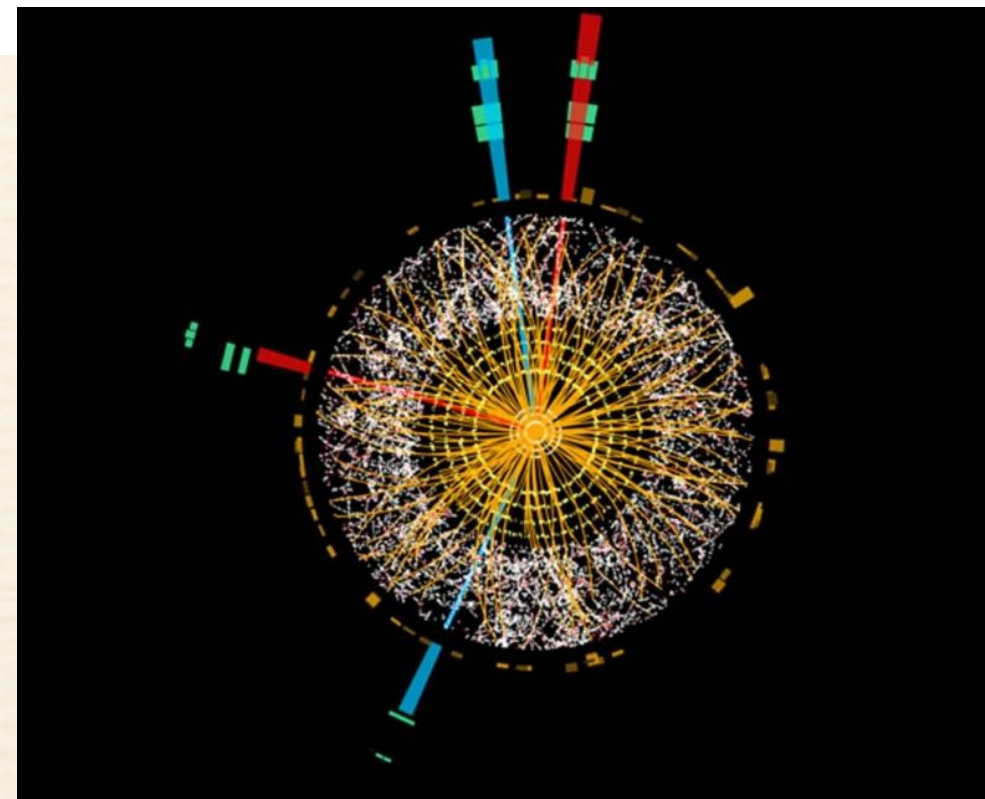
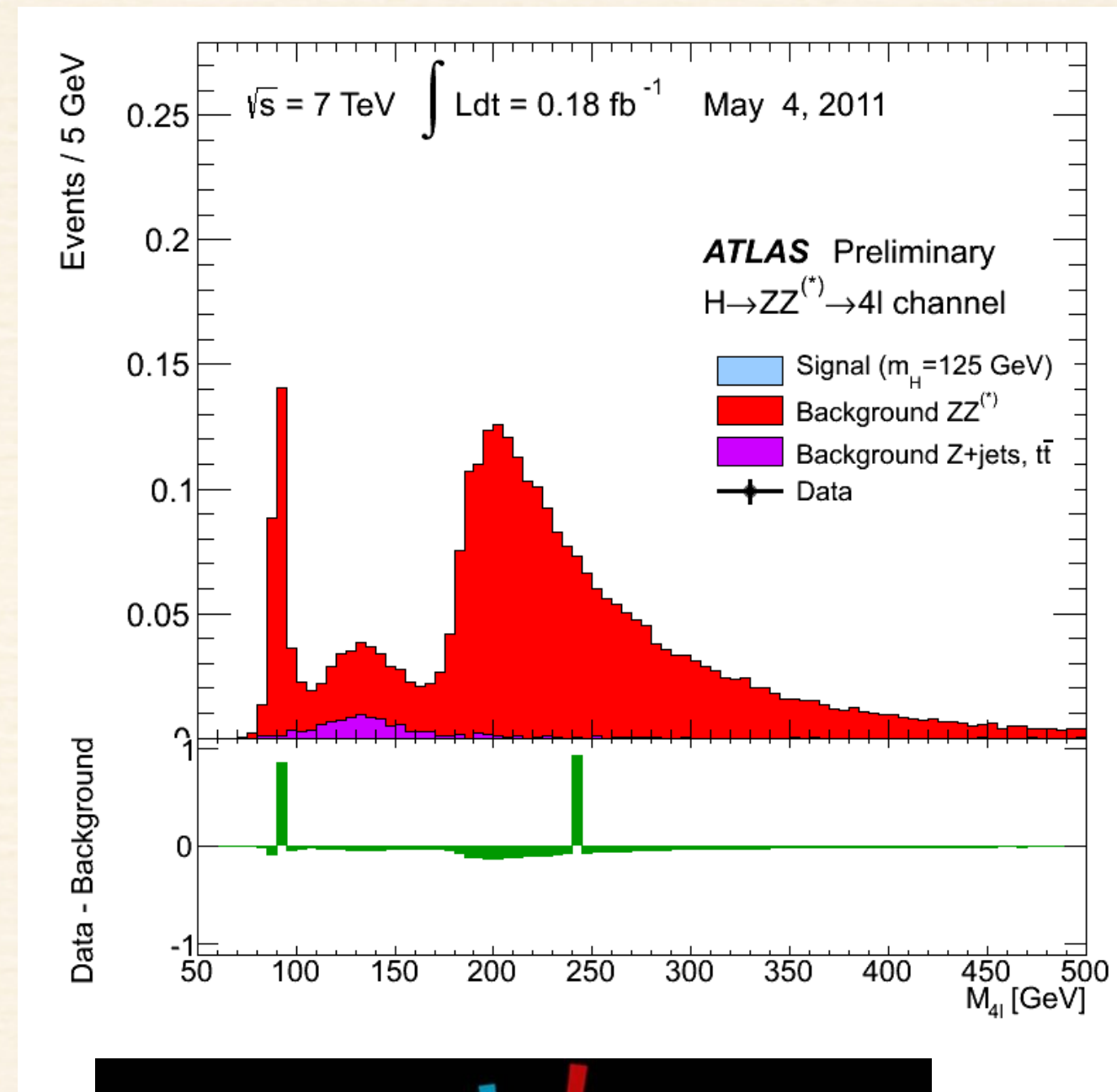
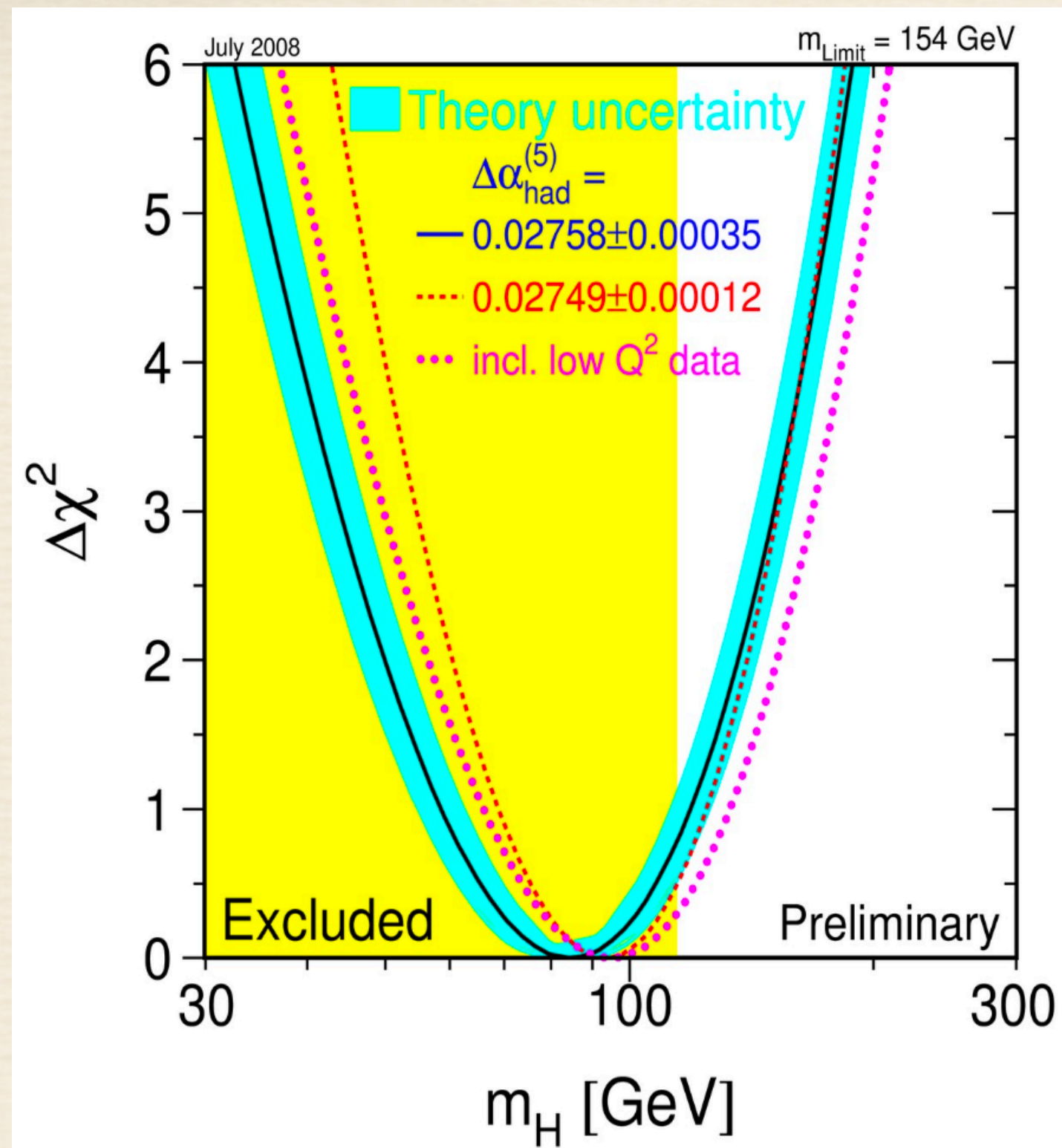
$$(\Delta r_{\overline{\text{MS}}})^{\text{SM}} = 0.0692(1) + 6.5 \times 10^{-4} \ln [m_H/126 \text{ GeV}]$$

$$m_H = 91^{+18}_{-16} \text{ GeV}$$

Higgs Discovery

$$H \rightarrow Z^0 Z^{0*} \rightarrow l_1^+ l_1^- l_2^+ l_2^-$$

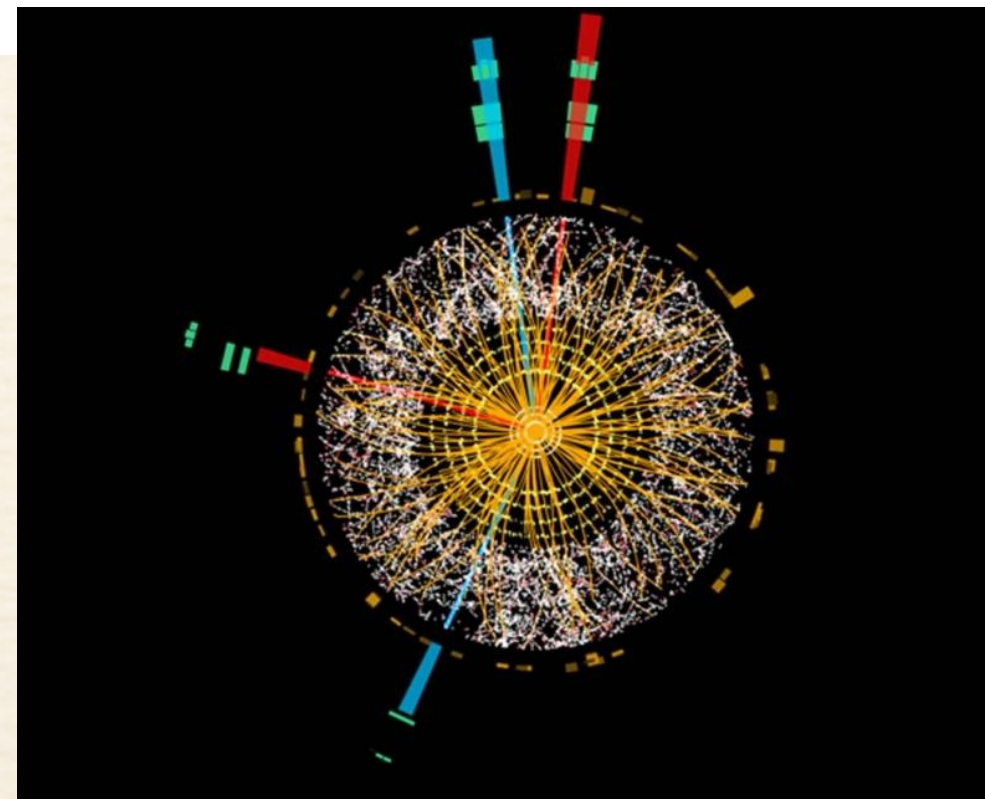
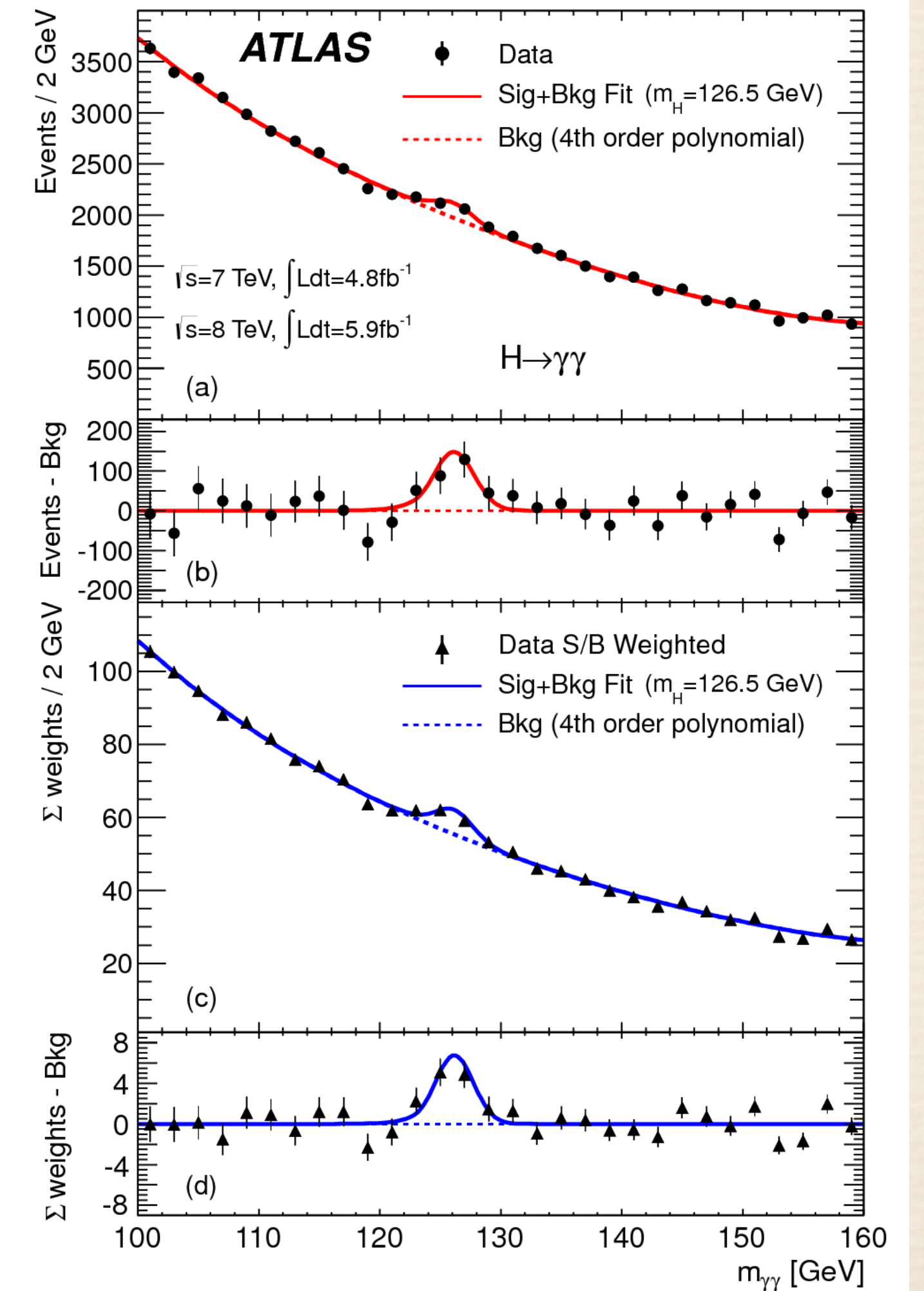
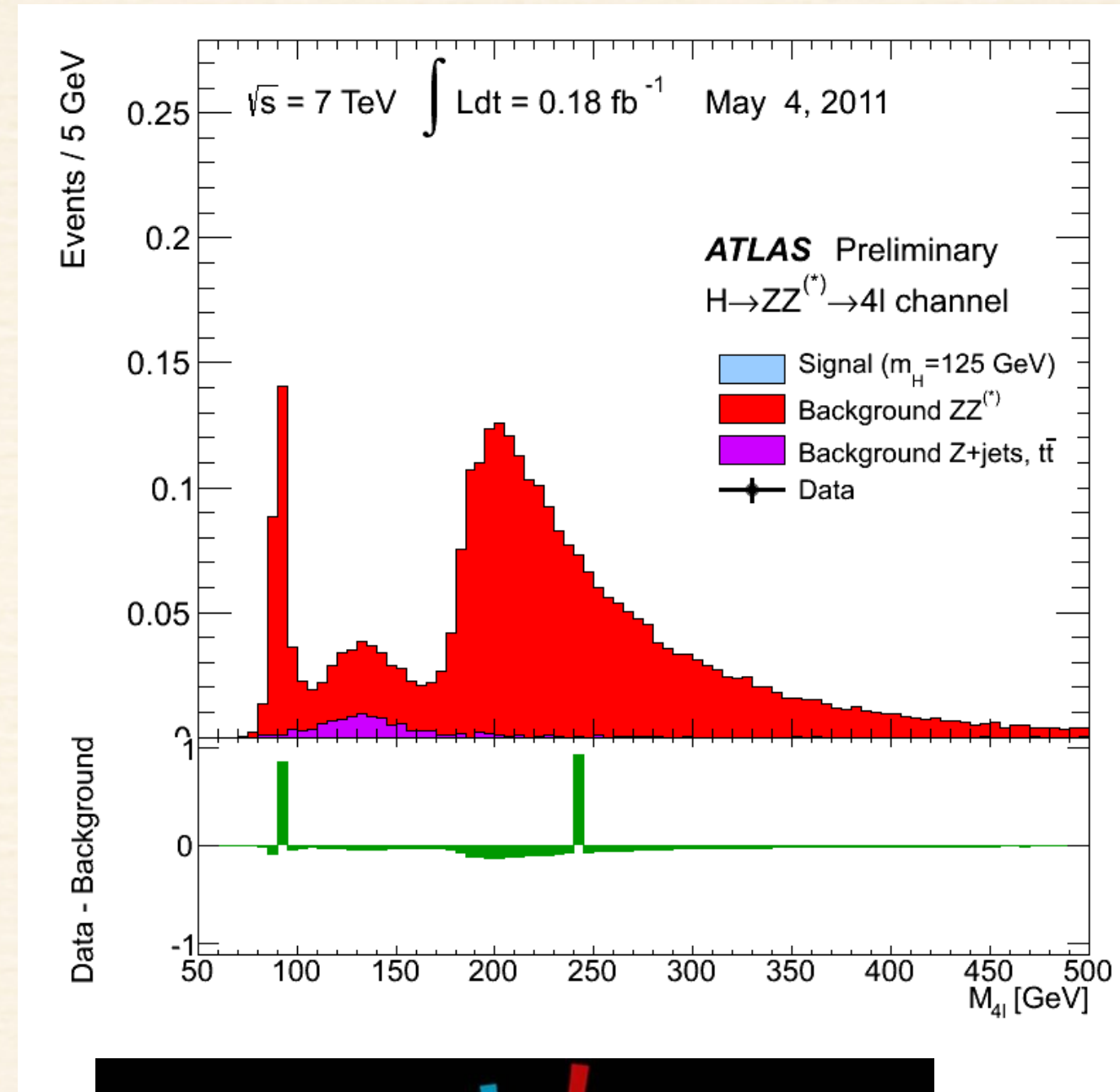
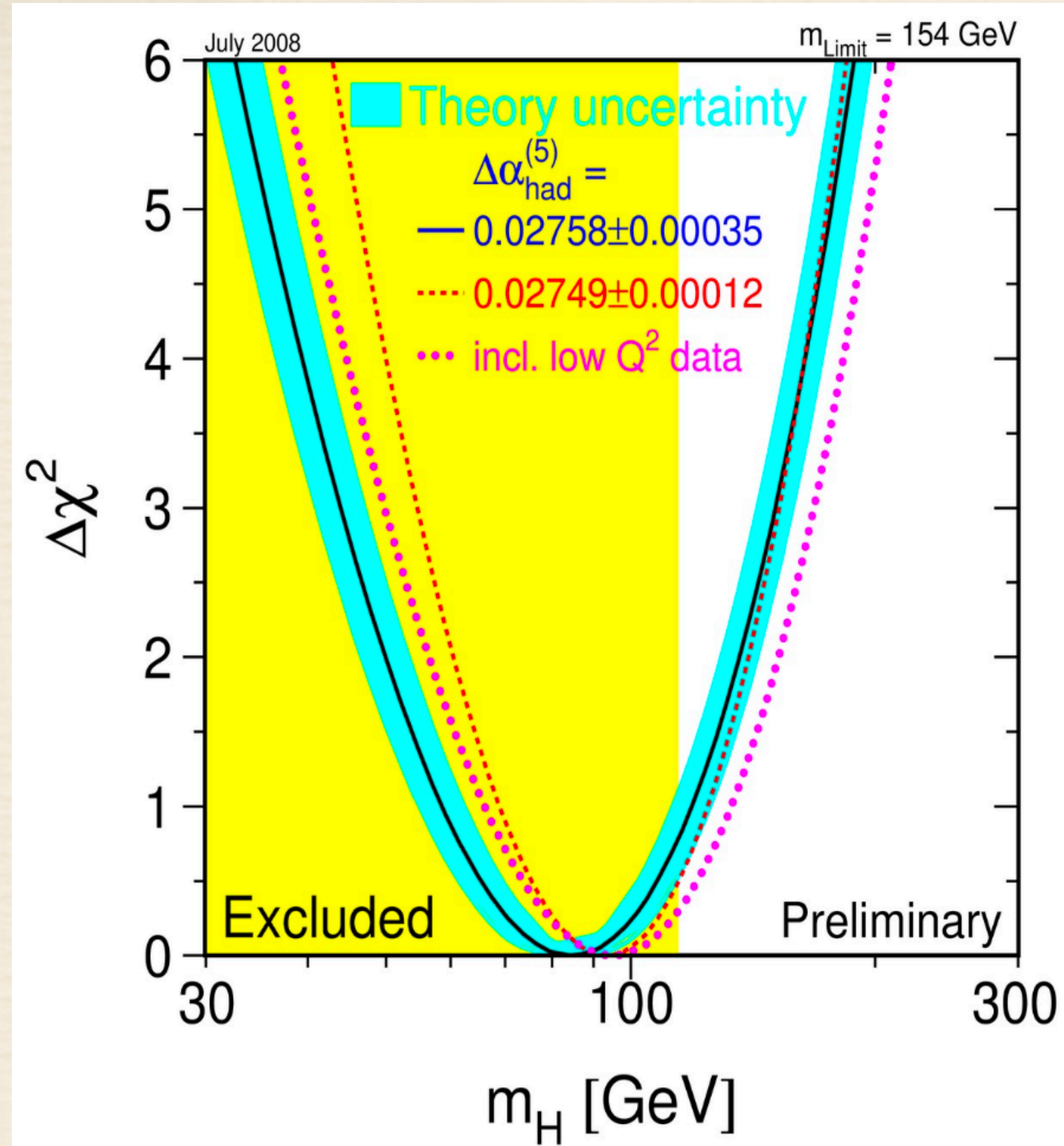
$$H \rightarrow \gamma\gamma$$



Higgs Discovery

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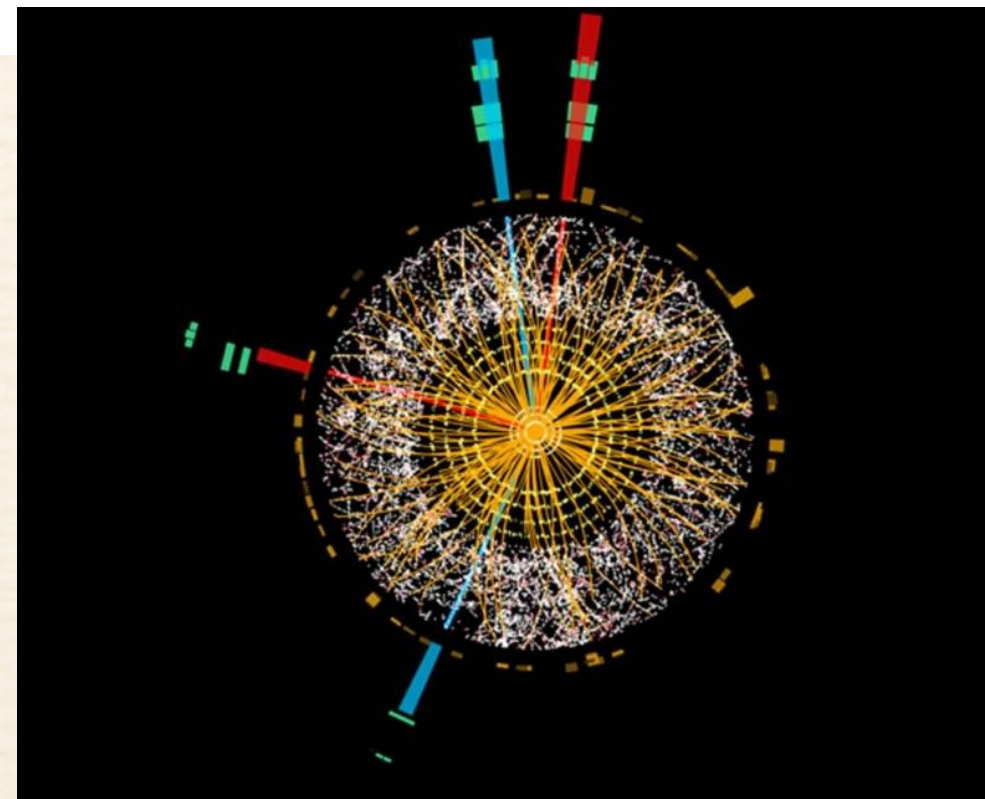
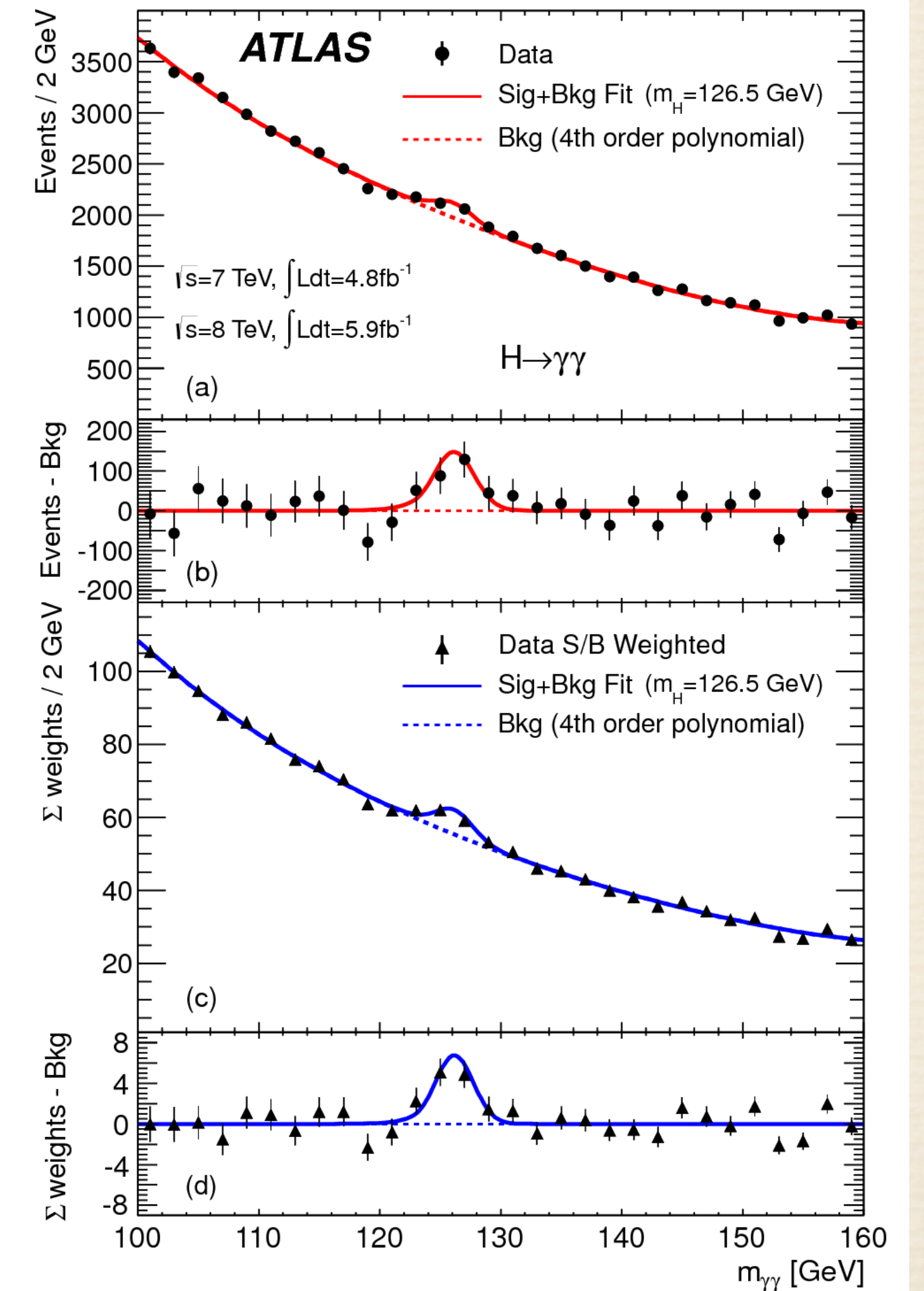
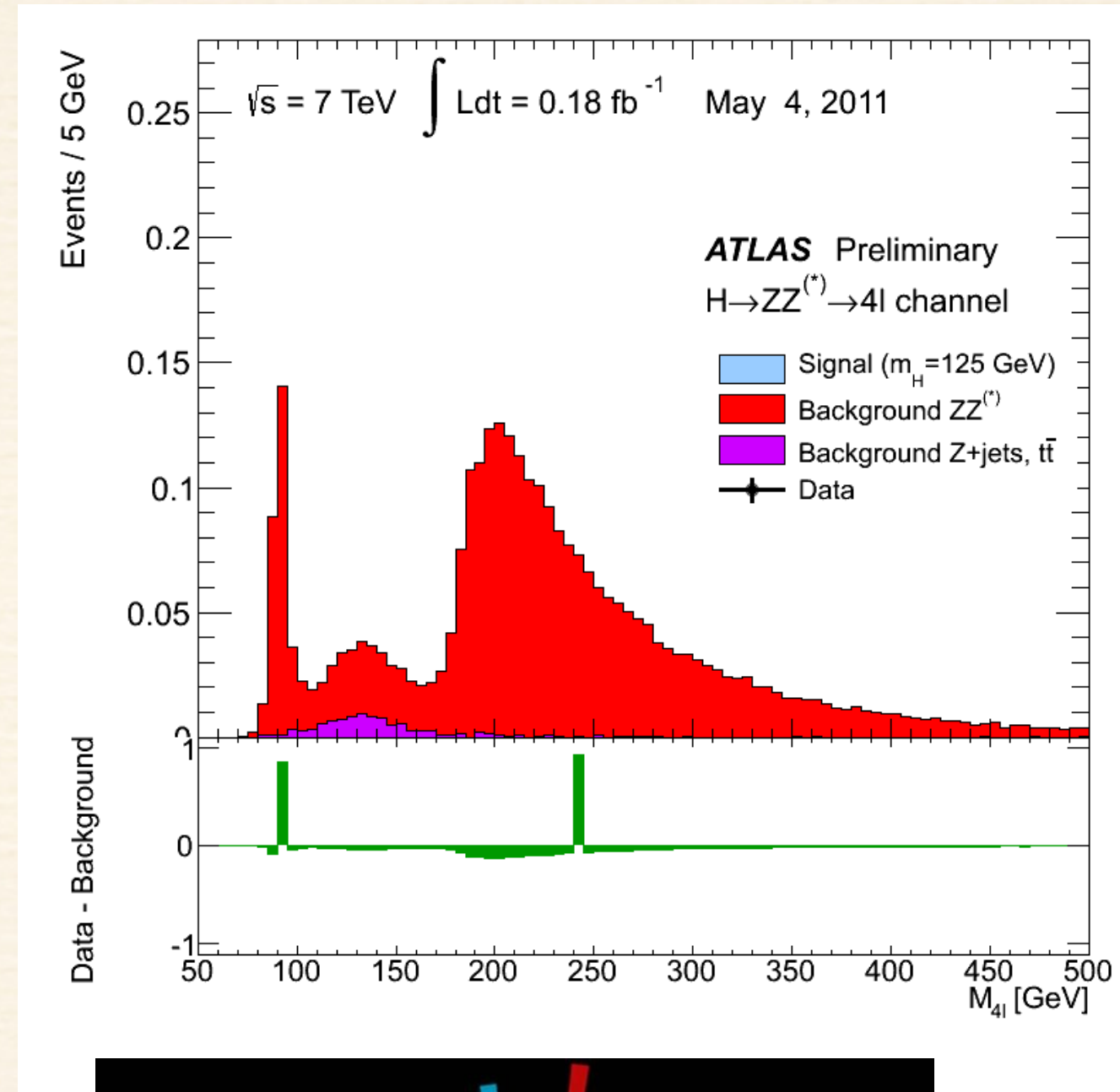
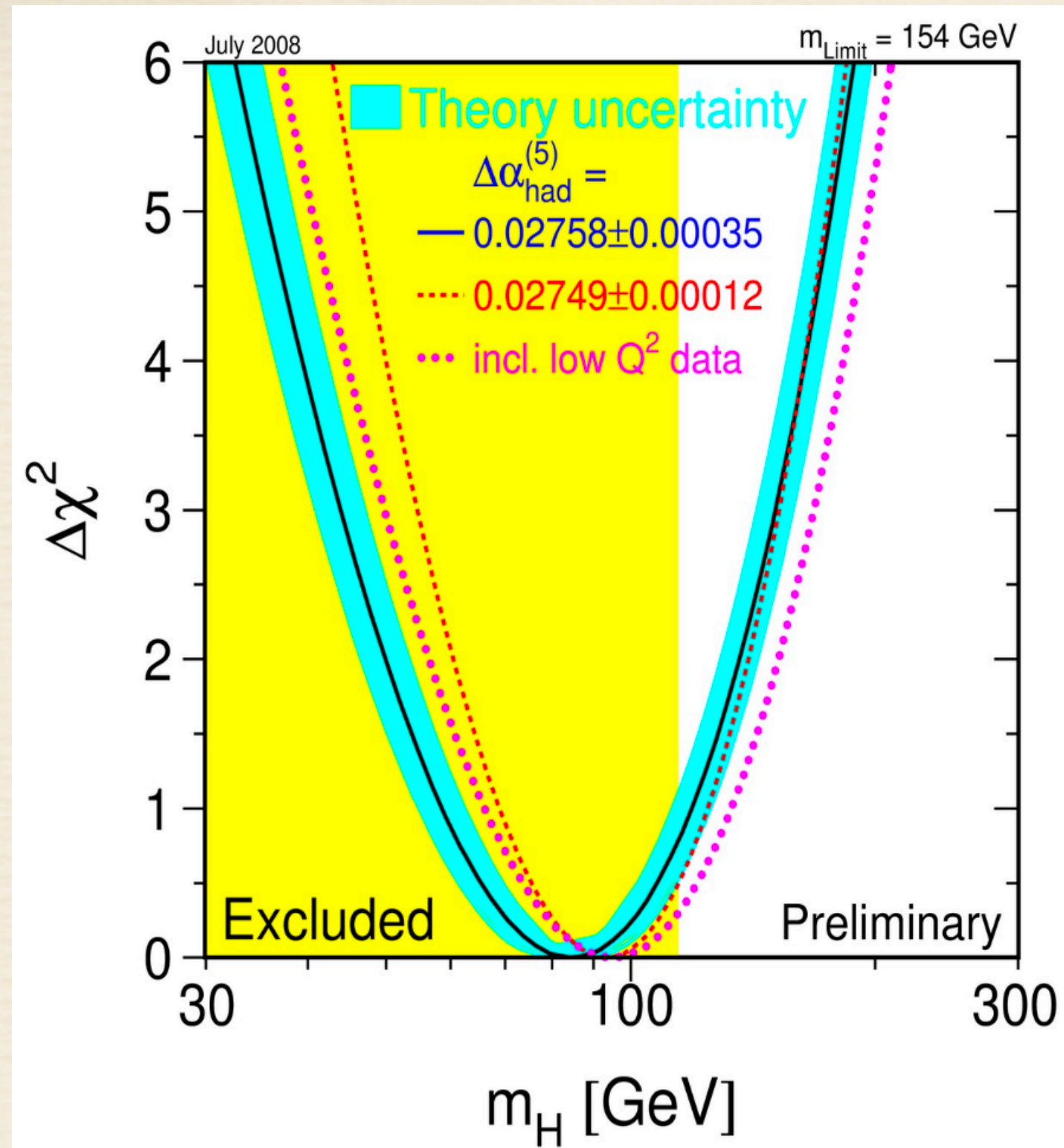
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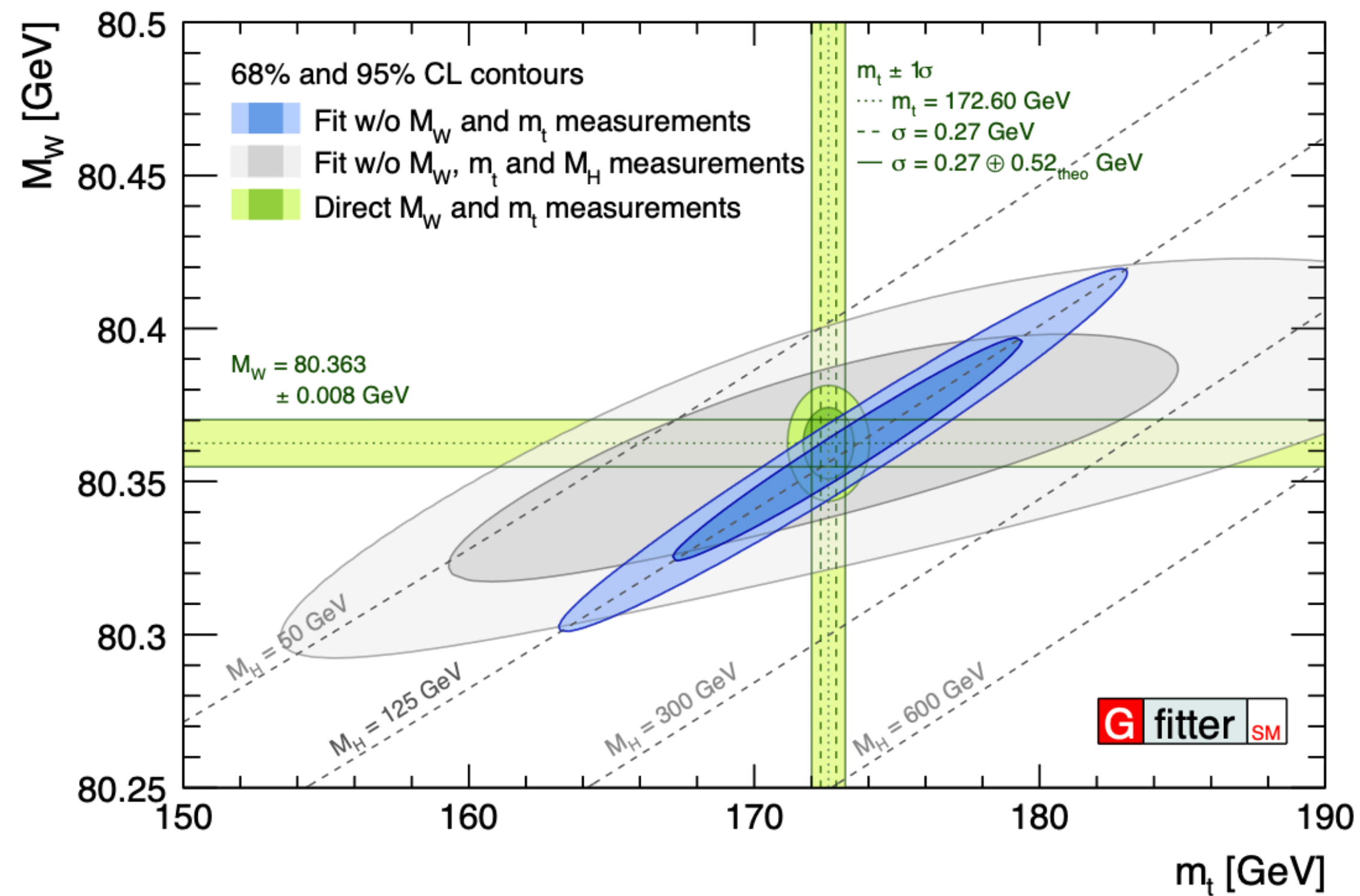
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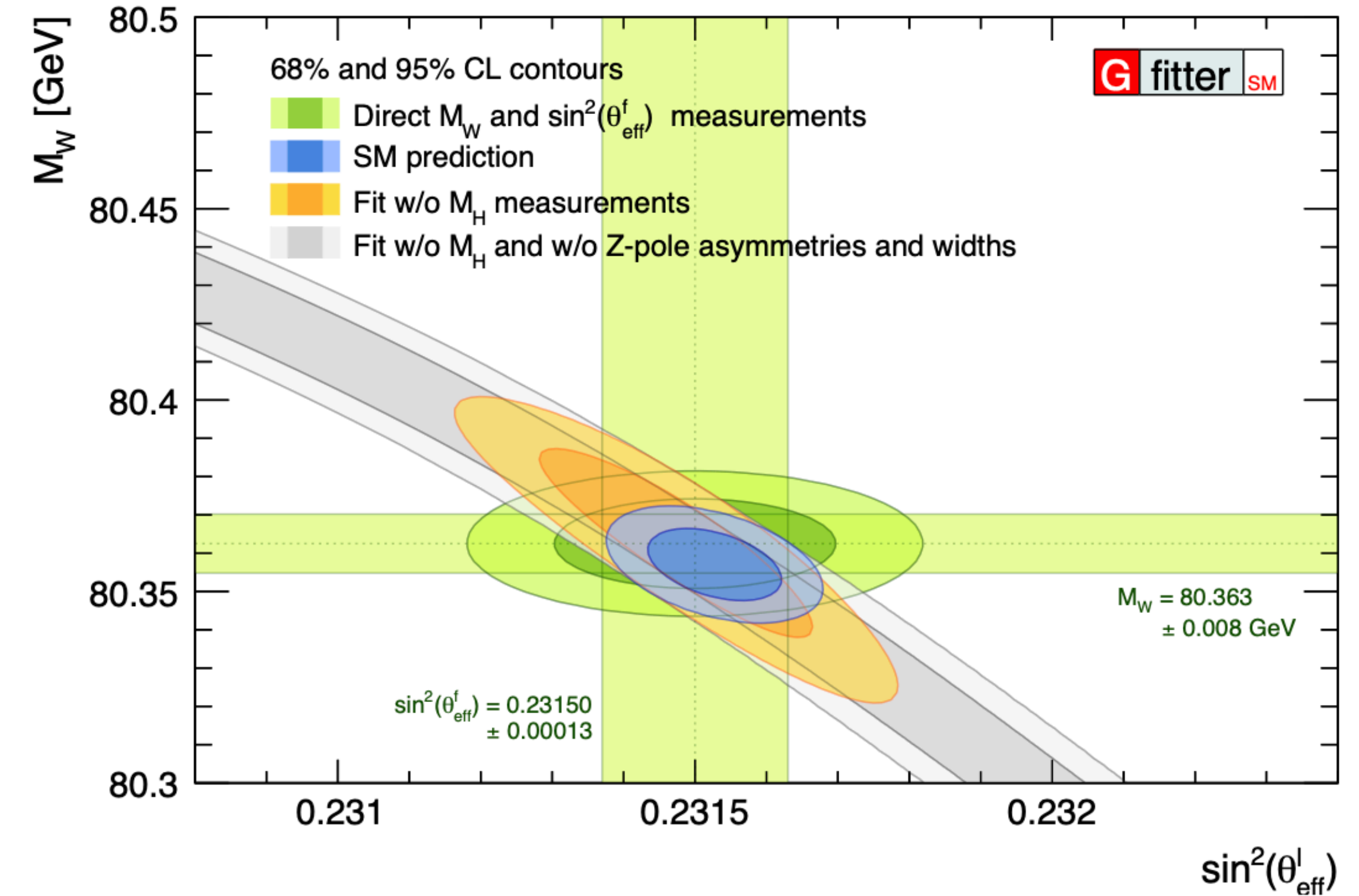
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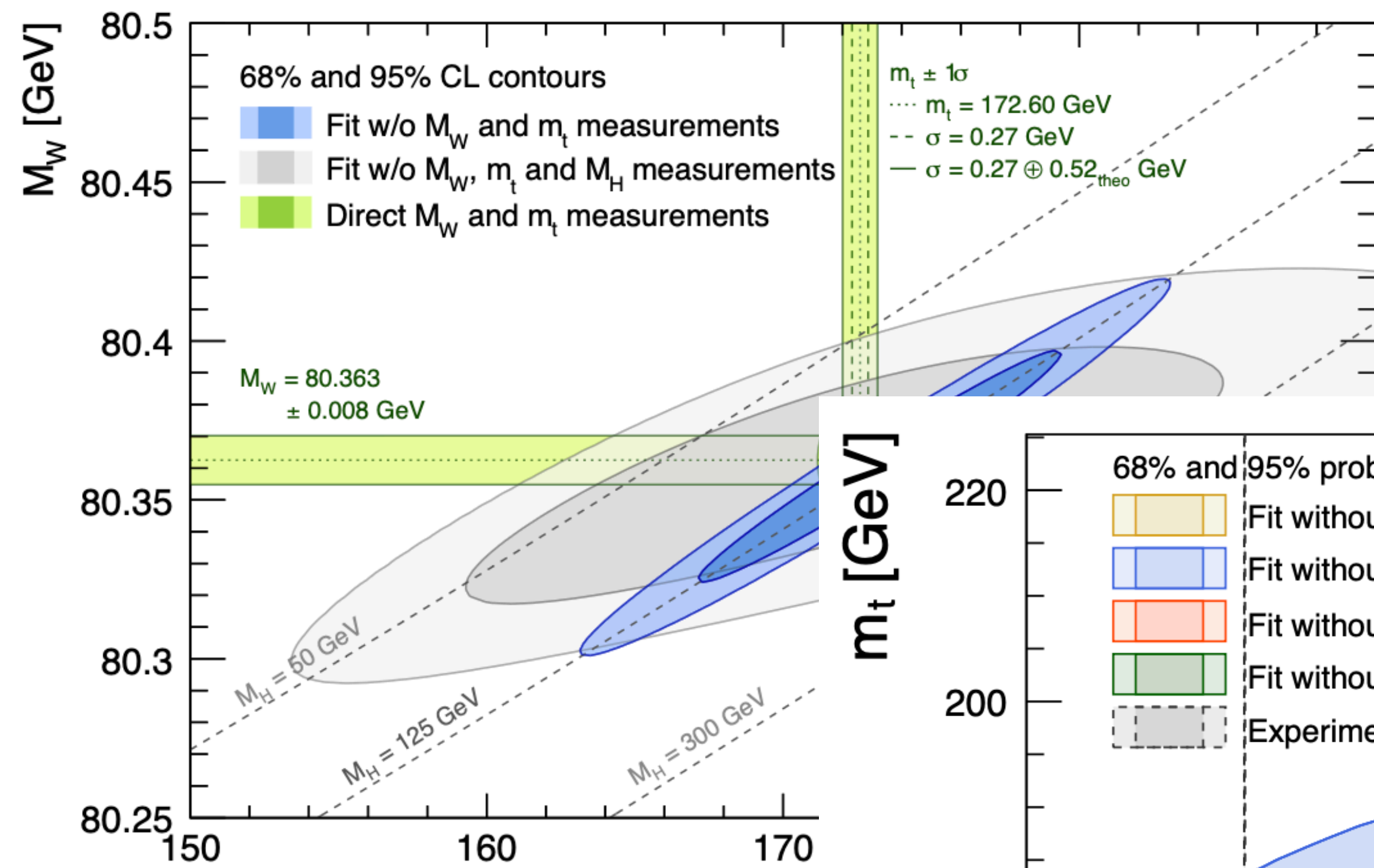
Global Fits



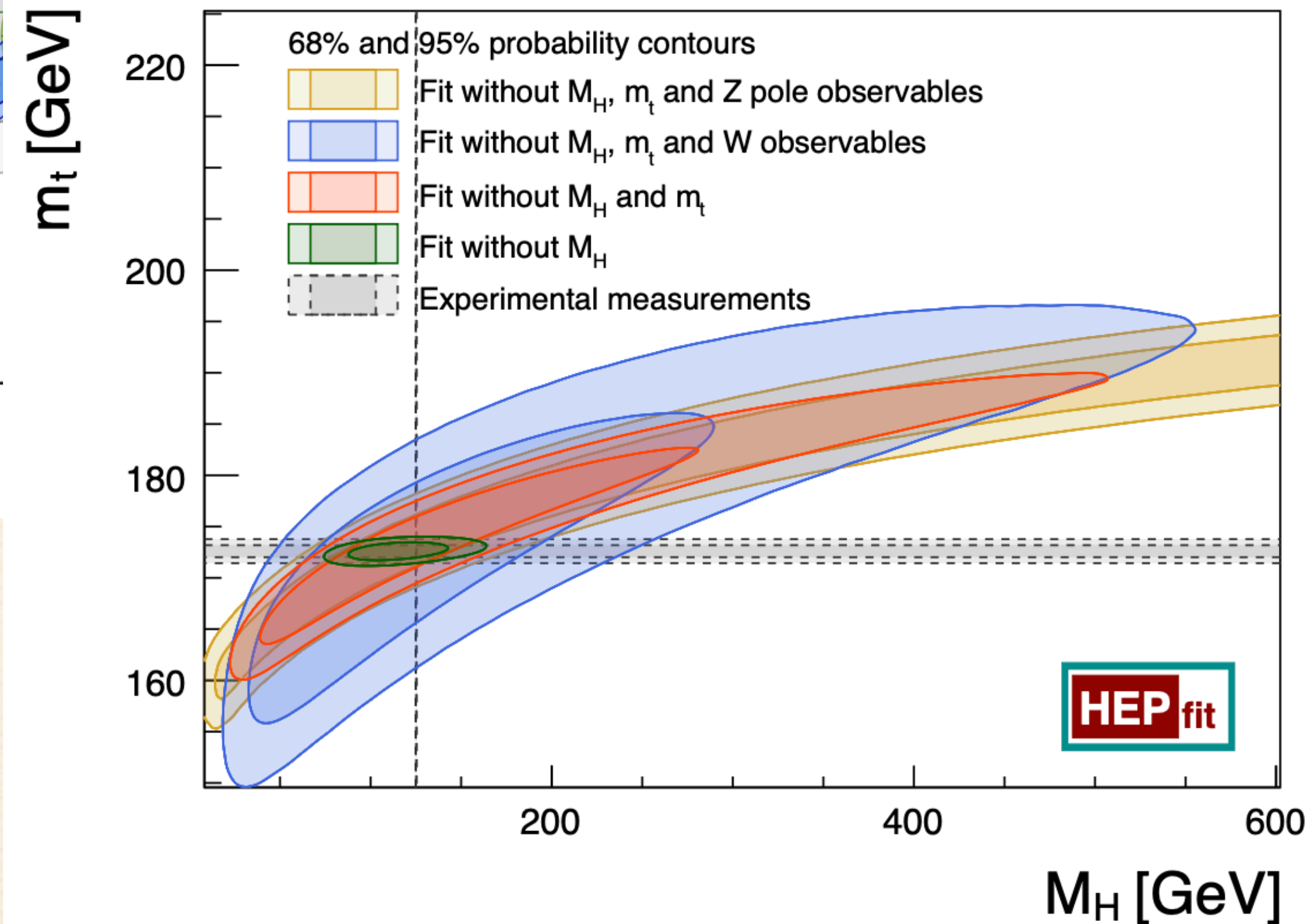
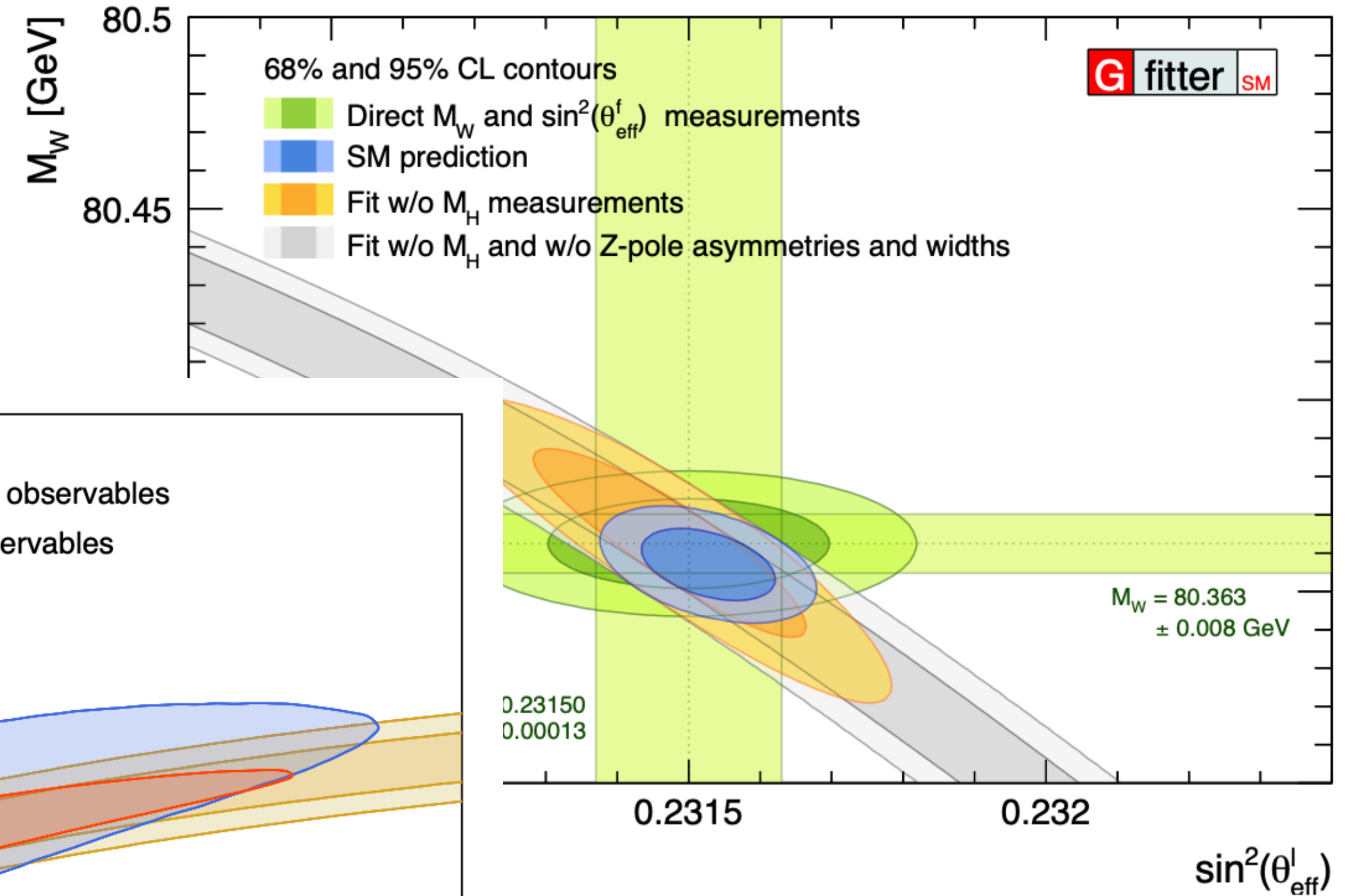
PDG
2026



Global Fits



PDG
2026



Open Questions

The Higgs Discovery was bittersweet!

One free parameter: weak mixing angle θ_W

$$\begin{aligned}\tan \theta_W &= \frac{g'}{g} & A_\mu &= B_\mu^0 \cos \theta_W + W_\mu^0 \sin \theta_W \\ e &= g \sin \theta_W & Z_\mu &= W_\mu^0 \cos \theta_W - B_\mu^0 \sin \theta_W.\end{aligned}$$

Higgs Mechanism + Renormalizability

$$\sin^2 \theta_W^0 = \left(\frac{e^0}{g^0} \right)^2 = 1 - \left(\frac{M_W^0}{M_Z^0} \right)^2$$

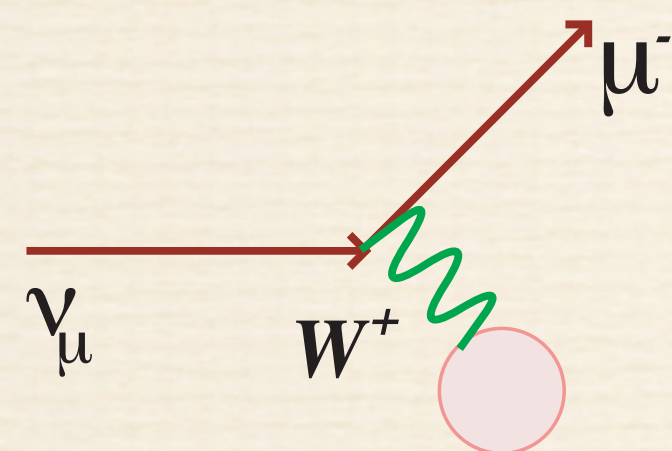
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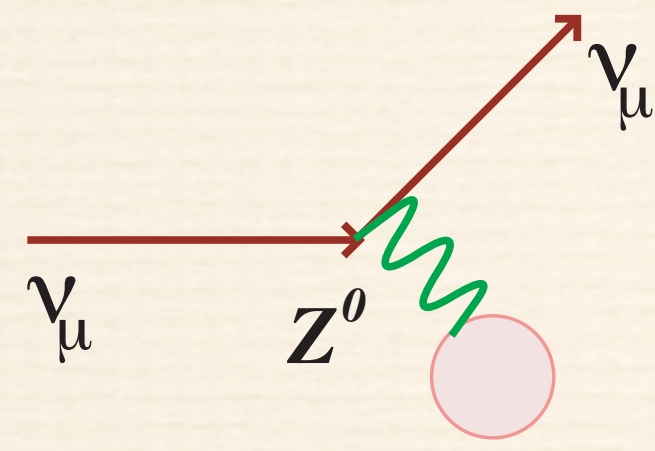
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Charged Current



Neutral Current

Higgs Mechanism + Renormalizability

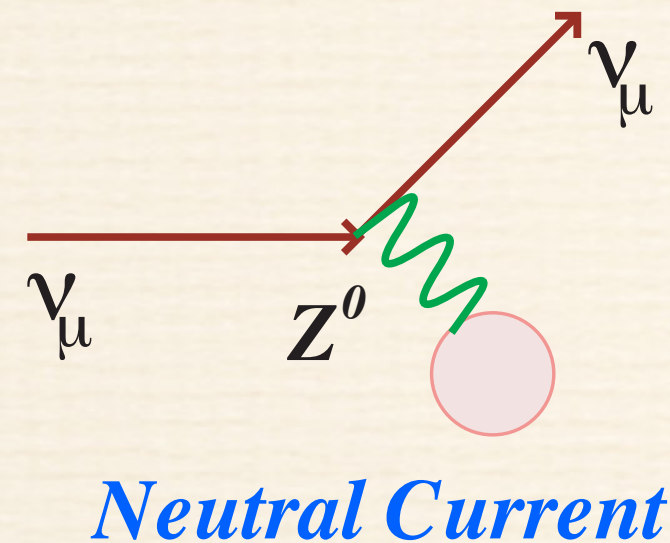
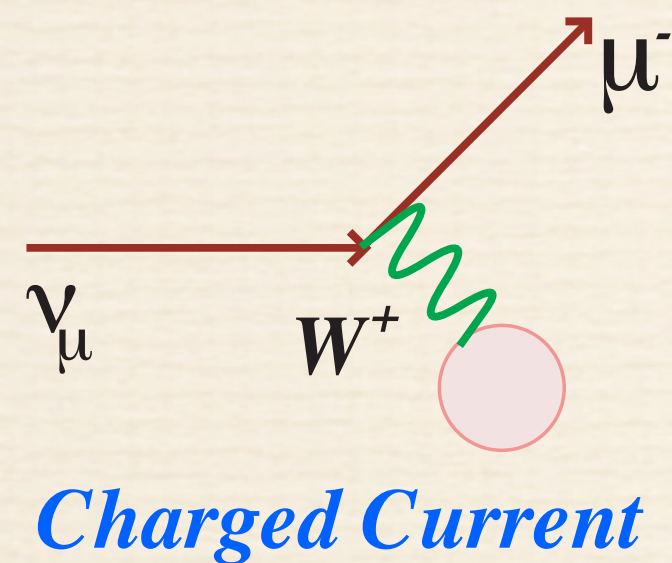
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- **Why is the weak boson scale 100 GeV?**
- **Why are there 3 generations of particles?**
- **How did matter come to dominate over anti-matter?**
- **Were there as yet unobserved new forces in the early universe?**
- **Is there a unifying framework to describe all forces?**
- **Why are neutrinos so light?**
- **Why is the top so heavy?**
- **...**

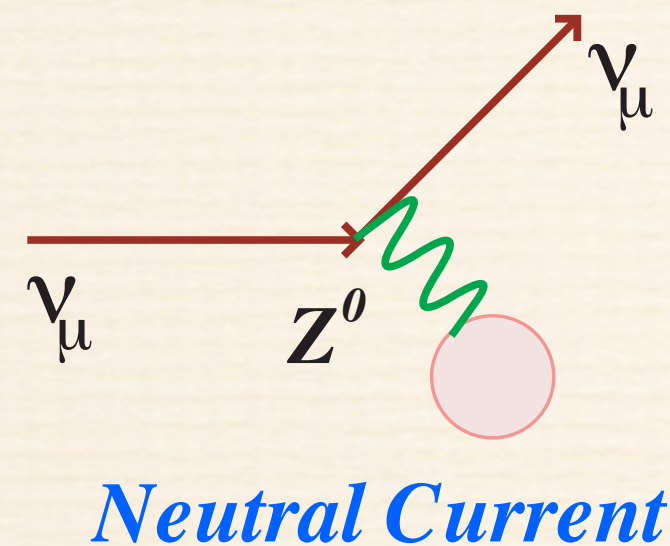
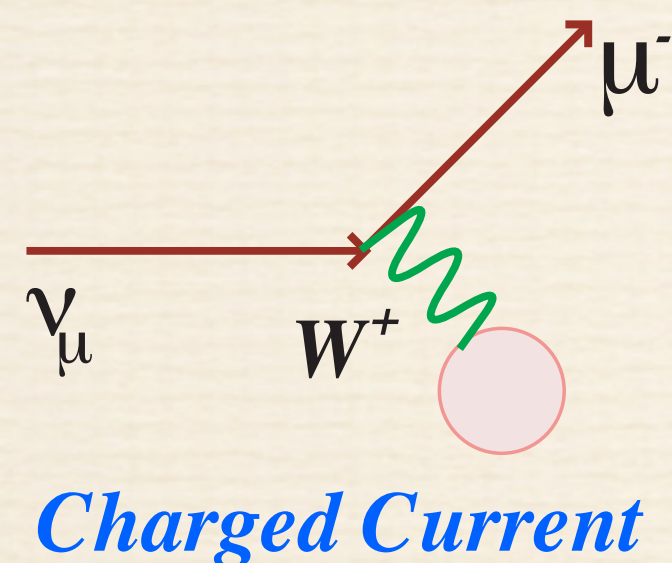
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No guidance on where to look!!! One has to take a very broad approach to make progress...

BSM Searches must be as model-independent as possible

Comprehensive Experimental Strategy

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

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Comprehensive Experimental Strategy

The High Energy Frontier: Collider Physics

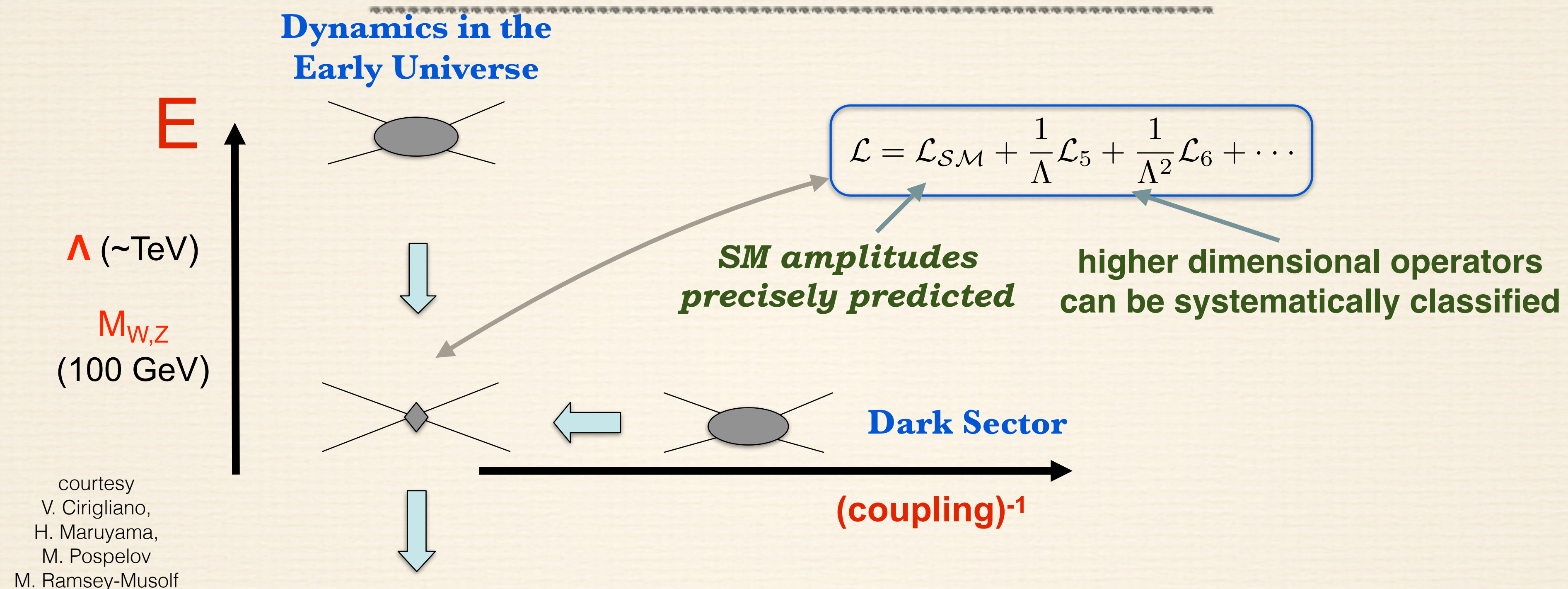
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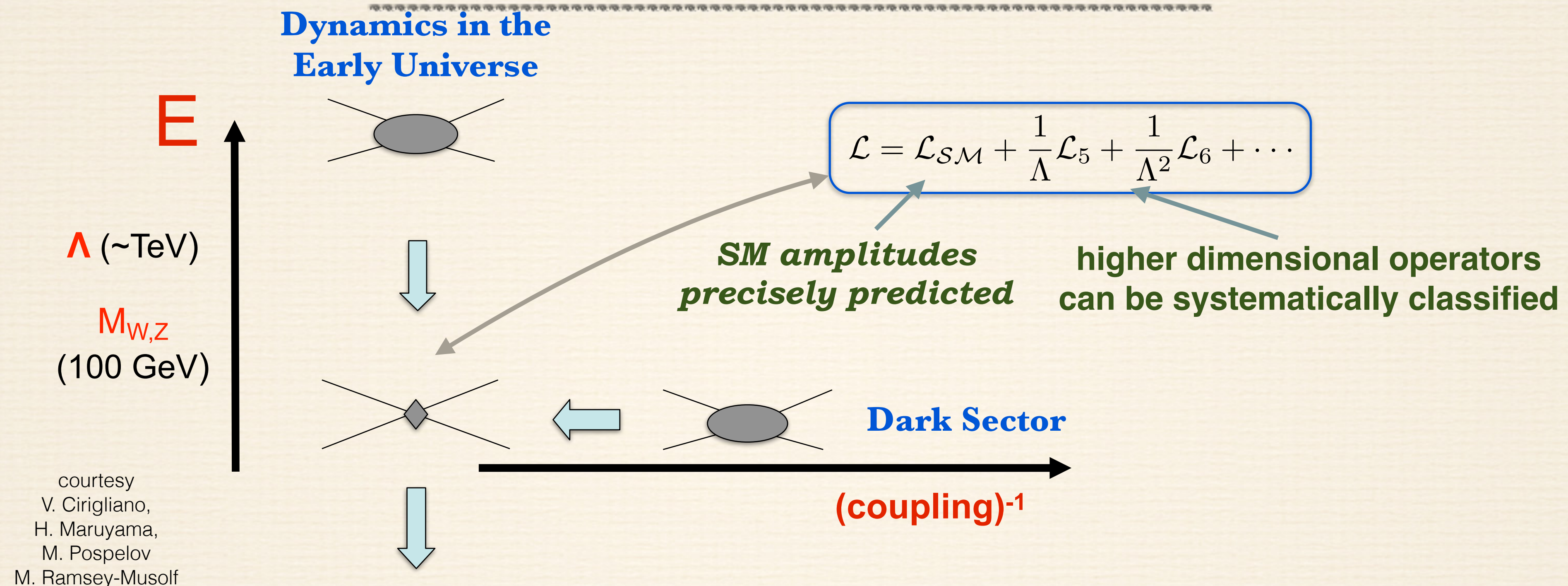
- ★ **Measurements of Neutrino Properties**
- ★ **Direct and Indirect Searches for Dark Matter**
- ★ **Searches for Violation of Accidental (?) Symmetries**
- ★ **Precise Measurements of SM observables**

Intensity Frontier Strategy



Discoveries and Insights about Big Questions

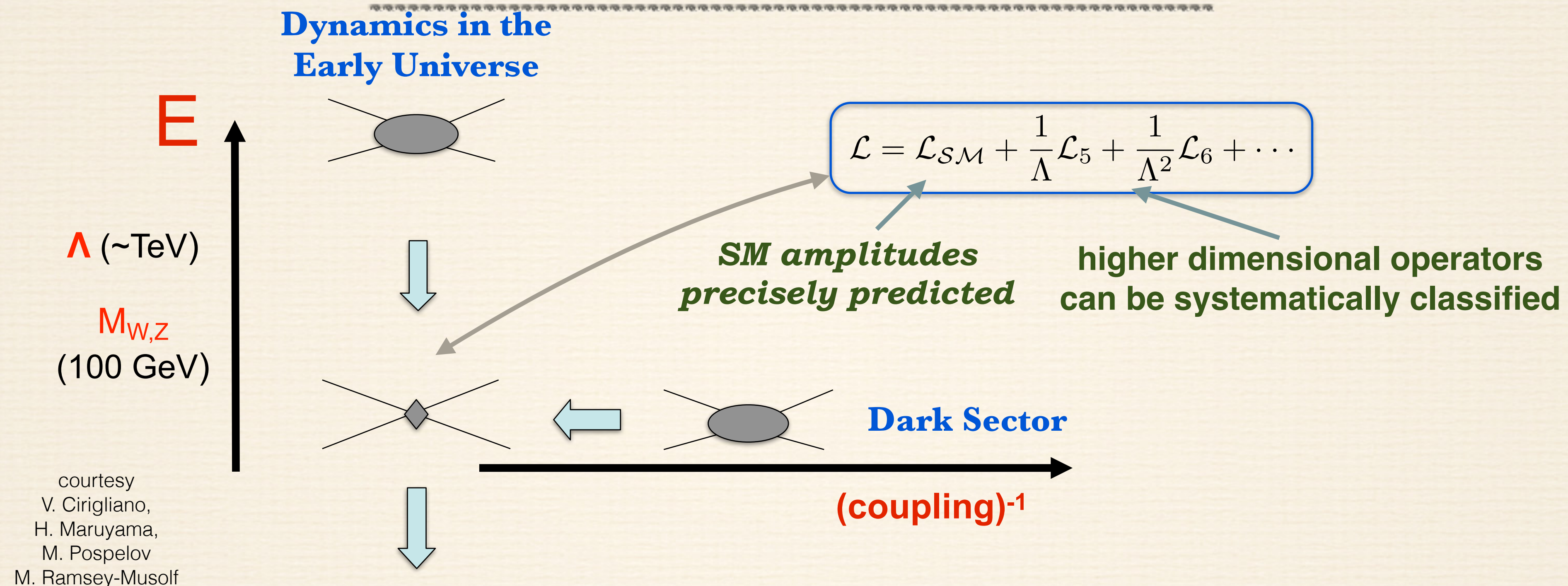
Intensity Frontier Strategy



Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

Intensity Frontier Strategy



Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

In most cases, observables exploit a symmetry principle

Timescales and Length Scales

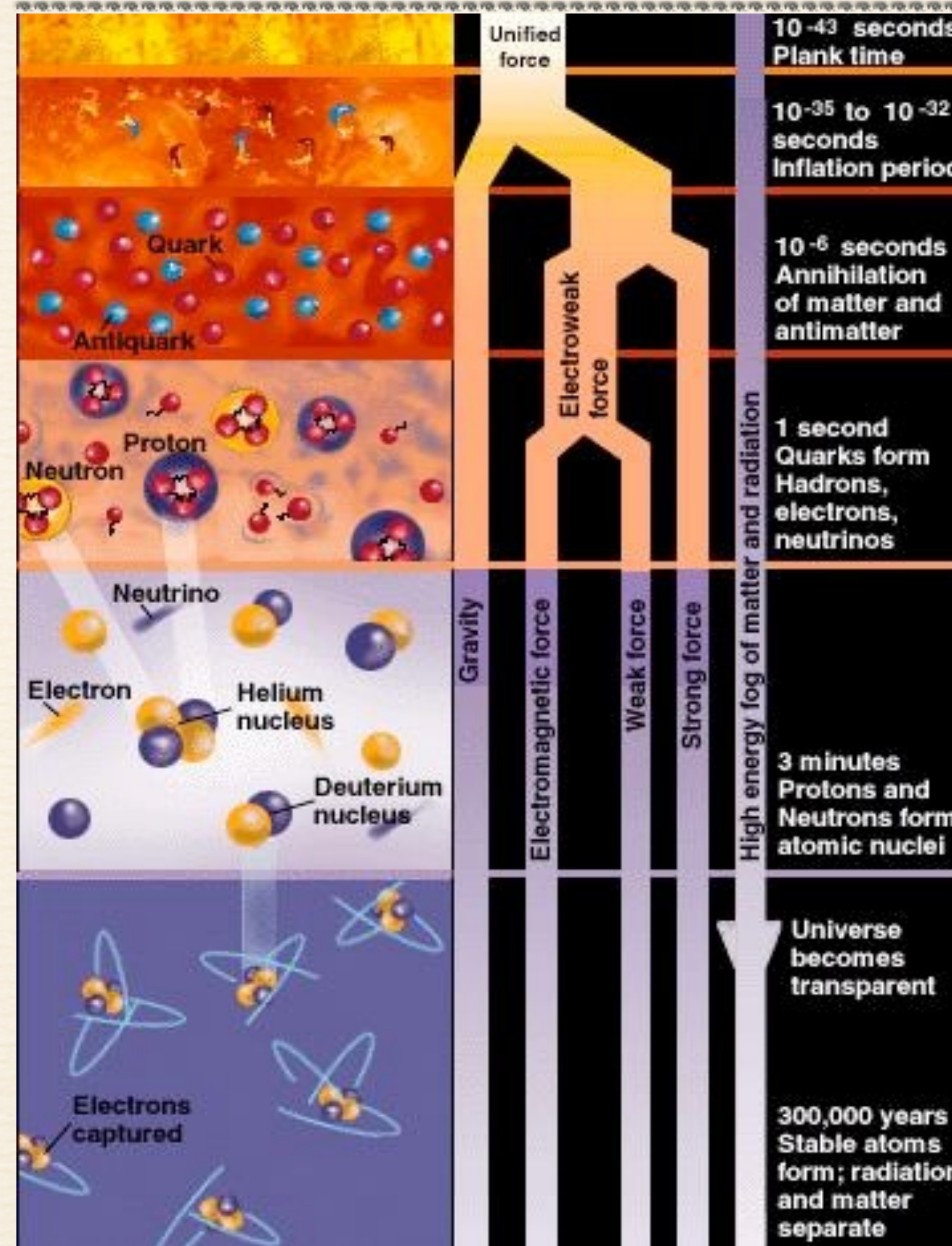
?

↑

attometers

↑

femtometers



femtometers

↓

picometers

General BSM EFT Framework

Describe new physics originating at $\Lambda \gg v_{ew}$ through local operators of increasing mass dimension

$[\Lambda \leftrightarrow M_{BSM}] \quad C_i [g_{BSM}, M_a/M_b]$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

Weinberg 1979,
Wilczek-Zee 1979,
Buchmuller-Wyler 1986,

Grzadkowski-Iskrzynski- Misiak-Rosiek 2010,
Alonso, Jenkins, Manohar, Trott 2013
...

“Standard Model EFT” (SMEFT):

- ★ Build operators out of **SM fields**
- ★ Impose **Lorentz + SM gauge symmetry**
- ★ Organize operators according to mass dimension
power counting in $E/\Lambda, M_W/\Lambda$

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Two Classes of Operators

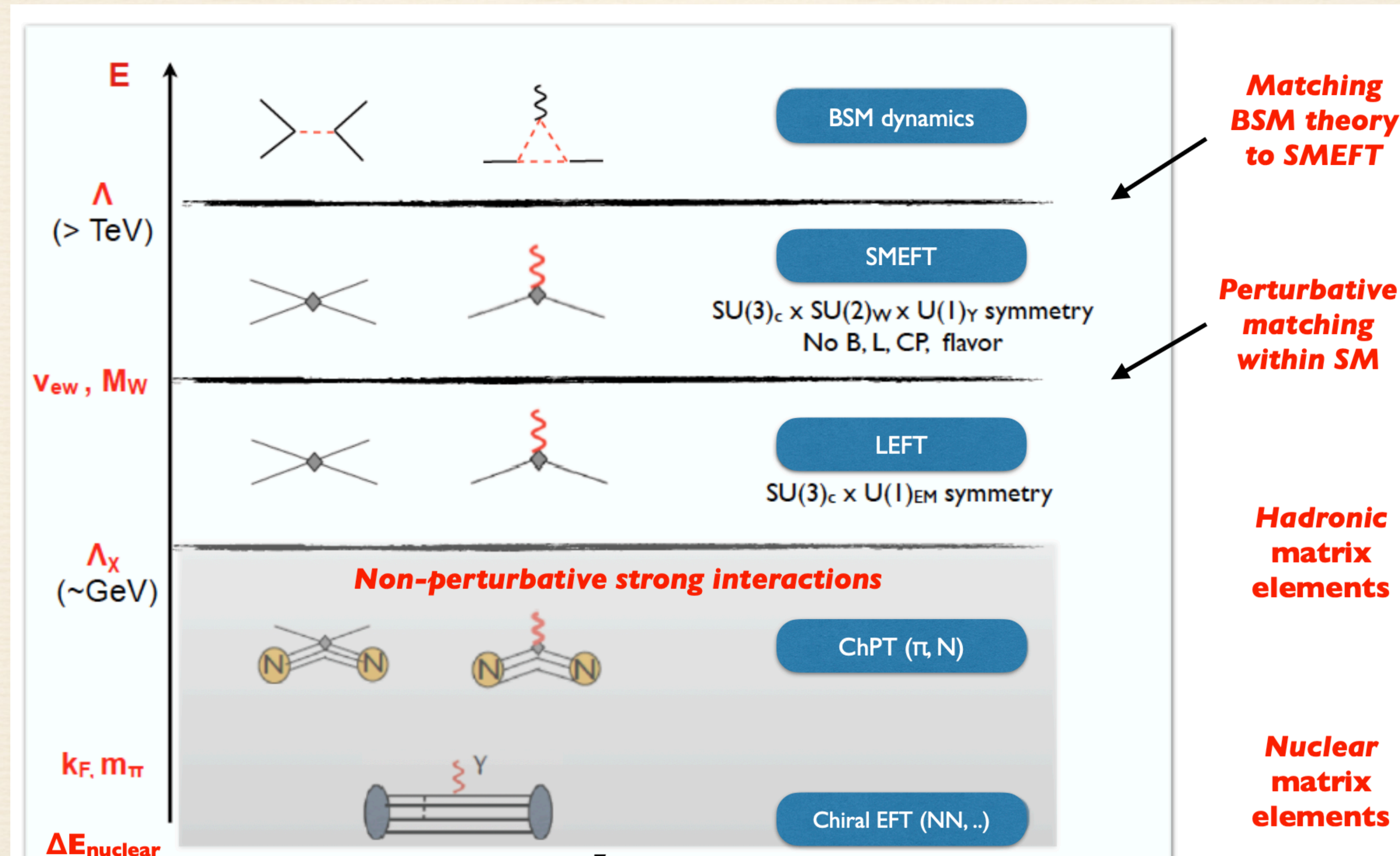
Operators that **violate approximate or exact symmetries of the SM**: mediate rare or forbidden processes (proton decay, $0\nu\beta\beta$, EDMs, $\mu \rightarrow e$, quark flavor violation, ...)

Operators that **give corrections to SM “allowed” processes**: probe them with precision measurements (muon g-2, weak decays, electron scattering ...)

Connecting Scales

V. Cirigliano

To connect new physics to low-energy, use a tower of EFTs in which **SMEFT** is the **SM-BSM link**



Tools to Probe BSM Physics

Intensity Frontier Experimental Facilities/Initiatives/Programs

- **Electron Beams:** *charged current couplings, weak mixing angle, dark photons*
 - ➔ *Jefferson Lab, Mainz MESA, Electron-Ion Collider*
- **Muons, Kaons, Pions:** *Lifetimes, Precision Bus, Flavor Universality, muon $g-2$, EDMs*
 - ➔ *BNL, PSI, TRIUMF, FNAL, J-PARC*
- **Neutrino Beams:** *Oscillations, PMNS matrix, CP-violation*
 - ➔ *Fermilab, KEK, CERN*
- **Neutrons:** *Lifetime, Asymmetries, EDM*
 - ➔ *LANSCCE, NIST, SNS, other international labs..*
- **Underground Detectors:** *Direct Dark Dark Matter, Double-Beta Decay*
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- **Nuclei:** *Precision Weak Decays, Atomic Parity Violation, EDMs*
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JLab can contribute and complement some of these topics

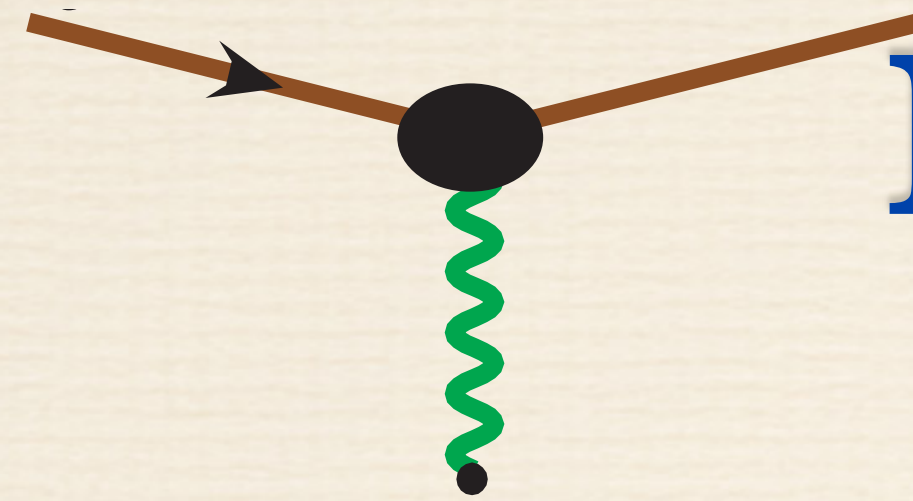
Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

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New Physics via SMEFT

◆ Violation of Lepton Number

★ Neutrinoless Double-Beta Decay, muon and tau appearance at the EIC, MOLLER at JLab

$$\frac{1}{\Lambda} \mathcal{L}_5 \quad 10^{15} \text{ GeV} \quad \frac{1}{\Lambda^5} \mathcal{L}_9 \quad \text{multi-TeV}$$

◆ Violation of Time Reversal Symmetry

★ Non-zero Electric Dipole Moment of the Electron, T-odd observables at the EIC

100s of TeV

◆ Violation of Charged Lepton Flavor

★ muon-to-electron conversion, tau appearance at the EIC

100s of TeV

◆ Flavor changing neutral currents

★ Rare pion and kaon decays, direct leptoquark production at EIC

100s of TeV

$$\frac{1}{\Lambda^2} \mathcal{L}_6$$

◆ Flavor conserving neutral currents

★ Precision weak mixing angle measurements at JLab and EIC

10s of TeV

Lecture 1 Summary

- **Symmetries and Conservation Laws**
 - *Powerful conceptual avenue to synthesize our current understanding of fundamental interactions and how to channel our creativity for new discoveries*
- **Electroweak Interactions**
 - *Since the 1990's, we have made enormous progress in understanding electromagnetic and weak interactions at extraordinary precision*
 - *We now have complete verification of physics at the scale of electroweak symmetry breaking including Higgs boson interactions*
- **BSM Physics**
 - *There is a worldwide systematic push to search for new physics beyond the Standard Model using a large and varied array of experimental techniques*