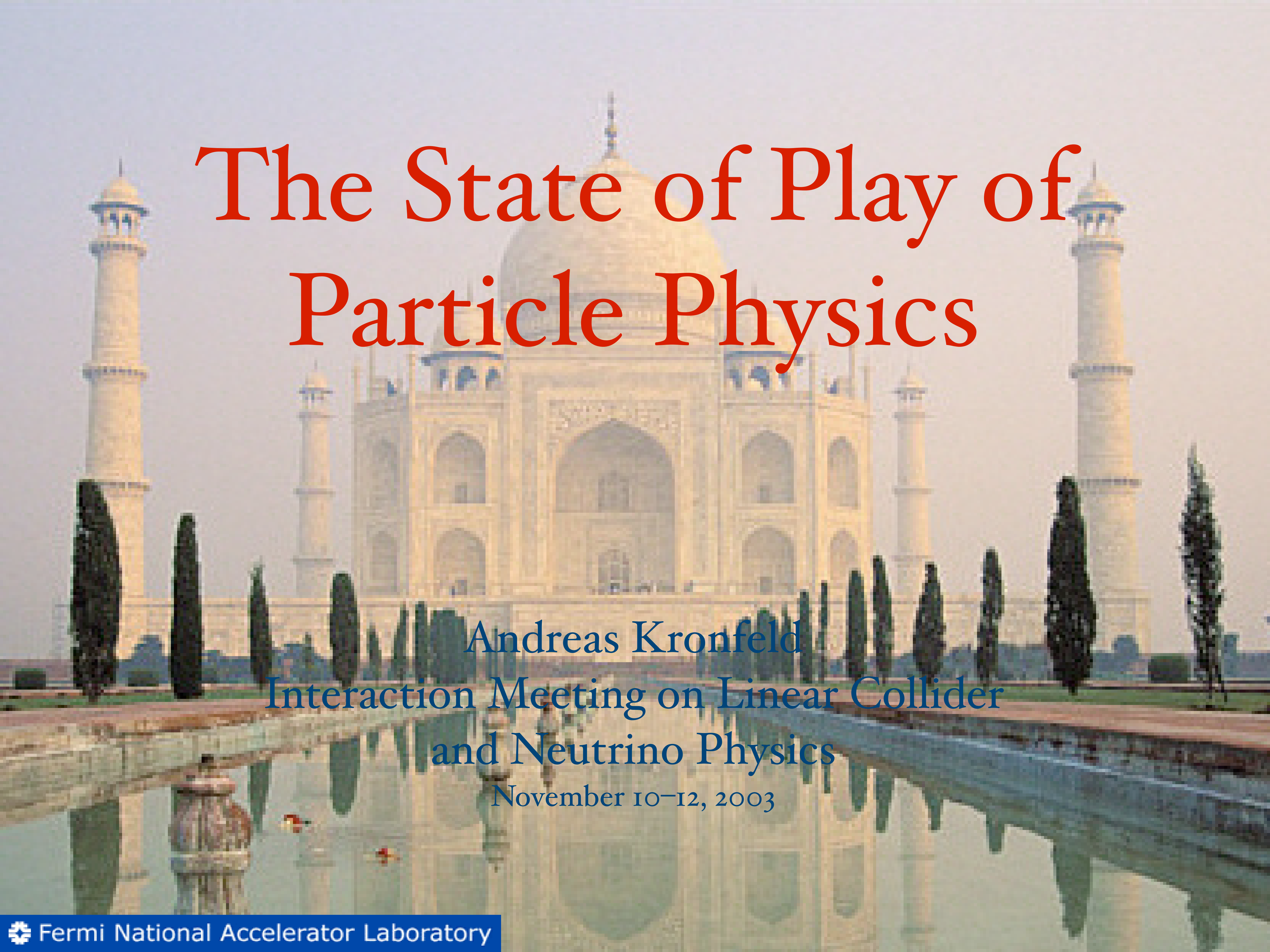
The State of Play of Particle Physics

Andreas Kronfeld

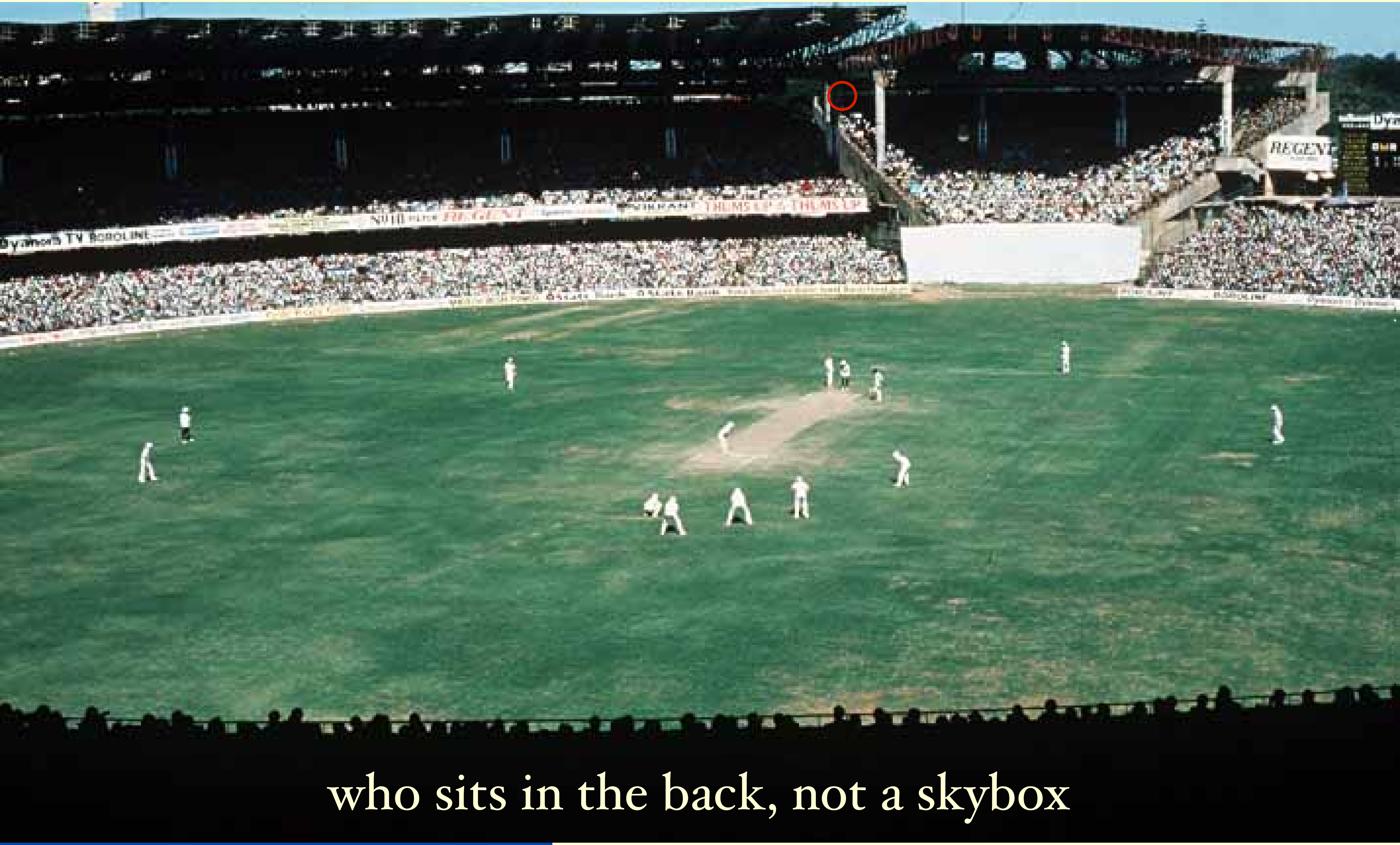
Interaction Meeting on Linear Collider and Neutrino Physics

November 10–12, 2003



Fermi National Accelerator Laboratory

View of a Spectator



who sits in the back, not a skybox

Physical Theory: Superb, Good or Speculative?

Andreas Kronfeld

Emperor's New Mind

- Several years ago, Roger Penrose, an eminent British theorist, wrote a wonderful book called *The Emperor's New Mind.*
  - Lucid on accepted ideas (quantum mechanics, relativity, quantum field theory).
  - Speculative about some (of his own) new ideas.
  - *Honest* about the difference.
- In *ENM* Penrose classifies physical theories into three categories: *superb*, *good*, & *speculative*.

- Superb means so successful, in breadth & depth, that a newer theory of the same phenomena would subsume it.

- Good means astonishingly accurate and widely applicable, but not quite superb.

- Speculative means more thought or more data needed, before promoting or discarding the idea.

- Some new ideas remain unclassified, ideas that Pauli would have called, "Not even wrong."

Penrose's Classification

Superb	Good	Speculative
Classical Mechanics Special Relativity General Relativity Classical E & M	Epicycles ⇔ orbits	
Quantum Mech	***Standard Model*** Quantum E&M (QED) Electroweak QCD	Higgs boson
		String Theory

The Standard Model

of Elementary Particle Physics

Andreas Kronfeld

Elements of our SM

- Gauge symmetry: $\mathrm{SU}_c(3)\times\mathrm{SU}_T(2)\times\mathrm{U}_Y(1)$
  dictates how forces couple to matter

- Chiral quarks and leptons (c, T, Y):

$\bigoplus_{i=1}^{3}(3,\frac{1}{2},\frac{1}{6})$	left-handed quarks
$\bigoplus_{i=1}^{3}(3,0,-\frac{1}{3})$	right-handed down-type quarks
$\bigoplus_{i=1}^{3}(3,0,\frac{2}{3})$	right-handed up-type quarks
$\bigoplus_{i=1}^{3}(1,\frac{1}{2},-\frac{1}{2})$	left-handed leptons
$\bigoplus_{i=1}^{3}(1,0,-1)$	right-handed charged leptons

$$T_3 + Y = Q$$

- These glyphs summarize *laws of Nature!*

- But we also know that the electroweak part of the gauge symmetry is broken “spontaneously”

  - $\mathrm{SU}_T(2)\times\mathrm{U}_Y(1) \to \mathrm{U}_{\mathrm{EM}}(1)$ $\qquad T_3 + Y = Q$

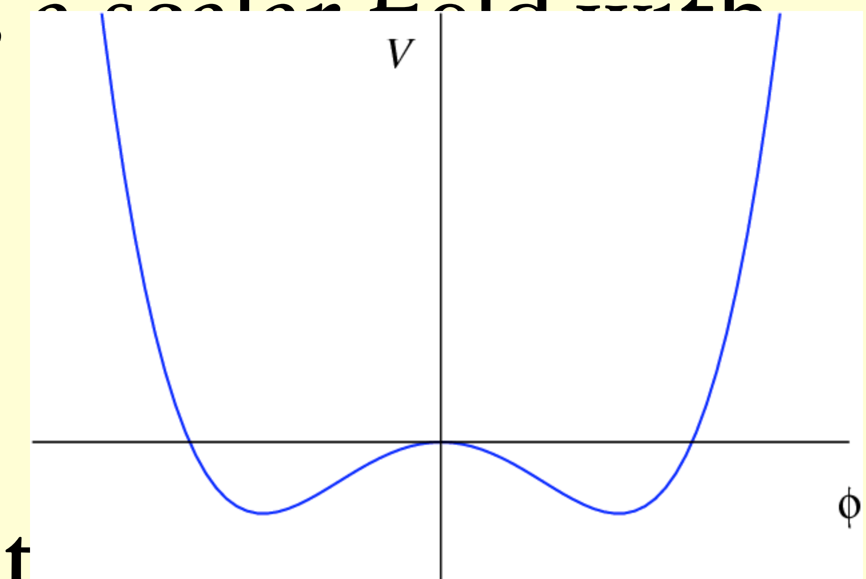
  - unbroken symmetry would predict $m_W = m_Z = 0$

  - But $m_W = 80.423$ GeV and $m_Z = 91.1876$ GeV
    ($m_p = 0.93927200$ GeV)

- We have hardly any idea what’s responsible!!!

Standard *Model*

- The most economical *model* is a scalar field with (c, T, Y) quantum number
  - $(1, \frac{1}{2}, \frac{1}{2})$ Higgs doublet □



- But we do not know whether this is the full story.
- We suspect it is not: theoretical and numerical studies strongly suggest that the Higgs model breaks down at some scale □ (perhaps ~ TeV).

Quarks & Higgs

- Interactions between quarks and Higgs break symmetry between generations.
- Generate quark masses, but the range is a puzzle (from $m_u = 0.003$ GeV to $m_t = 176$ GeV).
- Also generate flavor violation and *CP* Violation via the Cabibbo-Kobayashi-Maskawa (CKM) Matrix, but still being tested.
- These good features are general enough to survive in (some) extended Higgs models.

Experimental Status of the Standard Model

The Gauge Sector

- Portrait of Giovanni Arnolfini and his Wife

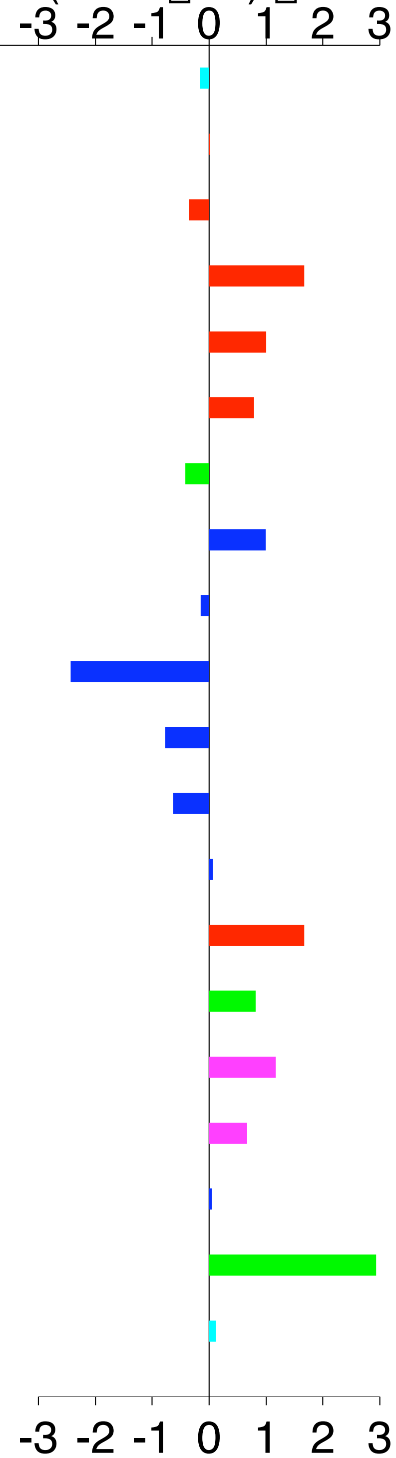
  Jan van Eyc

- SU(3)×SU(2)×U(1) gauge symmetry

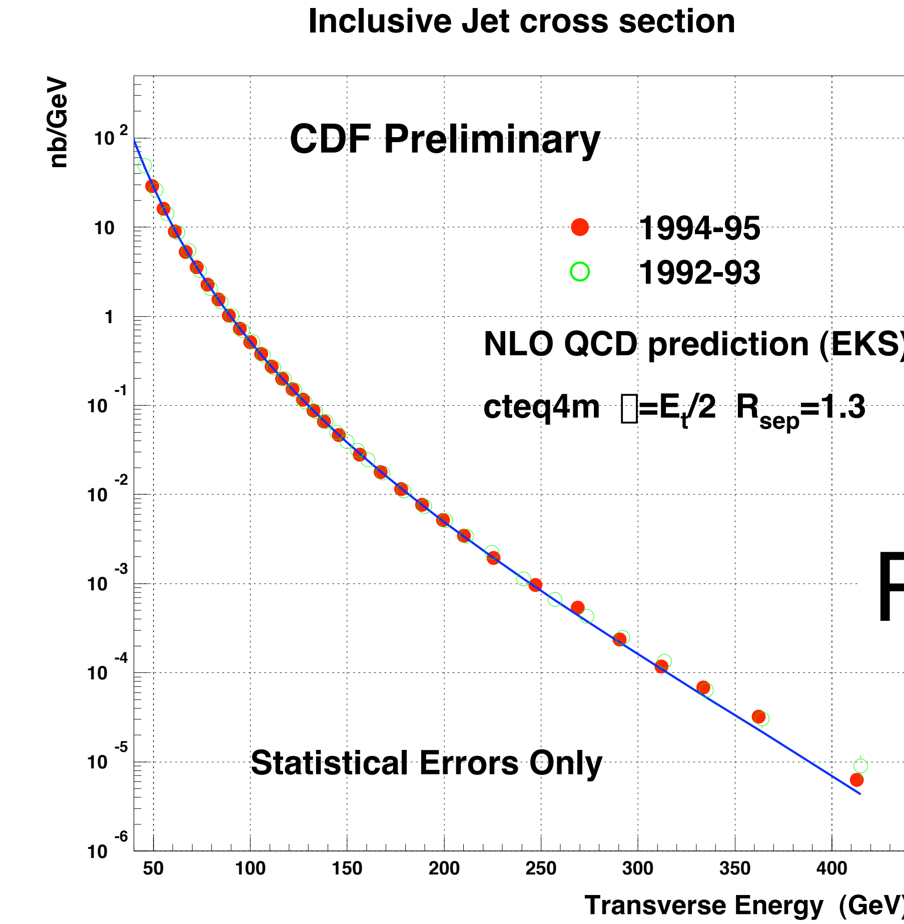
QCD

Electroweak Winter 2003

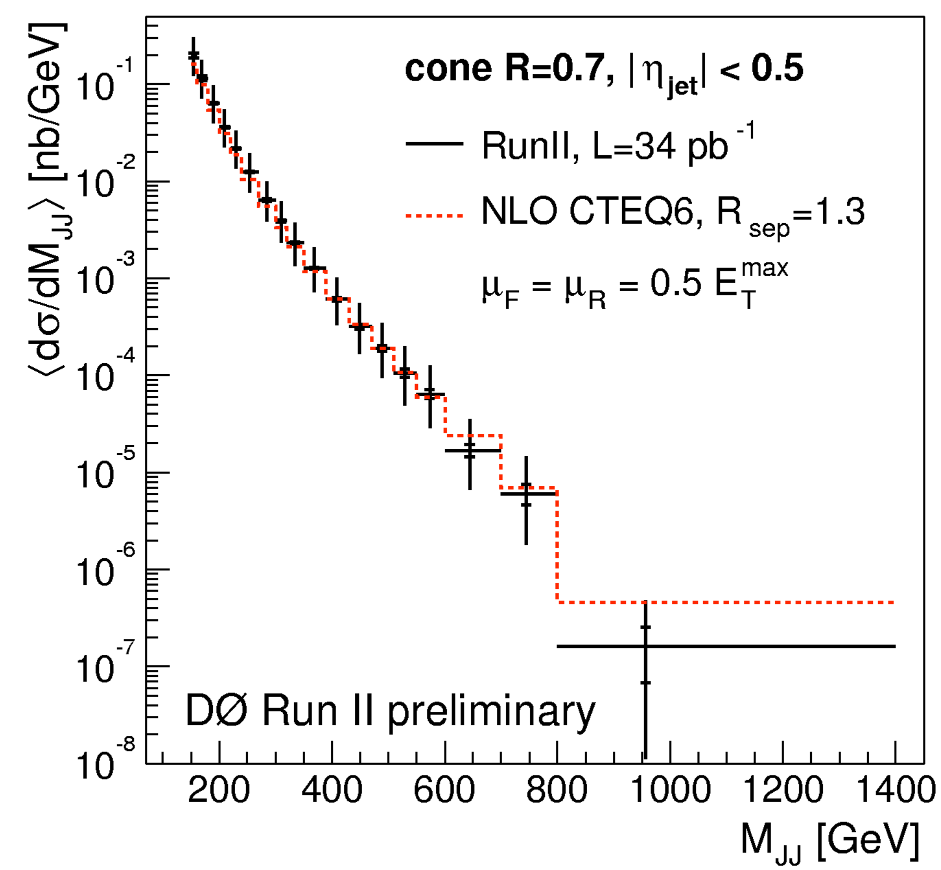
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	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



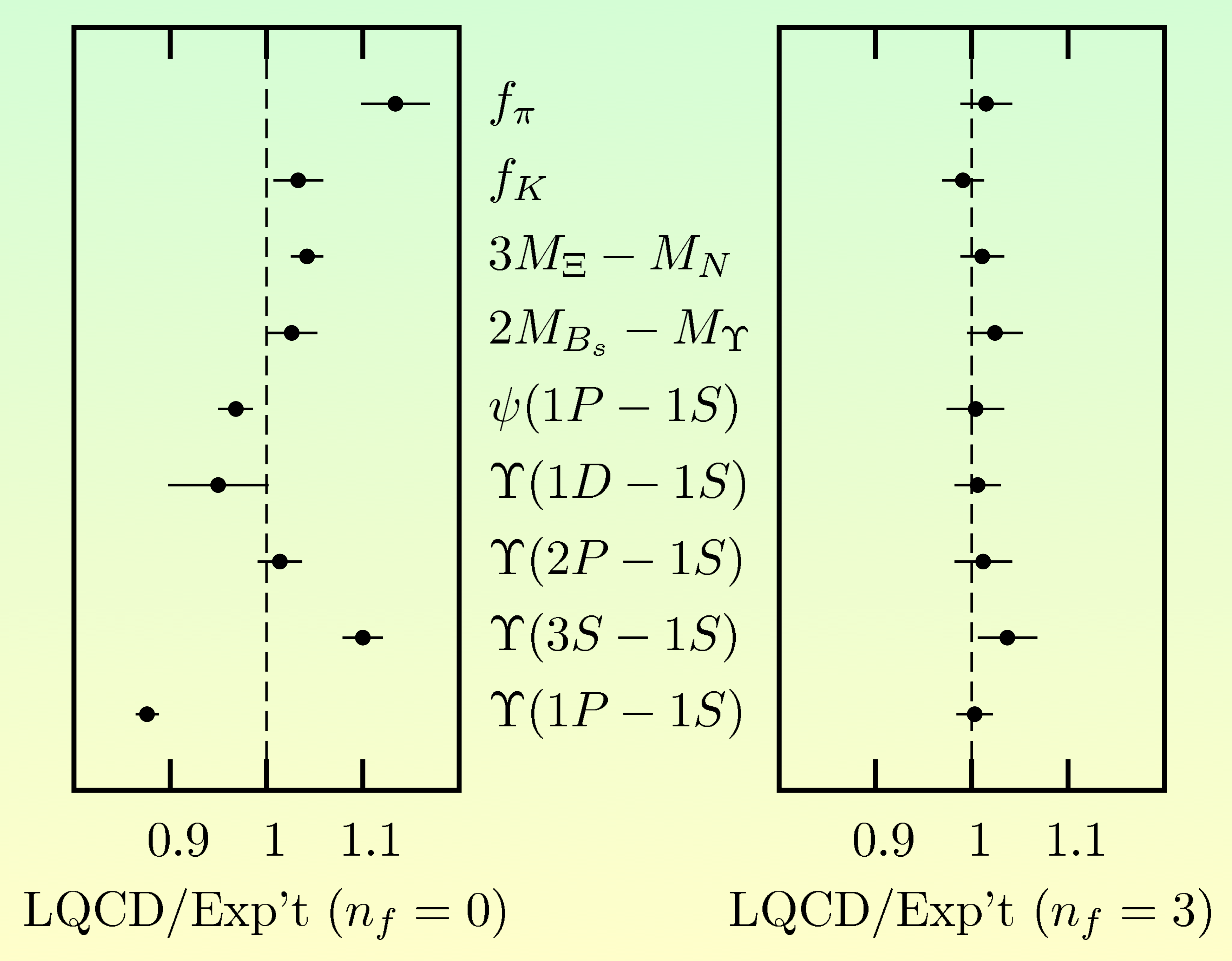
Run 1b



Run 2



QCD for Hadrons



$\alpha_s = 0.117 \pm 0.02$ from high-energy jets

$\alpha_s = 0.121 \pm 0.03$ from (low-energy) hadrons

The Quark Sector

- Sunlight on the Road to Pontoise

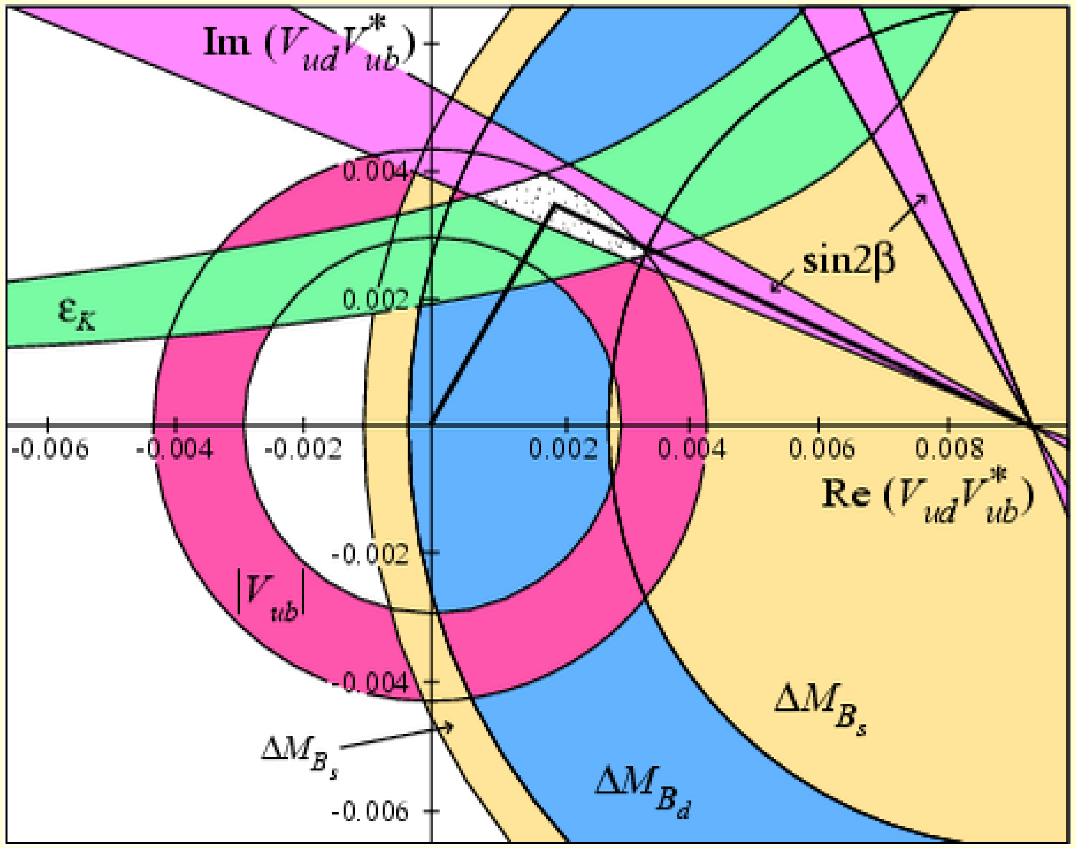
  Camille Pissaro

- CKM Matrix V
  - Flavor Violation
  - *CP* Violation

Quark Flavor Physics

- Quark interactions and *CP* violation, called "flavor physics" (6 flavors of quark), are under extensive experimental test.
- The aim is to see if the good theory will become superb or will submerge into something grander.
- The standard model has many constraints
  - $$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$
  - complex numbers = strength of flavor change

CKM Matrix 2003



The Unitarity Triangle
[PDG 2003]

- The constraints can be drawn as triangles in the complex plane
- Semi-leptonic decays measure CKM
- Mixing & rare decays test CKM
- CKM passes at 20% accuracy (from QCD)

The Higgs Sector

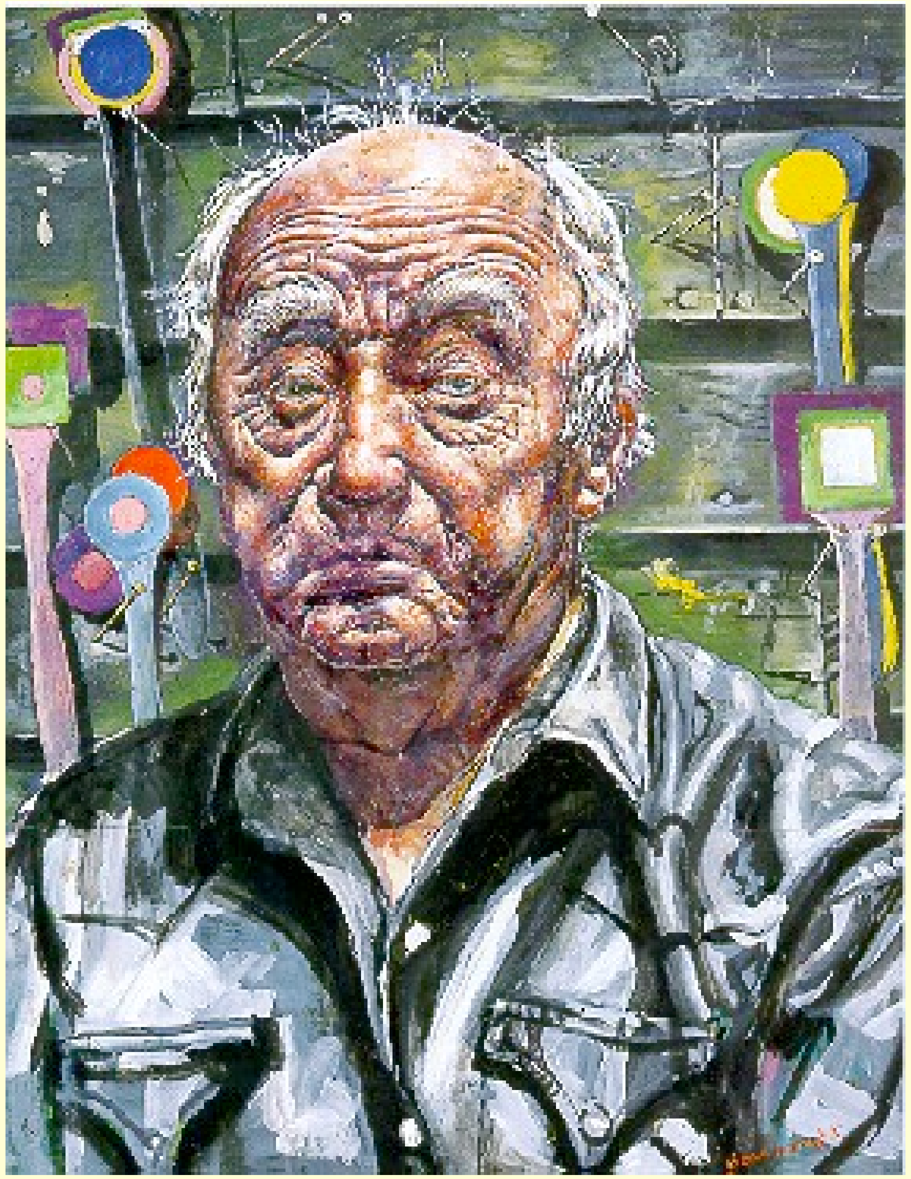
- Self-portrait in Georgia

  Ivan Albright
  (of Warrenville, Illinois)

- $\mathrm{SU}(2) \times \mathrm{U}_Y(1) \to \mathrm{U}_{\mathrm{em}}(1)$

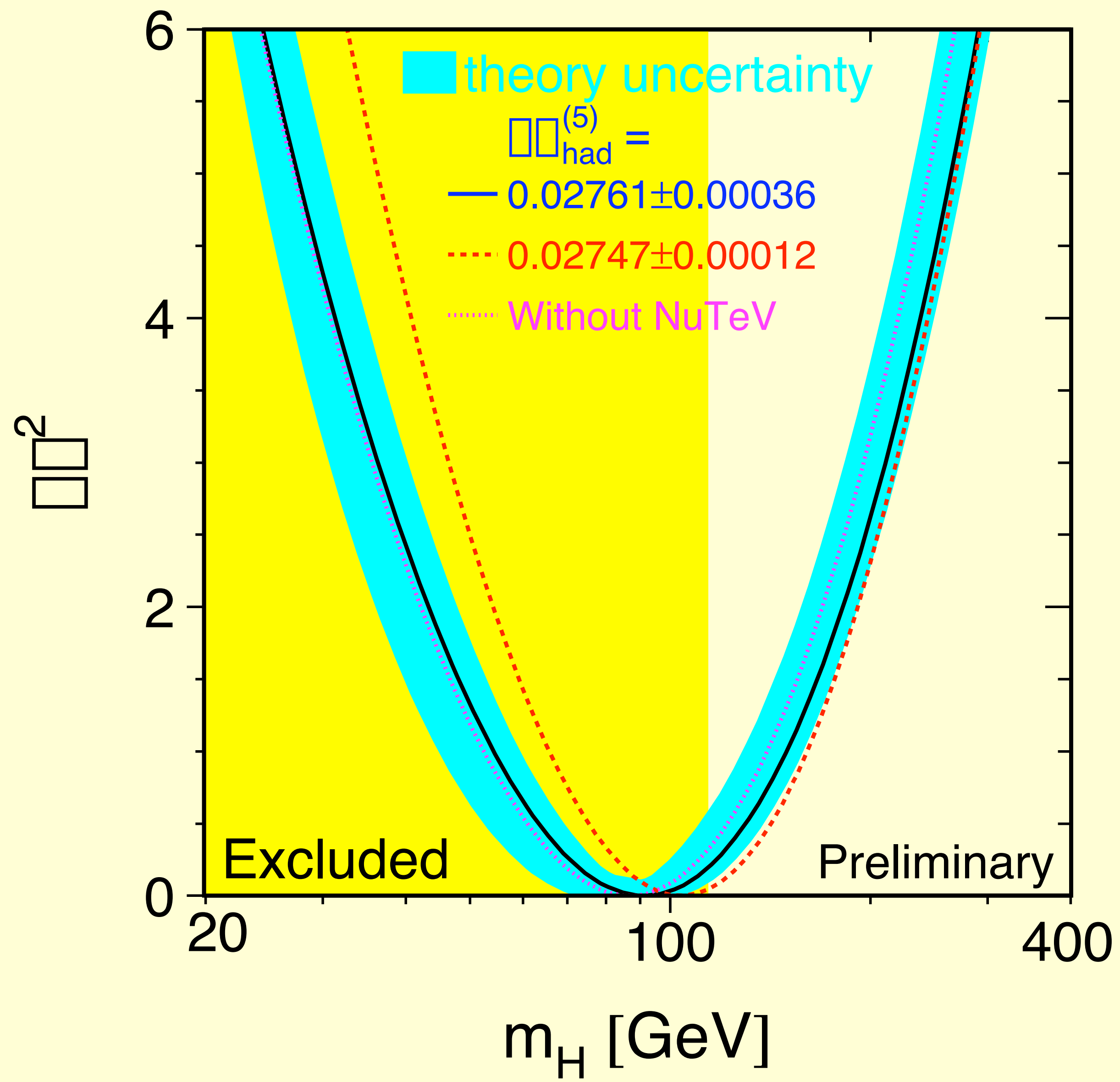
- How? Not a clue!

- Standard: doublet gives $W_{\mathrm{L}}^{\pm}$, Z_{L}^{0}, and *Higgs boson*

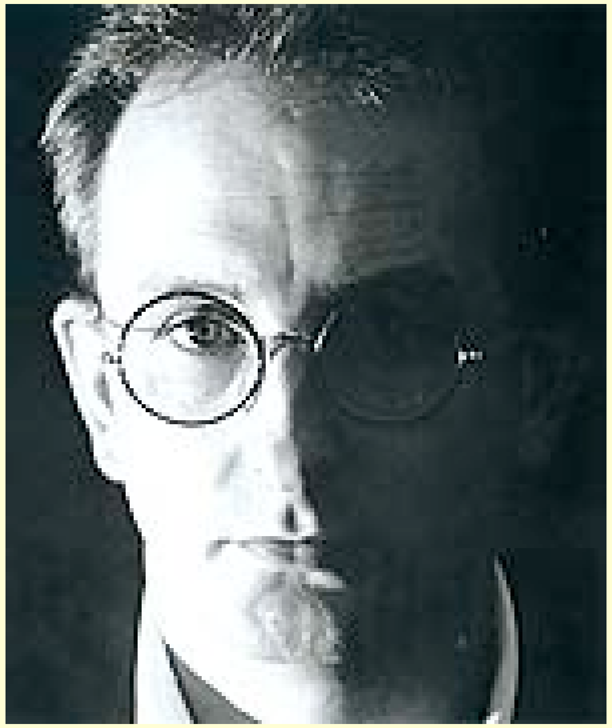


Standard Higgs?

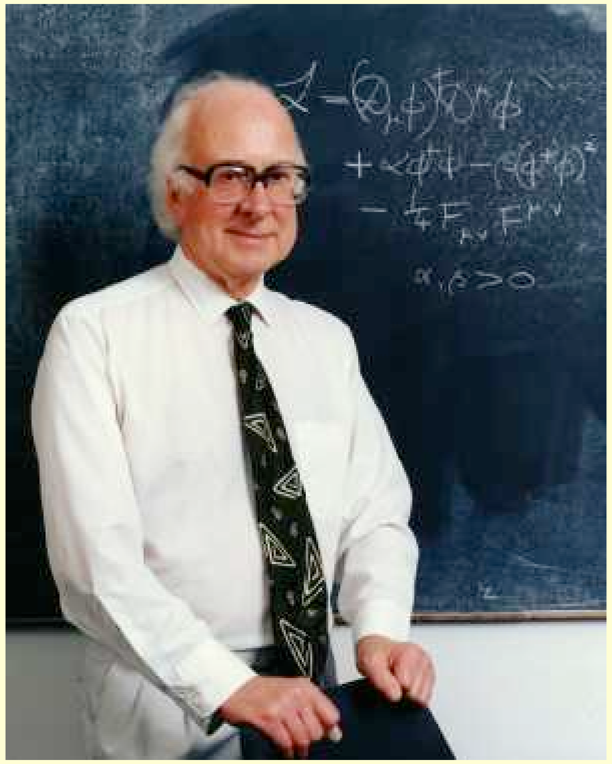
- LEPEWWG "blue band"
- Assumes Standard Higgs (one doublet)
- Direct exclusion: real Higgs bosons not yet seen
- Indirect effects of virtual Higgs bosons
- Incipient clash?



But which Higgs?



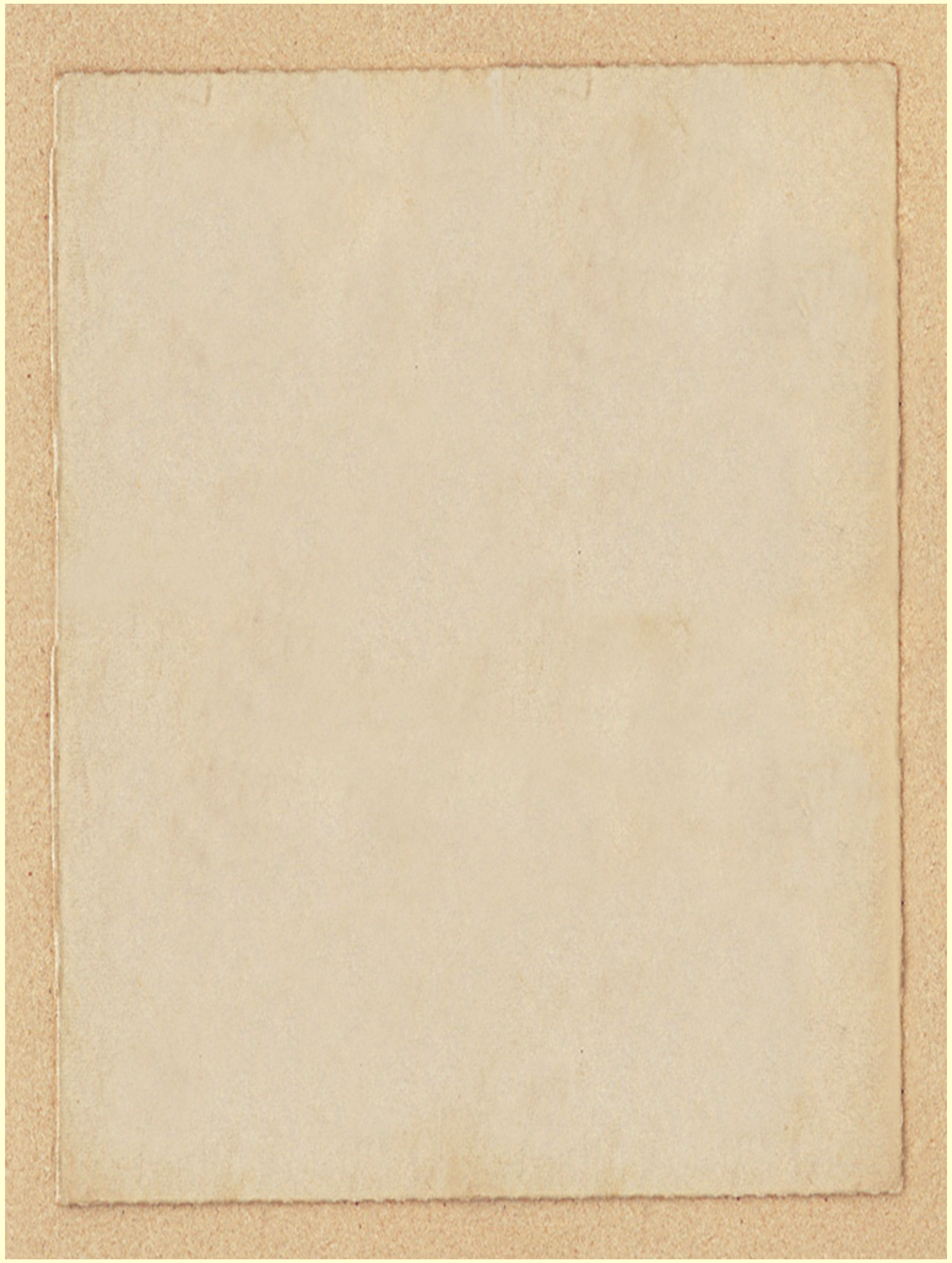
Higgs Boson
musician



Peter Higgs
physicist

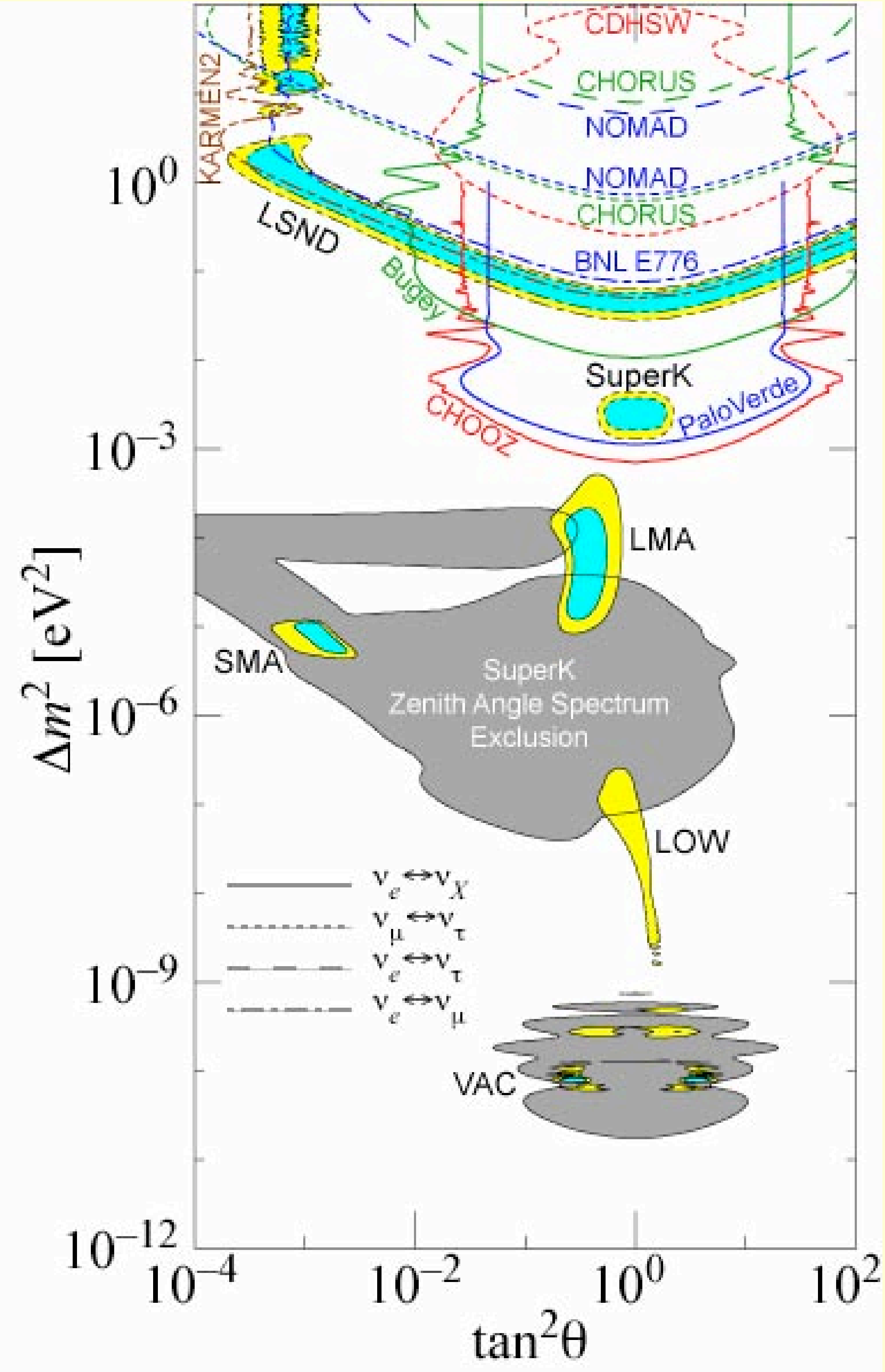
The Lepton Sector

- Neutrino part yet to be painted
- MNS matrix describes lepton mixing
- Leptogenesis? Leading to baryogenesis?



Neutrino Oscillations

- In the SM, charged leptons (e, μ, τ) also acquire mass from Higgs, but neutrinos should be massless.
- Recent experiments show that neutrinos turn from one flavor into another.
- Which means they have mass: SM is ~~wrong~~ incomplete



Classification 2003

Superb	Good	Speculative
Classical Mechanics Special Relativity General Relativity Classical E & M		

Standard Model

$SU(3)\times SU(2)\times U(1)$	Quark Flavor Physics	Neutrino Masses *One* Higgs Doublet
		String Theory

Unanswered Questions

Unity and Coherence?

- A nearly ideal (and real) theory: QCD on its own
  - one symmetry group; few parameters (1 + 6)
  - theoretically sound at all energies
  - rich phenomena: quarks give rise to hadrons
- SM as a whole, is homely by comparison
  - 3 symmetry groups; 19 parameters (+ 7 for neutrinos)
  - many sectors, bolted together *ad hoc*
  - some break down at high energies

Identity?

- What *really* turns W^0 and B into Z and □?
- How do such disparate quark masses arise? Lepton masses?
- Why are the patterns of quark mixing and lepton mixing so different?

Symmetry?

- Is the Standard Model a relatively unsymmetric limit of a symmetric set of laws?
- Or a relatively symmetric emergent structure from a disoriented morass?
- (Is there a difference?)

Answers?

- Answers to questions to these are settled by observed phenomena.

- In this case, those observed at accelerators.

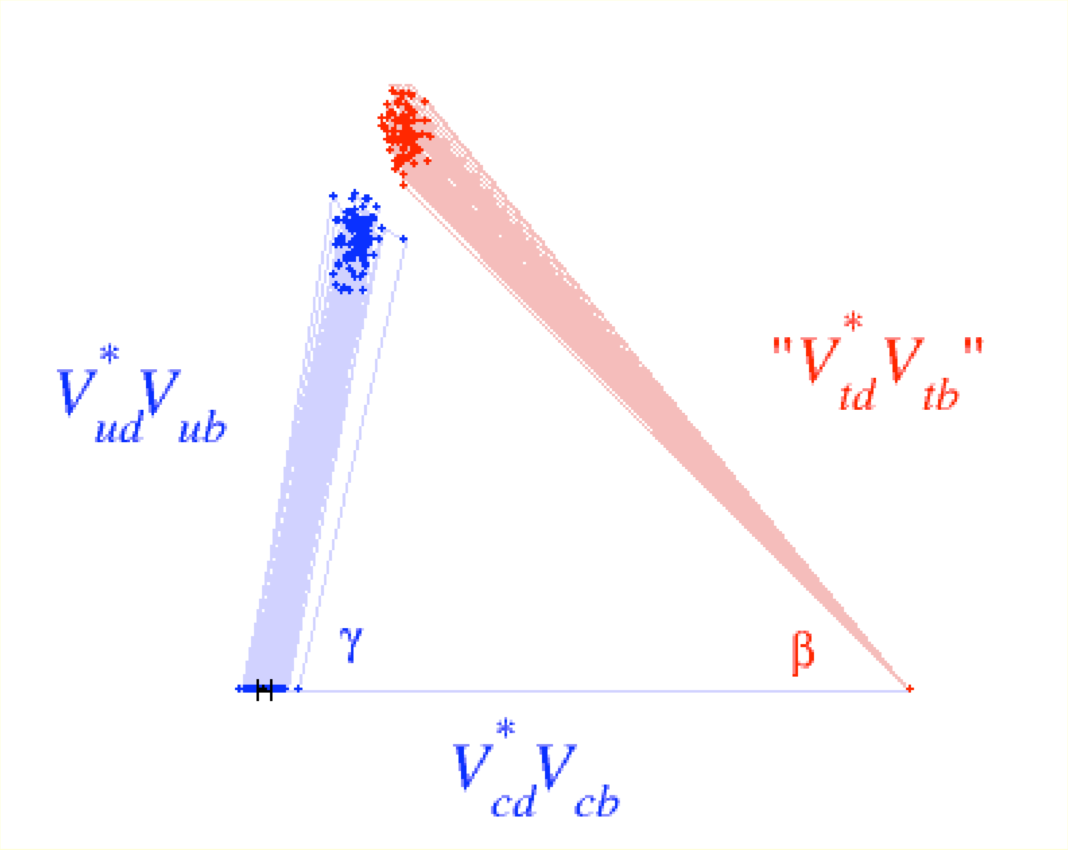
- We tend to emphasize discoveries that transform speculative ideas into good theories.

- Don't forget the developments that render good theories superb laws.

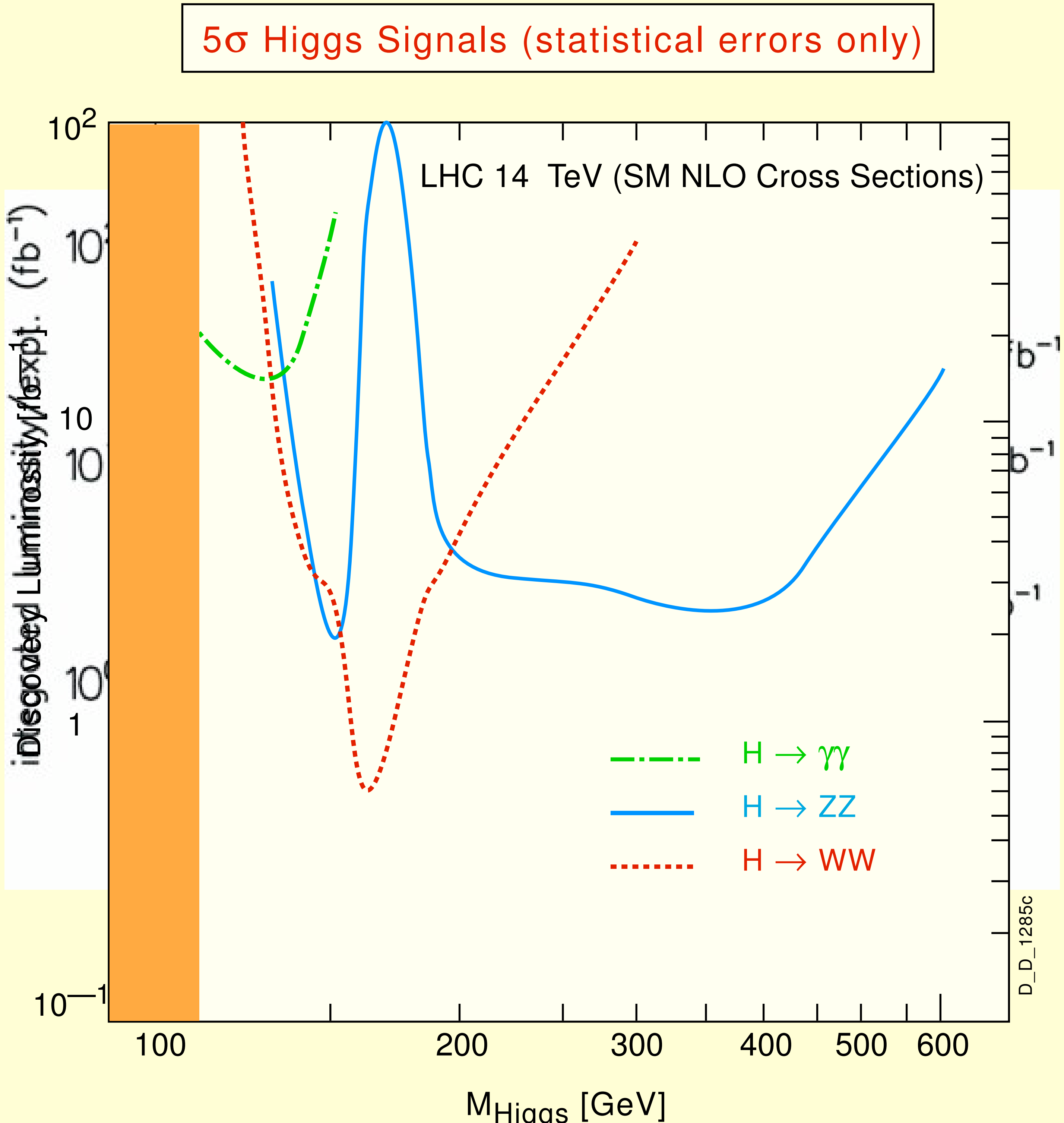
Or reveal good theories to be bad ideas!

MATRIX RELOADED

- With some improvements in experiment
  - angles □ and □ to 2–3%
- With better calculations from (lattice) QCD
  - lower side to 2%
  - other sides to 5%

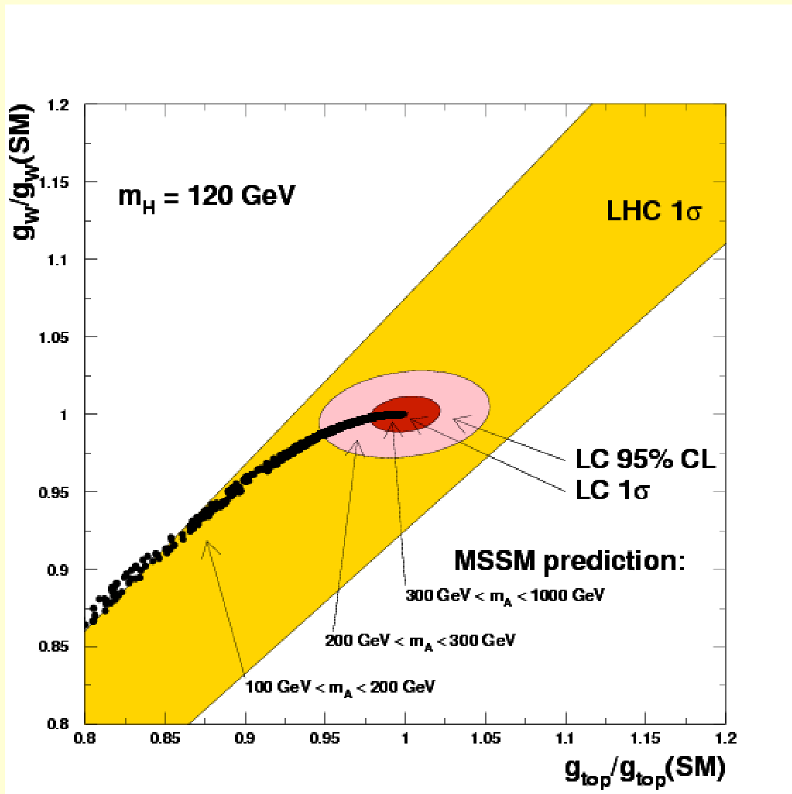


Hunt for the Higgs

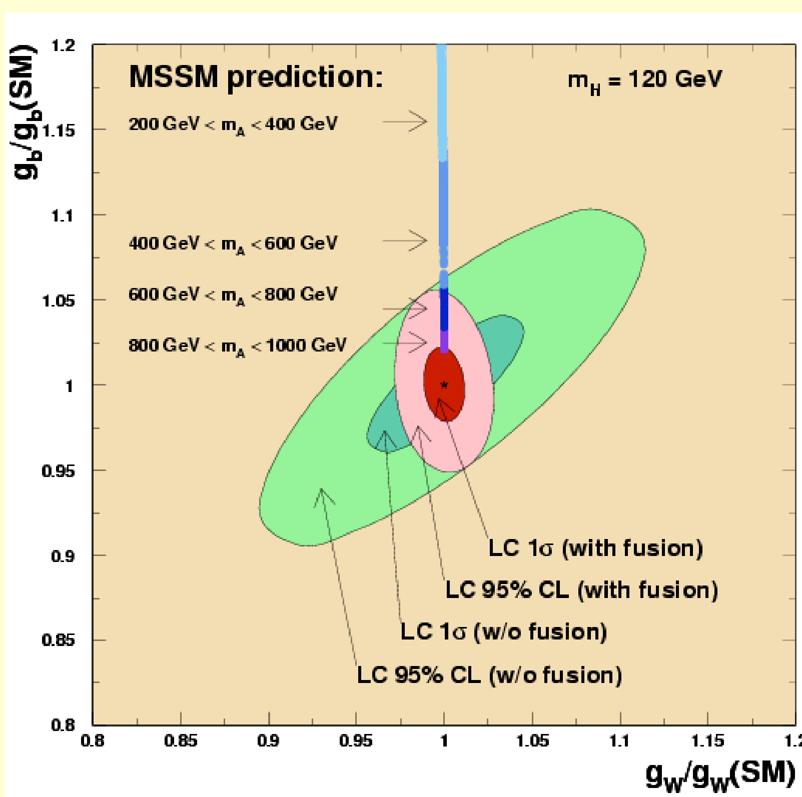


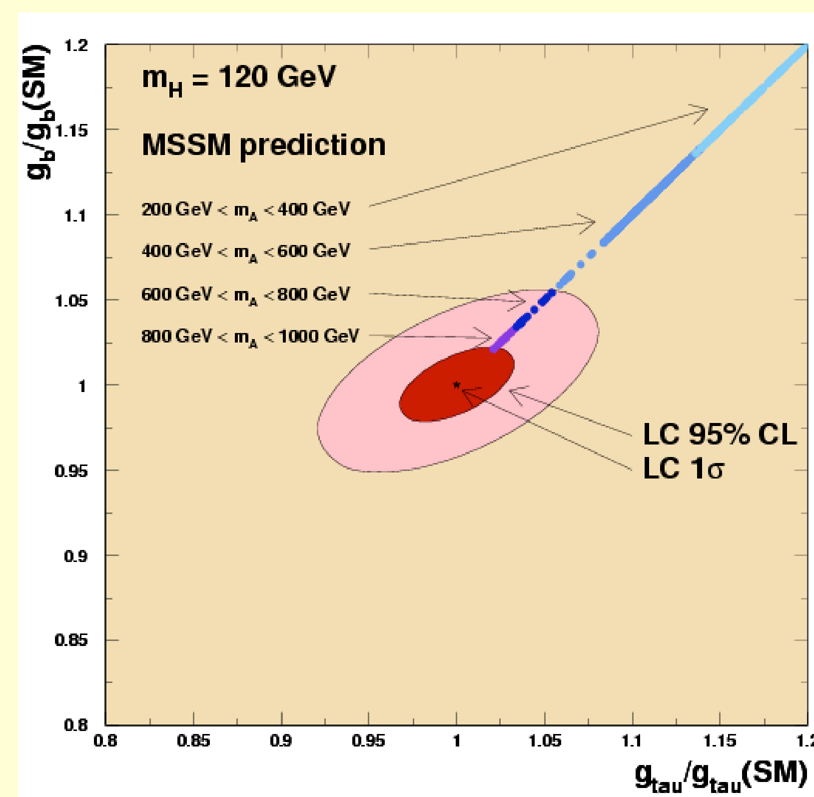
- There is a chance that the standard Higgs will be seen at Fermilab.
- If not it is almost certain to be found at the Large Hadron Collider (LHC), scheduled to start in 2007.

Linear Collider Physics

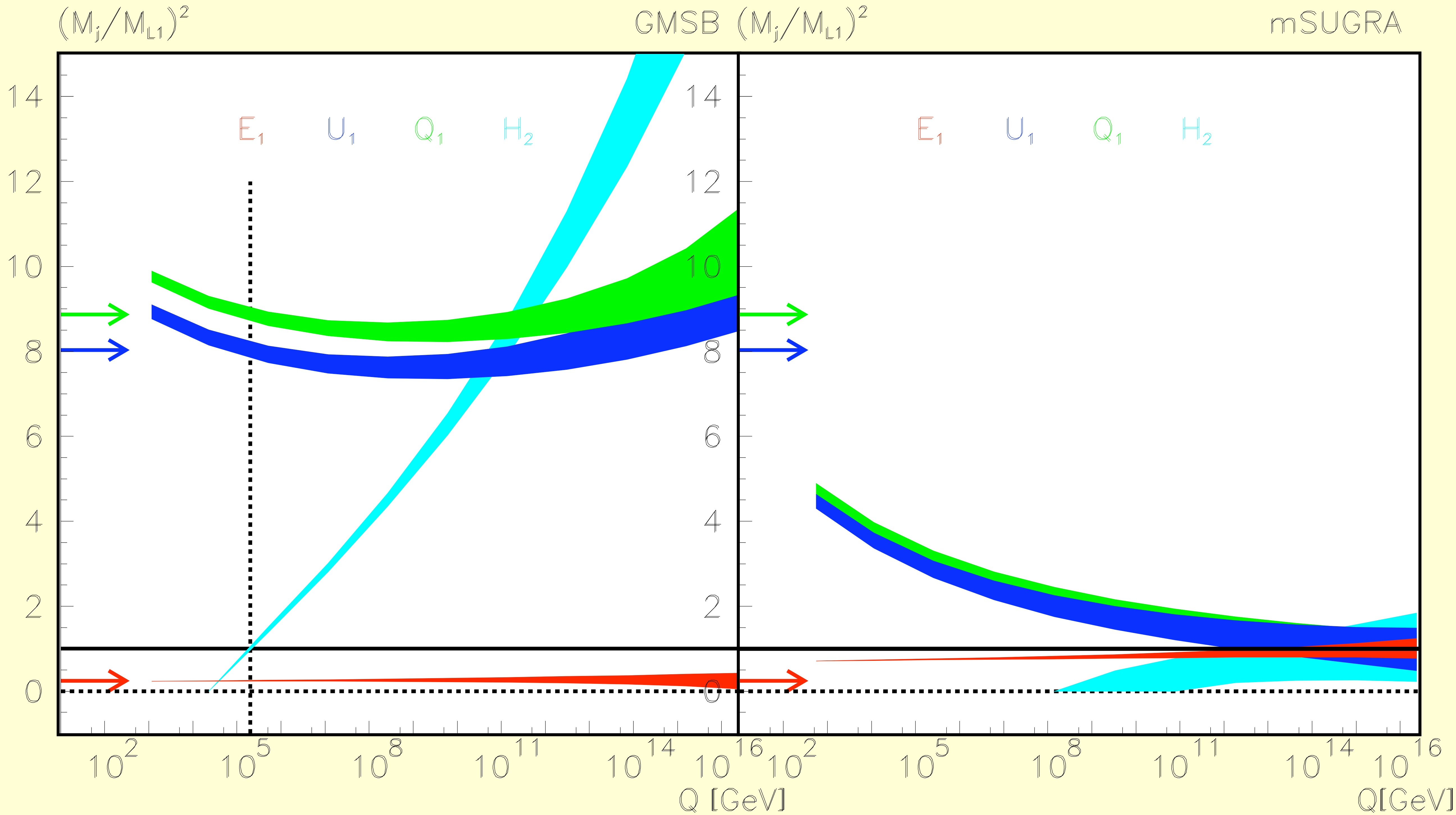


- Some examples of the LC precision





How is Susy Broken?



Classification 2025?

Superb	Good	Speculative
Classical Mechanics Special Relativity General Relativity Classical E & M		
A New Standard Model		
SU(3)×SU(2)×U(1) CKM Matrix MNS Matrix Higgs sector + susy	A good theory of flavor Susy breaking	
	Stringy black holes	M Theory