Particle Physics Phenomenology

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What is phenomenology?

Philosophy:
the study of what we experience subjectively as consciousness

Disclaimer: I am not a philosopher

Particle physics:
the analyses or calculations that connect theory to concrete experimental predictions

Really just a subdivision of theoretical particle physics; term is used to distinguish from formal theory / string theory / quantum field theory / etc.

Particle interactions are fundamentally quantum-mechanical.

Cannot predict what will come out from any particular particle collision.

But, can predict probabilities with great precision.

- Probability distribution is randomly populated by each collision: subject to statistical uncertainties

- Collect enough data to test probabilistic prediction

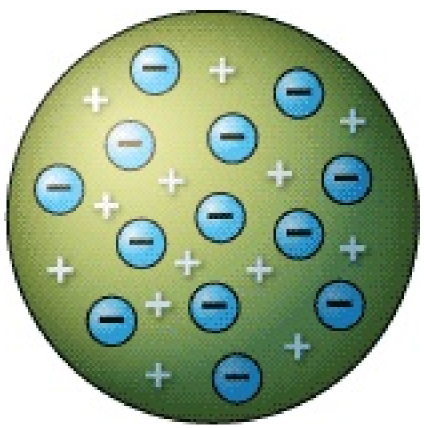
An early example: learning about the structure of the atom

- Atoms have (negatively charged) electrons in them

- Atoms are net neutral

- There must be some positively charged stuff in the atom too.

Plum pudding model (Thomson, after discovery of the electron)

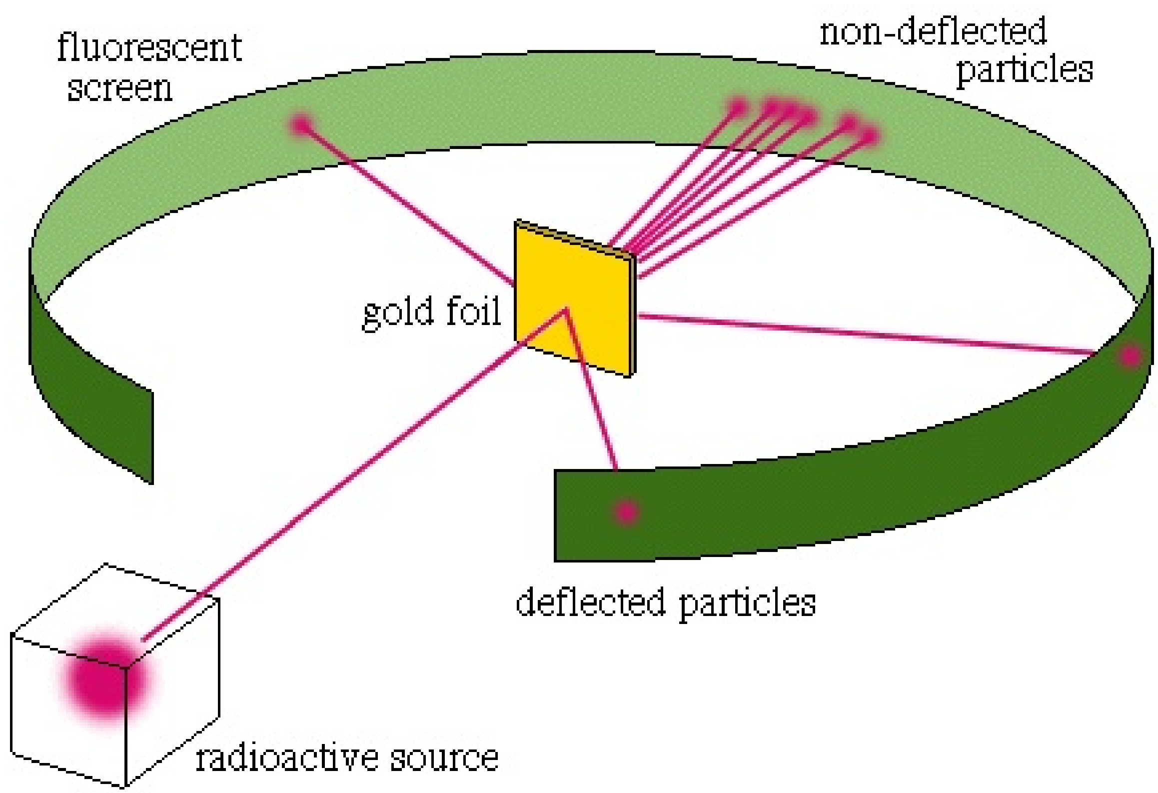


But how do you test this? Atoms are too small to see.

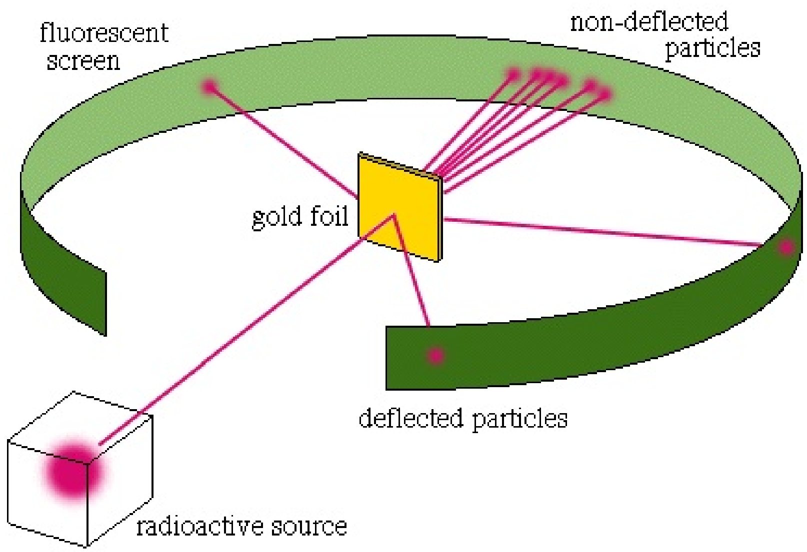
Answer: shoot stuff at it! we have been doing this ever since

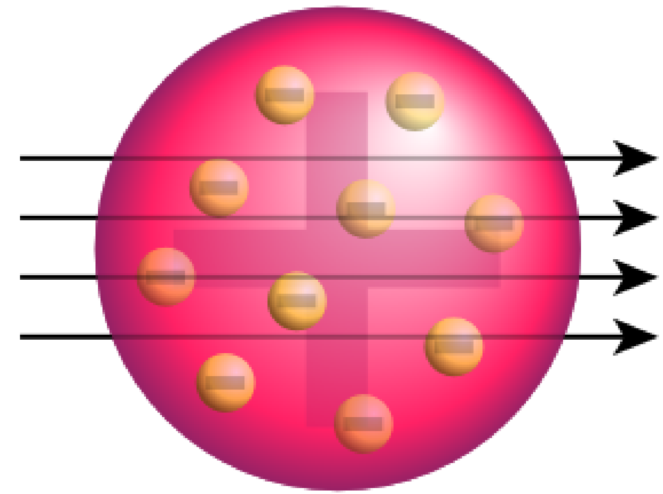
Radioactive elements had been discovered by then: use a source that emits alpha particles.

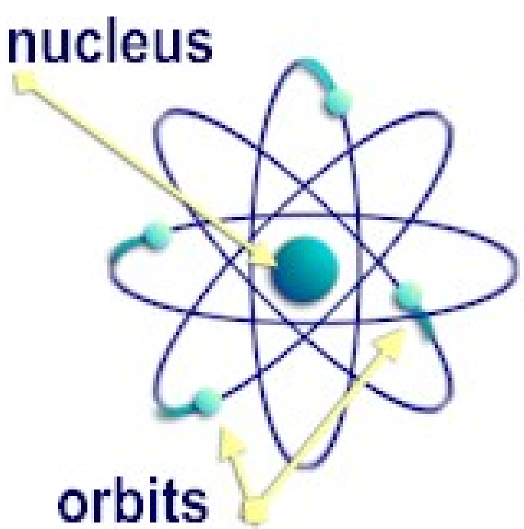
"Rutherford scattering" experiment (done 1909 by Geiger & Marsden, working under Rutherford's direction)

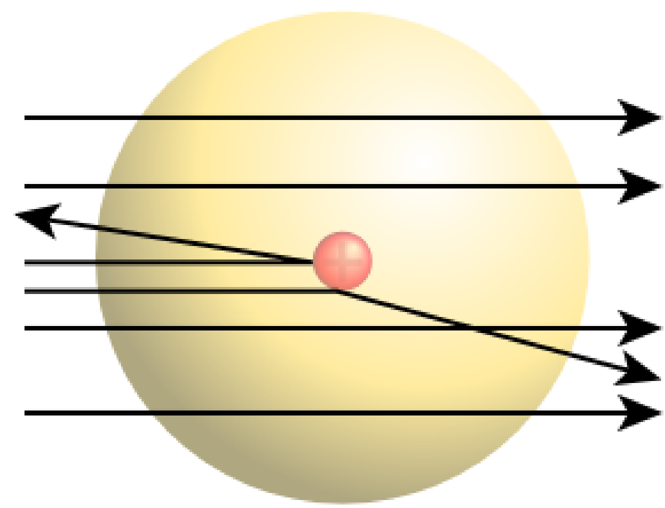


Surprising thing was the large-angle deflections.



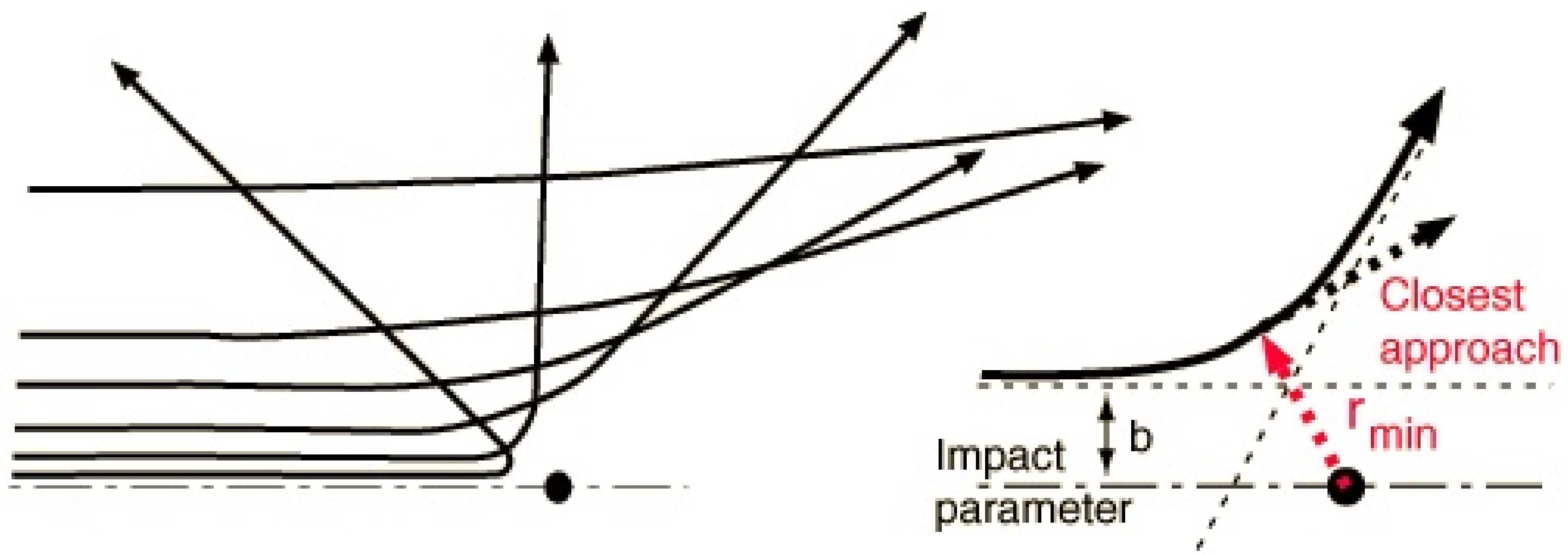


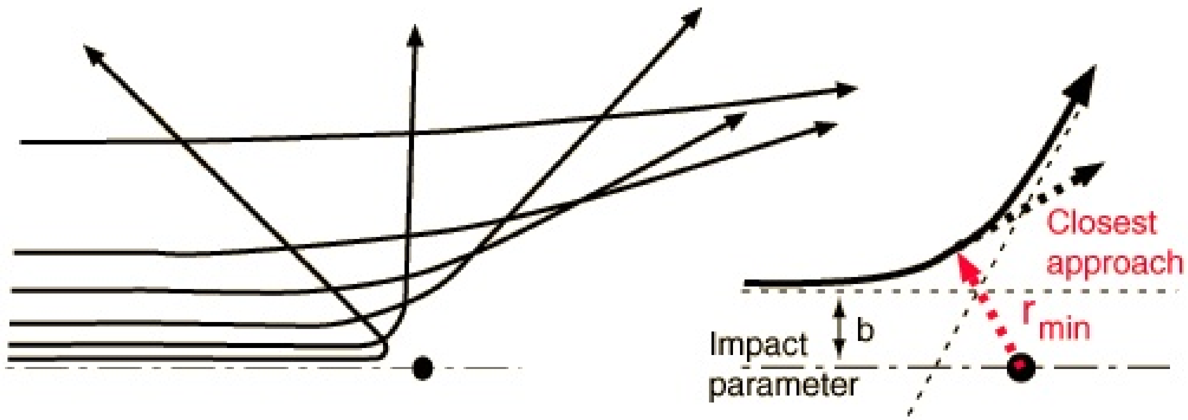




Experiment done 1909, but theoretical interpretation only worked out by Rutherford in 1911.

Understand this using scattering theory: an established idea in classical mechanics.





- Hypothesize the force law from the target:

  Coulomb force in this case, $\vec{F} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}\hat{r}$ outside the nucleus
- Pick a value for the "impact parameter"
- Figure out projectile motion using $\vec{F} = m\vec{a}$
- Predict the scattering angle θ

- Average over the impact parameter: gives a prediction for "count density" as a function of angle.

- Compare to experiment to test the force law hypothesis!

To make things more general, divide out the number of incoming projectiles per square centimetre per second.

This gives what's called a differential cross section (a function of scattering angle in this case): expected number of events per unit angle per unit incoming beam flux. units of cross section are cm^2

- Predicted by the underlying interaction hypothesis
- Can be tested quantitatively in a scattering experiment

This concept is absolutely central in modern particle physics experiments.

Example: [Tevatron]

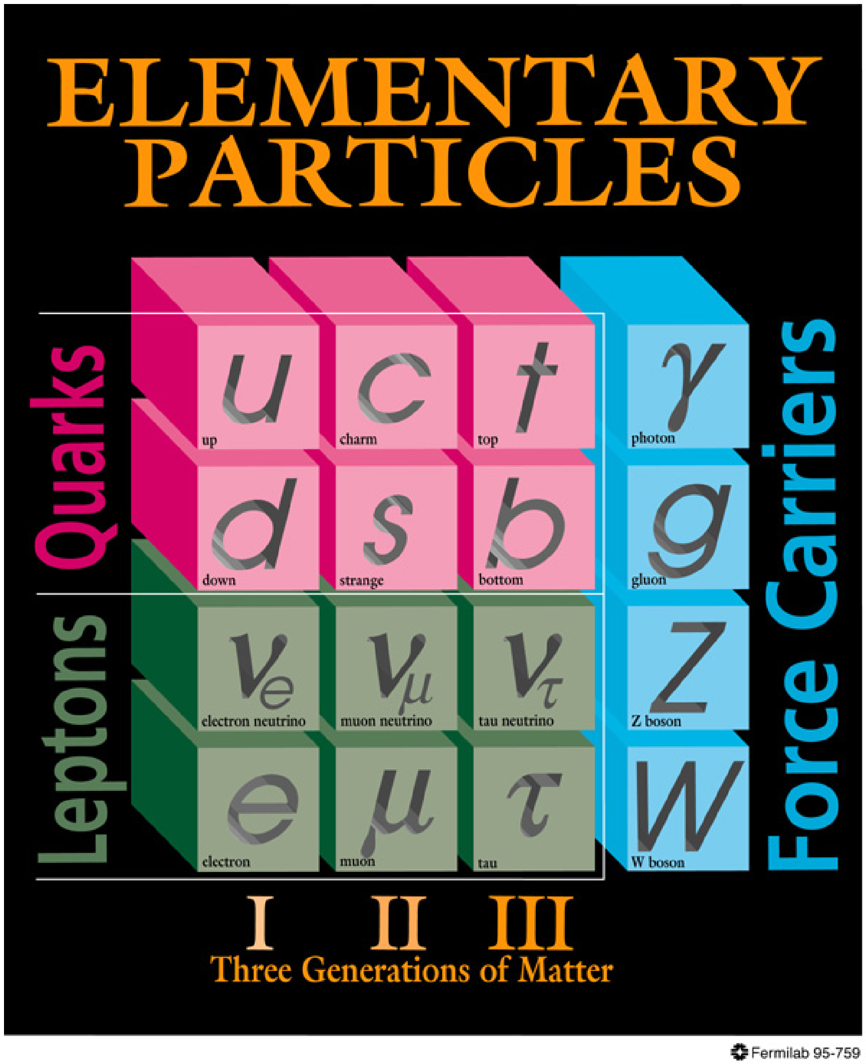
proton + antiproton $\rightarrow$ W boson $\rightarrow$ electron + neutrino

- See the electron in the detector

- See a momentum-conservation mismatch from the neutrino
  (it does not leave a signal in the detector)

- Want to use this, e.g., to measure the W boson mass

W boson changes $u \leftrightarrow d$ or $e^- \leftrightarrow \nu_e$ (for example).
W interacts only with left-handed fermions: nontrivial angular dependence.



Basic process:

$$\bar{u}\ d \to W^- \to e^-\,\bar{\nu}$$

Calculate the differential cross section using Feynman diagrams.

Result is (in the $\bar{u}\,d$ centre-of-mass frame, ignoring quark and electron masses),

$$\frac{d\sigma}{d\cos\theta^*} = \frac{1}{192\,\pi}\left(\frac{g}{2\sqrt{2}}\right)^4 \frac{\hat{s}\,(1+\cos\theta^*)^2}{(\hat{s}-M_W^2)^2+(M_W\Gamma_W)^2}$$

M_W is the W mass
Γ_W is the W decay width
$\hat{s}$ is the square of the centre-of-mass collision energy
θ^* is the angle between the d and e^- momentum vectors

Concrete prediction!

But the Tevatron collides protons and antiprotons, not quarks.

- In each event, the $\bar{u}$ and d can have different energies.
- $\hat{s}$ and $\cos\theta$ were defined in the centre-of-mass frame, which is not the same as the lab frame in each event.
- Have to multiply our differential cross section by the $\bar{u}$ and d quark densities in the colliding protons.

$$\frac{d\sigma(pp \to e^- \bar{\nu})}{d\cos\theta^*} = \int dx_1 dx_2 f_{\bar{u}/\bar{p}}(x_1, q^2) f_{d/p}(x_2, q^2) \frac{d\sigma(\bar{u}d \to e^- \bar{\nu})}{d\cos\theta^*} + \text{same with } f_{\bar{u}/p} f_{d/\bar{p}}$$

$f(x, q^2)$ are parton density functions that describe the quark content of the proton: fitted to data from previous experiments (another job for phenomenologists)

Another complication: the momentum of the W in the beam direction is different event-by-event!

If we could measure the momenta of the e^- and $\bar{\nu}$ in each event, we could calculate the momentum of their parent W, boost to its rest frame, and figure out $\hat{s}$ and $\cos\theta^*$.

But the neutrino is invisible to the detector: we can't measure the component of the W momentum along the beam direction!

(We can infer the transverse components of the neutrino's momentum by measuring the momentum-conservation mismatch.)

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Difficulty: don't know how fast the W is going along the beam direction when it's produced.

Instead, measure a rather esoteric quantity called the "transverse mass" in each event, made up just of the energy/momentum perpendicular (transverse) to the colliding beams:

$$M_T = \sqrt{(E_T^e + E_T^\nu)^2 - (\vec{p}_T^e + \vec{p}_T^\nu)^2}$$

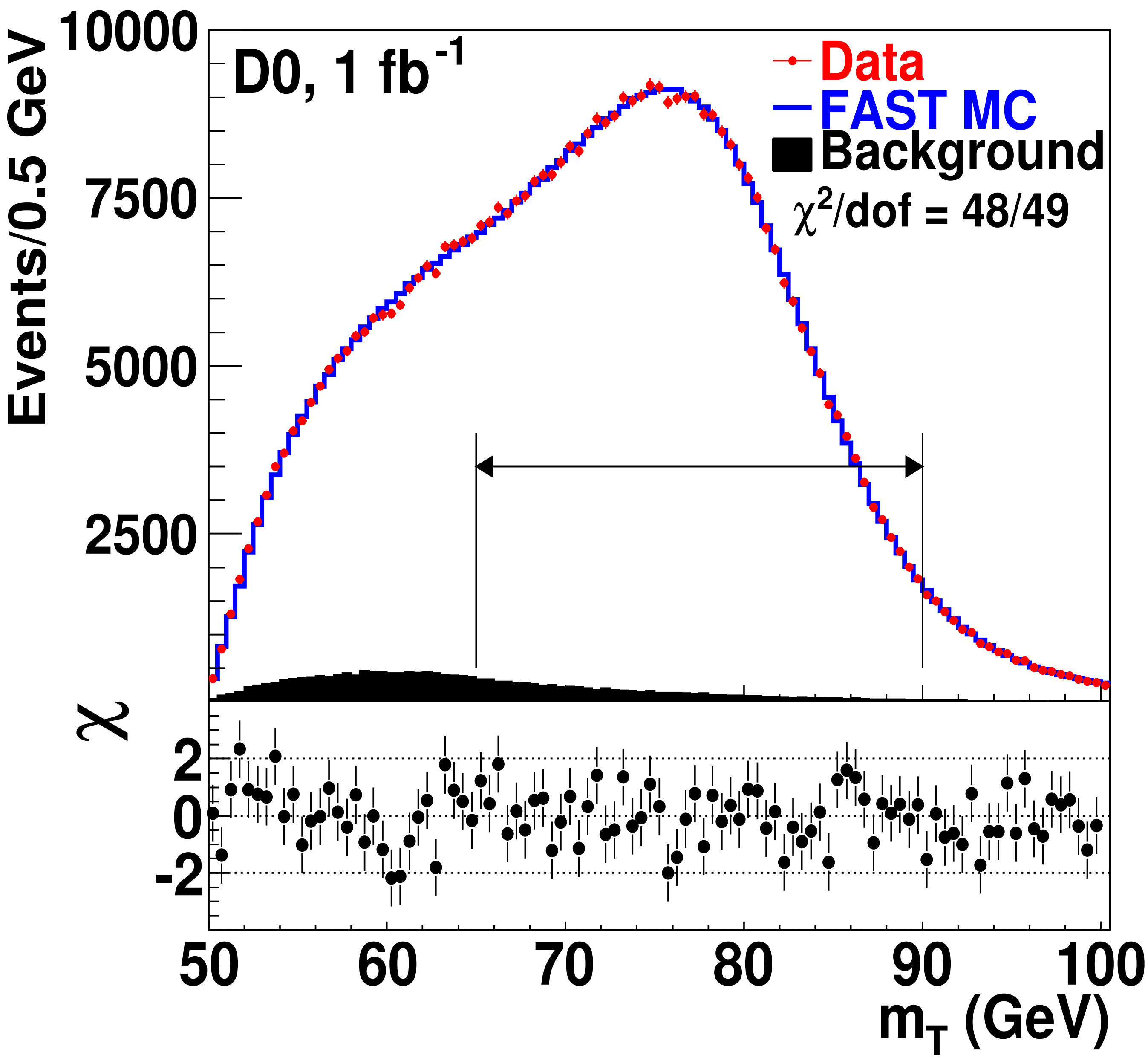
M_T is not the same in each event.
- depends on which direction the W decay products come out

But we (phenomenologists) can predict the probability distribution for M_T very precisely if we know the W boson's mass and decay width.

- Make the prediction for a bunch of different mass guesses.
  need to calculate the M_T probability distribution for each guess

- Collect a lot of data.
  need enough events to statistically populate the distribution

- Check how well each mass hypothesis fits the data.
  find the mass value that gives the best fit to the data
  simultaneously fit the W width



Just under 500,000 $W \to e\,\nu$ candidates from the D0 detector at the Tevatron collider at Fermilab

Fitted W mass:

80.401 $\pm$ 0.043 GeV

(precision of 1 part in 2000!)

see, e.g., PoS EPS-HEP2009, 361 (2009) The hard work here is the detector calibration!

MC = Monte Carlo:

Physicists' name for a computer program that simulates events based on a probability distribution. A reference to "rolling the dice" :)

Lets us produce "simulated events" with the same features that you would measure in an actual detector:

- map the differential cross section without doing awful integrals

- do a dry run of the analysis, develop good techniques

- see what "backgrounds" (known processes) will look like

- figure out what the "signal" we're looking for will look like, depending on the underlying physics

- finally, use all this to work backwards to figure out the underlying physics

Why have specialists in phenomenology?

- large-scale, complicated calculations often needed for precise predictions: particularly processes involving strong interactions

- figure out how to search for new models for "new physics": Start with some "elegant" symmetry structure, proposed to solve some problem of the Standard Model.
Have to work out what the particles are, how they would be produced, how they would decay, how all this depends on free parameters of model, and how to tell this model apart from competing models.

- invent new data-analysis methods to search for particles or make desired measurements

- gather experience with many "new physics" models:
Develop "intuition" to guess type of underlying physics based on characteristics of new signatures

So why do we care about the W mass so much?

- It's a fundamental parameter of the Standard Model

- Its value affects other predictions for cross sections, etc

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Who cares?

The real reason is that it tells us about the Higgs!

The electroweak part of the Standard Model has only 3 basic parameters:

- Z boson mass
- electromagnetic coupling constant
- muon decay constant (related to Higgs vacuum expectation value)

All 3 are measured super precisely
$\rightarrow$ Predict the W mass!

But this prediction gets small shifts due to radiative corrections (also the job of phenomenologists), which depend on:
- top quark mass (measured)
- Higgs boson mass (unmeasured Holy Grail of the LHC!)

Measure M_W $\rightarrow$ get a handle on the Higgs mass!

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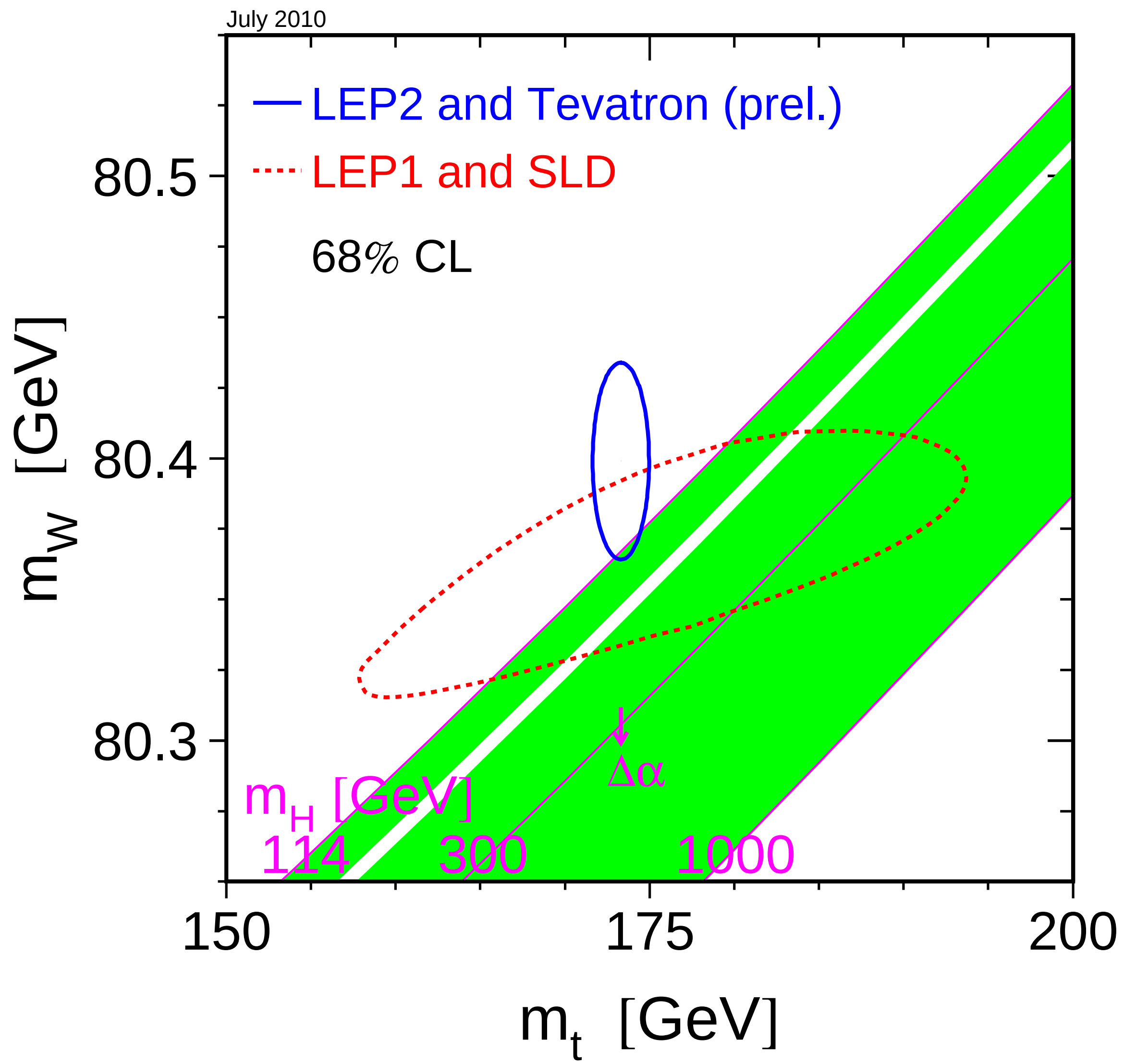
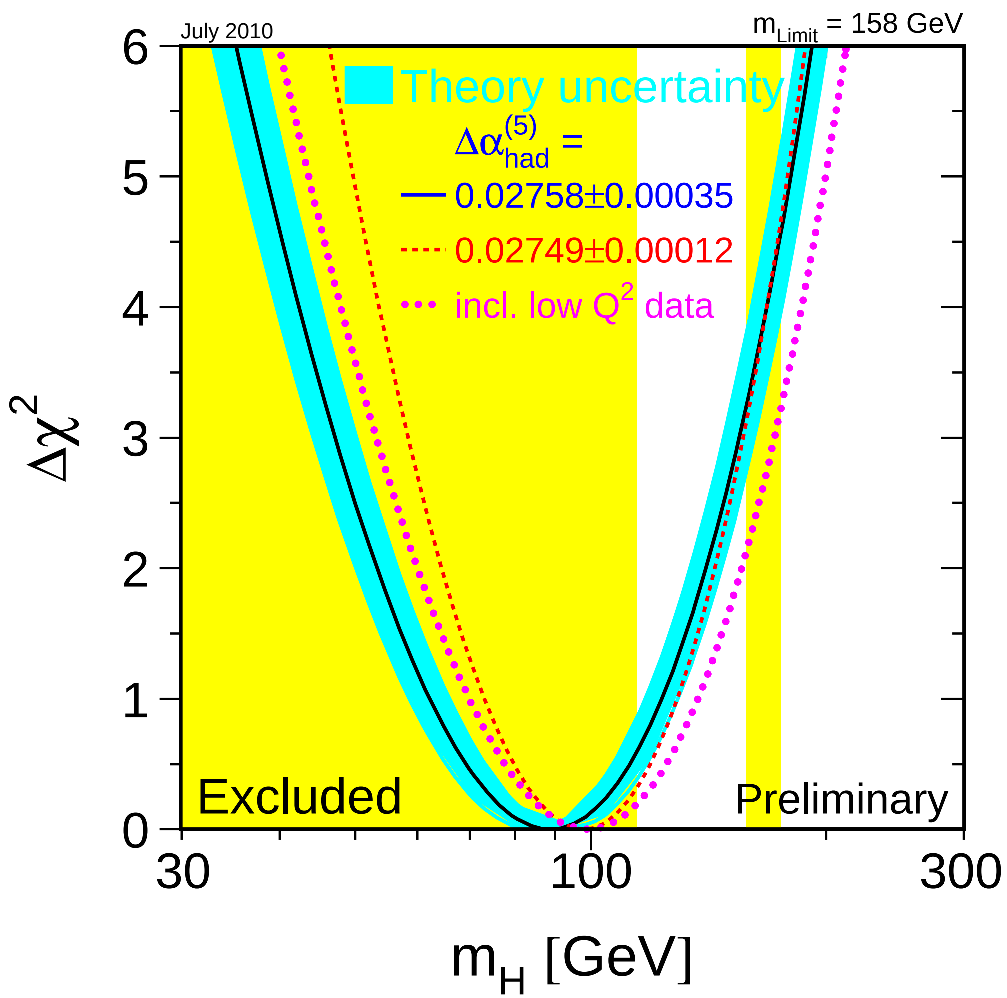
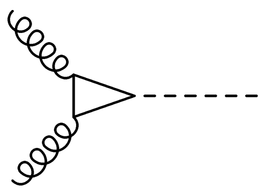


- Tells us where to concentrate our Higgs searches
- If a heavier Higgs is found, tells us there is also New Physics

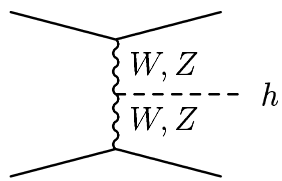


Phenomenologists also help figure out how to look for the Higgs. Predictions for Higgs production...

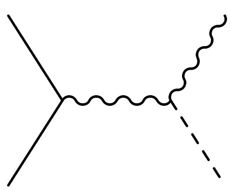
- Gluon fusion, $gg \to H$



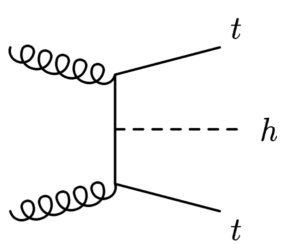
- Weak boson fusion, $qq \to Hqq$

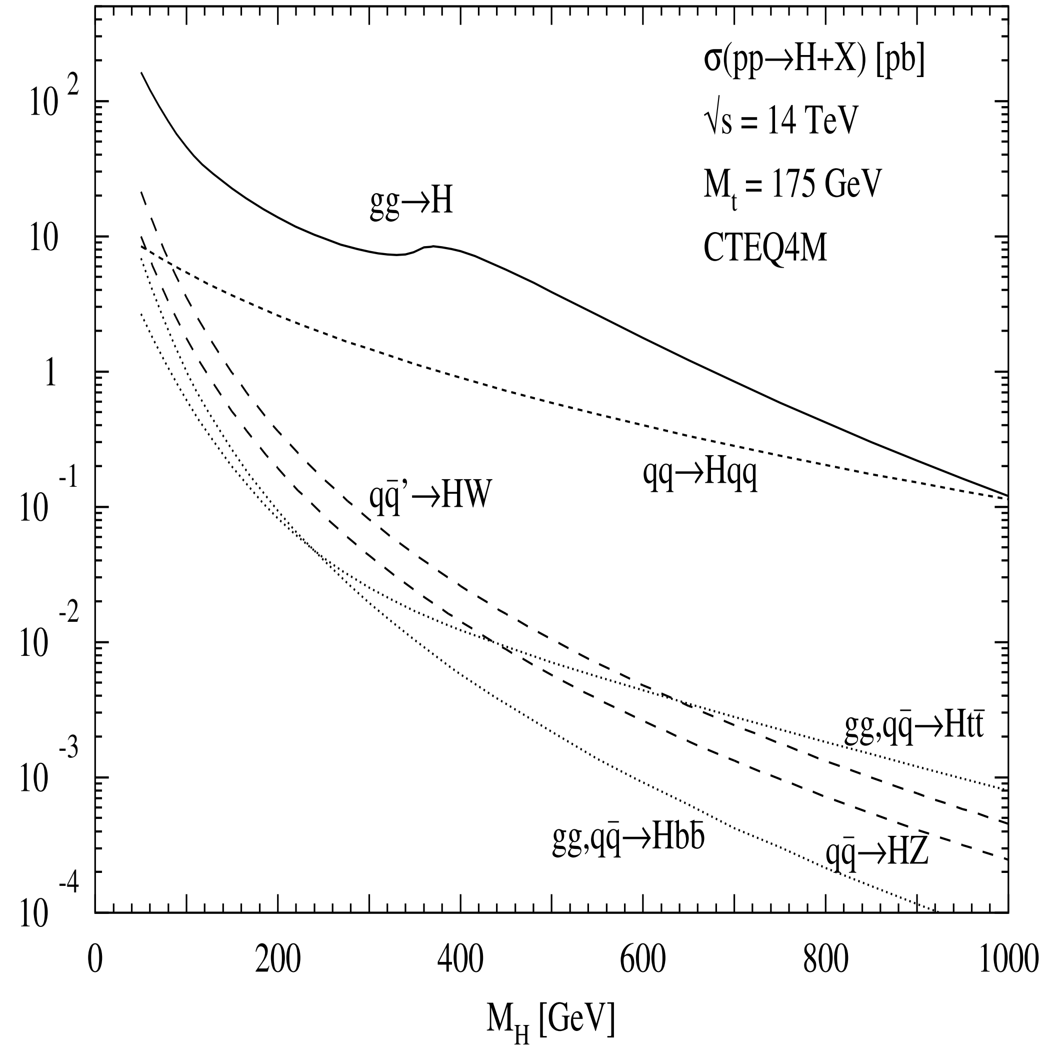


- WH, ZH associated production



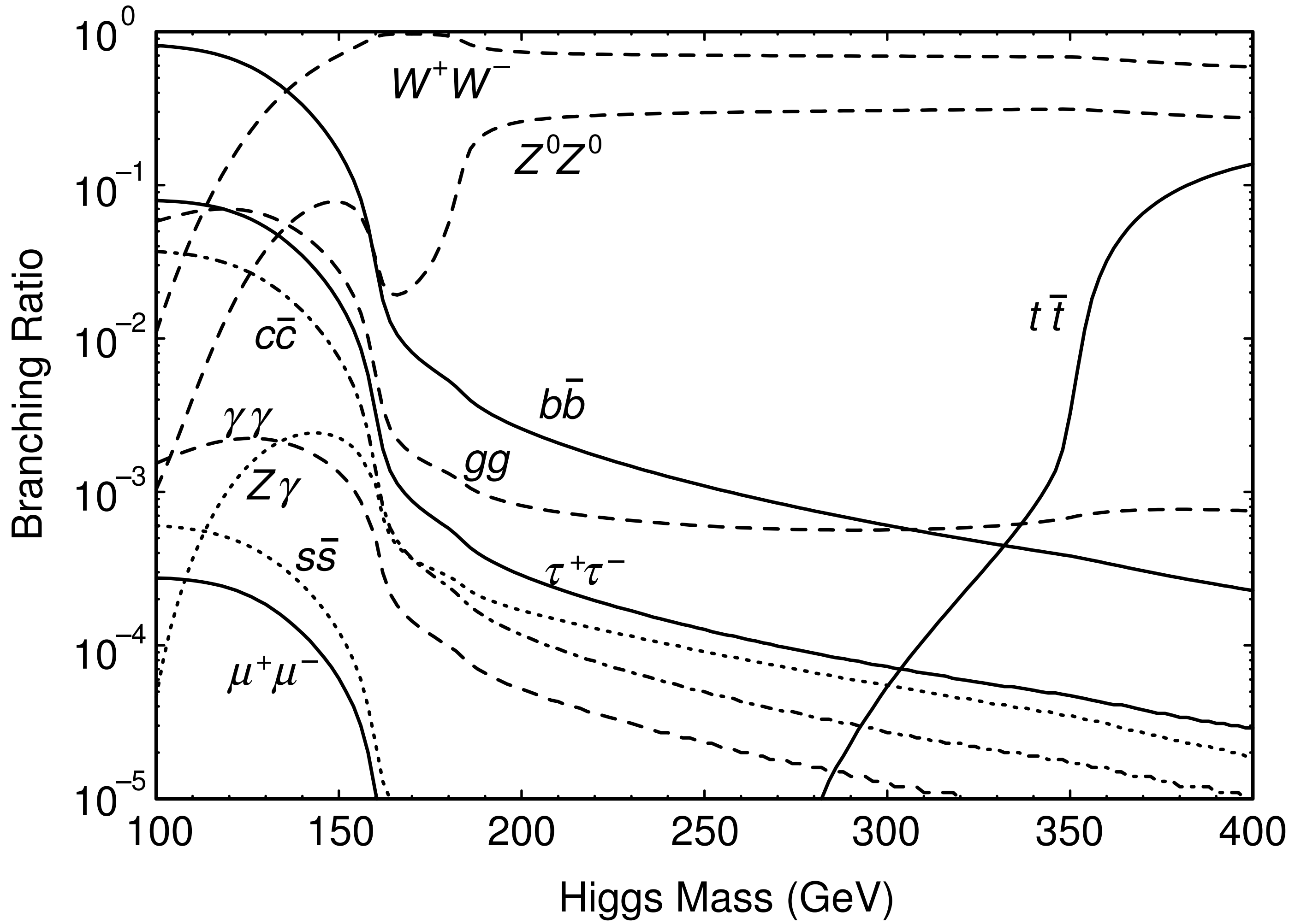
- ttH associated production





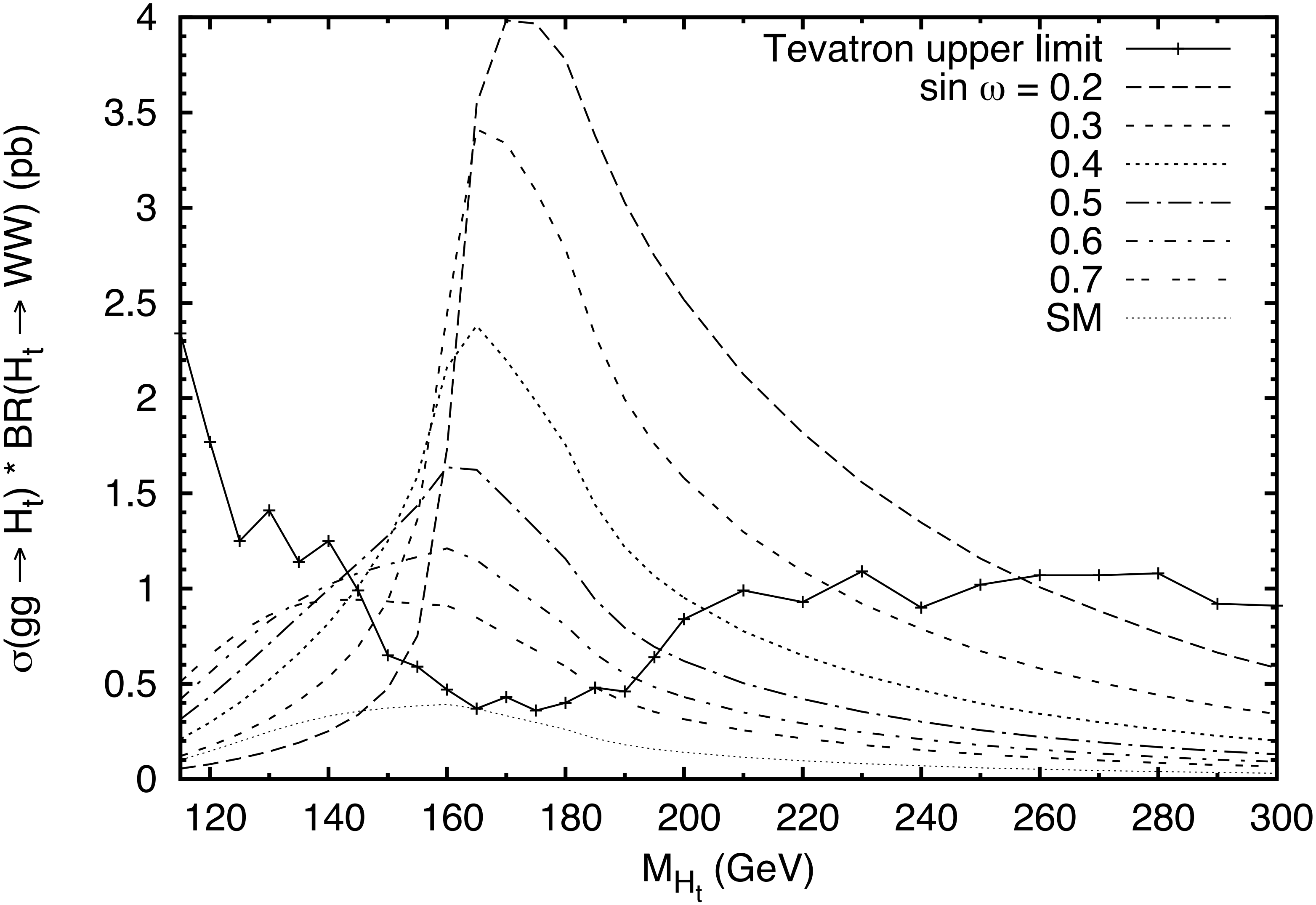
M. Spira, Fortsch. Phys. 46, 203 (1998)

Phenomenologists also help figure out how to look for the Higgs.
... and decay...



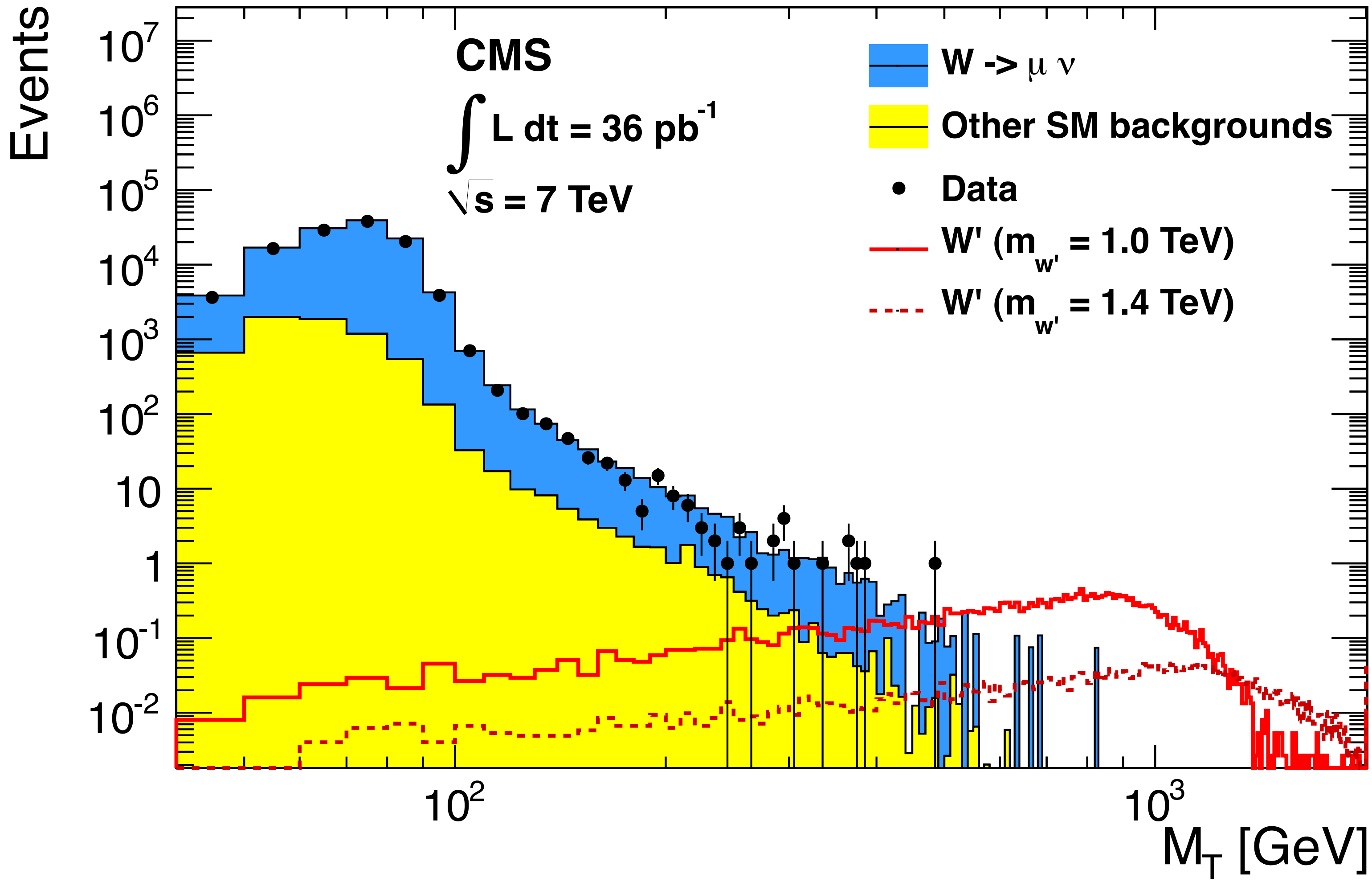
HDECAY (Decay modes depend on Higgs mass.)

Phenomenologists also help figure out how to look for the Higgs.
... and how to look for exotic Higgses in New Physics models.



[Chivukula et al, arXiv:1101.6023]

At the same time, use these techniques to search for New Physics



CMS, arXiv:1103.0030 (data from 2010 LHC run)

exclusion limit 1.4 TeV for SM-strength couplings; 1.58 TeV when combined with $e\nu$ channel

Outlook

Right now particle physicists are tremendously excited about the potential for new discoveries at the LHC.

The next 2 - 12 - 24 months could revolutionize our understanding of physics at the smallest scales.

- March-April 2011: analyses of the first LHC data collected last year will be finishing.
- LHC will run all this year and 2012, then shut down for $\sim$1 year for installation of new parts that will let it run at higher energy.

Phenomenology helps us know what to expect, what to look for, and (hopefully) how to interpret new results!