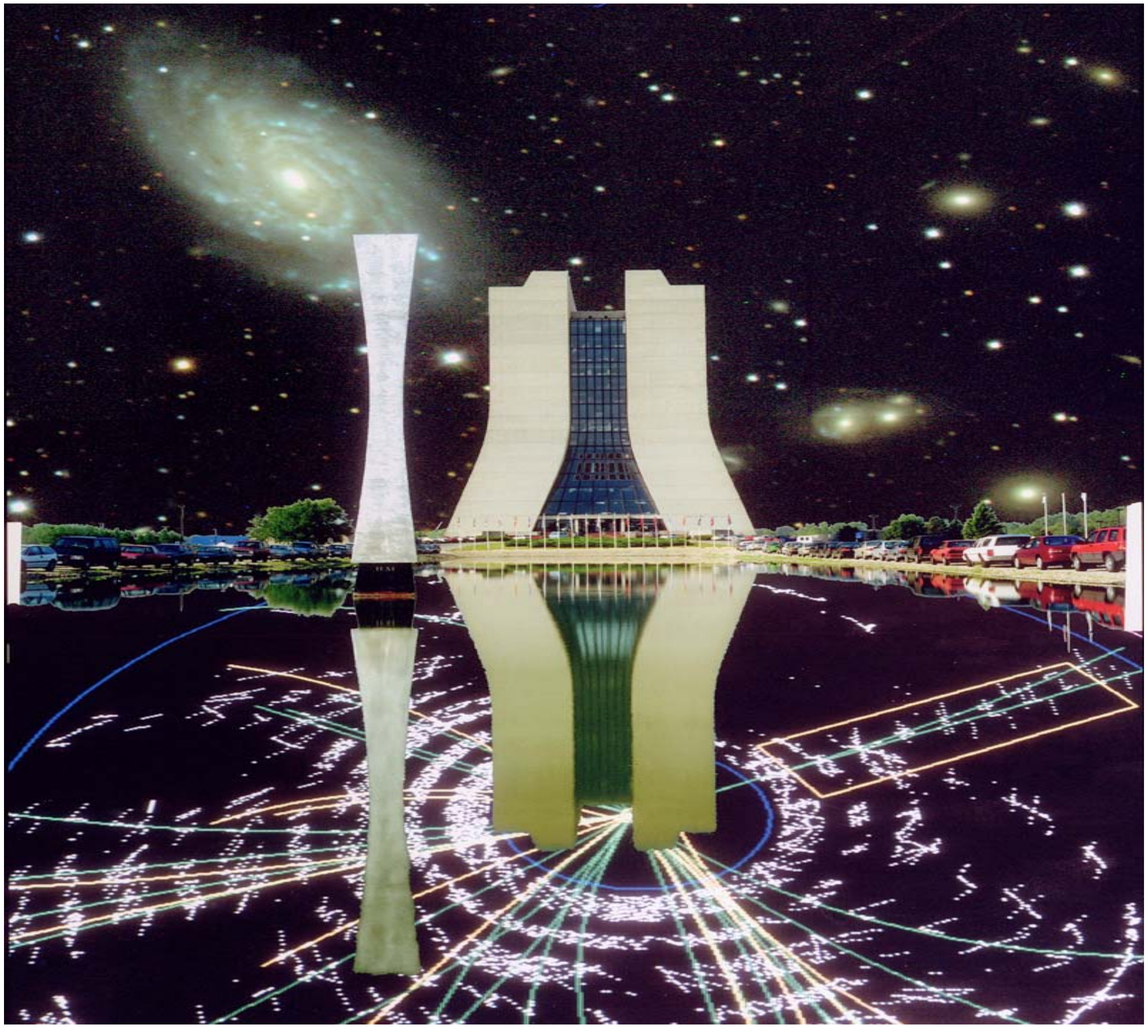
Exploring the Higgs Sector of the Standard Model

Ashutosh Kotwal



Graduate Research Seminar
1 December 2010

Spontaneous Symmetry Breaking

- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

Yoichiro Nambu

- Experimentally, jury is still out on Higgs mechanism of Electroweak Symmetry Breaking in the Standard Model of Particle Physics

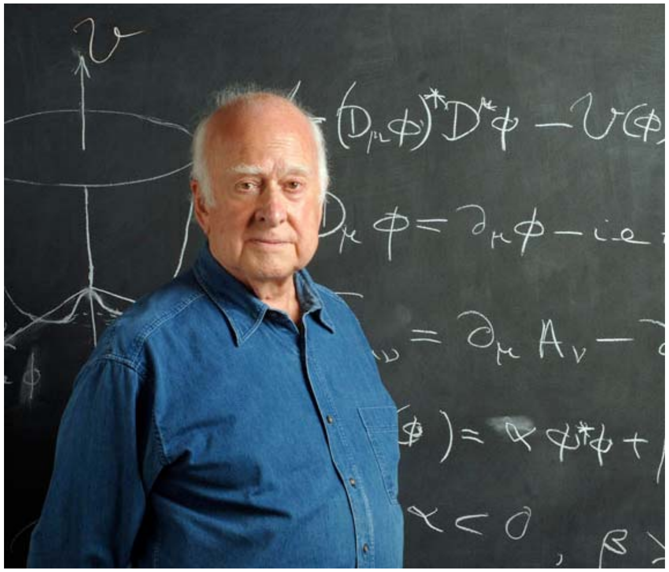
Outline

- Standard Model of Particle Physics – how did we get here?

- Why is the Higgs mechanism so important to confirm?

- How my research is related to investigations of the Higgs mechanism
  - Checking the consistency of the Higgs mechanism using precise measurements of Standard Model parameters
    - W boson mass
    - Top quark mass
  - Direct search for the Higgs boson
- Physics beyond Higgs – extra dimensional Gravity

Peter Higgs

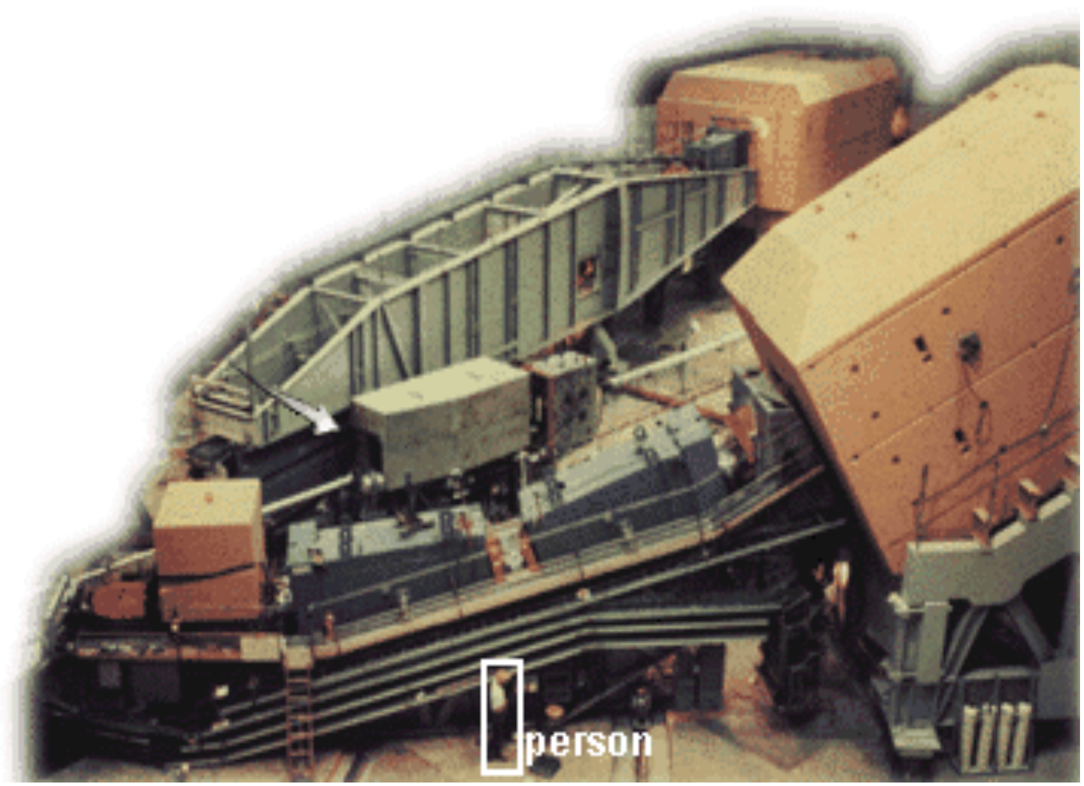


Search for New Symmetries Beyond Standard Model

- Theories of unification of forces predict new force-mediating particles
- Heavy graviton states in extra-dimensional theories of gravity
  - PRL 102, 091805 (2009)
- Larger fermionic representations → exotic fermion states
  - Exotic electron states (H. Gerberich Ph.D.): PRL 94, 101802 (2005)
  - Exotic muon states (E. Daverman, undergrad): PRL 97, 191802 (2006)
- Spontaneous symmetry breaking of parity in the weak interaction
  - Doubly charged particles (J. Tuttle M.Sc): PRL 95, 071801 (2005)

A Century of Particle Physics: Standard Model

- Quark constituents of nucleons established in high energy electron scattering experiments at Stanford Linear Accelerator Center (SLAC), 1966-1978
  - Point-like particles explain high scattering rate at large energy and angle



A Century of Particle Physics: Standard Model

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental matter particles (and their antimatter counterparts) fit neatly into an elegant mathematical framework

pattern of masses
not fully understood

Quarks

u < 1 GeV	c ~ 1.5 GeV	t ~ 175 GeV
d < 1 GeV	s < 1 GeV	b ~ 4.5 GeV

Leptons

$\nu_e < 1$ eV	$\nu_\mu < 0.17$ MeV	$\nu_\tau < 24$ MeV
e 0.5 MeV	μ 106 MeV	τ 1.8 GeV

A Century of Particle Physics: Standard Model

- The "charm quark" (*c*) discovered at SLAC in 1974
- The heaviest lepton, "τ" was also discovered at SLAC in 1975

A Century of Particle Physics: Standard Model

- The heaviest "top quark" (*t*) discovered at Fermilab in 1995

- The next heaviest, "bottom quark" (*b*) was also discovered at Fermilab in 1977

- Appearance of τ lepton in ν_τ beam established at Fermilab

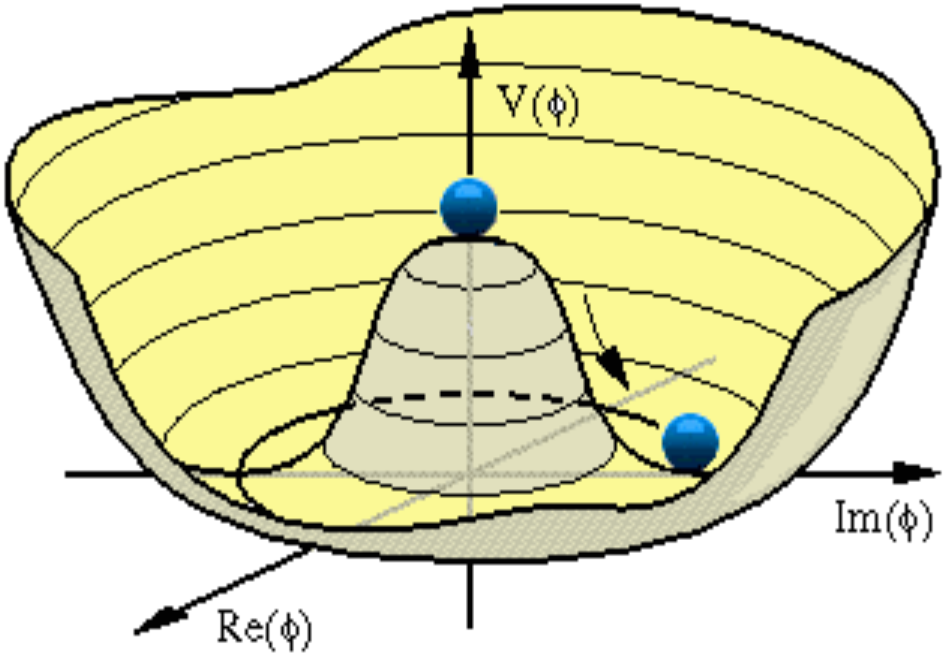
A Century of Particle Physics: Standard Model

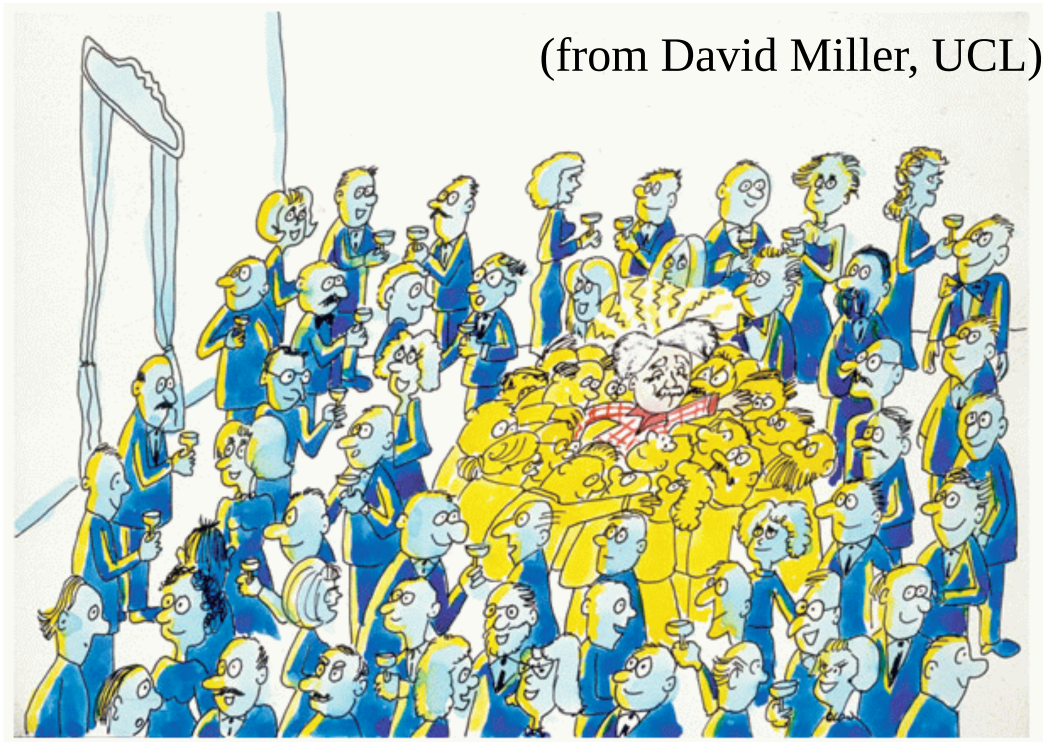
- Success # 2: gauge invariance predicts the properties of fundamental forces
  - matter particles (quarks and leptons) transform in internal spaces
    - Electroweak: SU(2) x U(1)
    - QCD: SU(3)

- Analogous to the Coriolis and Centrifugal forces generated in rotating frames of reference

The "Problem", thus Excitement, of Particle Physics

- As generators of gauge transformations, gauge bosons should be massless
  - Obviously not true in nature for weak interaction
  - W and Z gauge bosons very massive (W ~ 80 GeV, Z ~ 91 GeV)
- Unconfirmed postulate of scalar Higgs field which develops a vacuum expectation value via spontaneous symmetry breaking



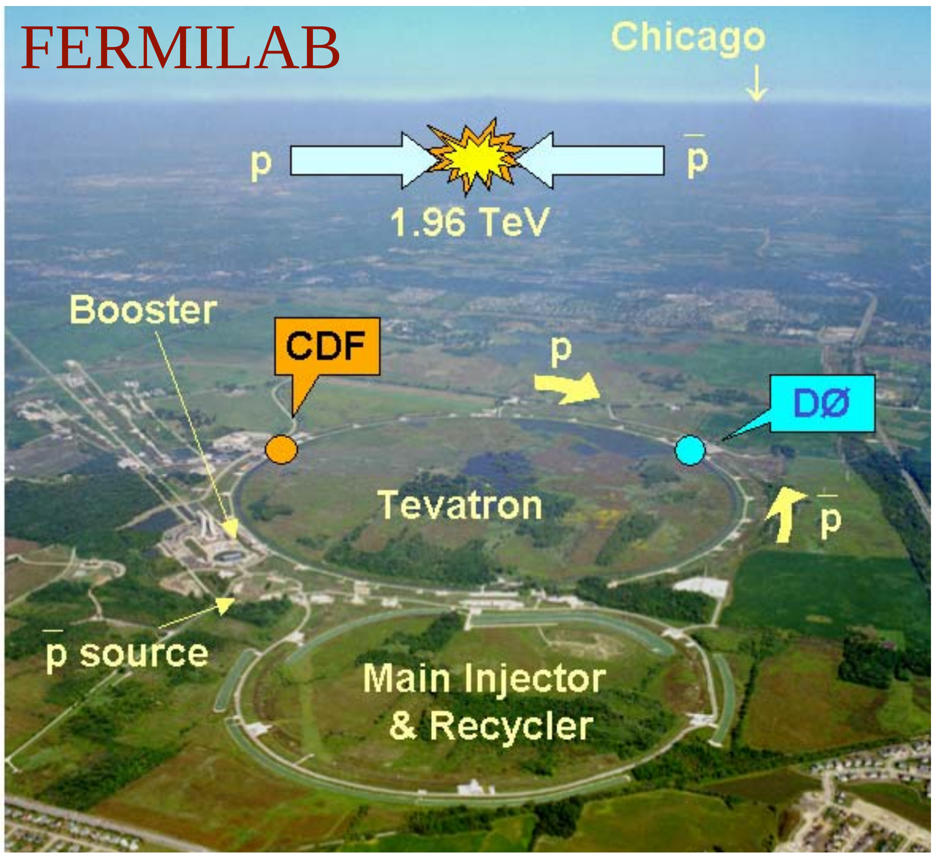


(from David Miller, UCL)

Crossing the Energy Threshold for Higgs Excitations

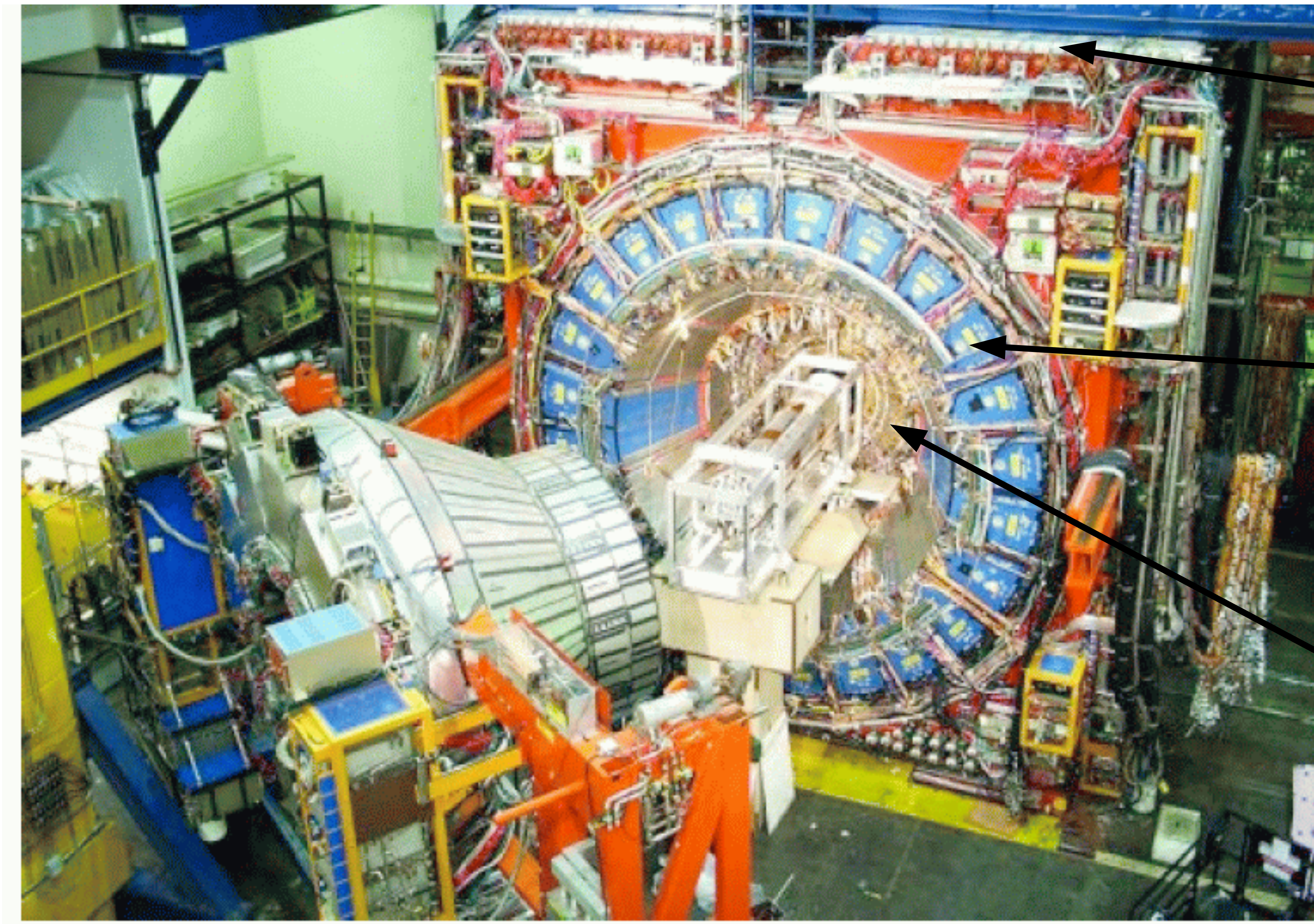
Higgs boson (or alternative) should show up at mass ≈ 1 TeV or lower

Accelerators at Fermilab (running now with 2 TeV energy) and CERN (LHC running with 7 → 14 TeV energy) are at the energy at which the Higgs Boson is expected to show up



Search for Higgs boson is a key mission of the High Energy Physics program

Collider Detector at Fermilab (CDF)



Muon detector

Central hadronic calorimeter

Central outer tracker (COT)

CDF Tracking Chamber

Reconstruction of particle trajectories, calibration to ~2 μm accuracy:

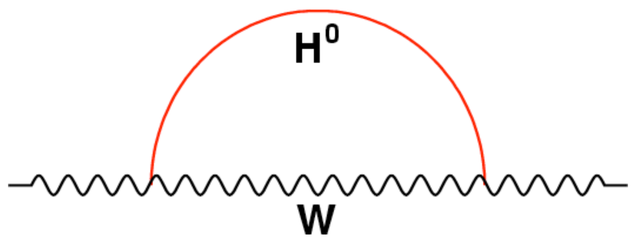
AVK, H. Gerberich and C. Hays, NIM A506, 110 (2003)

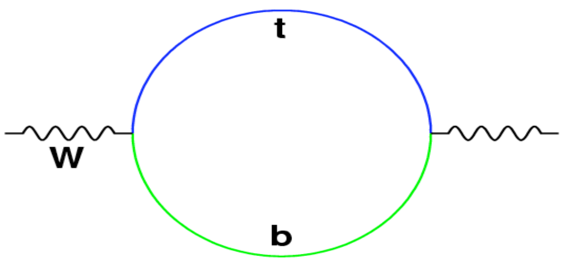
C. Hays et al, NIM A538, 249 (2005)

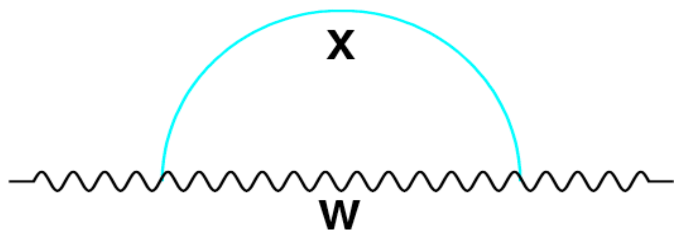
Precision Standard Model Measurements
Constraining the Higgs and New Physics

Precision Measurements of W boson and top quark masses

- Radiative corrections due to heavy quark and Higgs loops and exotica



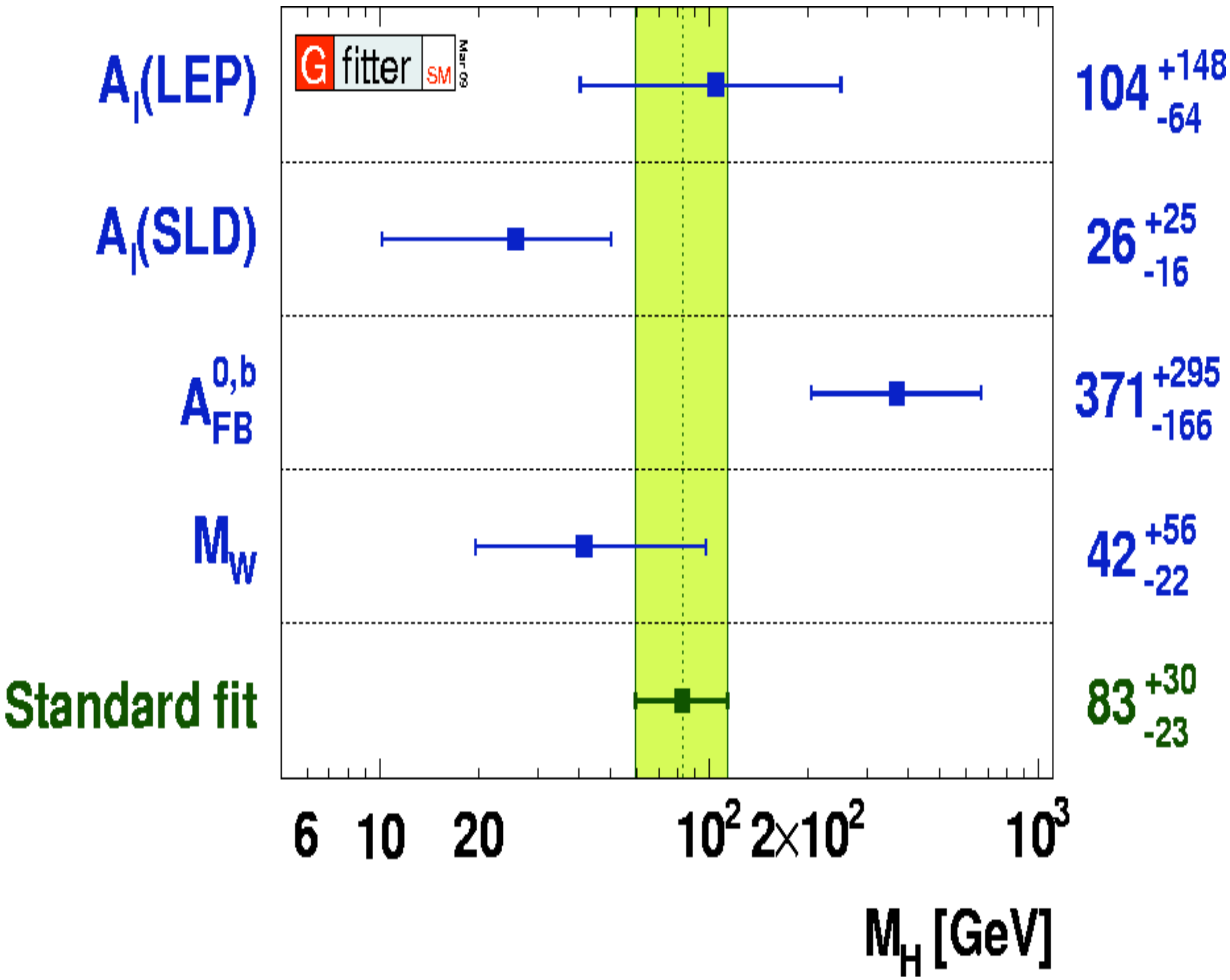




- Top quark mass and W boson mass constrain the mass of the Higgs boson, and possibly new particles beyond the standard model
  - Part of my research focuses on the precise mass measurements of these two particles

Motivation

- SM Higgs fit: $M_H = 83^{+30}_{-23}$ GeV (gfitter.desy.de)
- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs, is there another missing piece in this puzzle?

(A_{FB}^{b} *vs* A_{LR}: 3.2σ)

Must continue improving precision of M_W, M_{top} ...

other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 15$ MeV

Motivate direct measurement of M_W at the 15 MeV level

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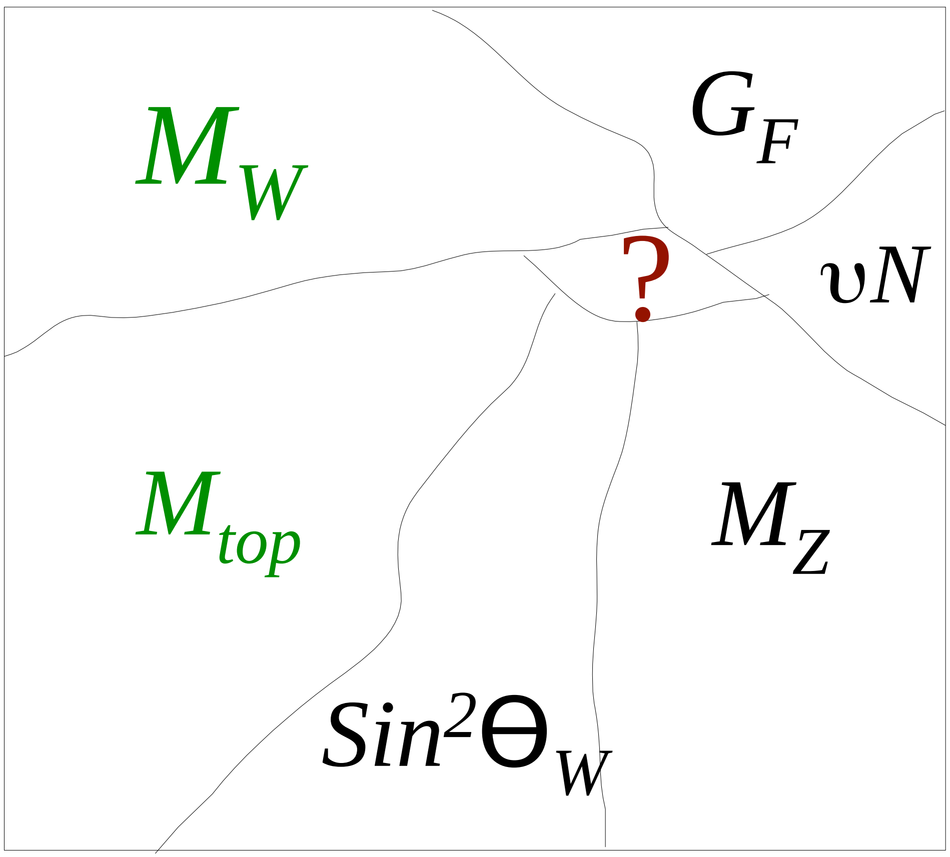

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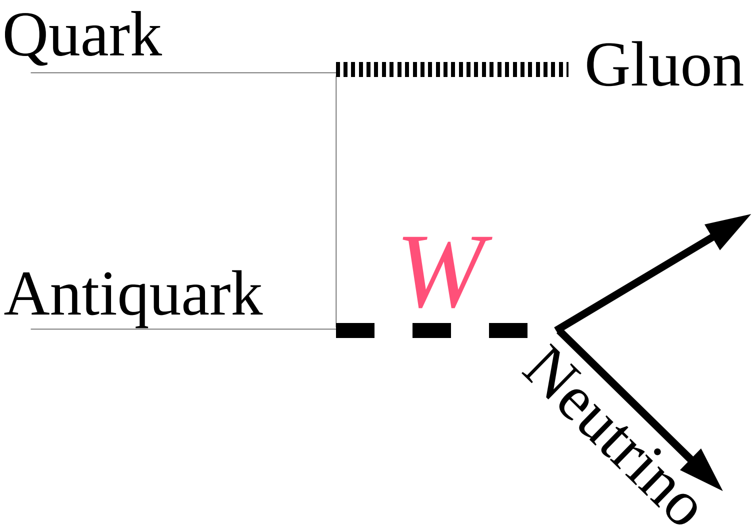
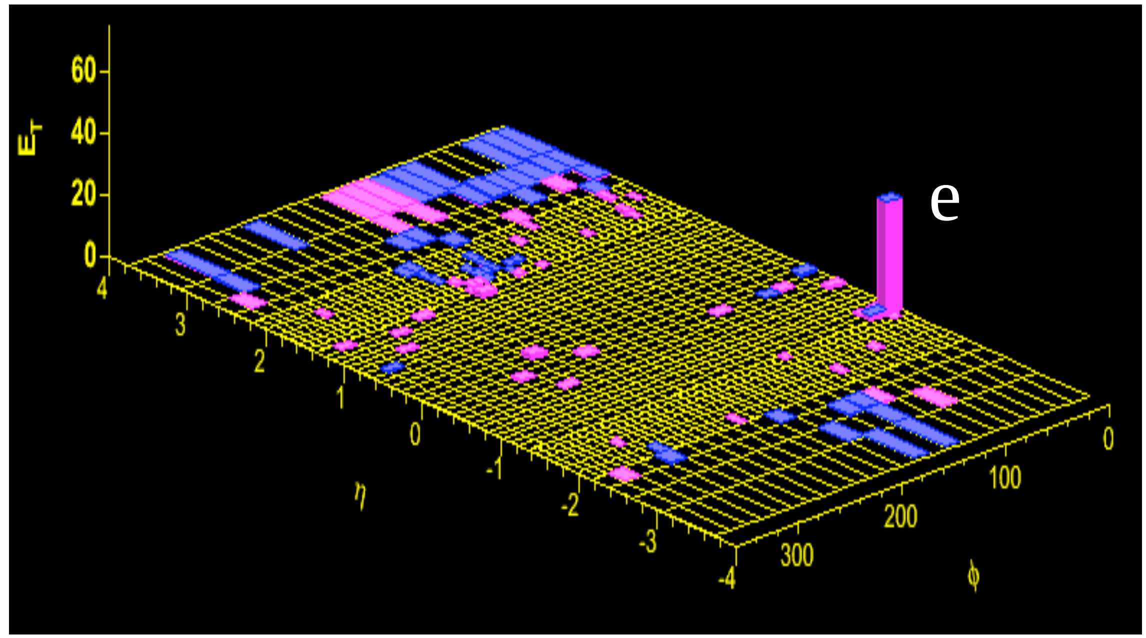
W Boson Mass Measurement

W Boson Production



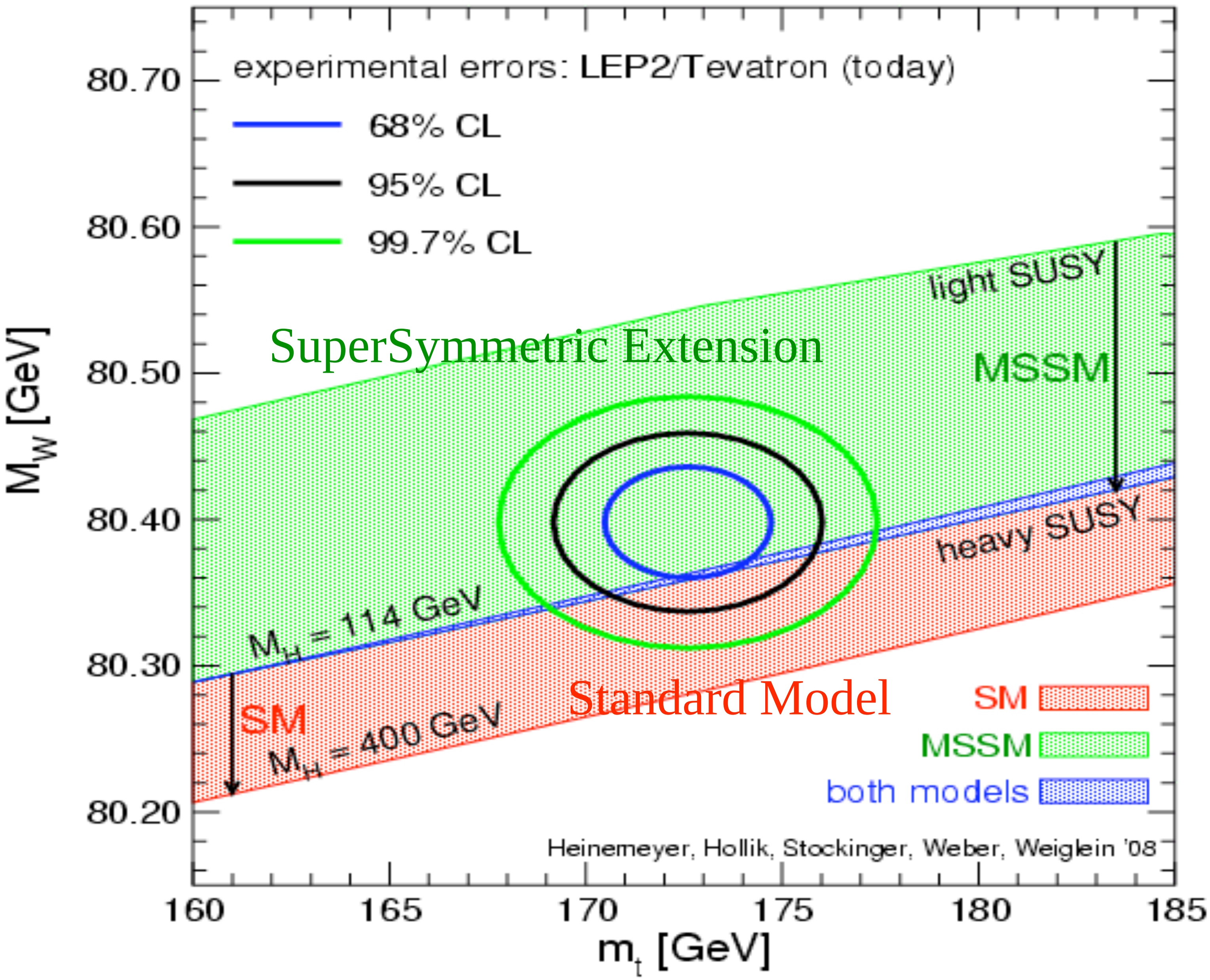


Quark-antiquark annihilation dominates (80%)

Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.05% precision)

Ph.D. Student Yu Zeng working on factor of 2 improvement in precision

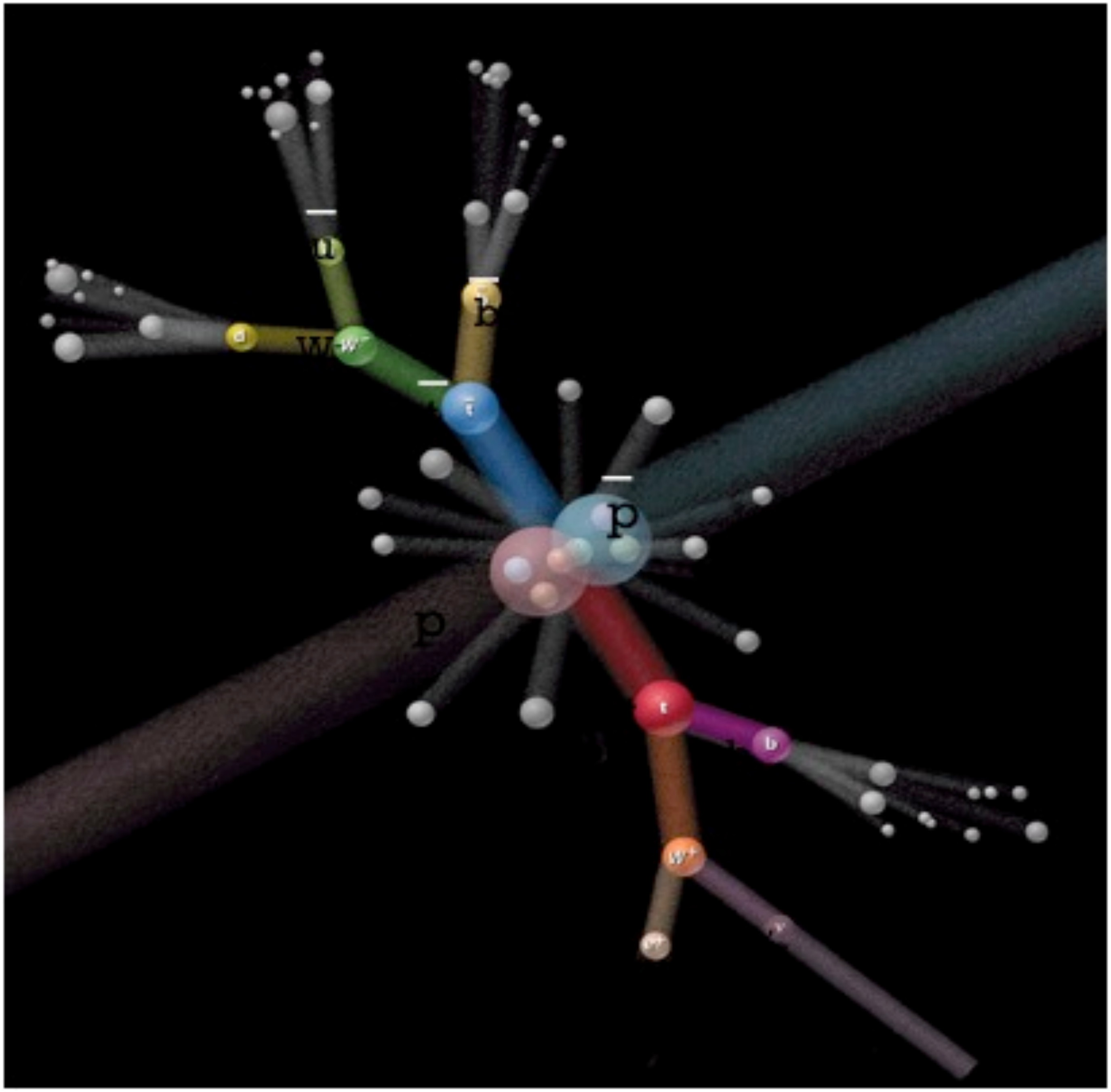
M_W *vs* M_{top}



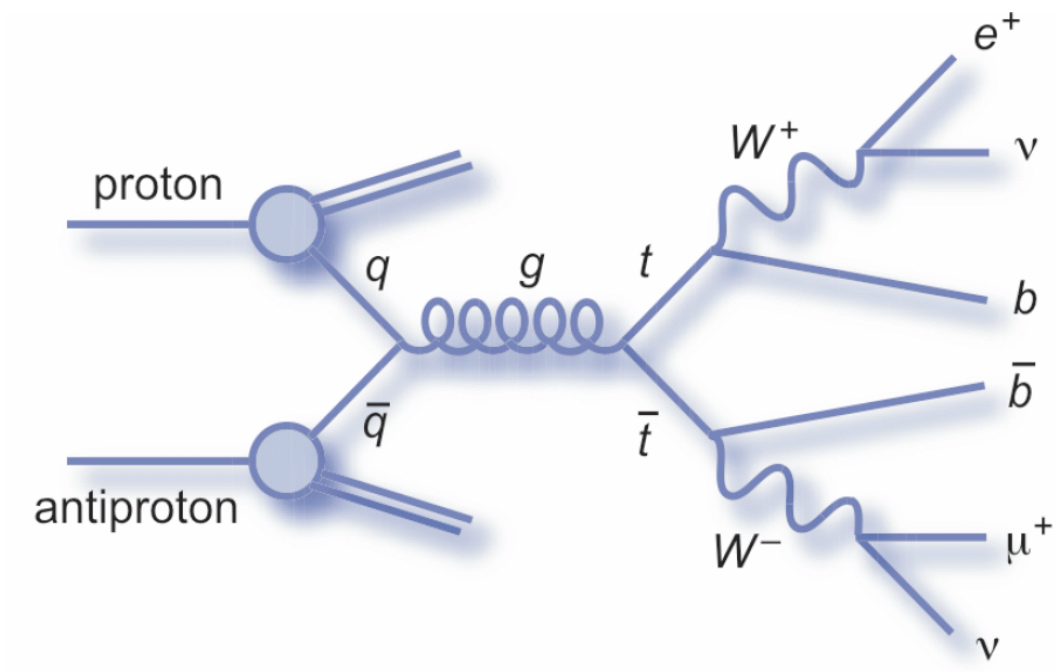
Lightest neutral supersymmetric particle could be dark matter candidate

Top Quark Mass Measurement

Top Quark Pair Production



Top Mass Measurement in Dilepton Decay Channel

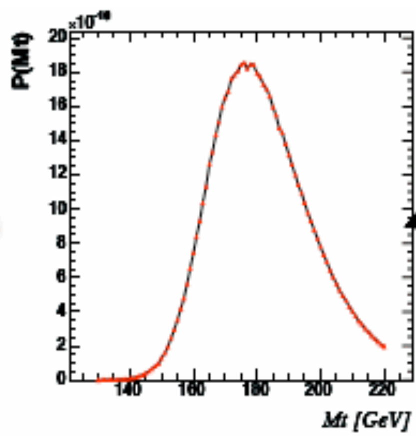


Likelihood Fitting for Top Mass

Use differential cross-section to calculate probability of event coming from M_{top}

$$\frac{d\sigma(M_t)}{d\mathbf{x}} = \int d\Phi \boxed{|\mathcal{M}_{t\bar{t}}(p_i; M_t)|^2} \boxed{\prod W(p_i, \mathbf{x})} f_{PDF}(q_1) f_{PDF}(q_2)$$

$$\frac{1}{\sigma(M_t)} \frac{d\sigma(M_t)}{d\mathbf{x}} \Rightarrow$$



Probability curve rather than single mass per event

Likelihood Fitting for Top Mass

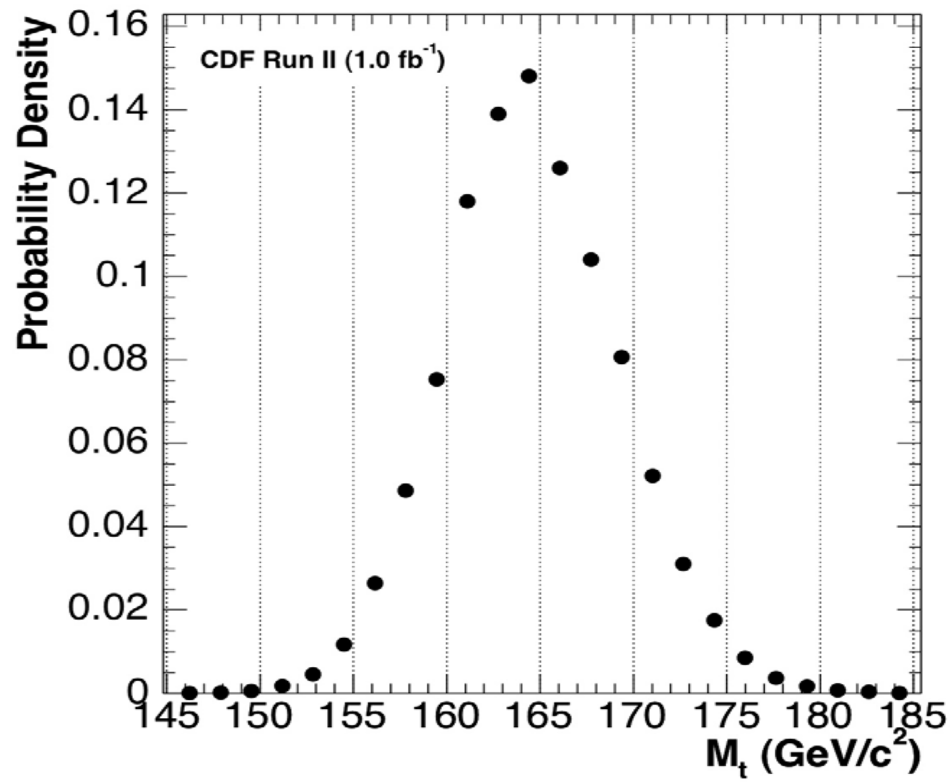
$$P(\mathbf{x}|M_t) = P_s(\mathbf{x}|M_t)p_s + P_{bg_1}(\mathbf{x})p_{bg_1} + P_{bg_2}(\mathbf{x})p_{bg_2} + \cdots$$

Advantage of this method: use all information from standard model about top quark and backgrounds, with M_{top} as only free parameter

M_{top} measurement in dilepton channel:

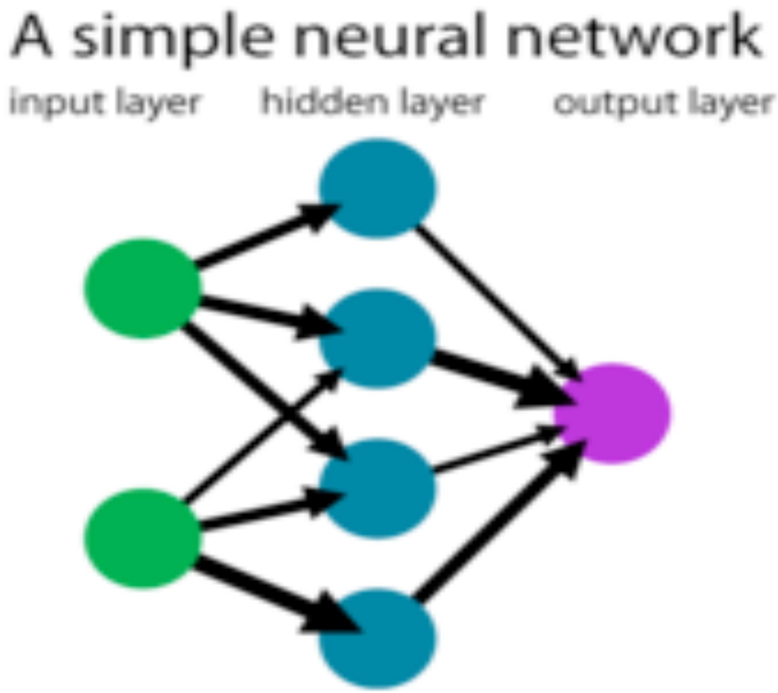
$M_{top} = 164.5 \pm 3.9(\text{stat}) \pm 3.9(\text{syst})$ GeV

PRD 75, 031105 (R) (2007)



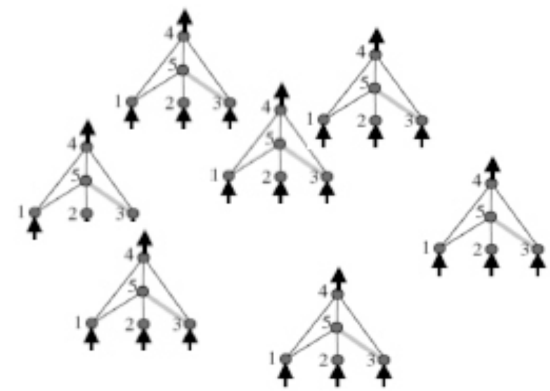
Optimizing Event Selection for Top Mass Measurement

- Artificial Neural Networks: use to construct non-linear function of event kinematics

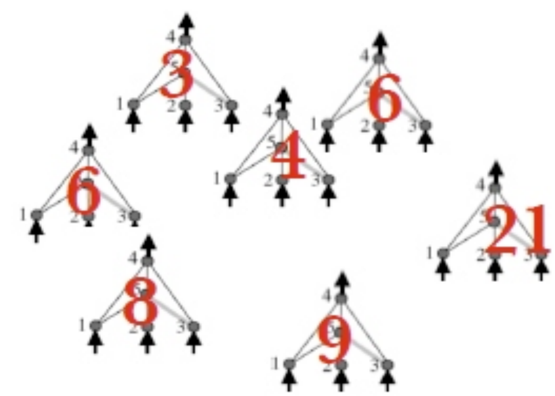


- First use in particle physics: training neural network using genetic evolution algorithm

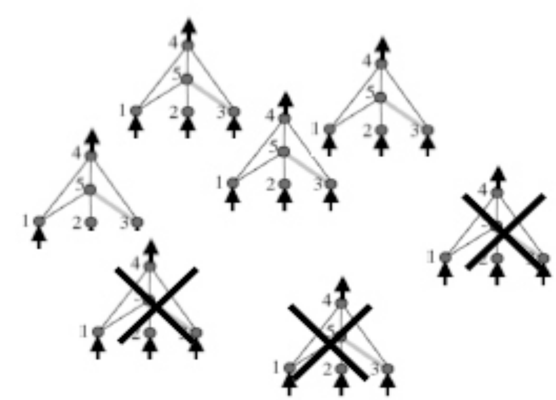
Genetic Neuro-Evolution



- Goal: single multi-variate selection criterion yielding most precise measurement of the top quark mass

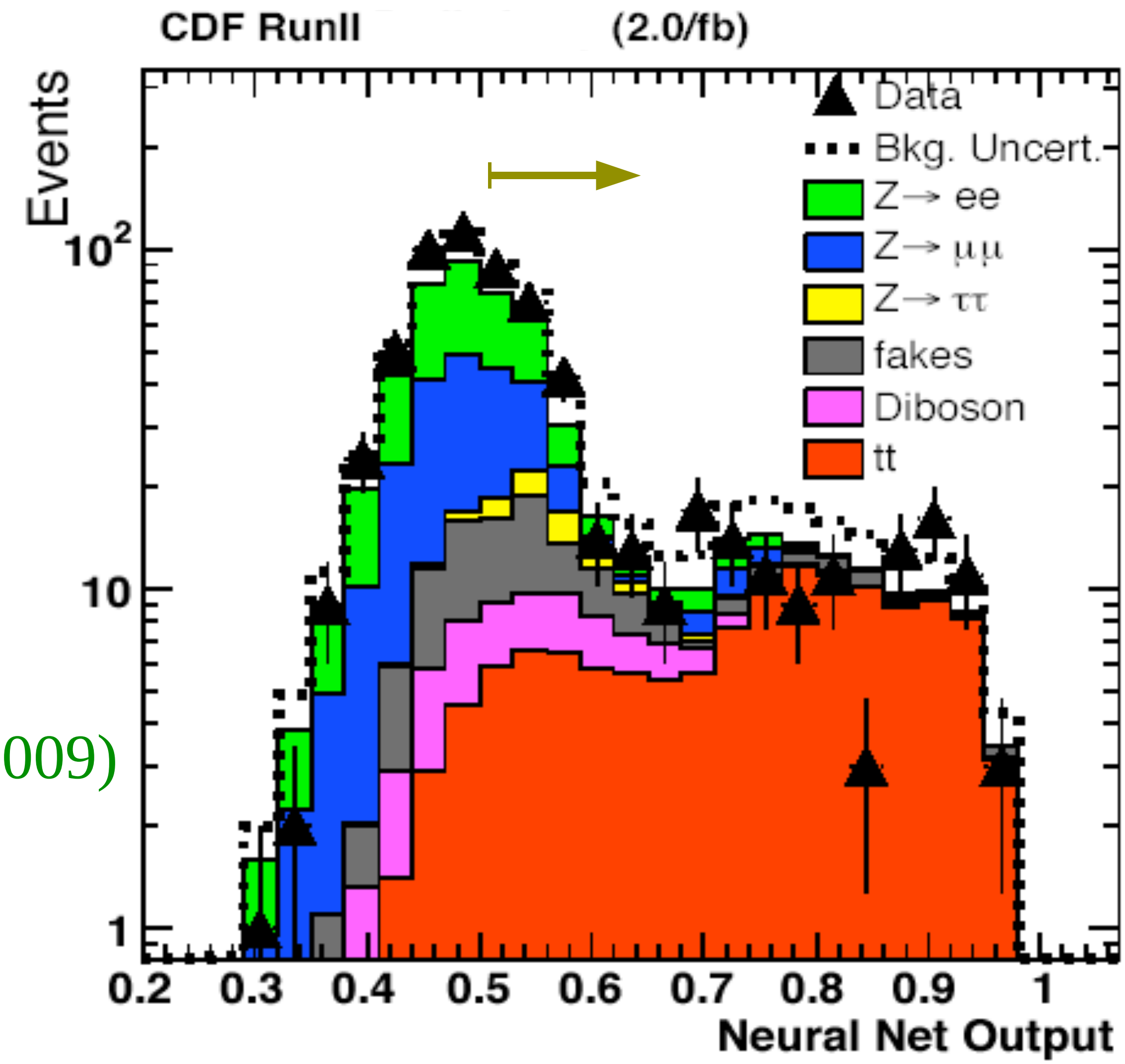


- Genetic evolution:
  - Random initial set of neural networks
  - Evaluate resulting M_{top} precision using each network
  - Discard networks yielding low precision
  - Mutate and breed high-precision networks



Measurement of M_{top} in the dilepton channel

Neural Network for optimized event selection

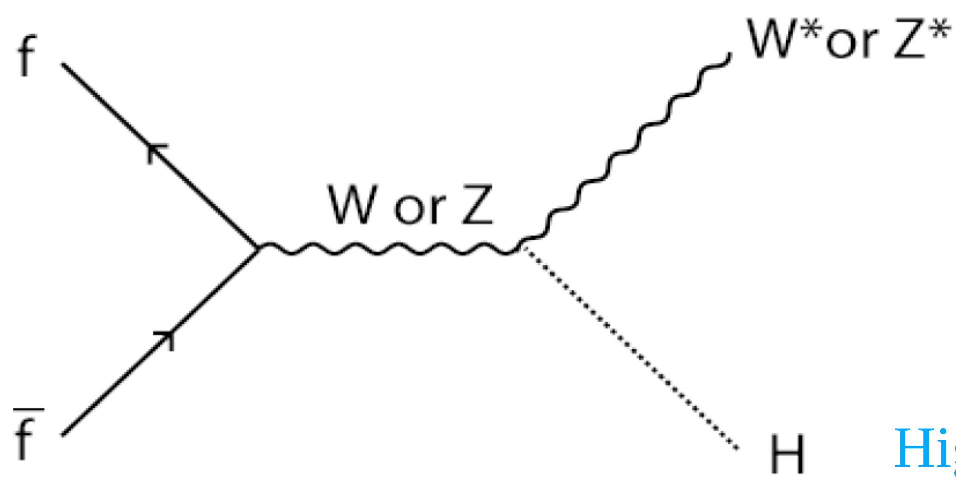


PRL 102, 152001 (2009)

Best M_{top} measurement in dilepton channel: $M_{top} = 171.2 \pm 4.0$ GeV

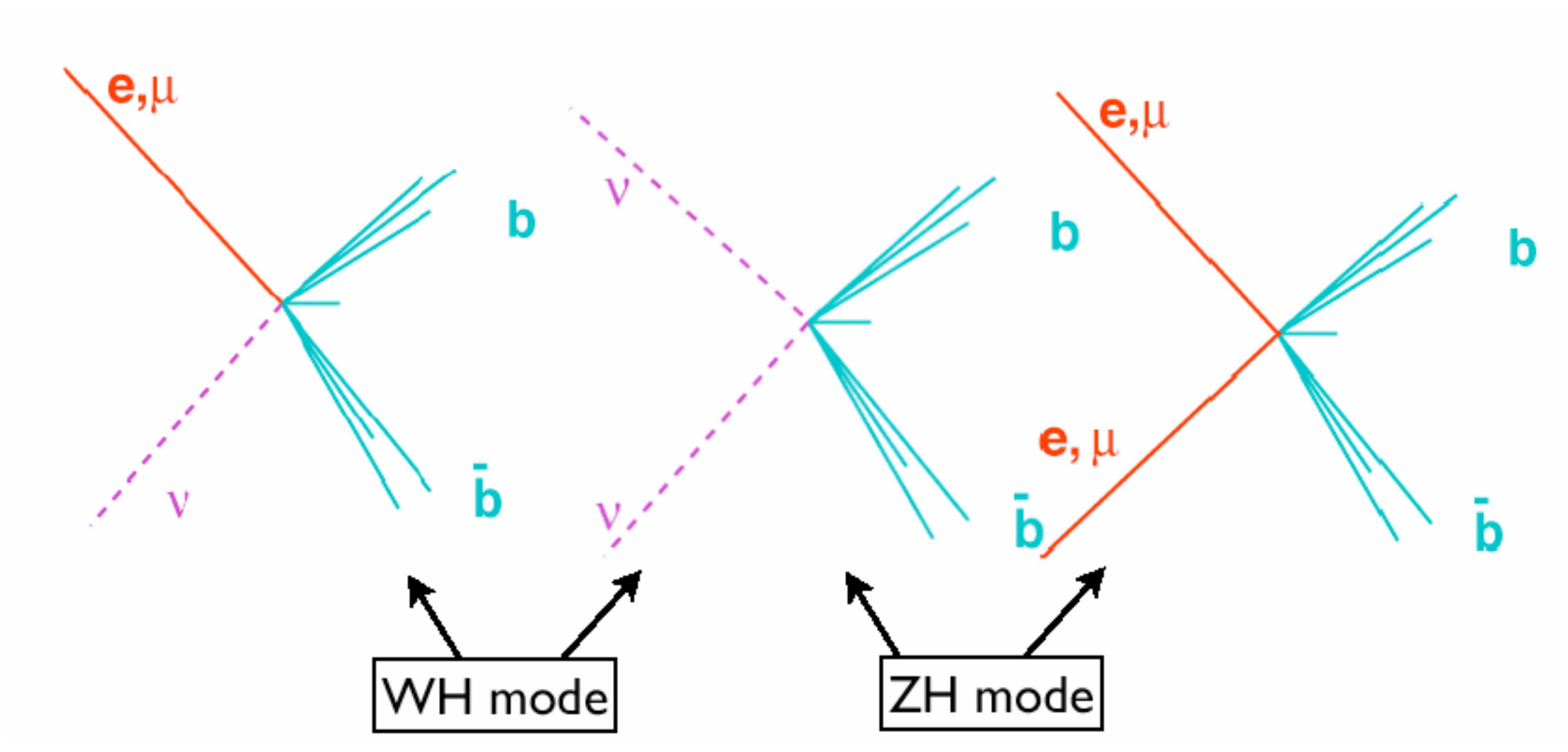
Standard Model Higgs Boson Production and Decay

Light Higgs Boson Production and Decay

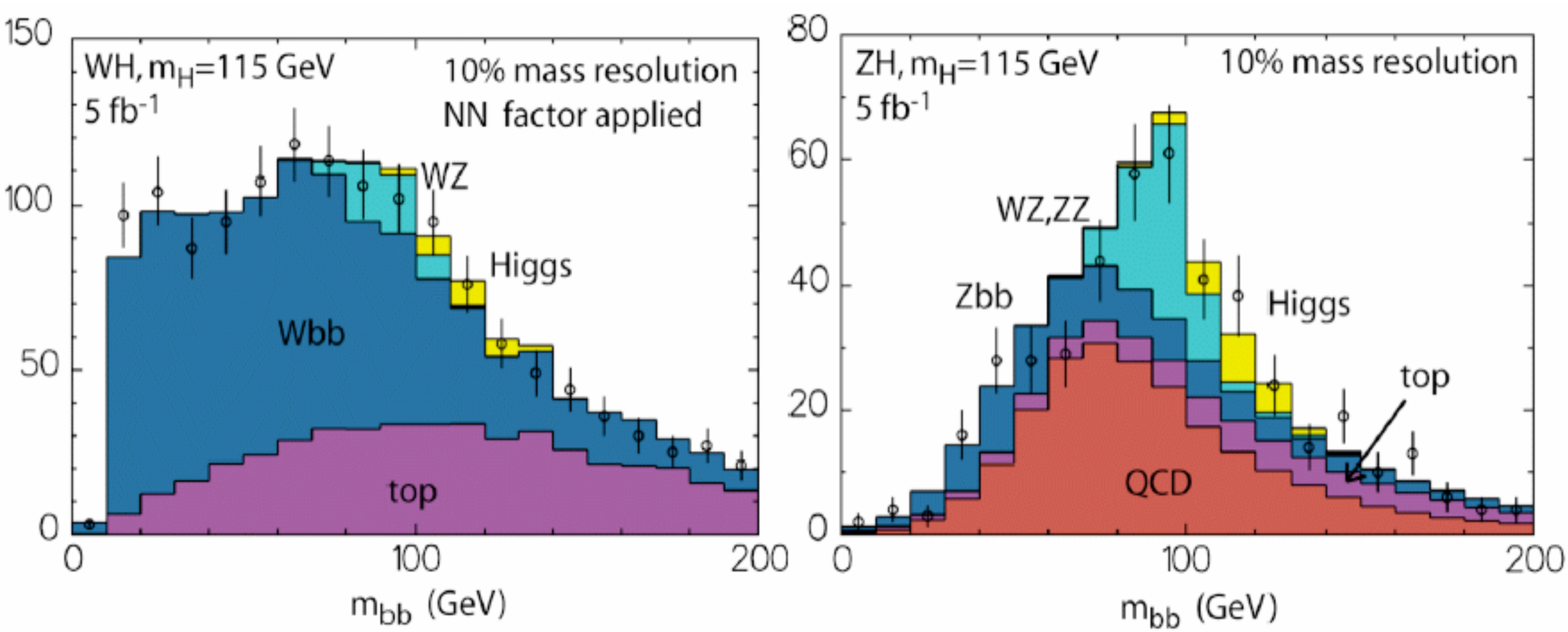


W, Z decay to electrons, muons, τ, and/or neutrinos

Higgs boson decays to bottom quarks



Simulated Higgs Signal on Expected Backgrounds



Key requirements for observing signal:

Excellent lepton identification, good calorimeters for jet and Missing E_T reconstruction, excellent silicon detectors for b jet identification

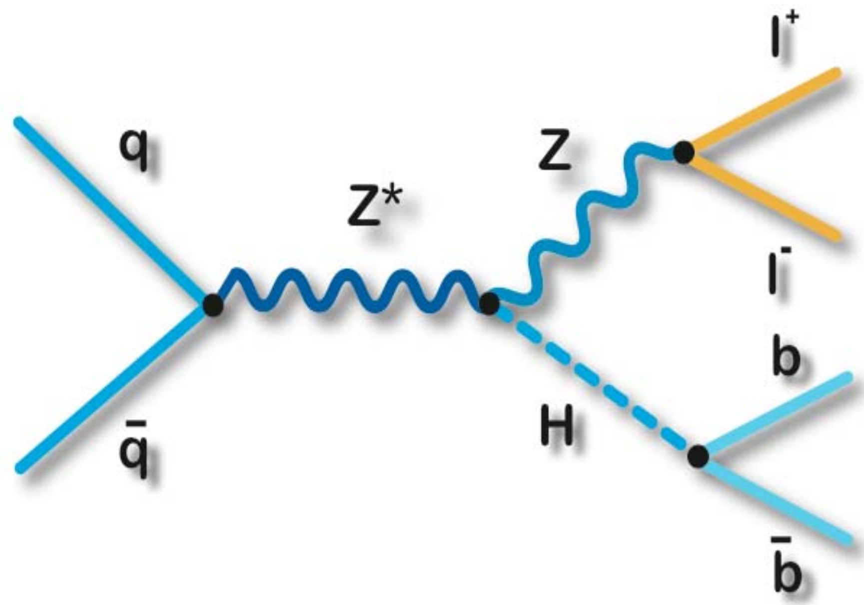
Good reconstruction of decay particle momentum vectors

Good simulation of signal and background events

SM Higgs: ZH → llbb

Ravi Shekhar
M.Sc. Thesis

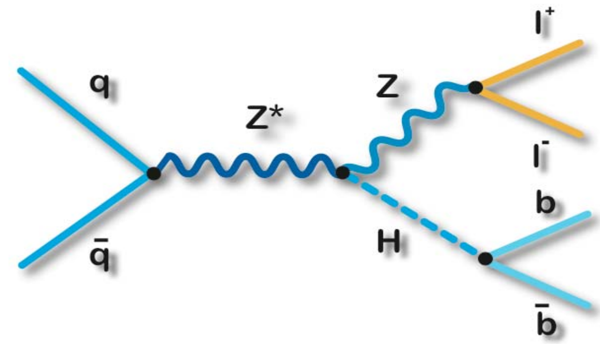
PRD 80, 071101 (R)



$$P(\mathbf{x}|M_H) = \frac{1}{\sigma(M_H)} \int d\Phi \boxed{|\mathcal{M}_{ZH}(p_i;M_H)|}^2 \prod \boxed{W(p_i;\mathbf{x})} f_{pdf}(q_1) f_{pdf}(q_2)$$

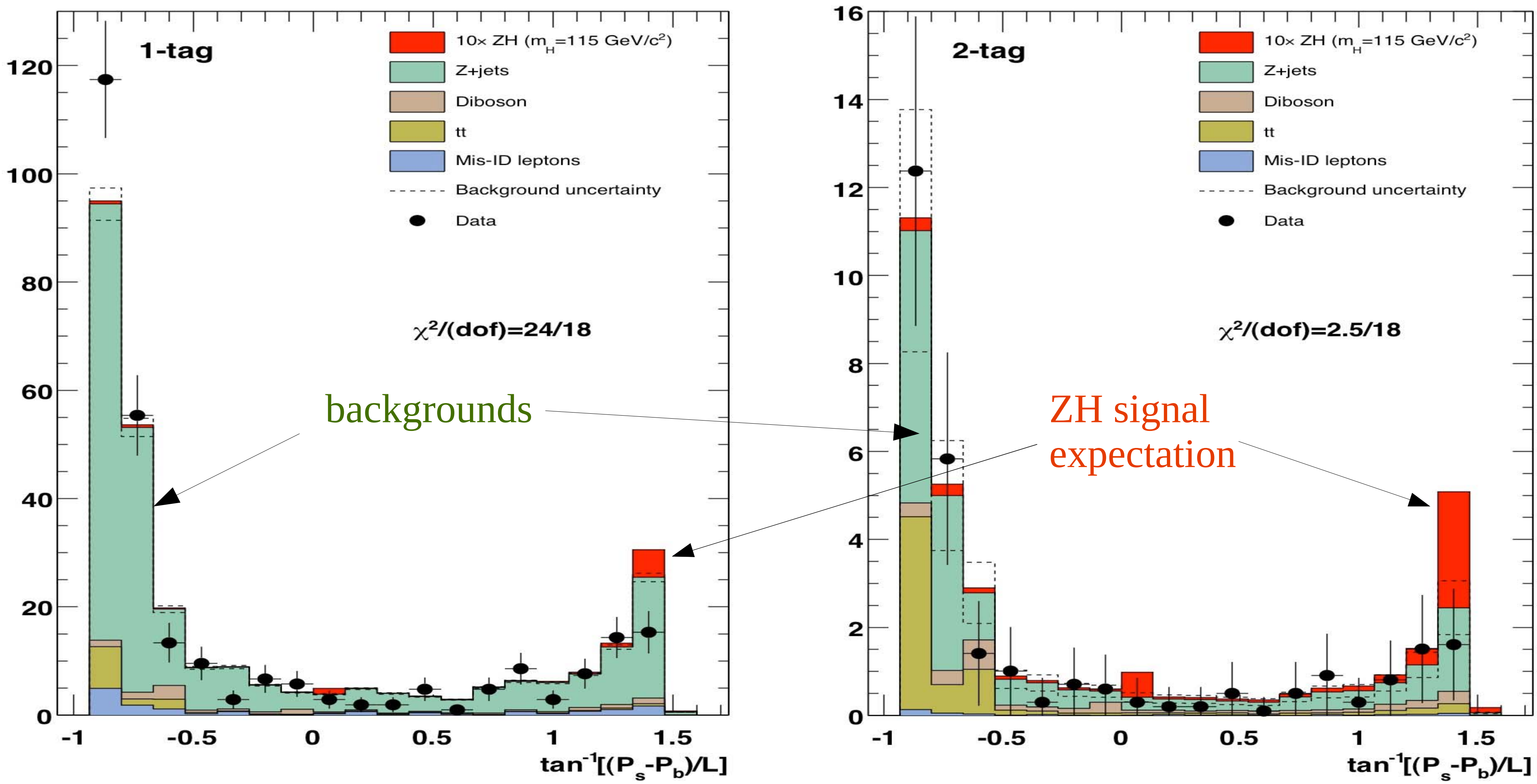
$$\mathcal{L}(S) = \prod_{events} (S) P_{signal}(\mathbf{x}) + (1-S)(\vec{\lambda}_{back} \cdot \vec{P}_{back}(\mathbf{x}))$$

SM Higgs: ZH → llbb



Signal *vs* background discriminant = $(P_s - P_b) / L$

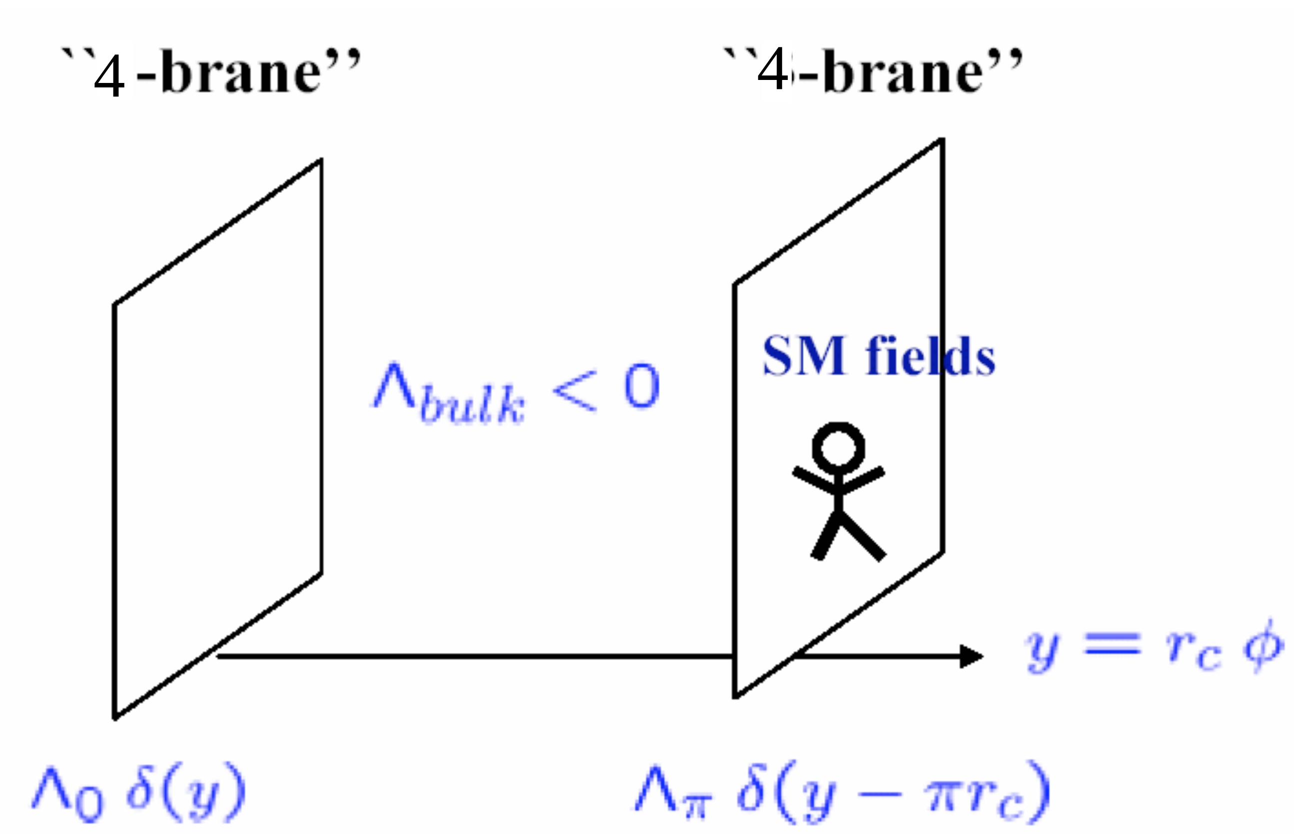
Shown for simulated events and data events



Searches for new particles and forces at LHC

Searching for new heavy particles

- Gravity also enters the game
- Randall-Sundrum model of “gravity unification”
  - a.k.a. “why is gravity so much weaker than electroweak force?”
- Suggested solution: its not really, but just appears to be so weak...

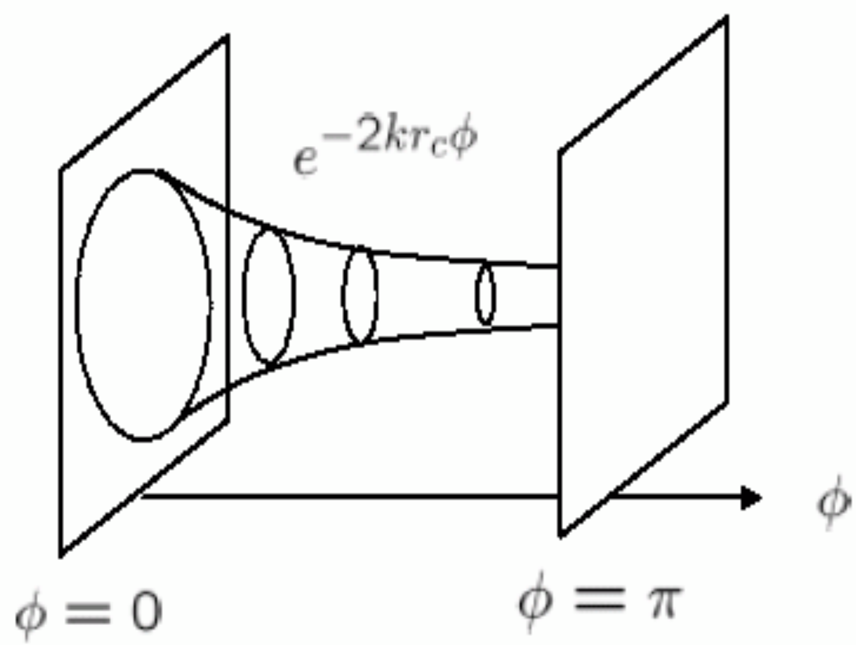


Randall and Sundrum, PRL 83 (1999) 3370

Prediction for Heavy Graviton

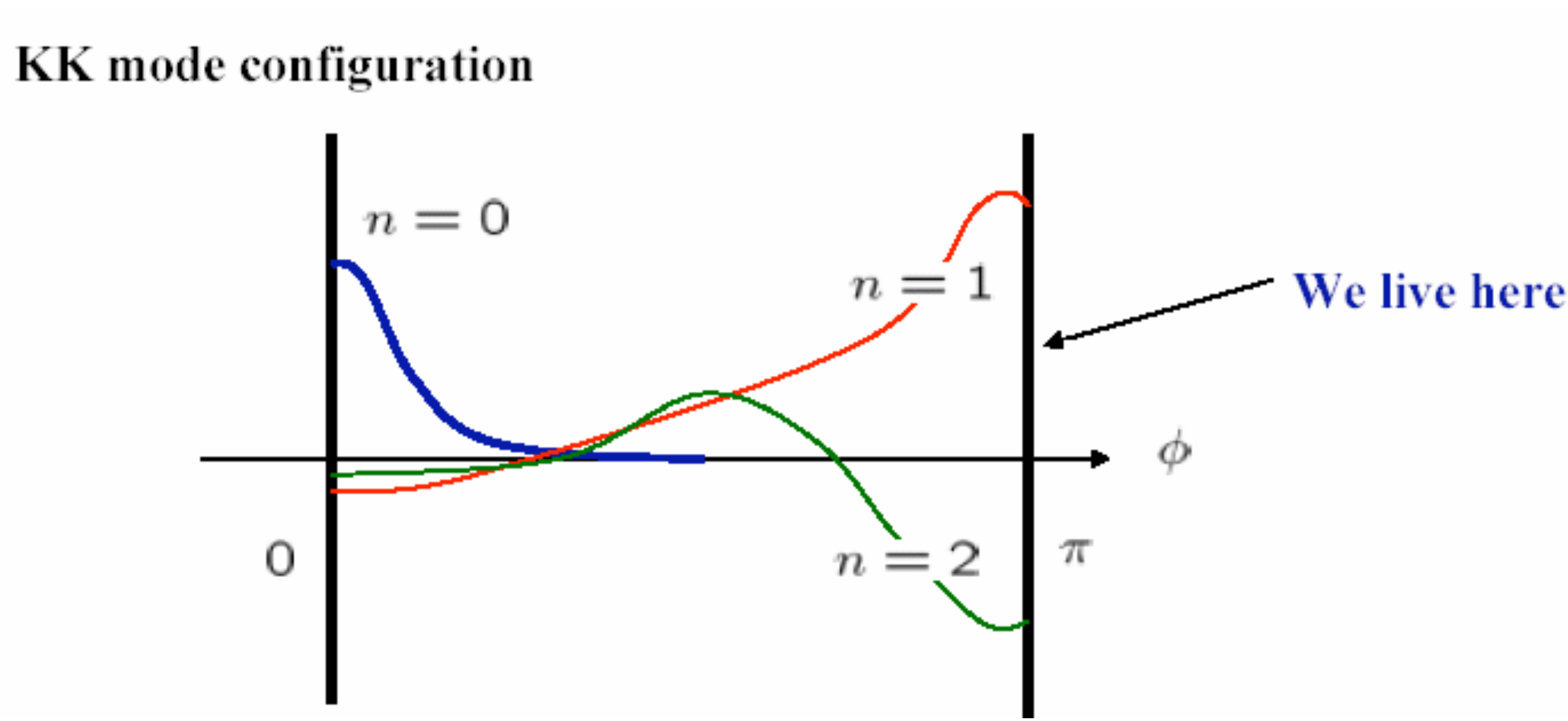
- Randall-Sundrum prescription
  - Construct Gravitational Lagrangian in bulk and on branes
  - Derive equation of motion for the metric, from principle of stationary action
  - Solve for metric $g_{\mu\nu}$:

Solution: $$\boxed{ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^{\mu}dx^{\nu} + r_c^2 d\phi^2}$$



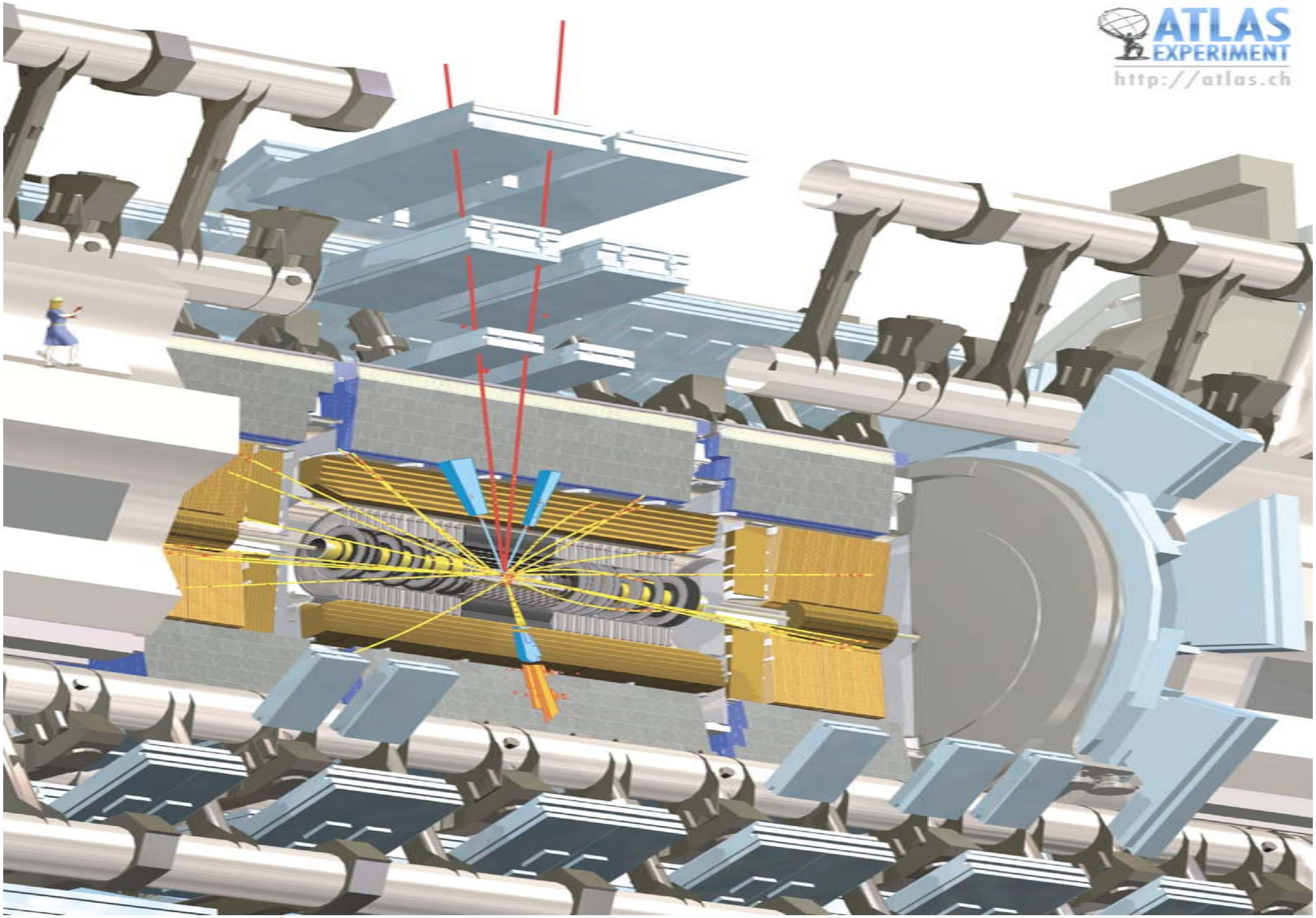
Heavy Gravitons

- Randall-Sundrum prediction:
  - Ground-state wave function of graviton small on our brane, ie gravity appears weak
  - But excited states of graviton wave function has big overlaps, ie. Massive gravitons with electroweak-strength couplings to standard model particles on our brane



Large Hadron Collider at CERN, Geneva, Switzerland

ATLAS Experiment at Large Hadron Collider



I am currently leading the heavy graviton search on ATLAS

Students: Ben Cerio (PhD) and Siyuan Sun (undergraduate)

Plenty of opportunities for students: precision measurements and direct searches