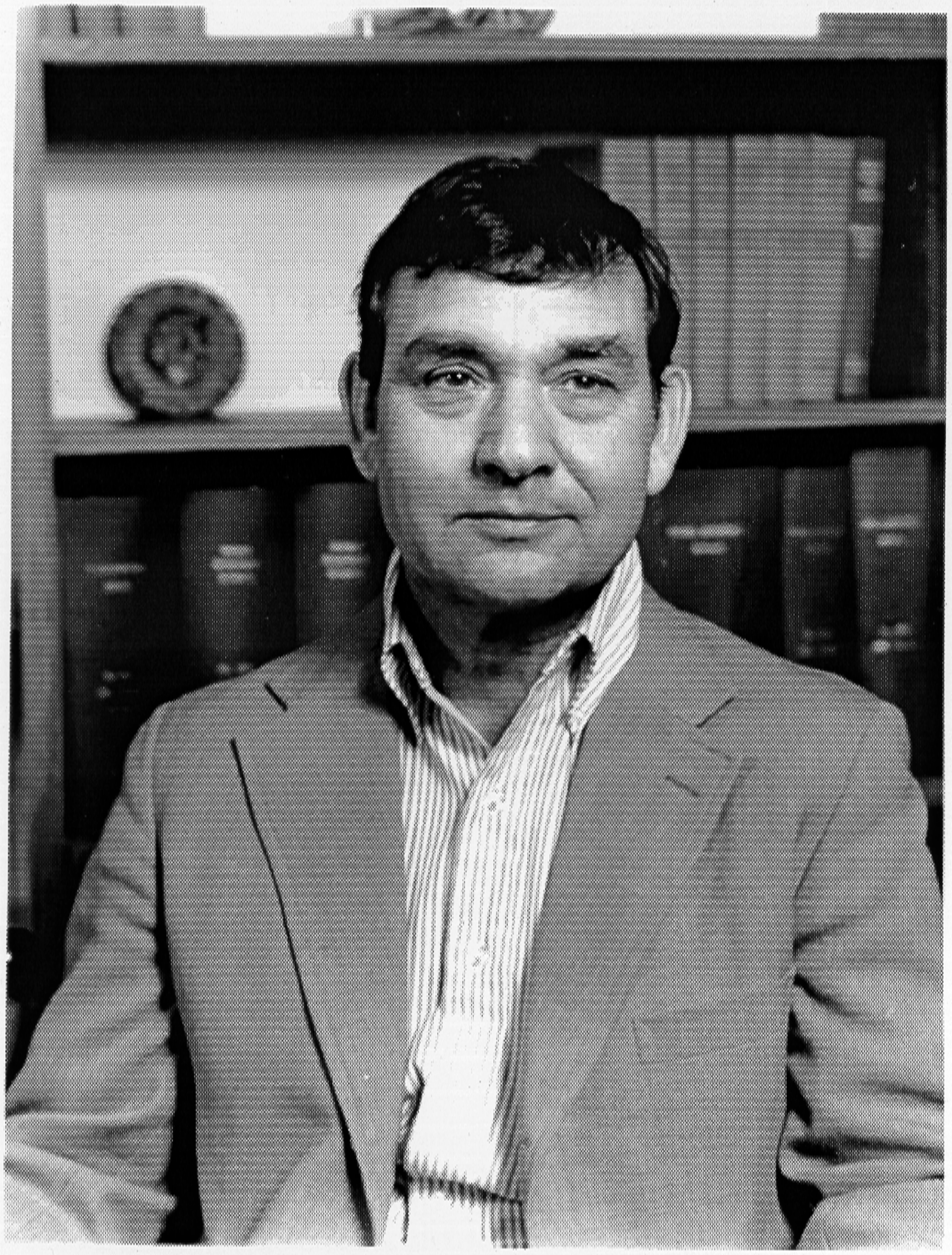
THE STATE OF THE STANDARD MODEL

CHRIS QUIGG
Fermilab

μμ99
San Francisco · 15 December 1999



Sam Treiman

ARNPS 46, 1 (1996)

OUR PICTURE OF MATTER

(November Revolution + 25 Years) 11.11.74

Pointlike ($r < 10^{-18}$ m) quarks

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

and leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

with interactions specified by

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

gauge symmetries

QCD IS PART OF THE STD. MODEL ...

A REMARKABLY
SIMPLE,
SUCCESSFUL,
AND RICH THEORY
(cf. F. Wilczek, hep-ph/9907340)

Perturbative QCD

- Exists, thanks to ASYMPTOTIC FREEDOM
- Describes many phenomena in quantitative detail:
  - ▶ Q^2-evolution of Structure Fcns.
  - ▶ Jet production in $\bar{p}p$
  - ▶ Many decays, evt. shapes, ...

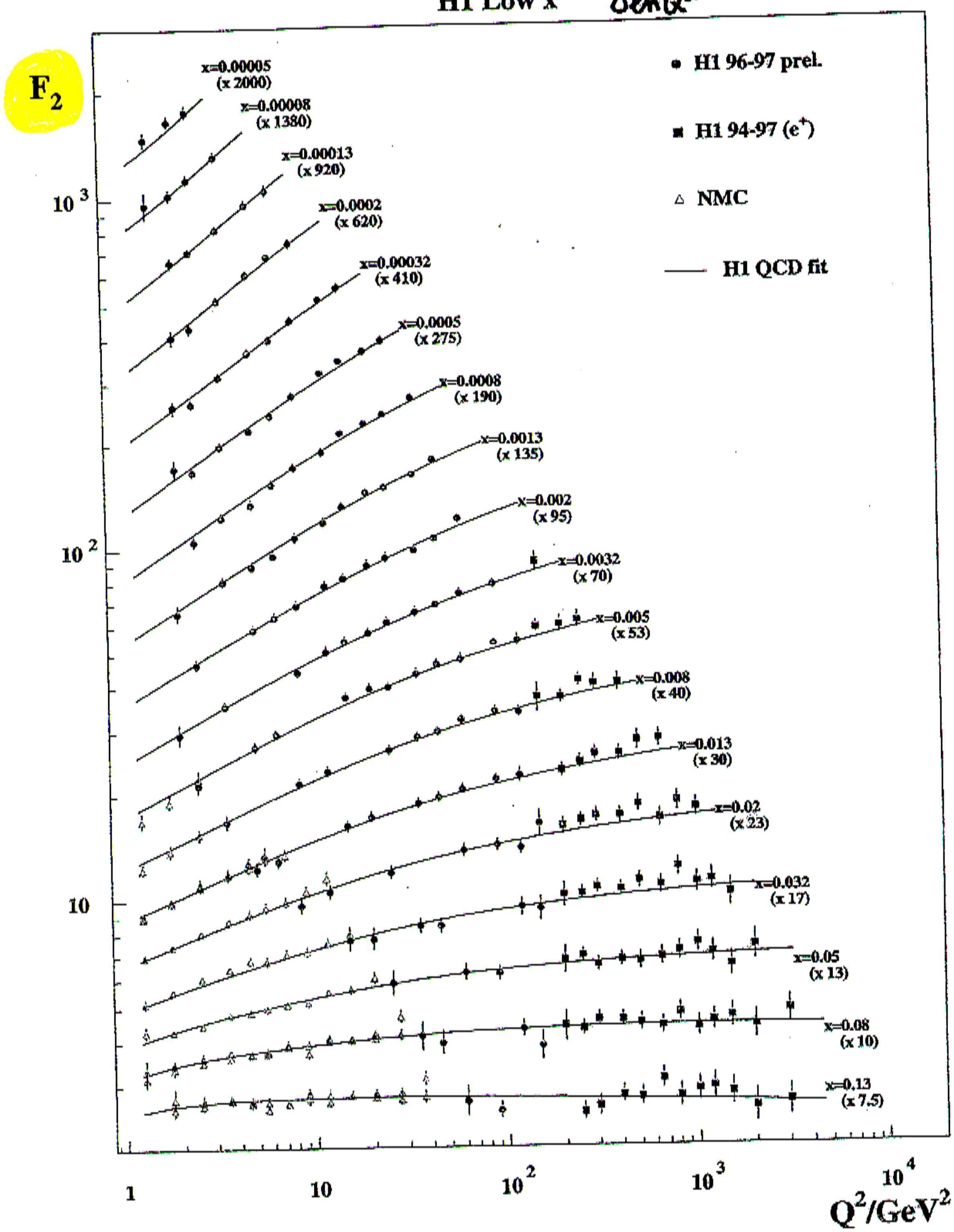
We can measure the running of α_s
(engineering value for unification)

Nonperturbative (Lattice) QCD

- Predicts the hadron spectrum
- Gives our best information on quark masses, etc.

large scaling violations described by NLO DGLAP

$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s \cdot xg$



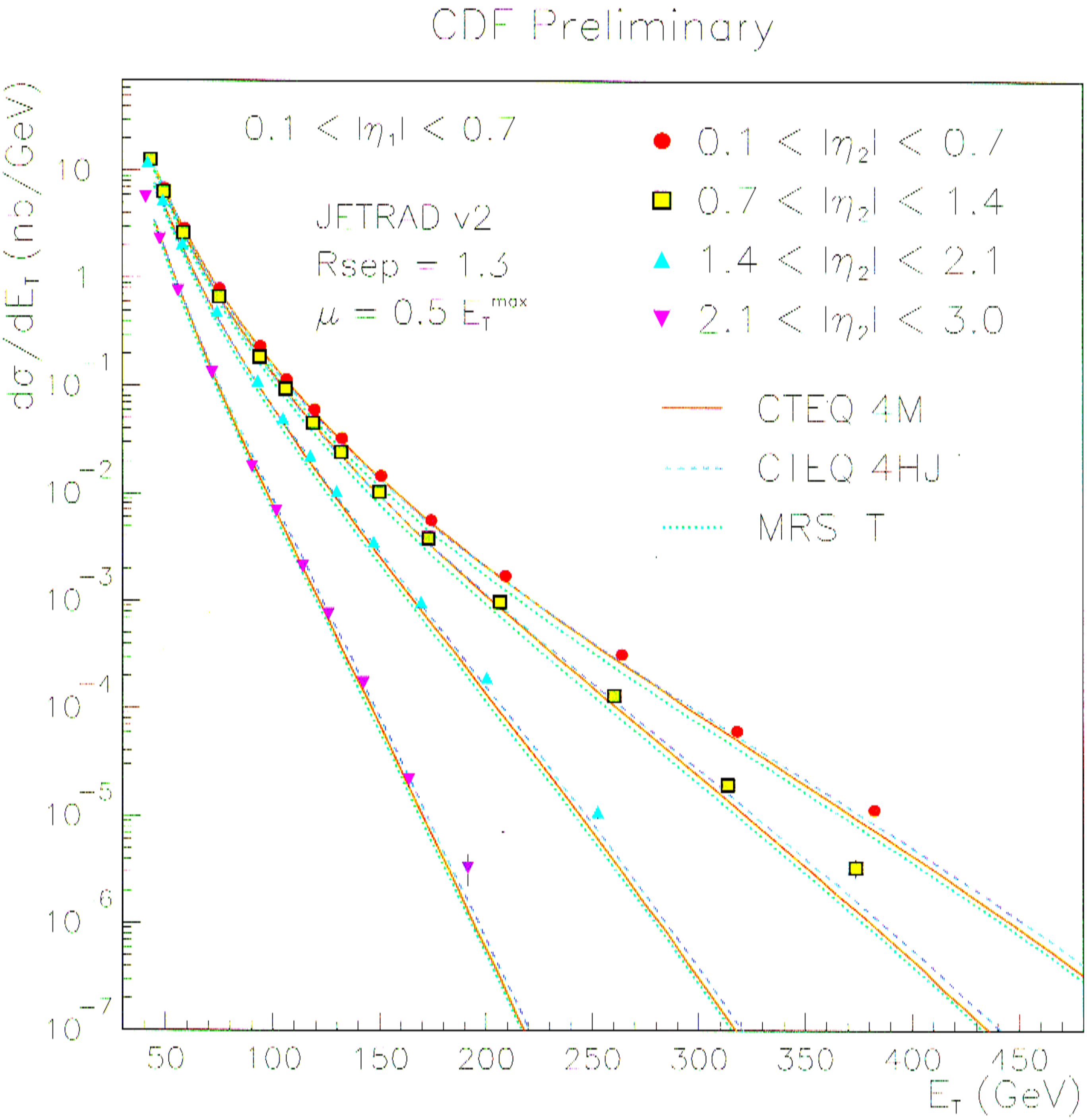
where is BFKL, $\ln 1/x$ terms ?

cf. Proc. DIS99

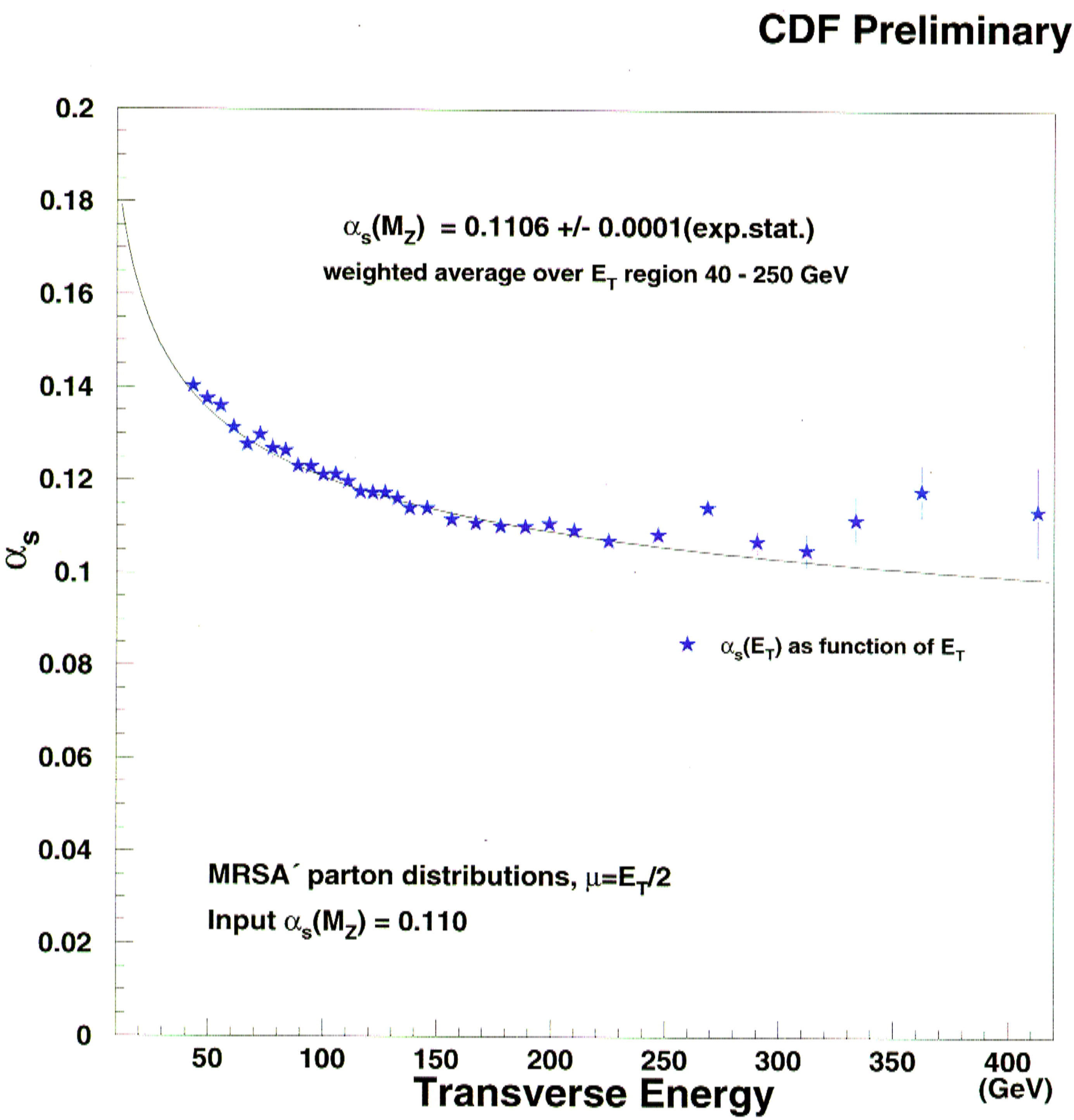
Balitzkii, Fadin, Kuraev, Lipatov 1975,78

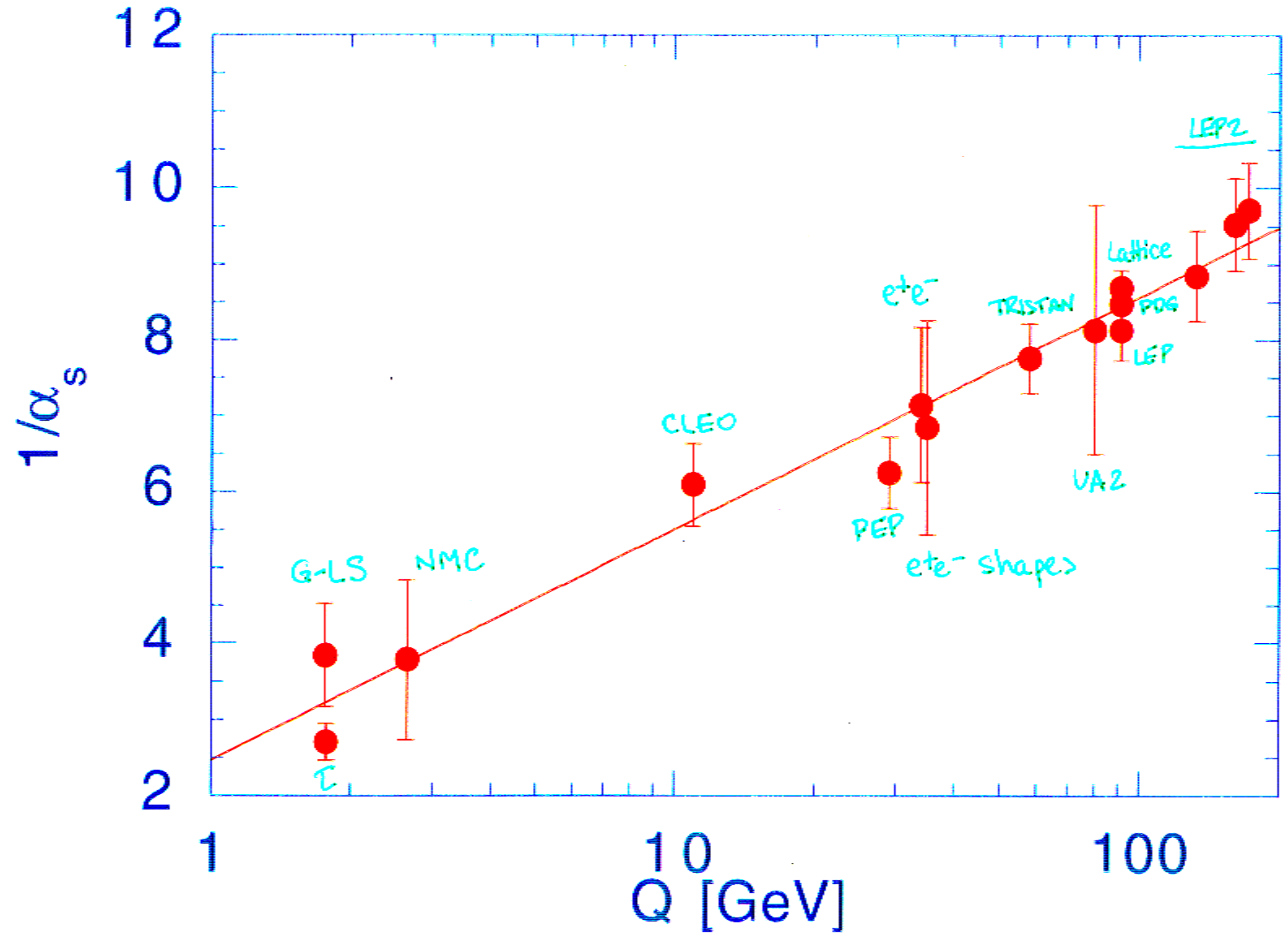
Ciafaloni, Fadin, delDuca
Thorne ...

$\bar{p}p \longrightarrow jet_1 + jet_2 + anything$

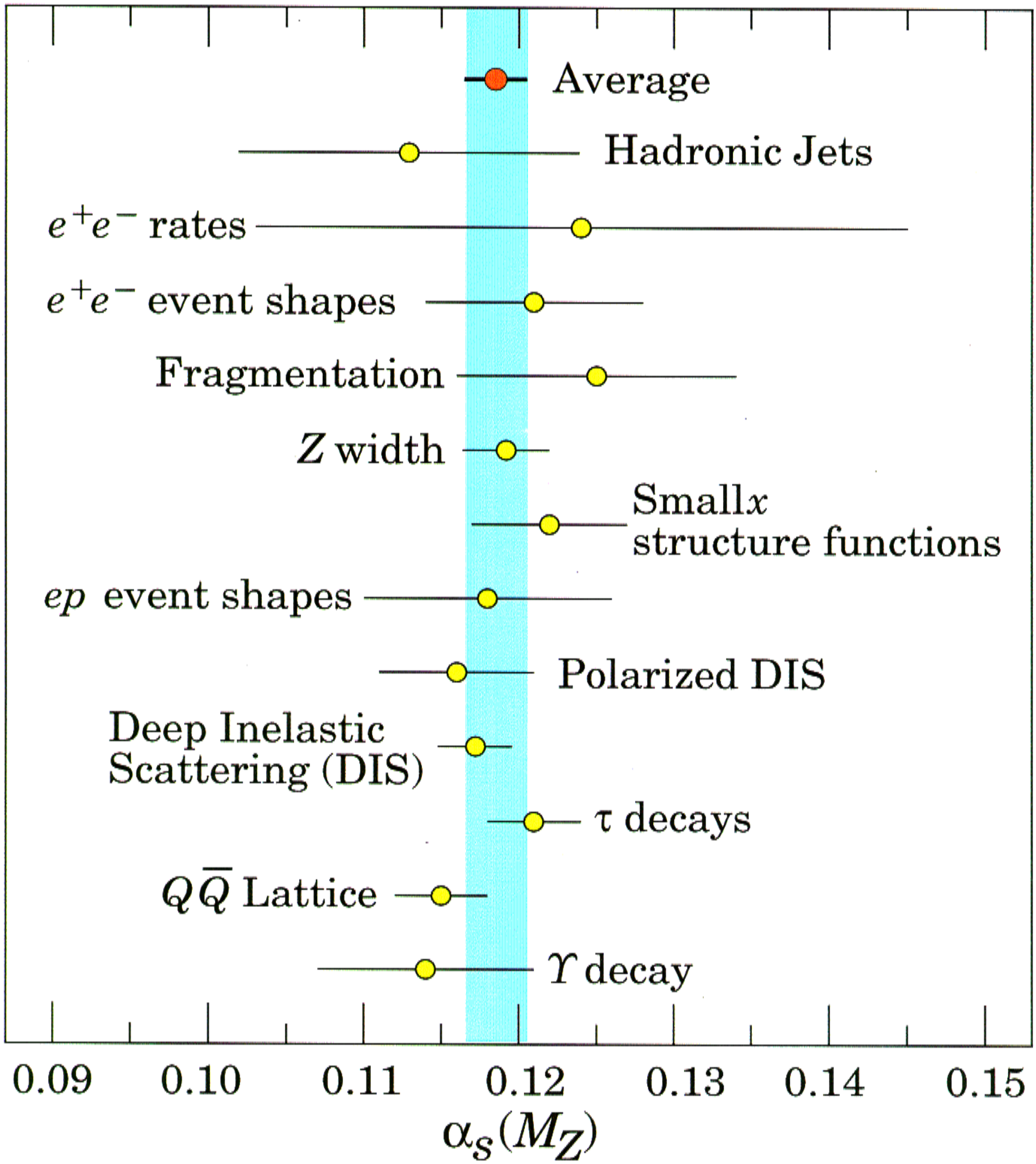


α_s determined from $\bar{p}p \to jet_1 + jet_2 +$ anything



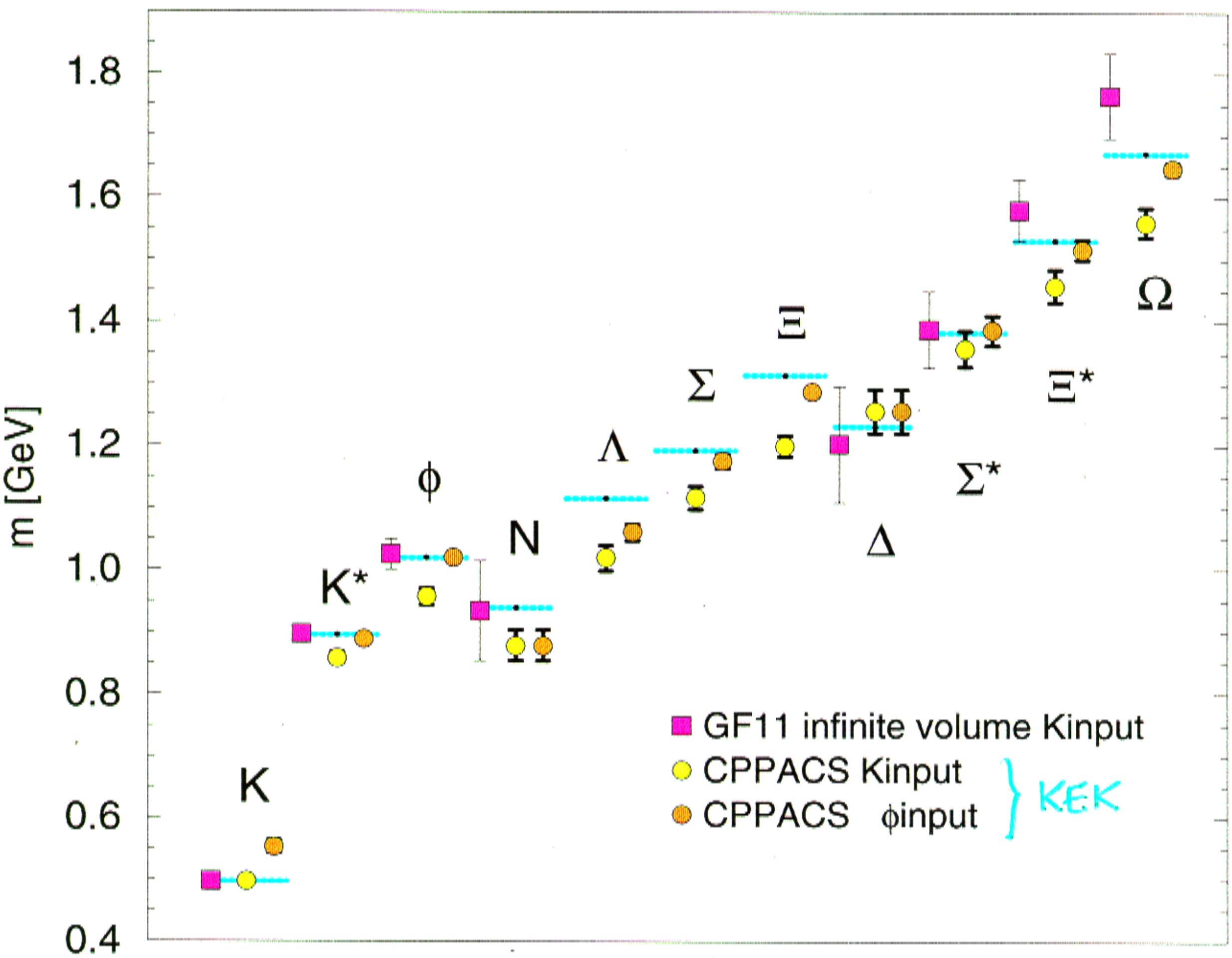


12
10
8
6
4
2
1/α_s
1
10
100
Q [GeV]
G-LS
NMC
τ
CLEO
PEP
e+e-
e+e- shapes
TRISTAN
VA2
Lattice
PDG
LEP
LEP2



Average
Hadronic Jets
e^+e^- rates
e^+e^- event shapes
Fragmentation
Z width
Small x
structure functions
ep event shapes
Polarized DIS
Deep Inelastic
Scattering (DIS)
τ decays
$Q\overline{Q}$ Lattice
Υ decay
0.09
0.10
0.11
0.12
0.13
0.14
0.15
$\alpha_s(M_Z)$

PDG



No dynamical fermions (coming soon)

R. Burkhalter, hep-lat/9810043

THE $SU(2)_L \otimes U(1)_Y$ ELECTROWEAK THEORY

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

+ IDEALIZATION THAT NEUTRINOS ARE MASSLESS

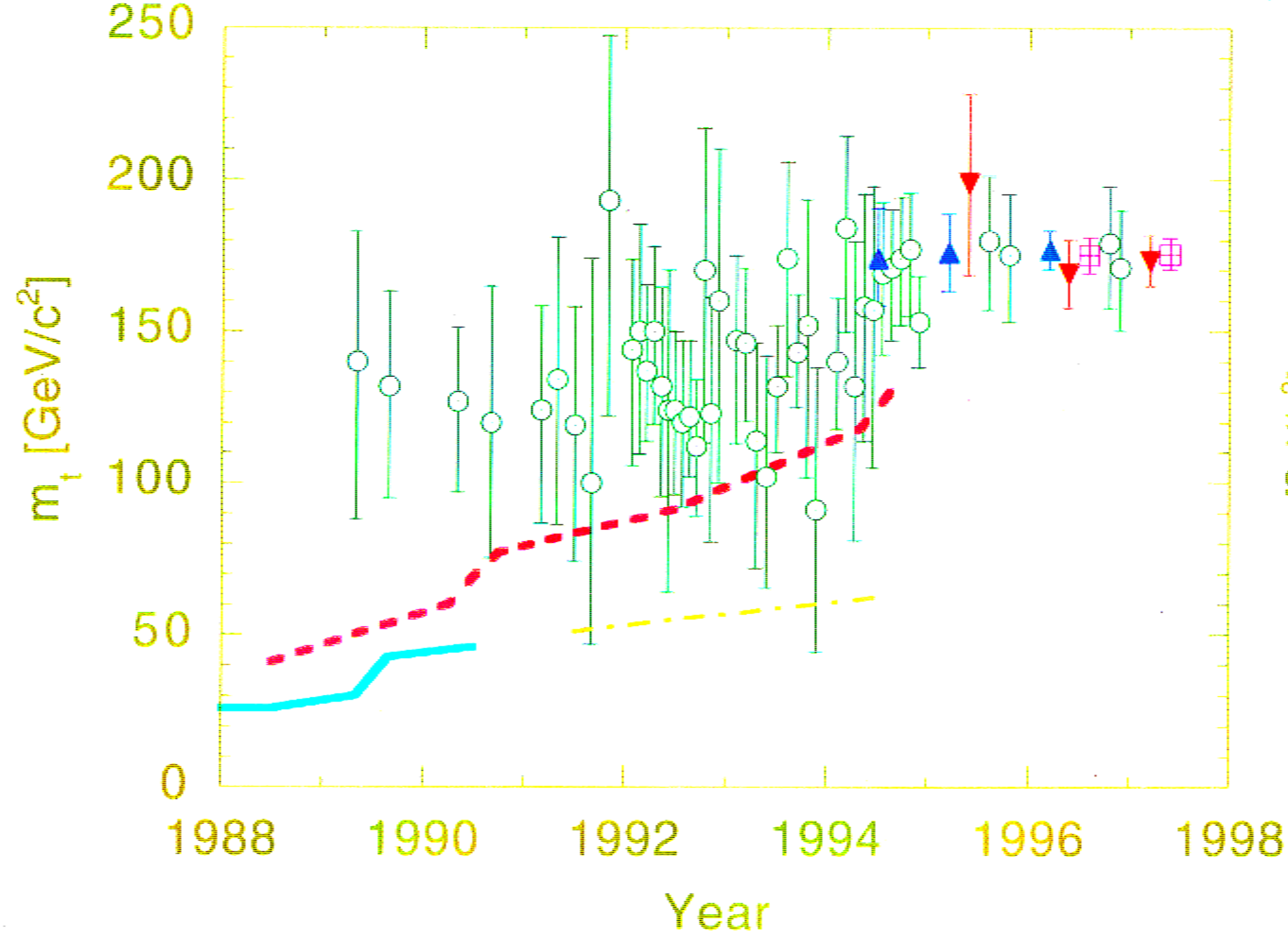
- MANY SUCCESSES:
  - Neutral Currents
  - Charm
  - $W^\pm$, Z^0
  - ⋱

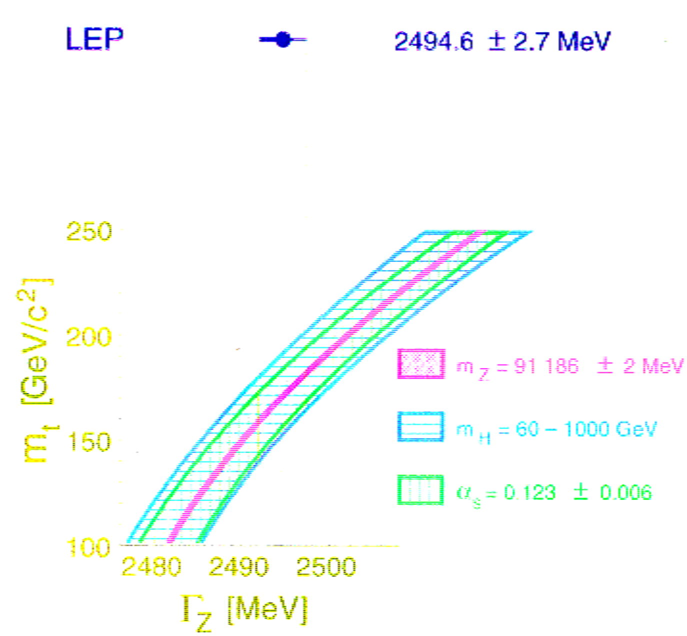
- PRECISION MEASUREMENTS (10 years of LEP et al.)
  - Testing the Quantum Field Theory
  - Looking for new physics "in the sixth place of decimals"

Cf. A. Sirlin, hep-ph/9912227

Global Fits to precision EW measurements

- precision improves with time
- calculations have improved with time

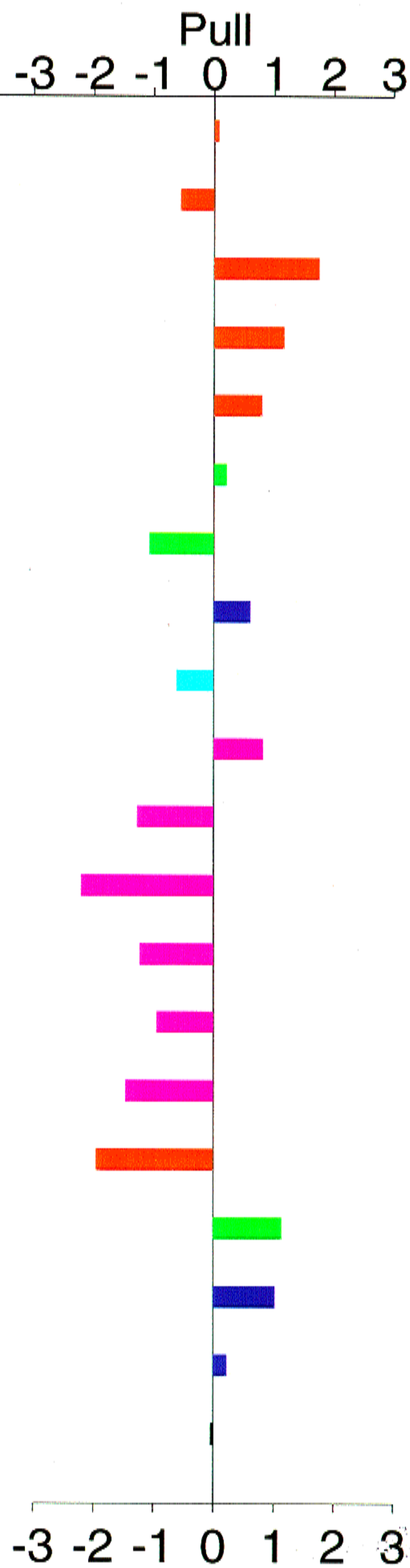




11.94: LEPEWWG: $m_t = 178 \pm 11^{+18}_{-19}$ GeV/c^2 (174.3 ± 5.1 GeV/c^2)

Stanford 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05



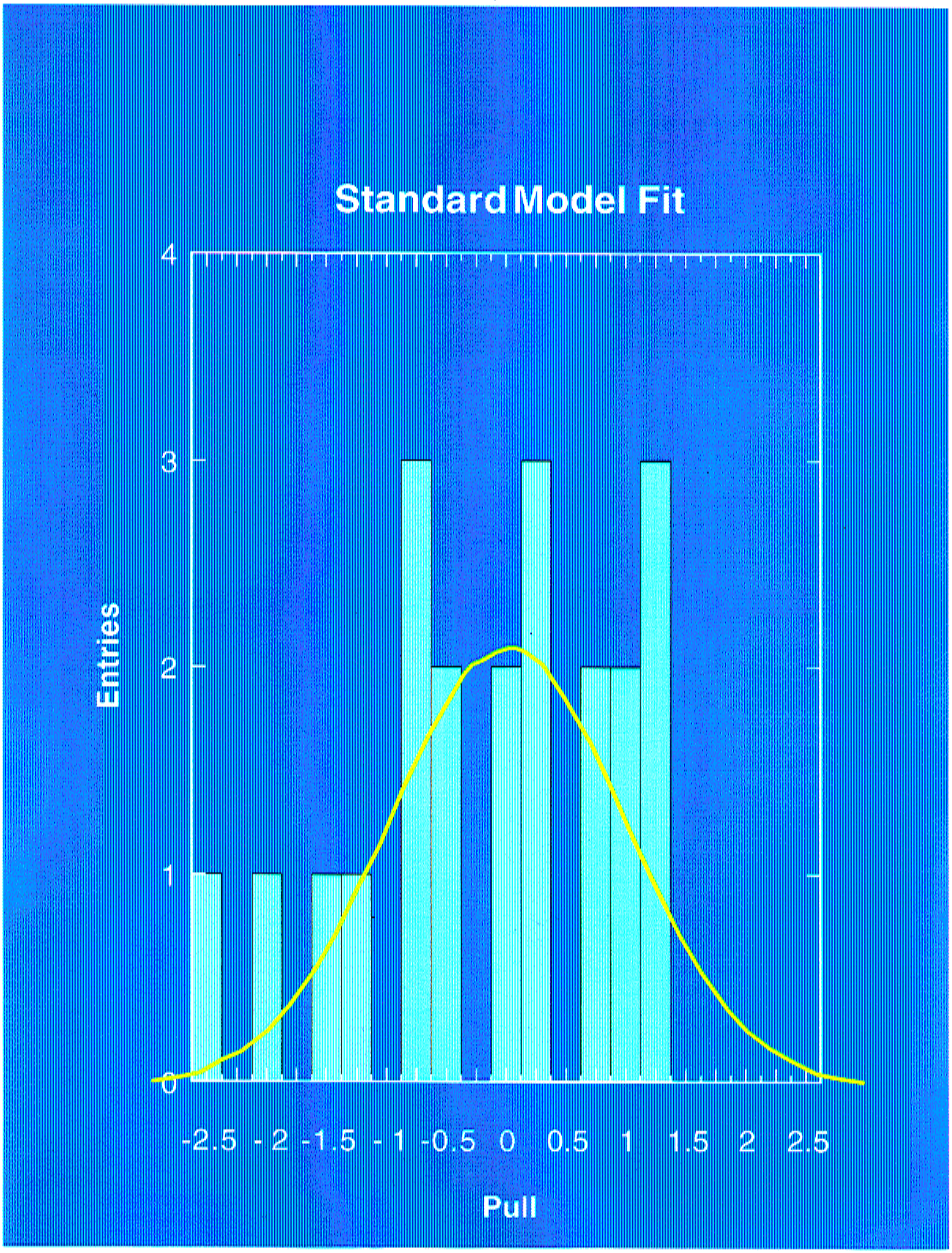
Cho+Hagiwara, hep-ph/9912260

	data	SM*	pull*
LEP 1 [11]			
line-shape & FB asym.:			
m_Z (GeV)	91.1867 ± 0.0021	—	—
Γ_Z (GeV)	2.4939 ± 0.0024	2.4972	−1.4
σ_h^0(nb)	41.491 ± 0.058	41.474	0.3
R_ℓ	20.765 ± 0.026	20.747	(0.7)
$A_{\rm FB}^{0,\ell}$	0.01683 ± 0.00096	0.01651	(0.3)
for each lepton:			
R_e	20.783 ± 0.052	20.747	0.7
R_μ	20.789 ± 0.034	20.747	1.3
R_τ	20.764 ± 0.045	20.795	−0.7
$A_{\rm FB}^{0,e}$	0.0153 ± 0.0025	0.0165	−0.5
$A_{\rm FB}^{0,\mu}$	0.0164 ± 0.0013	0.0165	−0.1
$A_{\rm FB}^{0,\tau}$	0.0183 ± 0.0017	0.0165	1.1
τ polarization:			
A_τ	0.1431 ± 0.0045	0.1484	−1.2
A_e	0.1479 ± 0.0051	0.1484	−0.1
b and c quark results:			
R_b	0.21656 ± 0.00074	0.21566	1.2
R_c	0.1735 ± 0.0044	0.1721	0.3
$A_{FB}^{0,b}$	0.0990 ± 0.0021	0.1040	−2.4
$A_{FB}^{0,c}$	0.0709 ± 0.0044	0.0744	−0.8
jet charge asymmetry:			
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.2321 ± 0.0010	0.2314	0.7
SLC [11]			
A_{LR}^0	0.1510 ± 0.0025	0.1484	1.0
A_b	0.867 ± 0.035	0.935	−1.9
A_c	0.647 ± 0.040	0.668	−0.5
Tevatron + LEP 2 [32]			
m_W (GeV)	80.410 ± 0.044	80.402	0.18
$\chi^2_{\rm tot}$ (19 data points)			19.8
Parameters	**Constraints**		
m_t (GeV) [29]	173.8 ± 5.2	175.0	—
$\alpha_s(m_Z)$ [29]	0.119 ± 0.002	0.118	—
$1/\alpha(m_Z^2)$ [30]	128.90 ± 0.09	128.90	—
[31]	128.94 ± 0.04	—	—

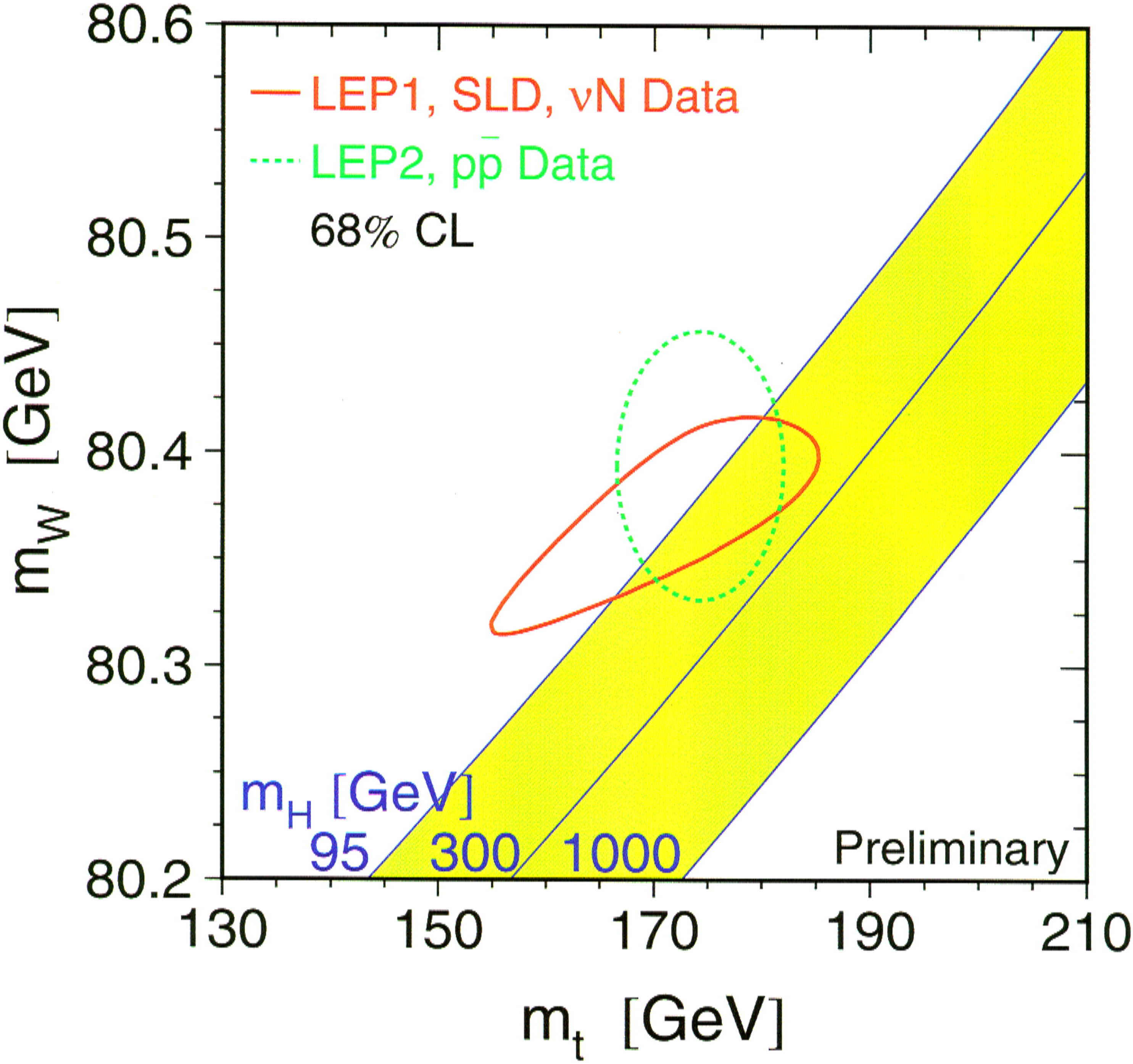
Anomalous $Z \to b_R \bar{b}_R$? ⇒ FCNC in $b \to s, d$; $s \to d$

Table 1: Electroweak measurements at LEP, SLC and Tevatron. The average W-boson mass is found in ref. [32]. The reference SM predictions and the corresponding 'pull' factors are given for $m_t = 175$ GeV, $m_{H_{\rm SM}} = 100$ GeV, $\alpha_s(m_Z) = 0.118$ and $1/\alpha(m_Z^2) = 128.90$. Correlation matrix elements of the Z line-shape parameters and those for the heavy-quark parameters are found in ref. [11]. The data R_ℓ and $A_{\rm FB}^{0,\ell}$ are obtained by assuming the e-μ-τ universality, and are not used in our χ^2 analysis.

(cf. W.J. Marciano, hep-ph/9902332)



Cho + Hagiwara



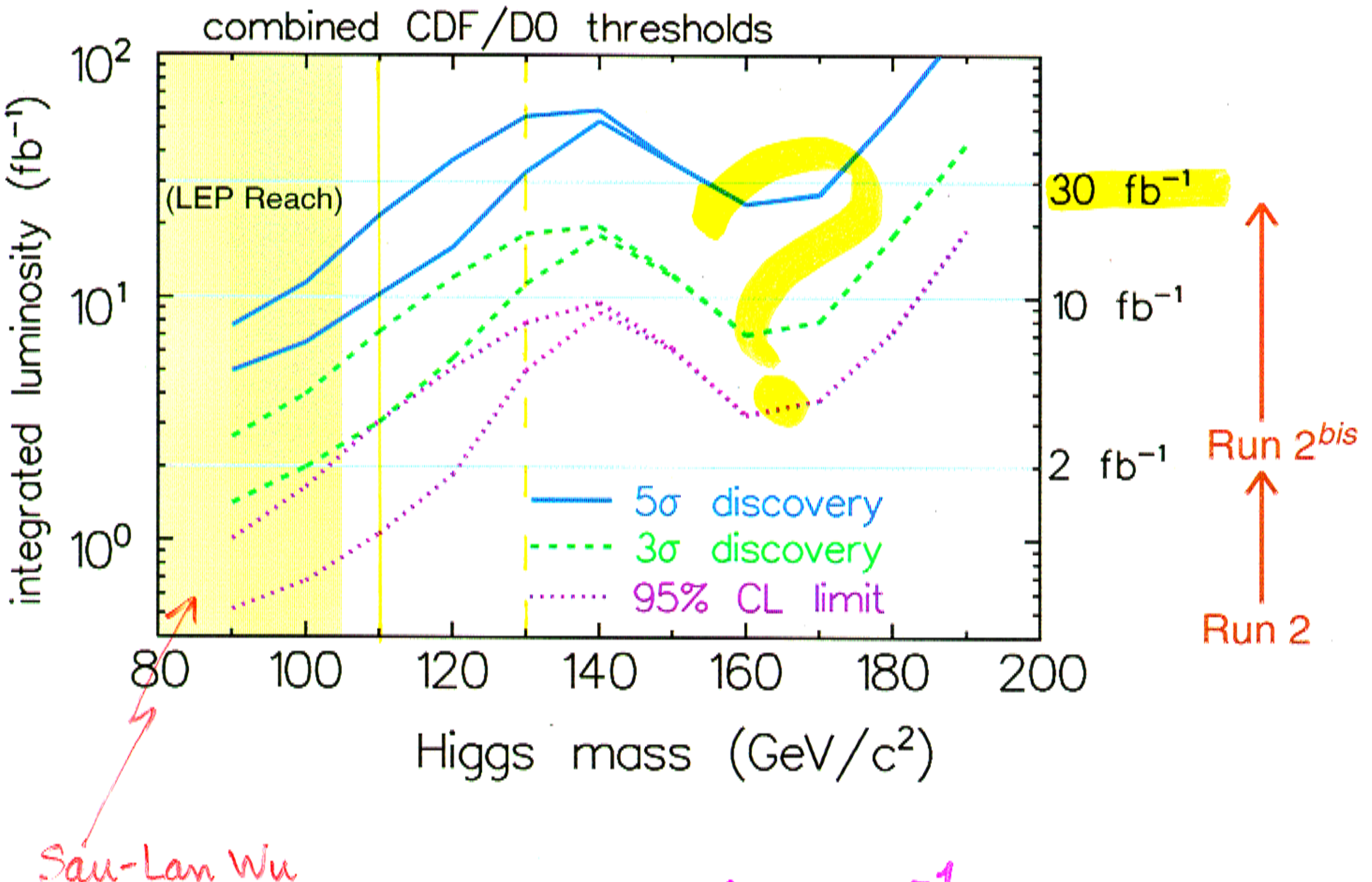
(Bill Marciano for details)

SEARCH FOR THE HIGGS BOSON AT THE TEVATRON

(J. Hobbs)

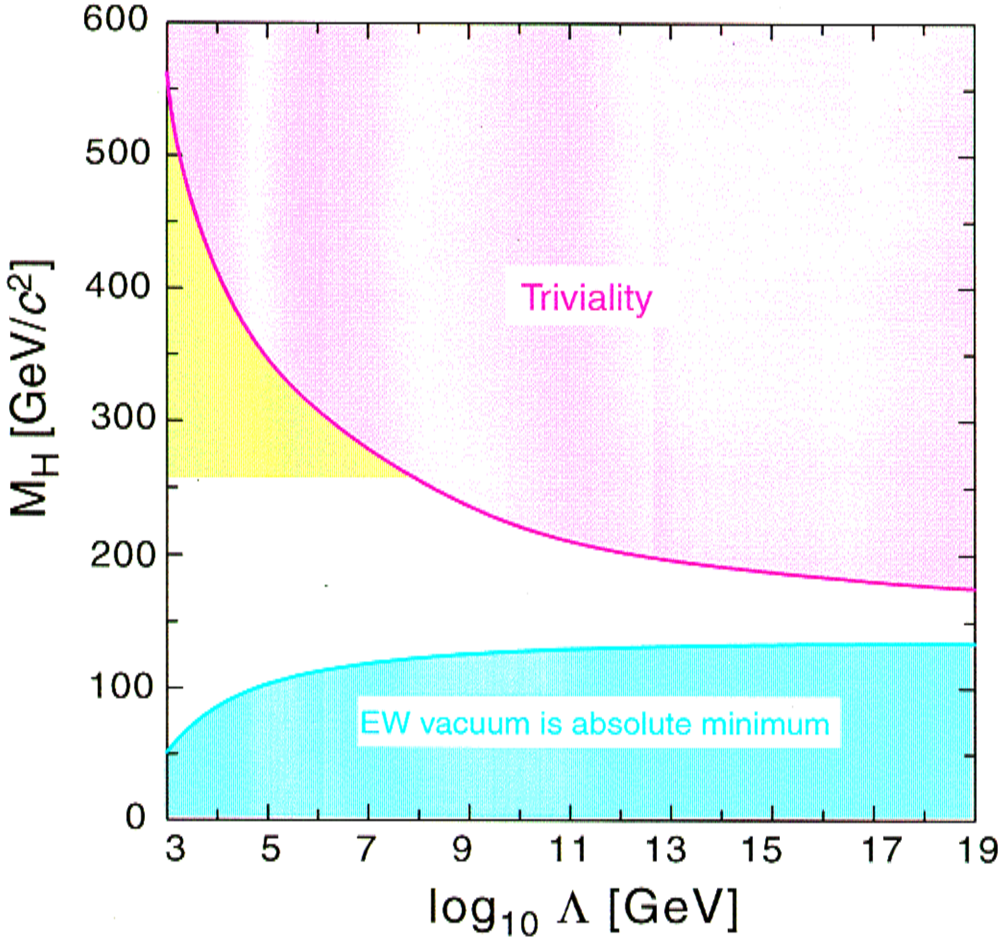
$\bar{p}p \to H + (W^\pm, Z) + \cdots$
$\quad \hookrightarrow b\bar{b}$

Key improvements: $\mathcal{L}$, 10% $b\bar{b}$ mass resolution
measured in Run 2 $Z^0 \to b\bar{b}$



Goal of 30 fb^{-1} by 2007

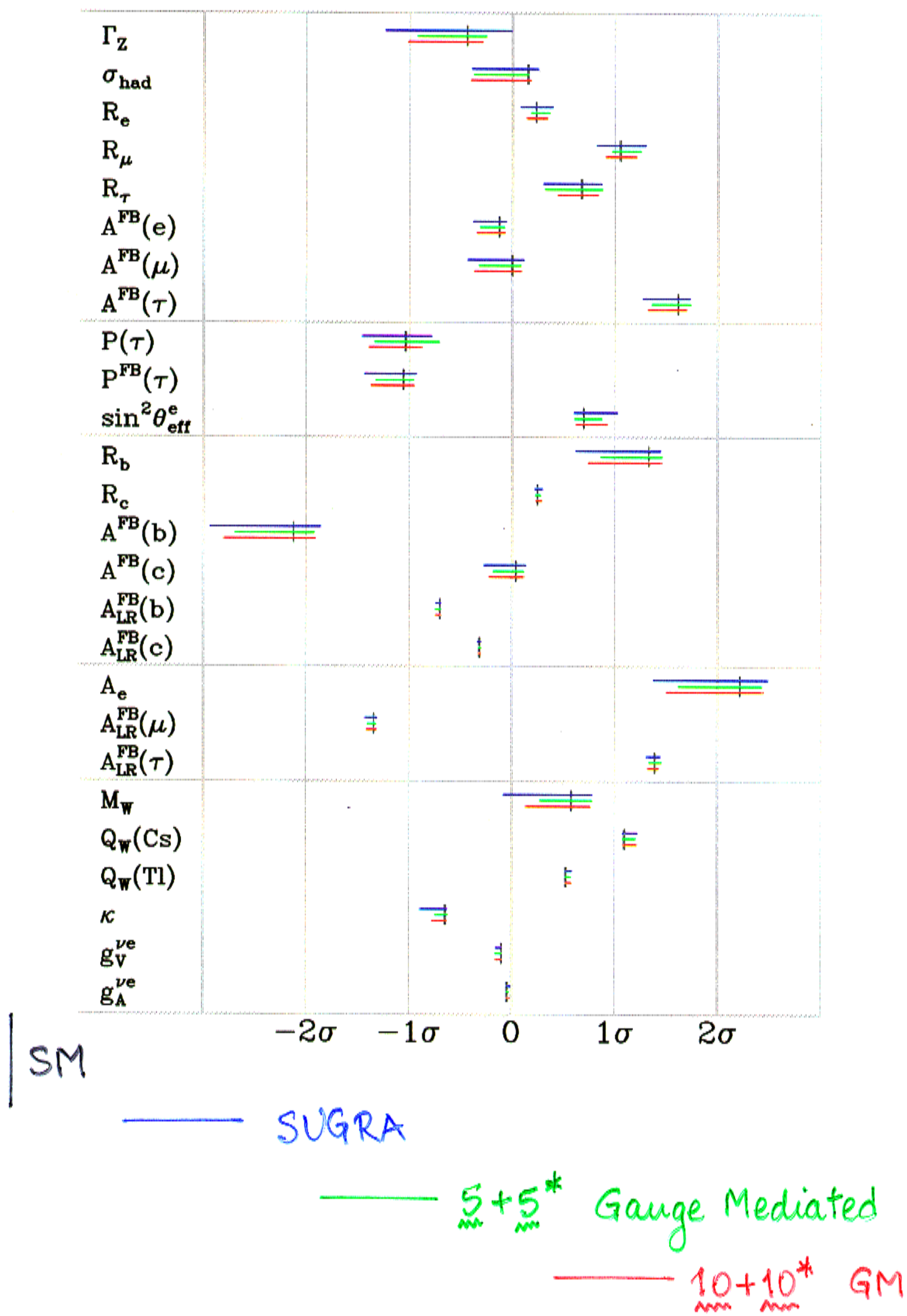
Extend reach to $M_H \approx 180$ GeV/c^2
using $H \to WW^*$?



600
500
400
300
200
100
0
M_H [GeV/c^2]
Triviality
EW vacuum is absolute minimum
3
5
7
9
11
13
15
17
19
log_10 Λ [GeV]

MSSM Closely Resembles the Standard EW Theory

Erler + Pierce: SUSY vs. SM (hep-ph/9801238)



PRECISION EW CONSTRAINTS ON SUSY SPECTRUM?

(Many recent papers)

Cho + Hagiwara (hep-ph/9912260) best overall fit:

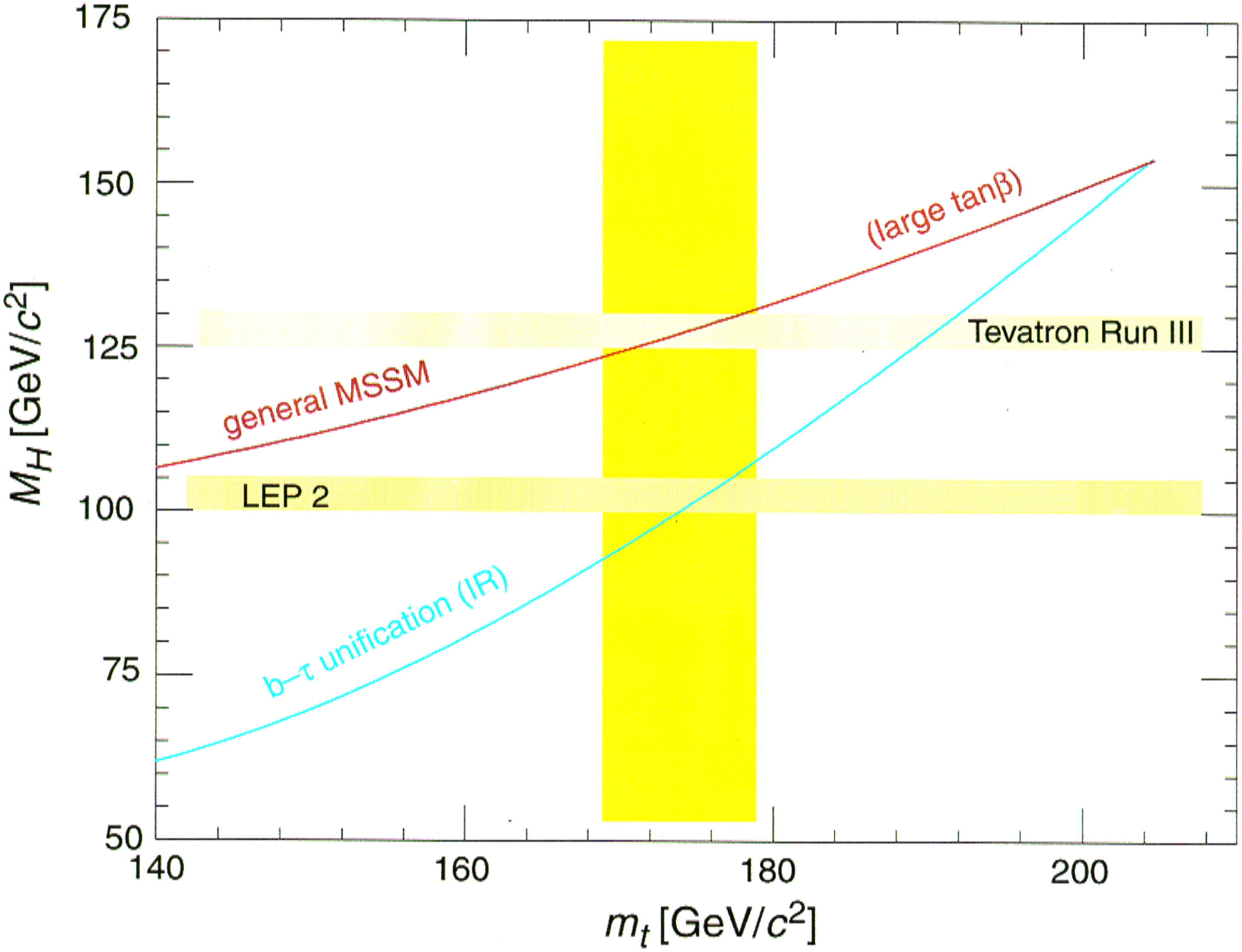
(WINO-LIKE) CHARGINOS, $M \sim 100$ GeV

$\tilde{\chi}_1^0$ ~ 50 GeV

DOUBLET SQUARKS $\gtrsim 200$ GeV

SLEPTONS heavier

$m_{\tilde{\tau}_1} \approx 134-169$ GeV



175
150
125
100
75
50
140
160
180
200
M_H [GeV/c^2]
m_t [GeV/c^2]
(large tanβ)
general MSSM
Tevatron Run III
LEP 2
b–τ unification (IR)

HOW MUCH CAN WE TRUST SM ANALYSIS TO BOUND M_H?

- Hall and Kolda

  Include higher-dimension ops. suggested by extra space dim.

  CONSTRAINTS EVAPORATE!

  Weakness - not shown to be the outcome of a real theory.

- Collins, Grant, Georgi hep-ph/9908330

  Topcolor seesaw model

  (1 additional heavy weak-1 fermion χ with $Y = 4/3$)

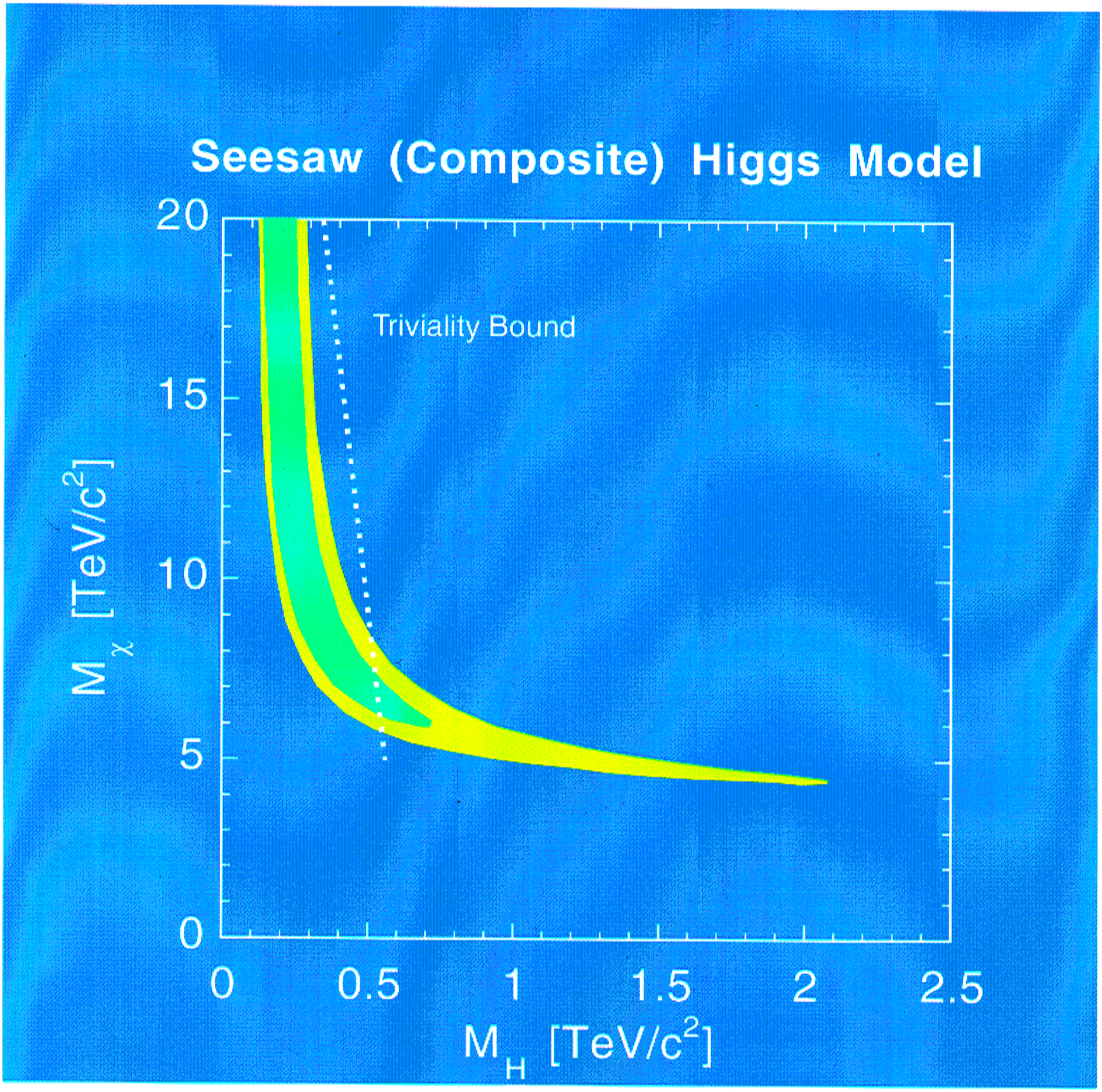
- $M_H \gtrsim 300$ GeV for $m_\chi \approx 5\text{-}7$ TeV

  (+ amusing model with 2 heavy fermions + 2 Higgs doublets $\Rightarrow$ heavy $h^0, H^0, H^\pm$, but light pseudoscalar)

See also: Chivukula + Evans, hep-ph/9907414

S. Chivukula's Circle Line talk (www-theory.fnal.gov)

Collins, Grant, Georgi, hep-ph/9908330



LOOKING FOR TROUBLE

Bennett + Wieman PRL 82, 2484 ('99)

measure weak charge Q_W in 6S-7S transition in Cs.

$$Q_W = -72.06 \pm 0.28 (\text{exp.}) \pm 0.34 (\text{th.})$$

7-fold improvement (on the 0.28 exp. error); improved (th.)

$$\approx Q_W^{(SM)} + 2.5\,\sigma$$

Erler + Langacker hep-ph/9910315

note that Q_W and Γ_Z* can be improved by adding a Z′ with mass ~ 800 GeV (E_6 Z_χ)

*in their fit, $N_\nu = 2.985 \pm 0.008 = 3 - 2\sigma$

The Vacuum Energy Problem (Veltman)

Higgs potential

$$V(\varphi^\dagger\varphi) = \mu(\varphi^\dagger\varphi) + |\lambda|(\varphi^\dagger\varphi)^2$$

At the minimum

$$\langle\varphi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \simeq \begin{pmatrix} 0 \\ 176\ \text{GeV} \end{pmatrix},$$

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0$$

IDENTIFY $M_H^2 = -2\mu^2$.

Higgs potential contributes a field-independent constant energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \gtrsim \underbrace{10^8\ \text{GeV}^4}_{M_H \gtrsim 100\ \text{GeV}}$$

Observed Vacuum Energy Density

$$\varrho_{vac} \lesssim 10^{-46}\ \text{GeV}^4$$

MISMATCH BY 54 ORDERS OF MAG.

How to zero ϱ_H?

THE PROBLEMS OF MASS, AND OF MASS SCALES

1) EWSB sets M_W, M_Z

$$M_W^2 = g^2 v^2/2 = \pi\alpha / G_F\sqrt{2}\,\sin^2\theta_W$$

$$M_Z^2 = M_W^2 / \cos^2\theta_W$$

EW scale is $v = (G_F\sqrt{2})^{-1/2} = 246$ GeV

But it is not the only scale...

certain: $M_{Planck} = 1.22 \times 10^{19}$ GeV (from G_N)

probable: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ unification scale

somewhere: flavor scale

→ Famous problem of Higgs scalar mass:

how to keep scales from mixing /

how to stabilize M_H?

(unification doesn't help)

Problems of mass ...

2) Each fermion mass $\Rightarrow$ a new, unknown, Yukawa coupling

$$L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L , \quad R \equiv e_R$$

$$\mathcal{L}^{(e)}_{Yuk} = -\zeta_e \left[\bar{R}(\varphi^{+}L) + (\bar{L}\varphi)R \right]$$

$$m_e = \zeta_e v/\sqrt{2}$$

All fermion masses ~ physics beyond the S.M.

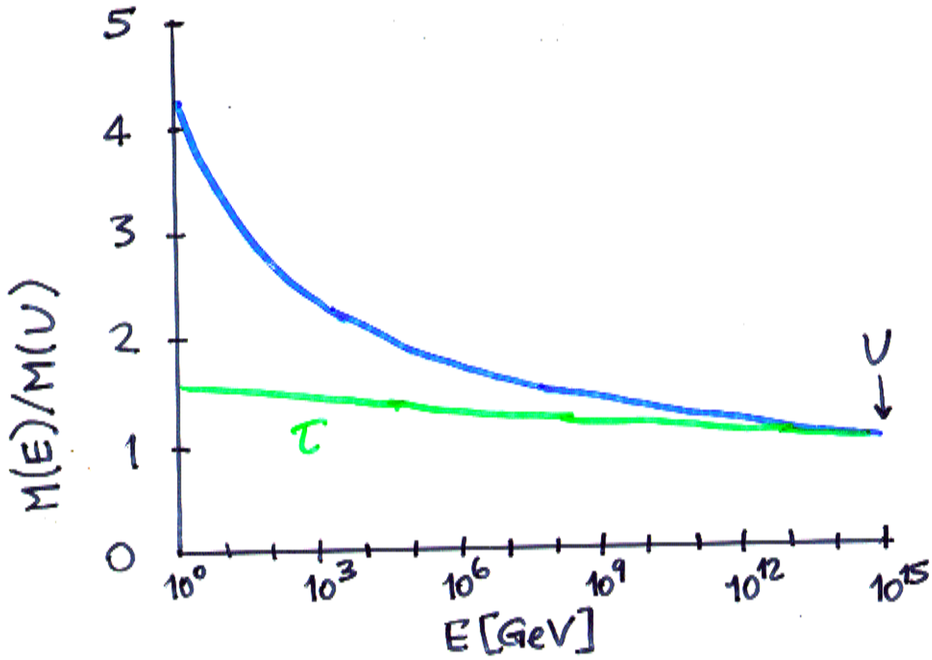
$$\zeta_t \simeq 1, \quad \zeta_e \approx 3\times 10^{-6}, \quad \zeta_\nu \approx 10^{-10} \ ??$$

What accounts for the range (and values) of the Yukawa couplings?

Best hope until now:

Unified theories suggest pattern of fermion masses simplifies on high scales

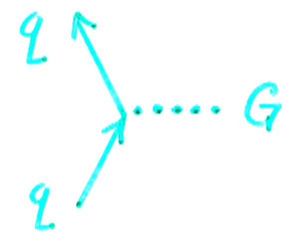
Famous triumph: m_b/m_τ



Perhaps all fermion masses arise on high scales and show simple patterns there?

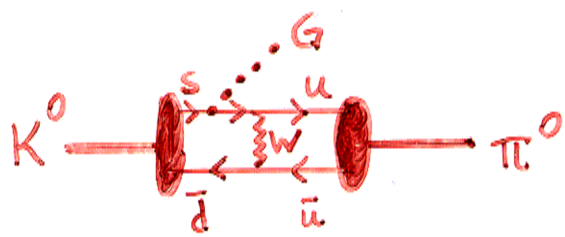
+ G_N small (M_{Pl} large) $\Rightarrow$

Gravitation irrelevant for particle physics



$\sim \frac{E}{M_{Pl}}$

Estimate $B(K \to \pi G) \sim \left(\frac{M_K}{M_{Pl}}\right)^2 \sim 10^{-38}$



+ We know from EW theory alone that the 1-TeV scale is special

$M_H^2 < \frac{8\pi\sqrt{2}}{3G_F} \simeq 1\ \text{TeV}^2$ (Higgs boson or new physics)

So to eliminate the hierarchy problem, consider EW physics beyond the standard model.

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ <
- Composite Higgs (Technicolor, ...)
- Supersymmetry

CONVENTIONAL APPROACH TO NEW PHYSICS

Extend Standard Model to understand

why $(M_H, v) \ll M_{Pl}$

(A. Masiero)

NOVEL SPECULATION

Change Gravity to understand

why $M_{Pl} \gg v$

Expt.: Gravity follows Newtonian force law down to 1 mm. (FIG.)

Below 1 mm, limits deteriorate rapidly

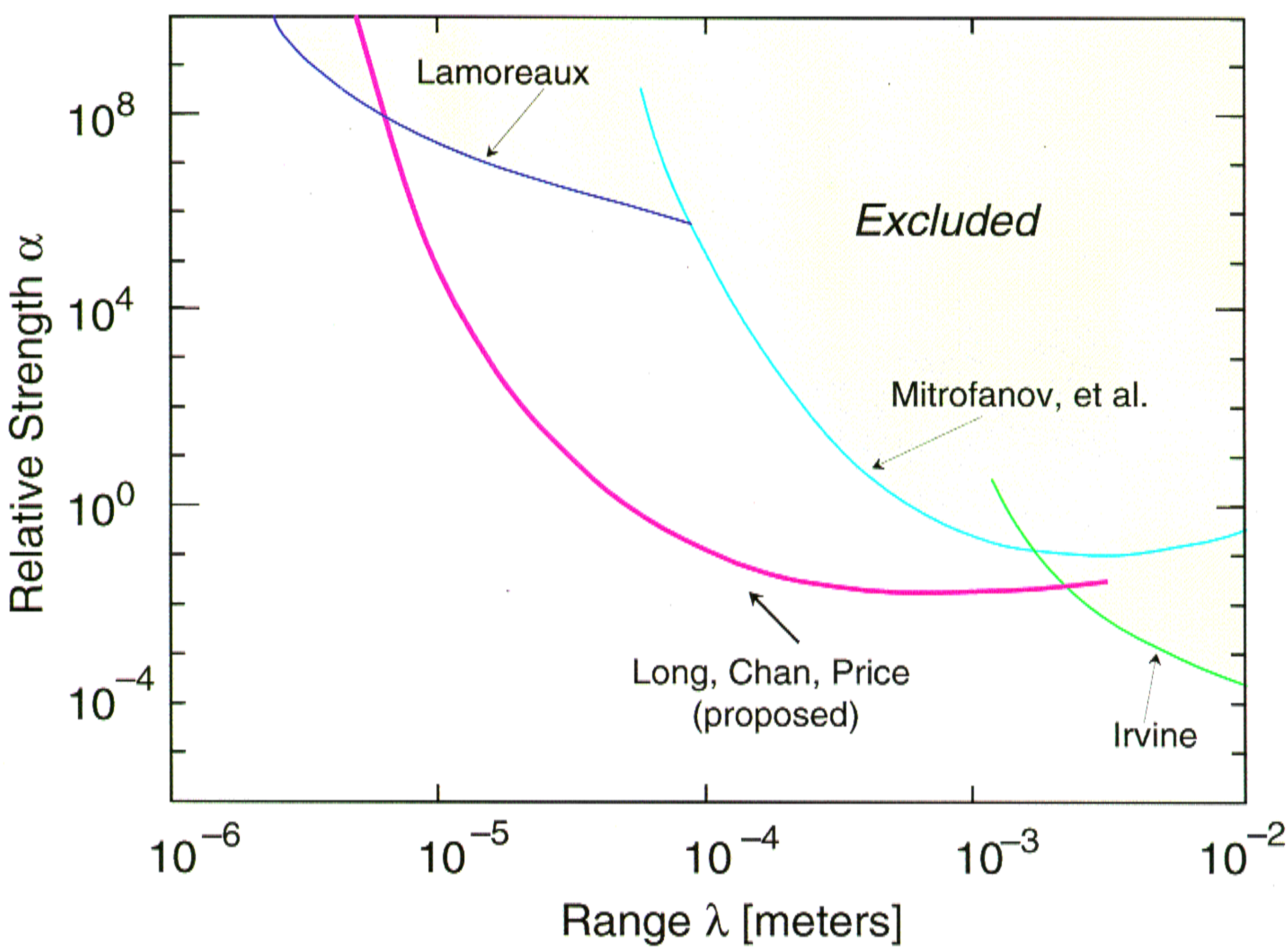
String theory requires 6/7 extra dimensions

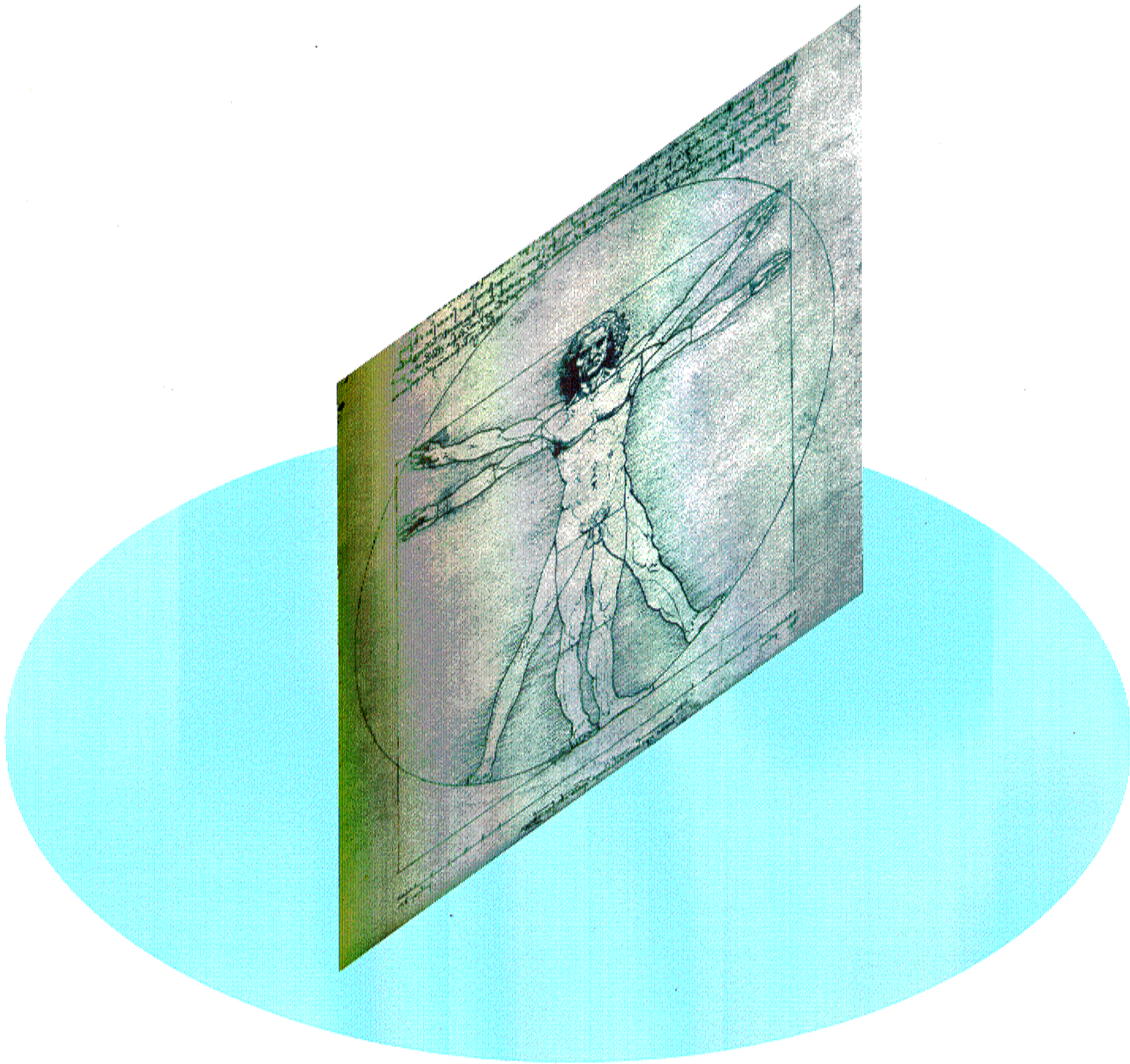
Assumed natural to take

$R_{unobserved} \approx 1/M_{Pl} \approx 1.6 \times 10^{-35}$ m

New Wrinkle:

- $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ (+ needed extensions) live on 4-dim branes, not in extra dim.
- Gravity propagates in extra dim.


Lamoreaux
Excluded
Mitrofanov, et al.
Long, Chan, Price
(proposed)
Irvine
Relative Strength α
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Range λ [meters]



Dimensional analysis changes: (Gauss's law)

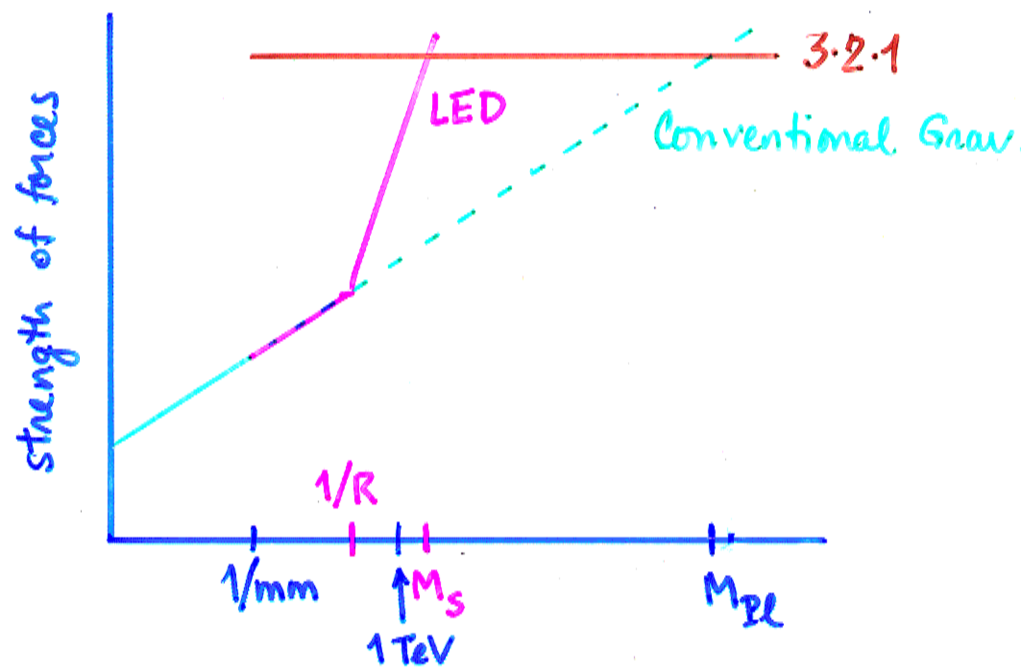
n extra dim. with radius R $\Rightarrow$

$$G_N \sim M_{Pl}^{-2} \sim M_s^{-n-2} R^{-n}$$

If $M_s \sim 1$ TeV, $R \lesssim 1$ mm for $n \geq 2$

$$M_{Pl} = M_s (M_s R)^{n/2}$$

would mean that M_{Pl} results from a false extrapolation:

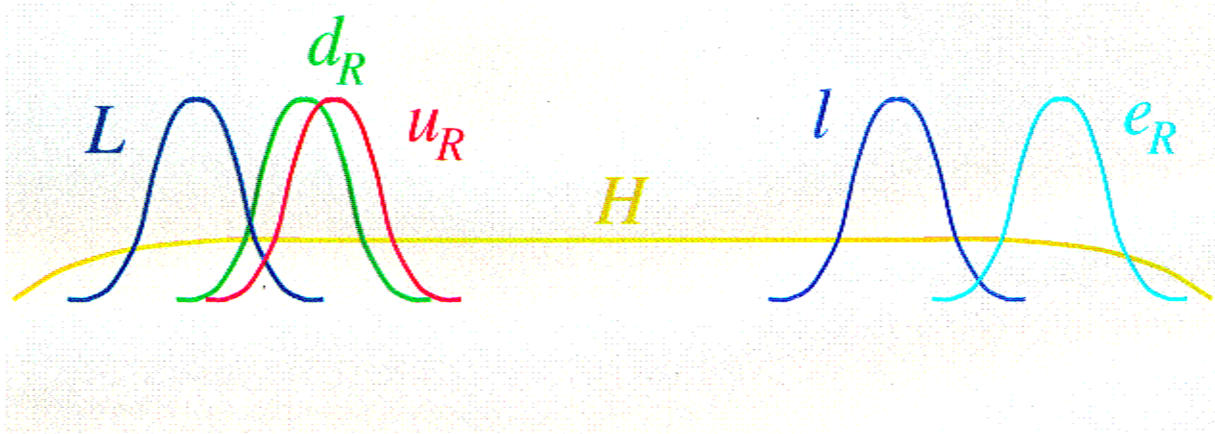


<Gravity's true scale could be near EW scale>

Graviton excitation of a tower of Kaluza-Klein modes in the extra dimensions?

- Missing energy signature for colliders (provatons)

Might Extra Dimensions Explain the Range of Fermion Masses?



$$\mathcal{L}_{\text{Yukawa}} = -\zeta_e \left[\bar{e}_R (H^\dagger \ell) + (\bar{\ell} H) e_R\right]; \qquad \langle H \rangle_0 = \begin{pmatrix} 0 \\ 1/\sqrt{G_F \sqrt{8}} \end{pmatrix},$$

$$m_e = \zeta_e \cdot 176 \text{ GeV}/c^2 \Rightarrow \zeta_e \approx 3 \times 10^{-6}$$

$$m_t = \zeta_t \cdot 176 \text{ GeV}/c^2 \Rightarrow \zeta_t \approx 1$$

Does localization of fermion wave functions within a brane of small but finite thickness explain the exponential hierarchy?

Mirabelli + Schmaltz, hep-ph/9912265 Ar Kani-Hamed, Schmaltz ...

QCD and the Electroweak Theory

Because QCD is asymptotically free and becomes strong at low energies, it has a rich phase structure...

- Chiral Symmetry Breaking as a (model) mechanism for EWSB.

  Ginzburg-Landau ⟷ Higgs (Meissner)

  BCS ⟷ χSB (TC)

- Do the other interesting phases of QCD (e.g., color superconductivity) hold lessons for EWSB.

QCD MAY HIDE $SU(2)_L \otimes U(1)_Y$ SYMMETRY

- APPLY $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ TO MASSLESS UP + DOWN QUARKS
- TREAT $SU(2)_L \otimes U(1)_Y$ AS PERTUBBATION

WITH $m_u = m_d = 0$, $\mathcal{L}_{QCD}$ HAS EXACT (GLOBAL) $SU(2)_L \otimes SU(2)_R$ CHIRAL SYMMETRY

AT ENERGY SCALE Λ_{QCD}, STRONG COLOR FORCES BREAK $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$ (ISOSPIN).

SSB $\rightarrow$ GOLDSTONE BOSONS, MASSLESS PIONS.

BROKEN GENERATORS ARE 3 AXIAL CURRENTS COUPLING TO PIONS $\sim f_\pi$.

WHEN $SU(2)_L \otimes U(1)_Y$ IS TURNED ON, EW GAUGE BOSONS COUPLE TO AXIAL CURRENTS AND ACQUIRE MASSES

$$m^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g^2 \end{pmatrix} f_\pi^2/4$$

(columns labelled W^+, W^-, W_3, a)

SAME STRUCTURE AS IN STANDARD EW THEORY

DIAGONALIZE:

$$M_W^2 = g^2 f_\pi^2 / 4$$

$$M_Z^2 = (g^2 + g'^2) f_\pi^2 / 4$$

SO THAT

$$M_Z^2 / M_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W \quad ✓$$

$$M_\gamma^2 = 0 \quad ✓$$

BUT (BECAUSE $f_\pi = 93$ MeV)

$$M_W \approx 30 \text{ MeV}$$

$$M_Z \approx 34 \text{ MeV}$$

1/2650 TIMES TRUE MASSES

(IF ONLY WE DIDN'T KNOW f_π)

TRANSCRIPTION TO TECHNICOLOR

MASSLESS u, d QUARKS → NEW FERMIONS
"TECHNIFERMIONS"

QCD → NEW INTERACTION
"TECHNICOLOR"

FOR WHICH WE CHOOSE SCALE OF INTERACTION
SO THAT

$f_\pi \longrightarrow F_\pi = v = (G_F\sqrt{2})^{-1/2}$

Generates correct M_W, M_Z

but produces no Yukawa couplings, so no fermion masses.

SHOWS POSSIBILITY THAT

Gauge-boson masses
&
Fermion masses

HAVE DIFFERENT ORIGINS.

Wonderful opportunities await particle physics over the next decade:

1-TeV scale (LEP → Tevatron → LHC)

Problem of Identity (B, K, ν)

Probe dimensionality of spacetime?

If we are inventive enough:

Neutrino factory

e^+e^- Linear collider

⇒ A REMARKABLE FLOWERING OF Experimental Particle Physics

and of

Theory engaged with experiment.