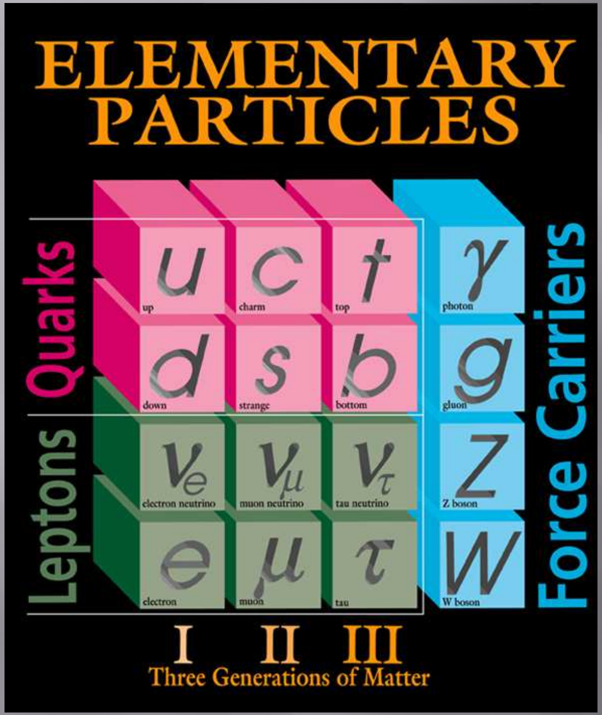
LECTURE 3

Standard Model

It Works!

Why do we believe in it?



- ❖ All gauge bosons and fundamental fermions experimentally verified
- ❖ Electroweak precision measurements at LEP(CERN), SLC(SLAC), Tevatron(Fermilab) have confirmed SM predictions to 0.1% accuracy
- ❖ Anomalous magnetic moment of the electron Theory : g/2 = 1.001 159 652 180 85 (76), a precision of better than one part in a trillion

Fundamental Particles and their interactions understood in terms of the Standard Model

SM has been extremely successful.

The problem facing particle physics is that
"the Standard Model worked too well!"

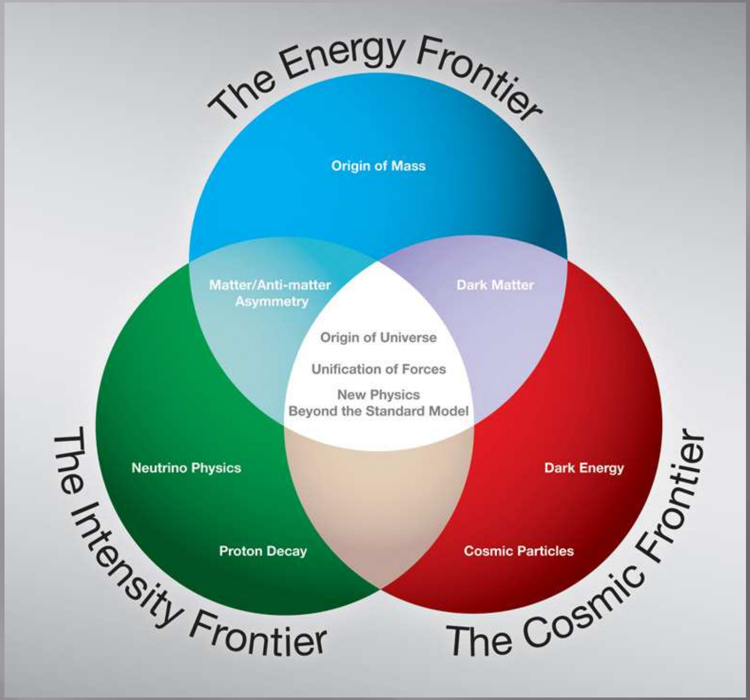
There are many unresolved questions

Why a problem?

- Why are there 3 generations ?
- What determines the patterns of the masses and mixings of quarks and leptons?
- CP Violation:Matter-Antimatter asymmetry of the Universe
- The Hierarchy Problem
- How to include Gravity?
- What is dark matter/dark energy?

⇒there must be Physics beyond the SM.

Towards Search for New Physics



Energy Frontier

Particle collisions at higher energies will
Produce particles that signal new phenomena
LHC, ILC

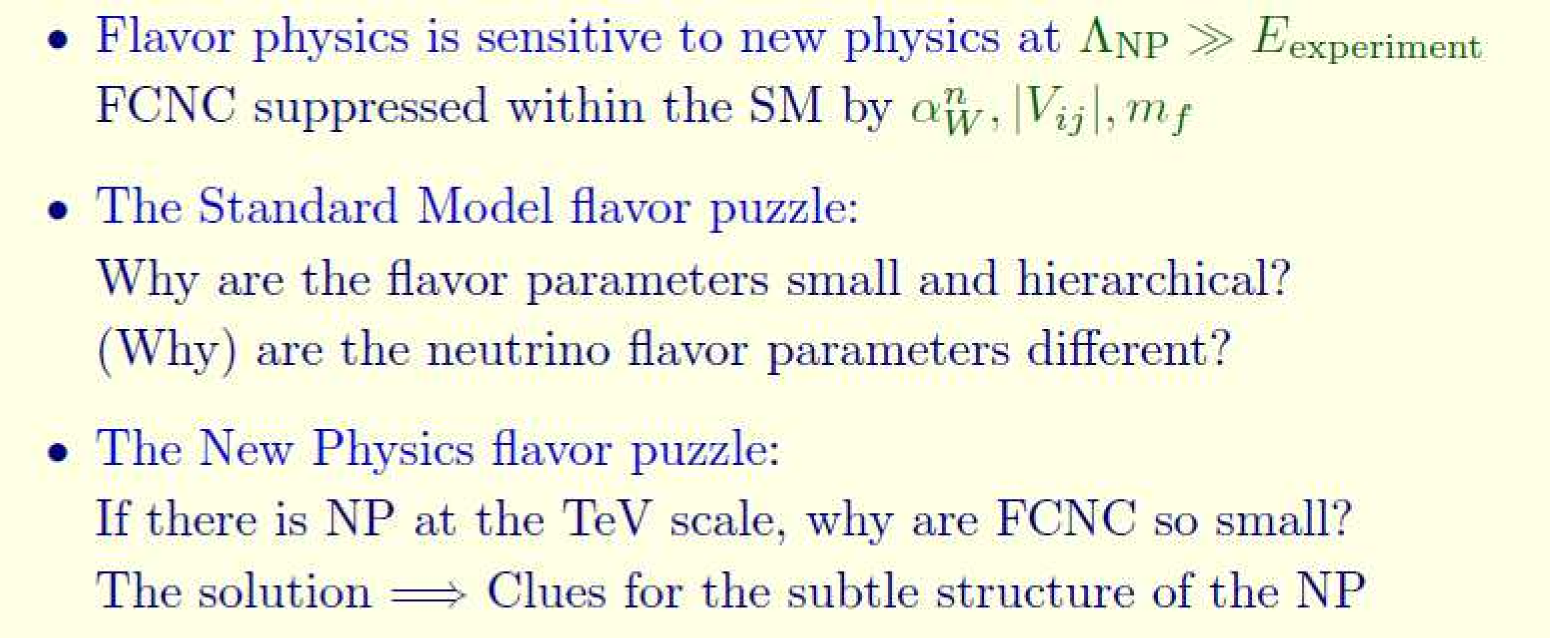
Intensity Frontier

Intense beams of particles (at lower energies)
to obtain larger number of particles:
for measurement of rare processes
Flavour Physics Experiments
Neutrino experiments, B factories

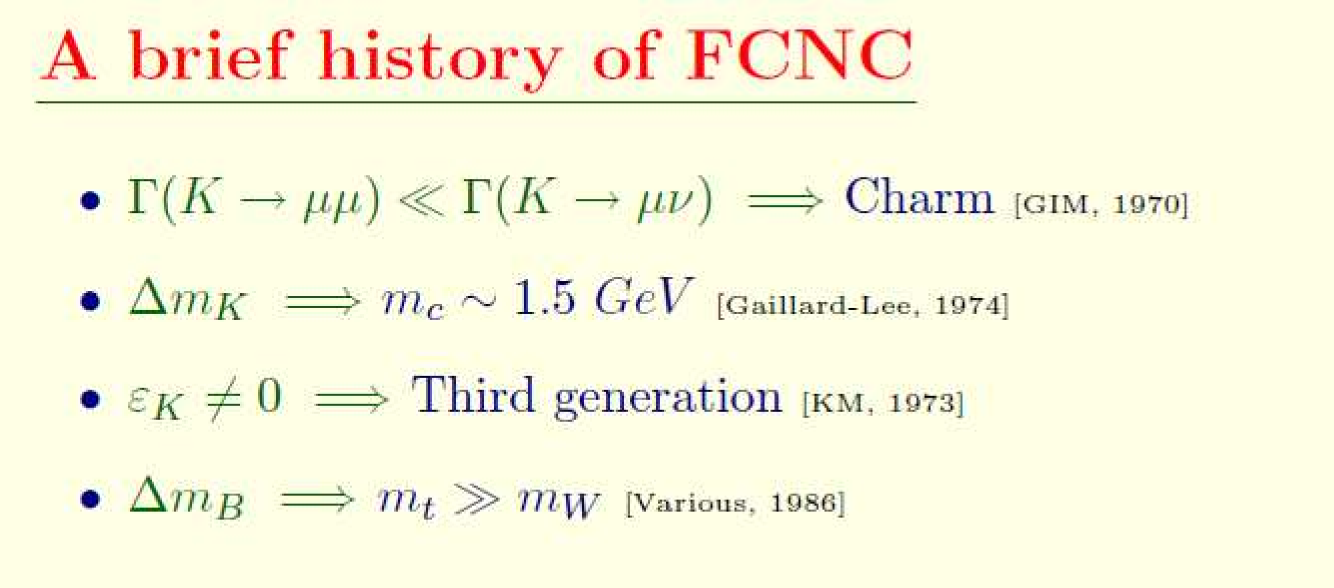
CosmicFrontier

A combination of underground experiments,
ground and space based telescopes will explore
the mysterious Dark phenomena

What role does Flavour Physics and CPV play in search for New Physics



- Flavor physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiment}$
  FCNC suppressed within the SM by $\alpha_W^n, |V_{ij}|, m_f$
- The Standard Model flavor puzzle:
  Why are the flavor parameters small and hierarchical?
  (Why) are the neutrino flavor parameters different?
- The New Physics flavor puzzle:
  If there is NP at the TeV scale, why are FCNC so small?
  The solution $\Longrightarrow$ Clues for the subtle structure of the NP



A brief history of FCNC

- $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu) \quad \Longrightarrow$ Charm [GIM, 1970]
- $\Delta m_K \quad \Longrightarrow m_c \sim 1.5\ GeV$ [Gaillard-Lee, 1974]
- $\varepsilon_K \neq 0 \quad \Longrightarrow$ Third generation [KM, 1973]
- $\Delta m_B \quad \Longrightarrow m_t \gg m_W$ [Various, 1986]

Why is CPV interesting?

- SM CPV cannot explain the baryon asymmetry – a puzzle:
  There must exist new sources of CPV
  Electroweak baryogenesis? (Testable at the LHC)
  Leptogenesis? (Window to $\Lambda_{\rm seesaw}$)
- Within the SM, a single CP violating parameter η:
  In addition, QCD = CP invariant ($\theta_{\rm QCD}$ irrelevant)
  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector

Parameterization-invariant measure of KM $\not{C}\not{P}$ is

$$D_{CP} = \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) \quad J_{CP}$$

where[†]

$$J_{CP} = \mathrm{Im}(\mathbf{V}^*_{\mathbf{ud}} \mathbf{V}_{\mathbf{ub}} \mathbf{V}^*_{\mathbf{cb}} \mathbf{V}_{\mathbf{cd}}) = -\mathrm{Im}(\mathbf{V}^*_{\mathbf{cb}} \mathbf{V}_{\mathbf{cd}} \mathbf{V}^*_{\mathbf{td}} \mathbf{V}_{\mathbf{tb}}) \simeq 3 \times 10^{-5}\,,$$

i.e., KM $\not{C}\not{P}$ $\longleftrightarrow$ flavor structure of SM

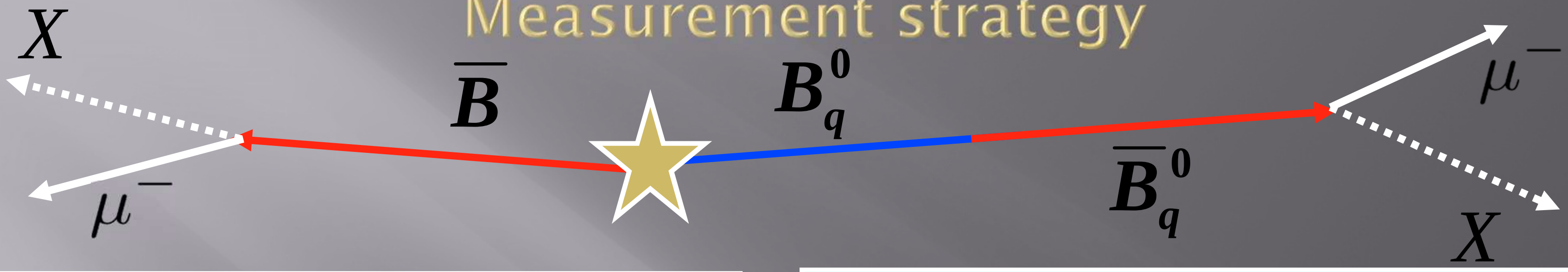
Prediction of KM mechanism:

- $\not{C}\not{P}$ effects $\propto D_{CP}$
- $\not{C}\not{P}$ effects in flavor-diagonal amplitudes $\ni$ particle EDMs
  tiny!

[†] In general, $J_{CP} = \mathrm{Im}(\mathbf{V}^*_{\mathbf{km}} \mathbf{V}_{\mathbf{kn}} \mathbf{V}^*_{\ell\mathbf{n}} \mathbf{V}_{\ell\mathbf{m}})$ where $k \neq \ell \neq m \neq n$.

Di Muon Events at D0

Measurement strategy



$$A_{sl}^b = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst}))\%$$

$$\boldsymbol{A_{sl}^b = (0.506 \pm 0.043)a_{sl}^d + (0.494 \pm 0.043)a_{sl}^s}$$

- Measure two raw asymmetries-include muons from all sources:

raw dimuon charge asymmetry

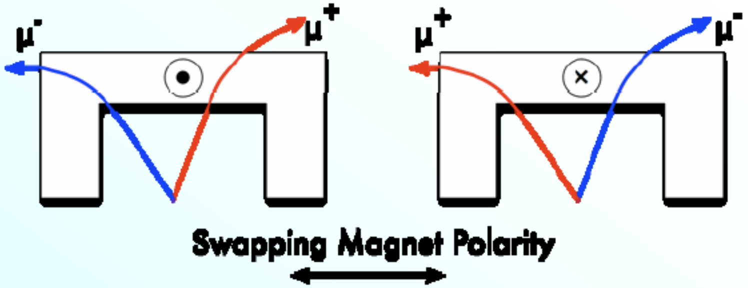
$$\boldsymbol{A \equiv \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = (0.564 \pm 0.053)\%}$$

raw inclusive muon charge asymmetry

$$\boldsymbol{a \equiv \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)} = (0.955 \pm 0.003)\%}$$

  - contribution from $A^b{}_{\mathrm{sl}}$ to a is strongly suppressed by k=0.041±0.003
- Both asymmetries contain contributions from $A^b{}_{\mathrm{sl}}$ and detector-related background asymmetries
- Determine background contributions A_{bkg} and a_{bkg} using data with minimal input from simulation
- Exploit the correlation of background content in raw asymmetries to reduce the uncertainty on $A^b{}_{\mathrm{sl}}$

- N_b^{++}, N_b^{--} – number of events with two b hadrons decaying semileptonically and producing two muons of the same charge
- One muon comes from direct semileptonic decay $b \rightarrow \mu^- X$
- Second muon comes from direct semileptonic decay after neutral B meson mixing: $B^0 \rightarrow \overline{B}^0 \rightarrow \mu^- X$



- Polarities of DØ solenoid and toroid are reversed regularly
- Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnet polarity
- by analyzing 4 samples with different polarities (++, −−, +−, −+)
- the difference in the reconstruction efficiency between positive and negative particles is minimized

Going Beyond SM

- Standard Model cannot be the complete theory
  - Hierarchy problem
  - New sources of CPV required to generate the Baryon asymmetry
  - Neutrino masses
  - Dark Matter …….
- Extend the SM Lagrangian by higher dimension operators, suppressed by Powers of the NP scale
- example: in SM for Δ F=2 processes,

Measurements ⇒

$$-\mathcal{L}_{eff} = \frac{\overset{\nearrow\,\mathcal{O}(1)}{C_0}}{4\underset{\searrow}{\Lambda_0^2}}(V_{ti}^* V_{tj})[d_{Li}\gamma_\mu d_{Lj}]^2$$

~ 2.5 TeV(scale for loop suppressed SM process)

The NP effective operator

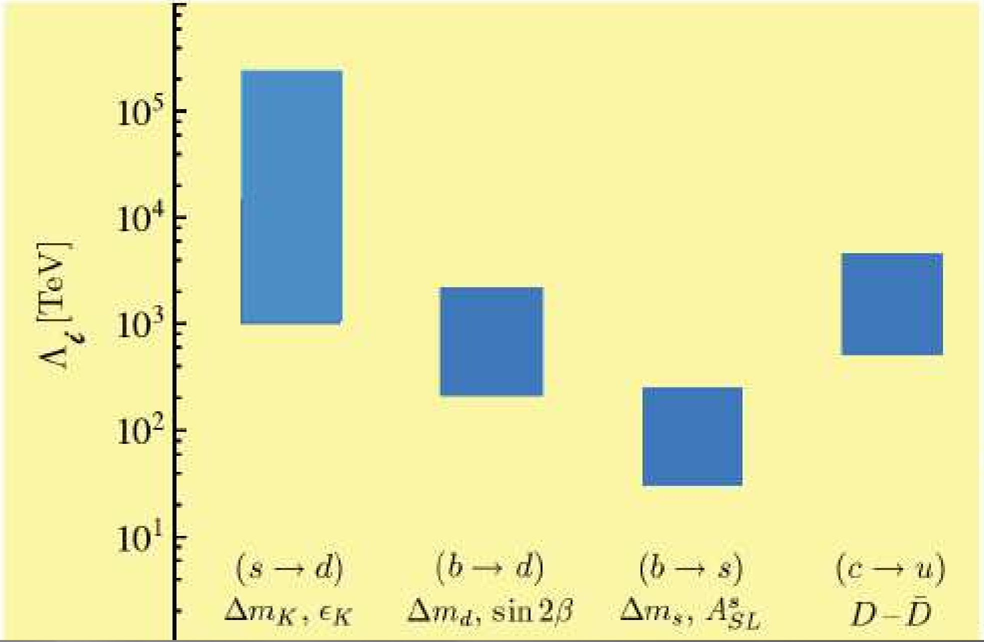
$$-\mathcal{L}_{eff}^{NP} = \frac{\overset{\nearrow\,\mathcal{O}(1)}{C_{NP}}}{\underset{\searrow}{\Lambda_{NP}^2}}[d_{Li}\gamma_\mu d_{Lj}]^2$$

~ mass of NP particle

$$\Lambda_{NP} > \begin{cases} 2 \text{ x } 10^4\ \varepsilon_k \\ 1 \text{ x } 10^3\ \Delta\ m_k \\ 9 \text{ x } 10^2\ \Delta\ m_D \\ 4 \text{ x } 10^2\ \Delta\ m_B \\ 7 \text{ x } 10^1\ \Delta\ m_{B_s} \end{cases}$$

NP Flavor puzzle!

- Already excluded ranges from box diagrams
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$, take $c_i \sim 1$



Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

Possible new sources of $\not{C}\!P$

Extensions of SM $\longrightarrow$ entail, in general, larger **non-gauge sector**
i.e., extended Higgs- and Yukawa sector

$\Rightarrow$ new $\not{C}\!P$ interactions for quarks and leptons possible
Notice: The appearance of such interactions is natural, but not imperative!

Important new features may arise:

- new $\not{C}\!P$ need not be related to mixing of fermion generations
- if $\not{C}\!P$ Higgs-interactions exist, then effects grow drastically with mass of fermion f

Scale of new physics probed by EDM:

Assume: $d_f \propto m_f$, generated @ 1 loop, $\not{C}\!P$ phases are $\mathcal{O}(1)$

$$\Rightarrow \qquad d_f \sim e\frac{m_f}{16\pi^2 M^2}$$

electron: $d_e \sim 6 \times 10^{-26} \mathrm{e\ cm} \times (1 \mathrm{TeV}/M)^2$, comparison with d_e^{exp}: $\Rightarrow$ $M \sim 5$ TeV
neutron $d_n \leftrightarrow d_u, d_d$ comparison with d_n^{exp}: $\Rightarrow$ $M \sim 5$ TeV

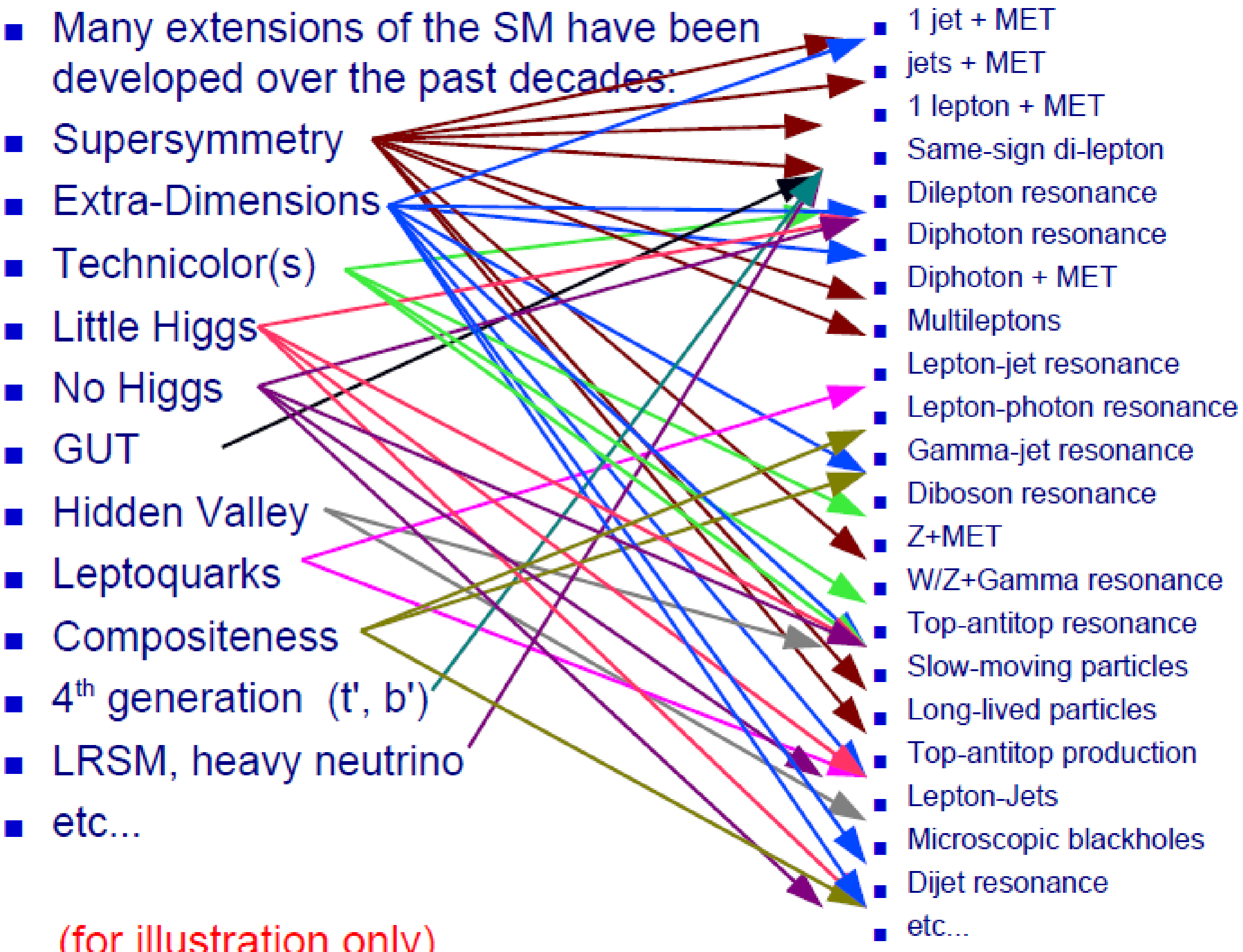
scale M decreases if $d_f \propto m_f^p$ oder generated @ higher loop-order

New physics possibilities....

- New symmetries
- New particles
- New (anomalous) interactions

- Extra compact spacelike dimensions

A very long list of models x signatures



- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

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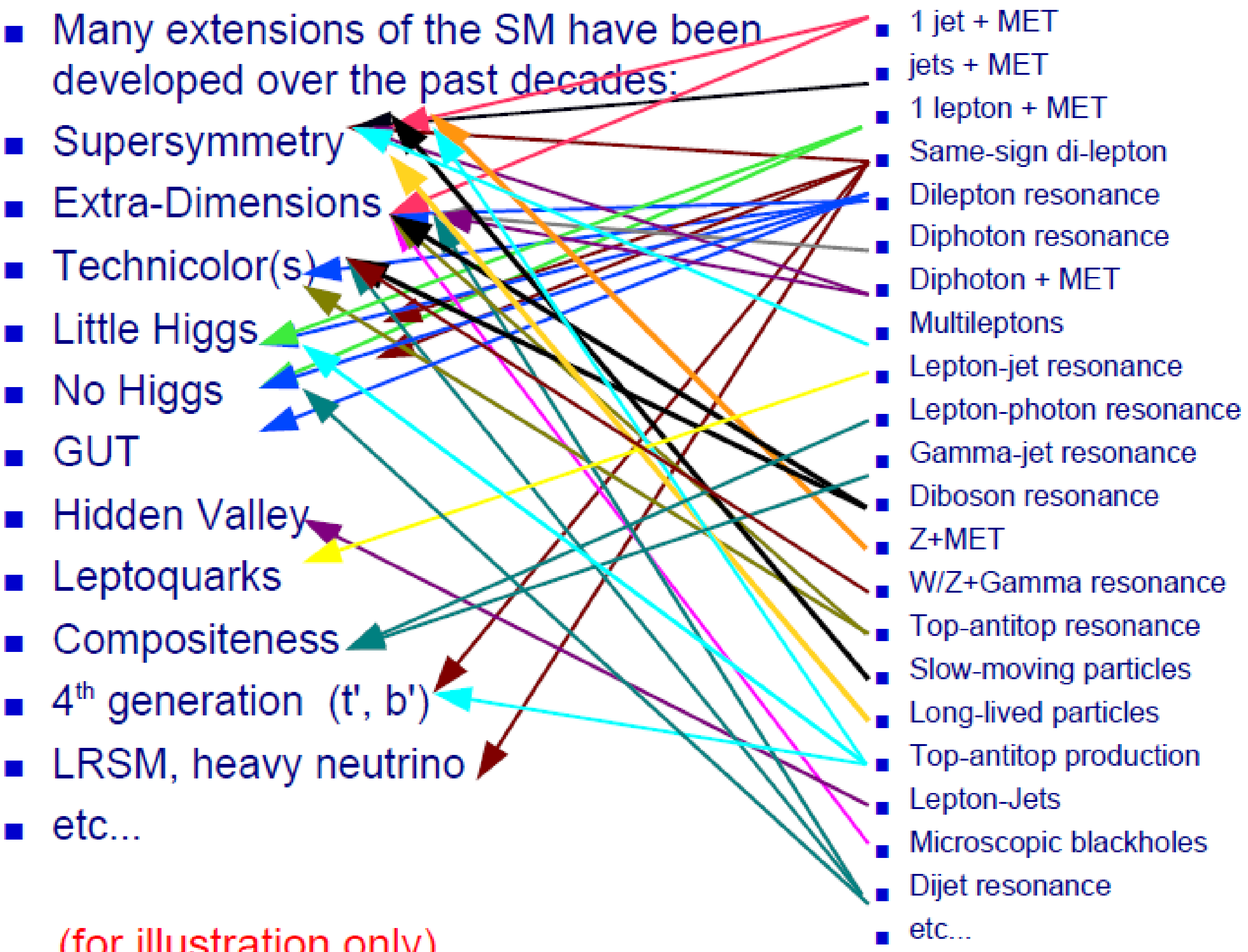

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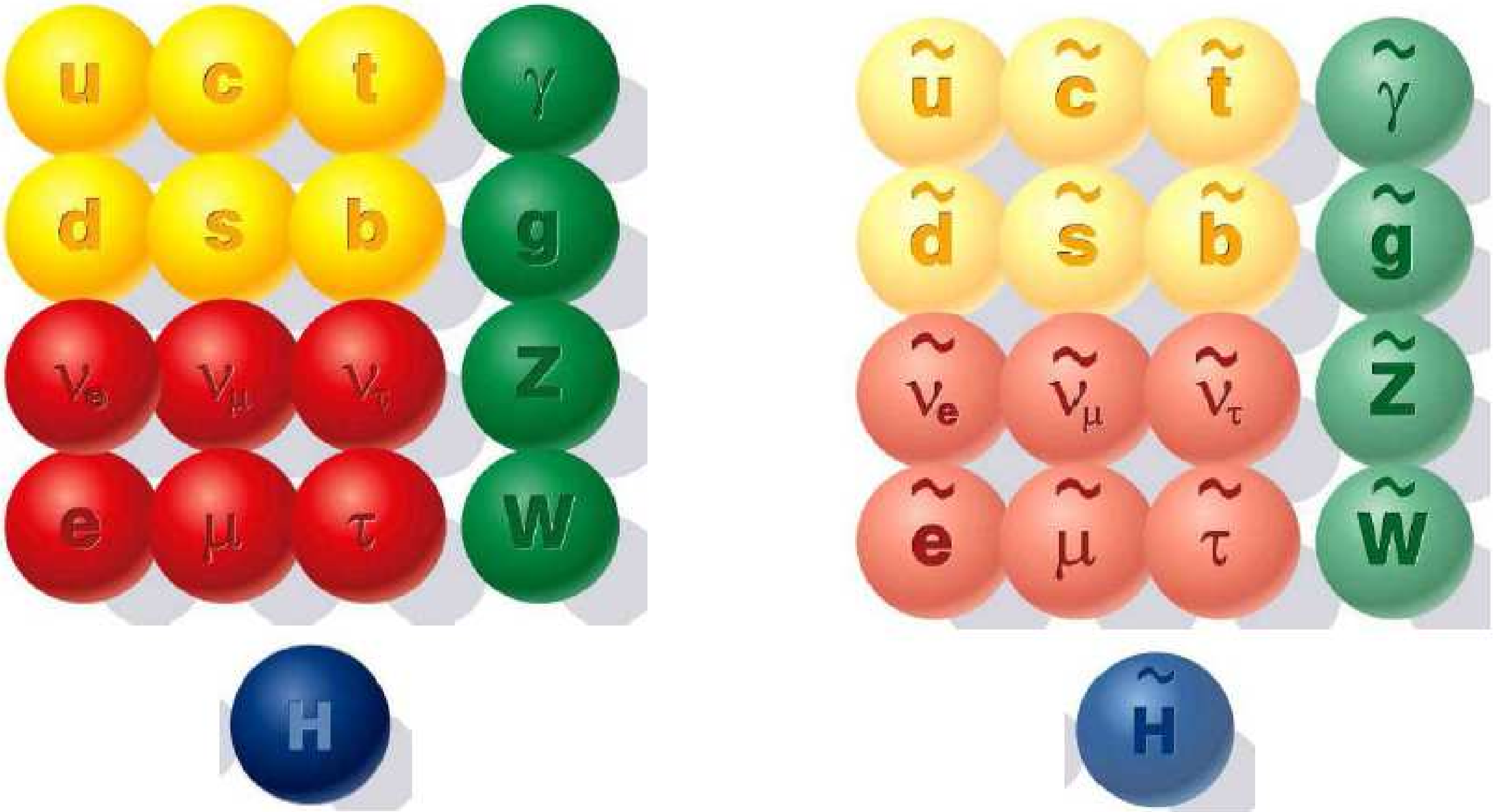
A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

- → Practical
- → Less model-dependent
- → Important to cover every possible signature

Supersymmetry (SUSY)

Supersymmetry: fermion ⟷ boson symmetry,
leads to compensation of large quantum corrections



The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

$$[u,d,c,s,t,b]_{L,R} \quad [e,\mu,\tau]_{L,R} \quad [\nu_{e,\mu,\tau}]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$[\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{t},\tilde{b}]_{L,R} \quad [\tilde{e},\tilde{\mu},\tilde{\tau}]_{L,R} \quad [\tilde{\nu}_{e,\mu,\tau}]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \qquad \tilde{\chi}^\pm_{1,2} \qquad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^\pm$

General parametrisation of possible SUSY-breaking terms
⇒ free parameters, no prediction for SUSY mass scale

Hierarchy problem ⇒ expect observable effects at TeV scale

Higgs mass stabilisation + dark matter:

Supersymmetry (SUSY): A frequently explored possibility
A fermion for every boson and vice versa

A ready cancellation of large Higgs mass corrections
A dark matter candidate suggested

SUSY necessitates at least two Higgs doublets:

$\Rightarrow$ several Higgs-like fields (scalar, pseudoscalar, charged)

Supersymmetry

Supersymmetry extends the ideas of symmetry

For every fermion there is a corresponding boson & vice versa

$$\begin{array}{ccccccc}
quark\,(1/2) & \leftrightarrow & squark\,(0) & \qquad & W\,(0) & \leftrightarrow & Wino\,(1/2) \\
electron\,(1/2) & \leftrightarrow & selectron\,(0) & & Z\,(0) & \leftrightarrow & Zino\,(1/2) \\
muon\,(1/2) & \leftrightarrow & smuon\,(0) & & Photon\,(0) & \leftrightarrow & Photino\,(1/2) \\
tauon\,(1/2) & \leftrightarrow & stauon\,(0) & & Gluon\,(0) & \leftrightarrow & Gluino\,(1/2)
\end{array}$$

While mathematically appealing, the symmetry is clearly broken (we do not see the supersymmetric particles)

SUSY

- With squarks and sleptons, more possible ways for flavour violation.
- Parameters controlling flavour violation in MSSM numerous
  - ⇒ Huge flavour violation.
- Defuse this "SUSY Flavour problem" by Alignment
- Assume sfermion masses are approximately aligned with fermion masses
- Scalar mass matrices are approximately diagonal.
- Off diagonal sfermion mass terms treated as interactions, perturbative expansion of FCNC amps. in terms of mass insertions.

Models with CMFV

✓The CKM flavour pattern of the SM successful
- explains most flavour physics data.

✓Hence any NP has to be a small perturbation
of the main bulk contribution of the SM

This has led to models with Constrained Minimal Flavour Violation :

☐ CKM matrix of the SM, the only source of flavour violation.

☐ Only operators that are relevant are the those already in SM.

ΔM_q can have NP contributions only in the short distance functions.

SUSY-breaking scenarios

“Hidden sector”: $\longrightarrow$ Visible sector:

SUSY breaking MSSM

“Gravity-mediated”: SUGRA
“Gauge-mediated”: GMSB
“Anomaly-mediated”: AMSB

. . .

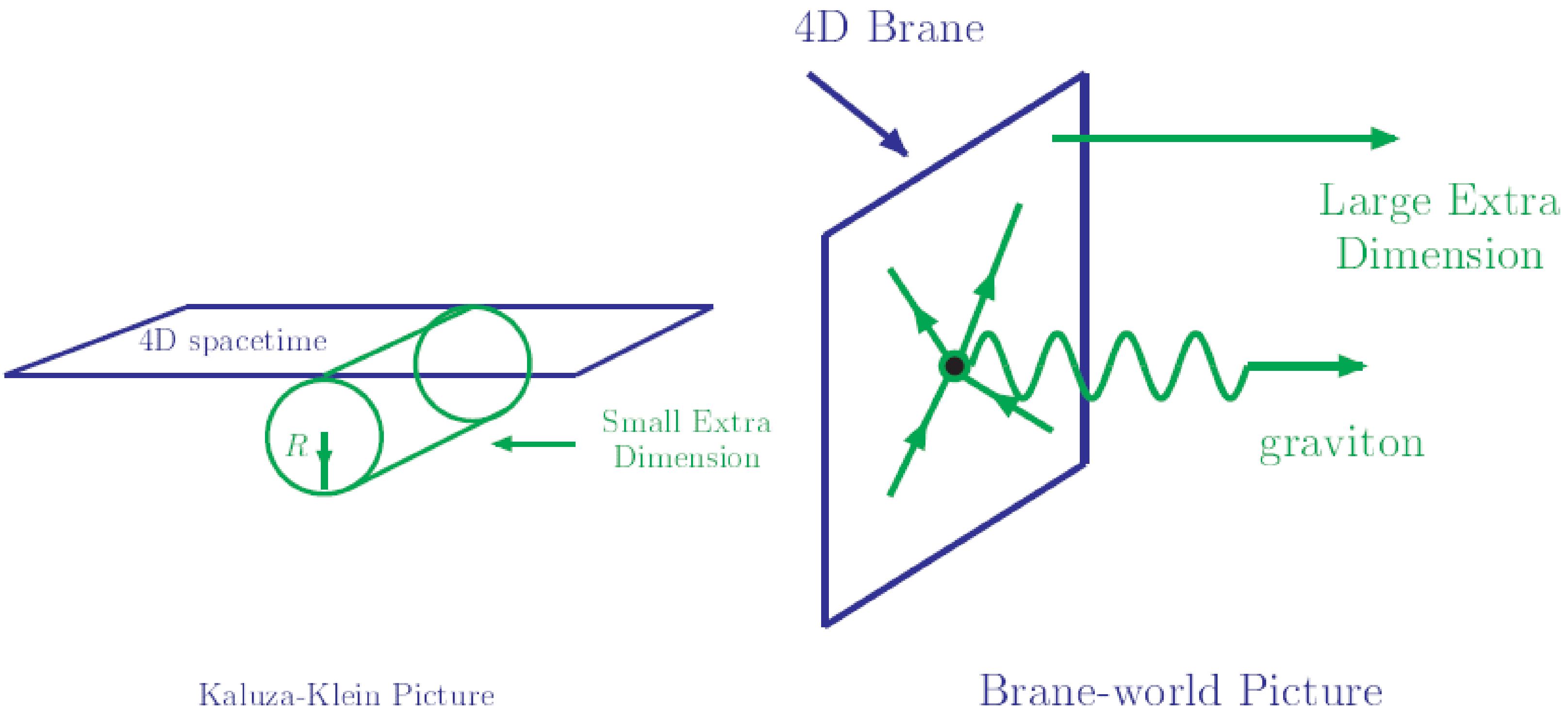
SUGRA: mediating interactions are gravitational

Connection of gravity and electroweak physics

Flavour off-diagonal and $\mathcal{CP}$-violating effects?

SUGRA with universality assumptions $\Rightarrow$ CMSSM, $\tilde{\chi}_1^0$ LSP

Models with extra dimensions of space



Hierarchy between M_{Planck} and M_{weak} is related to the volume or the geometrical structure of additional dimensions of space

$\Rightarrow$ observable effects at the TeV scale