Smashing particles at the high energy frontier

Assistant Professor Evelyn Thomson
University of Pennsylvania
Department of Physics & Astronomy Colloquium
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Outline

Introduction

Measurements of top quark properties: the study of the most massive fundamental particle

Search for the Higgs boson: the hunt for the most elusive fundamental particle

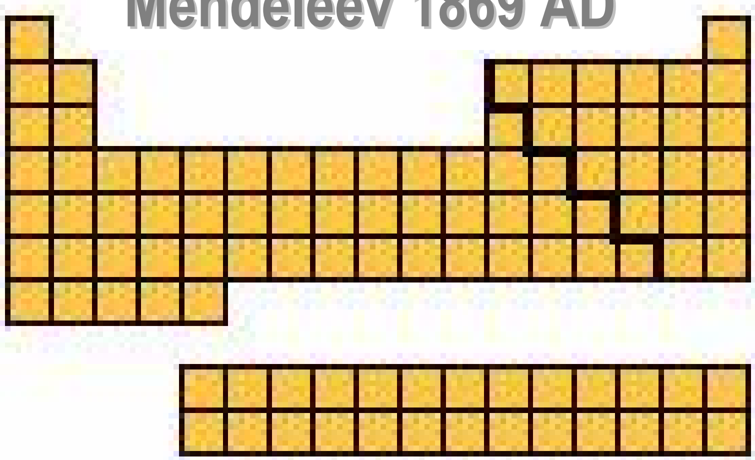
Commissioning of the ATLAS experiment: looking forward to a giant expansion of the high energy frontier

Conclusions

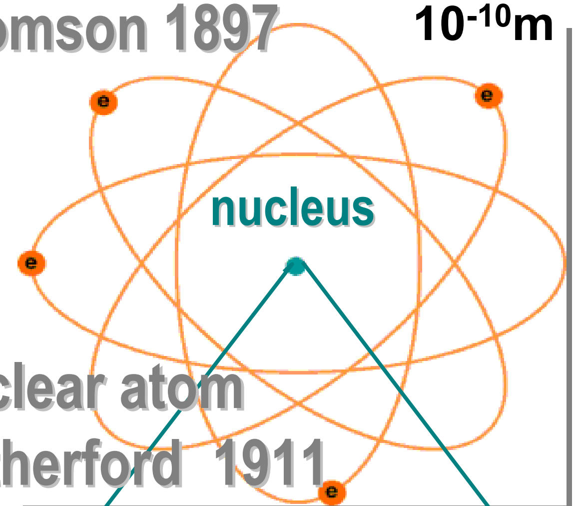
What are the basic building blocks of Nature?

Elements
Aristotle
330 BC

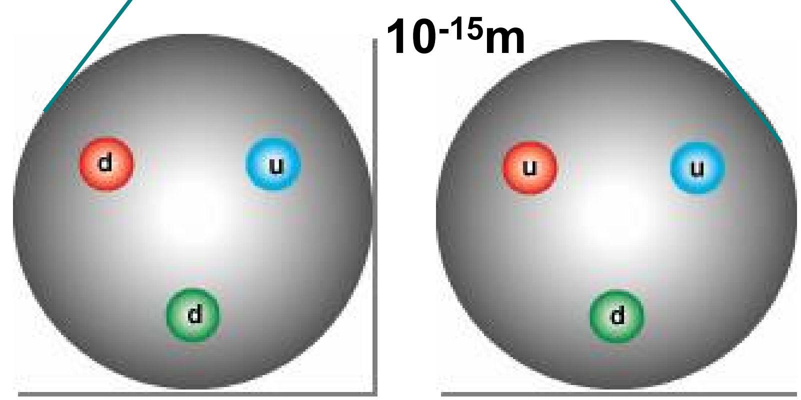
Periodic Table of Elements
Mendeleev 1869 AD



electron
Thomson 1897



Nuclear atom
Rutherford 1911



neutron
Chadwick 1932

proton

Center for Particle Cosmology at the University of Pennsylvania

Outstanding Questions for 21st Century

Is a New Theory of Matter and Light Needed at the Highest Energies?

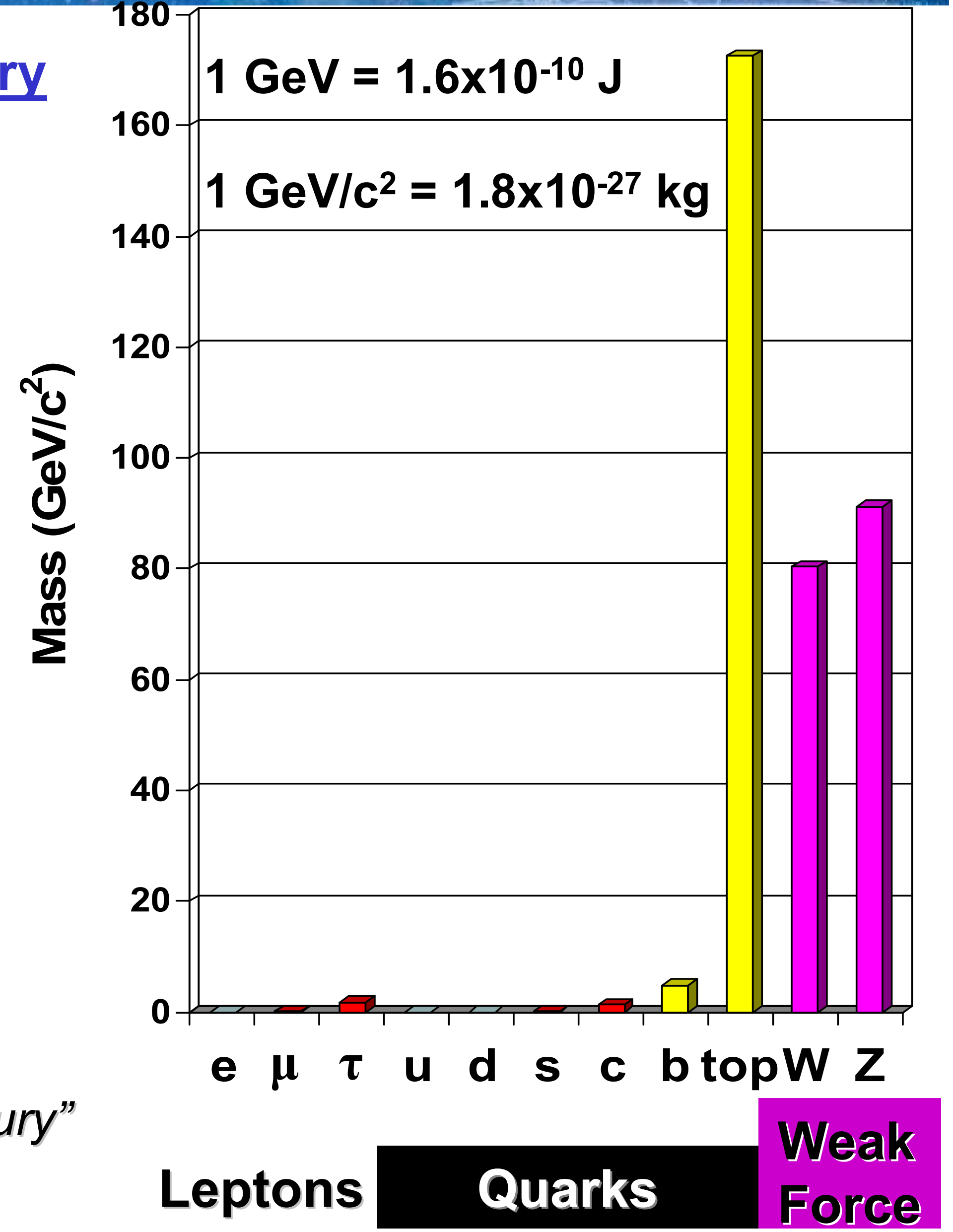
Are there Additional Space-Time Dimensions?

What are the Masses of Neutrinos and How Have They Shaped the Evolution of the Universe?

What is Dark Matter?

What is the Nature of Dark Energy?

"Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" (National Academies Press 2003)



How to produce massive particles

Need high energy to make massive particles: E=mc^2

- **For example: to produce a pair of top quarks with mass 172 GeV, need at least 344 GeV of energy available**

How to reach high enough energy? Accelerate particles and collide with:

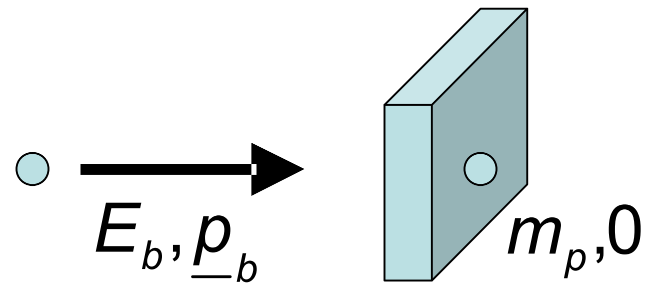
- **stationary fixed target**
- **another bunch of particles moving in opposite direction**

Head-on collisions are most efficient

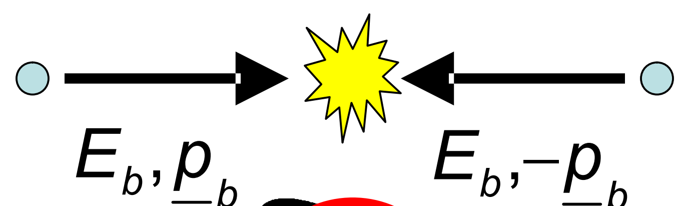
- **All of beam energy is available to make new particles**
- **"do cross the beams!"**

Energy available to make new particles at…

Fixed Target $\propto \sqrt{E_b}$



Collider $= 2E_b$

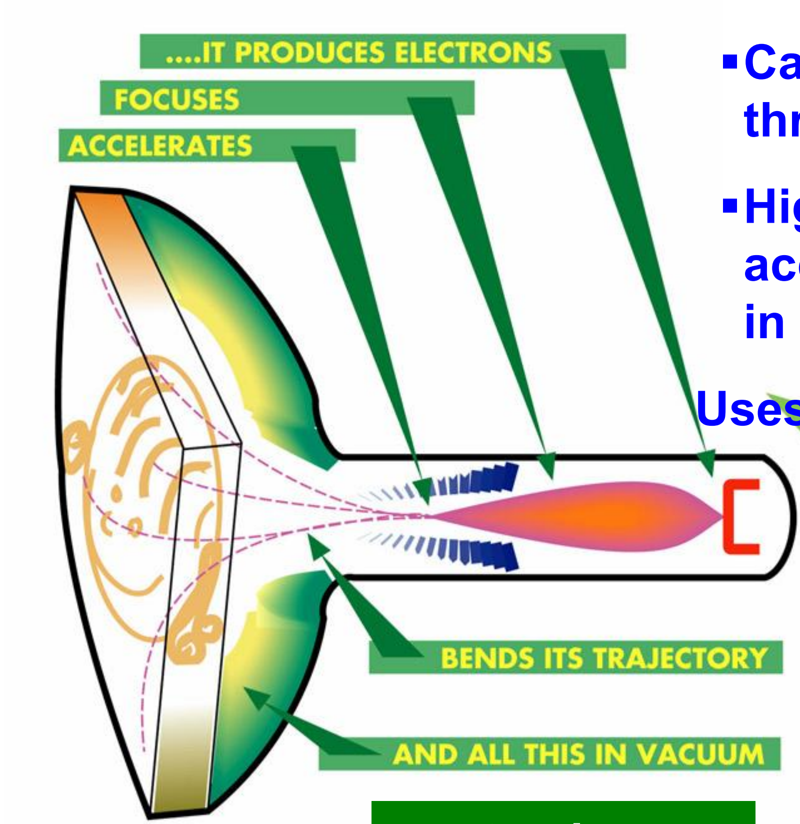


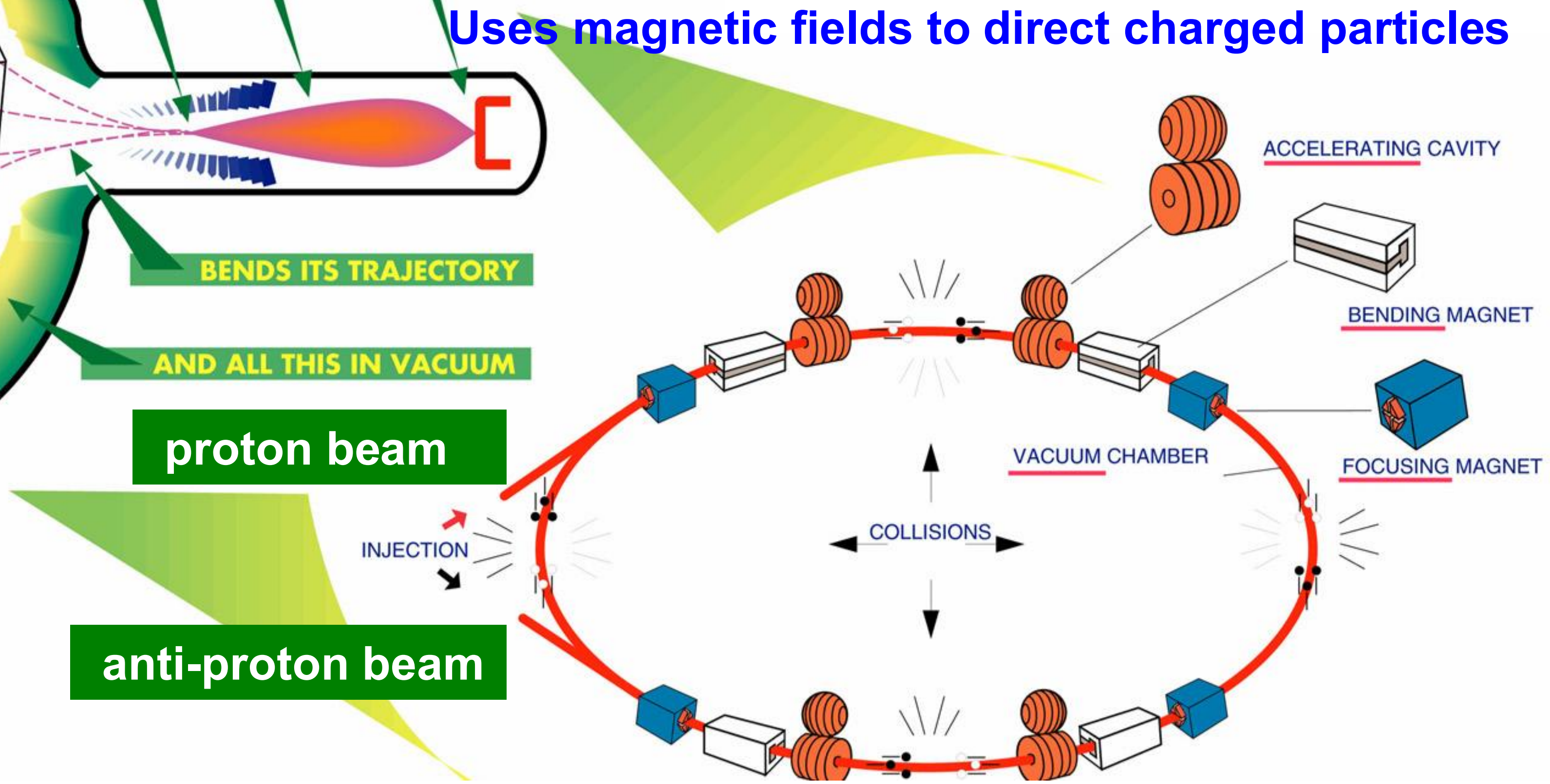
Did you know your old cathode ray tube TV set is a particle accelerator?

Uses electric fields to accelerate charged particles

- Cathode ray tube TV set: electrons accelerate through 20 thousand volts
- Highest energy accelerators in world: protons accelerate through 980 billion volts in USA, and in future through 7000 billion volts in Europe

Uses magnetic fields to direct charged particles





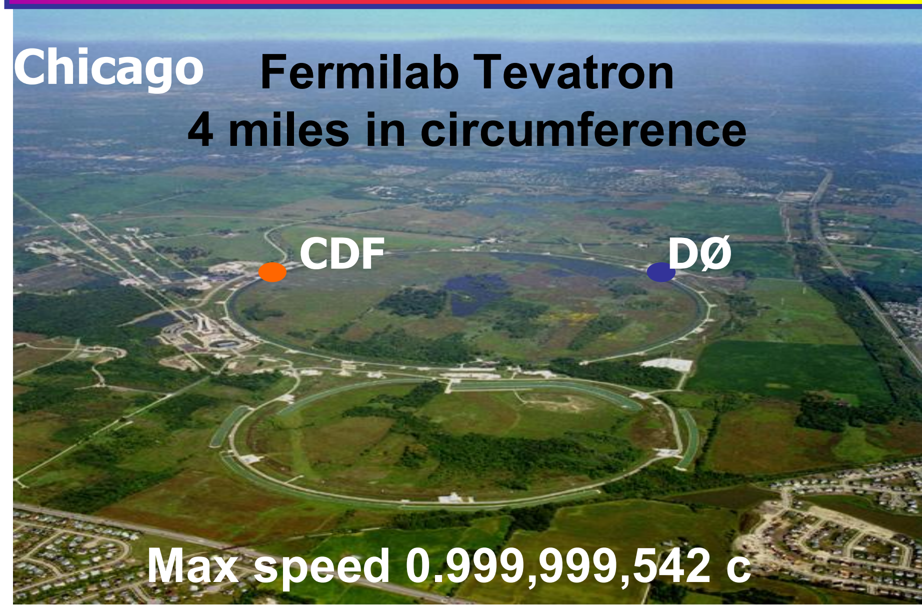
Colliders at the high energy frontier

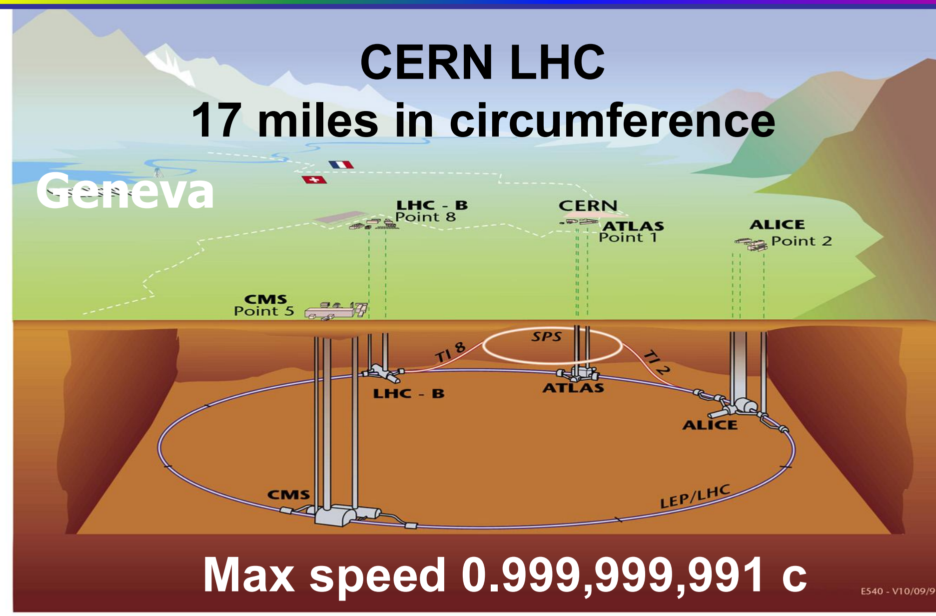
FNAL Tevatron Run II 2001-2010
1960 GeV proton on anti-proton
- ✓Top quark mass & properties
- ✓W boson mass & properties
- ✓B physics
- ✓Exclude Higgs 160-170 GeV
- ?Keep searching for Higgs boson
- ?Search for new physics

CERN LEP collider 1989-2000
Up to 209 GeV e^- on e^+
- ✓Z and W masses & properties
- ✓Exclude Higgs mass < 114 GeV

CERN Large Hadron Collider 2009+
14,000 GeV proton on proton
- ?Discover Higgs if mass < 1000 GeV
- ?Search for new physics

2000 2005 2010 2015 2020





LHC magnets

Dipole Magnetic field is 8.3 T for 7000 GeV protons

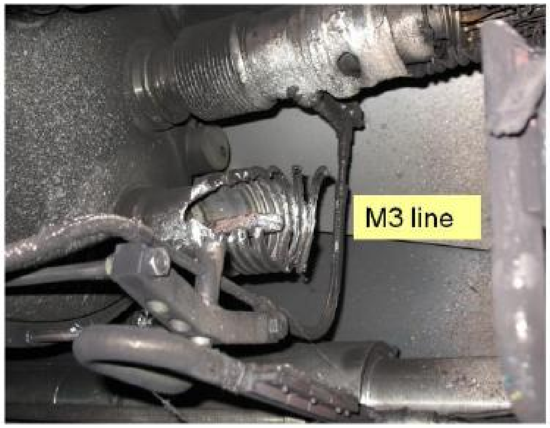
- 80,000 times strength of Earth's field
- Superconducting Nb-Ti magnets at 1.9 K
- Superfluid helium cooling (120 tonnes)
- 1232 dipole magnets, 15 m long, L=100 mH

$$\vec{F} = q\vec{v} \times \vec{B} = m\frac{v^2}{R} \text{ so } B = \frac{p}{qR}$$

First beam 9/10/08, then accident 9/19/08 due to bad connection between magnets

When is R=220 nΩ a problem? If current I=8700 A…

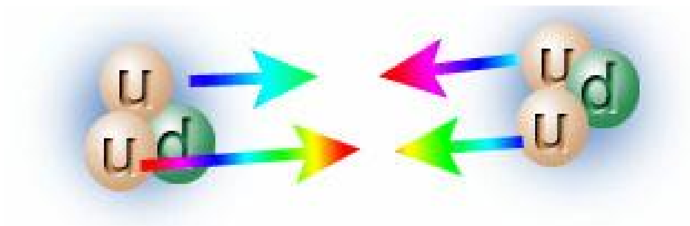
- Stored energy U=1/2 LI^2 = 3.8 MJ per magnet
- Bad connection Power dissipation = I^2R = 17 W
- Thermal run-away: 4 MJ in 1 second
- Dissipated 270 MJ in electrical arcs (enough to melt 375 kg of copper!)
- Lost 6 tonnes of He



Restart in November 2009
Repairs required to 755 m
Replace 39 dipoles
Repair other bad connections
Run at lower energy for safety

Proton Collisions

Collide constituents of proton: quarks & gluons

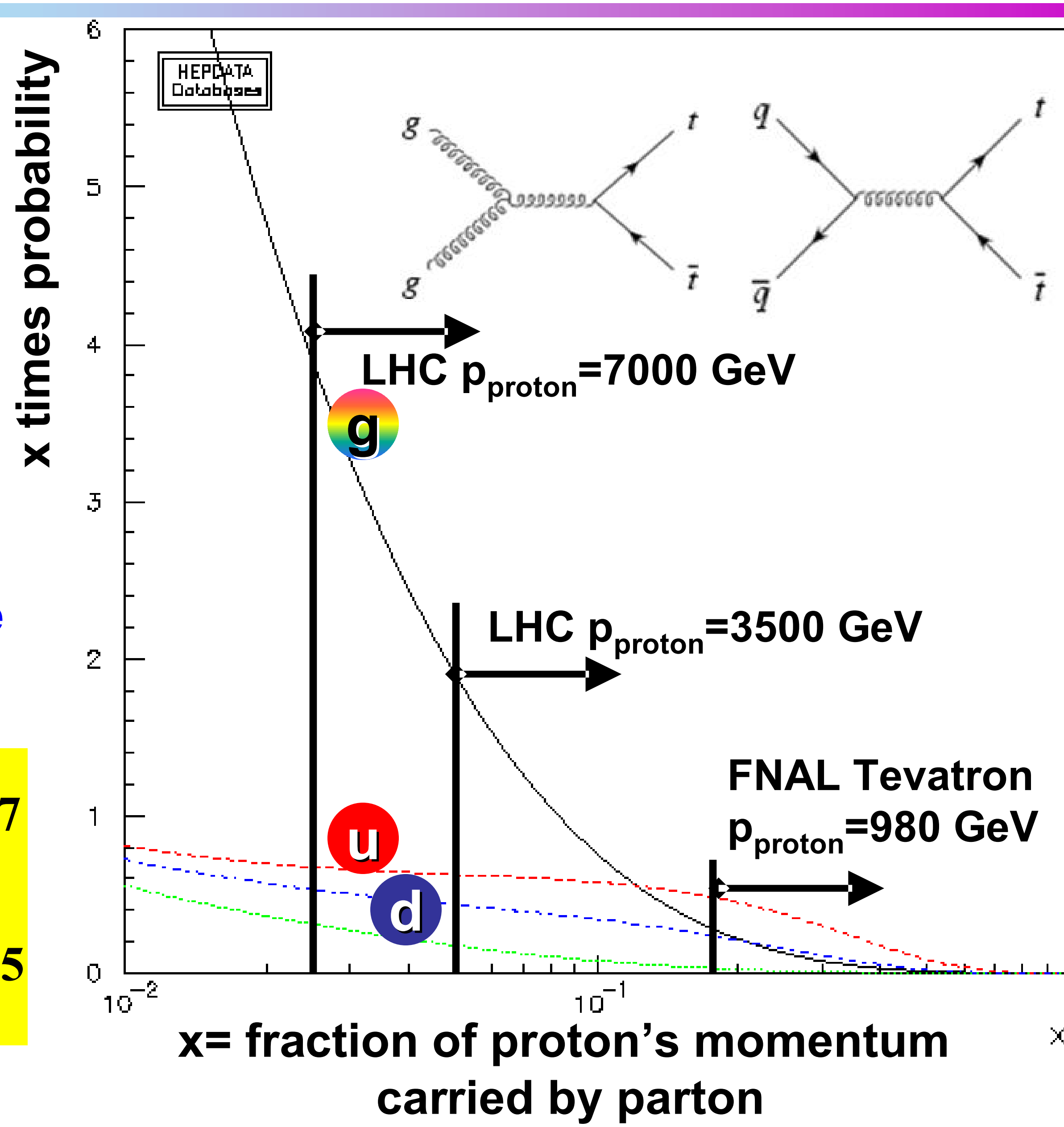


Each constituent carries a only fraction x of proton's momentum

Need $x \geq 172/p_{proton}$ to make a pair of top quarks

$$\text{FNAL } x \geq \frac{172}{p_{\text{proton}} = 980} = 0.17$$

$$\text{LHC } x \geq \frac{172}{p_{\text{proton}} = 7000} = 0.025$$



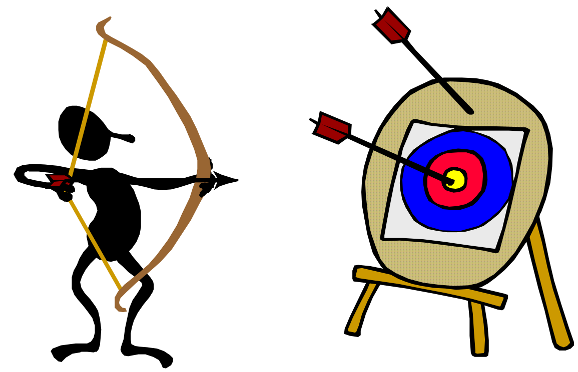
Barns and inverse barns?

Cross section: calculate probability for particular outcome of a collision in terms of area

1 barn = 10 fm x 10 fm =10^{-28} m^2 =10^{-24} cm^2

Interesting processes are rare so units are small

- **nb = nano-barns 10^{-9} barns = 10^{-33} cm^2**
- **pb = pico-barns 10^{-12} barns = 10^{-36} cm^2**
- **fb = femto-barns 10^{-15} barns = 10^{-39} cm^2**



Luminosity: collider figure-of-merit is product of number of particles in each beam per unit area per second. Fermilab's instantaneous luminosity of 1×10^{32}cm^{-2} s^{-1} = 0.1 nb^{-1} s^{-1} is due to

- **50 billion protons & 10 billion anti-protons per bunch**
- **colliding bunches 1.7 million times each second**
- **tiny transverse area of beam of 30 μm x 30 μm**

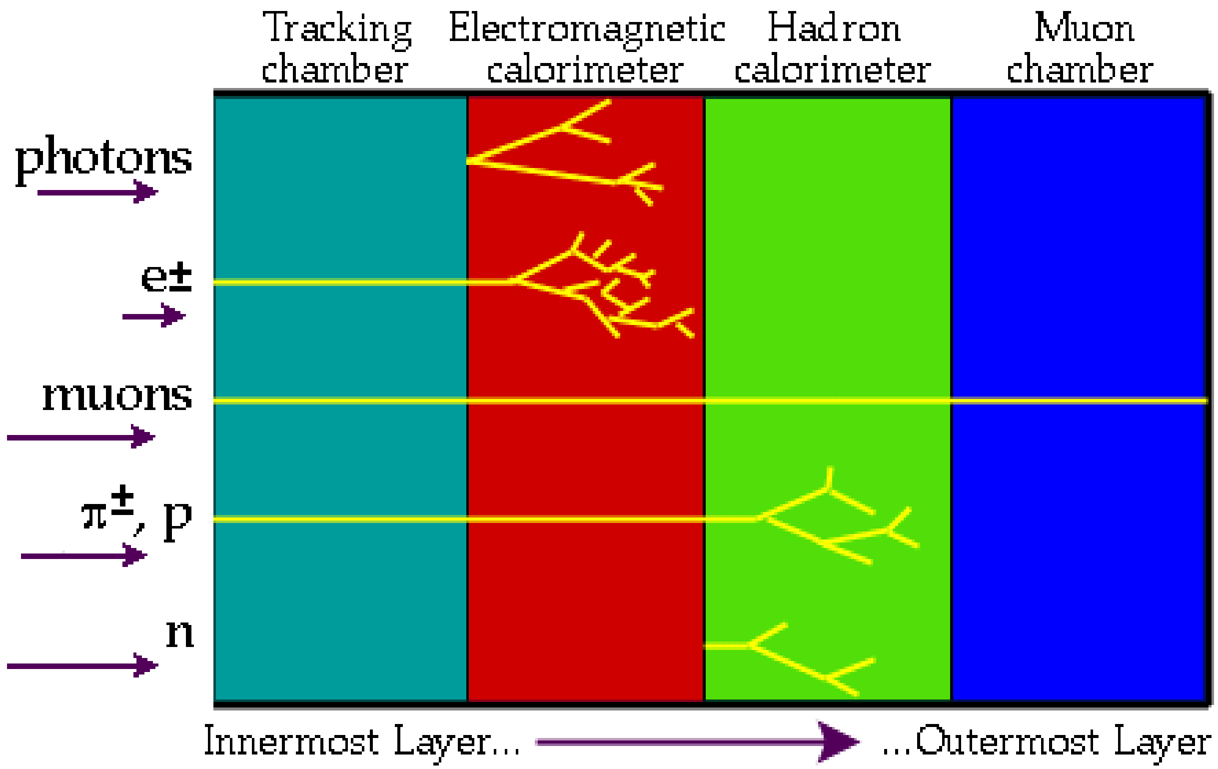
Here are the average rates for some types of collisions at Fermilab

- **Anything inelastic 60 mb x 0.1 nb^{-1} s^{-1} = 6 million each second**
- **W→eν 2 nb x 0.1nb^{-1} s^{-1} = 1 event every 5 seconds**
- **top & anti-top 7 pb x 0.1nb^{-1} s^{-1} = 1 event every 24 minutes**
- **Higgs WH→eνbb 10 fb x 0.1 nb^{-1} s^{-1} = 1 event every 10 days**

Detect energy, momentum, identity of particles

All charged particles leave "tracks"
either ionize noble gas or create e-hole pairs in silicon
Measure momentum from track curvature in magnetic field

$$\frac{\sigma}{p_T} = 5\times10^{-4}\, p_T \oplus 0.01$$



Muons escape calorimeter with little energy loss (only from ionization)

Most particles stop in calorimeter and deposit all their energy

EM shower of photons/electrons/positrons

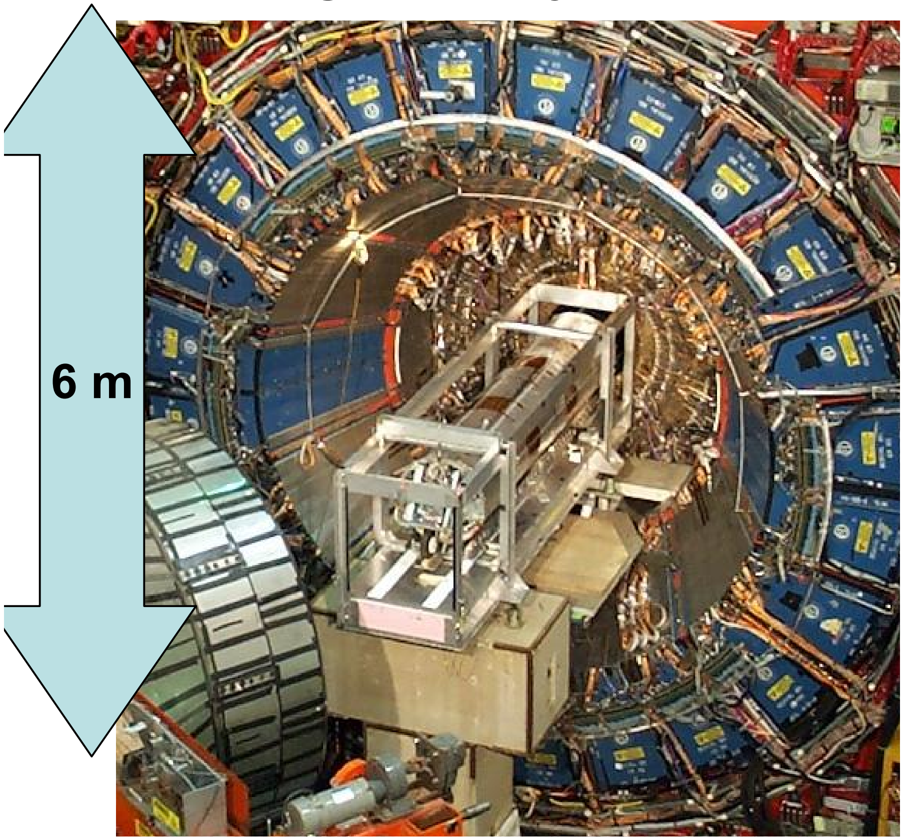
$$\frac{\sigma}{E} = 0.1/\sqrt{E} \oplus 0.007$$

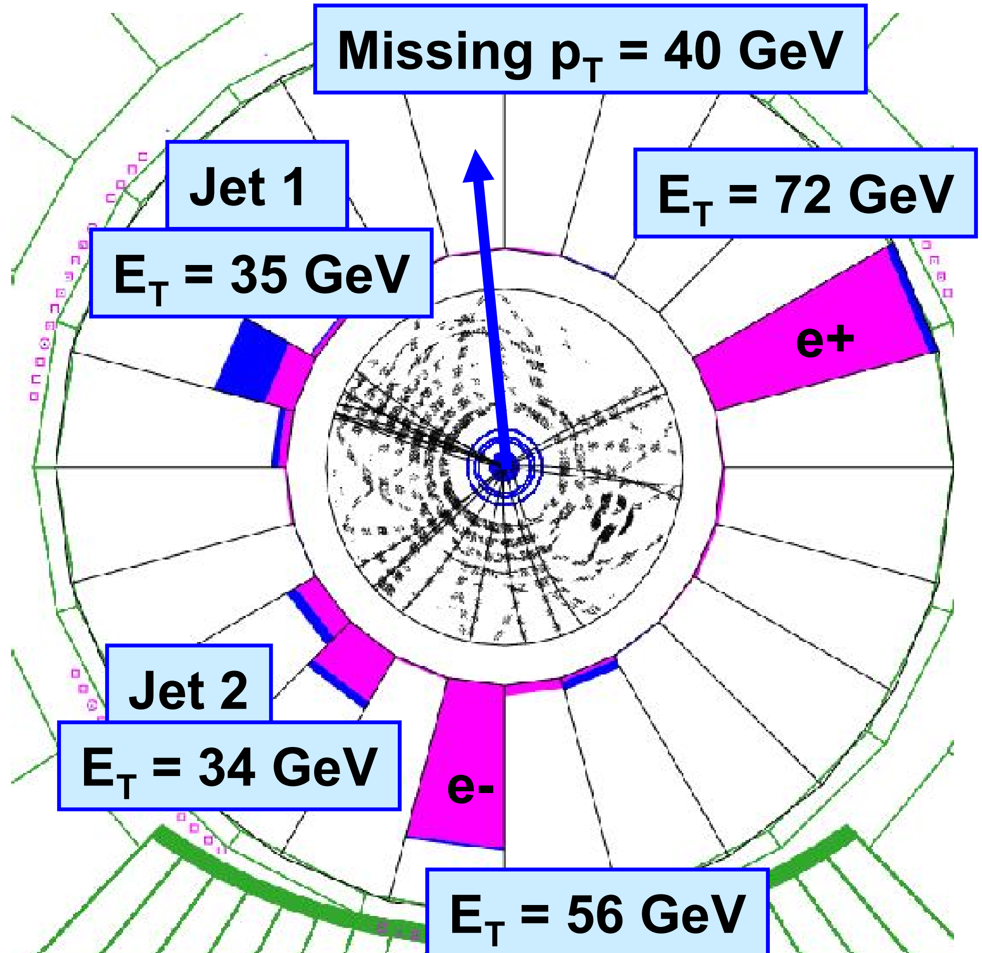
Nuclear collisions for hadrons (proton, neutron, pion, kaon)

$$\frac{\sigma}{E} = 0.5/\sqrt{E} \oplus 0.03$$

Detector and Display of debris from collision

Collider Detector at Fermilab (CDF) during assembly in 2000



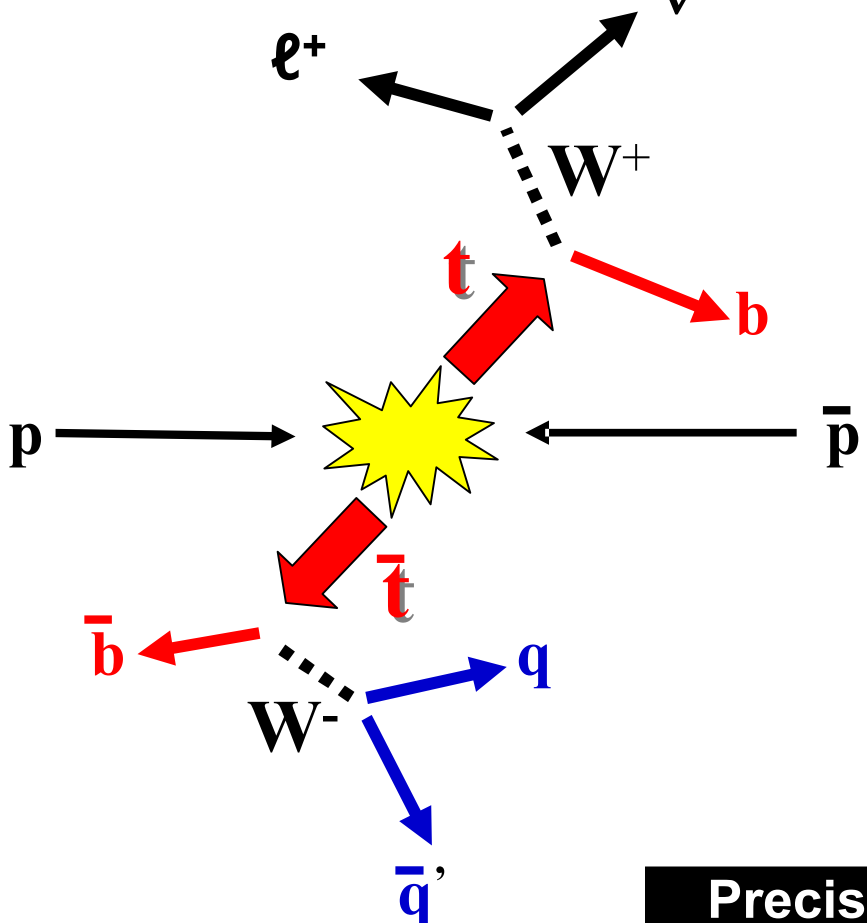


M_{ee} = 118 GeV/c^2 and $\sum E_T$ = 237 GeV

Transverse view (x-y plane) of collision debris (protons fly into/out of board +-z)
Initial p_x,p_y are zero, conservation of momentum implies final p_x, p_y are zero too
Unknown boost along z-direction due to collision of constituents of proton

Is this the standard model Top Quark?

Observed Top Quark Pair Production in all final states



Test Top Quark Pair Production

- Pair Production Rate
- New massive resonance $X \rightarrow tt$?
- Top spin
- Tests of NLO kinematics

Test Top Quark Decay

- Top always decays to $W^{+}b$?
- Any Charged Higgs from $t \rightarrow H^{+}b$?
- Top electric charge is +2/3?
- W helicity "right"?
- Anomalous FCNC $t \rightarrow Zc, gc, \gamma cb$?

Precision measurement of top quark mass

Co-leader of CDF Top quark physics group (22 papers 2004-2006)
Co-author of 2008 Annual Review of Nuclear and Particle Science article on Top-quark properties and Interactions

Top Quark Pair Production

Important to test:

- Anomalously high or low rate: is a new massive particle producing top quarks?
- Agreement between different final states: is top quark decay as expected?

Primary author of combination of CDF pair production measurements

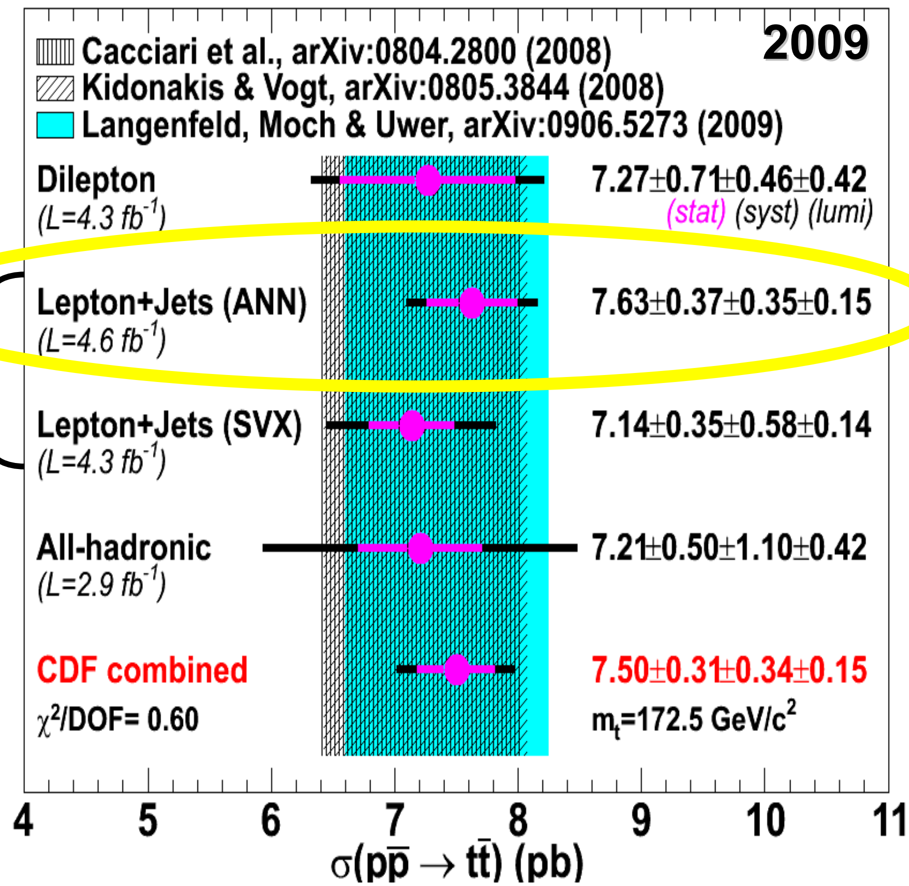
- 6% experimental precision compared to 10% precision of theory
- Good agreement across different final states and with predictions

Detected Final State

2 charged leptons

1 charged lepton

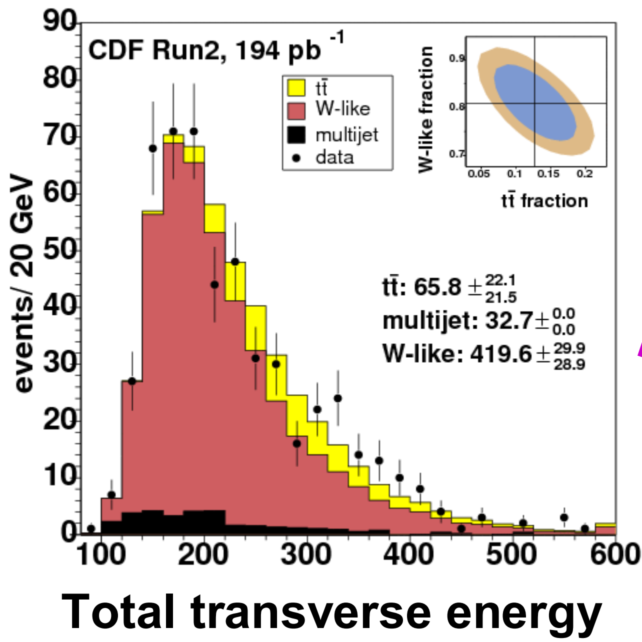
0 charged leptons

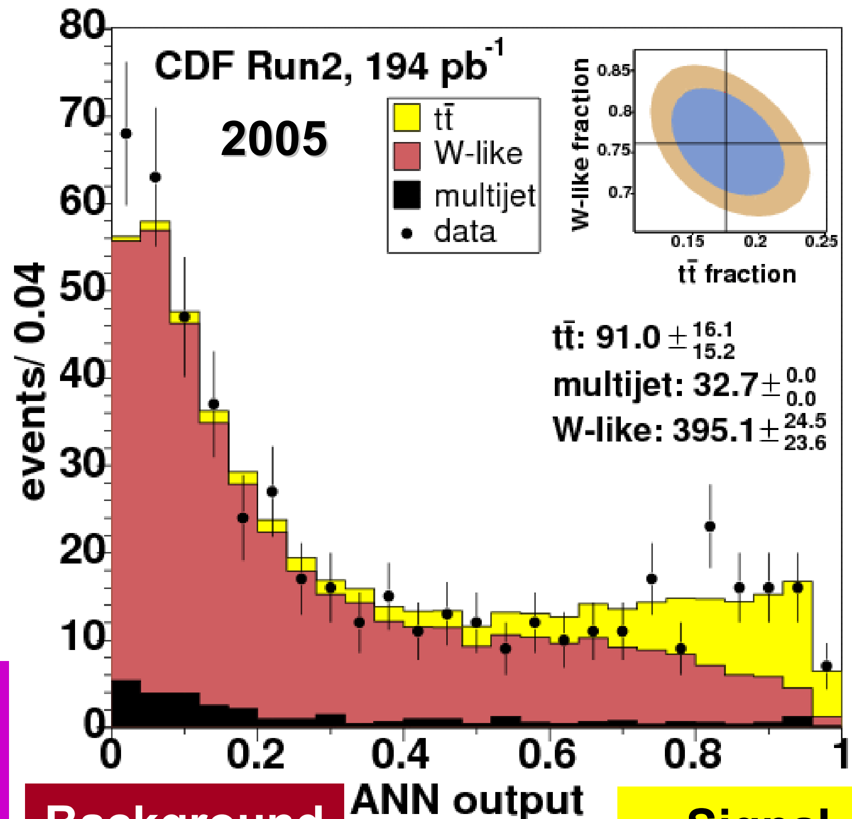


Top Quark Pair Production

Developed advanced technique to statistically separate top quark pair production from background

- Primary author of detailed paper in *Physical Review D 72, 052003 (2005)*
- Colleagues on CDF continue to apply it with 23 times more data, obtain best single measurement in 2009
- Several groups on future LHC experiments plan to use this method



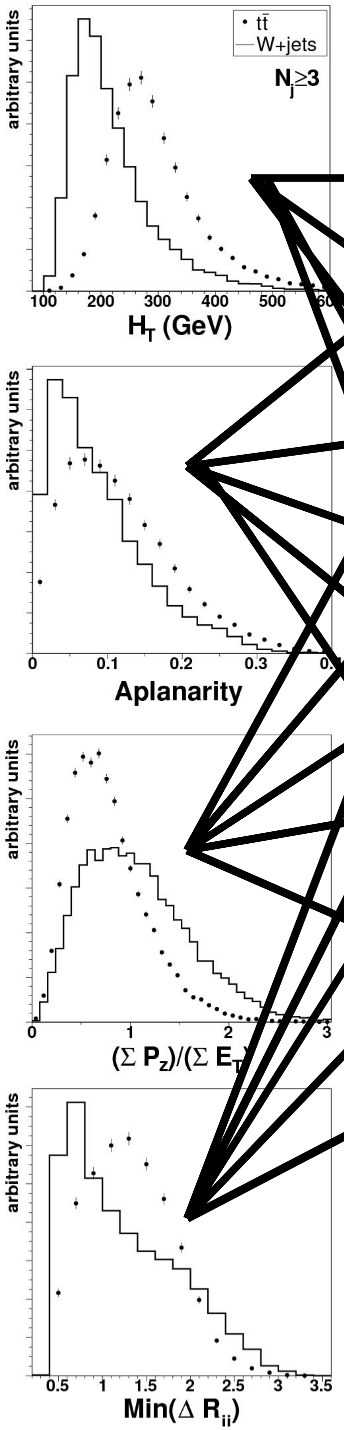


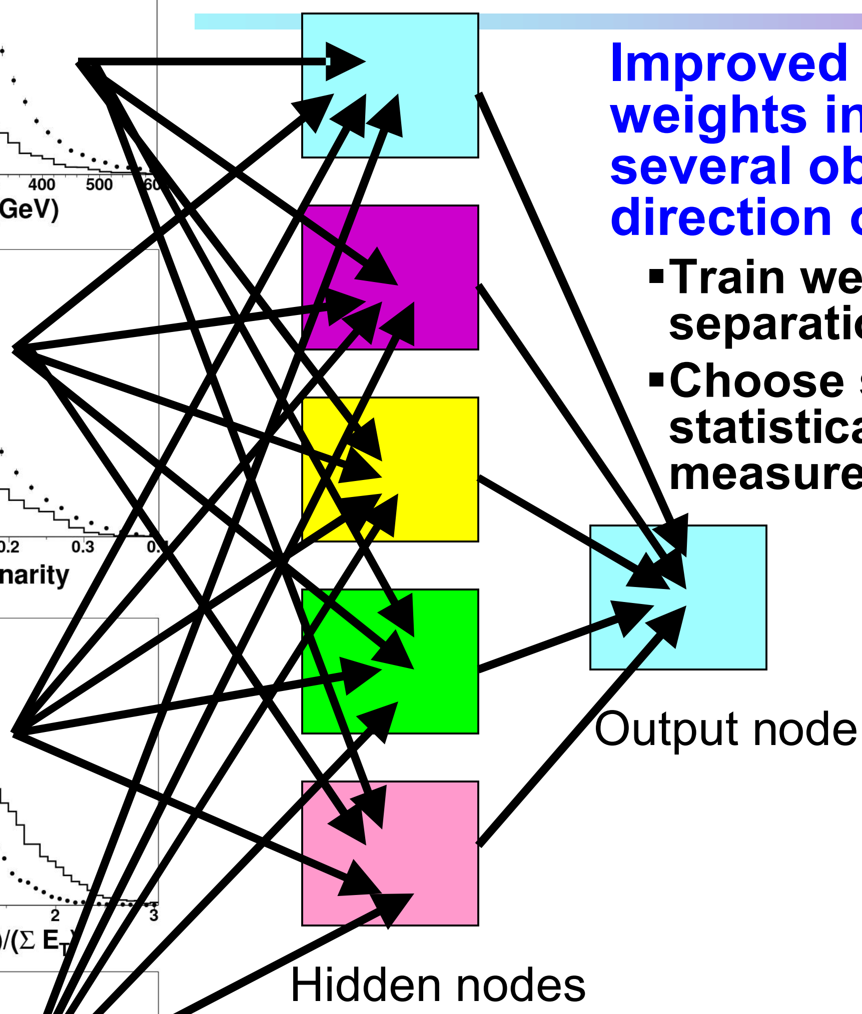
See big improvement in discrimination going from single observable to combination of 7 observables via artificial neural network (ANN)

Background dominated

Signal dominated

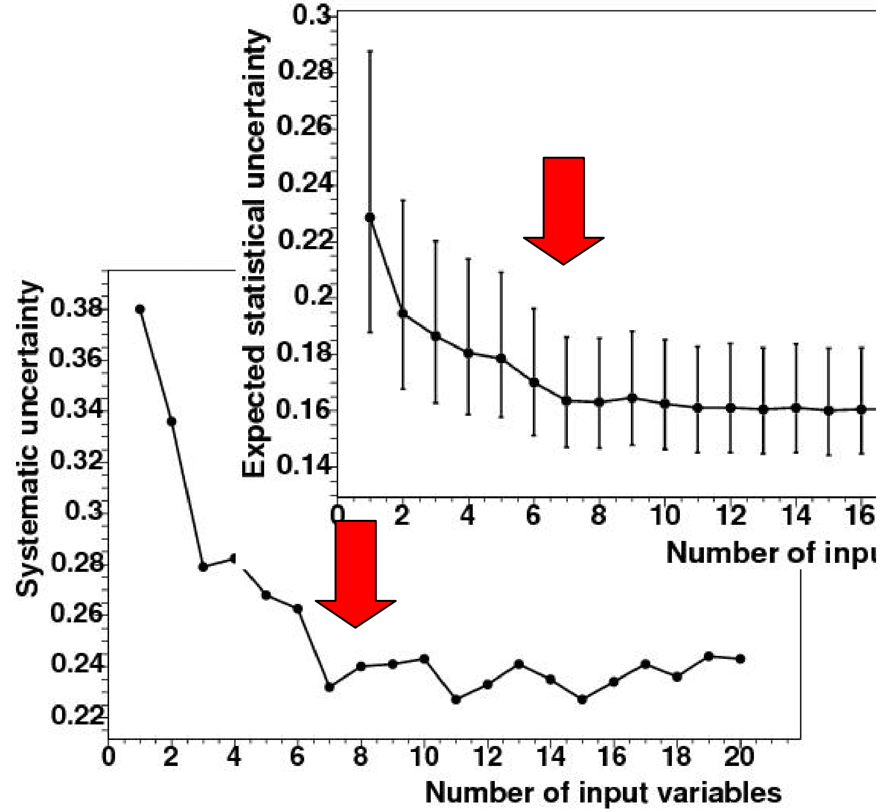
Artificial Neural Network





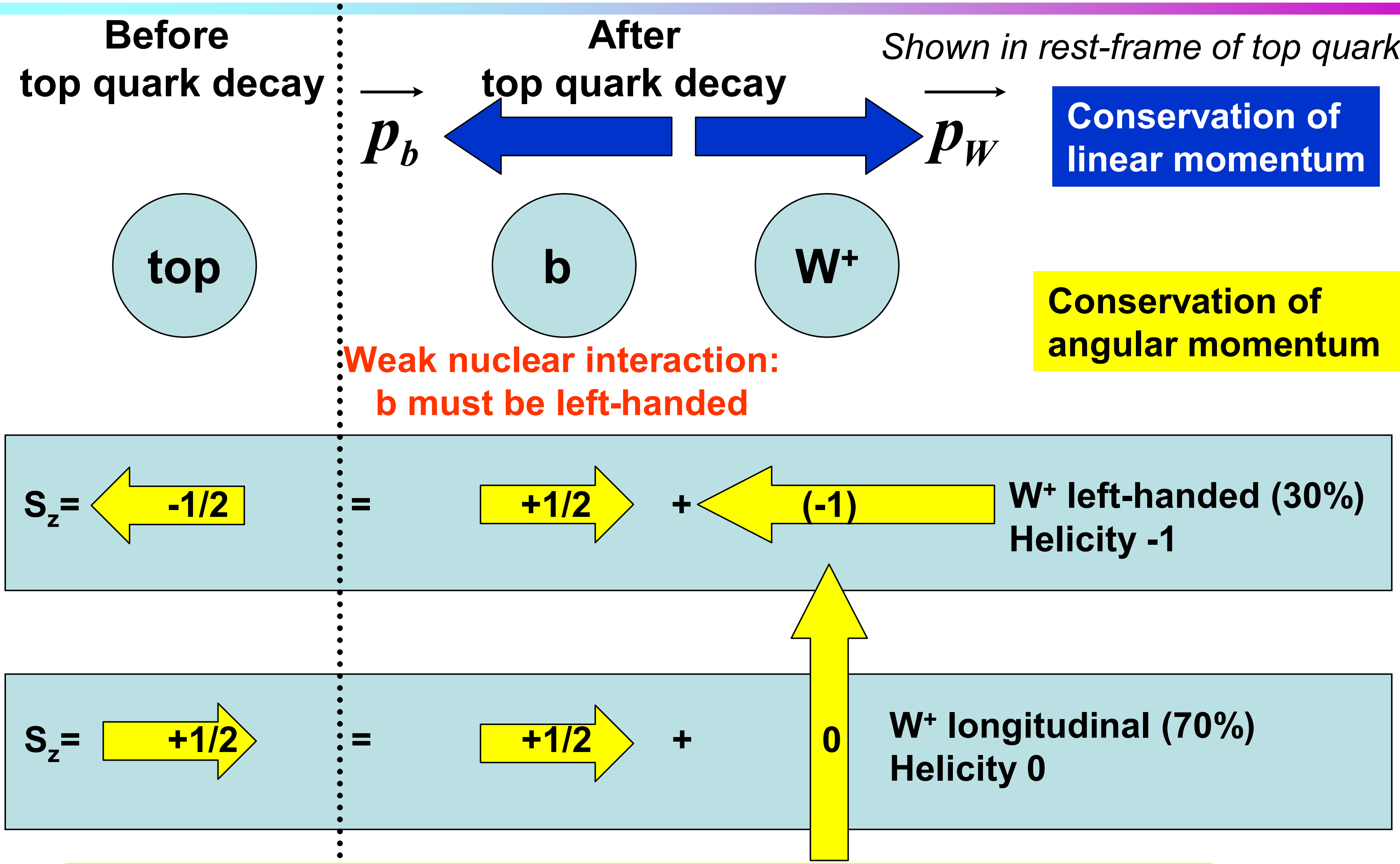
Improved discrimination by combining with weights in a network the information from several observables based on energy and direction of detected objects in final state

- **Train weights in network to maximize separation of signal and background**
- **Choose simplest network that minimizes statistical and systematic uncertainty on measurement of top quark pair production**



Hidden Node value
$=\sum_{inputs}$Weight_i * Input_i
Output Node value
$=\sum_{hidden}$Weight_j * Hidden_j

Top Quark Decay: Momentum Conservation & Top Explosions!



Yellow Arrows show projection of particle's spin vector onto axis defined by momentum vector of W^+ boson

Top Quark Decay: Result

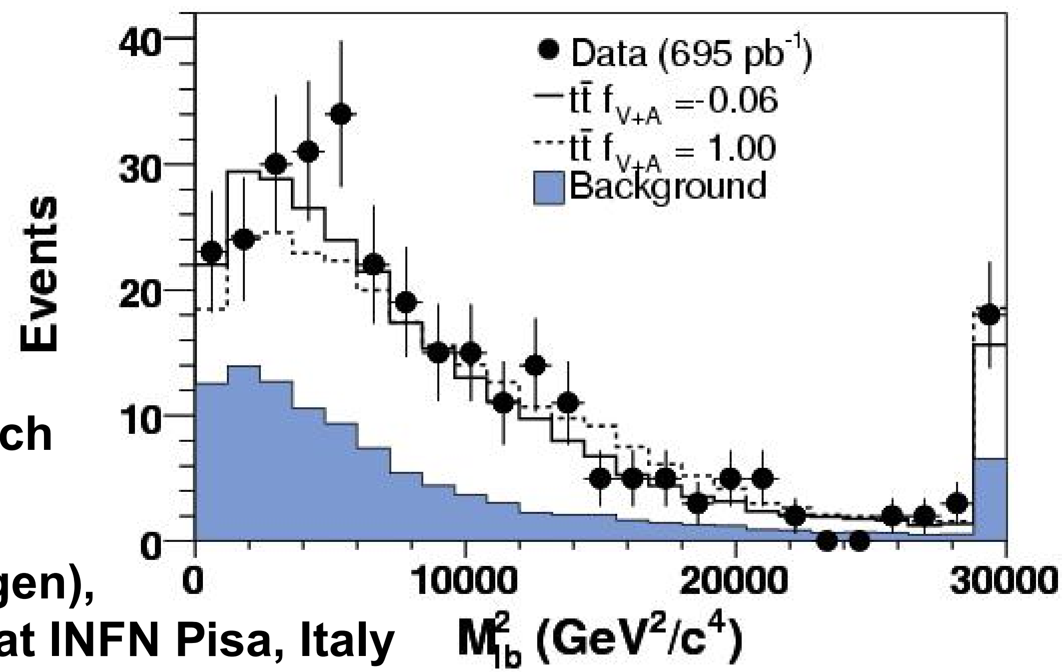
Experimental technique:

- Measure momenta of charged lepton and jet identified as b quark
- Invariant mass of lepton and jet is sensitive to W boson helicity

Data: see no evidence for right-handed W^+ boson helicity

- Set upper limit that fraction of right-handed W^+ boson is < 0.09
- Factor of two improvement on previous limit
- Primary author of *Phys. Rev. Lett. 98, 072001 (2007)*

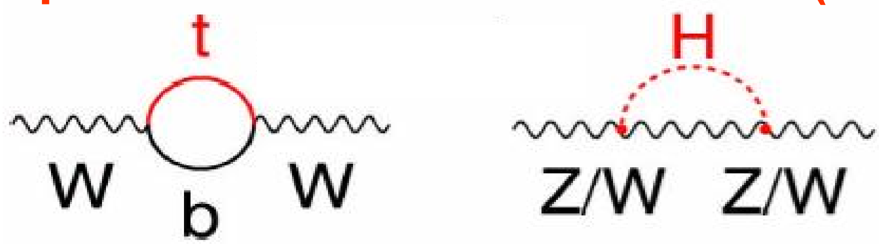
Dr. Joel Heinrich



Dr. Aafke Kraan (PhD NBI Copenhagen), advanced to EU Marie Curie Fellow at INFN Pisa, Italy

What else can studies of the top quark tell us?

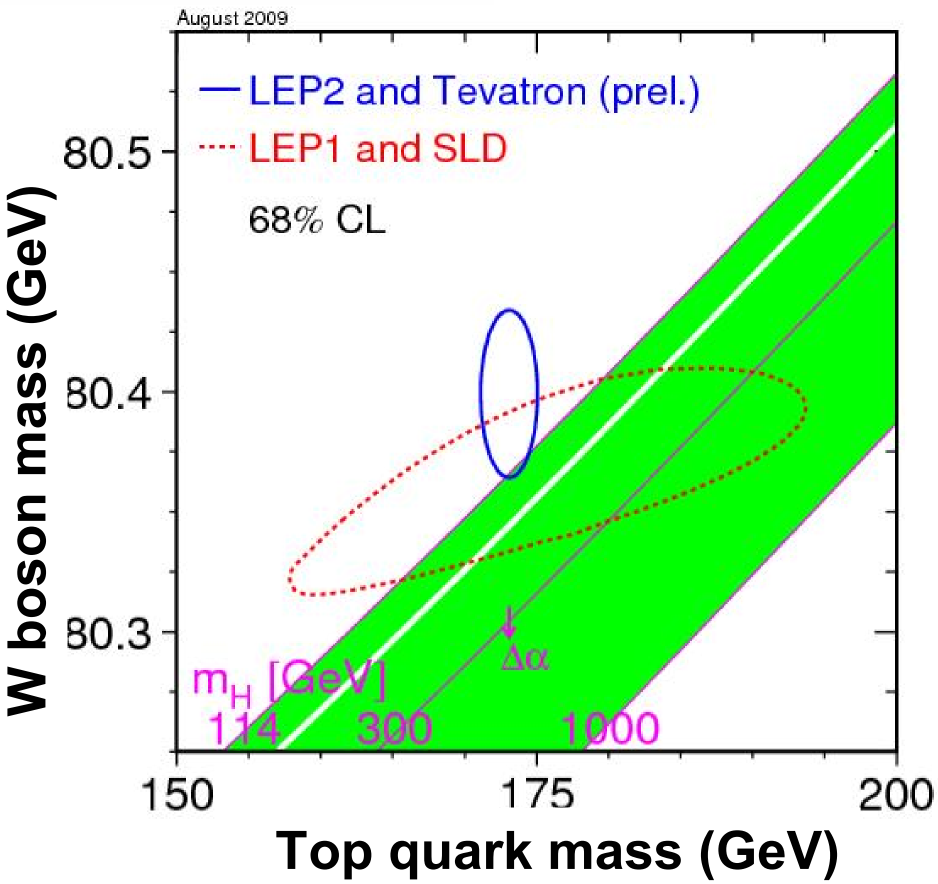
Answer: the most probable mass range to hunt for the Higgs boson, the most elusive particle in the standard model (40+ years search!)



Experimental confirmation that top quark behaves as expected

- **Validates using measurement of top quark mass to compute quantum loop corrections**
- **Constrains size of other corrections from only undiscovered particle in standard model: Higgs boson mass < 157 GeV @ 95% CL**

Quite astonishing that virtual particles have real effects on measured mass!



Synopsis of Higgs Saga

Highest priority question in particle physics is experimentally proven explanation for origin of electroweak symmetry breaking

- Electromagnetic force carrier (photon) massless
- Weak force carriers (W and Z) massive

Higgs is one explanation

Higgs is a scalar particle (spin-0 boson)

Higgs couples to mass

- Important implications for how it is produced and decays

Mass of Higgs itself is not predicted by theory

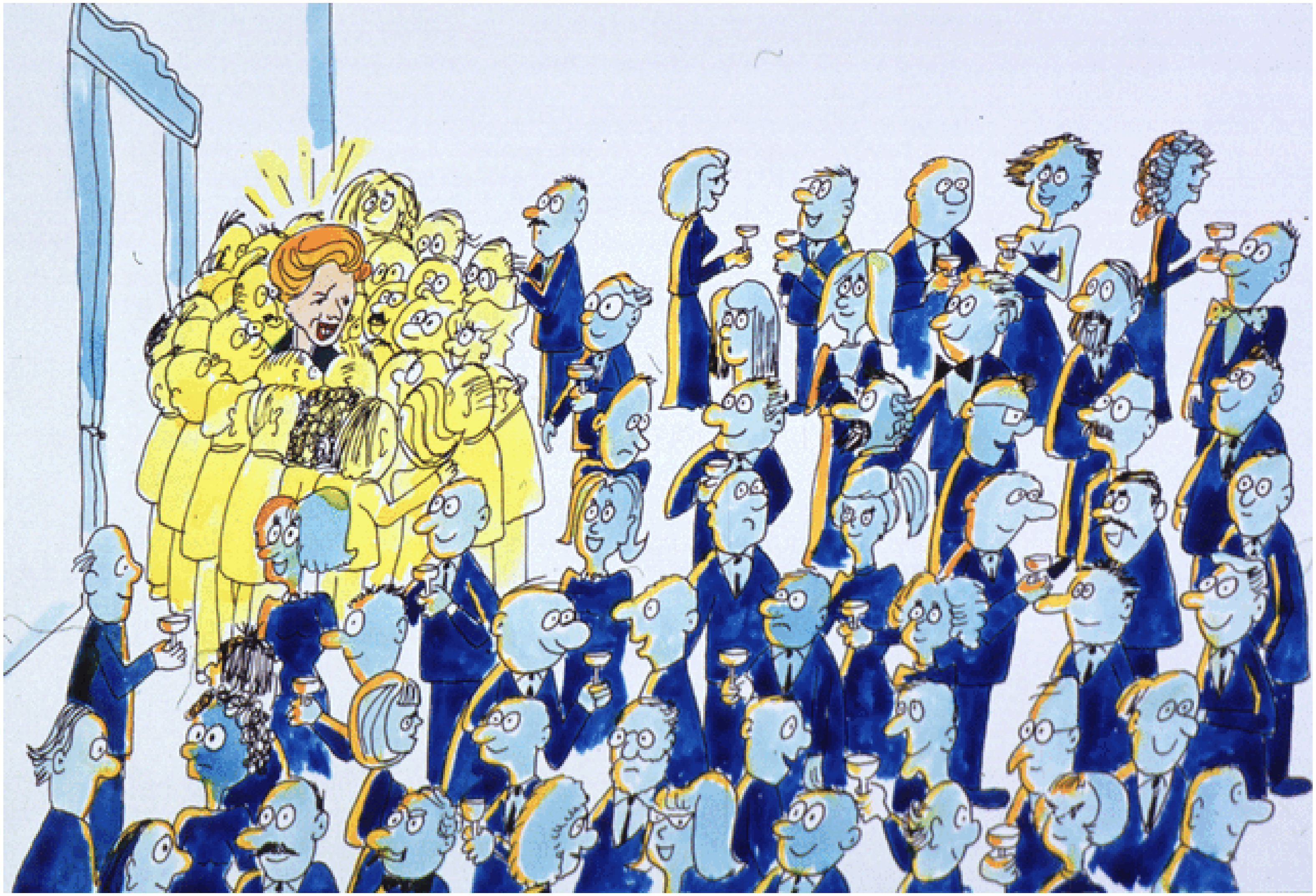
- In 2000, experiments excluded mass < 114 GeV
- In 2009, Fermilab excluded mass in range 160-170 GeV
- In 2009, precision measurements say mass < 157 GeV

The 40+ year search will conclude in next few years

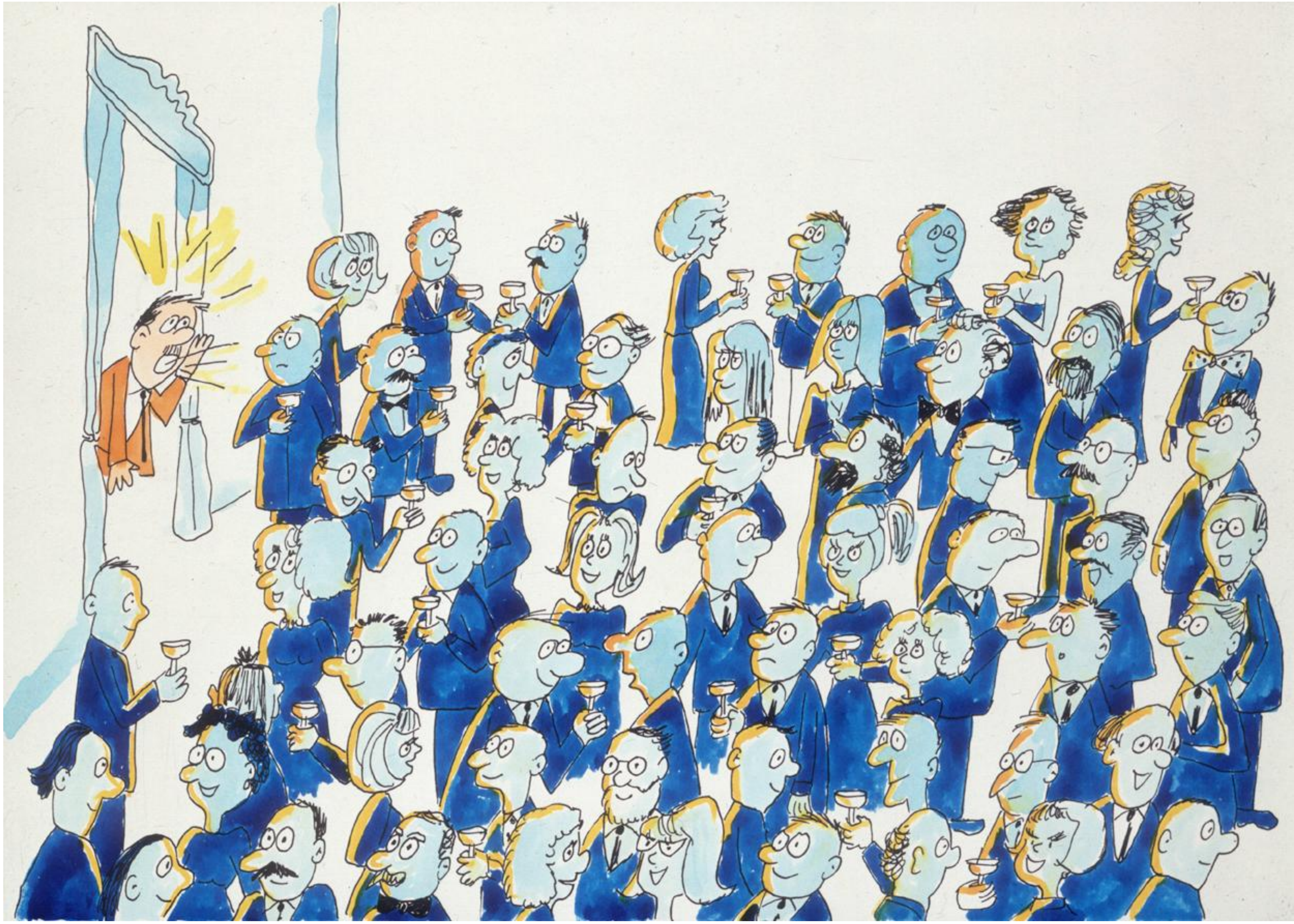
- exclude at FermilabTevatron
- discover at CERN LHC

Vacuum is like a room full of politicians (Higgs field) at a cocktail party

A famous politician (W boson) walks into the room, interacts with other politicians (Higgs field) and gains mass!

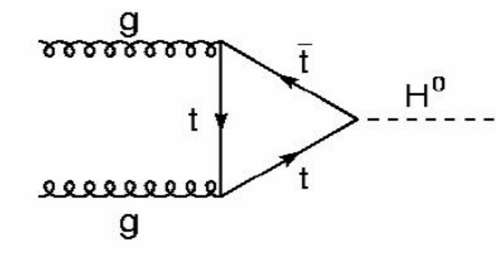


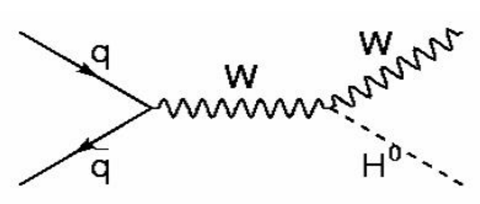
What is Higgs boson? Imagine someone whispers a rumour…

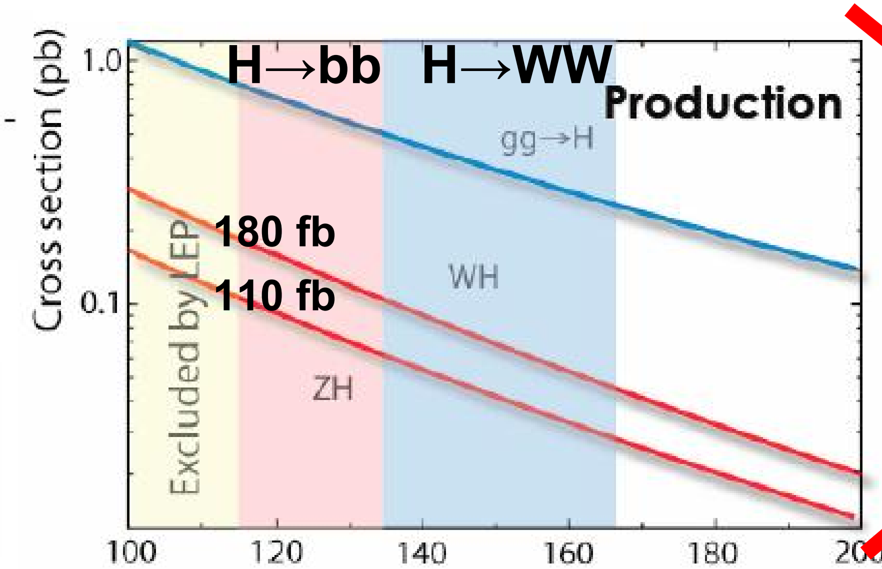


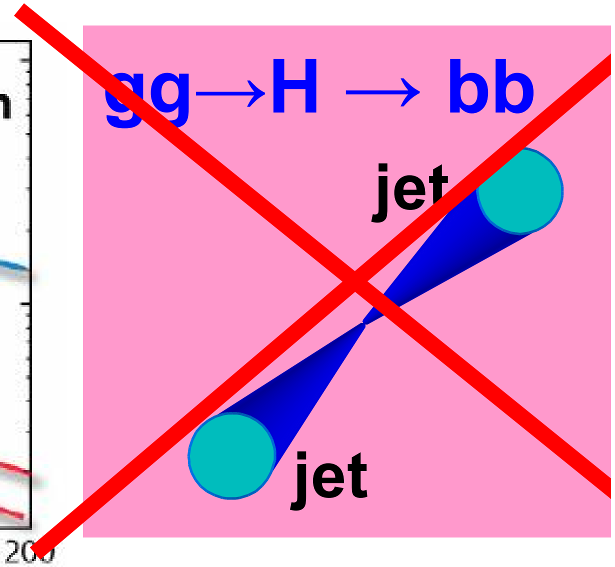
Rumour crosses room…
rumour is like Higgs boson

Higgs search at low masses: m_H 115-135 GeV



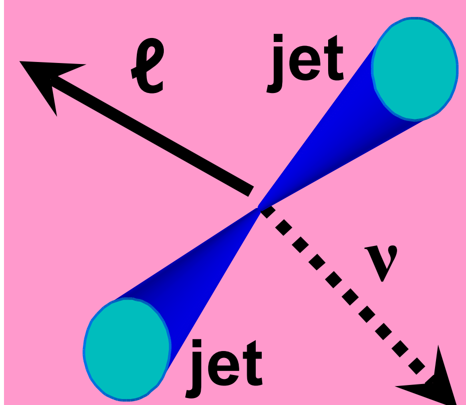






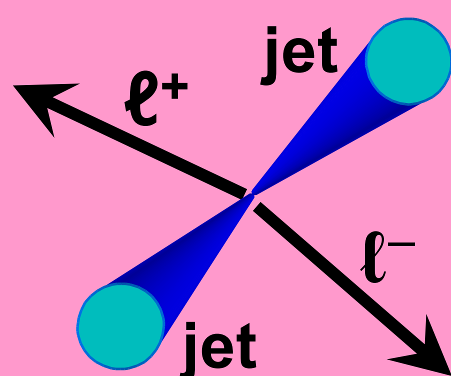
WH →ℓ⁺ν bb 42 fb

Wjj background



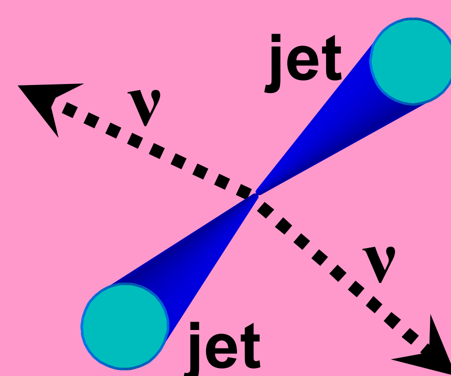
ZH →ℓ⁺ℓ⁻ bb 7 fb

Zjj, tt backgrounds



ZH → νν bb 16 fb

QCD background

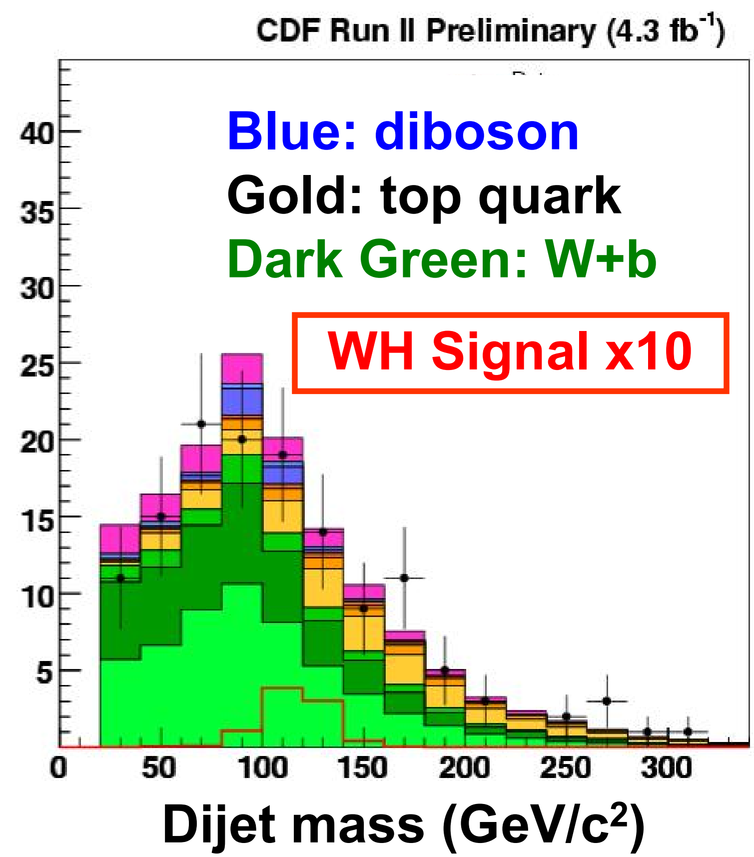


Improving the Higgs search: m_H 115-135 GeV

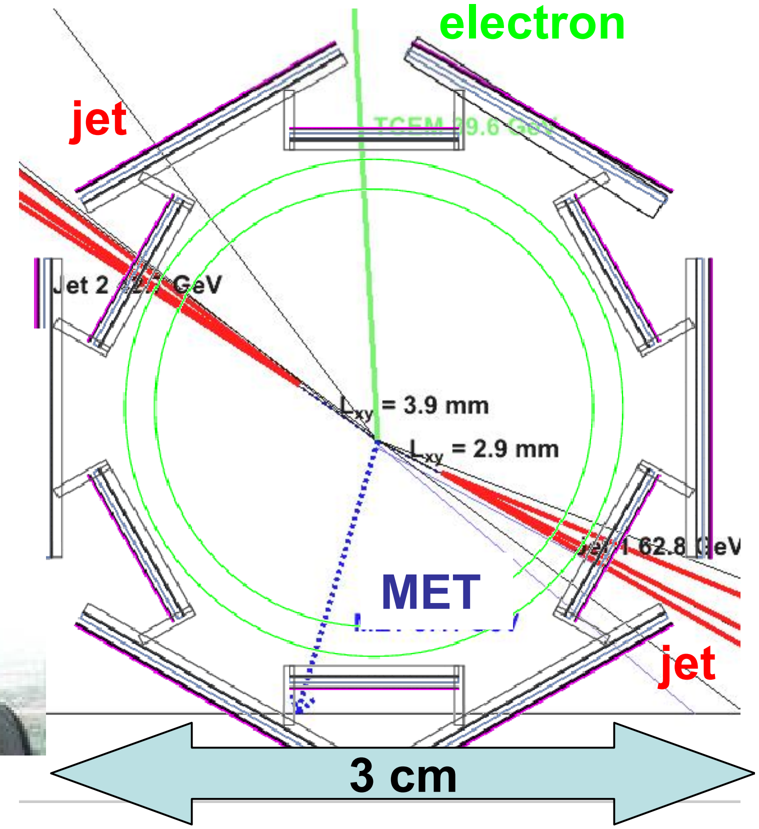
To exclude, need to collect 3x data or improve search performance by 50%

We increased b-jet identification efficiency

- Added 20% more signal to best signal-to-background region for √1.2 improvement in search performance in summer 2009



Penn Fall 2005



Test search technique by observing standard model WZ with Z→bb

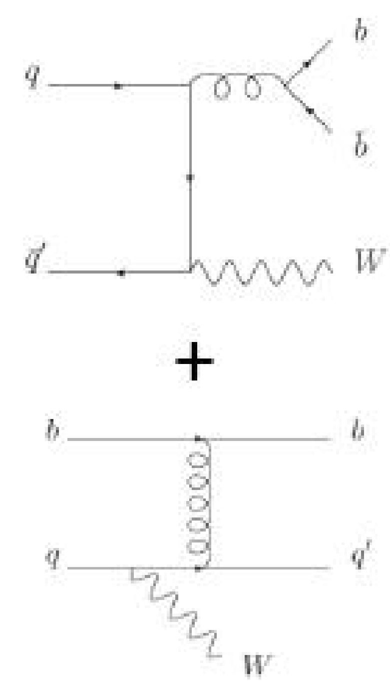
Improve model of dominant background from W boson & b jet production

- Uncertainty on W boson & b jets is 30-40%, this is 10x size of WH signal!

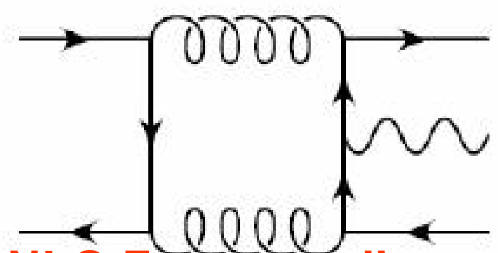
W boson & b jets: theory

Why is the theoretical calculation so difficult?

- Poor convergence in perturbation expansion due to large value of coupling constant for the strong interaction
  - leading-order (LO) picks up 35% correction at next-to-leading-order (NLO)
- NLO has large number of Feynman diagrams
- b-quark mass important as cuts off divergence of calculation for soft or collinear radiation
- Recent theory papers addressing these important issues for first time
  - 2006 Cordero, Reina, Wackeroth
    PRD 74, 034007
  - 2007 Campbell, Ellis, Maltoni, Willenbrock
    PRD 75, 054015
  - 2009 Campbell, Ellis, Cordero, Maltoni, Reina, Wackeroth, Willenbrock
    PRD 79, 034023



Leading Order



1 NLO Feynman diagram

W boson & b jets: experiment

Experimentally challenging since two main backgrounds not well-predicted either!!

- W boson & jets is 100 times more common; misidentified as b jet
- W boson & charm has significant lifetime: misidentified as b jet

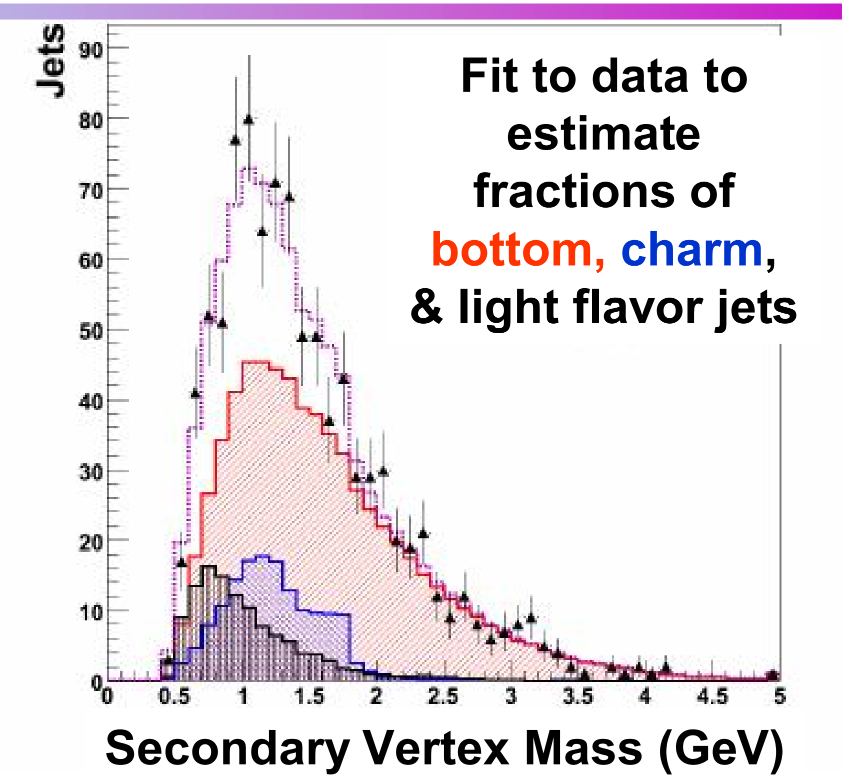
Keystone to measurement:

- Use data to subtract contribution from these charm & light flavor backgrounds
- Only use theory for well-predicted backgrounds like top quark

Primary author of first measurement of total rate, better than 20% precision

- 2.74 ± 0.27 (stat) ± 0.42 (syst) pb
- Submitted to PRL arXiv.0909.1505
- Twice size of NLO prediction!

Work in progress: extend to measurement of differential rates



Dr. Chris Neu (PhD Ohio State) celebrating tenure-track professorship at University of Virginia

Outline

✓Introduction

✓Measurements of top quark properties: the study of the most massive fundamental particle

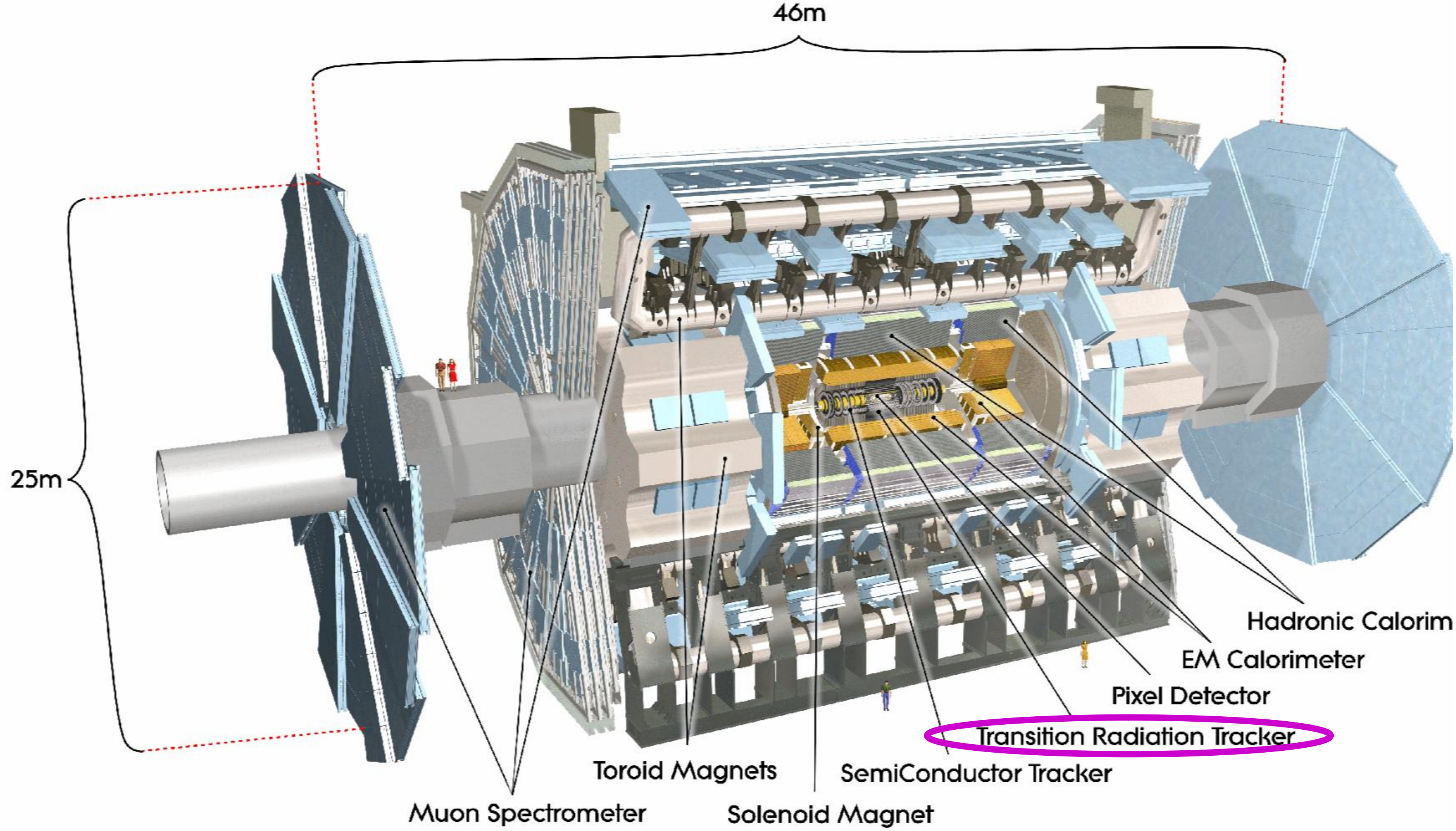
✓Search for the Higgs boson: the hunt for the most elusive fundamental particle

Commissioning of the ATLAS experiment: looking forward to a giant expansion of the high energy frontier

Conclusions

Giant ATLAS experiment

2500 scientists from over 160 universities and labs around the world

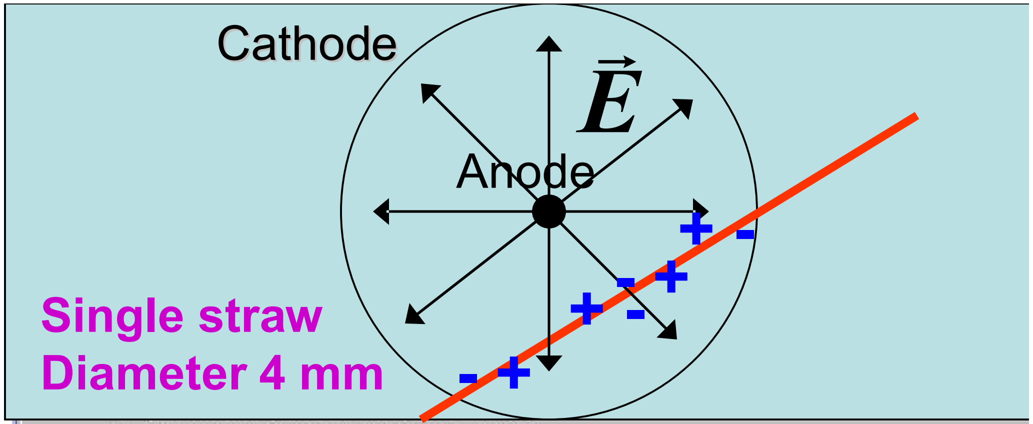


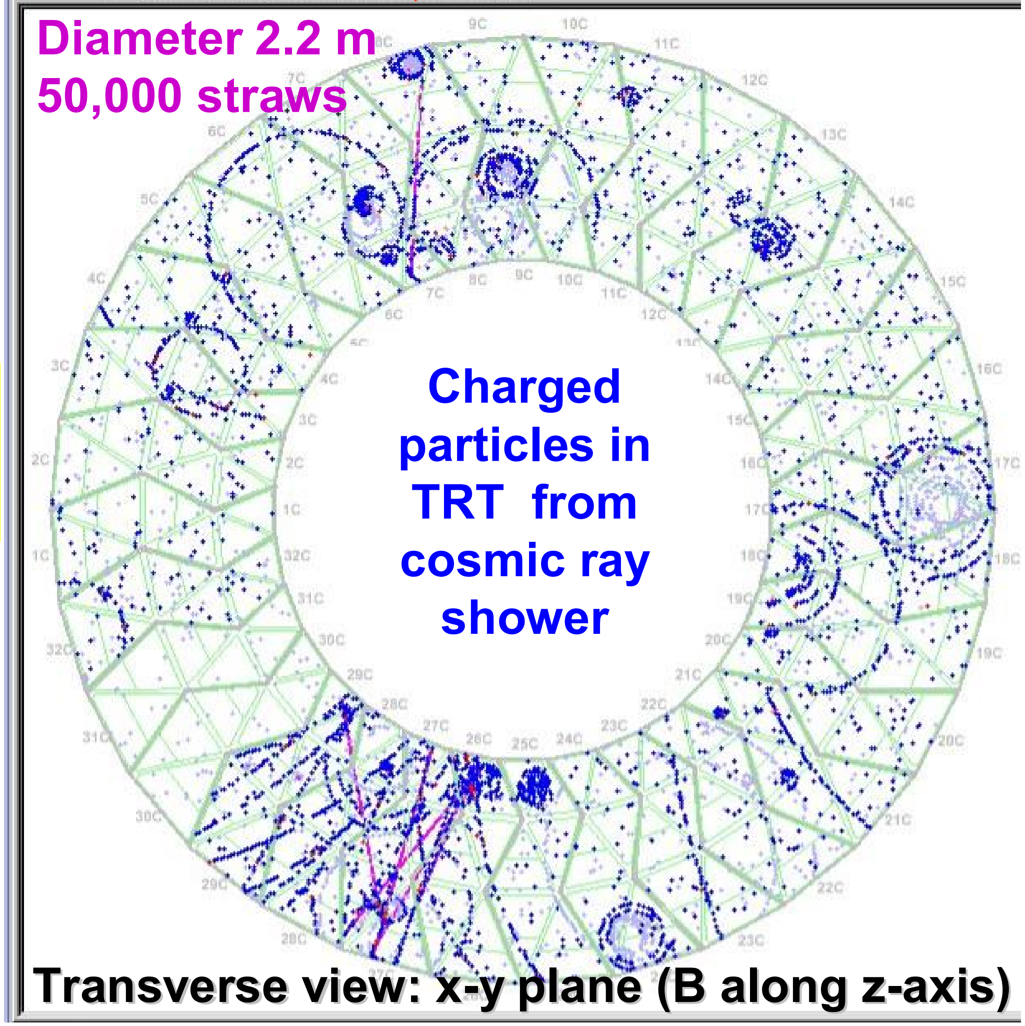
TRT: Transition Radiation Tracker

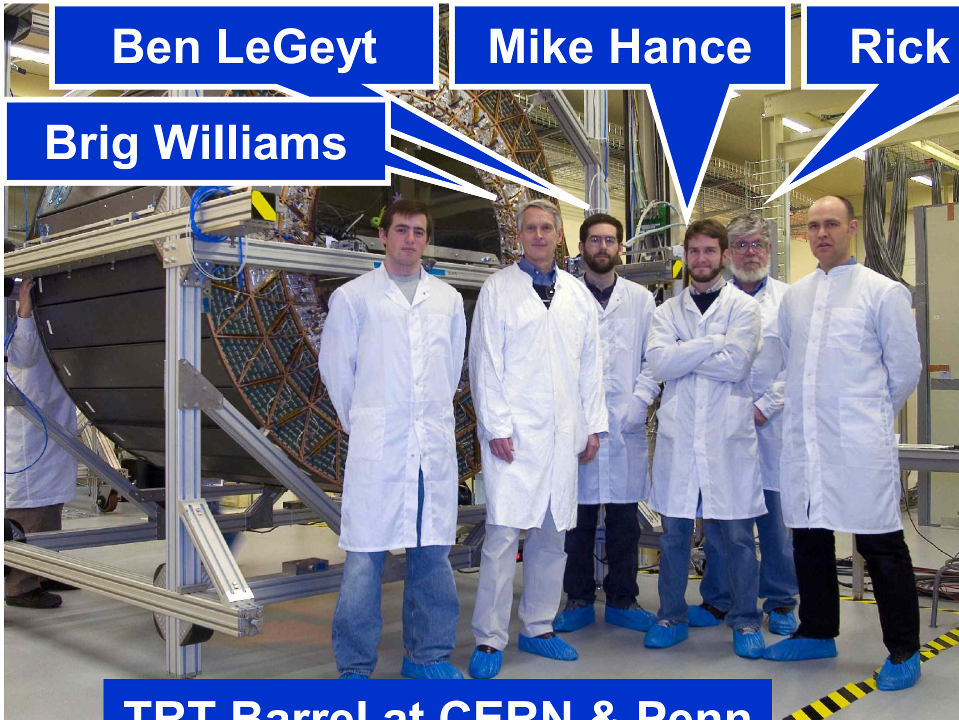
- Reconstruct trajectory of charged particles (tracks), which pass through gas-filled straws and lose energy by ionization of gas molecules, creating clusters of ions and electrons. Max drift time to anode is 60 nano-seconds. Position resolution 130 μm.

$$\vec{F} = q\vec{v} \times \vec{B} = m\frac{v^2}{R} \text{ so } p_T = qRB_z$$

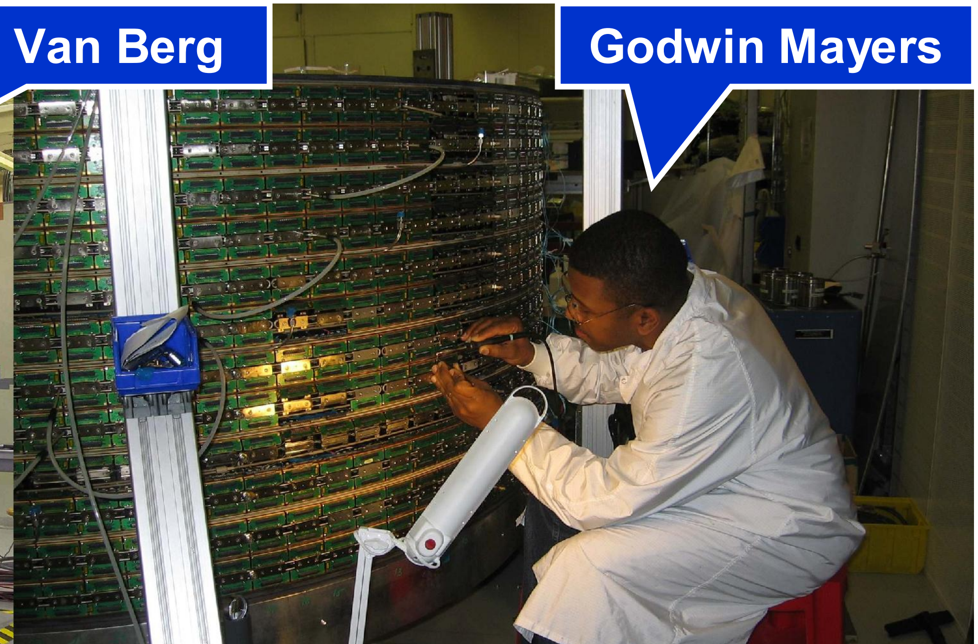
- Particle identification: electrons pass through foil between straws, radiate X-rays due to transition between different materials. X-rays are absorbed by Xenon gas to give 100 times higher signal.







TRT Barrel at CERN & Penn



TRT Endcap undergoing delicate repairs

My group benefits greatly from experience & huge contribution to ATLAS since 1994 by Penn's

Brig Williams
Rick Van Berg
Mitch Newcomer

& high energy electronics instrumentation group:

Paul Keener, Godwin Mayers, Nandor Dressnandt, Mike Reilly, Walt Kononenko, Ben LeGeyt

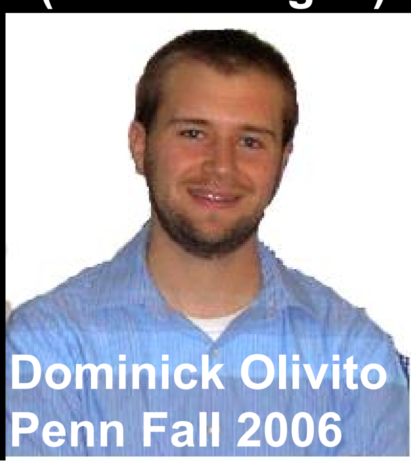
TRT Barrel during 2006 installation at CERN

TRT Data Quality & Operation

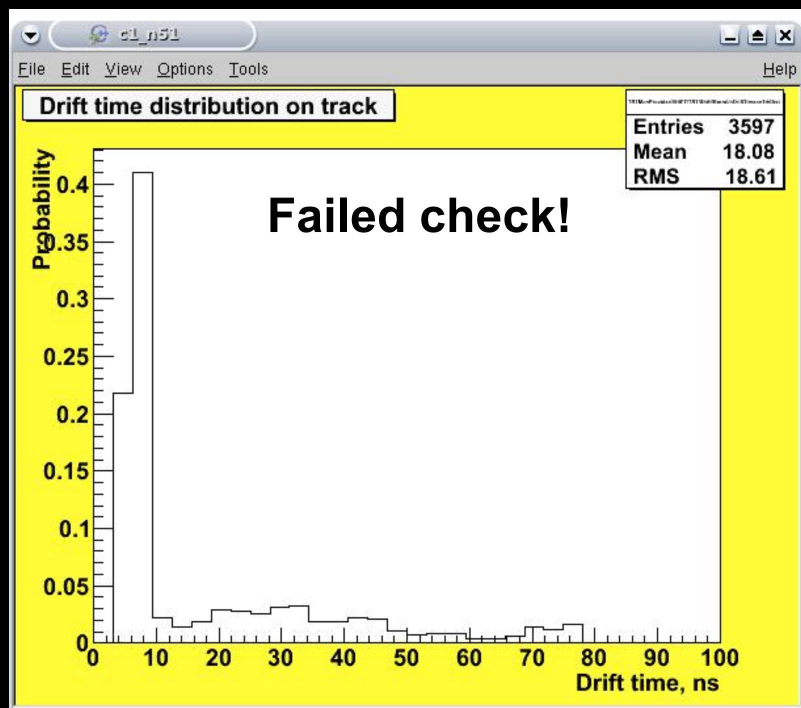
Primary responsibilities of my group:

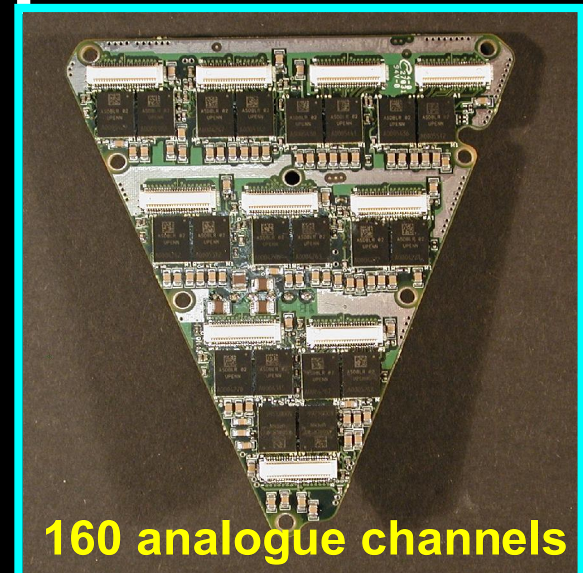
- Data quality software to automatically check performance of 350,000 electronic channels
- Operation & commissioning of detector (Degenhardt deputy leader 2009-2010)

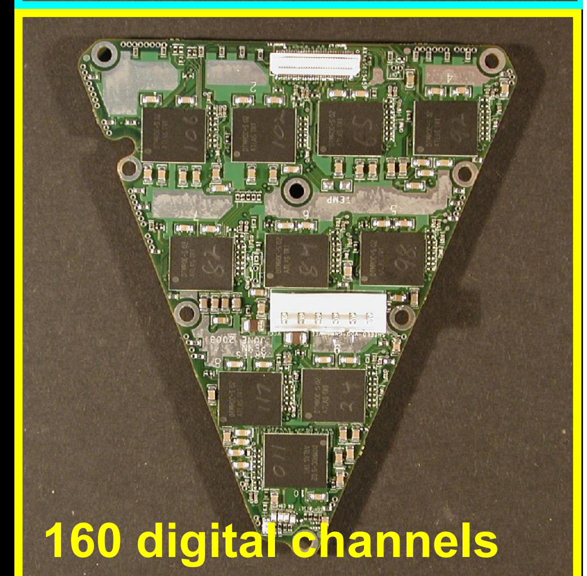
Dr. Jim Degenhardt
(PhD Michigan)



Dominick Olivito
Penn Fall 2006







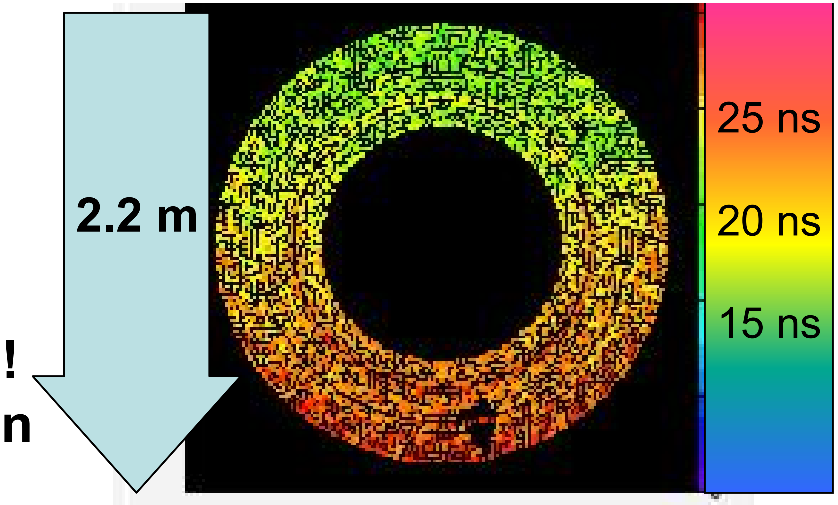
Penn Instrumentation Group: Double-sided Electronics!
Analogue fC signal (Amplifier/shaper/discriminator/baseline)
Ternary Digital output every 3.125 ns above low/high threshold

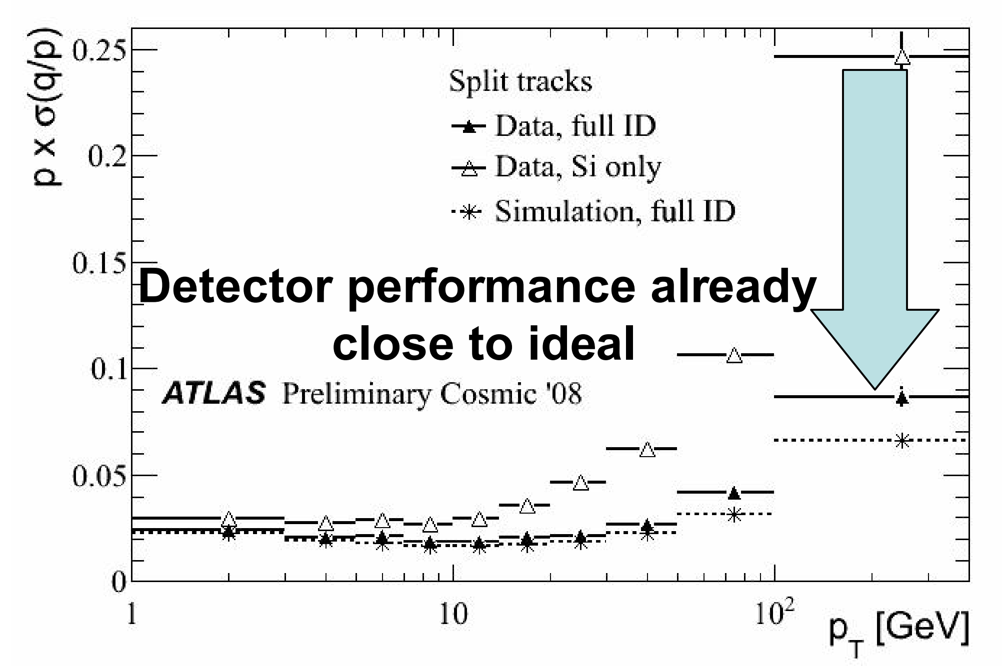
TRT Performance and Calibration

Primary responsibilities of my group:

- Performance and calibration (Fratina data analysis group leader 2009-2010)
  - 24-hour turn-around on calibrations
- Synchronization of TRT read-out for 350,000 channels to better than 1 ns
  - Clearly see 7 ns time-of-flight for cosmic ray muons flying downwards!
  - Helping synchronize rest of ATLAS in preparation for first collisions
- Plan to study transition radiation and particle identification with electrons in first LHC collisions

Time muon passed TRT straw





Conclusions

Measurements of top quark properties:

Production and decay in agreement with expectations

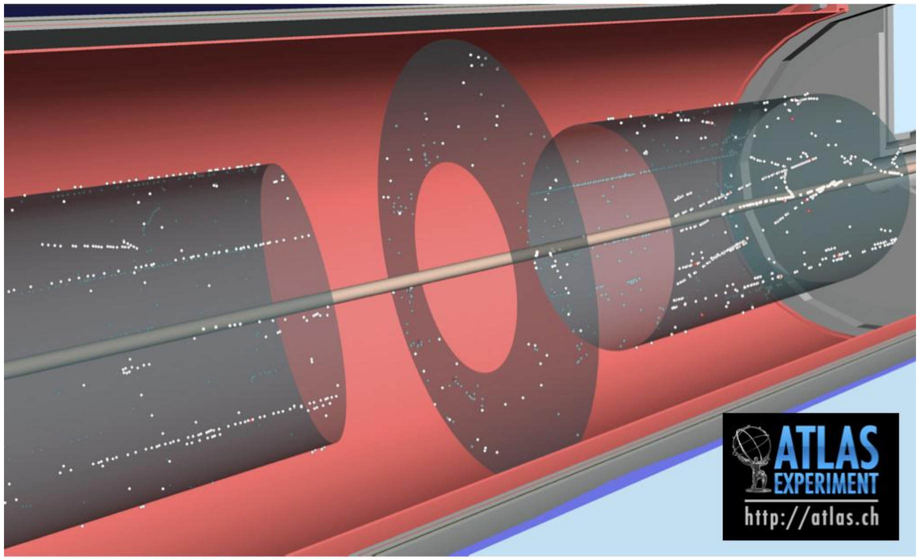
Search for the Higgs boson:

Can exclude in next few years at Fermilab Tevatron

Commissioning of the giant ATLAS experiment:

Cosmic ray data put to good use to commission detector

Looking forward to lots of physics analysis with data from proton collisions at highest energies ever in lab…and celebrating discoveries!



beam halo event seen in ATLAS