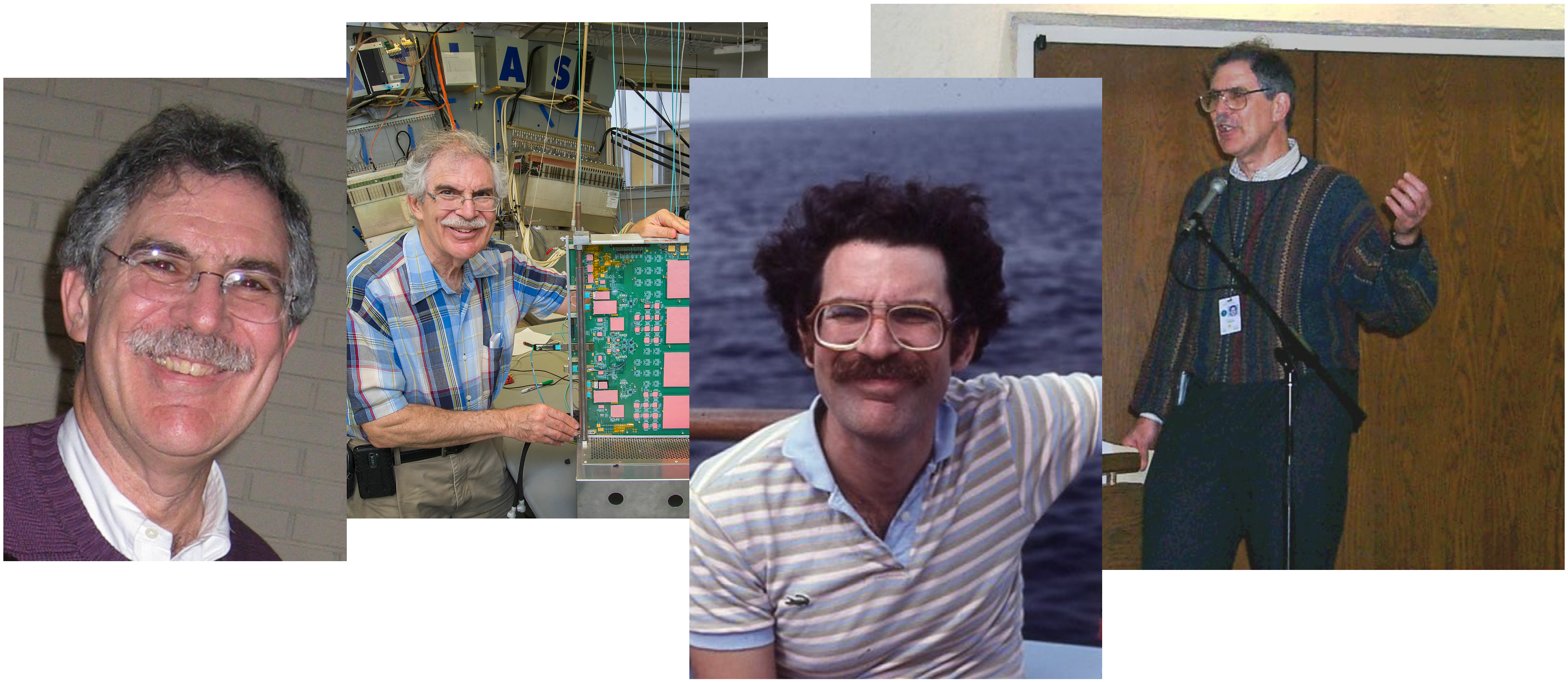
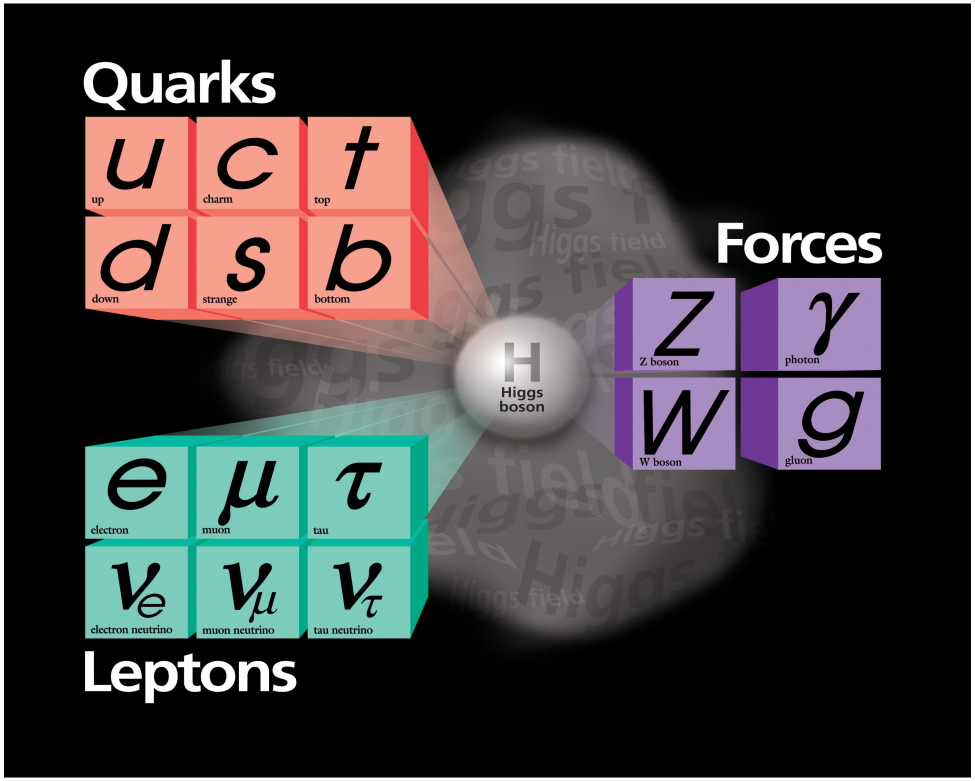
Howard Gordan: A Remarkable Physics Journey



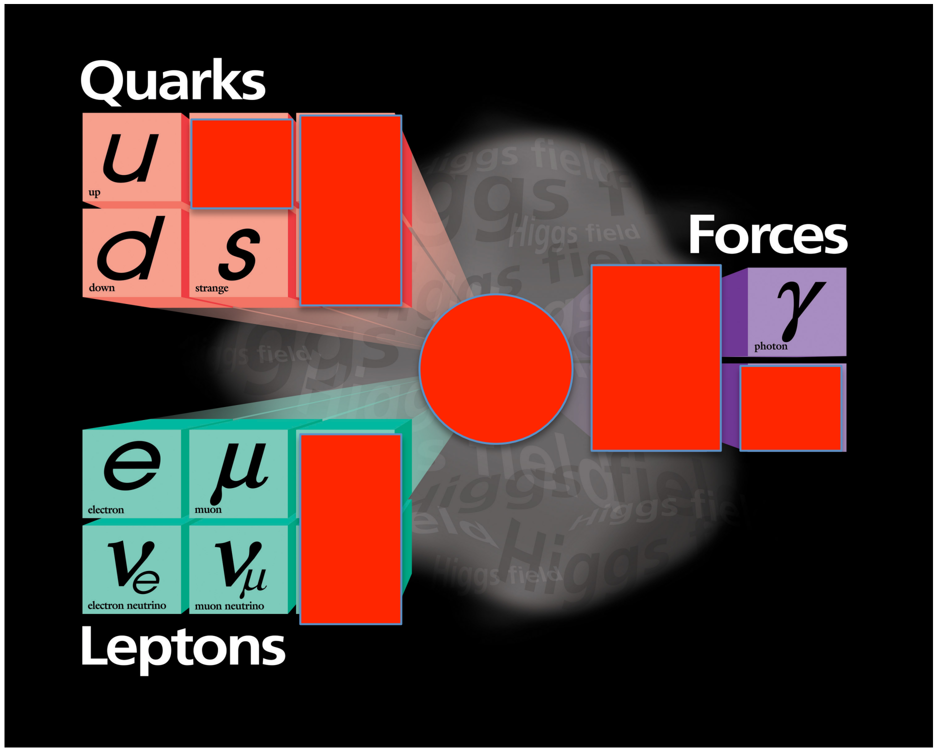
S. Dawson, BNL, October 2, 2017

Present Day: We have a Standard Model



In the beginning….

- When Howard began his career, no Standard Model



- Howard has made major contributions to filling in and ***understanding*** many of these boxes!

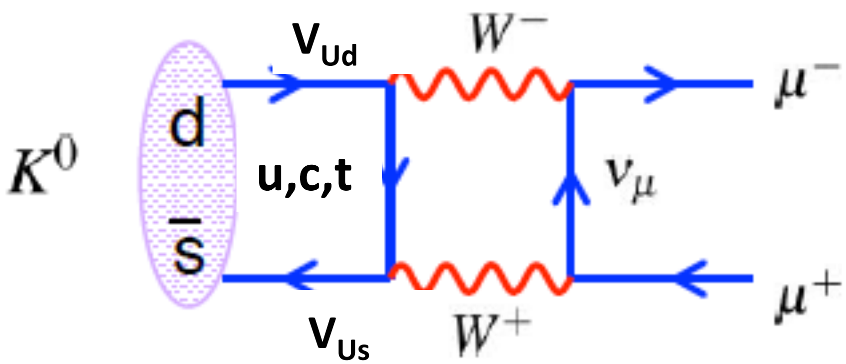
Fast pace of Discovery

- Charm, 1974
- Tau, 1974-1976
- Bottom, 1977
- Gluon jets, 1979
- W/Z, 1983
- Top, 1995
- Higgs, 2012
- ***????***

- Bubble chamber experiments
- $K_L \rightarrow \mu\mu$, BNL (1973)
- E268, FNAL (1973-1976), Measurements of η, π_0, ω rates from π, K, p beams
- E686, BNL (1976-1981), Search for associated charm at the AGS
- Isabelle, BNL (1976-1982)
- ISR807, CERN (1979-1982), jets
- D0, FNAL (1983-1995), Top quark discovery, SM measurements, BSM searches
- Empact/Gem, (SSC) 1988-1993
- ATLAS, 1994-, Higgs, SM measurements, BSM searches

Understanding Quarks

- $K_L \rightarrow \mu^+\mu^-$ (BNL) (1973) $BR(K_L^0 \rightarrow \mu^+\mu^-) = 14^{+13}_{-7} \times 10^{-9}$
- 6 authors on paper!



- Suppressed by GIM mechanism
- Sensitive to top and charm quark masses

PDG 2016 K_L^0 **DECAY MODES** Fraction (Γ_i/Γ)

$\mu^+\mu^-$ $(6.84 \pm 0.11) \times 10^{-9}$

Understanding Quarks….

- BNL E777 (1985-1988) : K→π μ e
  - Do weak decays conserve electron and muon numbers?
- (Still a question for understanding ν mass!)

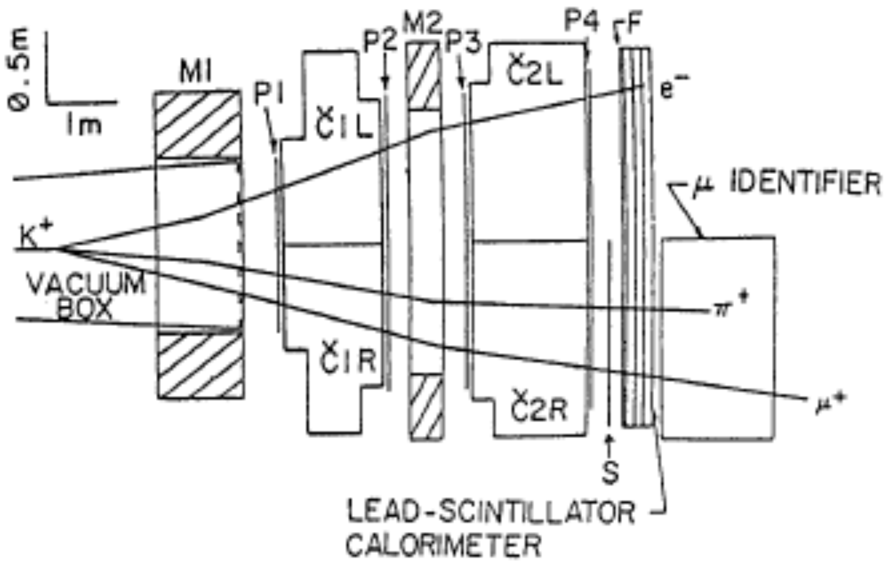


Figure 2.3: Experiment 777 apparatus.

Fermilab-E268 (1973-1976)

- Producing π, K, ω, η from π, K, p beams
  - Searched for η_c after charm quark discovery
- Measure rates at high transverse momentum
- Measure energy and particle species dependence
- Important insight: High p_T scattering led to the understanding that the underlying theory has point-like quarks and gluons

Part of a program of high p_T experiments at Fermilab leading to experimental understanding of quark model

Fermilab- E268

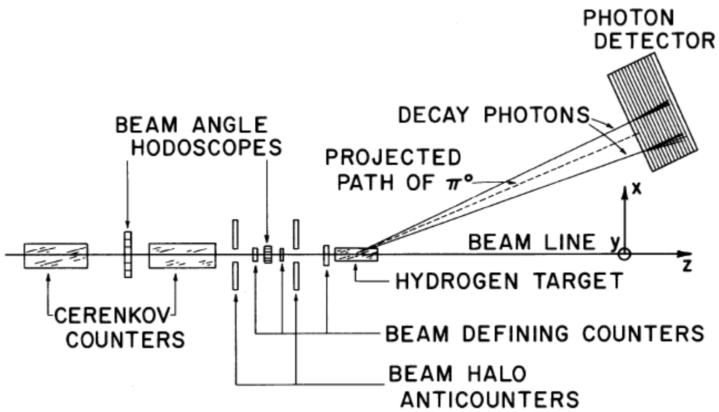
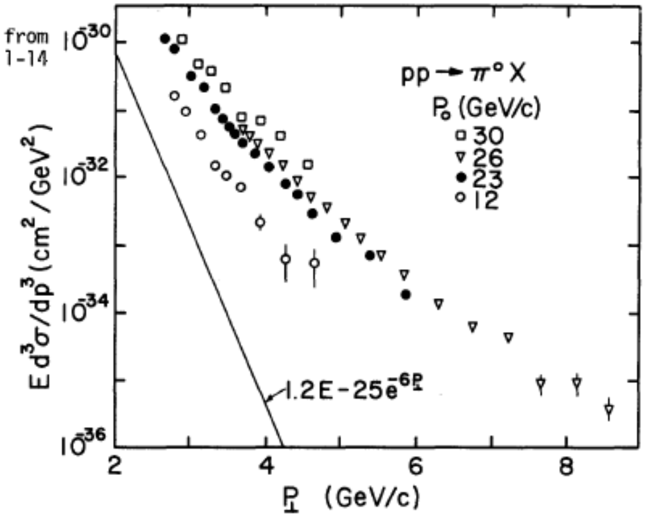


Fig. 1-7 from Ref. 1-14



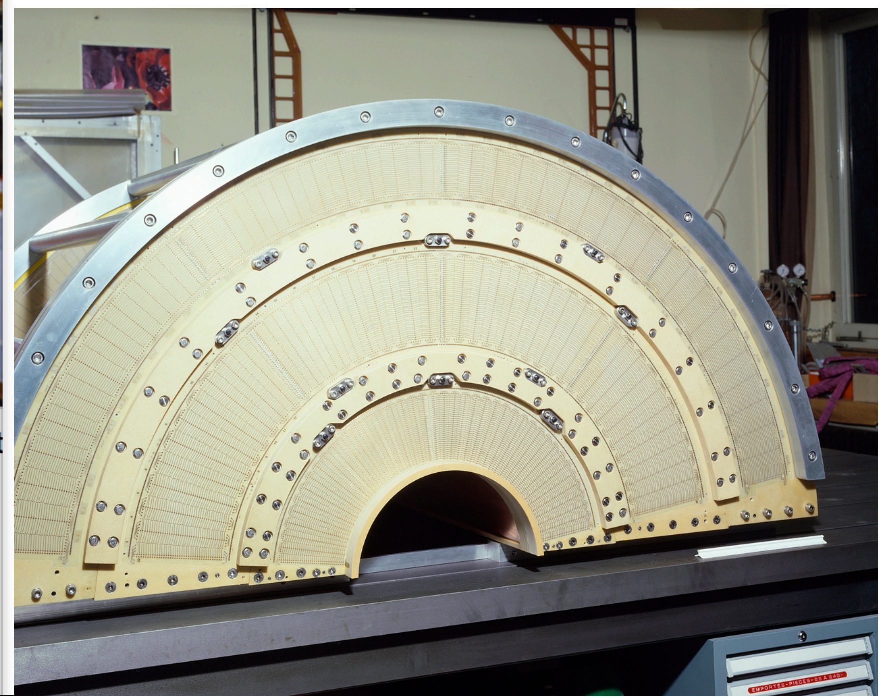
This phenomena may have the same significance as the famous Rutherford α-particle scattering experiments (Ref. 1-15). The low $P_{\perp}$ data indicate that hadron-hadron scattering is somehow "soft", leading to small average $P_{\perp}$. At high $P_{\perp}$, however, we must invoke some sort of parton - or quark - hard scattering, viewing the hadrons as clusters of these perhaps pointlike constituents.

(1978)

R807 @CERN (1979-1982)

- Look for jets at large p_T in calorimeter
- (At the time it wasn't clear this could be done)
- Jets are now critical tool for collider physics

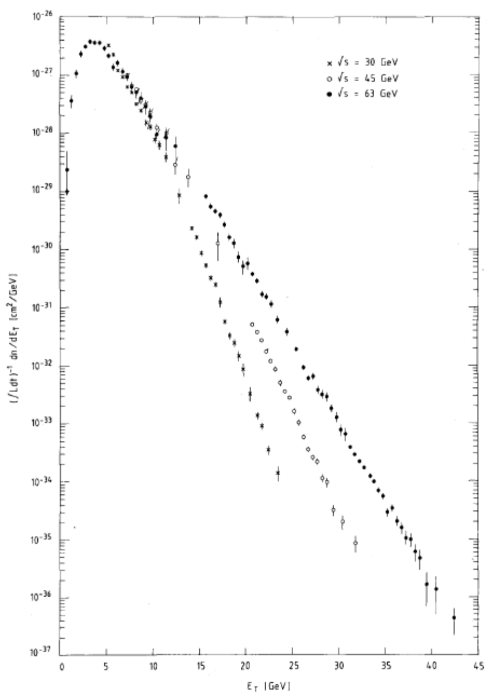
A view of the Axial Field Spectrometer – the last large experiment at the ISR. The horizontal top and vertical outer arrays of the uranium-scintillator hadron calorimeter are clear to be seen, with the blue cylindrical pole piece of the magnet just visible. The pipes that are visible in front of the pole piece are cryogenic feed pipes for the superconducting low-beta quadrupoles.



See McCubbin talk

CERN R807

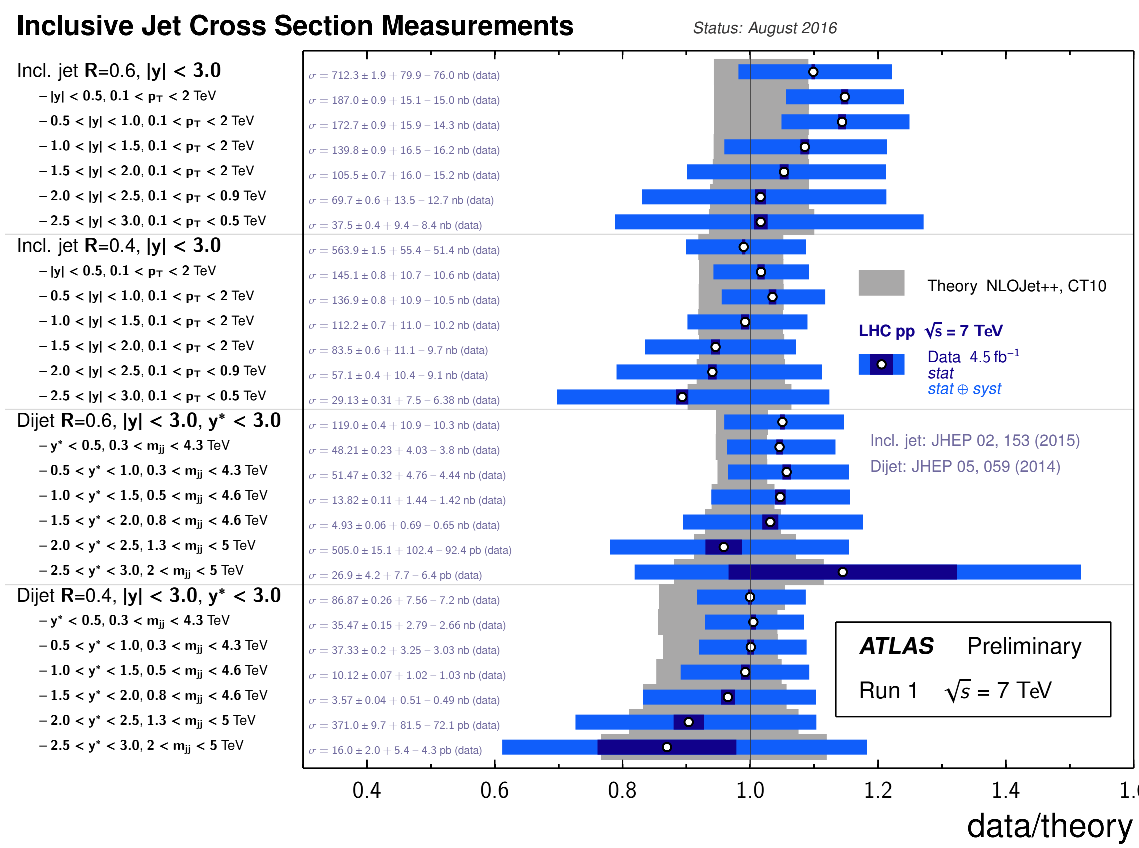
Events with a large transverse energy in a calorimeter with full azimuthal coverage and $|y| < 0.9$ have been investigated in pp collisions at $\sqrt{s} = 30, 45$, and 63 GeV. A striking change in the event structure, corresponding to a clear emergence of high-p_T jets, is observed at $\sqrt{s} = 63$ and 45 GeV in the region between 25 and 35 GeV in transverse energy. At $\sqrt{s} = 30$ GeV, the data extend to $E_T \sim 20$ GeV, but no such change in the event structure is observed.



Another piece of evidence for the quark model

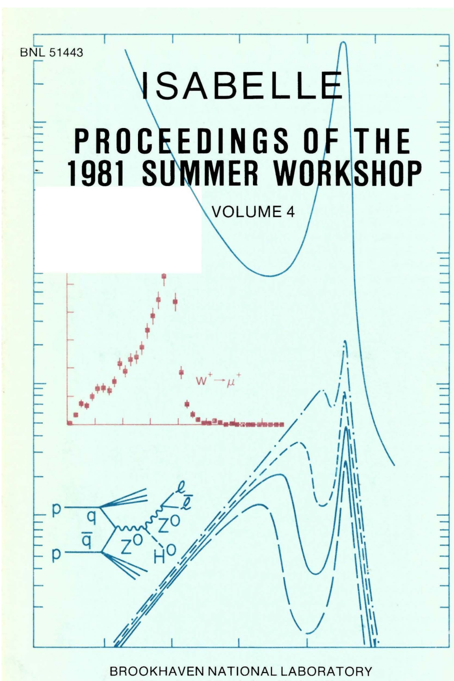
Today: Jets are a tool

ATLAS jet measurements



Exploring the Electroweak Theory at Isabelle (1976-1982)

- Need to discover W and Z bosons and then measure their properties*:* ***Is SU(2) x U(L) the right theory?***
- Designing detectors!

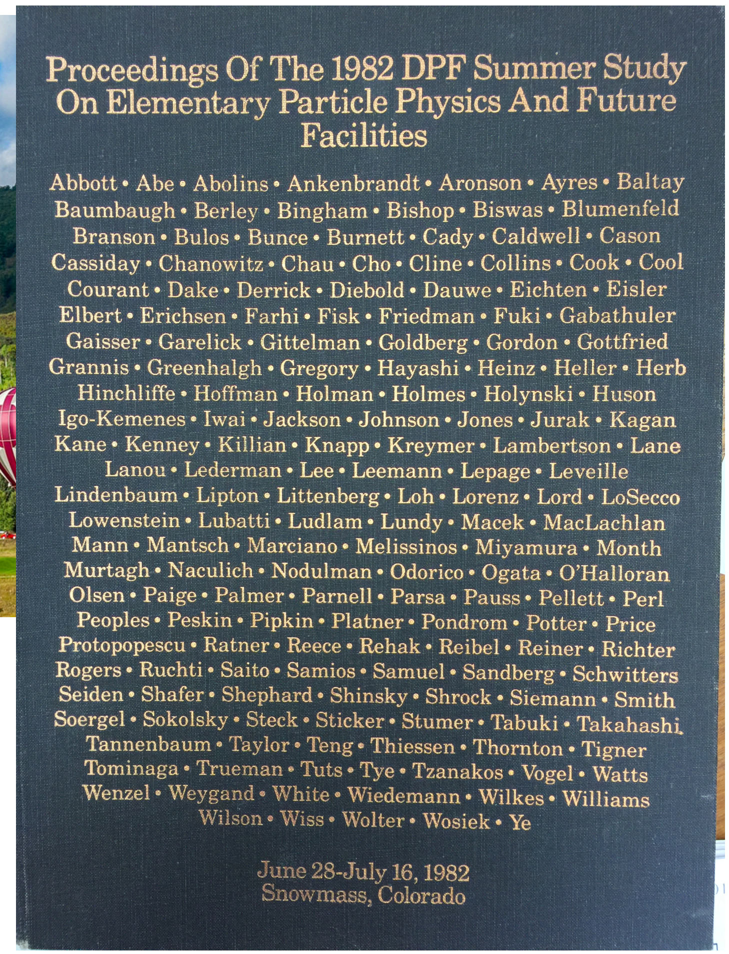


There was a consensus that physics with Phase I ($E_{cm} \approx 700$ GeV and $L \sim 2 \times 10^{31}/cm^2/sec$, with bunched beams) was feasible, important and exciting. It has been known for years that the orthodox gauge theories will be critically tested by studying the $W^{\pm}$, Z^0 and high $p_{\perp}$ phenomena. The Z^0 has a reasonable chance of being found at the $\bar{p}p$ colliders if luminosities reach $10^{30}/cm^2/sec$, but its properties will be difficult to decipher. Seeing the $W^{\pm}$'s or new heavy quarks is less probable and measuring their properties is even less likely. At ISABELLE these phenomena can all be studied with high precision. But the more exciting

Beginning of Howard's focus on the experimental exploration of electroweak symmetry breaking

The Search for Electroweak Symmetry Breaking

- Serious study started on a mountain in Colorado



Physicists go to summer camp

Later Snowmass studies had 1000 participants!

How can we Find the Higgs Boson?

- Snowmass, 1982:

HEAVY HIGGS PRODUCTION AND DETECTION

H.A. Gordon, W. Marciano and F.E. Paige
Brookhaven National Laboratory
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Physics Dept., S.U.N.Y at Stony Brook
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Philadelphia, PA 19104

Table I. H^{o} Production

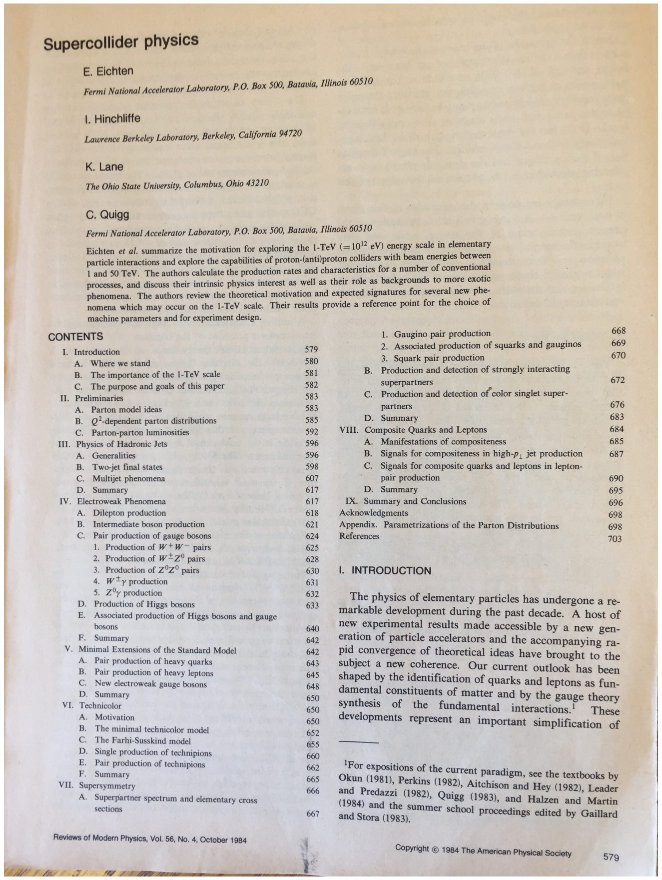
$\sqrt{s}$ (GeV)	Number of H^{o} $(Lt=10^{40}\ cm^{-2})$ m_H = 200 GeV	300 GeV	400 GeV
800	78	8	1
1,000	190	30	5
2,000	1.5×10^{3}	476	183
5,000	1.1×10^{4}	4.9×10^{3}	2.7×10^{3}
10,000	3.8×10^{4}	1.9×10^{4}	1.2×10^{4}
20,000	1.2×10^{5}	6.5×10^{4}	4.4×10^{4}

Consensus: We need the SSC
The start of a long, dedicated effort to find the Higgs

Next Stop: The SSC

SSC Physics Menu

- Find the top quark
- Measure di-jet events
- Find multi-jet events
- Measure pair production of WW,WZ,ZZ
- Find the Higgs boson
- Find new heavy gauge bosons
- Find Technicolor
- Find Supersymmetry
- Find Composite Quarks



Supercollider physics

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Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

I. Hinchliffe
Lawrence Berkeley Laboratory, Berkeley, California 94720

K. Lane
The Ohio State University, Columbus, Ohio 43210

C. Quigg
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

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I. INTRODUCTION

The physics of elementary particles has undergone a remarkable development during the past decade. A host of new experimental results made accessible by a new generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject a new coherence. Our current outlook has been shaped by the identification of quarks and leptons as fundamental constituents of matter and by the gauge theory synthesis of the fundamental interactions.[1] These developments represent an important simplification of

[1] For expositions of the current paradigm, see the textbooks by Okun (1981), Perkins (1982), Aitchison and Hey (1982), Leader and Predazzi (1982), Quigg (1983), and Halzen and Martin (1984) and the summer school proceedings edited by Gaillard and Stora (1983).

Reviews of Modern Physics, Vol. 56, No. 4, October 1984

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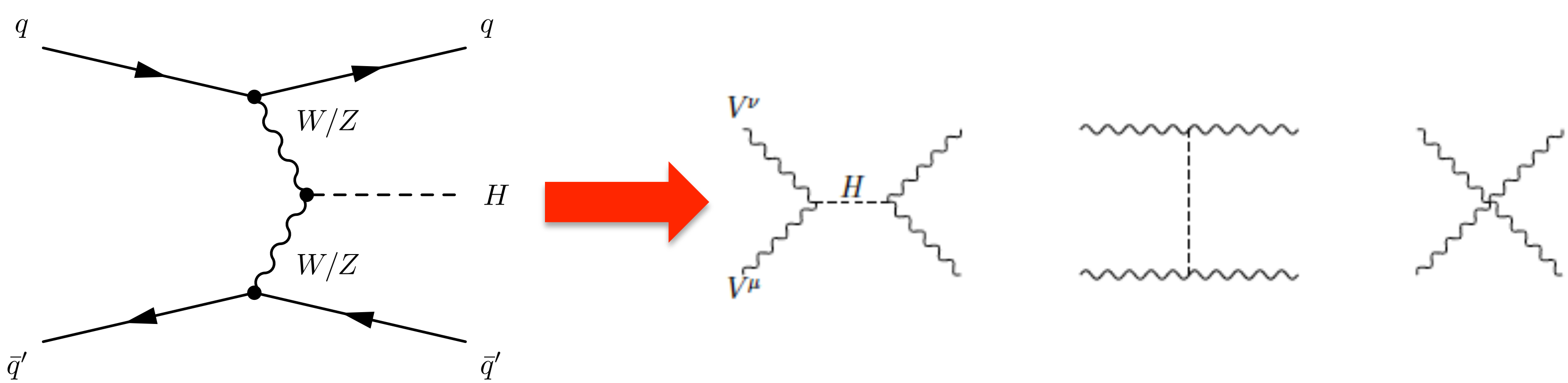
LHC is still working on these…

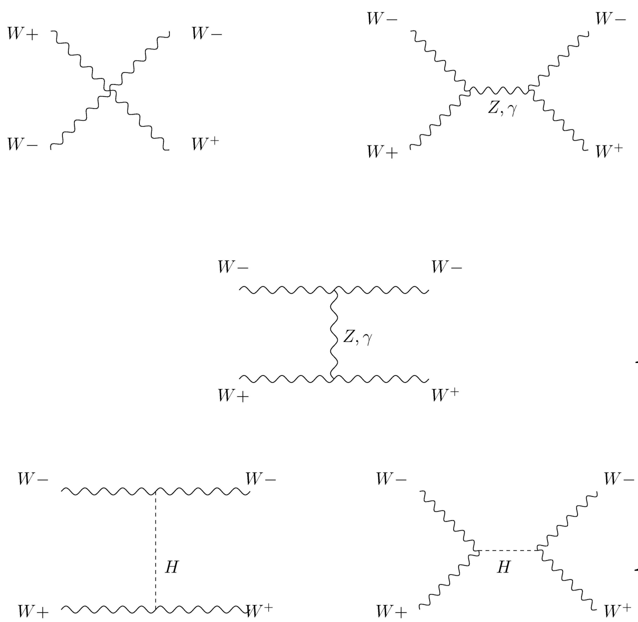
“No-Lose” Theorem at the SSC

- SSC would either find a light Higgs ($M_H < 800$ GeV) or would see strong WW scattering
- Measuring WW scattering and seeing the role of the Higgs boson remains a quest of the LHC and future colliders



Does the Higgs interact with gauge bosons as predicted?

Aside: VV Scattering



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

E^4 terms cancel between TGC and QGC

Terms which grow with energy cancel for $E \gg M_H$

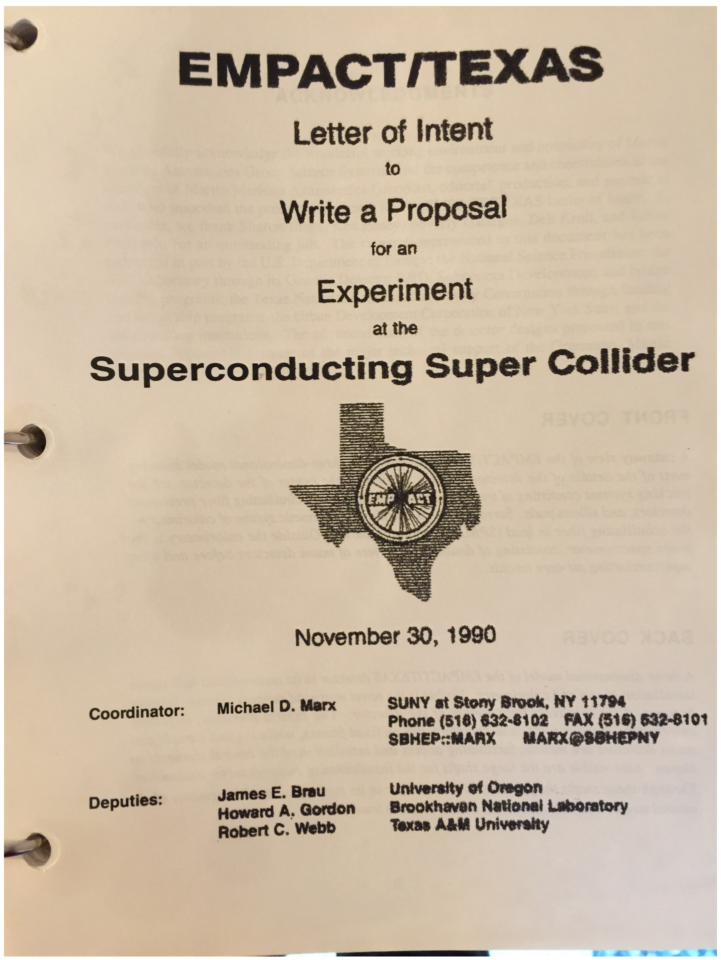
This cancellation requires $M_H < 800$ GeV

SM particles have just the right couplings so amplitudes don't grow with energy

THE LHC STILL NEEDS TO DEMONSTRATE THIS

Pulling together the community

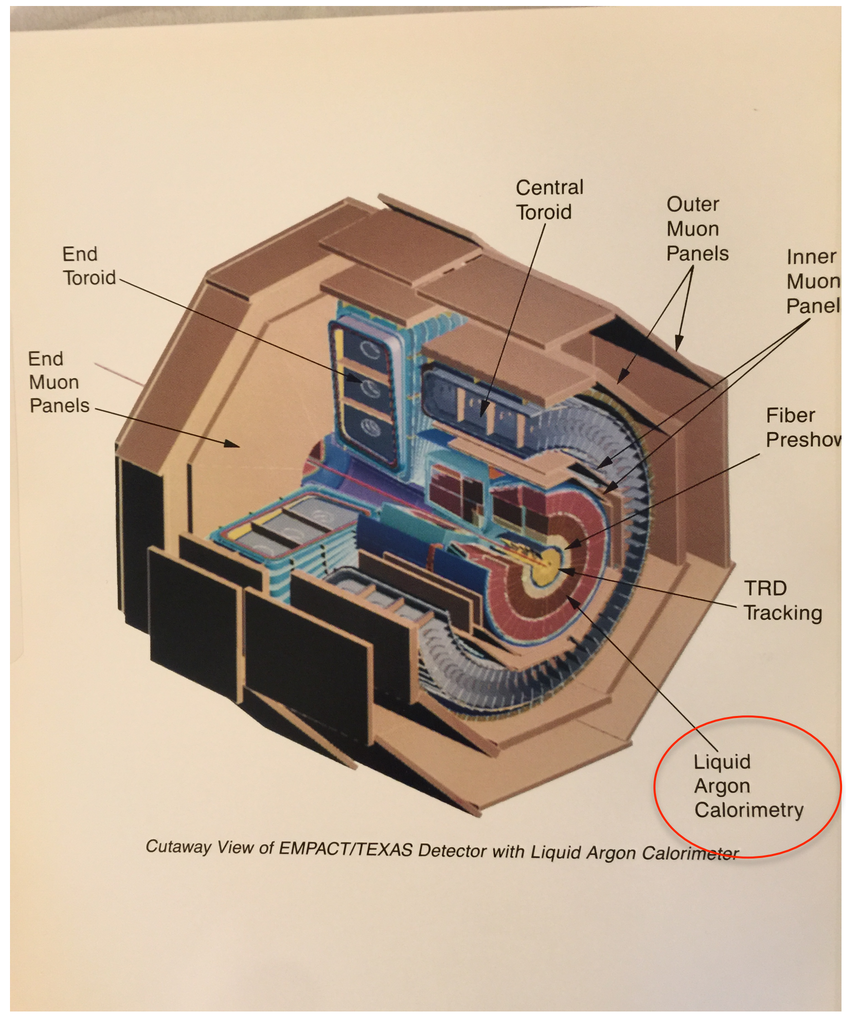
- Detectors and collaborations for SSC physics


EMPACT/TEXAS

Letter of Intent
to
Write a Proposal
for an
Experiment
at the
Superconducting Super Collider

November 30, 1990

Coordinator:	Michael D. Marx	SUNY at Stony Brook, NY 11794 Phone (516) 632-8102 FAX (516) 632-8101 SBHEP::MARX MARX@SBHEPNY
Deputies:	James E. Brau Howard A. Gordon Robert C. Webb	University of Oregon Brookhaven National Laboratory Texas A&M University



Cutaway View of EMPACT/TEXAS Detector with Liquid Argon Calorimeter

Ready for the Higgs

- Development of many technical capabilities that would be put to excellent use at D0 and ATLAS

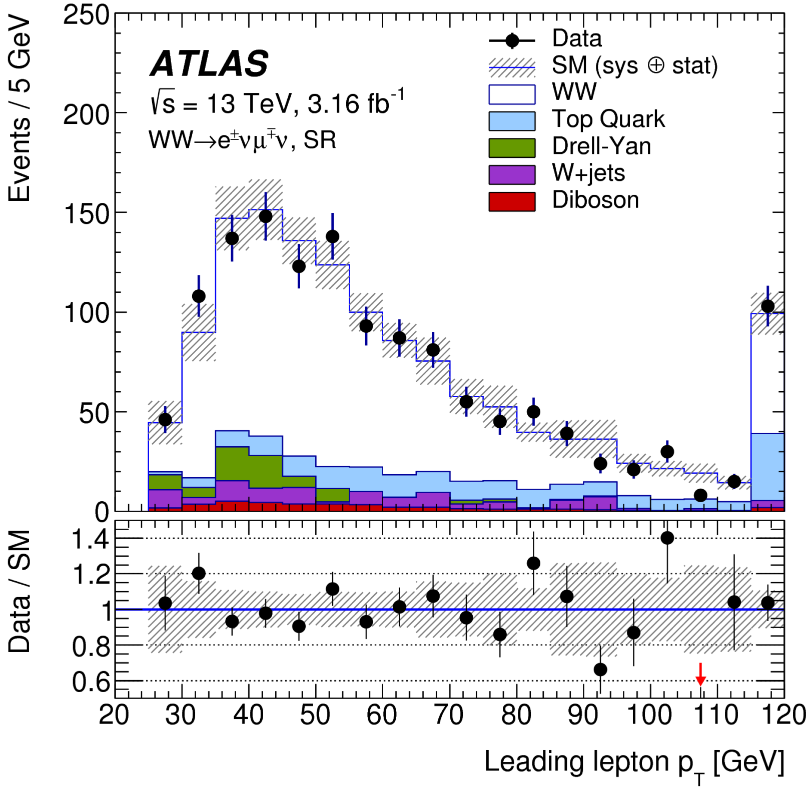
- SSC cancelled 1993

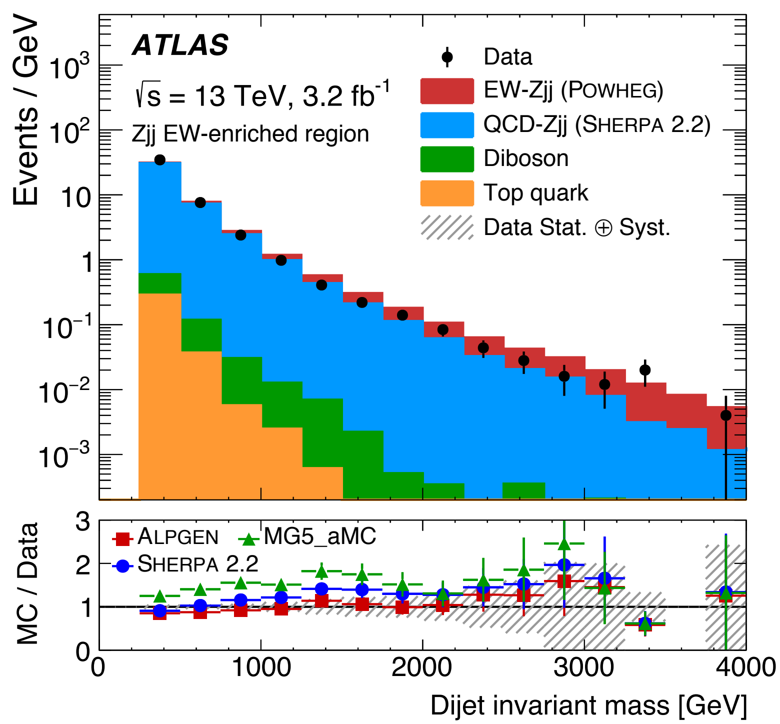
D0 and the Top Quark

- Howard and the BNL group turned their efforts and technical expertise to the D0 experiment
  - If the Higgs had been lighter, we might have seen it at the Tevatron
  - At the time we had no idea what the top quark or Higgs masses were
- Why were we so sure we would find the top quark?
  - By then, properties of the b quark were well measured at LEP
  - From Zbb interactions, b quark is an isospin T_3=-1/2 particle
  - It must have a T_3=1/2 partner (the top quark) for the SM fermion interactions to be correct

See Grannis talk for the many scientific discoveries at D0!

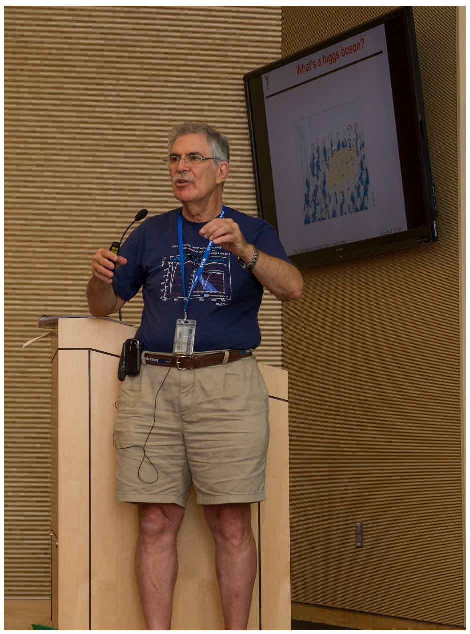
Today: The Top quark is a background





Finally the Higgs……

- ATLAS collaboration and the successful discovery of the Higgs aren't the end of our quest for understanding electroweak symmetry breaking

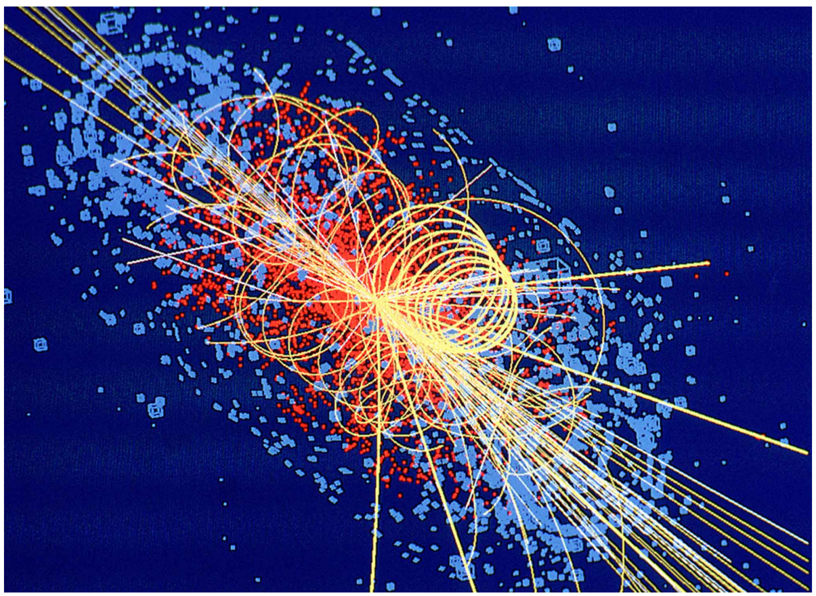


We haven't yet measured all the properties of the Higgs or determined if there are more Higgs bosons

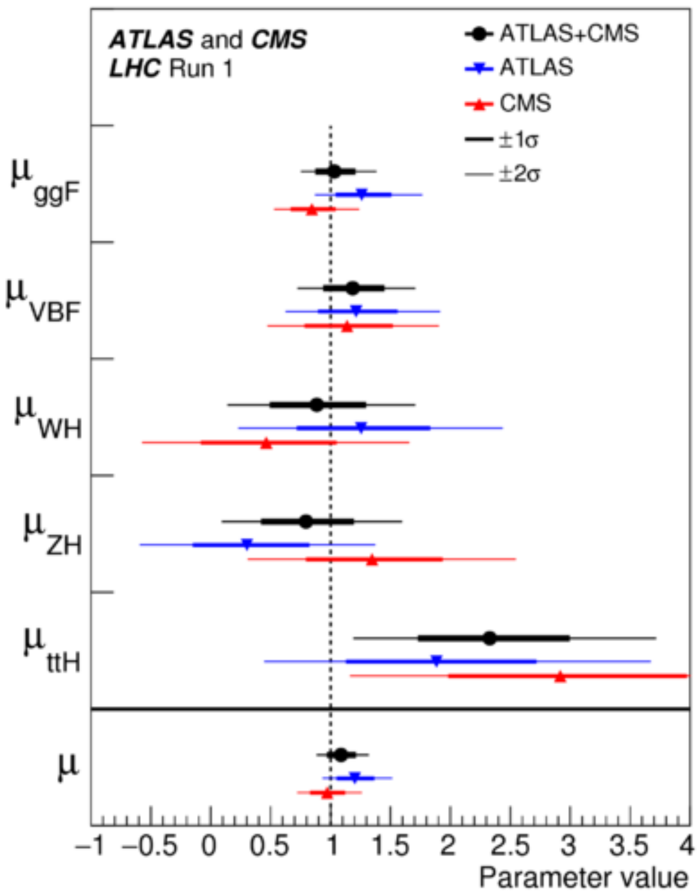
See Jenni and Taylor talks for the glories of ATLAS!

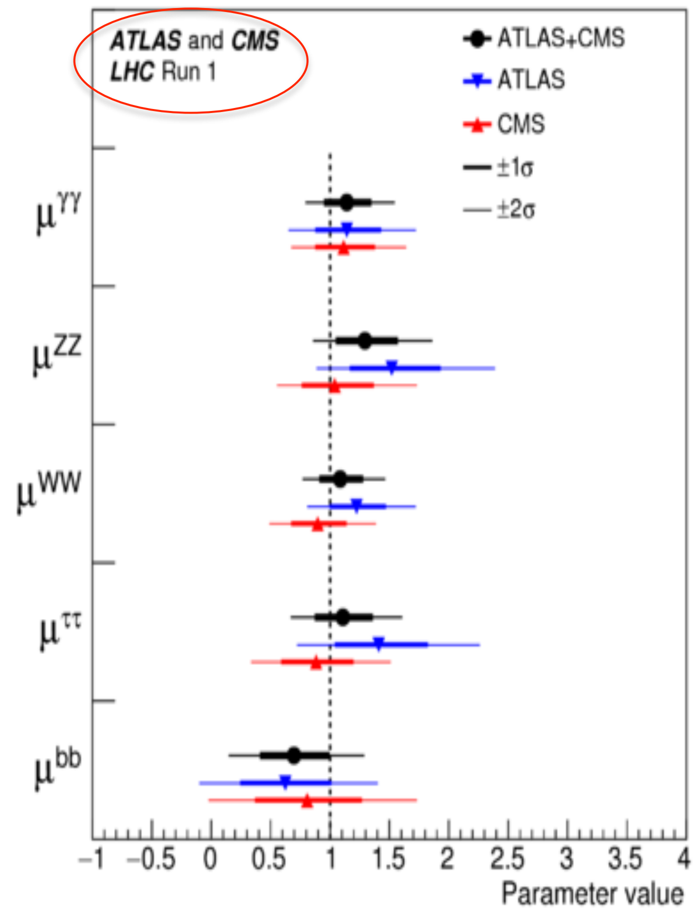
In the last 4 years….

- 2012: LHC discovered the Higgs boson; it appears to have predicted properties
- Incredible advances in our knowledge



Precision Higgs Measurements

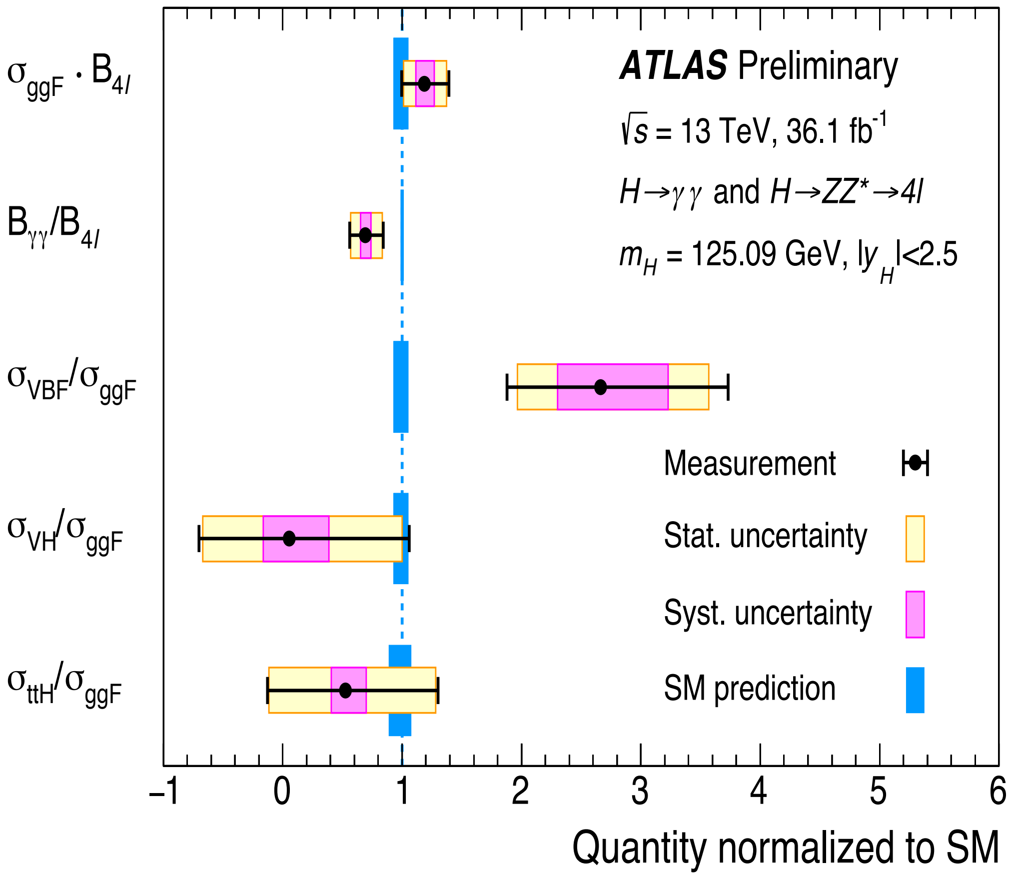


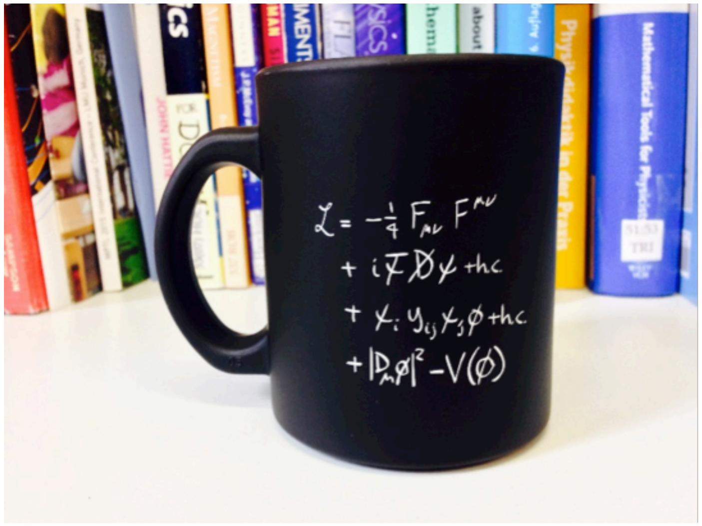


$$\mu = \frac{\sigma}{\sigma_{SM}}$$

Always normalized to SM *(Theory matters!)*

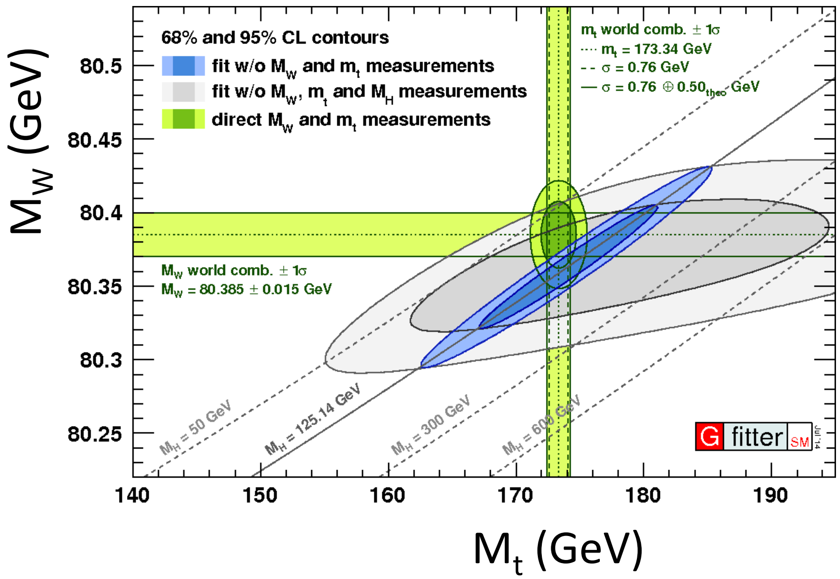
Model is very predictive





Still lots of exciting, important physics to do at the LHC

The SM Works! (Global Fit)



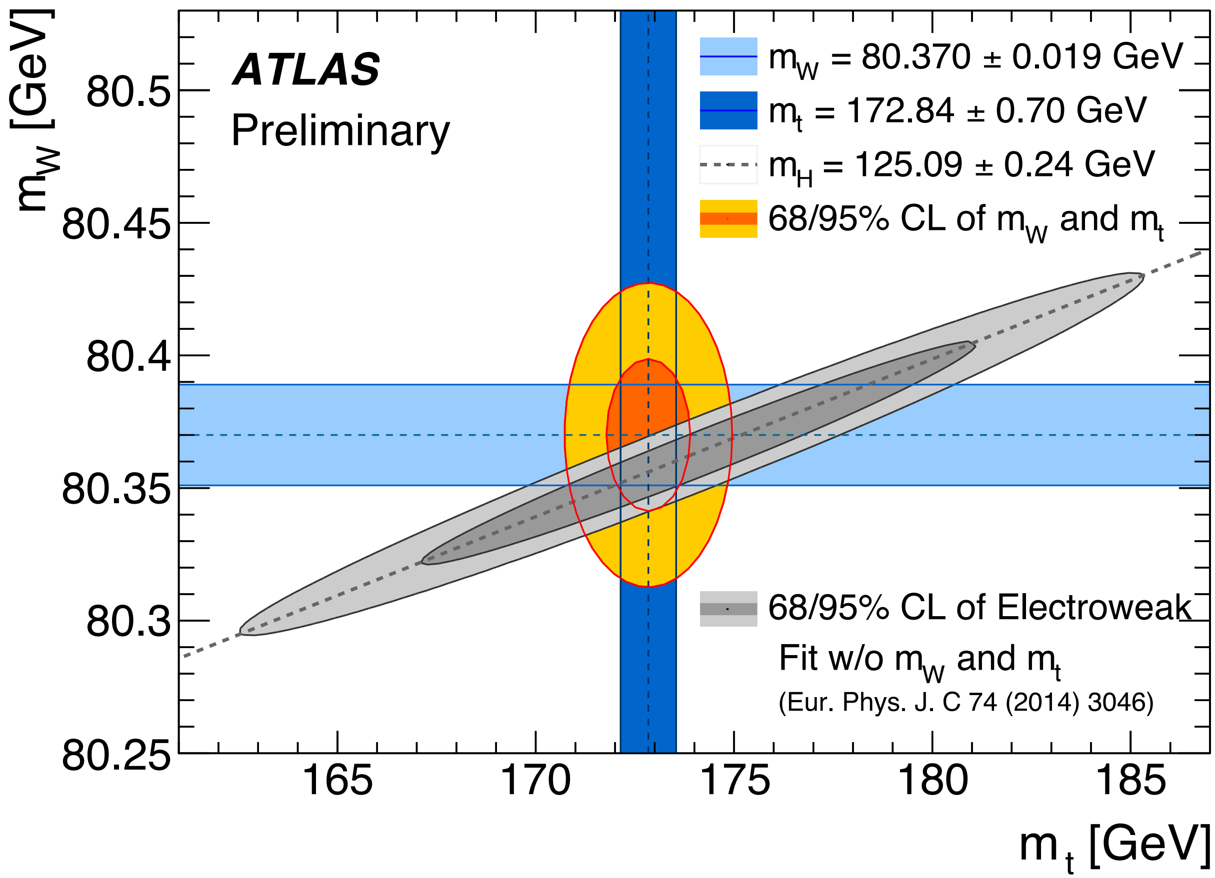
Measurements sensitive to $\ln(M_H)$ terms

Heavy Higgs excluded by precision measurements even without observation

Corollary: New Physics highly restricted by data

**So why are we still talking about BSM physics in the Higgs sector?*

Fit supports Higgs Theory



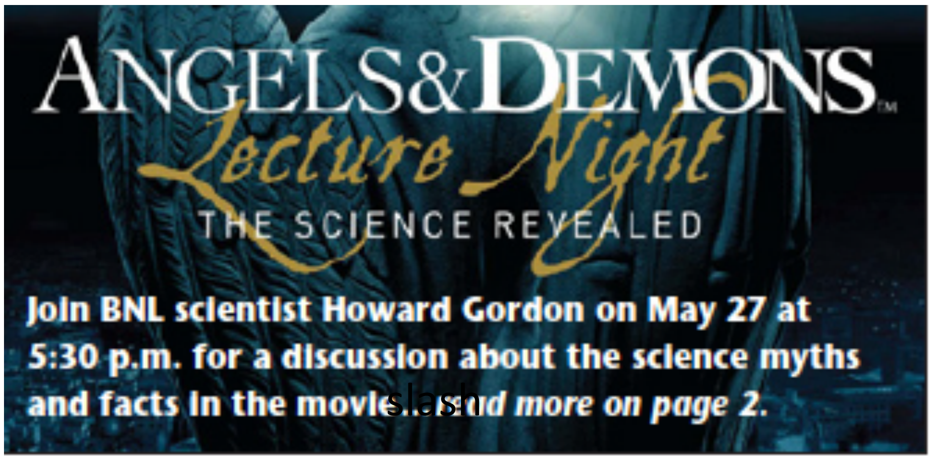
NEW

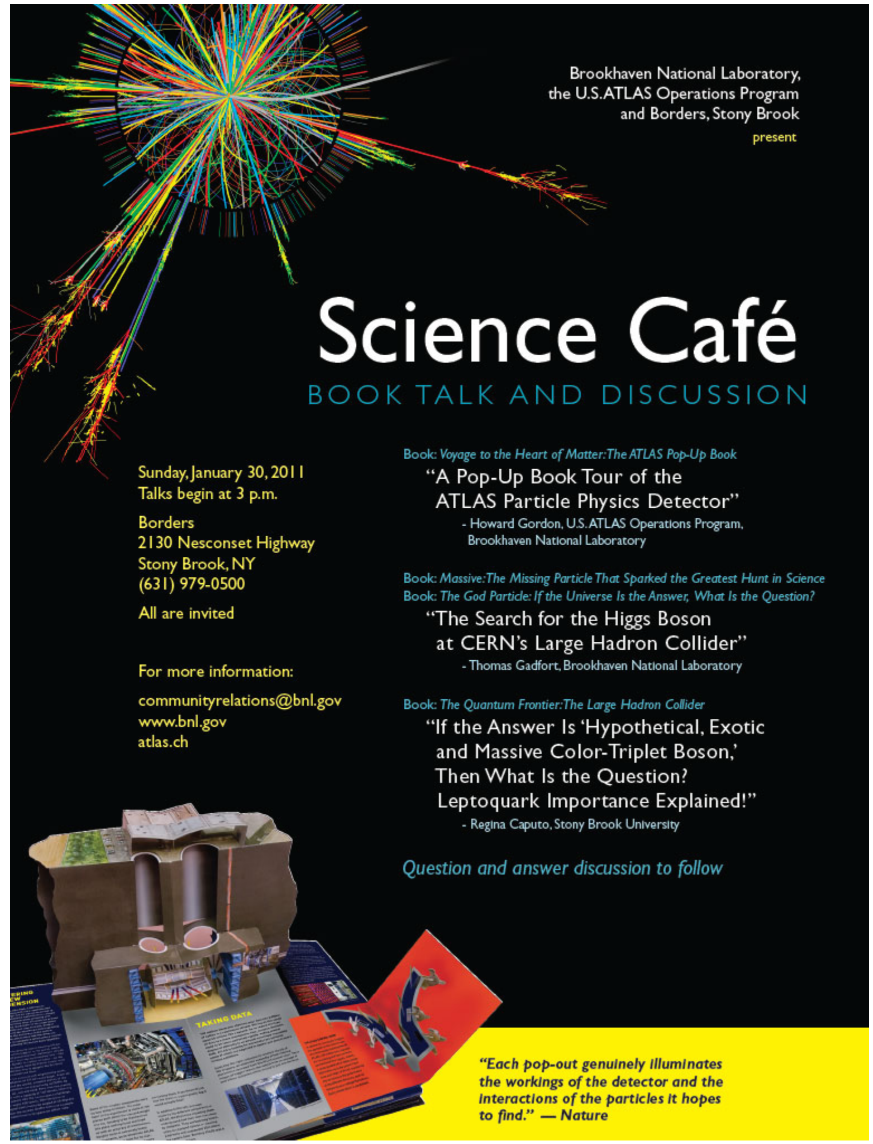
Standard Model fits data very well at the quantum level

Astounding progress during Howard's Career:

- The Standard Model has been experimentally verified *(mostly)*
- We can accurately calculate in the context of the quark model and the SM gauge theory *(mostly)*
- Howard has made crucial contributions to this understanding
  - Quark model, jets, top quark, Higgs boson, detectors
- The particle physics community now has a theory that explains *(pretty much)* everything
  - (Not dark matter, the top quark mass, neutrino masses....)

Howard has always been generous with his time





Best of luck on your future journeys

May you have many more discoveries