Experimental Particle Physics
PHYS6011
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1. **Introduction & Accelerators**
2. **Particle Interactions and Detectors (2)**
3. **Collider Experiments**
4. **Data Analysis**

Data Analysis

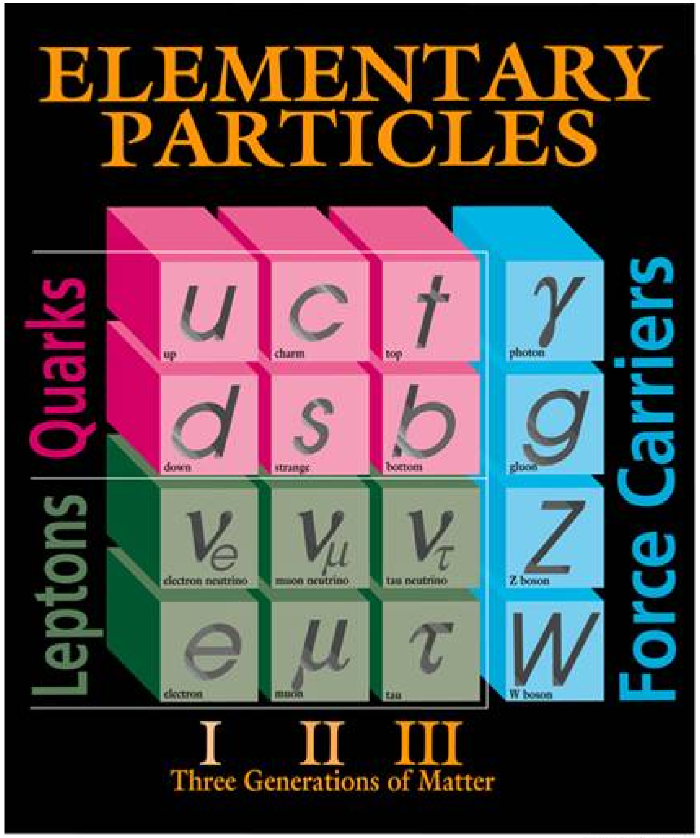
Extract physics from data

- ☐ Measure a quantity
- ☐ Search for new particles

1. Basic concepts
2. Monte Carlo methods
3. Signal
4. Backgrounds
5. Errors
6. Statistics
    - ➢ Higgs search at CDF

What do we measure?

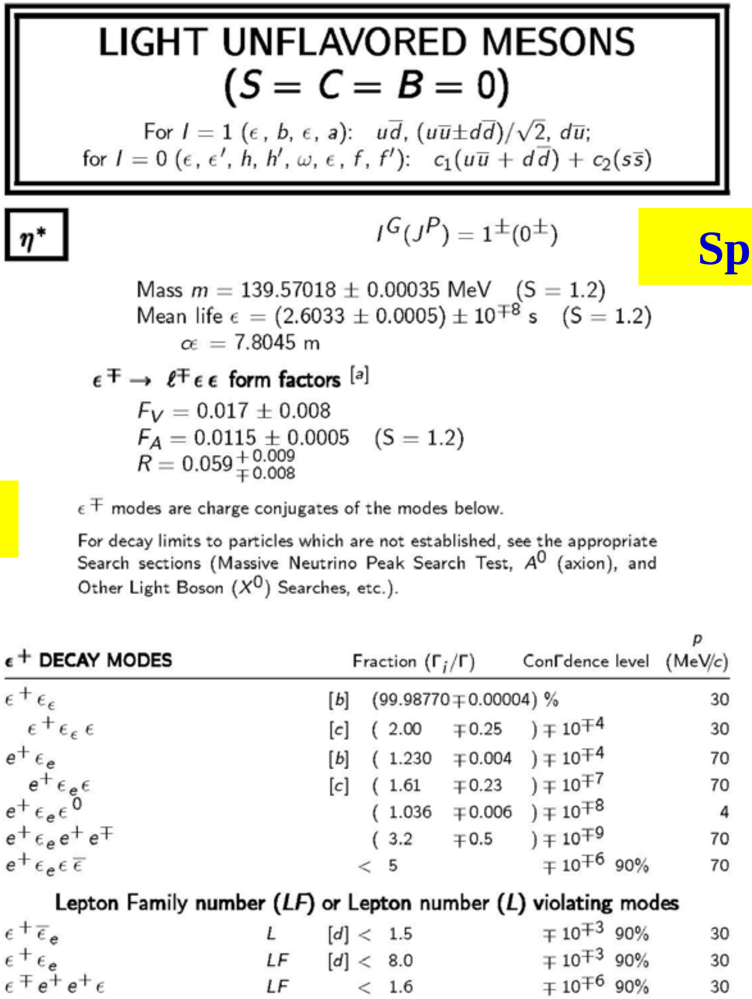
In principle:



Fermilab 95-759

But in reality:

Quark content



LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (ϵ, b, ϵ, a): $u\bar{d}$, $(u\bar{u} \pm d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (ϵ, ϵ', h, h', ω, ϵ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

η^*

$I^G(J^P) = 1^{\pm}(0^{\pm})$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\epsilon = (2.6033 \pm 0.0005) \pm 10^{\mp 8}$ s (S = 1.2)
$c\epsilon = 7.8045$ m

$\epsilon^{\mp} \rightarrow \ell^{\mp} \epsilon \epsilon$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0115 \pm 0.0005$ (S = 1.2)
$R = 0.059^{+0.009}_{\mp 0.008}$

$\epsilon^{\mp}$ modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the appropriate Search sections (Massive Neutrino Peak Search Test, A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

ϵ^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\epsilon^+ \epsilon_\epsilon$		[b]	(99.98770 ∓ 0.00004) %		30
$\epsilon^+ \epsilon_\epsilon \epsilon$		[c]	$(2.00 \mp 0.25) \mp 10^{\mp 4}$		30
$e^+ \epsilon_e$		[b]	$(1.230 \mp 0.004) \mp 10^{\mp 4}$		70
$e^+ \epsilon_e \epsilon$		[c]	$(1.61 \mp 0.23) \mp 10^{\mp 7}$		70
$e^+ \epsilon_e \epsilon^0$			$(1.036 \mp 0.006) \mp 10^{\mp 8}$		4
$e^+ \epsilon_e e^+ e^{\mp}$			$(3.2 \mp 0.5) \mp 10^{\mp 9}$		70
$e^+ \epsilon_e \epsilon \bar{\epsilon}$			$< 5 \mp 10^{\mp 6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\epsilon^+ \bar{\epsilon}_e$	*L*	[d]	$< 1.5 \mp 10^{\mp 3}$	90%	30
$\epsilon^+ \epsilon_e$	*LF*	[d]	$< 8.0 \mp 10^{\mp 3}$	90%	30
$\epsilon^{\mp} e^+ e^+ \epsilon$	*LF*		$< 1.6 \mp 10^{\mp 6}$	90%	30

Spin

Mass

Lifetime

Form factor

Decay Modes

Branching Fraction

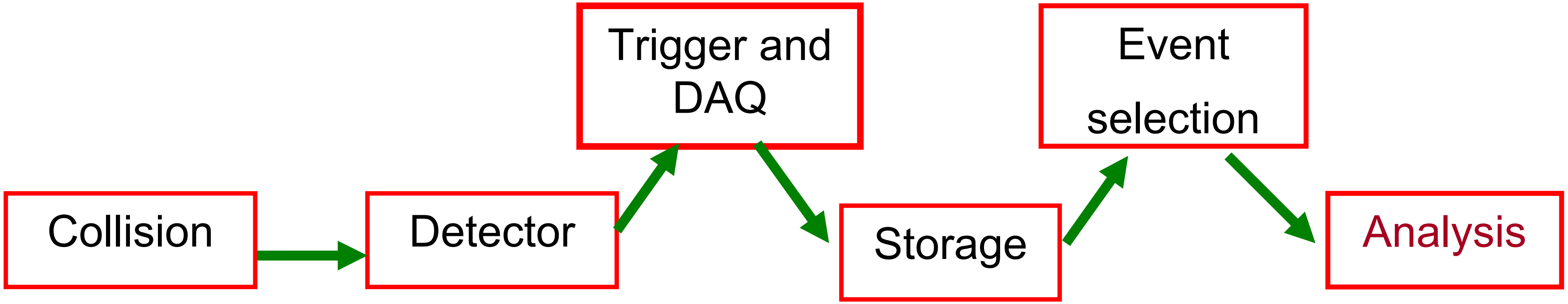
Particle Properties

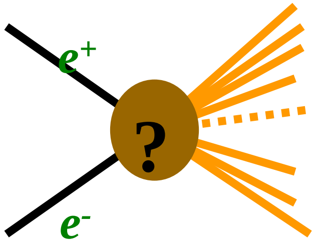
- Properties
  - Mass
    - Measure momentum and energy
  - Mass width → Lifetime
    - Measure momentum and energy or:
    - How many particles exist after t seconds
  - Branching Fraction
    - Reconstruct the decays and see how many there are.
  - Charge
    - Direction in a magnetic field
  - Spin
    - Angular distribution of decays
  - Structure e.g. Proton/Neutron/Nucleus
    - Scatter particles of the proton and look at distribution

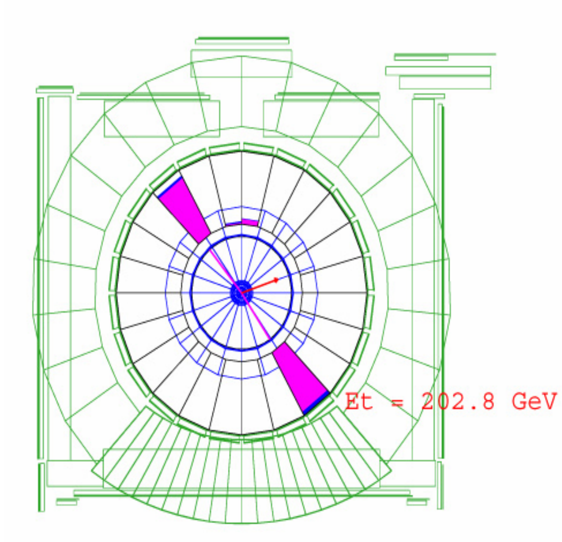
Data Flow

High Signal:Background

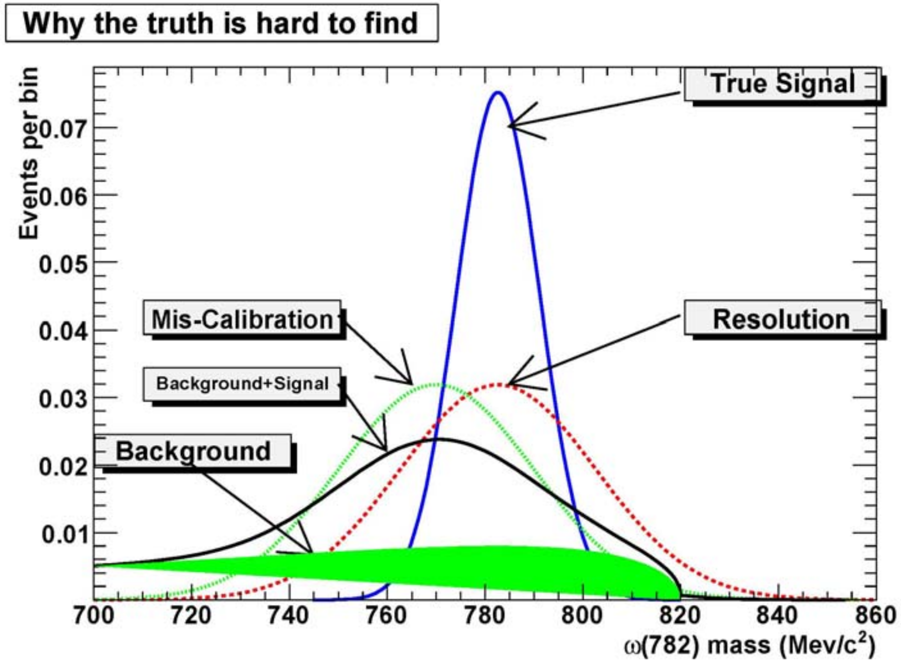
Low Signal:Background


Collision → Detector → Trigger and DAQ → Storage → Event selection → Analysis





Elements of Analysis



Not only *Data* but...

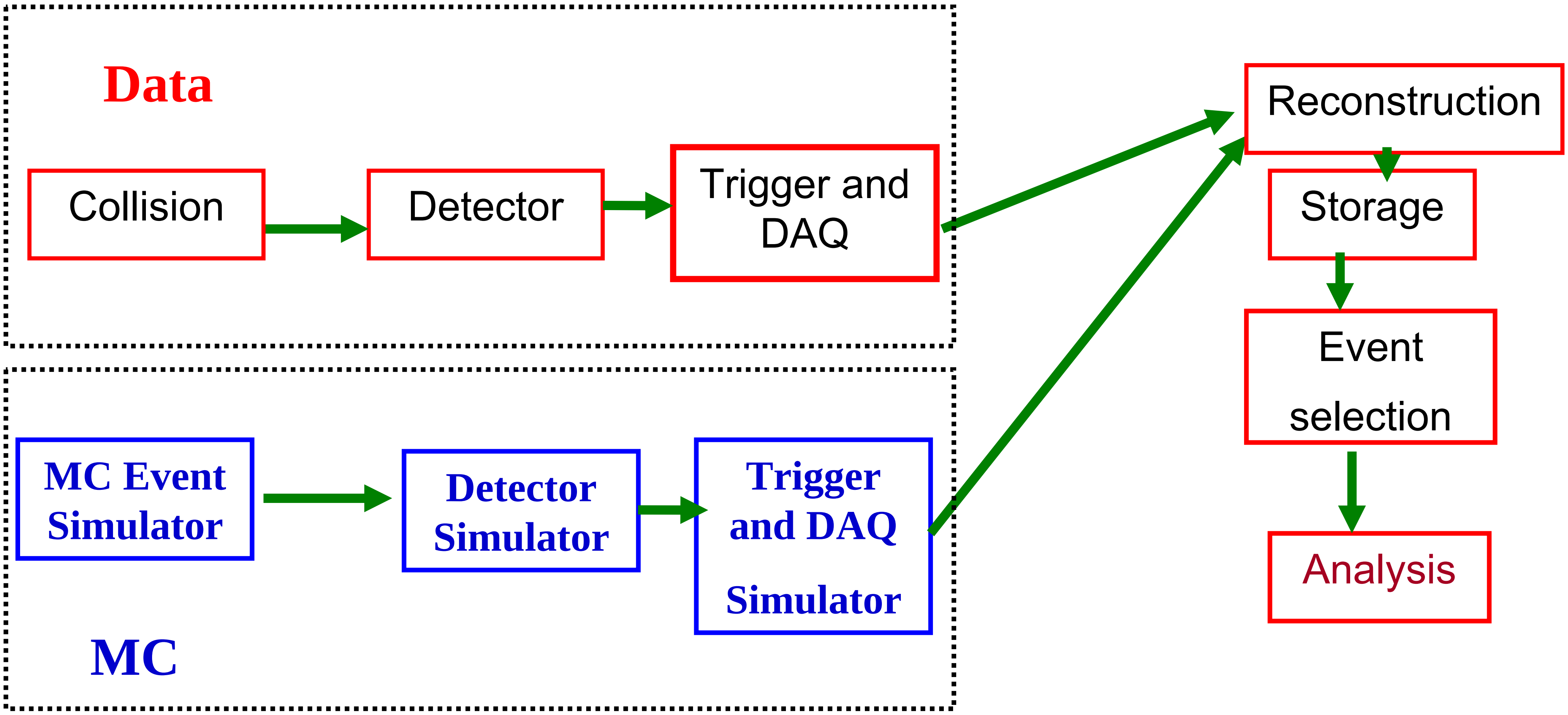
- Detector response to signal
- Background estimates
- Errors
    - statistical
    - systematic
- How to solve?
    - Try and evaluate from data
    - Sometimes need more...
        - Monte Carlo

Monte Carlo

1. Generate artificial data
2. Simulate detector response
3. Analyse simulated data as if it were real
    - Response to known input can be calculated
    - *Also used in detector design*

- Computer intensive
- Must be carefully tuned and checked

Data and Monte Carlo



Data

Collision

Detector

Trigger and DAQ

MC Event Simulator

Detector Simulator

Trigger and DAQ Simulator

MC

Reconstruction

Storage

Event selection

Analysis

Search for the Higgs

Higgs Boson - missing piece of Standard Model

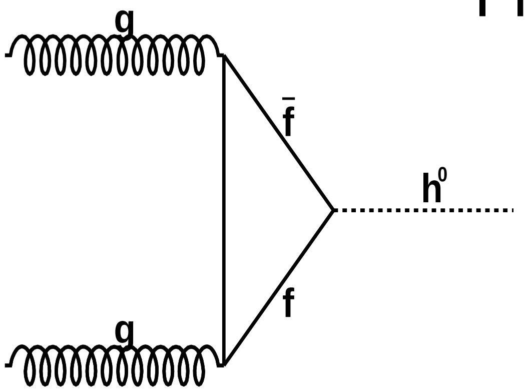
- SM Higgs theory well understood
  - Mass is only free parameter
  - Clear predictions to test
- Most new physics theories have something similar

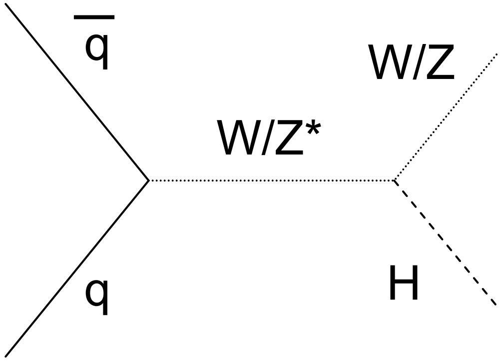
- Current limit is mass > 115 GeV (LEP)
  - *Some evidence of signal just beyond limit*

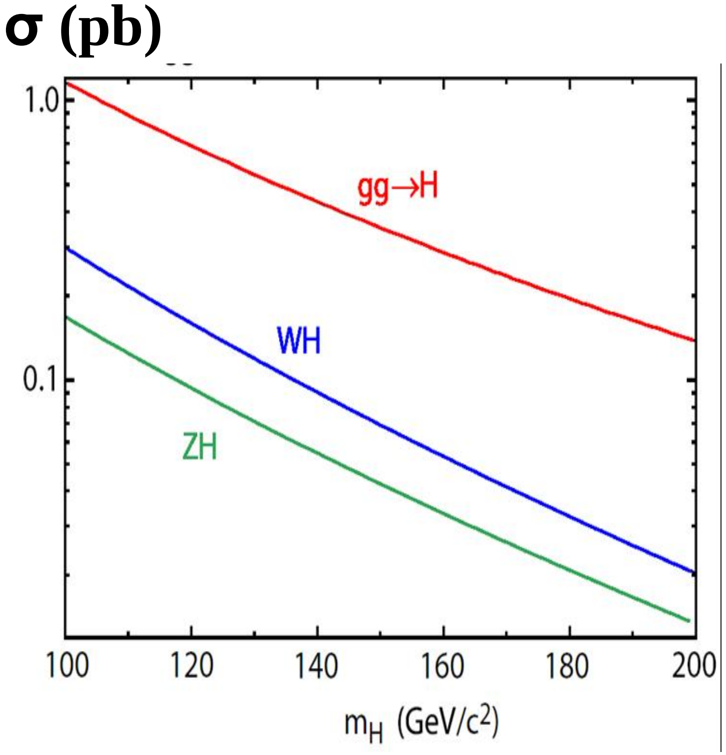
Can CDF see a Higgs at 120 GeV?

Higgs Production

First: *understand signal*

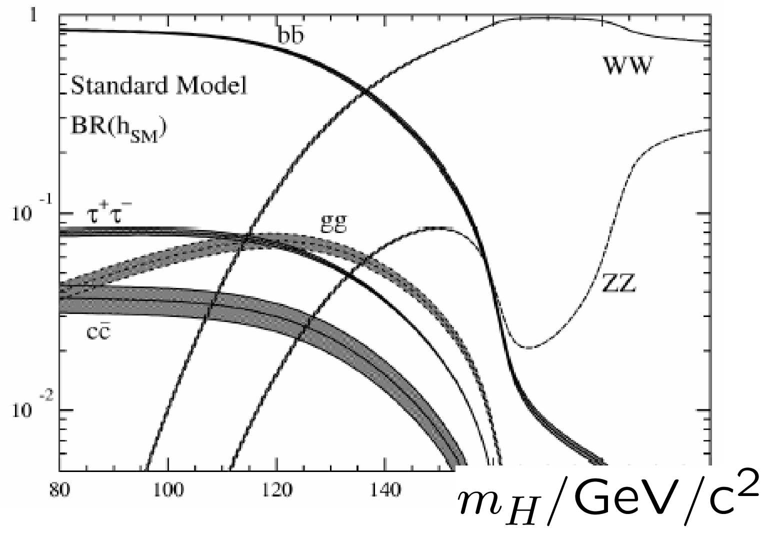






- Gluon fusion most promising

Higgs Decay

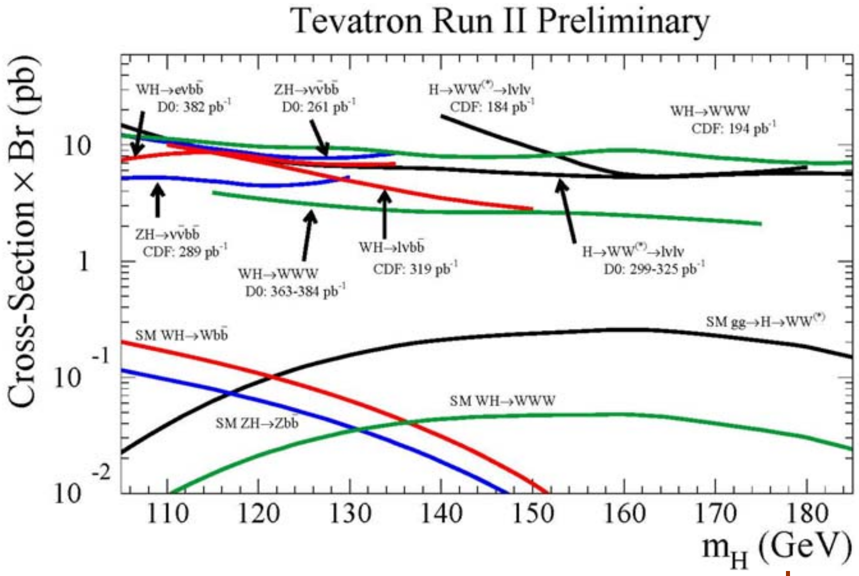


- At 120 GeV *H→bb* dominates
- Signature *gg→H→bb*:
  - 2 jets
  - One or two *b*-tags
- Swamped by dijet production
  - *bb* ~ μb
  - *qq* ~ mb *(fake b-tag rate small but not zero)*
- Have to use *W/Z+H* channel

Branching Ratio (BR): If produce 10^8 Higgs and measure 20 decays Higgs→gg with 0.00025% efficiency then Branching Fraction is:

$$BF(Higgs \rightarrow gg) = \frac{N_{decays}}{N_H * \eta} = \frac{20}{10^8 * 2.5\times10^{-6}} = 0.08$$

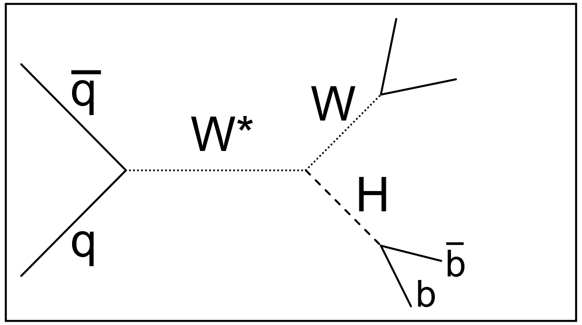
Associated Production



$W\to qq$ 70%

- final state *qqbb*
- Four jet backgrounds still too large

$qq\to WH$ with $H\to bb$



$W\to e\nu_e$ 10% $W\to \mu\nu_\mu$ 10%

Final state *lvbb*

- ❑ One electron or muon
- ❑ Missing transverse momentum
- ❑ Two jets
- ❑ One or two *b*-tags
- Easy to select in trigger and offline

$\sigma\times Br \approx 0.02$ pb

Efficiency

- Nature provides 20 fb of *WH→lvbb* events – *a handful per year*
- How many pass our trigger and analysis selection?
  - *Cleanly identified electron or muon in acceptance*
  - *Two jets*
  - *At least one b-tag*
  - *Large missing momentum*
  - *None overlapping*
    - Run thousands of MC events
    - Efficiency
    - Observe 2 per fb^{-1} per year

$$\epsilon = \frac{N_{selected}}{N_{generated}} \approx 10\%$$

Backgrounds

- Anything with signature similar to signal
    - *W*+*X*   (*X* can be *W*, *Z* or just 2 QCD jets)
    - $ZZ \rightarrow qql^+l^-$ (one lepton not identified)
    - $\tau\tau$
    - *b*-tags can be real, charm or fakes

- Estimate how many pass signal selection ⇒ *Monte Carlo*

- Largest is *W*+*bb*: about 250 fb
    - Signal to background about 1:100

Errors

Statistical

- Mostly counting events (data or MC)
- Poisson distribution: $\sigma = \sqrt{\mu} \approx \sqrt{N}$
  - *NB fractional error ~ $1/\sqrt{N}$*
- Efficiency follows binomial distribution: $\sigma_\epsilon = \sqrt{\epsilon(1-\epsilon)/N}$

Systematic

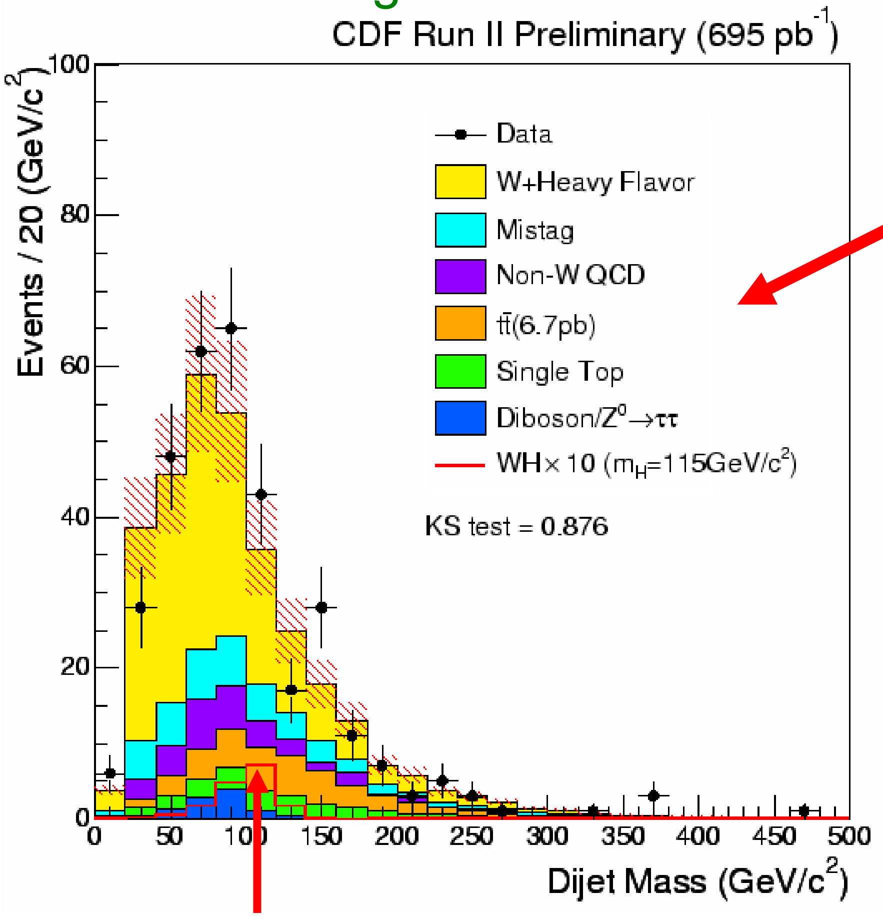
- Anything not completely understood may affect result
  - Detector performance, background rates, MC modeling…
- Estimate range of parameter
- Propagate in MC

Significance

- In a given amount of data we expect:
    - N_B background events
    - Statistical error on background ≈ $\sqrt{N_B}$
    - Systematic error on background = σ_{sys}
    - Add errors in quadrature to get σ_{TOT}
- Observe $N(>N_B)$ events in data. Could be:
    - random fluctuation in $N_B \pm \sigma_{TOT}$ background events
    - N_B background events & N_S signal events
- Significance $S = N_S/\sigma_{TOT}$
    - S = 3: probability of fluctuation ~10^{-3} – interesting...
    - S = 5: probability of fluctuation ~10^{-5} – discovery!!

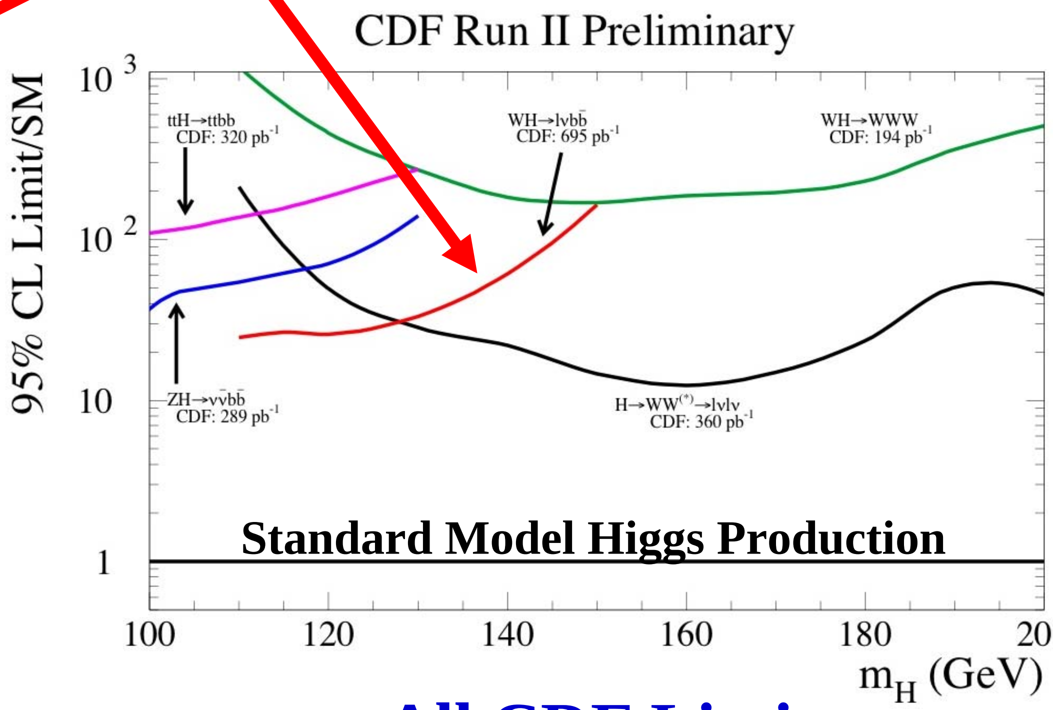
Latest CDF Results

- Data and background as function of *bb* mass



Expected signal × 10

$$WH \to l\nu b\bar{b}$$

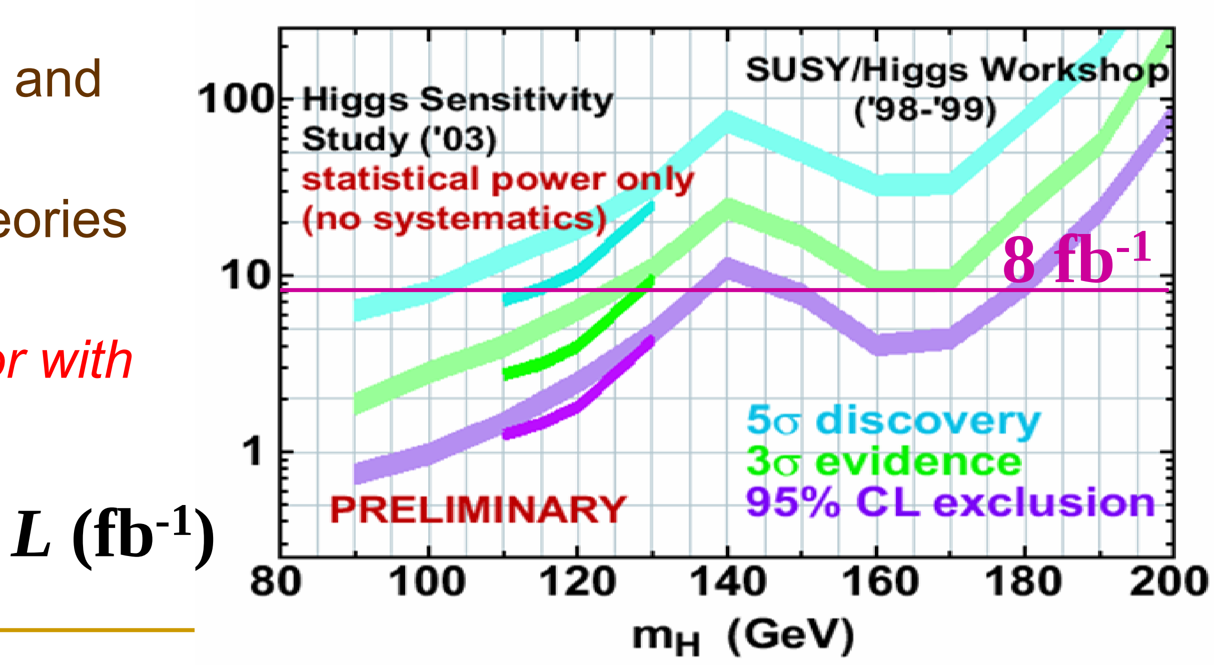


All CDF Limits

Predicted Sensitivity

- CDF expects a maximum of 8 fb^{-1} by 2009
    - 15-20 signal events
    - 2000 background
    - *S = 0.3* (ignoring systematics)

- Optimistic, combine channels and experiments predict *S ≈ 3*
- Higgs-like particles in new theories may be easier
- *Really need a new accelerator with higher energy and more luminosity…..*

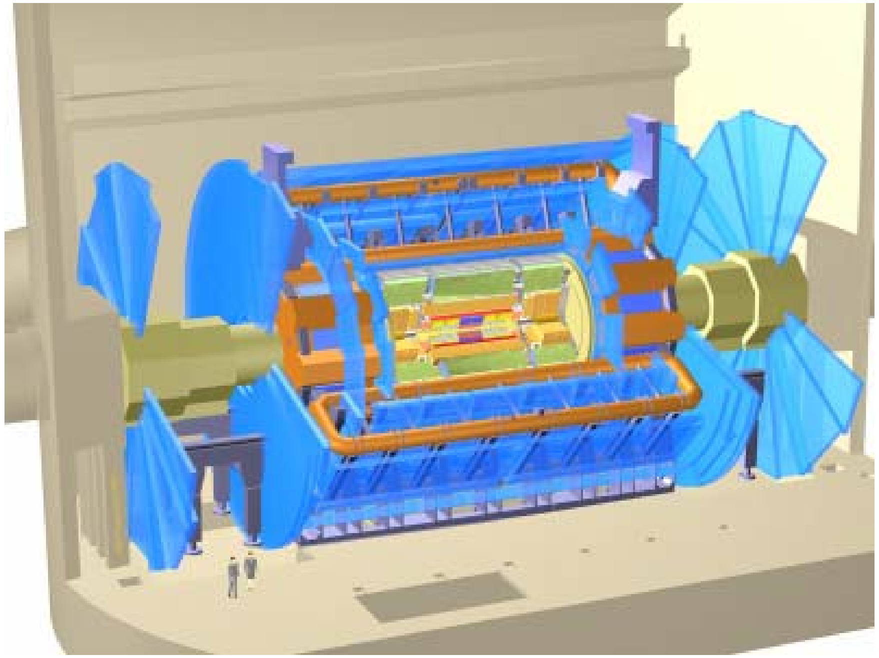


The LHC

- The Large Hadron Collider
- First collisions in 2008

- $\sqrt{s} = 14$ TeV
- $L \sim 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

LHC Experiments



- ATLAS and CMS designed to find Higgs
- *Good experiments to work on for a PhD…..*