Sub Z Supersymmetry

Precision Electroweak Studies in Nuclear Physics

M.J. Ramsey-Musolf

NSAC Long Range Plan

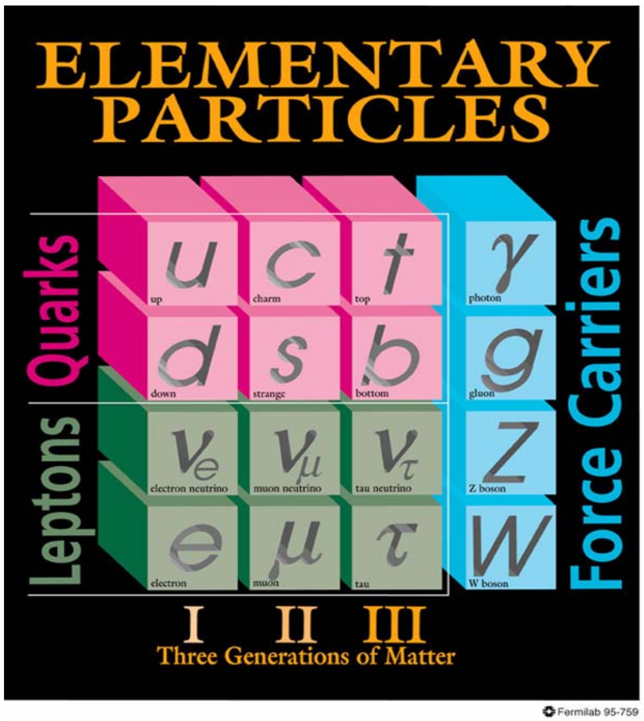
- What is the structure of the nucleon?
- What is the structure of nucleonic matter?
- What are the properties of hot nuclear matter?
- What is the nuclear microphysics of the universe?
- What is to be the new Standard Model?

Neutrino physics

→ Precision measurements: β-decay, μ-decay, parity violating electron scattering, EDM's…

What can they teach us about the new Standard Model?

The Standard Model of particle physics is a triumph of late 20th century physics



- It provides a unified framework for 3 of 4 (known) forces of nature in context of renormalizable gauge theory

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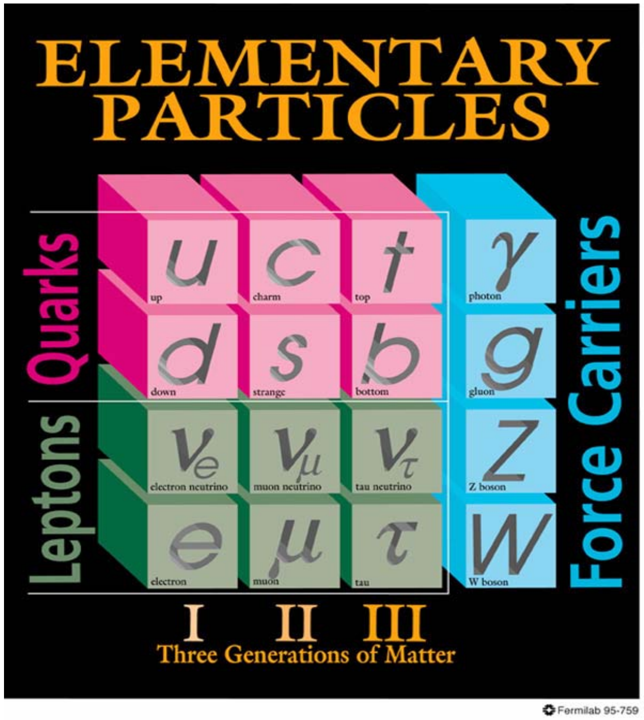

- Utilizes a simple & elegant symmetry principle to organize what we've observed

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

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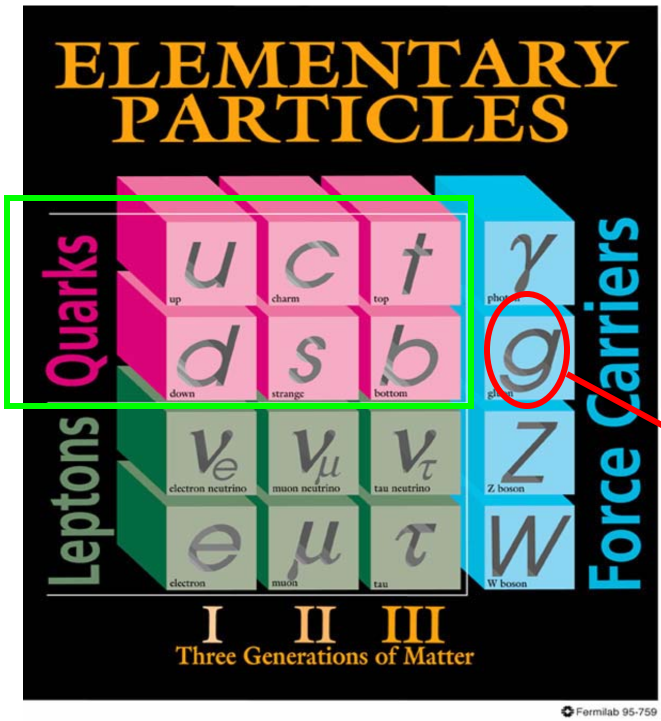

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$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Scaling violations in DIS
Asymptotic freedom
R(e^+e^-)
Heavy quark systems
Drell-Yan

Strong (QCD)

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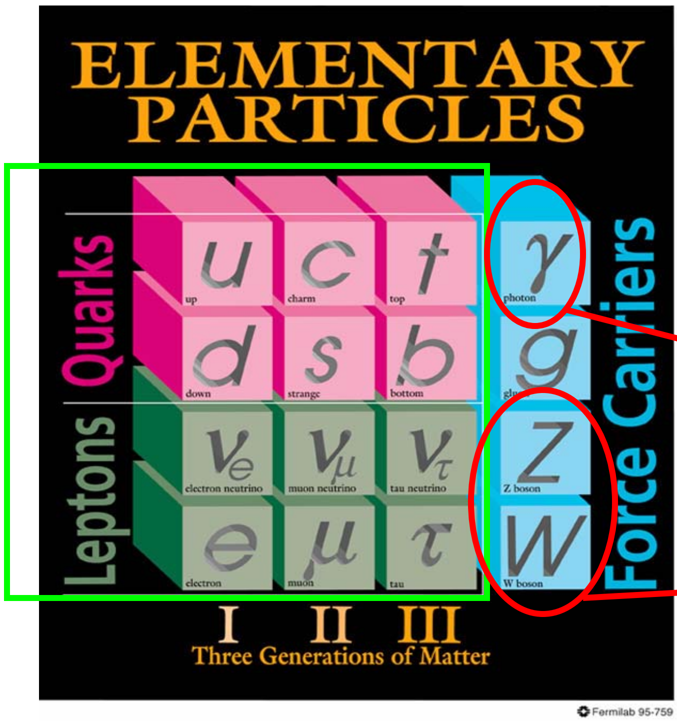


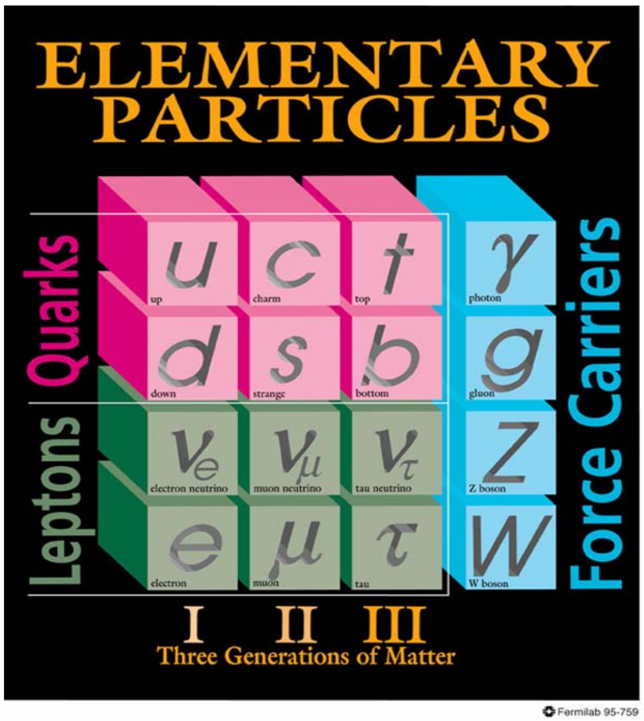
- Utilizes a simple & elegant symmetry principle to organize what we've observed

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

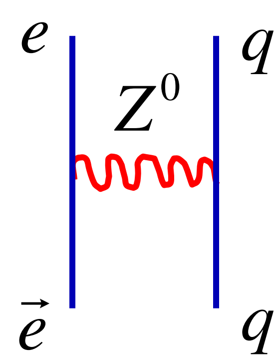
Electroweak (=weak + QED)

"Maximal" parity violation
Conserved Vector Current
CP-Violation in K, B mesons
Quark flavor mixing
Lepton universality…..

The Standard Model of particle physics is a triumph of late 20th century physics

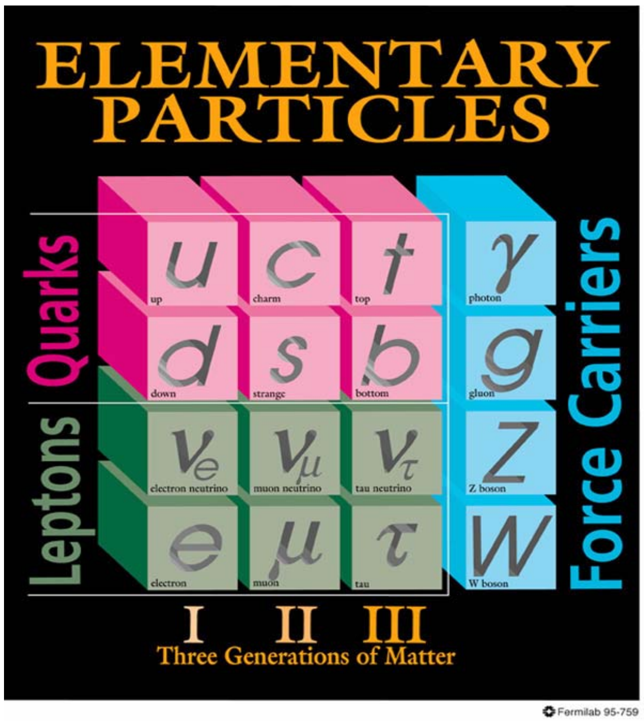


- Most of its predictions have been confirmed

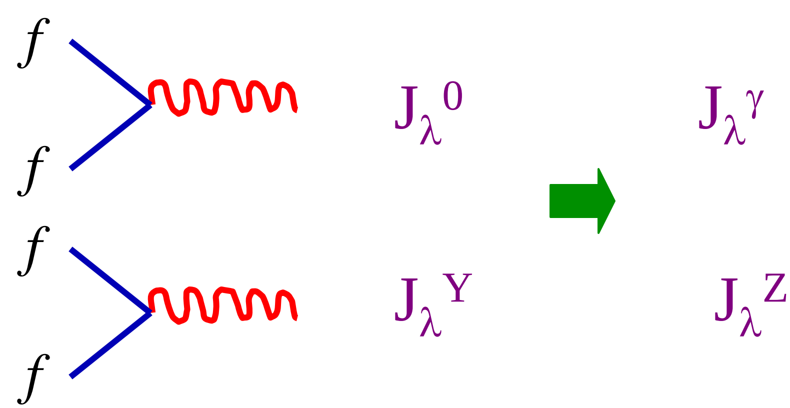


Parity violation in neutral current processes: deep inelastic scattering, atomic transitions

The Standard Model of particle physics is a triumph of late 20th century physics

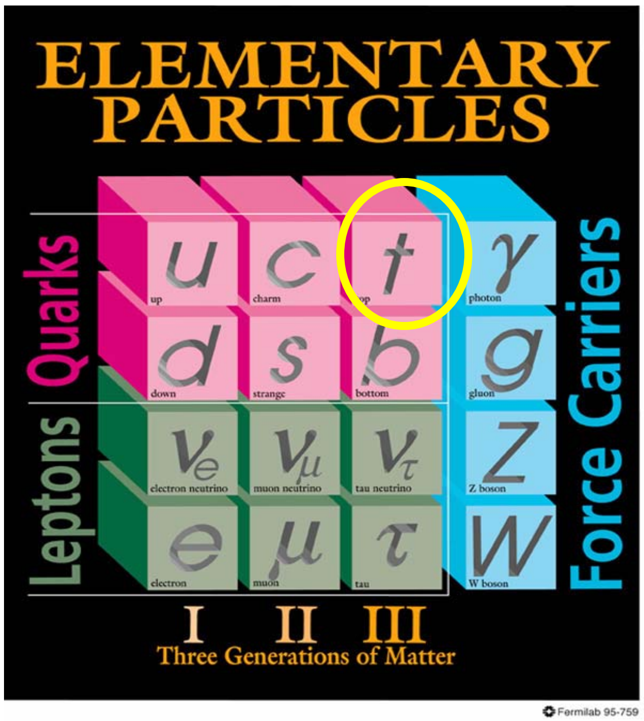


- Most of its predictions have been confirmed



Neutral currents mix $\sin^2\theta_W$

The Standard Model of particle physics is a triumph of late 20th century physics



- **Most of its predictions have been confirmed**
  - W, Z^0
  - 3rd fermion generation (CP violation, anomaly)
  - Higgs boson — Not yet!

New particles should be found

We need a new Standard Model

Two frontiers in the search

Collider experiments (pp, e^+e^-, etc) at higher energies ($E \gg M_Z$)

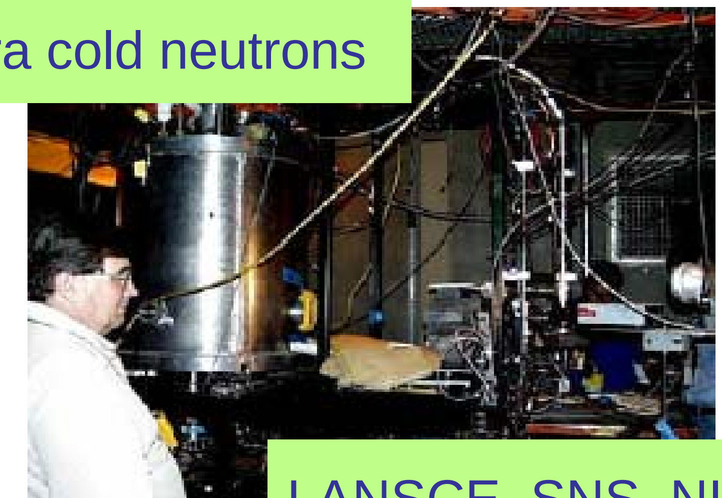
Indirect searches at lower energies ($E < M_Z$) but high precision

Large Hadron Collider

CERN

High energy physics

Ultra cold neutrons



LANSCE, SNS, NIST

Particle, nuclear & atomic physics

Outline

I. SM Radiative Corrections & Precision Measurements

II. Defects in the Standard Model

III. An Example Scenario: Supersymmetry

IV. Low-energy Probes of Supersymmetry

- Precision measurements
- “Forbidden processes”

- Weak decays
- lepton scattering

Outline

I. SM Radiative Corrections & Precision Measurements

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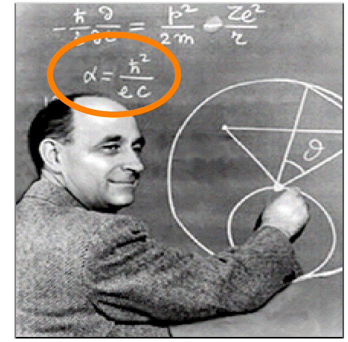
IV. Low-energy Probes of Supersymmetry

- Precision measurements
- "Forbidden processes" →

- EDM's
- $0\nu\beta\beta$ decay
- μ !e, μ !eγ…

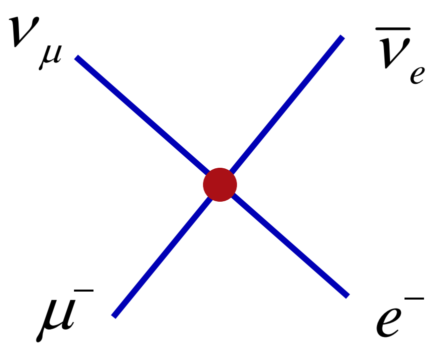
I. Radiative Corrections & Precision Measurements in the SM

The Fermi Theory of weak decays gave a successful, leading-order account

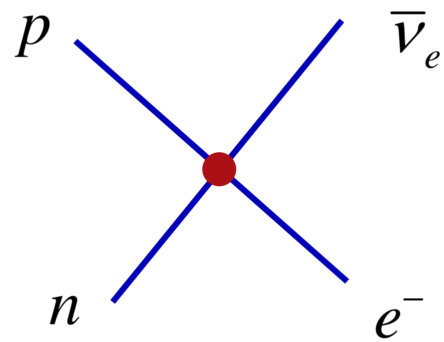


$$\mu^- \to \nu_\mu e^- \bar{\nu}_e$$

$$n \to p e^- \bar{\nu}_e$$



$$\frac{G_F^\beta}{G_F^\mu} < 1$$

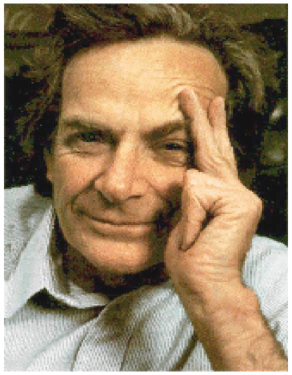


$$H_{EFF}^\mu = \frac{G_F^\mu}{\sqrt{2}} \bar{\nu}_\mu \gamma^\lambda \mu_L \bar{e}_L \gamma_\lambda \nu_e$$

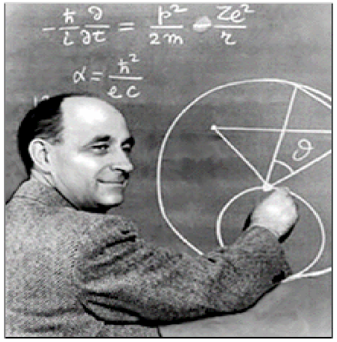
$$\bar{\nu}_\mu \gamma^\lambda (1 - \gamma_5) \mu$$

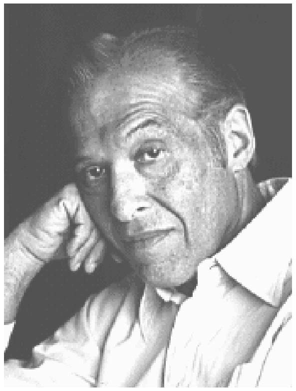
$$H_{EFF}^\beta = \frac{G_F^\beta}{\sqrt{2}} \bar{p} \gamma^\lambda (g_V + g_A \gamma_5) n \bar{e}_L \gamma_\lambda \nu_e$$

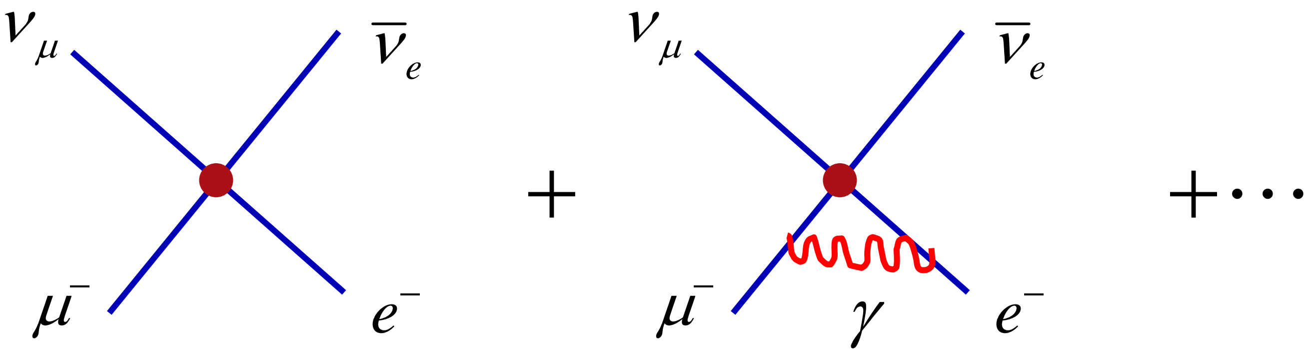
$$g_V = 1, \; g_A \approx -1.26$$



Fermi’s theory could incorporate higher order QED contributions



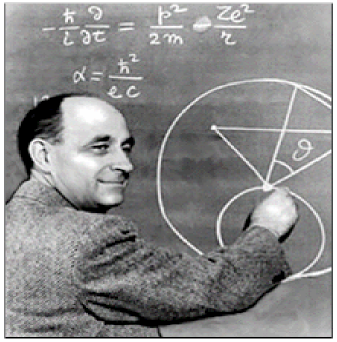


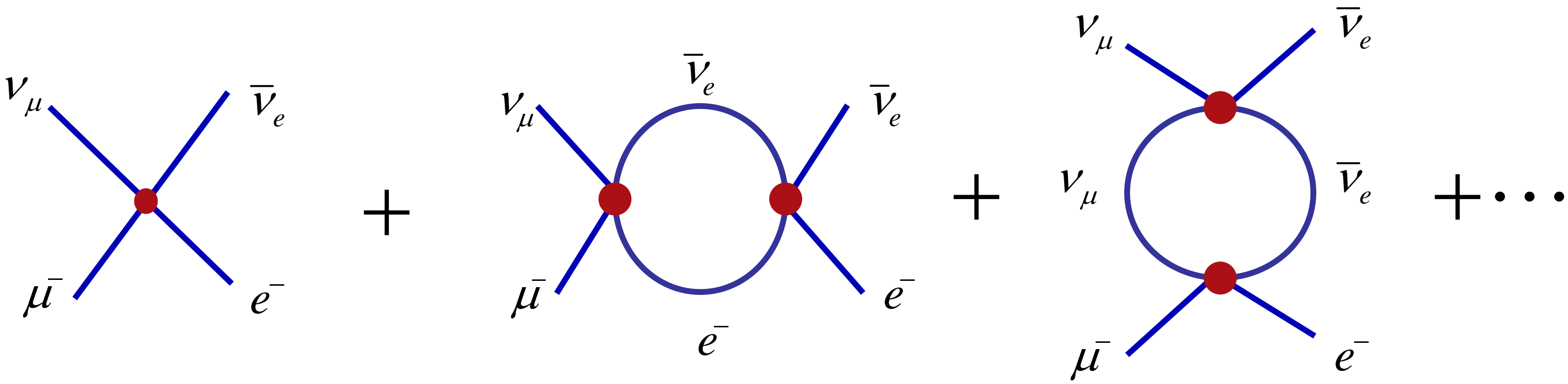


QED radiative corrections: finite

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left[1 + \frac{\alpha}{2\pi}\left(\frac{25}{4} - \pi^2\right) + \cdots\right]$$

The Fermi theory has trouble with higher order weak contributions

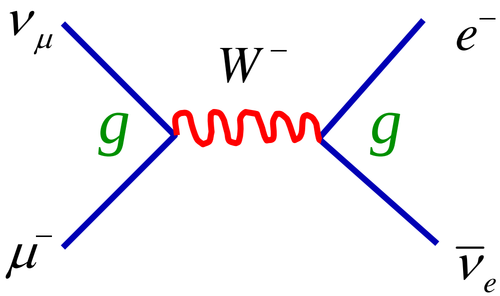




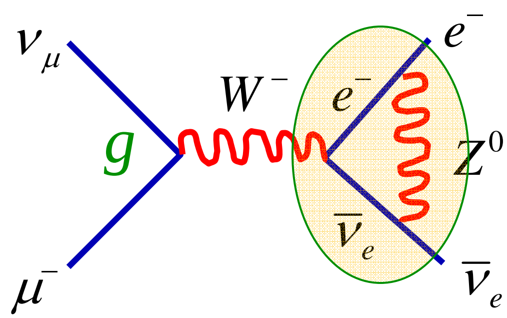
Weak radiative corrections: infinite

Can't be absorbed through suitable re-definition of G_F in H_{EFF}

All radiative corrections can be incorporated in the Standard Model with a finite number of terms

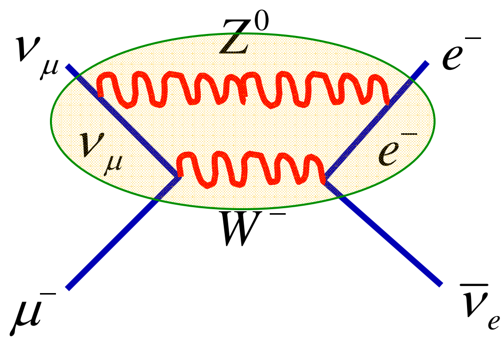


$+$



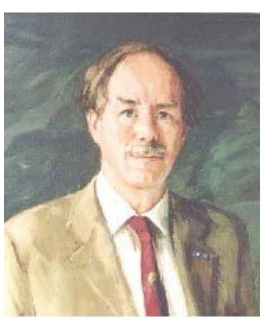
Re-define g

$+$

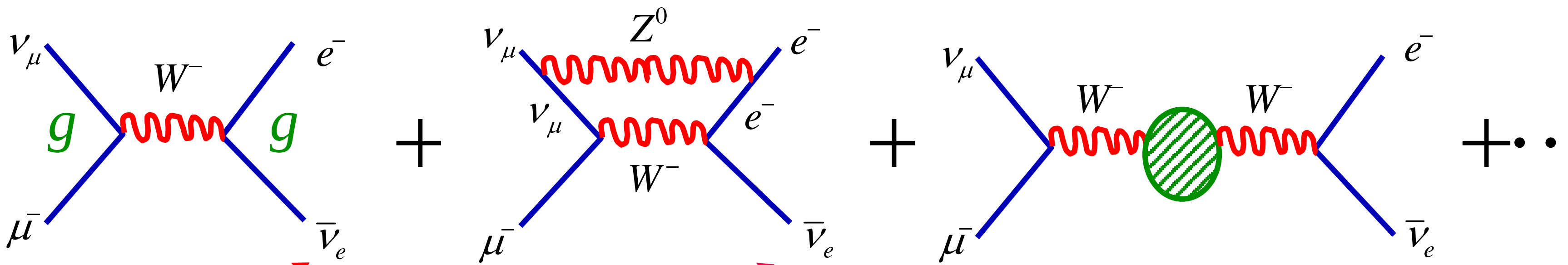


Finite

$+\cdots$



G_F encodes the effects of all higher order weak radiative corrections

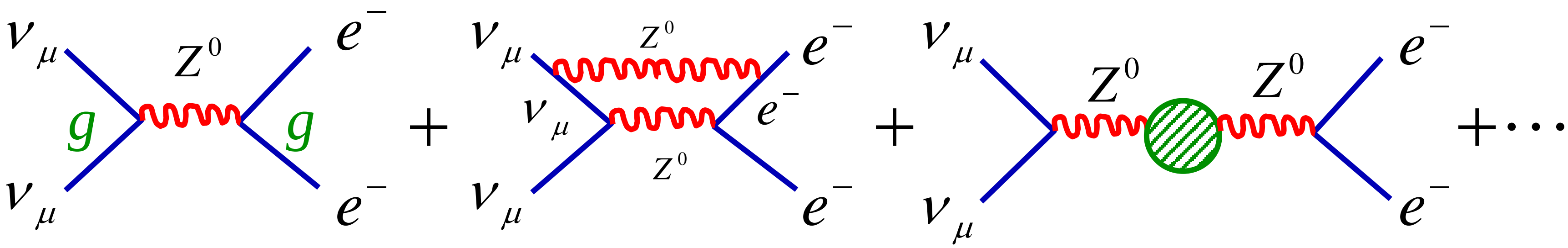


$$\frac{G_F^\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r_\mu\right)$$

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} + \cdots$$

Δr_μ depends on parameters of particles inside loops

Comparing radiative corrections in different processes can probe particle spectrum

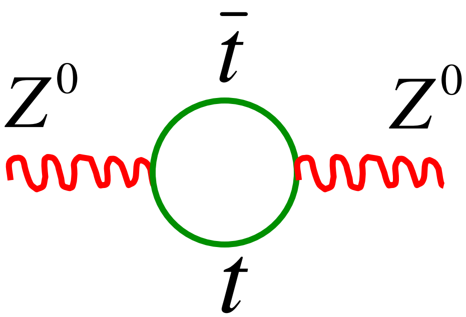


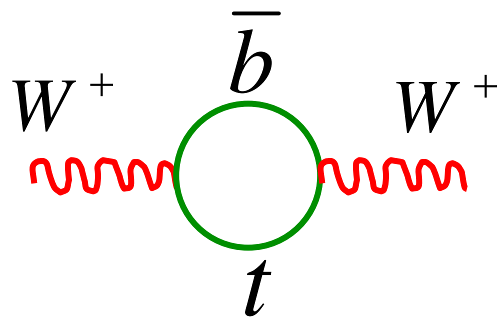
$$\frac{G_F^Z}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1+\Delta r_Z\right)$$

Δr_μ differs from Δr_Z

Comparing radiative corrections in different processes can probe particle spectrum

$$\frac{G_F^Z}{G_F^\mu} \approx \left(1 + \Delta r_Z - \Delta r_\mu\right)$$

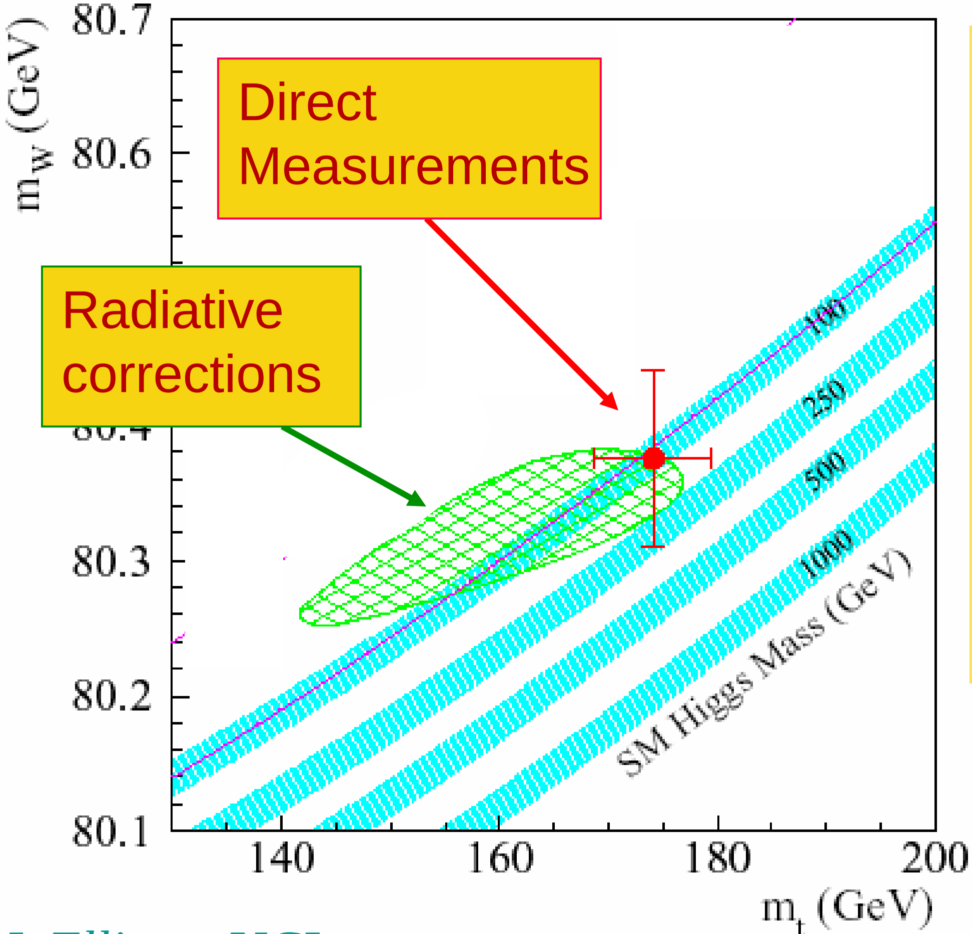




$$\Delta r_Z \sim \frac{\alpha}{\pi} \ln \frac{m_t^2}{M_W^2}$$

$$\Delta r_\mu \sim \frac{\alpha}{\pi} \frac{m_t^2}{M_W^2}$$

Comparing radiative corrections in different processes can probe particle spectrum



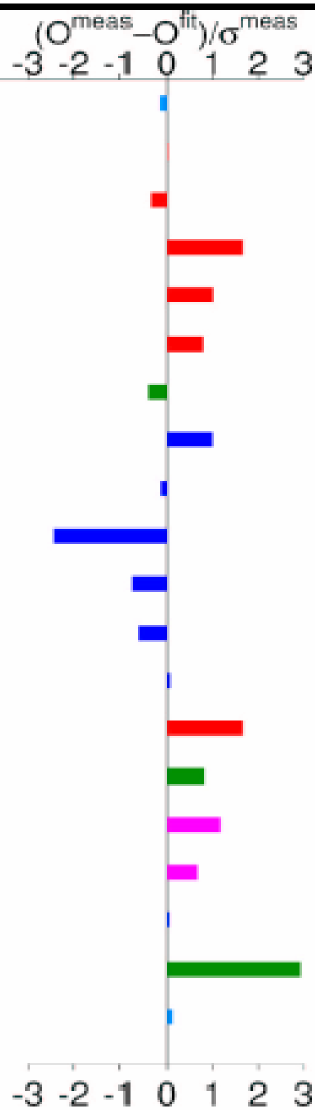
J. Ellison, UCI

- Precision measurements predicted a range for m_t before top quark discovery
- $m_t >> m_b$!
- m_t is consistent with that range
- It didn't have to be that way

Stunning SM Success

Global Analysis

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
$Q_W(Cs)$	-72.83 ± 0.49	0.12



M. Grunenwald

χ^2 per dof
= 25.5 / 15

Agreement with SM at level of loop effects ~ 0.1%

Collider Studies

LEP
SLD
Tevatron

Effective Z couplings

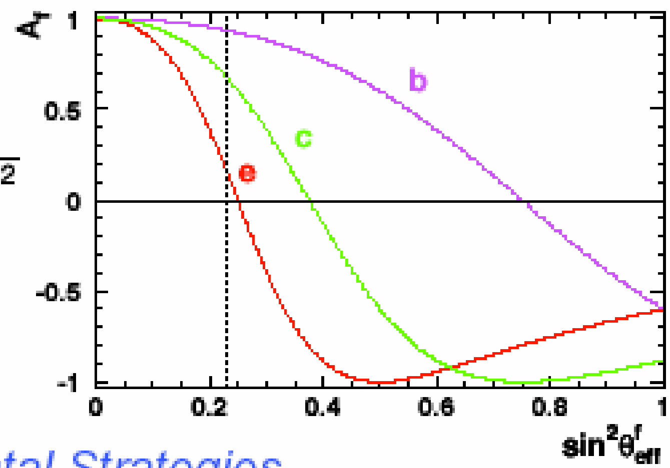
$$g_{Vf} = \sqrt{\bar\rho}\left(T_f^{(3)} - 2Q_f \sin^2\theta_{eff}\right)$$

$$g_{Af} = \sqrt{\bar\rho}\, T_f^{(3)}$$

$$\mathcal{A}_f = 2\frac{g_{Vf}\, g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\Gamma_{f\bar f} = \frac{G_F m_Z^3}{6\pi\sqrt{2}}(g_{Vf}^2 + g_{Af}^2)$$



Experimental Strategies

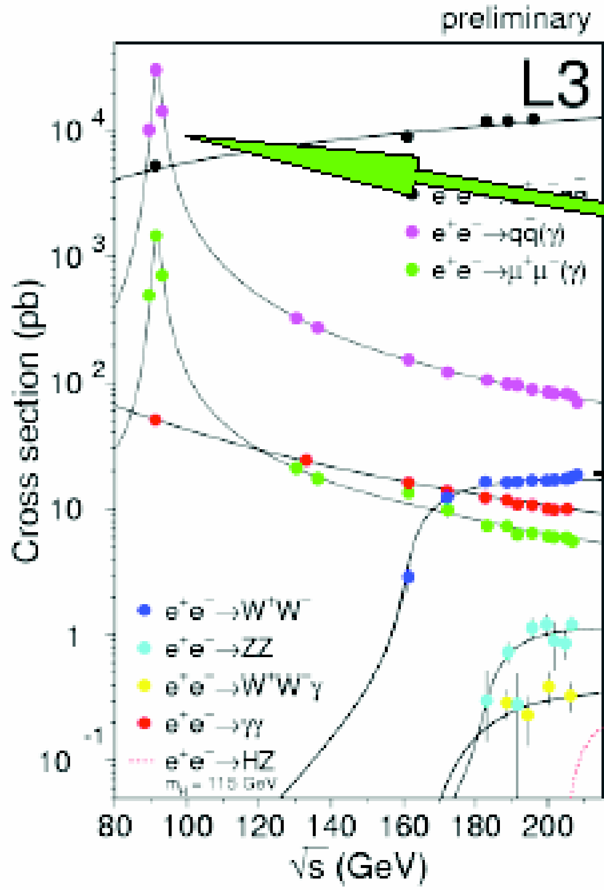
- FB asymmetries $\Rightarrow \mathcal{A}_e\mathcal{A}_f$
- τ polarisation $\Rightarrow \mathcal{A}_e$ and $\mathcal{A}_\tau$ separately
- SLD (polarised beams) $\Rightarrow \mathcal{A}_e$ (and $\mathcal{A}_\mu$, $\mathcal{A}_\tau$)

- Asymmetries $\Rightarrow g_V/g_A$
- Z partial decay widths $\Rightarrow g_V^2 + g_A^2$

R. Clare, UCR

Collider Studies

The LEP Heritage



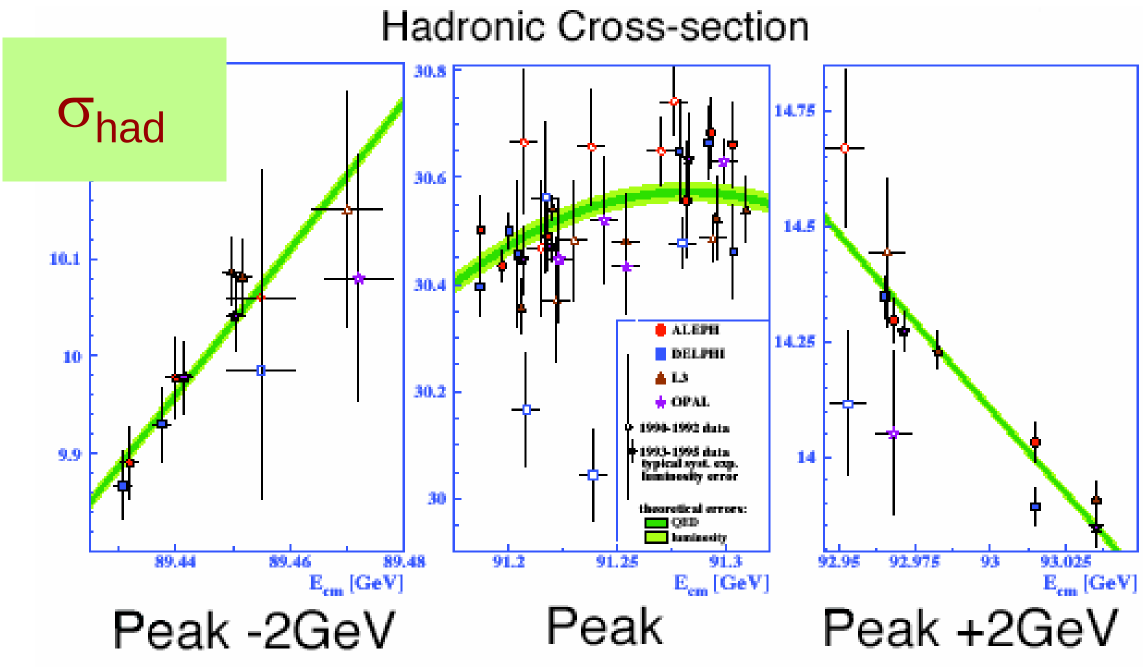
In total, for all 4 expts:

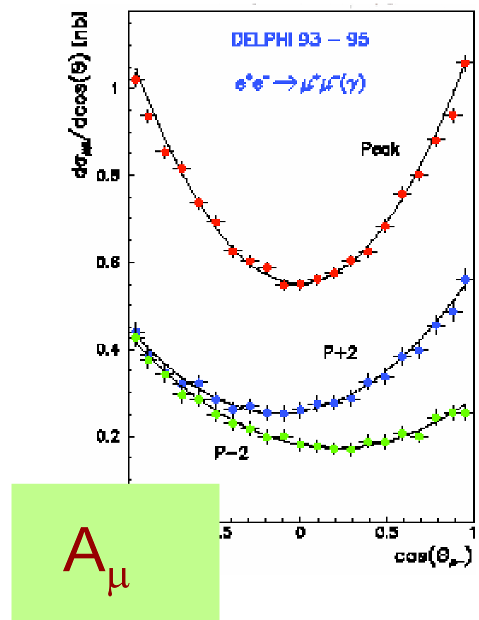
about 16 M Z

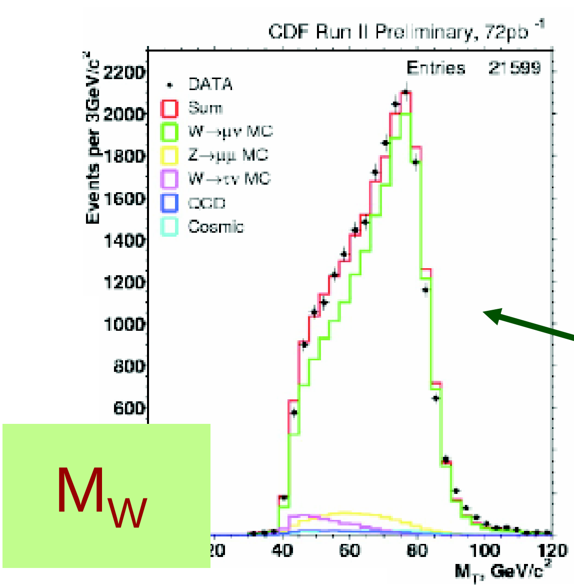
about 40000 W

about 0 H

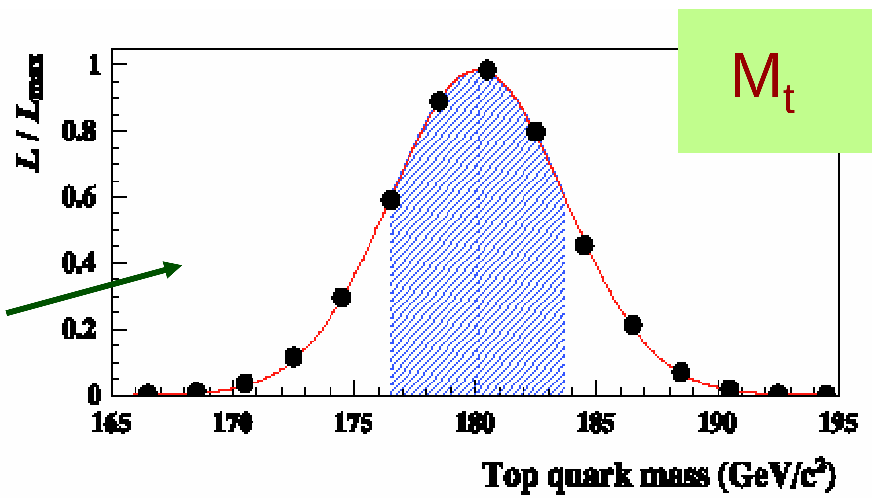
Collider Studies





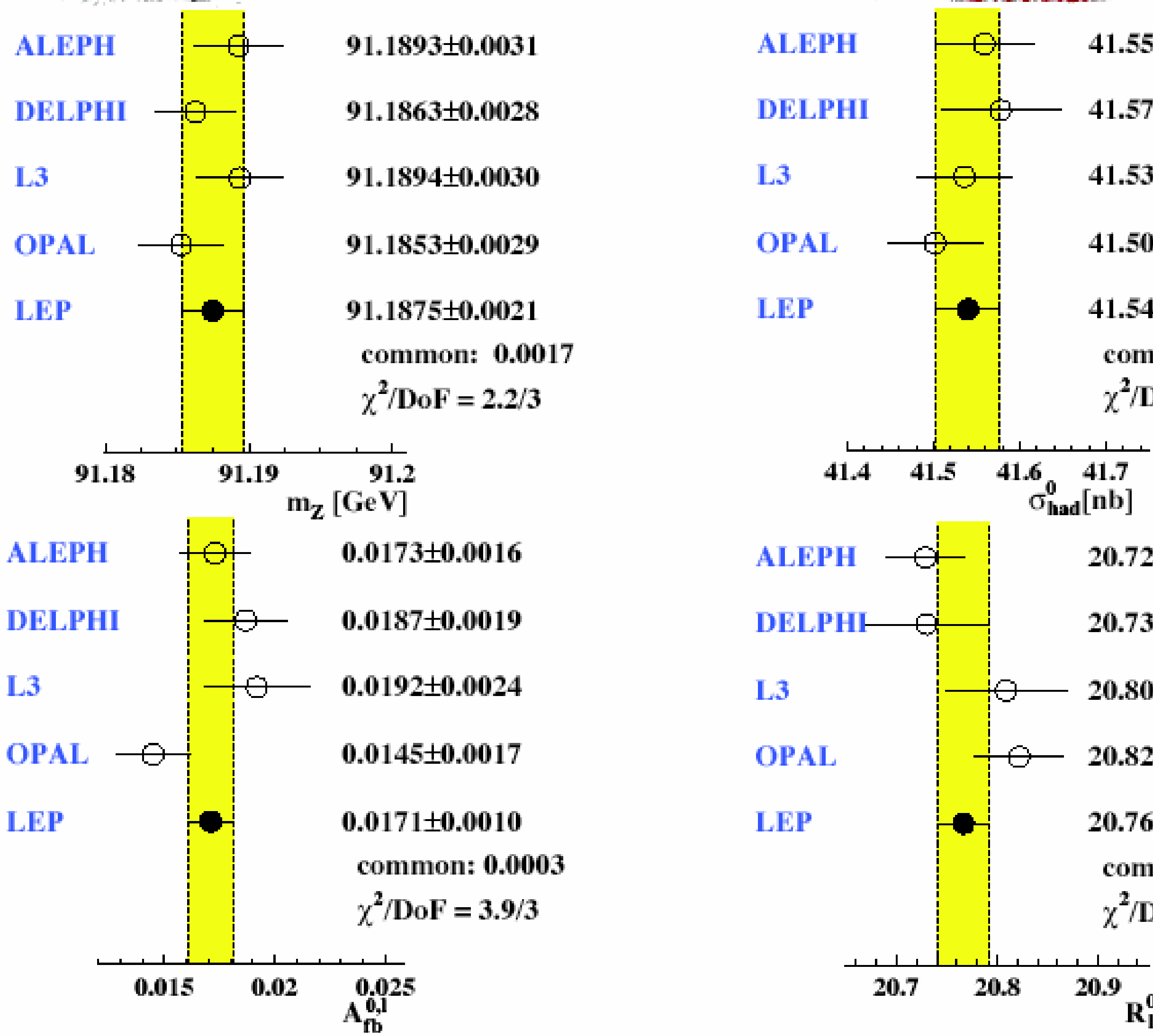


Tevatron



Collider Studies

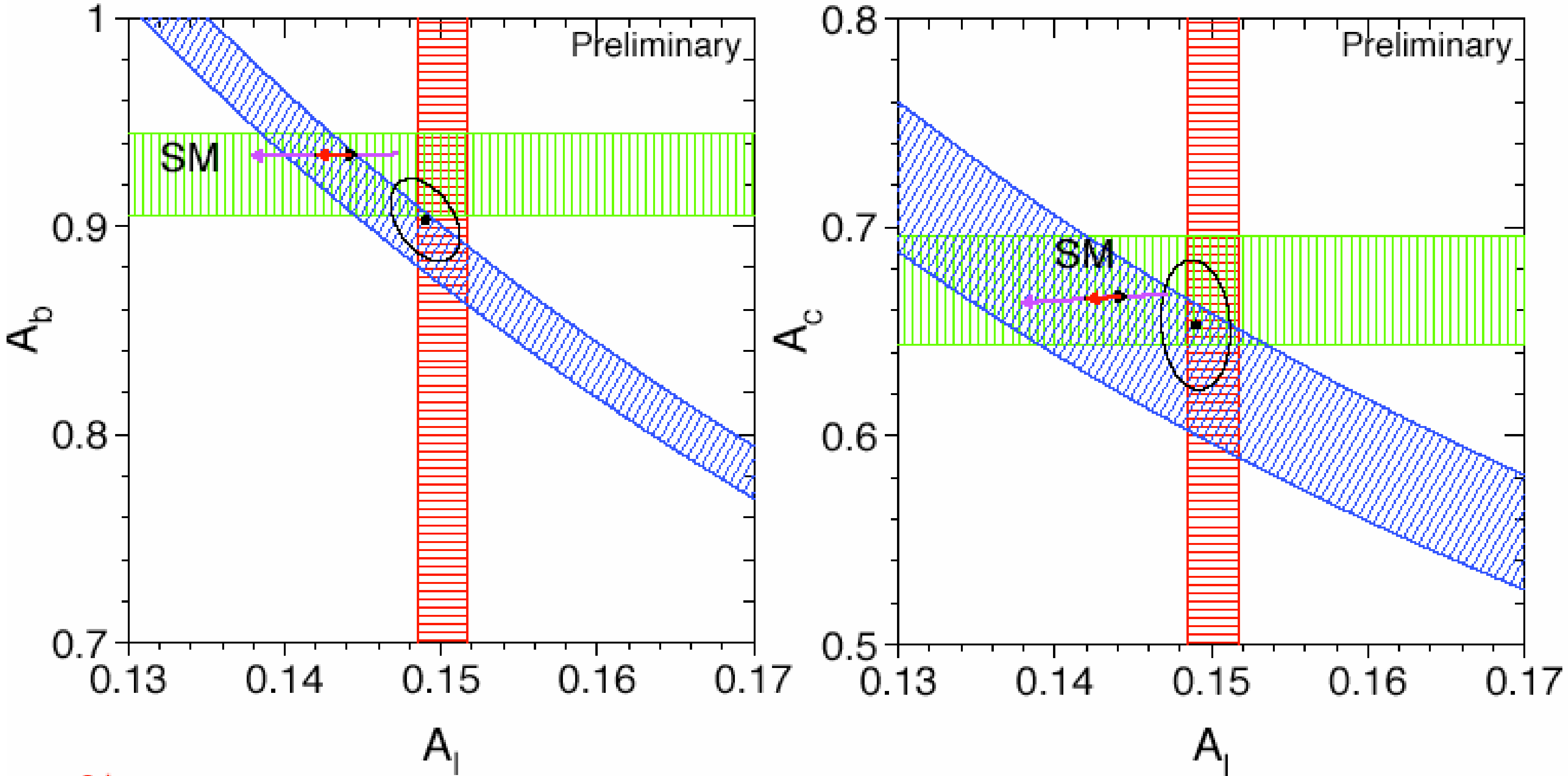
Comparisons of results



Collider Studies

Quarks vs Leptons

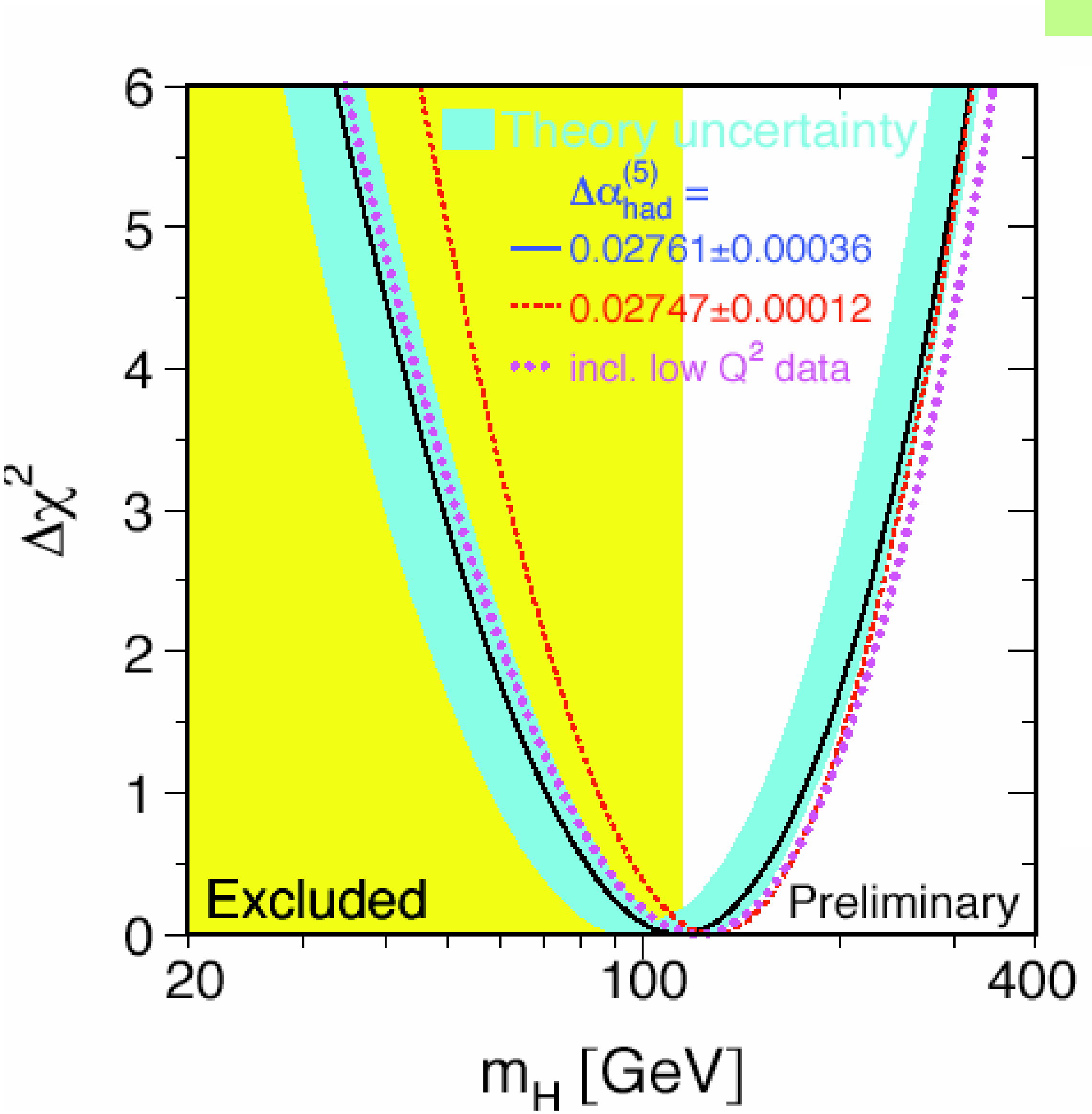
horizontal band: $\mathcal{A}_b, \mathcal{A}_c$(SLD); vertical band: $\mathcal{A}_\ell$(LEP+SLD);
diagonal band : $A_{FB}^{0,b}$, $A_{FB}^{0,c}$(LEP); $\longleftarrow m_H \in [114, 1000]$



$A_{FB}^{0,b}$ prefers high m_H; $\mathcal{A}_\ell$ prefers low m_H

Collider Studies

"Blue Band"



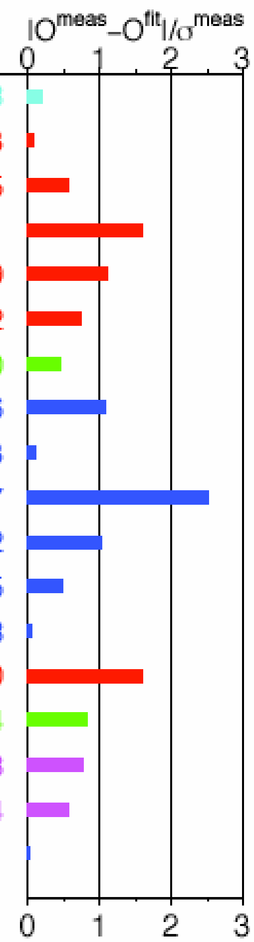
Global Fit: Winter 2004

χ^2 per dof
$= 16.3 / 13$

Largest contributions to χ^2 from

$A_{FB}^{0,b}$
$\mathcal{A}_\ell$ (from SLD)

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



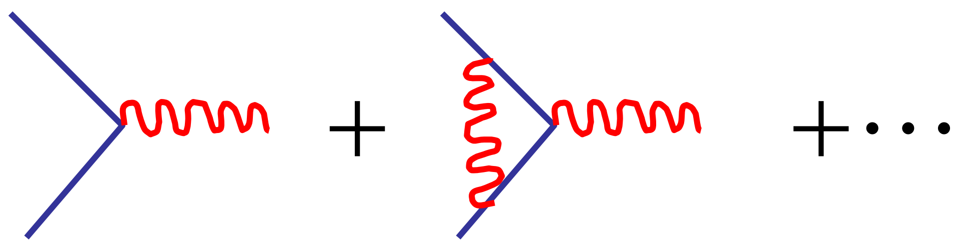
$A_{FB}^{0,b}$ and $\mathcal{A}_\ell$ pull in opposite directions (concerning effects on m_H)

II. Why a "New Standard Model"?

- There is no unification in the early SM Universe
- The Fermi constant is inexplicably large
- There shouldn't be this much visible matter
- There shouldn't be this much invisible matter

The early SM Universe had no unification

Couplings depend on scale

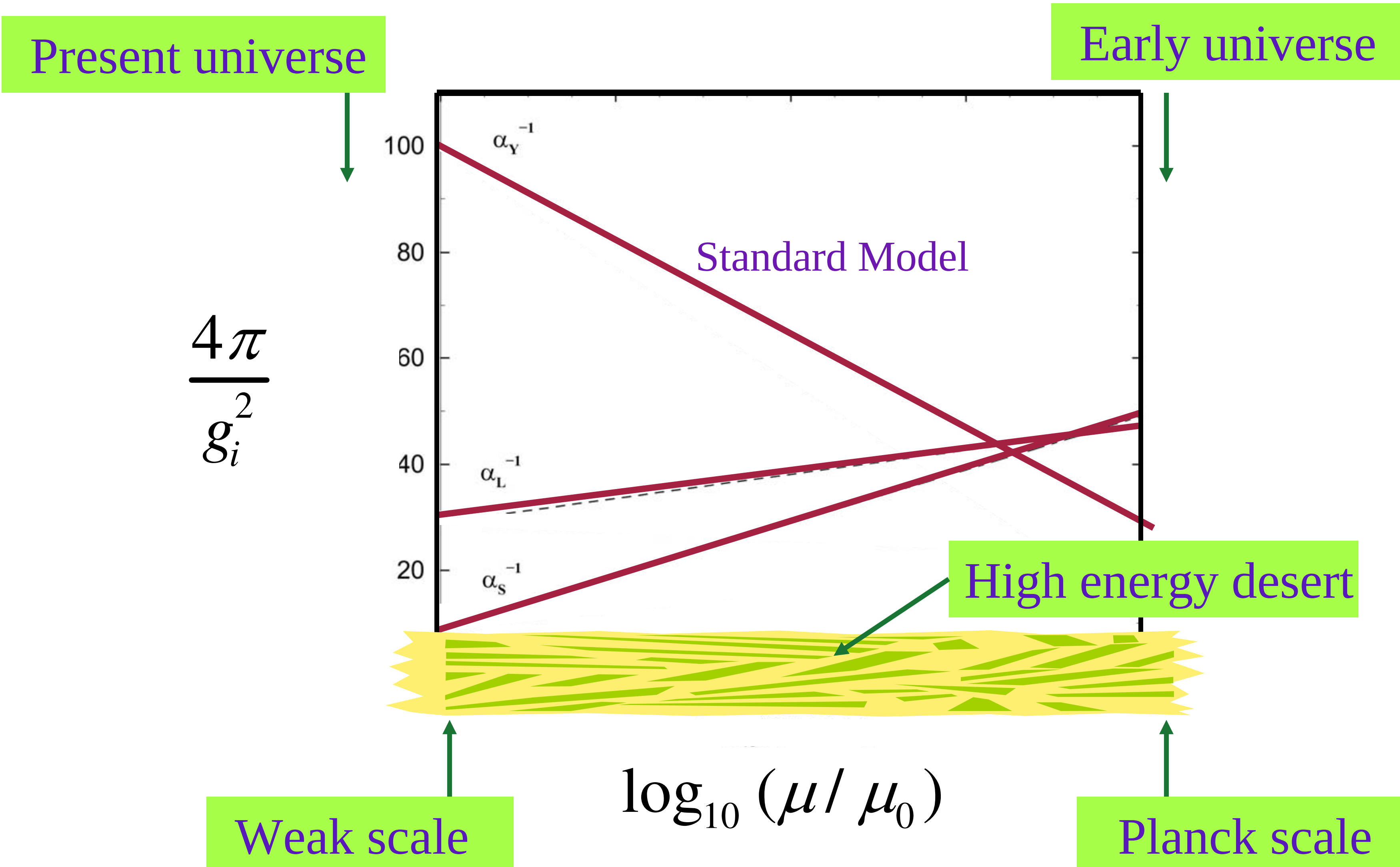


$$e = e(\mu)$$

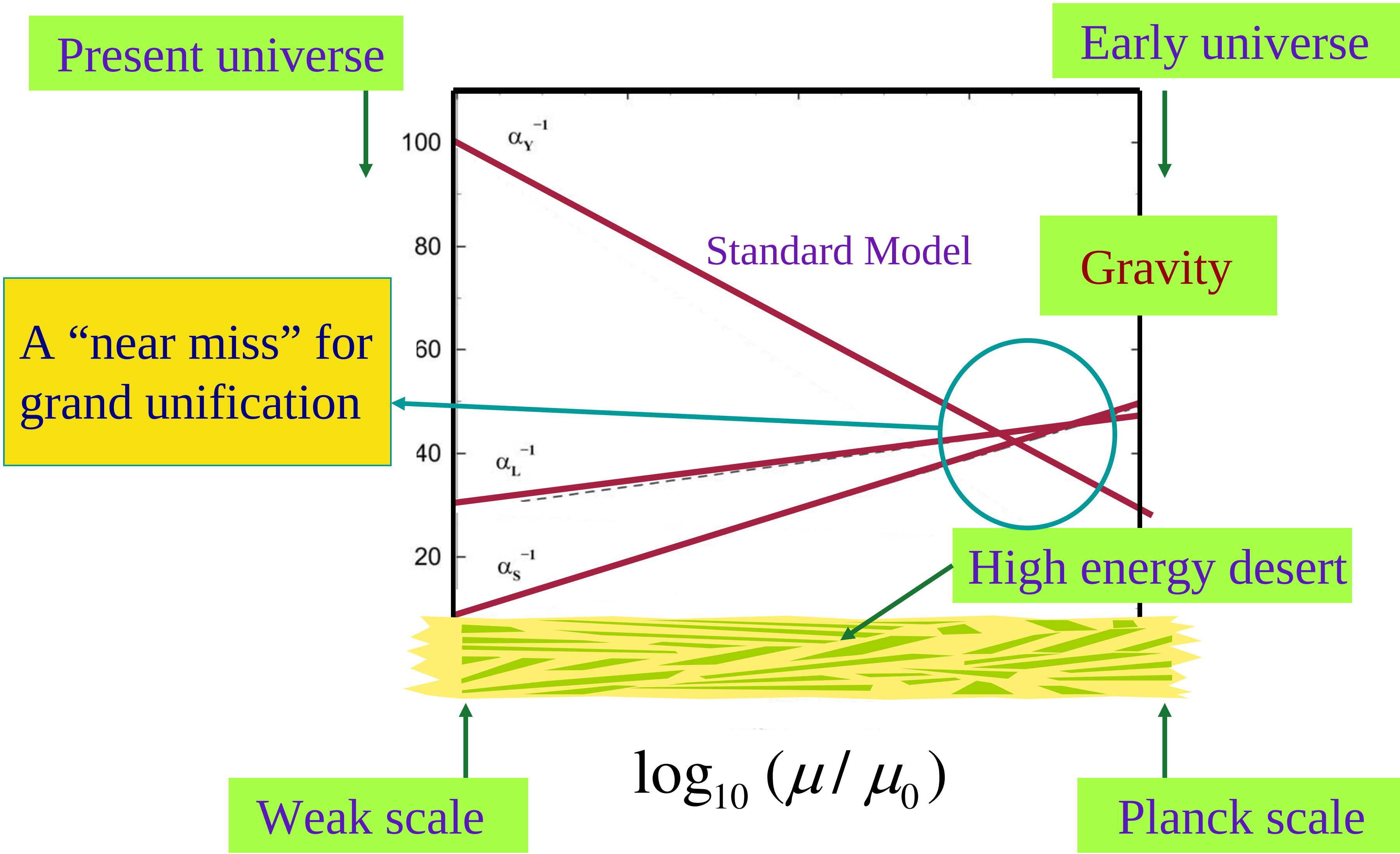
$$g = g(\mu)$$

Energy Scale ~ T

The early SM Universe had no unification



The early SM Universe had no unification

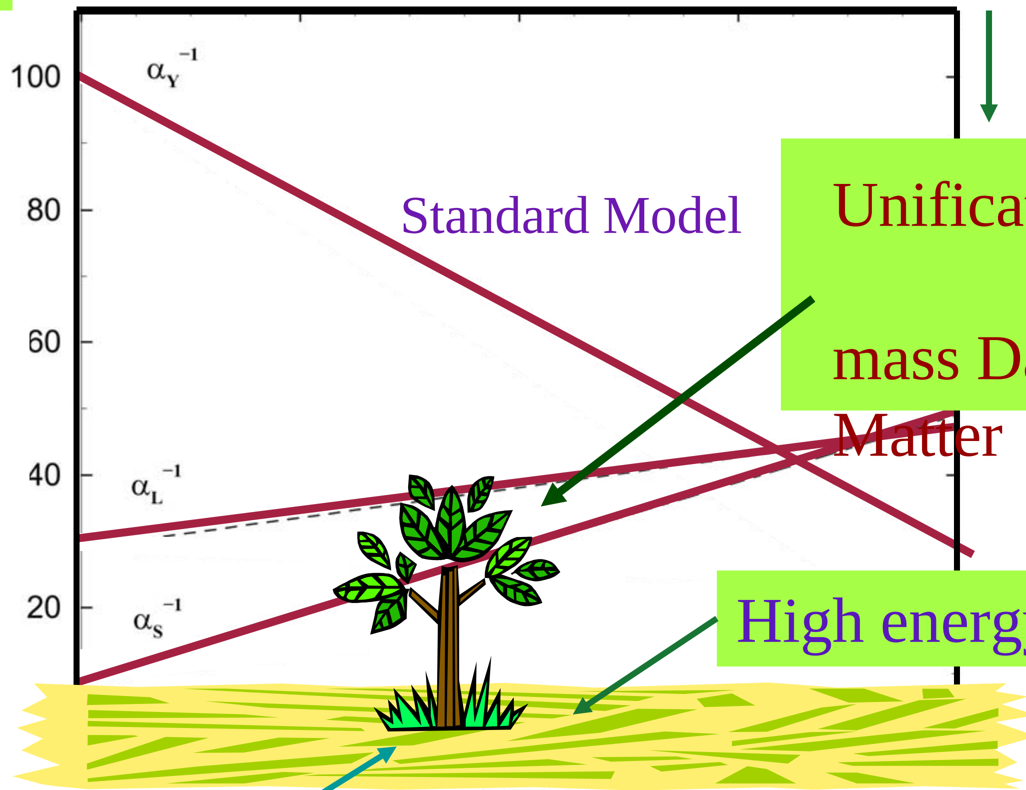


The Fermi constant is too large

Present universe

Early universe

G_F would shrink



Unification Neutrino mass Dark Matter

High energy desert

Weak scale

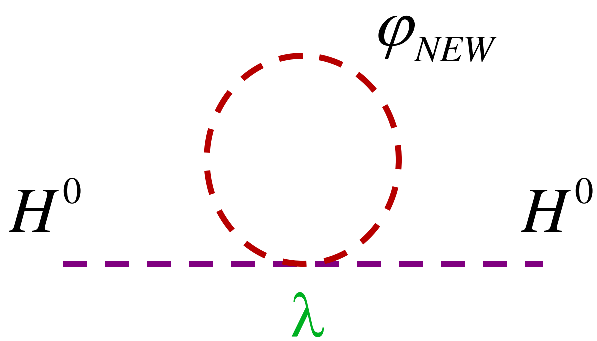
Planck scale

The Fermi constant is too large

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

$$M_W^2 = \frac{g^2\mu_{WEAK}^2}{4}$$

$\mu_{WEAK} \sim 250$ GeV $\quad G_F \sim 10^{-5}/M_P^2$



$$\Delta\mu_{WEAK}^2 \sim \lambda M_\varphi^2$$

A smaller G_F would mean disaster

The Sun would burn less brightly

$$p + p \rightarrow d + e^+ + \nu_e$$

$\Gamma \sim G_F^2$

Elemental abundances would change

$$p + e^- \leftrightarrow n + \nu_e$$

$T_{\text{freeze out}} \sim G_F^{-2/3}$

$$\frac{n}{p} = \exp\left(-\frac{m_n - m_p}{kT}\right)$$

$$Y(^4He) = \frac{2\,n/p}{1 + n/p}$$

Smaller G_F $\Rightarrow$ More ^{4}He, C, O…

There is too much matter - visible & invisible - in the SM Universe

Visible Matter from Big Bang Nucleosynthesis

$$n_B - n_{\bar{B}} \sim 10^{-10} n_\gamma$$

Measured abundances

$$n_B - n_{\bar{B}} \sim 10^{-18} n_\gamma$$

SM baryogenesis

Insufficient CP violation in SM

There is too much matter - visible & invisible - in the SM Universe

Invisible Matter

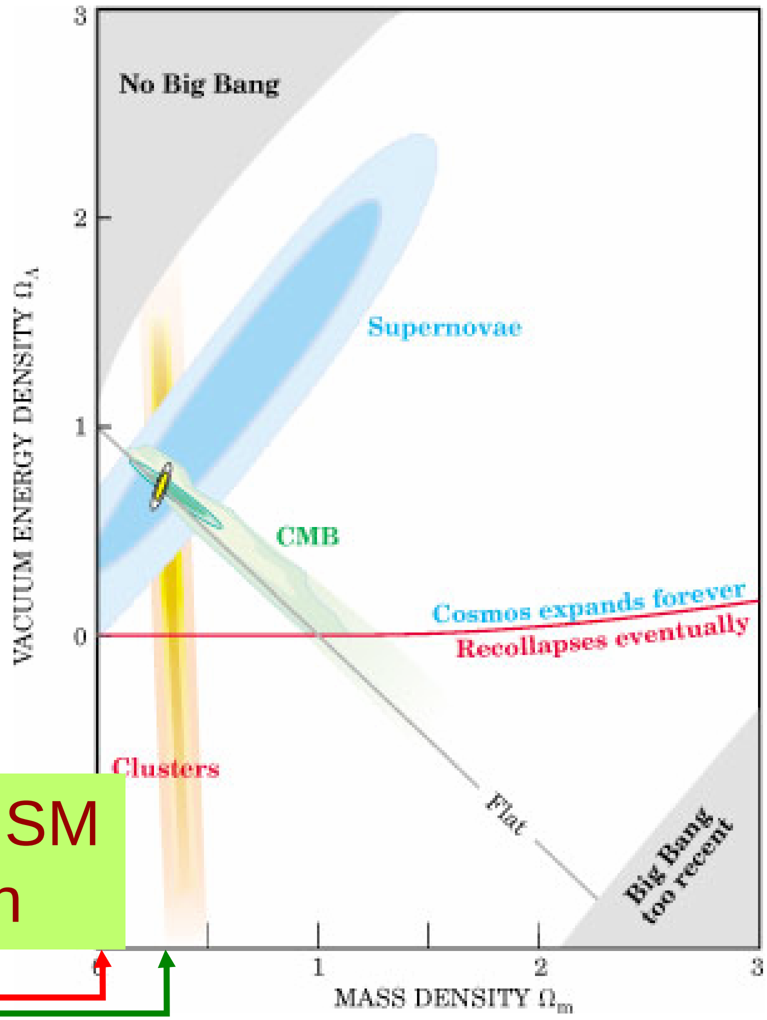
$$\Omega_M = \rho_M / \rho_c$$

No SM candidate

Dark

Insufficient SM CP violation

Visible



S. Perlmutter

There must have been additional symmetries in the earlier Universe to

- Unify all forces
- Protect G_F from shrinking
- Produce all the matter that exists

- Account for neutrino properties
- Give self-consistent quantum gravity

III. Supersymmetry

• **Unify all forces**	3 of 4
• **Protect G_F from shrinking**	Yes
• **Produce all the matter that exists**	Maybe so
• **Account for neutrino properties**	Maybe
• **Give self-consistent quantum gravity**	Probably necessary

SUSY may be one of the symmetries of the early Universe

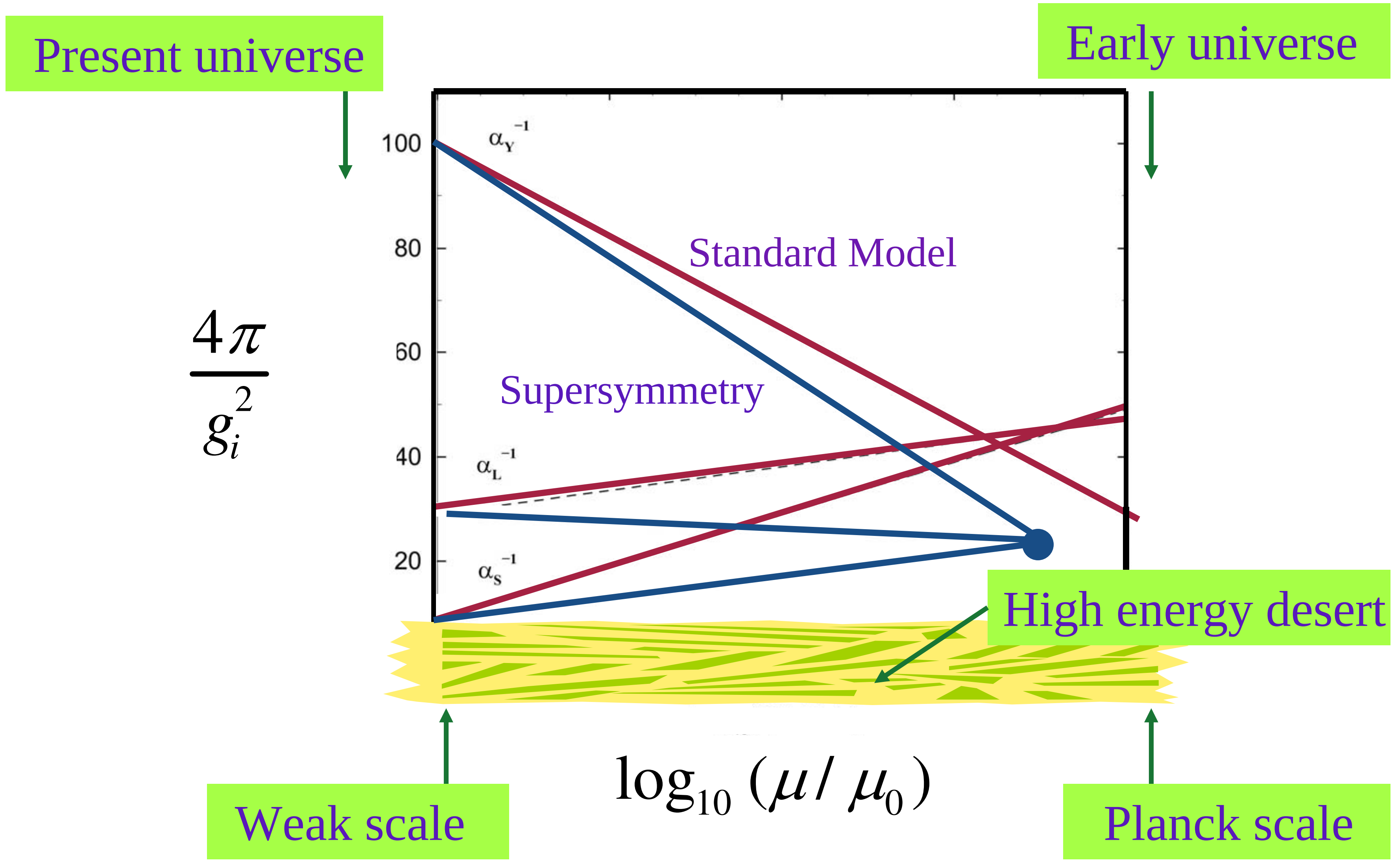
Supersymmetry

	Fermions		Bosons	
	$e_{L,R}\,,\ q_{L,R}$	$\Longleftrightarrow$	$\tilde{e}_{L,R}\,,\ \tilde{q}_{L,R}$	sfermions
gauginos	$\tilde{W}\,,\tilde{Z}\,,\tilde{\gamma}\,,\ \tilde{g}$	$\Longleftrightarrow$	$W\,,Z\,,\gamma\,,\ g$	
Higgsinos	$\tilde{H}_u\,,\ \tilde{H}_d$	$\Longleftrightarrow$	$H_u\,,H_d$	

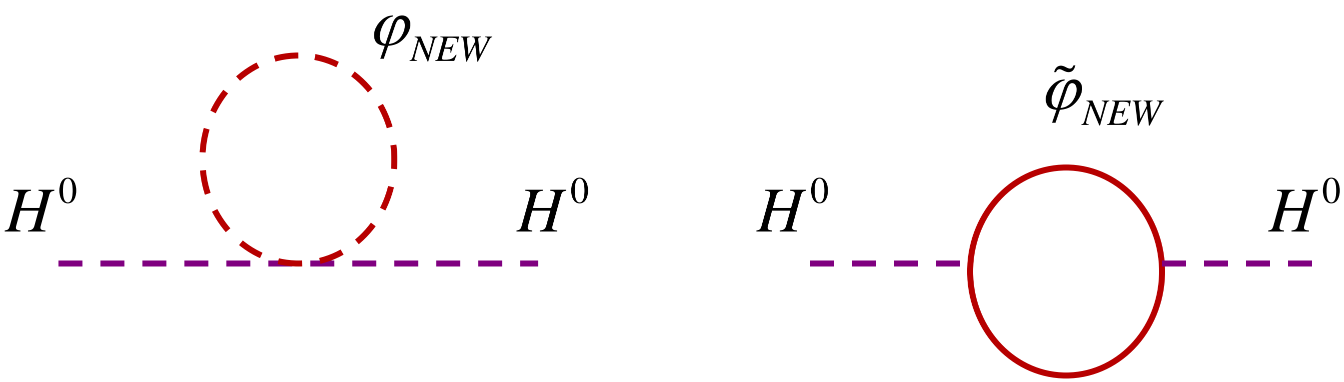
$$\tilde{W}\,,\tilde{Z}\,,\tilde{\gamma}\,,\tilde{H}_{u,\,d} \Rightarrow \ \tilde{\chi}^{\pm}\,,\tilde{\chi}^{0}$$

Charginos, neutralinos

Couplings unify with SUSY



SUSY protects G_F from shrinking



$$\Delta\mu^2_{WEAK} \sim M^2_{\varphi} - M^2_{\tilde{\varphi}} + \log terms$$

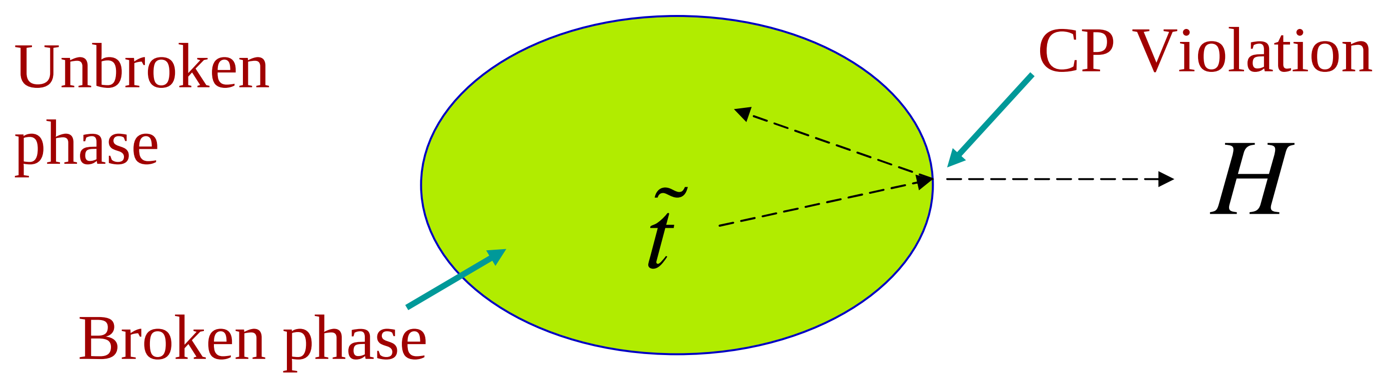
=0 if SUSY is exact

SUSY may help explain observed abundance of matter

Cold Dark Matter Candidate

χ^0 Lightest SUSY particle

Baryonic matter



SUSY must be a broken symmetry

Superpartners have not been seen

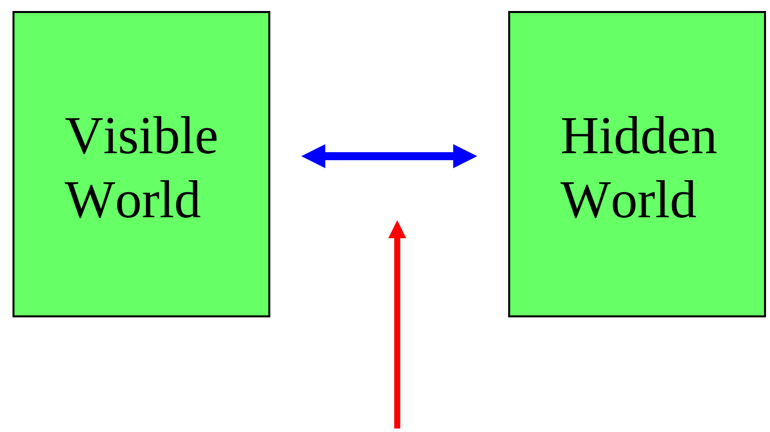
$$M_{\tilde{e}} >> m_e$$

$$M_{\tilde{q}} >> m_q$$

$$M_{\tilde{\chi}} >> M_{W,Z,\gamma}$$

Theoretical models of SUSY breaking

SUSY Breaking



Flavor-blind mediation

Minimal Supersymmetric Standard Model (MSSM)

$$L_{SM} \to L_{SM} + L_{SUSY} + L_{soft}$$

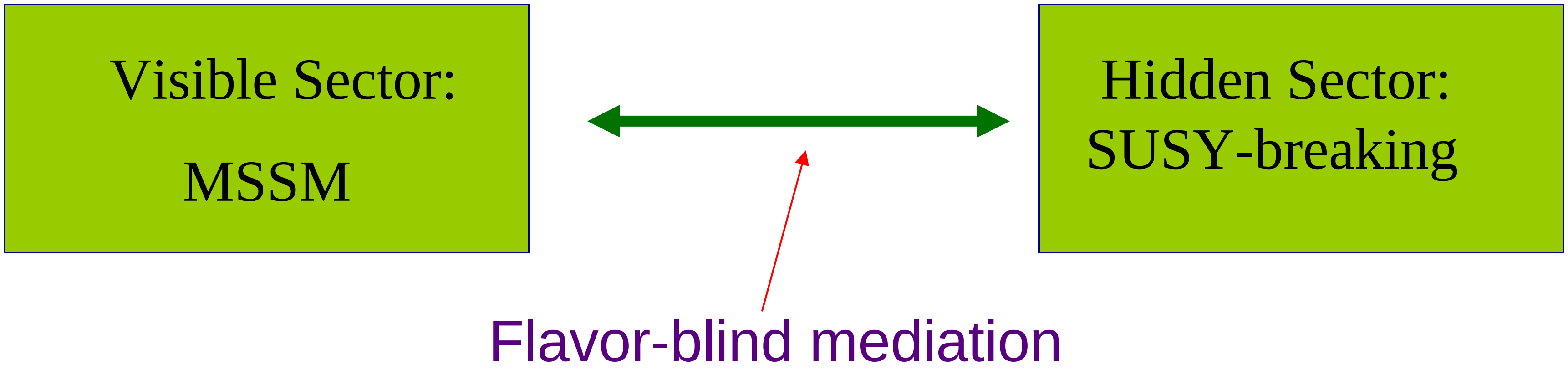
$$\tilde{M} \neq M$$

L_{soft} gives $\tilde{M} \neq M$

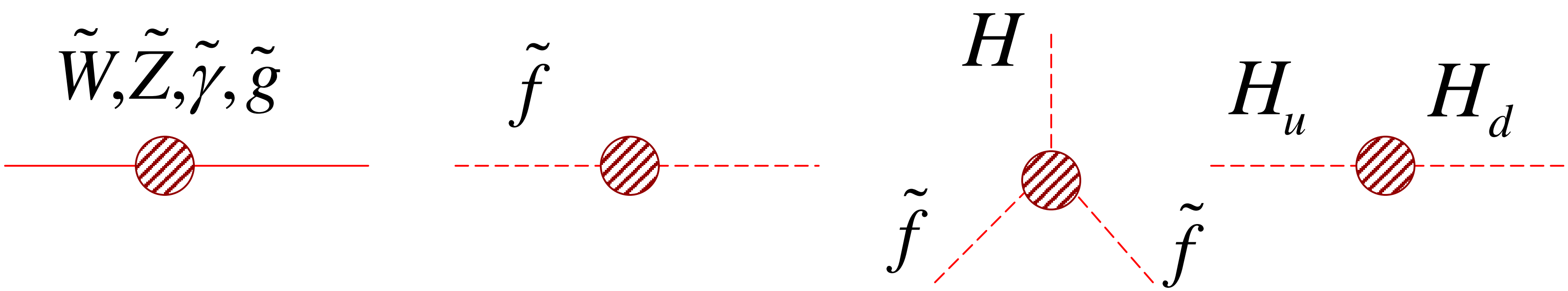
contains 105 new parameters

How is SUSY broken?

How is SUSY broken?



Gravity-Mediated (mSUGRA)



$M_{1/2}$ M_0^2 A_0 b_0

How is SUSY broken?

Visible Sector:

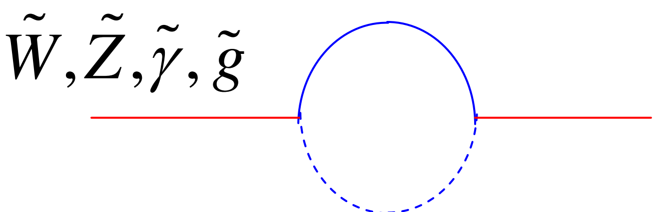
MSSM

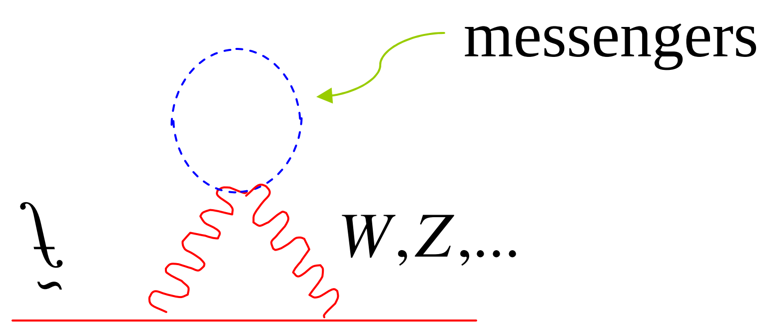
Hidden Sector:

SUSY-breaking

Flavor-blind mediation

Gauge-Mediated (GMSB)





$$A_0 \approx 0$$

$$M_{1/2} \approx \frac{\alpha_a}{4\pi} \Lambda \qquad M_0^2 \approx \Lambda^2 \sum \left(\frac{\alpha_a}{4\pi} \right) C_a \qquad b_0 \approx 0$$

Mass evolution

$$\frac{dM^2_{\tilde{f}}}{dt} = -\sum_{a=1}^{3} \alpha_a C_a^{\tilde{f}} \left|\tilde{M}_a\right|^2 \qquad t = \ln \mu$$

$\tilde{M}_a$ gaugino mass

$C_a^{\tilde{f}} \geq 0$ group structure

$M_{\tilde{f}}$ increases as μ decreases

$M_{\tilde{q}}$ increases faster than $M_{\tilde{\ell}}$ $(C_3^{\tilde{q}} > 0, C_3^{\tilde{\ell}} = 0)$

$M_{\tilde{q}} > M_{\tilde{\ell}}$ at the weak scale

Sfermion Mixing

$$\hat{M}^2 = \begin{pmatrix} \tilde{M}^2_{\tilde{f}_L} & M^2_{LR} \\ M^2_{LR} & \tilde{M}^2_{\tilde{f}_R} \end{pmatrix}$$

$$M^2_{LR} = \begin{cases} m_f(\mu \tan\beta - A_f) & Q_f < 0 \\ m_f(\mu \cot\beta - A_f) & Q_f > 0 \end{cases}$$

$$\tilde{f}_L, \tilde{f}_R \longrightarrow \tilde{f}_1, \tilde{f}_2$$

MSSM and R Parity

$$P_R = (-1)^{3(B-L)} (-1)^{2S}$$

Matter Parity: An exact symmetry of the SM

SM Particles: $P_R = +1$

Superpartners: $P_R = -1$

MSSM and R Parity

MSSM conserves P_R ⟹ vertices have even number of superpartners

Consequences

- Lightest SUSY particle $\left(\tilde{\chi}^0\right)$ is stable ⟹ viable dark matter candidate
- Proton is stable
- Superpartners appear only in loops