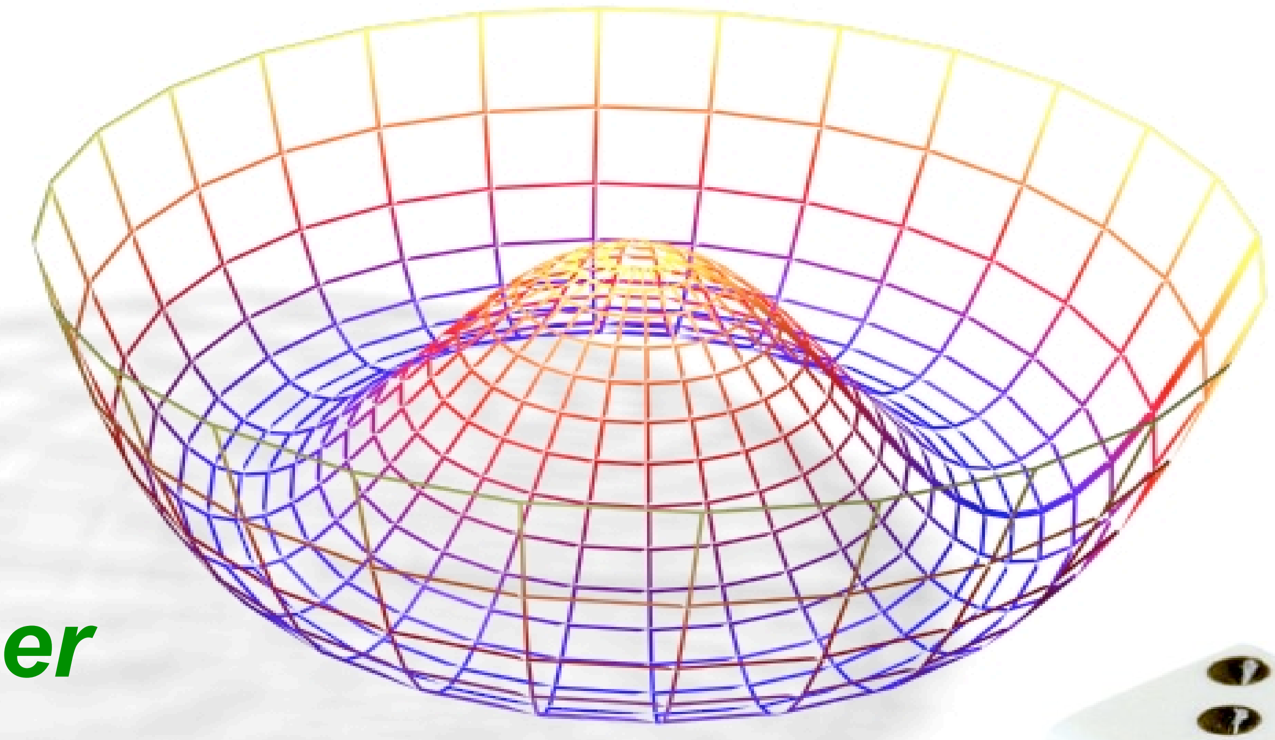
Progress, Challenges, and Future of Statistics for the LHC



Kyle Cranmer (BNL)

Overview

At PhyStat 05, I presented the "Statistical Challenges of the LHC"

- focused mainly on searches for specific signatures like the Higgs boson
    - with emphasis on systematics/nuisance parameters
- didn't have time to discuss the problems we face in other scenarios where the "signal" is poorly defined

Since the last PhyStat there has been a lot of progress

- I will present some of the major developments

I will also try address the challenge posed by the other scenarios

- Supersymmetry &"Beyond the Standard Model" (BSM) searches

I will end with some comments and outlook on statistical aspects of our field

Particle Physics in a Nutshell
&
Introduction to Notation

The Standard Model of Particle Physics

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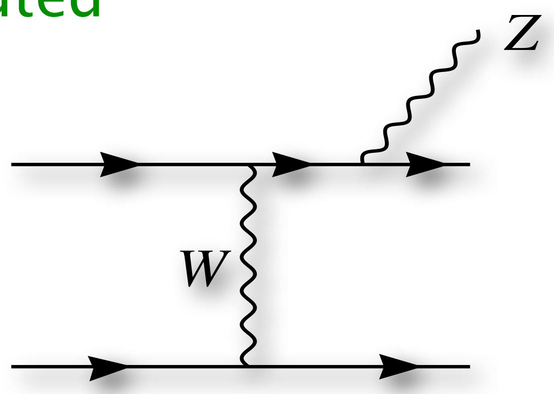
We have a theoretical formalism called Quantum Field Theory, which allows us to predict

- the probability a particular interaction will occur
  - called “cross-section” or rate of events
  - number of observed events n is Poisson distributed
- distributions of angles, energies, masses, etc. of particles produced
  - generically called discriminating variables,
  - denoted $f(m)$



The “Standard Model” is specific theory that has survived all our tests so far. It is our Null and is often called “background-only” hypothesis.

- expected rate typically denoted b

$$L(\mathbf{m}|H_0) = Pois(n|b) \prod_j^n f_b(m_j)$$

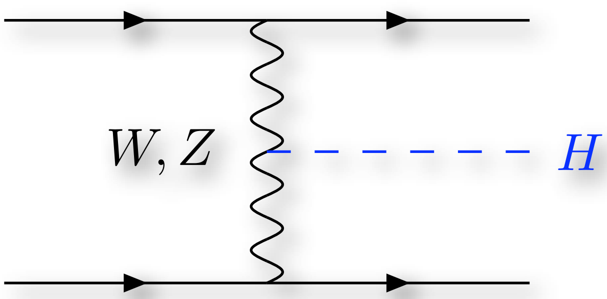
New Physics Signals

Many reasons to believe that the Standard Model is not complete and that we will see new particles produced at the LHC.

- new particles generically called "signal"
- many theoretical candidates for these new particles

Rate and distribution of new particles are also predicted

- rate denoted as s or μ and distribution denoted as $f_s(m)$
- consider case when signal is additive to the background



Leads to a likelihood ratio like this:

$$\frac{L(\mathbf{m}|H_1)}{L(\mathbf{m}|H_0)} = \frac{\prod_i^{N_{chan}} Pois(n_i|s_i+b_i) \prod_j^{n_i} \frac{s_i f_s(m_{ij}) + b_i f_b(m_{ij})}{s_i+b_i}}{\prod_i^{N_{chan}} Pois(n_i|b_i) \prod_j^{n_i} f_b(m_{ij})}$$

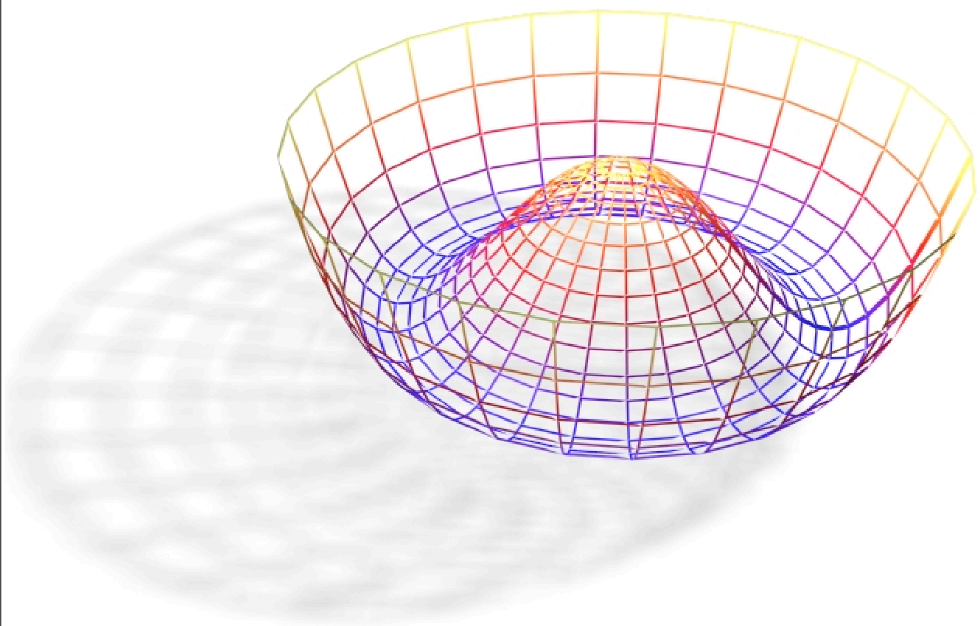
The theoretical model for the standard model **Higgs** only has **one free parameter**:

- The mass of the Higgs boson m_H

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

With m_H specified, the theory predicts:

- production rates
- angular distributions
- branching ratios $H \to ZZ, WW, \gamma\gamma, \tau\tau$



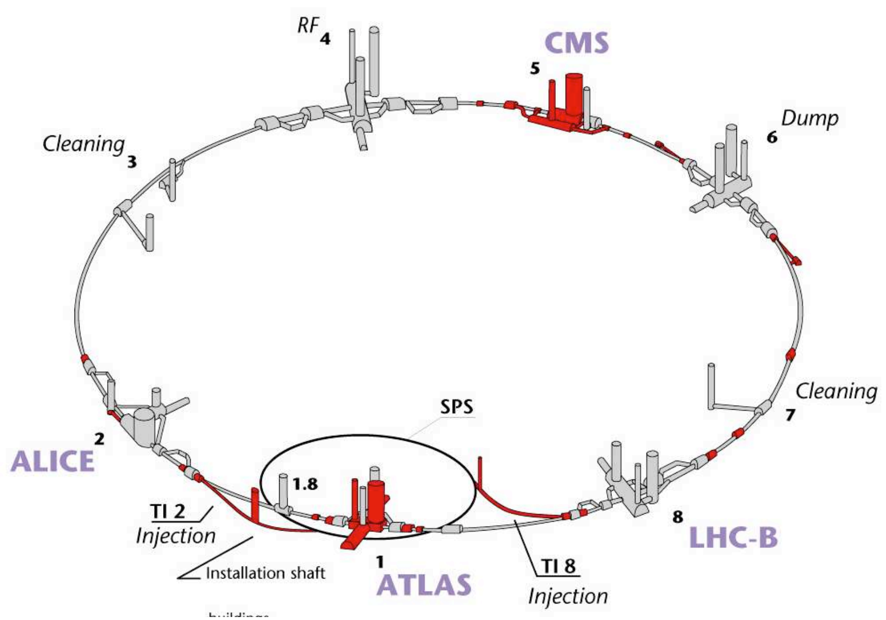
Supersymmetry is more of a framework than a theory *per se* (we don't know how the symmetry is broken)

MSSM is a parametrized theory of all soft-SUSY breaking terms: **has 105 parameters!**

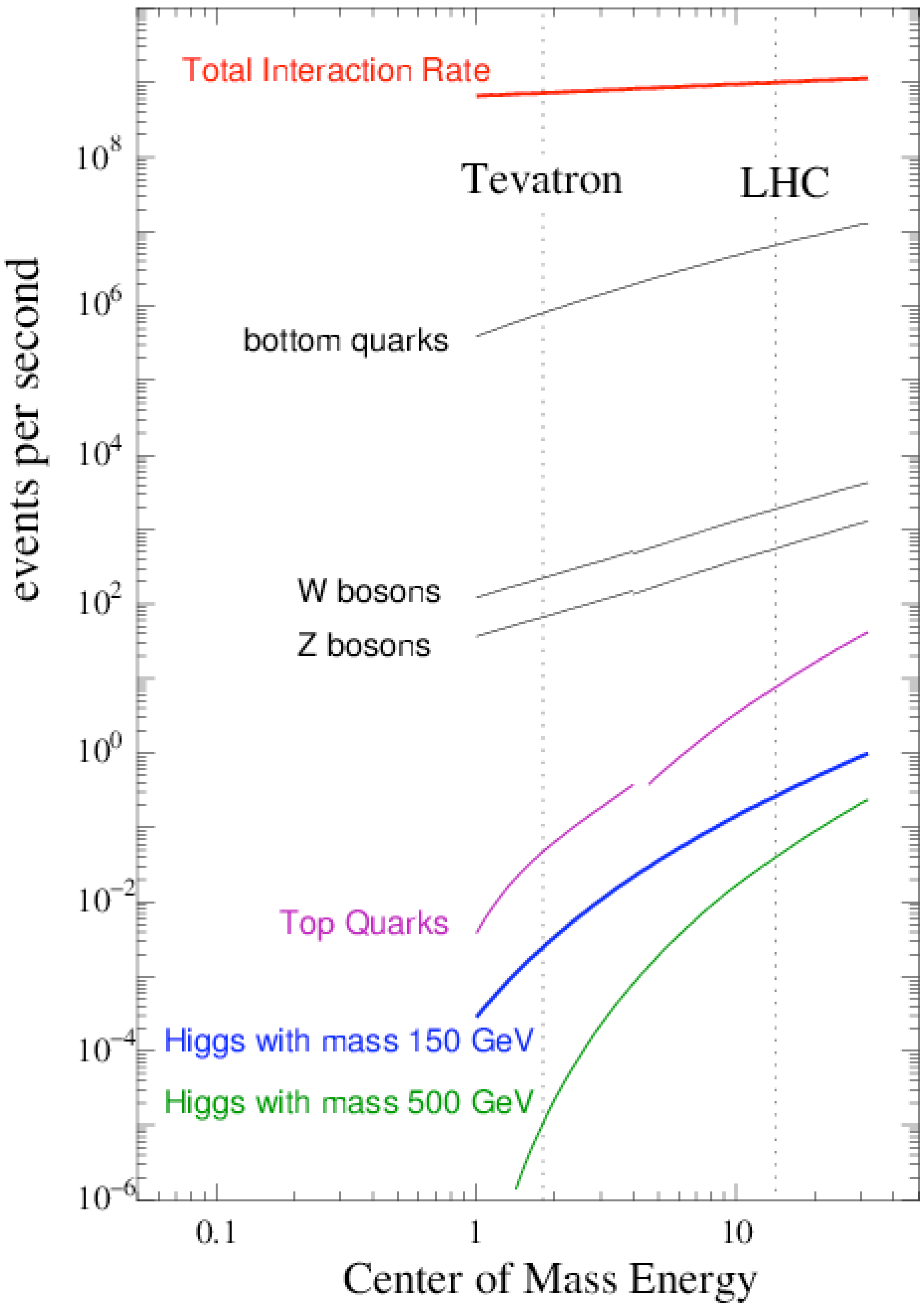
Other models like mSUGRA, mGMSB, mAMSB have $\sim$ 4 parameters

SUSY searches focused more on inclusive signatures for discovery and mass measurements for parameter determination

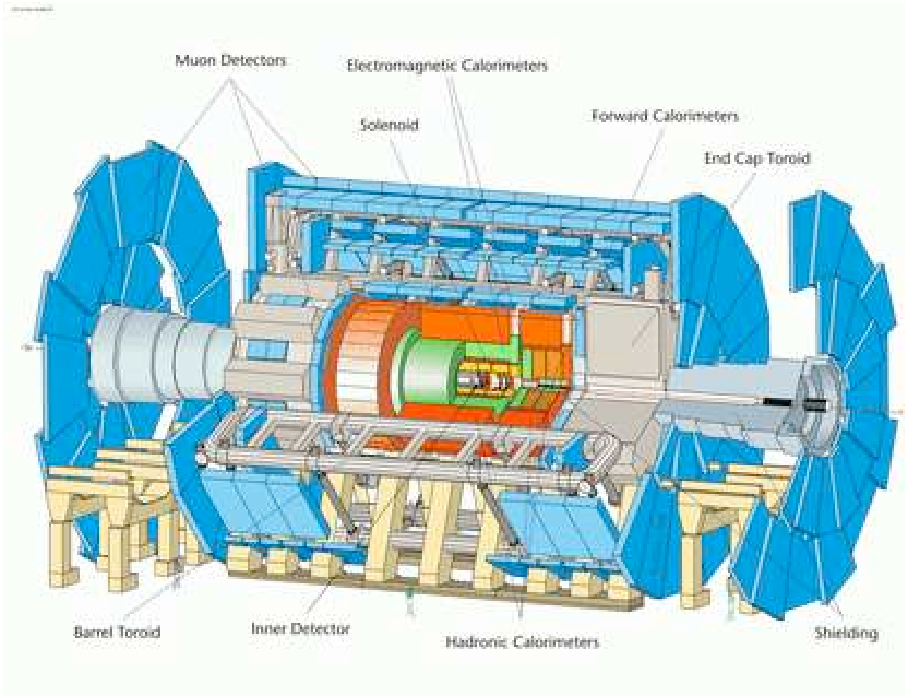
The LHC



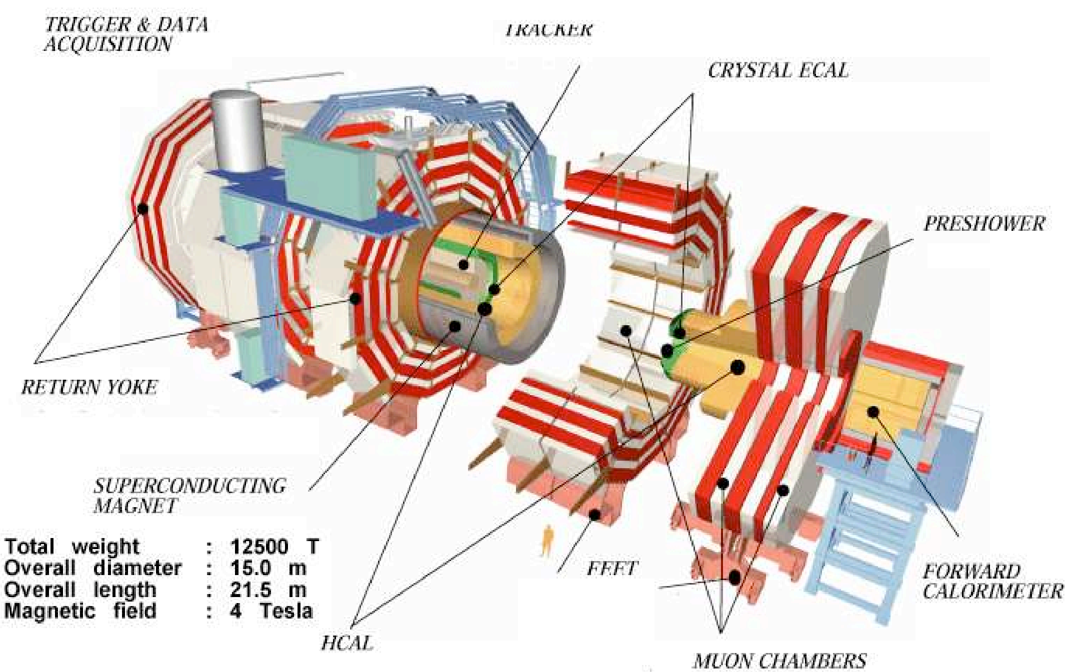
- 26 km in circumference
- p-p @ $\sqrt{s} = 14$ TeV
- Instantaneous Luminosity $\approx 10^{33} - 10^{34}$ cm^{-2}s^{-1}
- "pile-up" : 2-20 inelastic collisions per bunch crossing
- 40 MHz bunch crossings



ATLAS & CMS Detectors



Both experiments have ~2000 collaborators!



ATLAS

- Length ≈ 40 m
- Radius ≈ 10 m
- Weight ≈ 7000 tons
- Electronic Channels ≈ 10^8

The ATLAS & CMS are a multipurpose detectors...

flexible enough for the surprises which may lie ahead!

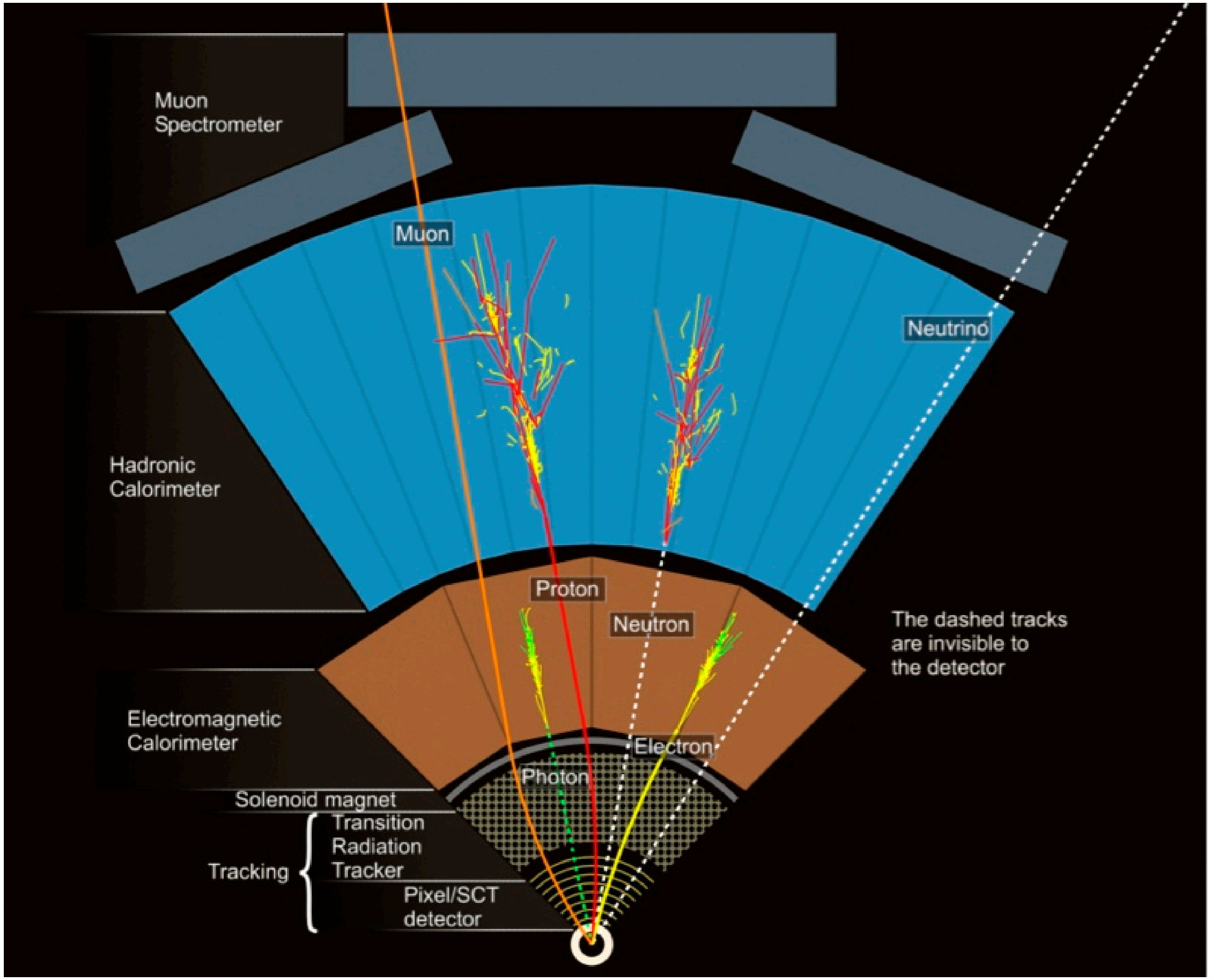
The advancements in theoretical predictions, detector technology, and computing set the bar high for equivalent advances in our statistical treatment of the data.

Reconstruction

Each event has information from nearly 10^8 electronic sensors!

Reconstruction algorithms try to identify the various particle types and measure their energy, direction, & charge

- 100 GeV electron measured to ~1%
  - fake rate from jet 10^{-5}
- Muon momentum resolution ~10% at 1TeV
- Jet response (optimistic) $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$
- for 50% τ efficiency, jet rejection about 500

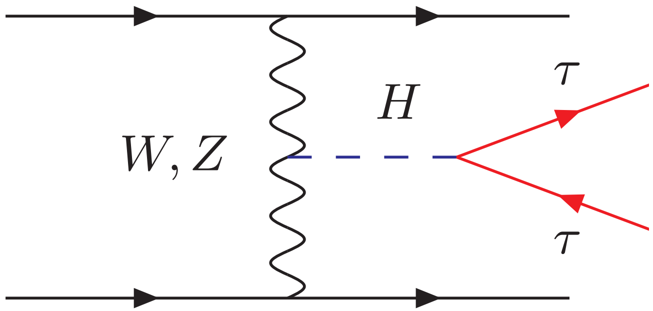


Experimental Effects

Ultimately, what we observe is a convolution of:

- some underlying particle interaction,
- the detector response, trigger, and reconstruction algorithms

$L(m|H) =$



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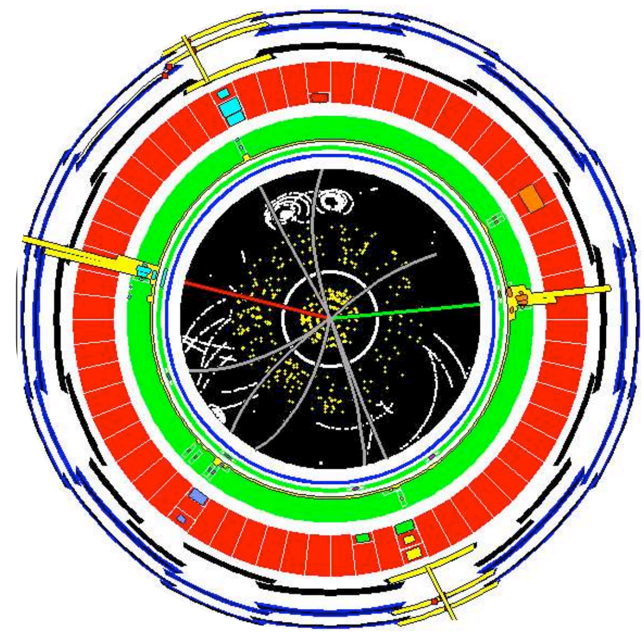

Understanding these effects is difficult and introduces systematic uncertainties!

Systematics, Systematics, Systematics

Classification of Systematic Uncertainties

Taken from Pekka Sinervo's PhyStat 2003 contribution

Type I – "The Good"

- can be constrained by other sideband/auxiliary/ancillary measurements and can be treated as statistical uncertainties
  - scale with luminosity

Type II – "The Bad"

- arise from model assumptions in the measurement or from poorly understood features in data or analysis technique
  - don't necessarily scale with luminosity
  - eg: "shape" systematics

Type III – "The Ugly"

- arise from uncertainties in underlying theoretical paradigm used to make inference using the data
  - a somewhat philosophical issue

A Prototype Problem

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What is significance Z of an observation $x = 178$ events in a signal like region, if my expected background $b = 100$ with a 10% uncertainty?

- if you use the ATLAS TDR formula $Z_{5'} = 5.5$
- if you use Cousins-Highland $Z_N = 5.0$

The question seems simple enough, but it is not actually well-posed

- what do I mean by 10% background uncertainty?

Typically, we consider an auxiliary measurement y used to estimate background (Type I systematic)

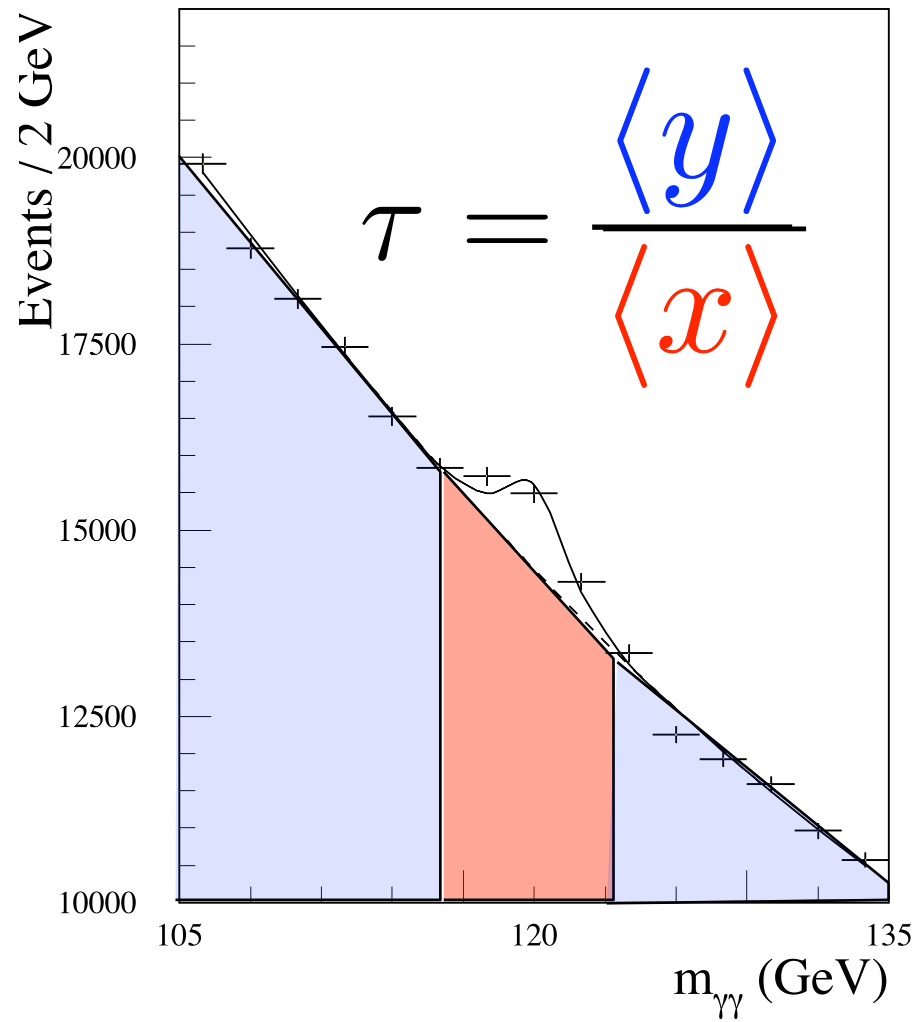
- eg: a sideband counting experiment where background in sideband is a factor τ bigger than in signal region

$$\boxed{L_P(x, y|\mu, b) = Pois(x|\mu + b) \cdot Pois(y|\tau b).}$$

Example Sideband Measurement

Sideband measurement used to extrapolate / interpolate the background rate in signal-like region

For now ignore uncertainty in extrapolation.



$$L_P(x, y|\mu, b) = Pois(x|\mu + b) \cdot Pois(y|\tau b).$$

Comparison of Methods for Prototype Problem

In my contribution to PhyStat2005, I considered this problem and compared the coverage for several methods

- See Linnemann's PhyStat03 paper

Major results:

- Cousins-Highland result (Z_N) badly under-covers (only 4.2σ)!
  - rate of Type I error is 110 times higher than stated!
  - much less luminosity required
- Profile Likelihood Ratio (MINUIT/MINOS) works great out to 5σ!

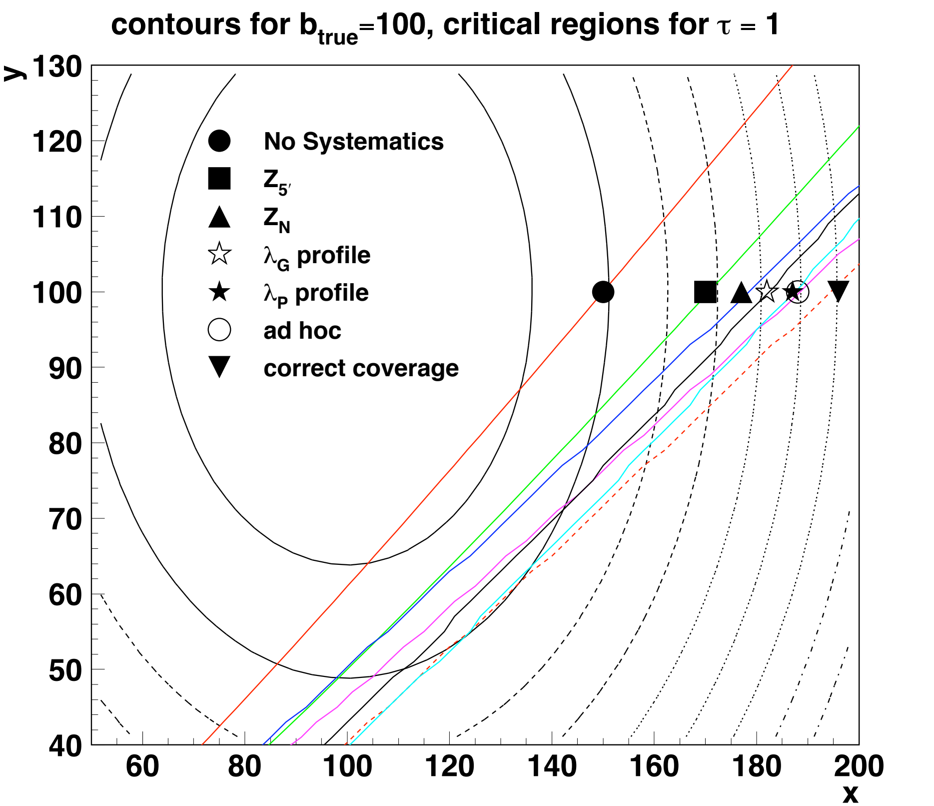


Figure 7. A comparison of the various methods critical boundary $x_{crit}(y)$ (see text). The concentric ovals represent contours of L_G from Eq. 15.

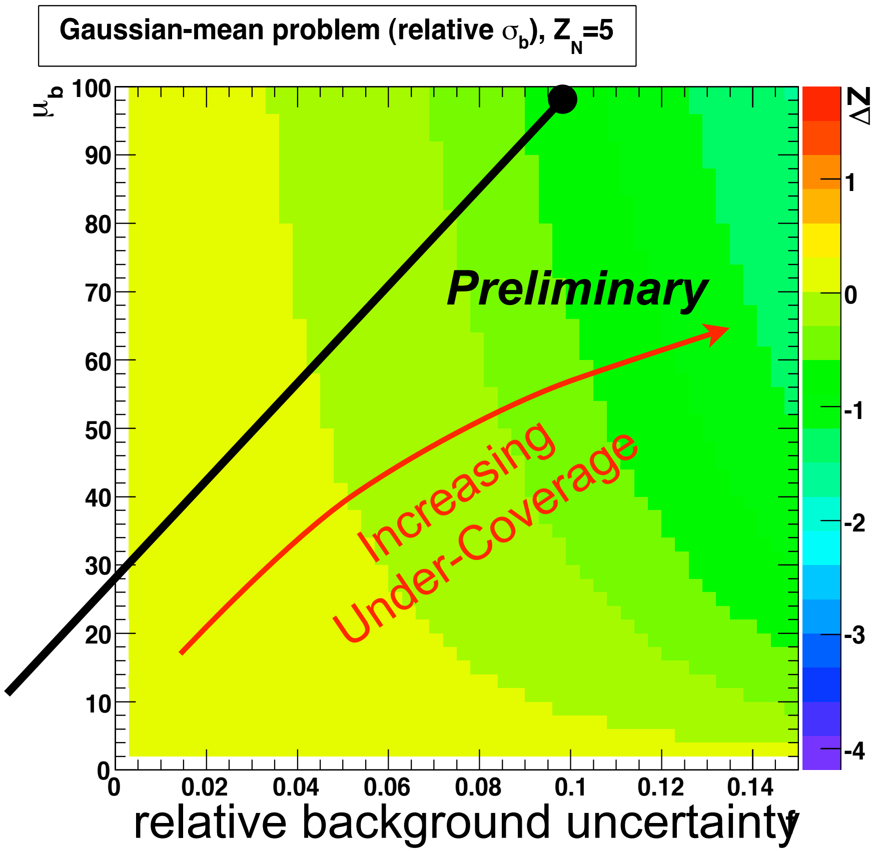
Method	L_G $(Z\sigma)$	L_P $(Z\sigma)$	$x_{crit}(y=100)$
No Syst	3.0	3.1	150
$Z_{5'}$	4.1	4.1	171
Z_N (Sec. 4.1)	4.2	4.2	178
ad hoc	4.6	4.7	188
$Z_\Gamma = Z_{Bi}$	4.9	5.0	185
profile λ_P	5.0	5.0	185
profile λ_G	4.7	4.7	$\sim$182

More on the problem with Z_N

The significant under-coverage of Z_N is important because:

- that is what was used for LEP Higgs
- that has been the standard of the Higgs group
- that was used in the CMS TDR

The result has been cross-checked and generalized by Bob Cousins and his student Jordan Tucker



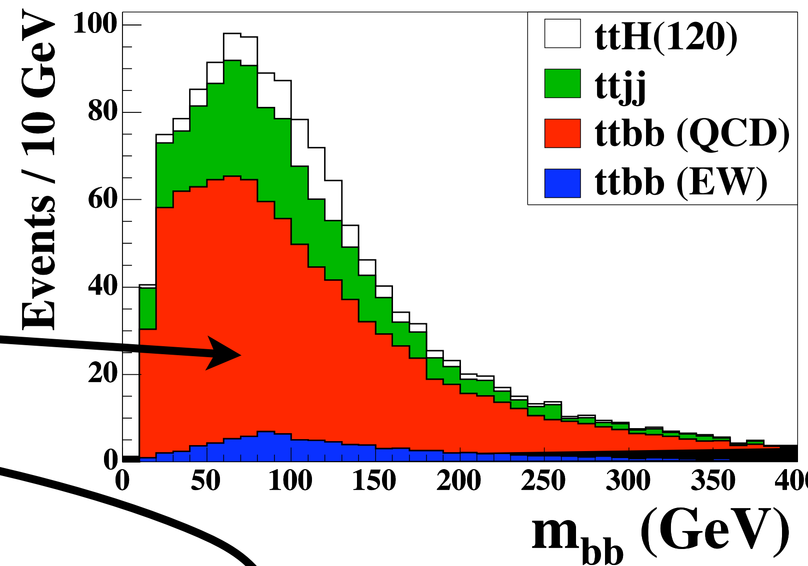
Recent work by Bob Cousins & Jordan Tucker, [physics/0702156]

Corollary: we don't want to be in a situation where ATLAS (CMS) uses one technique and CMS (ATLAS) uses another, which takes significantly less data to claim a discovery.

Type II Systematics

Type II systematics generally due to uncertainty in shape of background

- this uncertainty is limiting factor in $ttH(H \to bb)$ analysis
- also relevant for $H \to \gamma\gamma$



A huge amount of effort goes into identifying other measurements that can be used to estimate or constrain the background

- control samples are an important tool for experimentalists

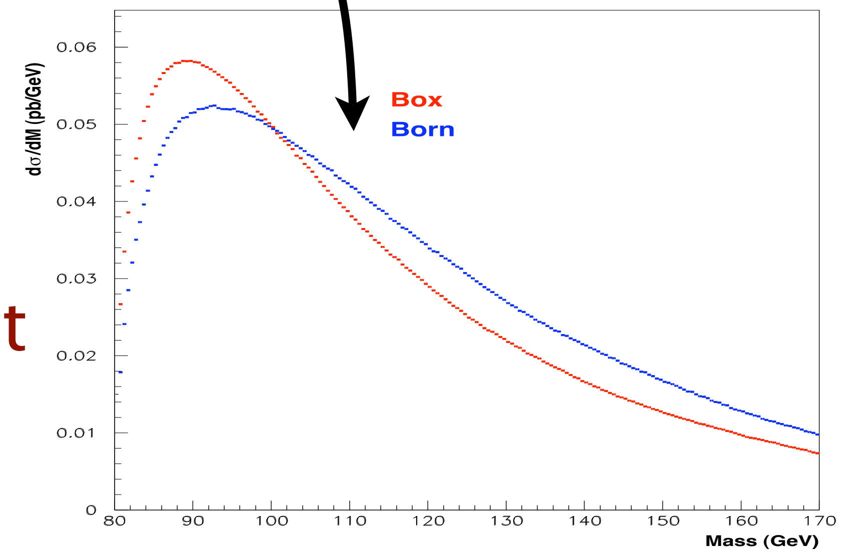


Figure 5. Two plausible shapes for the continuum $\gamma\gamma$ mass spectrum at the LHC.

Type III Systematics

Type III Systematics are related to variations in inference from uncertainty in the overall theoretical framework

- Bayesian approach: assign priors over the "framework space"
- Sinervo suggests Frequentist can't incorporate them because one cannot find an ensemble associated to the theories, but
  - theoretical framework should be thought of as an additional nuisance ***parameter*** (possibly discrete) – can be incorporated!
  - only need an ensemble of some observable if one wants to ***constrain*** the space of the theories, not to incorporate them
  - if theoretical framework influences our experimental result, then we don't really know what we are doing!

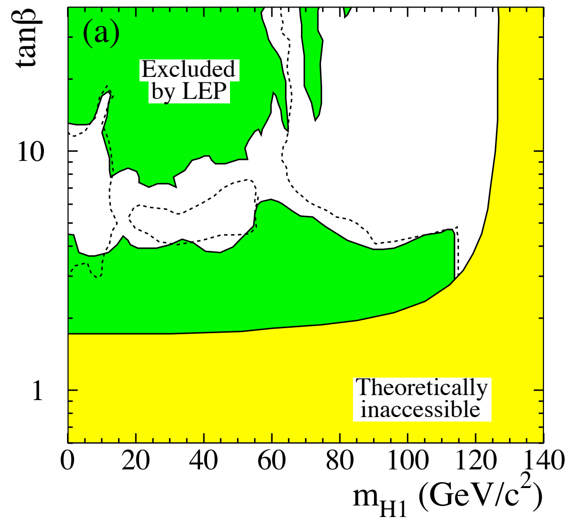
Taken from Cousins' Phystat05 talk:

- A.W.F. Edwards (in Kalbfleisch 1970): "Let me say at once that I can see no reason why it should always be possible to eliminate nuisance parameters. Indeed, one of the many objections to Bayesian inference is that is always permits this elimination."

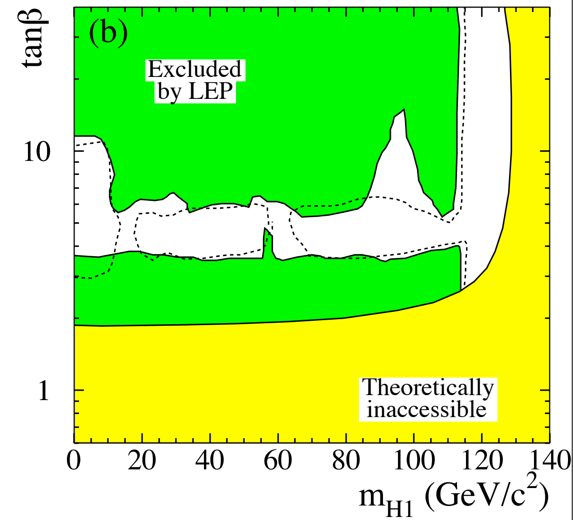
An Example of Type III Systematics

Two theoretical tools used to exclude regions of CPX Higgs scenario using the same measurement & statistical techniques

CPH calculation



FeynHiggs calculation

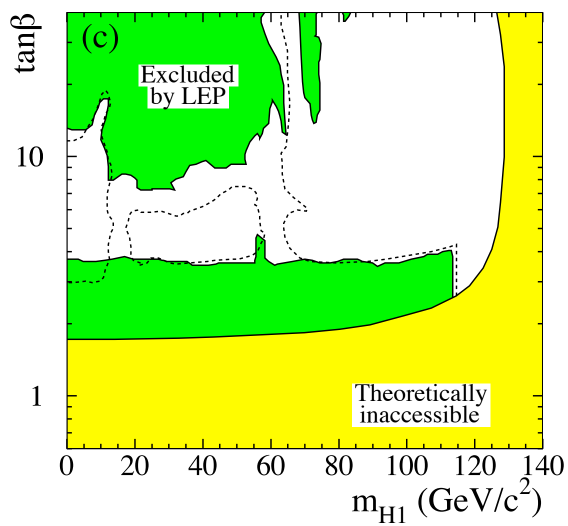


Do we want to weight these plots with a Bayesian prior,

– or –

Do we want to only exclude in the region where they both exclude?

CPH .OR. FeynHiggs



A Few Points on Multivariate Techniques

Results From CDF

PhyStat-LHC
June 27th, 2007

- CDF experiment also searched in 955 pb^{-1} of data
  - Three separate analyses find conflicting results
- Qualitatively different statistical treatments in each case
  - Neural Network: CLs-type confidence levels with profile LH
    - ➔p-Values defined for for **H0** [**H1**] : (1-CLb) [1-CLs+b]
    - ➔ie, fraction of pseudoexperiments with Q less than Q_o
  - MultiVariable LH analysis: CLs incorporating profile LH

Text

    - ➔Same as NN, but add CLs statistic
    - ➔CLs = CLs+b / CLb
  - Matrix Element: Bayesian with profile LH and non-profiled CLs
    - ➔Bayesian for measuring cross section
    - ➔CLs statistics for quoting p-Values
- *In all profiling applications, LH function defined in slightly different manner*

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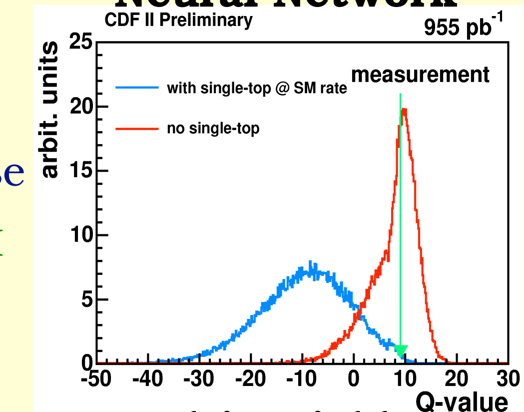
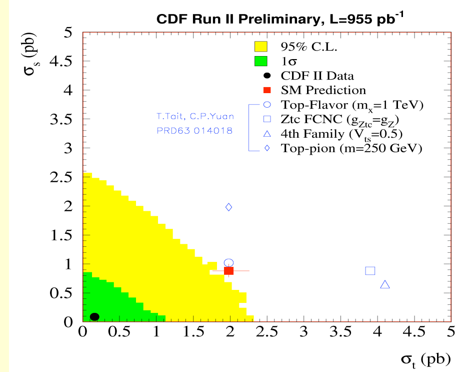
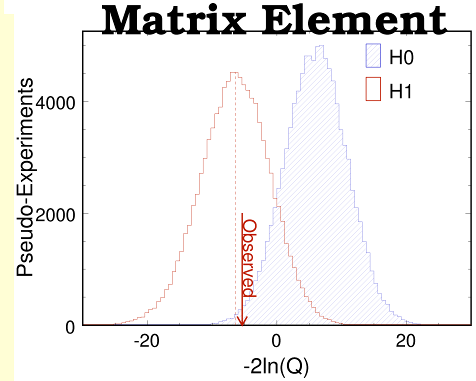
Neural Network



MultiVariable LH



Matrix Element



Wade Fisher (this morning)

Use of Multivariate Methods

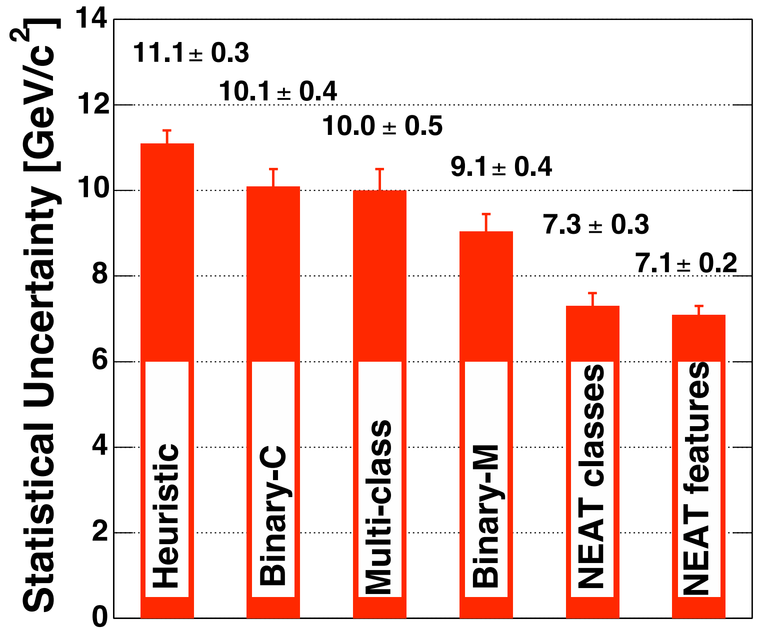
Multivariate methods are now ubiquitous in high-energy physics, the nagging problem is that:

- most multivariate techniques are borrowed from other fields, and they optimize some heuristic that physicists aren't interested in (like a score, or ad hoc training error)
- the difference can be quite large when systematic uncertainties are taken into account

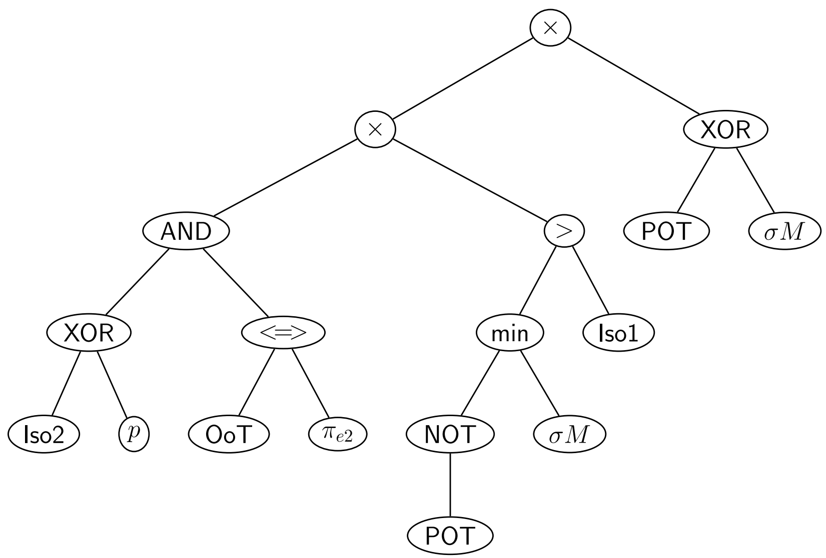
A few recent developments

- Evolutionary techniques
- Matrix Element techniques

Whiteson & Whiteson, hep-ex/0607012

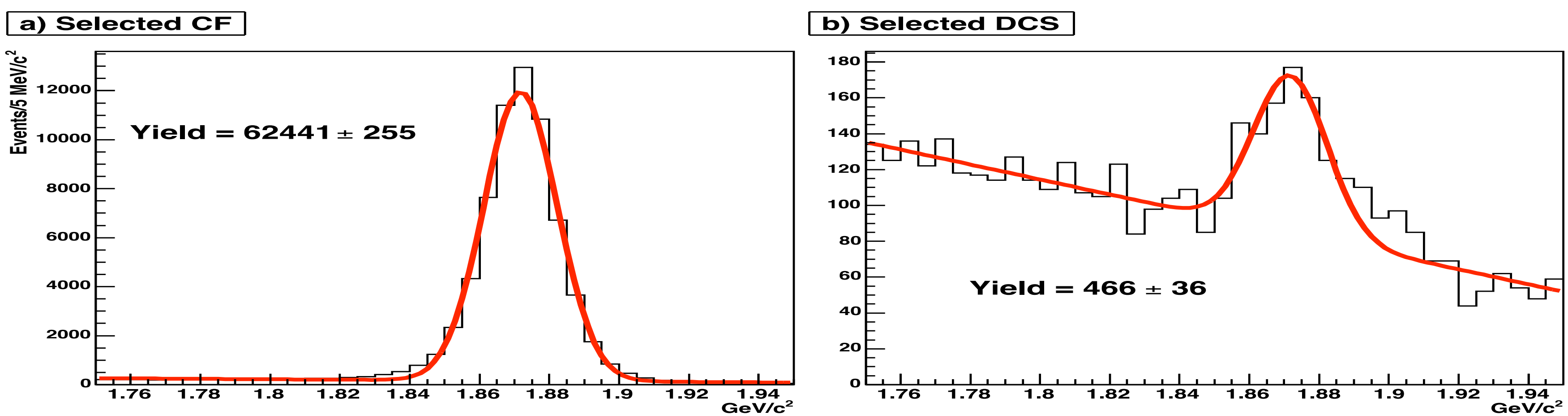


R.S. Bowman and I brought a technique called Genetic Programming to HEP. It's a program that actually writes programs to search for the Higgs! [physics/0402030]



The FOCUS collaboration has recently used Genetic Programming to study doubly Cabibbo suppressed decay of $D^+ \to K^+\pi^+\pi^-$ relative to Cabbibo favored $D^+ \to K^-\pi^+\pi^+$

hep-ex/0503007



The Neyman-Pearson Lemma

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The region W that minimizes the probability of wrongly accepting the H_0 is just a contour of the Likelihood Ratio:

$$\frac{L(x|H_0)}{L(x|H_1)} > k_\alpha$$

This is the goal!

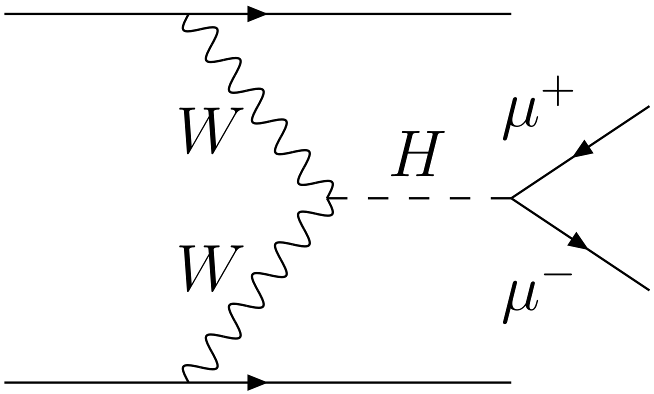
The problem is we don't have access to $L(x|H_0)$ & $L(x|H_1)$

The Neyman-Pearson Lemma

The region W that minimizes the probability of wrongly accepting the H_0 is just a contour of the Likelihood Ratio:

$$\frac{L(x|H_0)}{L(x|H_1)} > k_\alpha$$

$$L(x|H_0) =$$



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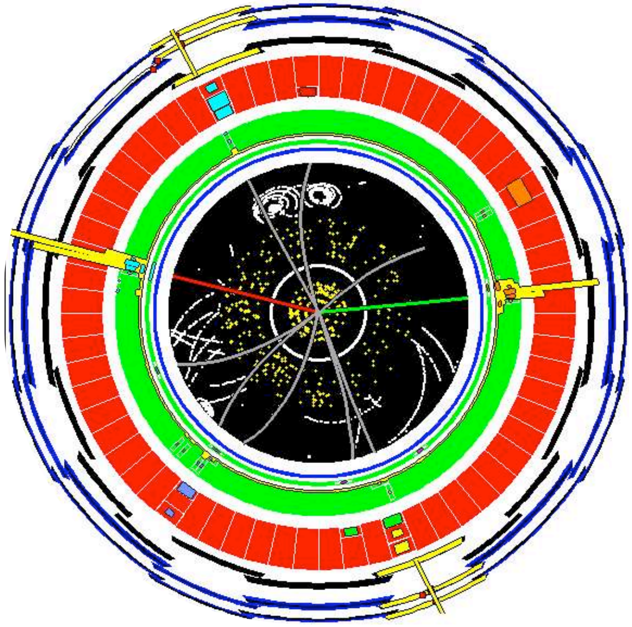
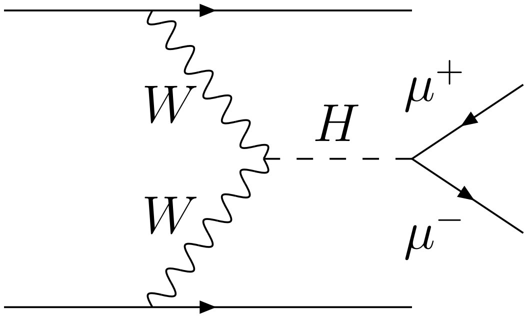


Matrix Element Techniques

Instead of using generic machine learning algorithms, some members of the TeVatron experiments are starting to attack this convolution numerically

$L(x|H_0) =$



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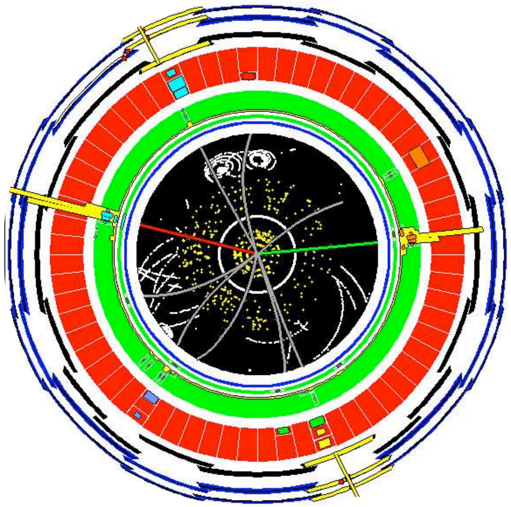
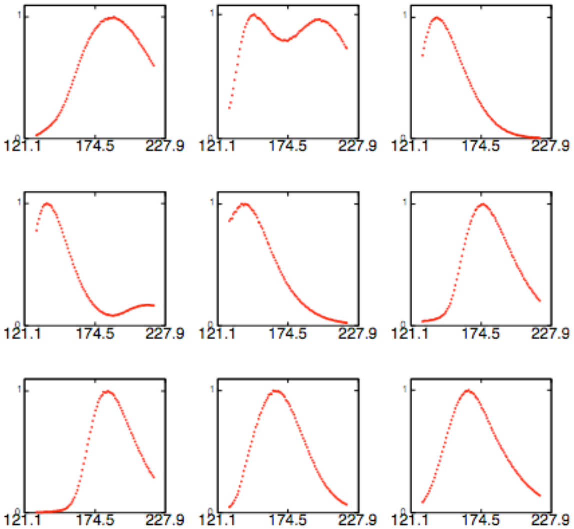
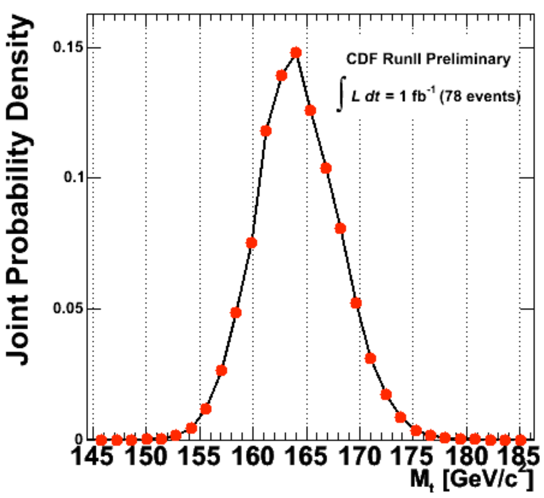






Matrix Element Techniques

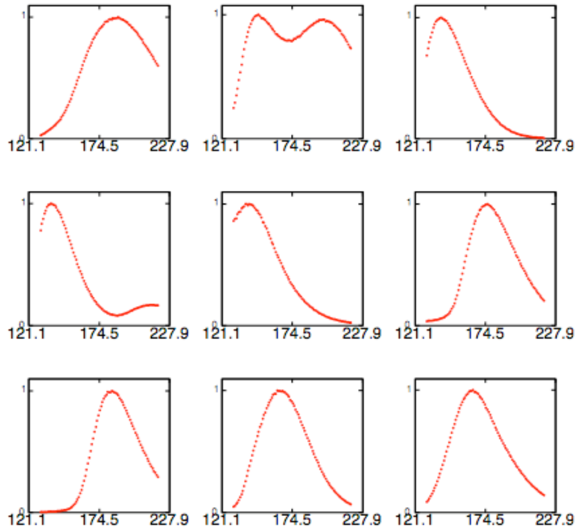
Instead of using generic machine learning algorithms, some members of the TeVatron experiments are starting to attack this convolution numerically

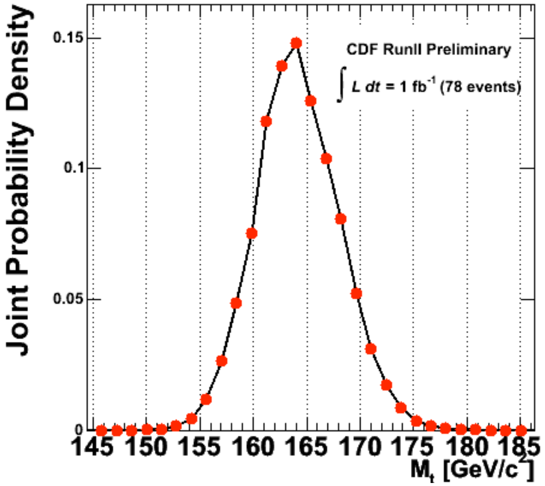
$$P(\mathbf{x}|M_t) = \frac{1}{N}\int d\Phi \; |\mathcal{M}_{t\bar{t}}(p; M_t)|^2 \prod_{jets} f(p_i, j_i) f_{PDF}(q_1) f_{PDF}(q_2)$$

Phase-space Integral

Matrix Element

Transfer Functions





Matrix Element Techniques for Theorists

About 2 years ago, I realized that phenomenologists doing sensitivity studies can use the Neyman-Pearson lemma directly

- directly integrate likelihood ratio
- model detector effects with transfer functions
  - numerically much easier than experimental situation because one generates hypothetical data
- just as one computes a cross-section for a new signal, one can compute a maximum significance (at leading order)

Experimental:
$x \sim$ observable

$$Q(\mathbf{x}) = \frac{L(\mathbf{x}|H_1)}{L(\mathbf{x}|H_0)} = \frac{\mathrm{Pois}(n|s+b)\ \prod_j^n f_{s+b}(x_j)}{\mathrm{Pois}(n|b)\ \prod_j^n f_b(x_j)}$$

$$q(\mathbf{x}) \equiv \ln Q(\mathbf{x}) = -s + \sum_{j=1}^{n} \ln\left(1 + \frac{s f_s(x_j)}{b f_b(x_j)}\right)$$

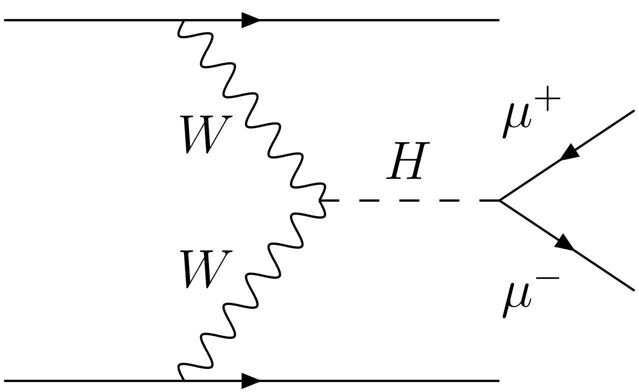
Theoretical:
$\vec{r} \sim$ phase space

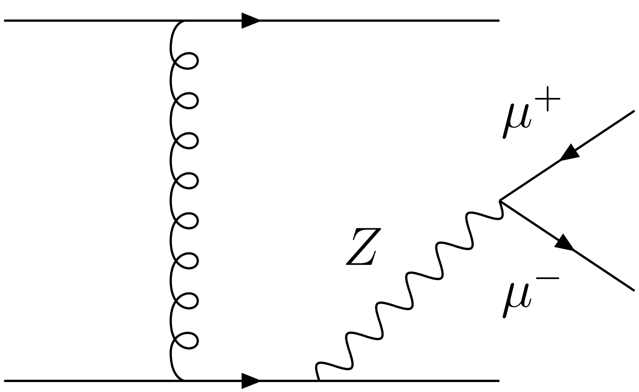
$$\boxed{q(\vec{r}) = -\sigma_{\mathrm{tot},s}\,\mathcal{L} \ + \ln\left(1 + \frac{d\sigma_s(\vec{r})}{d\sigma_b(\vec{r})}\right)}$$

Maximum Significance

Cranmer, Plehn. EPJ & hep-ph/0605268

With basic cuts, only need to consider signal and irreducible backgrounds





Phase Space:

2	for incoming quarks
$+(3 \times 4)$	for outgoing fermions
-4	for 4-momentum conservation
10	phase space dimensions

All other observables are a function of these. There is no more information available.

Re-write Higgs, EW Z, & QCD Z MC generators to run on same grid, sample same phase-space points

Incorporate experimental resolutions via nested integration, similar to “matrix element method” used for top mass measurement at TeVatron.

Recommendations & Recipes

Calibrating Our Statistical Apparatus

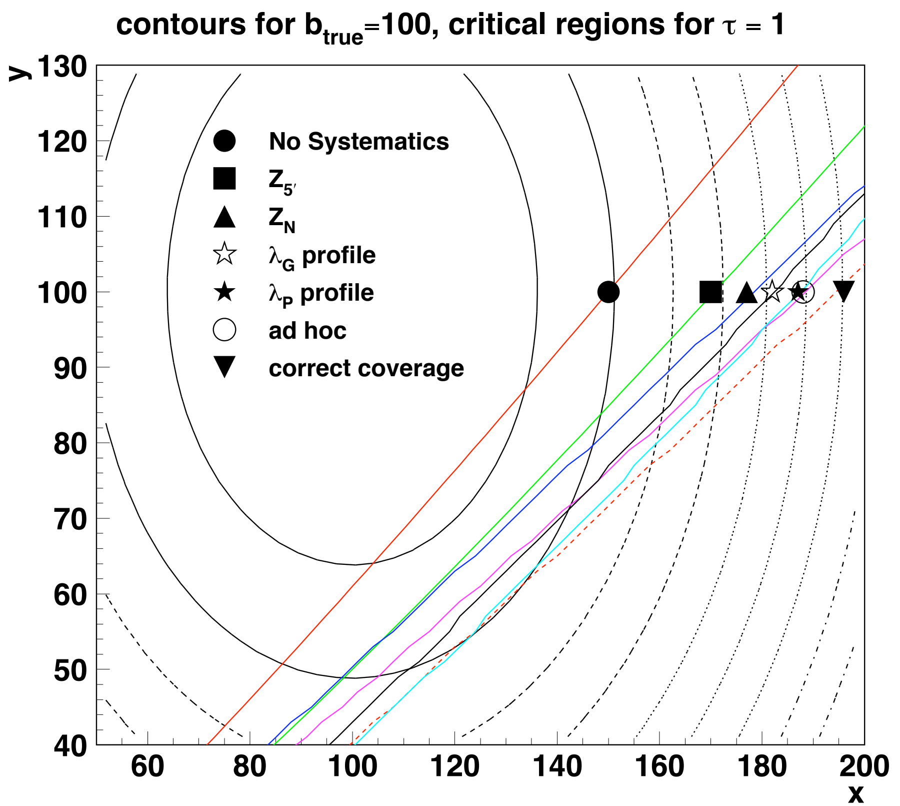


Figure 7. A comparison of the various methods critical boundary $x_{crit}(y)$ (see text). The concentric ovals represent contours of L_G from Eq. 15.

Method	L_G ($Z\sigma$)	L_P ($Z\sigma$)	$x_{crit}(y = 100)$
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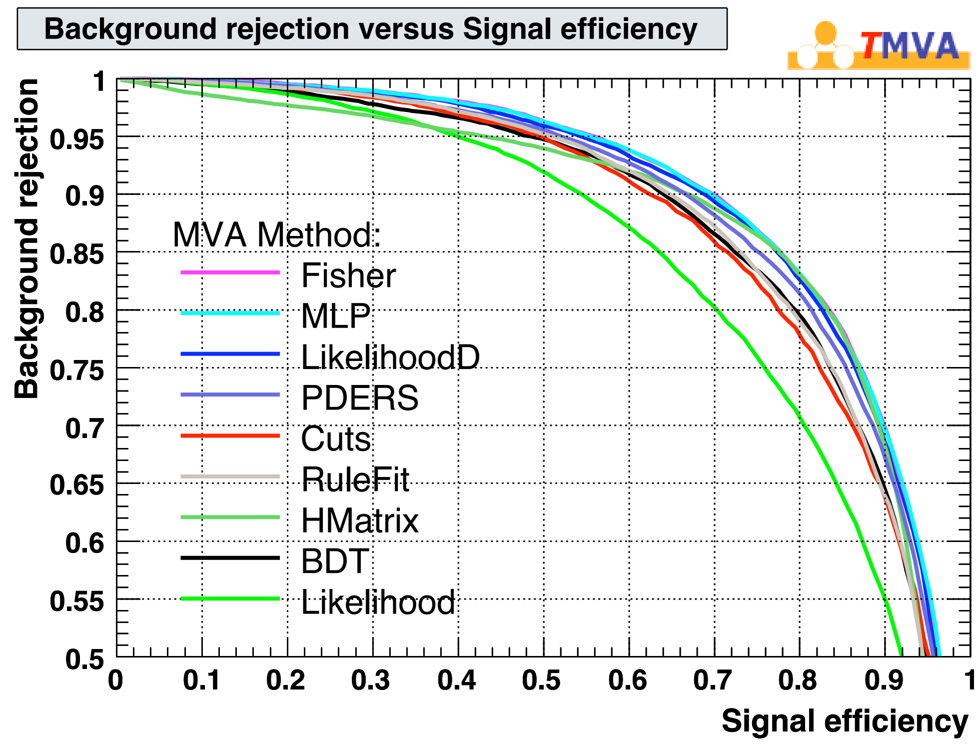

Inspired by TMVA's tools for comparing performance of different algorithms, plan to provide tools to compare coverage for different limit setting and discovery procedures

Many Methods, Many Similarities

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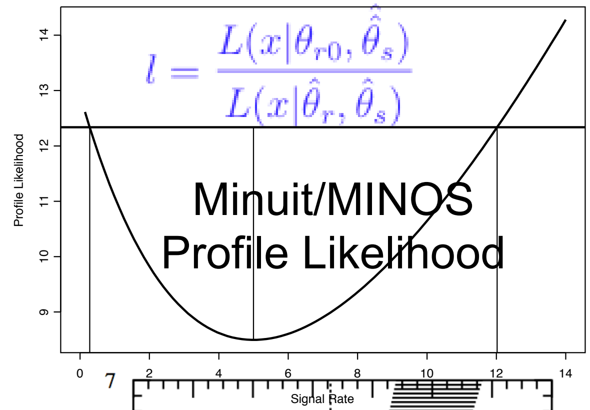
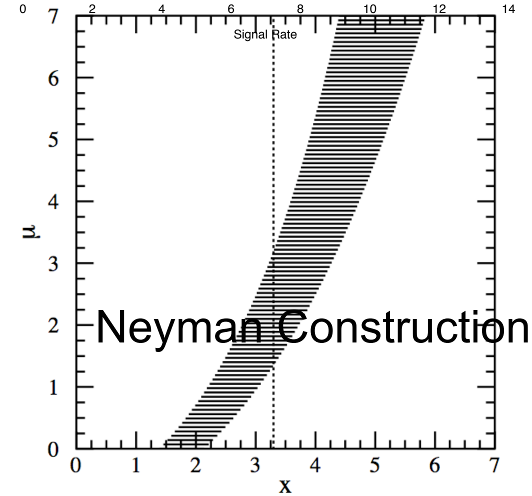
Essentially all methods start with the basic probability density function or likelihood function $L(x|\theta_r, \theta_s)$

- agreeing on one method impossible
- building a good model is the hard part!
- want to re-use it for multiple methods





$$L(b|Y) = \frac{L(Y|b)\ L(b)}{L(Y)}$$

Bayes Theorem

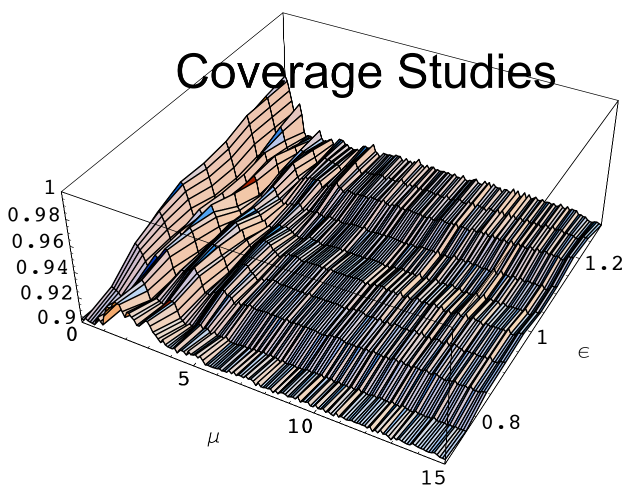
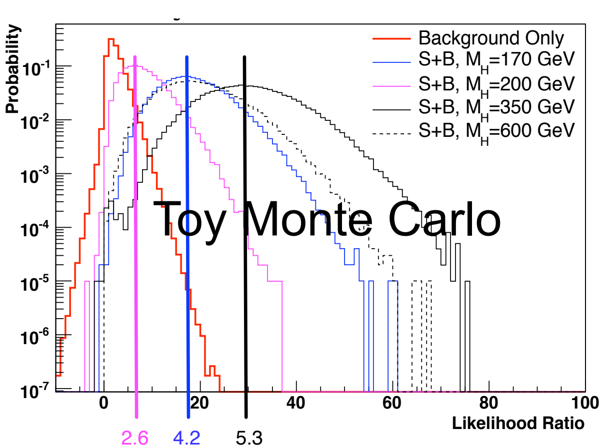


Fig. 2. Coverage plot for Unified limits, Gaussian uncertainty, $b = 3, \sigma = 0.1$.



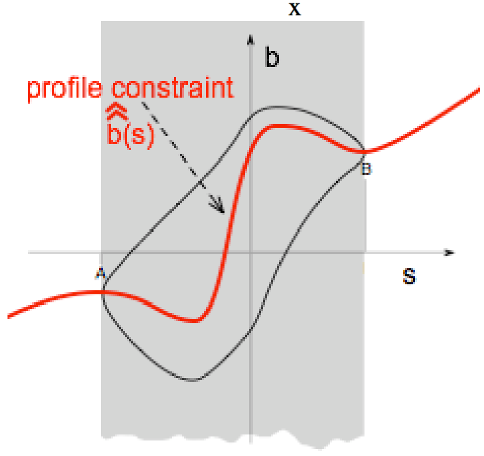


Figure 7.2: MINOS error confidence region for parameter 1

RooFit: A data modeling toolkit

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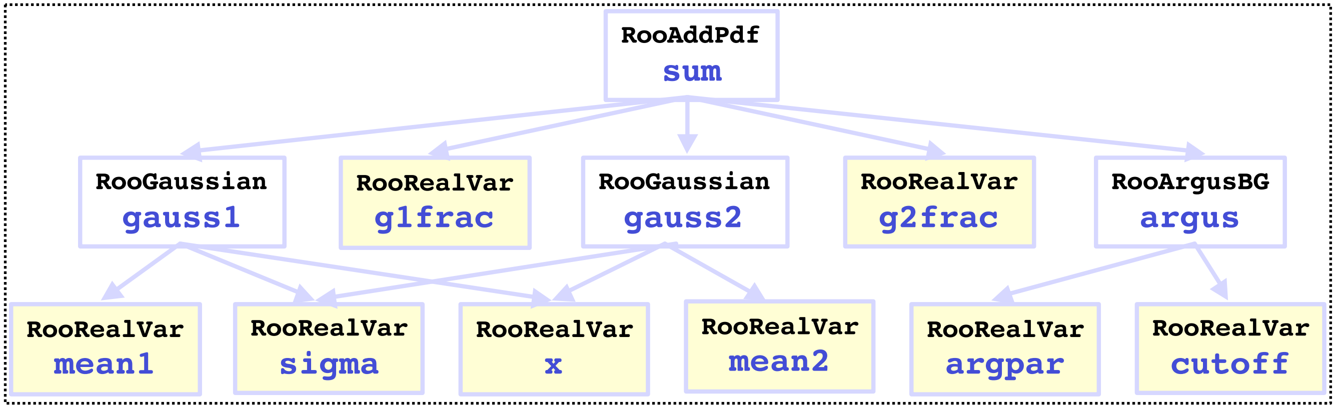
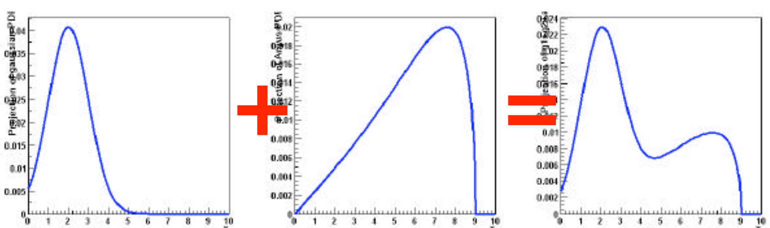
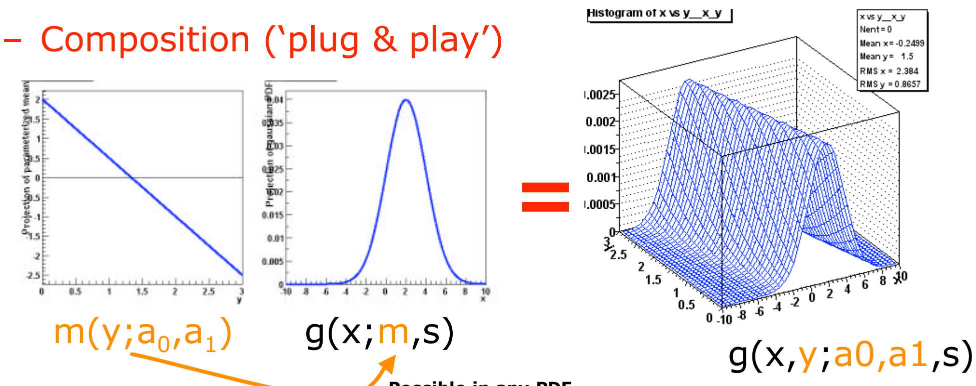
A major tool at BaBar. Fit complicated models with >100 parameters!



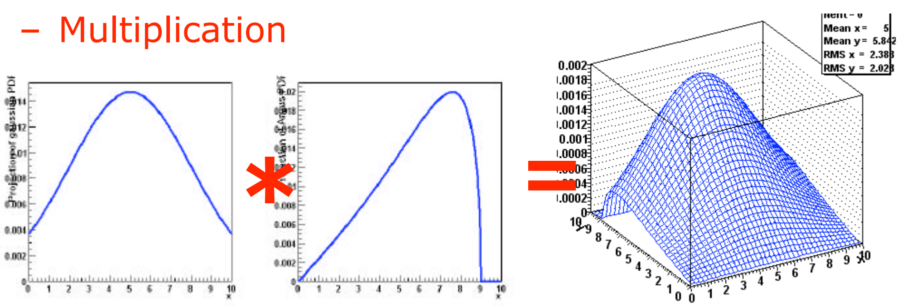
– Addition



– Composition ('plug & play')

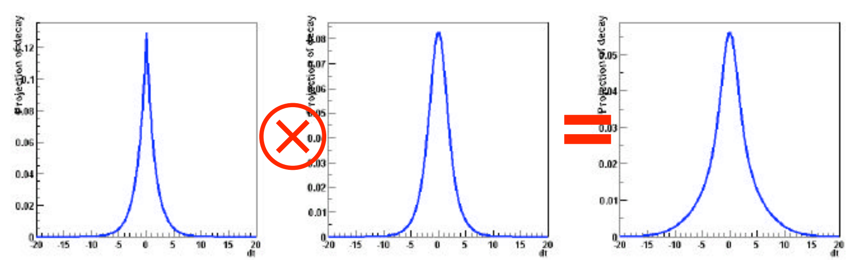


– Multiplication



Wouter Verkerke,

– Convolution

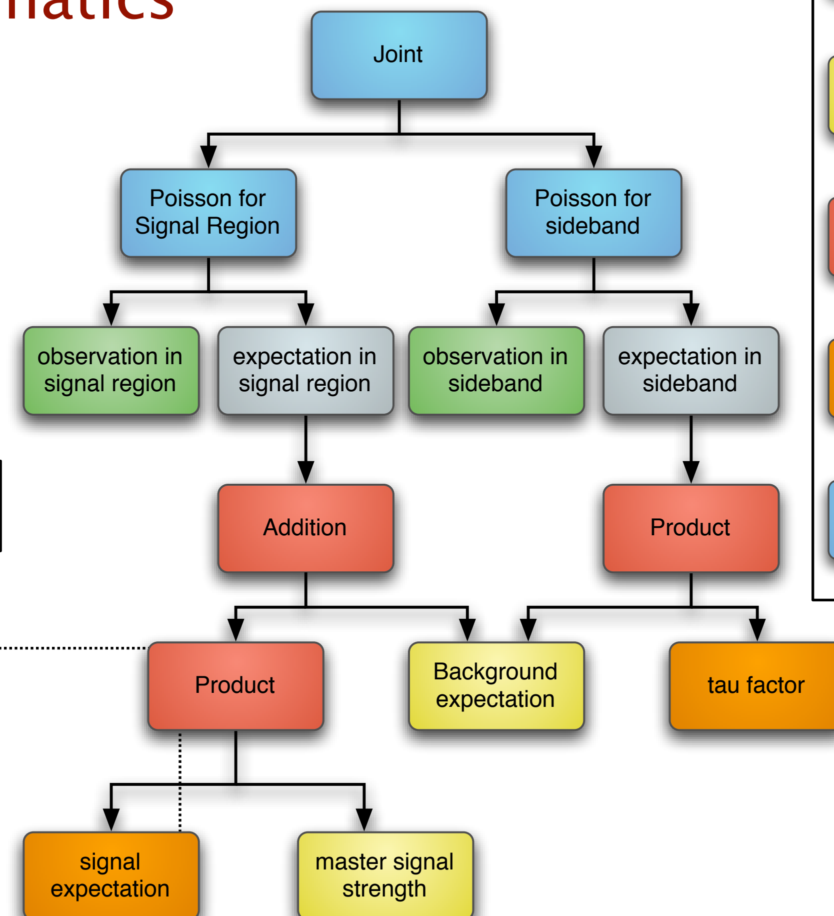


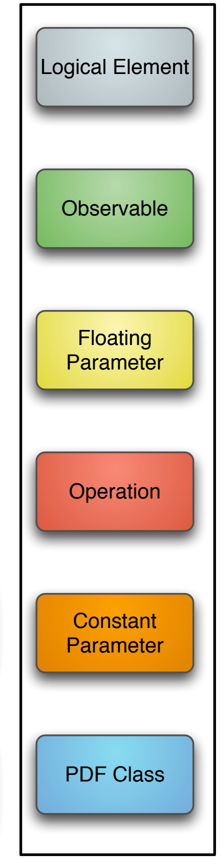
Wouter Verkerke, UCSB

A 1-Channel Example

Three representations of the 1-channel example

- RooFit code for model is small and simple
- Easy to include correlated systematics
- Very fast to evaluate
- Good coverage properties





$$L_P(x, y|\mu, b) = Pois(x|\mu + b) \cdot Pois(y|\tau b).$$

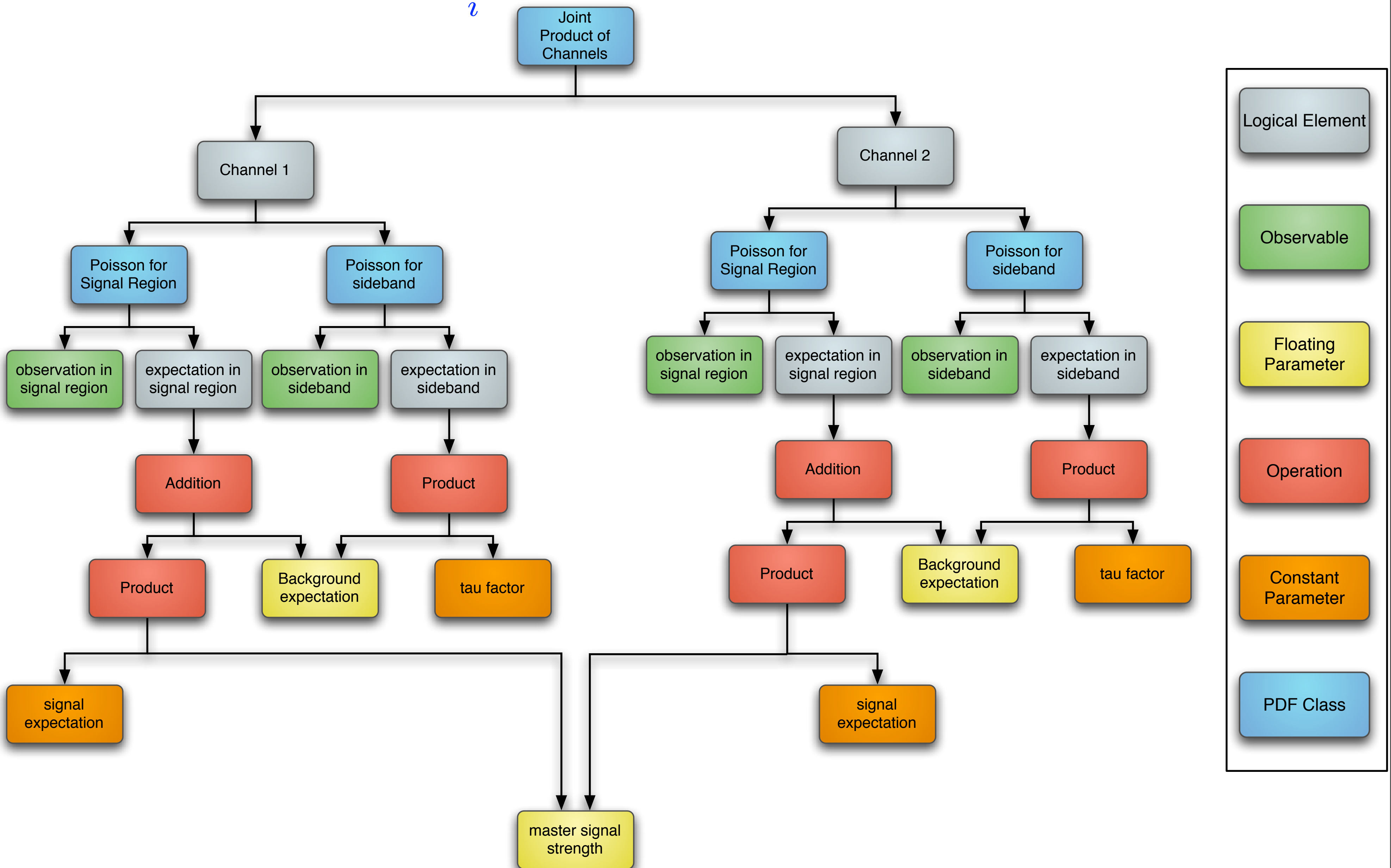
```
RooRealVar   s("s","s",_s, 0., 100.);
RooRealVar   b("b","b",_b,  0., 200.);
RooRealVar  tau("tau","tau",_tau,0,2);
tau.setConstant(kTRUE);
RooFormulaVar  splusb("splusb","s+b",RooArgSet(s,b));
RooProduct   bTau("bTau","b*tau",RooArgSet(b, tau));
RooRealVar   x("x","x",_s+_b, 0., 200.);
RooRealVar   y("y","y",_b*_tau,  0., 200.);

RooPoisson sigRegion("sigRegion","sigRegion",x,splusb);
RooPoisson sideband("sideband","sideband",y,bTau);

RooProdPdf joint("joint","joint", RooArgSet(sigRegion,sideband) );
```

A 2-Channel Example

$$L(\mathbf{x}, \mathbf{y}|\mu, \mathbf{s}, \mathbf{b}) = \prod_i Pois(x_i|\mu s_i + b_i)\, Pois(y_i|\tau b_i)$$

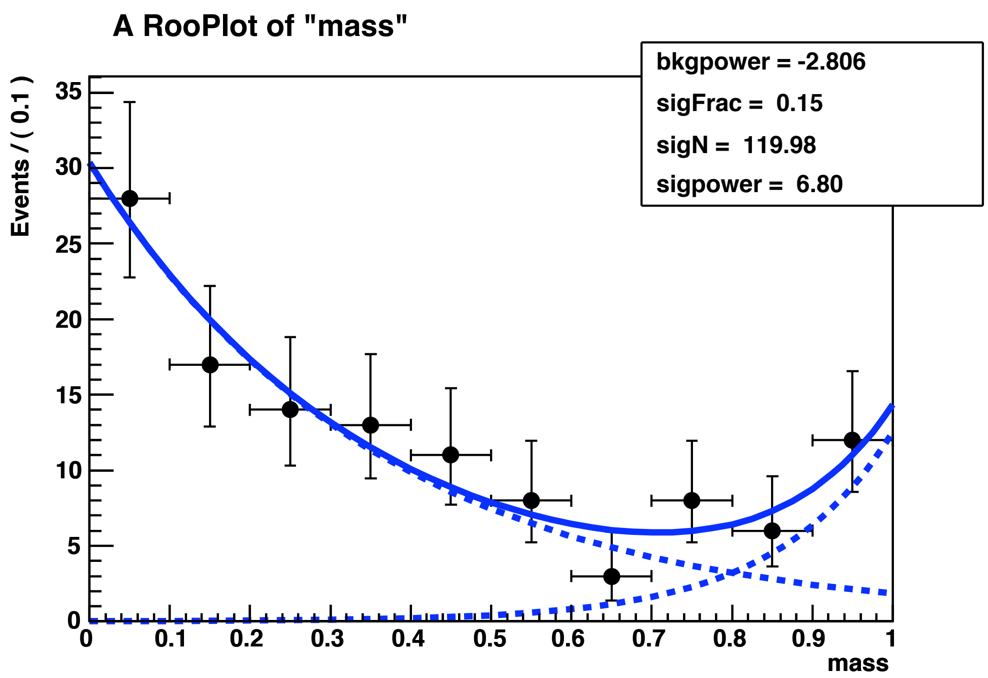


Beyond Number Counting

It is easy to extend the simple number counting to include a discriminating variable. Coverage studies look promising!

$$\mathcal{L}(n, n_b, \vec{x}|s,b) = P(n|s+b)P(n_b|\tau b)\prod_{i=1}^{n}\frac{sf_s(x_i|a)+bf_b(x_i|a)}{s+b}$$

$$f_s(x|s) = \frac{1}{N}e^{\ a(x-1)} \quad f_b(x|b) = \frac{1}{N}e^{-ax}$$



Nominal coverage = 5σ

MINUIT/MINOS coverage:

s	b	τ	a	Coverage	Power[%]
25	100	1	-1	**5.1**	**1.4**
50	100	1	-1	**5.0**	**12**
50	100	1	-3	**4.8**	**99**

... so far in all cases coverage > 4.8 (75 % > 5 σ)

K. Cranmer, Jan Conrad in preparation

The Profile Likelihood Combination

Recently I put together code to combine N-channels with simple number counting and systematic errors:

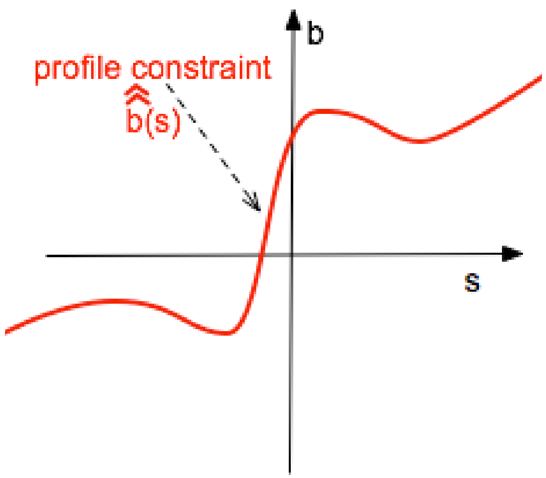
- Start with this likelihood function

$$L(\mathbf{x},\mathbf{y}|\mu,\mathbf{s},\mathbf{b}) = \prod_i Pois(x_i|\mu s_i + b_i)\, Pois(y_i|\tau b_i)$$

- Calculate this Likelihood ratio

$$\lambda = \frac{L(\mathbf{x},\mathbf{y}|\mu=0,\mathbf{s},\hat{\hat{\mathbf{b}}})}{L(\mathbf{x},\mathbf{y}|\hat{\mu},\mathbf{s},\hat{\mathbf{b}})}$$

  - Where $\hat{\mu},\hat{\mathrm{b}}$ are M.L.E.
  - and $\hat{\hat{\mathrm{b}}}$ is a conditional M.L.E. at $\mu=0$



- finally, use asymptotic relationship

$$-2\log\lambda \sim \chi^2$$

Simple Interpretation

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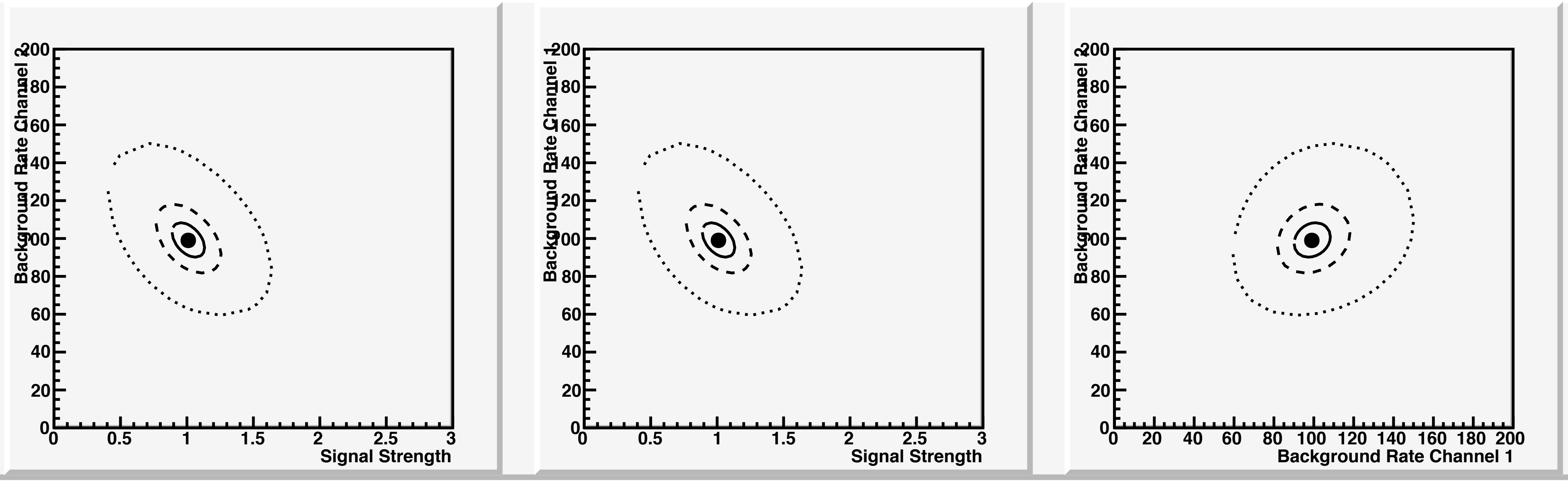
One can think of this technique as a fit to the overall signal strength (0=no signal; 1=Standard Model) and each of the backgrounds (nuisance parameters)

- Then we draw the 5σ contour around the best fit values, just like MINOS does
- If 5σ contour includes s=0, no discovery
- Significance defined as value of Z, where Zσ contour touches s=0



Previous Combinations

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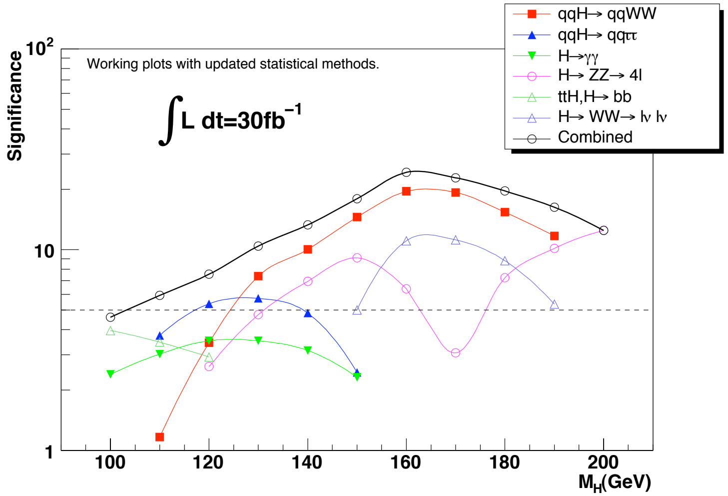
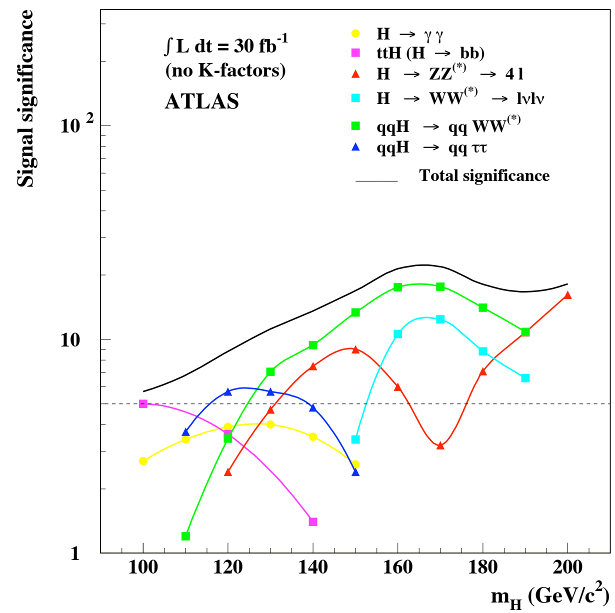




Statistical Methods to Assess the Combined Sensitivity of the ATLAS Detector to the Higgs Boson in the Standard Model

Kyle Cranmer, Bruce Mellado, William Quayle, Sau Lan Wu

University of Wisconsin - Madison
Department of Physics

ATL-PHYS-2004-034
01 December 2004

Abstract

We discuss statistical methods used to assess the combined sensitivity to the Standard Model Higgs boson using the ATLAS detector. The combination is performed using the likelihood ratio as a test statistic. Combined results are calculated using the results of a recent scientific note. Difficulties in calculating the significance using likelihood ratio techniques in the high event rate and high significance environment of the LHC are discussed, and software packages which implement solutions to these problems are presented. We also provide a brief discussion about different ways to incorporate systematic error and introduce the statistical notion of power to the ATLAS Higgs search.

Prospects for the Search for a Standard Model Higgs Boson in ATLAS using Vector Boson Fusion

S.Asai[8], G.Azuelos[5] C.Buttar[7], V.Cavasinni[6], D.Costanzo[6,a], K.Cranmer[9], R.Harper[7], K. Jakobs[4], J.Kanzaki[3], M.Klute[1], R.Mazini[5], B.Mellado[9], W.Quayle[9], E.Richter-Wąs[2], T.Takemoto[3], I.Vivarelli[6], Sau Lan Wu[9]

1 Physikalisches Institut, Universität Bonn, Germany.
2 CERN, Geneva, Switzerland[b] and Inst. of Nuclear Physics, Cracow, Poland.
3 High Energy Research Organisation (KEK), IPNS, Japan.
4 Institut für Physik, Universität Mainz, Germany.
5 University of Montreal, Canada.
6 INFN and University of Pisa, Italy.
7 Dept. of Physics and Astronomy, University of Sheffield, UK.
8 University of Tokio, Tokio, Japan.
9 University of Wisconsin-Madison, Wisconsin, USA.

Received: date / Revised version: date

Abstract. The potential for the discovery of a Standard Model Higgs boson in the mass range $m_H < 2m_Z$ in the vector boson fusion mode has been studied for the ATLAS experiment at the LHC. The characteristic signatures of additional jets in the forward regions of the detector and of low jet activity in the central region allow for an efficient background rejection. Analyses for the $H \to WW^{(*)}$ and $H \to \tau\tau$ decay modes have been performed using a realistic simulation of the expected detector performance. The results obtained demonstrate the large discovery potential in the $H \to WW^{(*)}$ decay channel and the sensitivity to Higgs boson decays into τ-pairs in the low-mass region around 120 GeV/c^2.

Results for 5 fb^{-1}

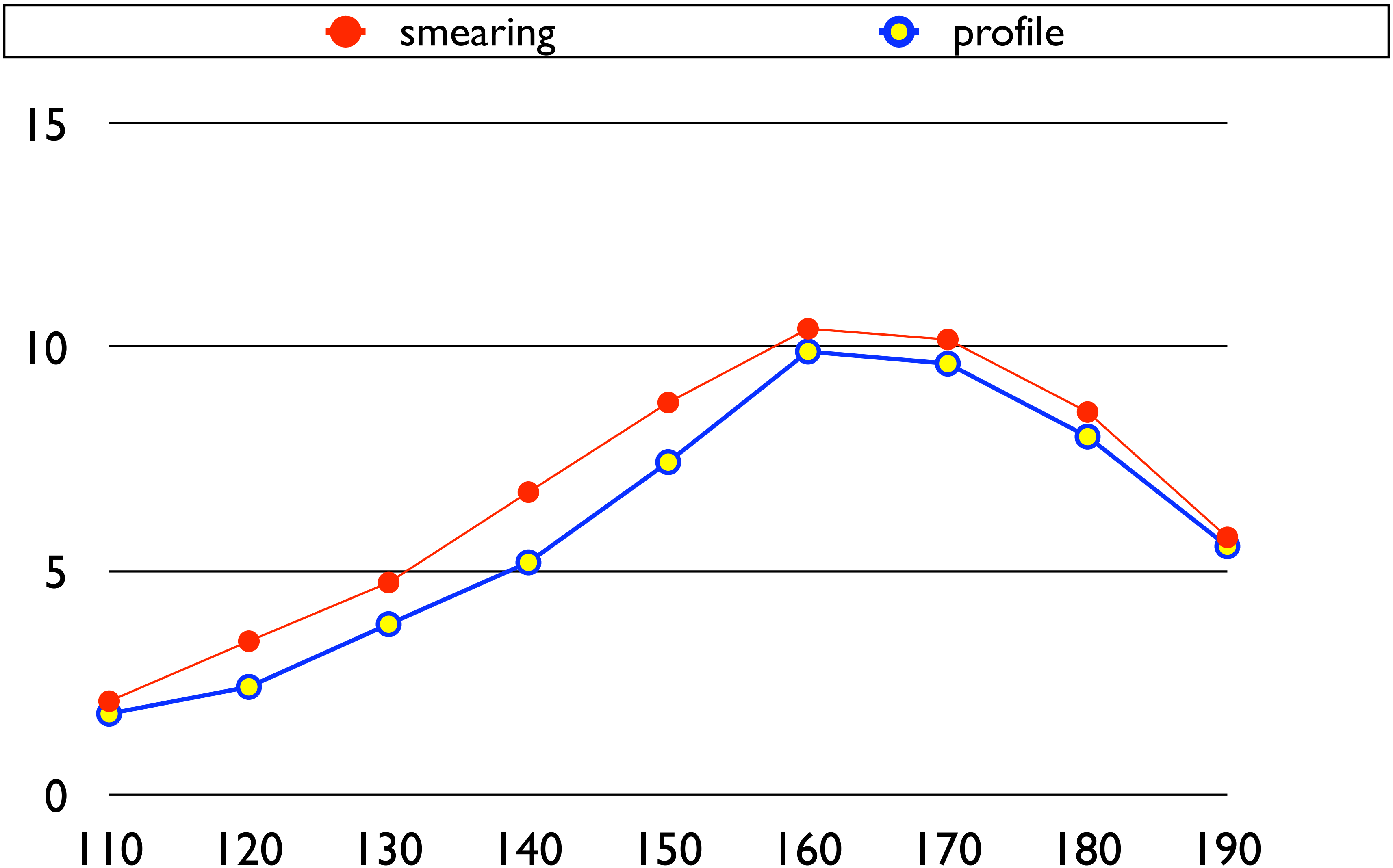
Using exactly the same input for the two columns

M_H (GeV)	Smearing (σ)	Profile (σ)
110	2.11	1.83
120	3.45	2.43
130	4.76	3.83
140	6.78	5.21
150	8.78	7.45
160	10.43	9.92
170	10.19	9.65
180	8.57	8.02
190	5.77	5.57

If the Profile is well calibrated, the Smearing is “optimistic”

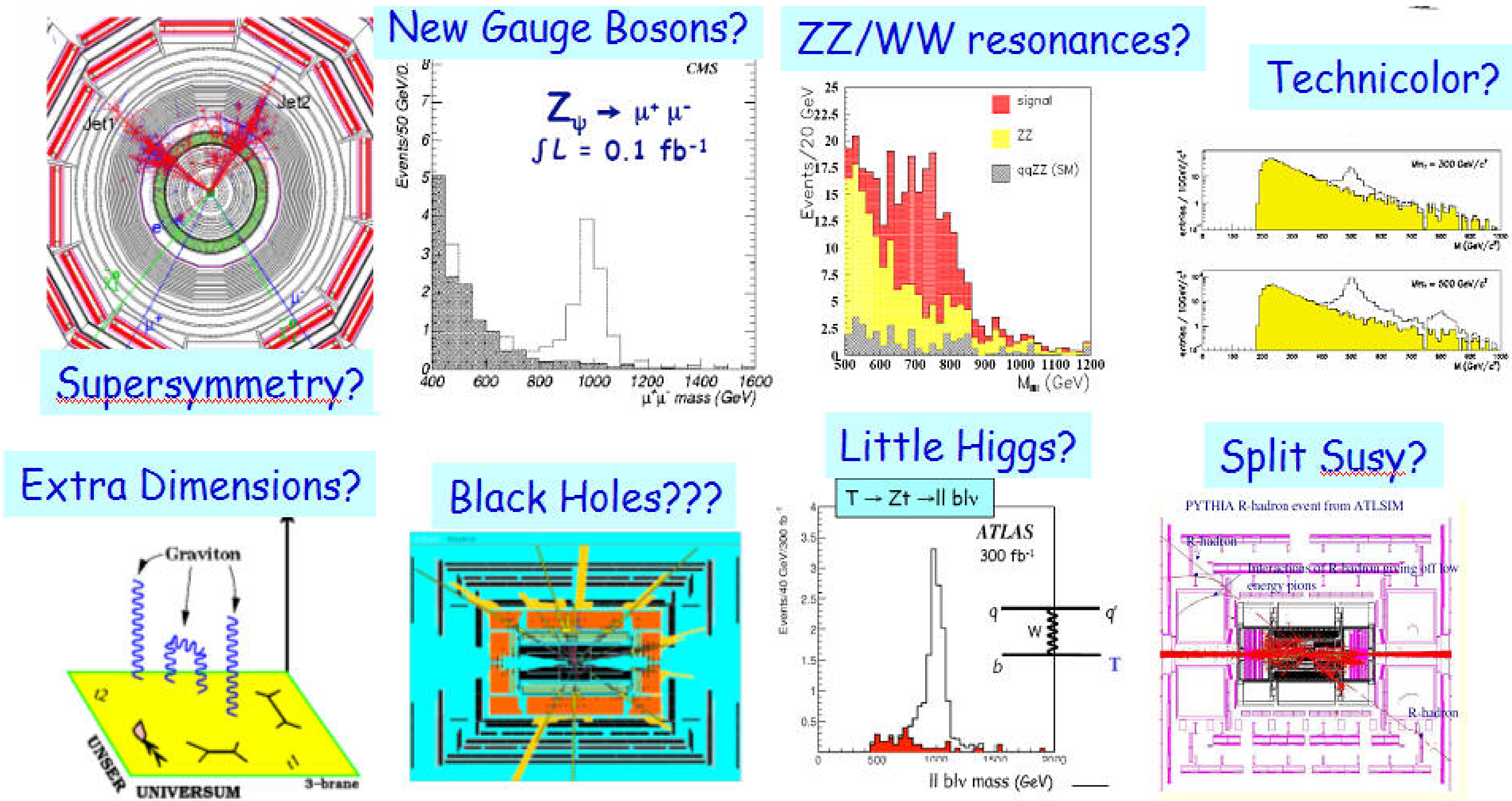
Results for 5 fb^{-1}

Same as previous table.



Search Strategies for New Physics

The Landscape



A. de Roeck, Snowmass 2005

The Landscape

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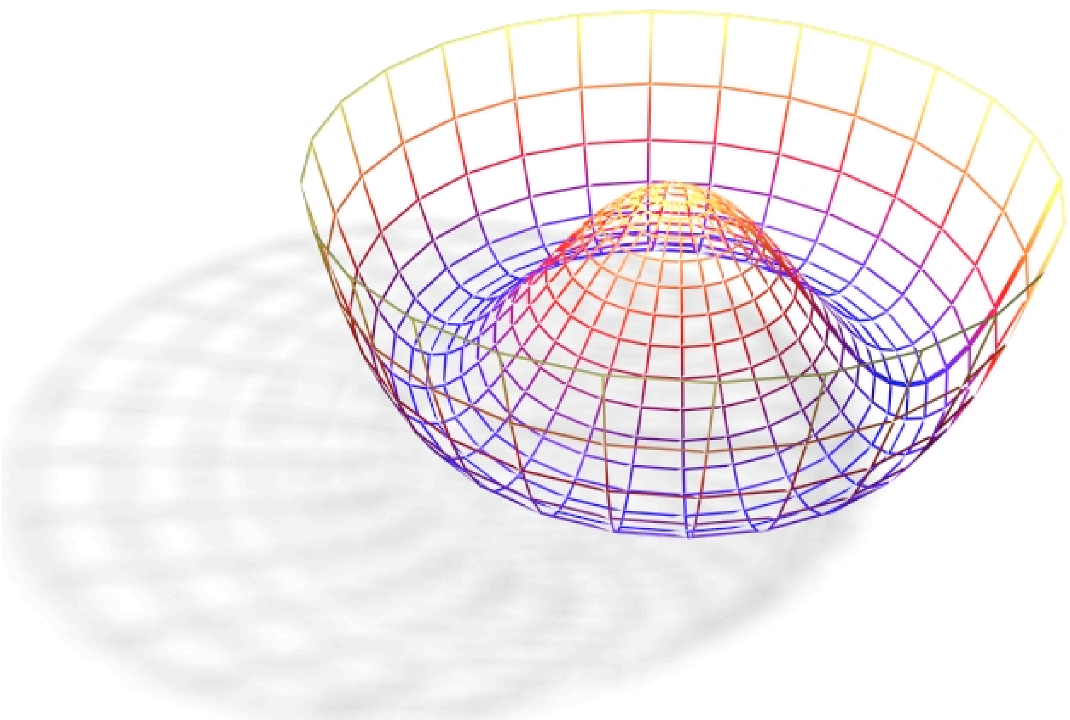
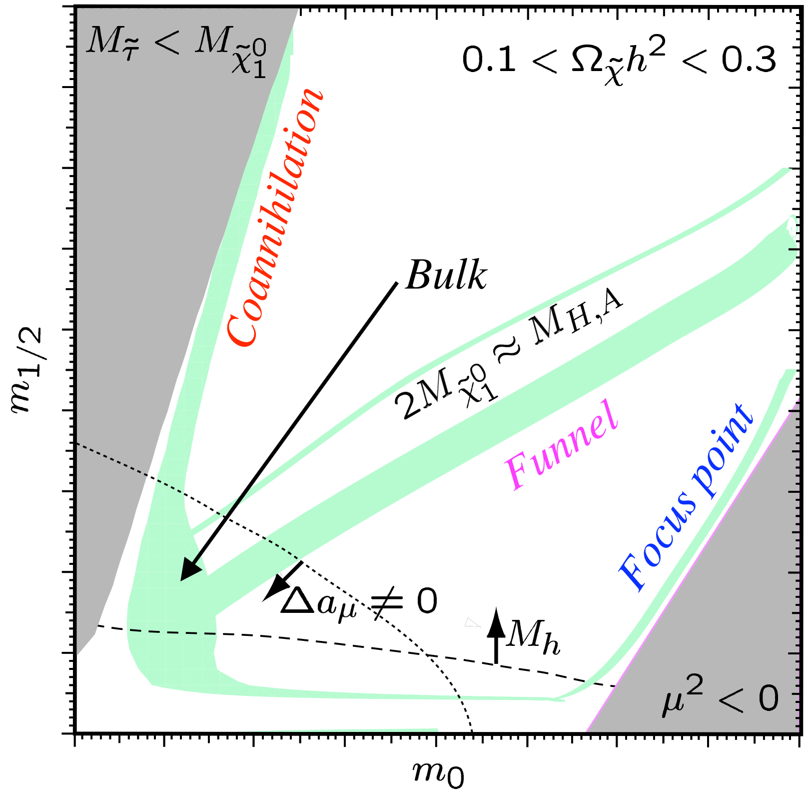
From H. Murayama

Simple vs. Complex Models



Simple model,
one free parameter



Complex Model,
many free parameters

Effectiveness of a given strategy depends on the complexity of the problem

The Challenge of BSM Searches

There are huge number of models to consider (or to ignore)

- some of those models have several parameters and describe very diverse phenomenology

This leads to a generic tradeoff between:

- powerful searches for more specific signatures, and
- less powerful, but more robust searches for generic signatures

If one does not have a clear idea of what the signal is, it is difficult to optimize an analysis

- formally the Neyman-Pearson lemma isn't so helpful
  - statistics jargon: no Universally Most Powerful test

Signature-Based Searches

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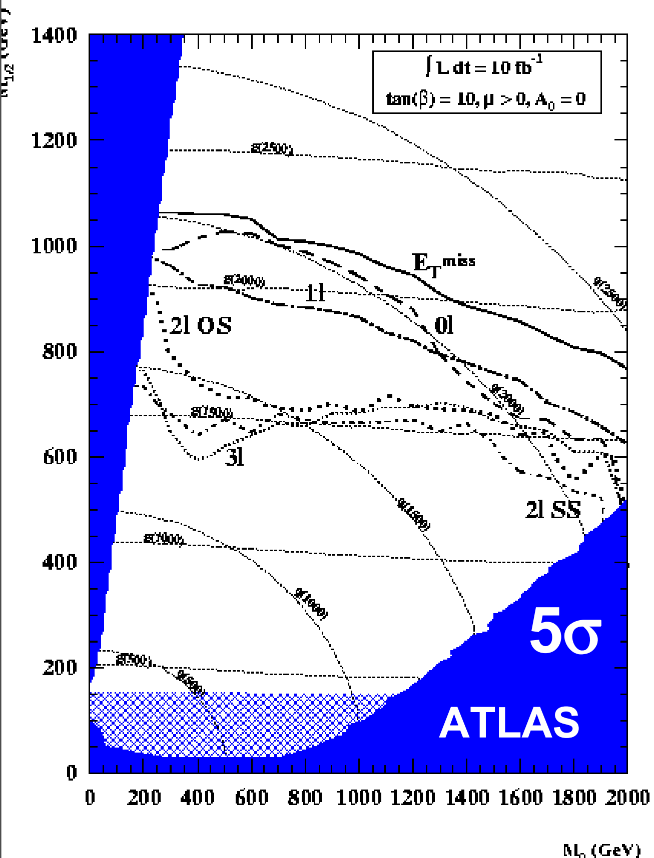
Perhaps the most common way to search for new physics without a specific theory in mind is to look for a “signature” that for new physics that is generic in a large class of models

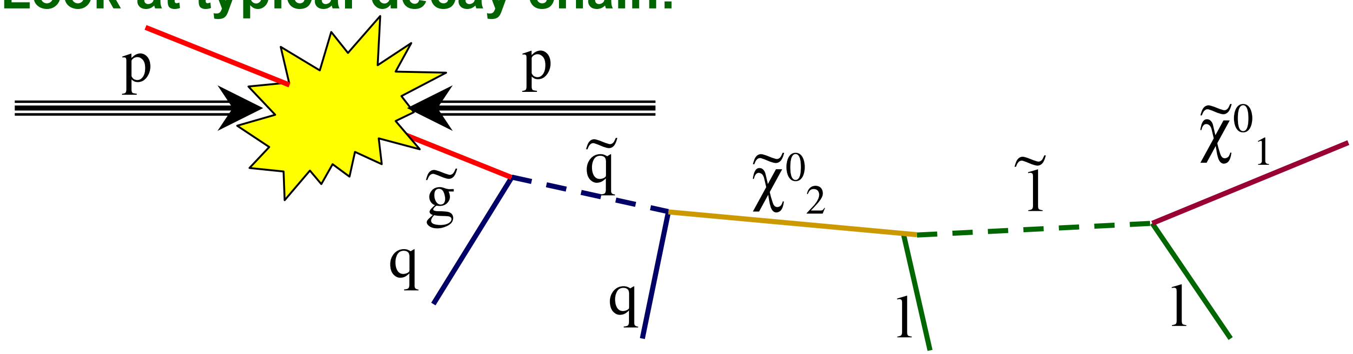
Sacrifice some power for a large gain in robustness



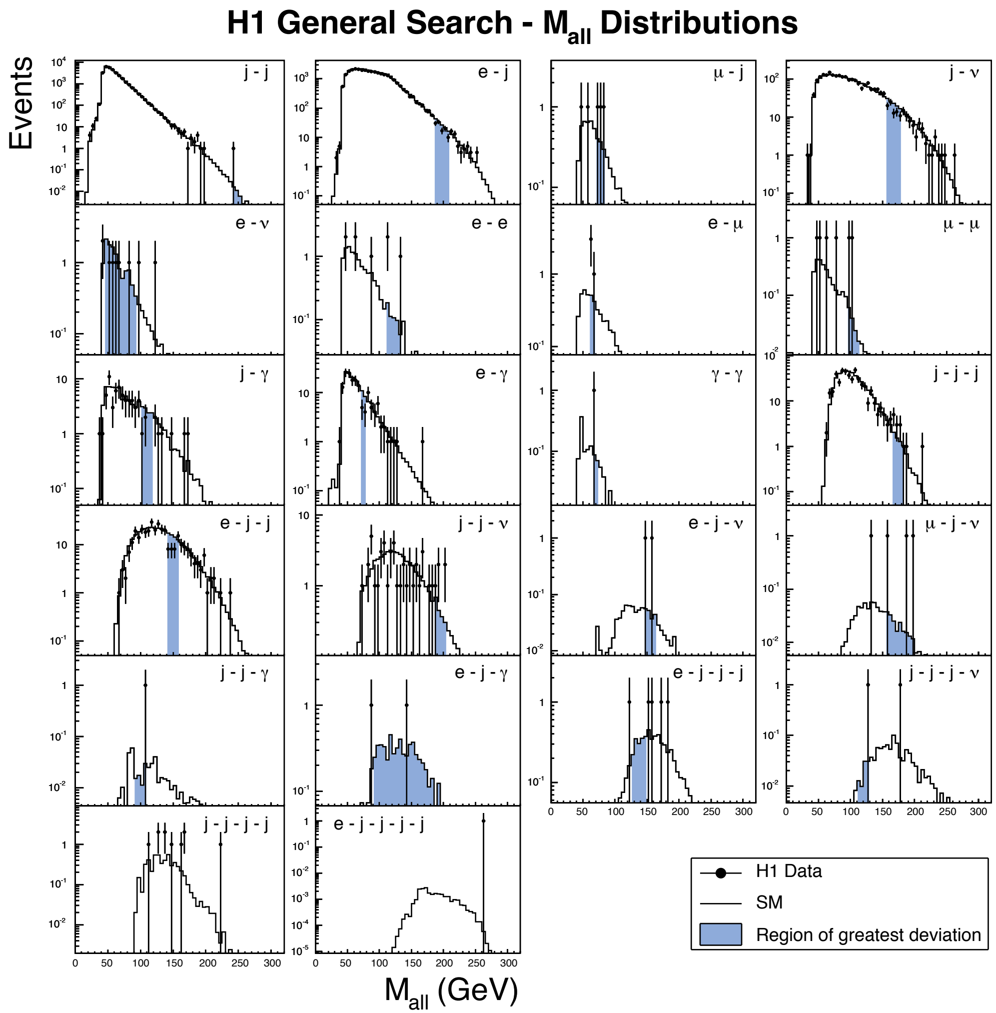
Example: R-partity conserving SUSY

Q: What do we expect SUSY events @ LHC to look like?

A: Look at typical decay chain:



The H1 General Search and SLEUTH are both "bump hunters" with statistically meaningful results



Look in data for region with biggest discrepancy from data.

Repeat many toy experiments based on Standard Model predictions to estimate chance of a discrepancy of that size.

See

- DØ (hep-ex/0006011)
- H1 (hep-ex/0408044)

Model-Independent Searches

The H1 General Search and SLEUTH are both “bump hunters” with statistically meaningful results

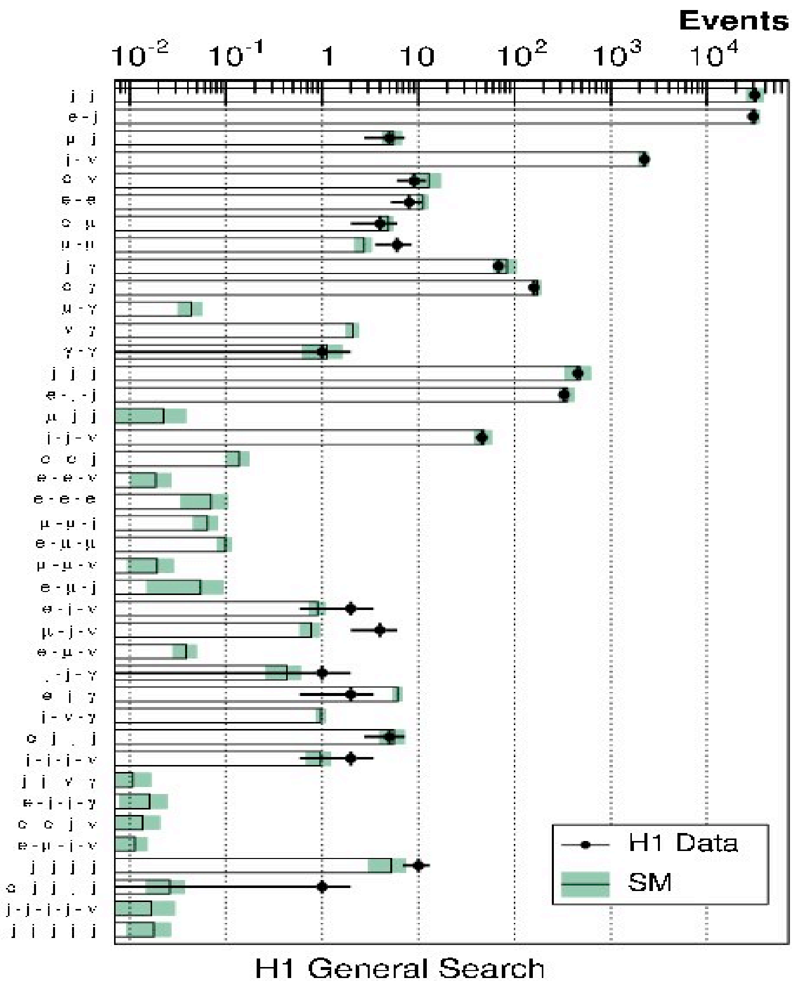


Figure 1: The data and the SM expectation for all event classes with a SM expectation greater than 0.01 events. The analysed data sample corresponds to an integrated luminosity of 117 pb^{-1}. The error bands on the predictions include model uncertainties and experimental systematic errors added in quadrature.

Look in data for region with biggest discrepancy from data.

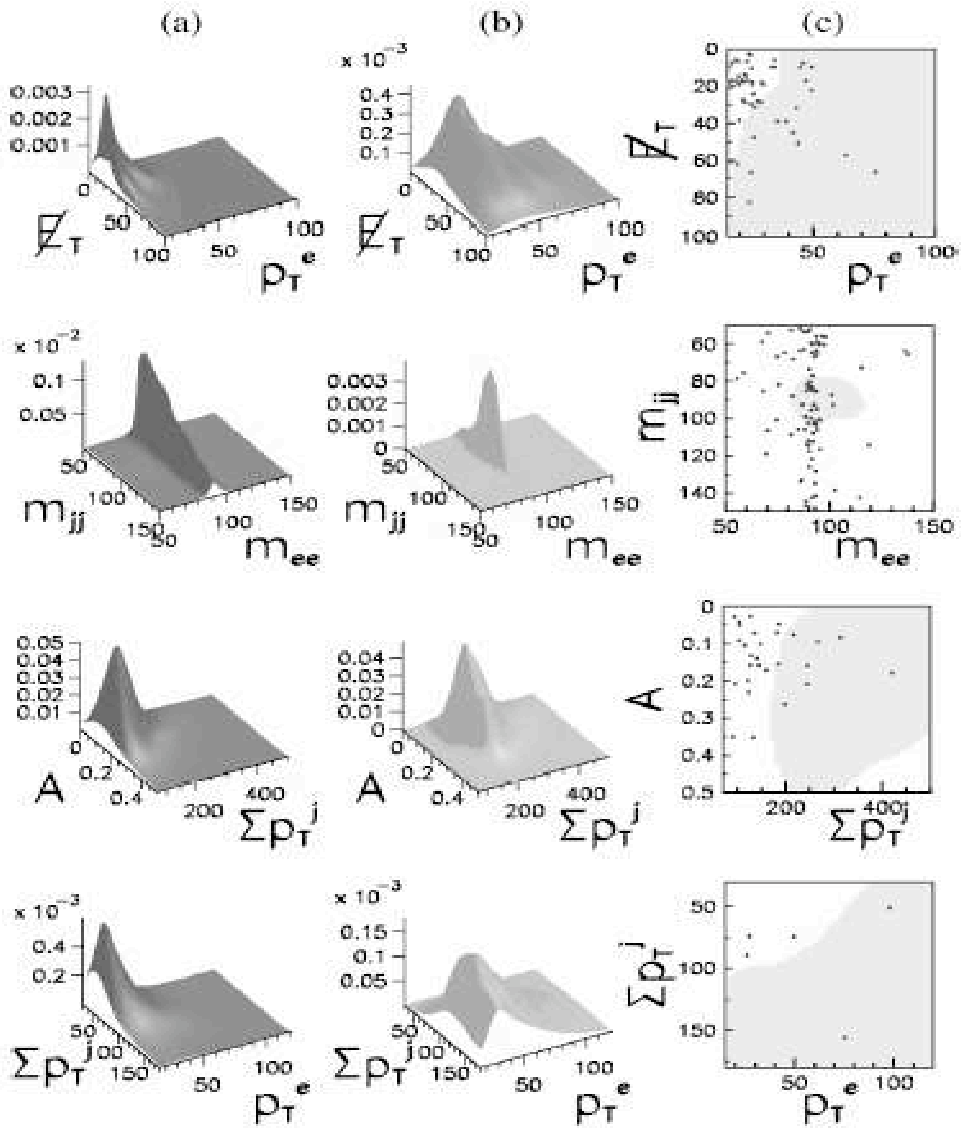
Repeat many toy experiments based on Standard Model predictions to estimate chance of a discrepancy of that size.

See

- DØ (hep-ex/0006011)
- H1 (hep-ex/0408044)

Thousands of eager experimentalists

Automated Analysis Procedures



Bruce Knuteson has developed an automated analysis procedure called QUAERO.

Has been used on several experiments.

DØ results published in *Phys. Rev. Lett.* **87**, 231801 (2001)

Given signal and background Monte Carlo, QUAERO constructs a set of cuts tailored to the signal.

Algorithms like Quaero allow us to scan a huge parameters space!

Correcting for The Trials Factor

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Significance in HEP searches

5 sigma ?

e.g. from Frodesen,Skjeggestad,Tofte (1978)

The following numbers apply to the year 1979:
-total number of events measured: 2*10^6
- average number of mass combination per event: 15
- number of combination in each histogramm 3000
- number of bins per histogramm : 40
This gives an estimated number of bin per year
equal to 2*10^6*15*40/3000 = 4*10^5 bins/per year.
Since the prob. of a positive fluctuation of minum 4 sigma is 3.2*10^-5 in any of these bins we must expect a total of approx. 13 occurancies per year of effects of at least for 4 sigma in magnitude.
This example illustrates why it has become custumary to require 5 or more standard deviations ....

5 sigma definition has to do with a guess of total number of tests made in HEP (not realistic anymore if algorithms can do the testing)

Attempt to correct for trails factor by adjusting Nσ discovery threshold, referred to as a Bonferroni-type correction

False Discovery Rate

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Introduced by Benjamini & Hochberg (1995)

Consider the possible outcomes:

	Reject Null	Maintain Null	
Null True	$N^{\text{reject}}_{\text{null true}}$	$N^{\text{maintain}}_{\text{null true}}$	$N_{\text{null true}}$
Null False	$N^{\text{reject}}_{\text{null false}}$	$N^{\text{maintain}}_{\text{null false}}$	$N_{\text{null false}}$
	N^{reject}	N^{maintain}	N

Table 1. Summary of outcomes in multiple testing.

Define False Discovery Rate as

$$\text{FDR} = \frac{N^{\text{reject}}_{\text{null true}}}{N^{\text{reject}}}$$

Controlling the False Discovery Rate in Astrophysical Data Analysis

Christopher J. Miller
Dept. of Physics, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA-15213

Christopher Genovese
Dept. of Statistics, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA-15213

Robert C. Nichol
Dept. of Physics, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA-15213

Larry Wasserman
Dept. of Statistics, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA-15213

Andrew Connolly
Dept. of Physics & Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA-15260

Daniel Reichart
Dept. of Astronomy, CalTech, 1201 East California Blvd, Pasadena, CA-91125

Andrew Hopkins
Dept. of Physics & Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA-15260

Jeff Schneider, Andrew Moore
School of Computer Science, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA-15213

arXiv:astro-ph/0107034 v1 2 Jul 2001

ABSTRACT

The False Discovery Rate (FDR) is a new statistical procedure to control the number of mistakes made when performing multiple hypothesis tests, *i.e.* when comparing many data against a given model hypothesis. The key advantage of FDR is that it allows one to *a priori* control the average fraction of false rejections made (when comparing to the null hypothesis) over the total number of rejections performed. We compare FDR to the standard procedure of rejecting all tests that do not match the null hypothesis above some arbitrarily chosen confidence limit, *e.g.* 2σ, or at the 95% confidence level. We find a

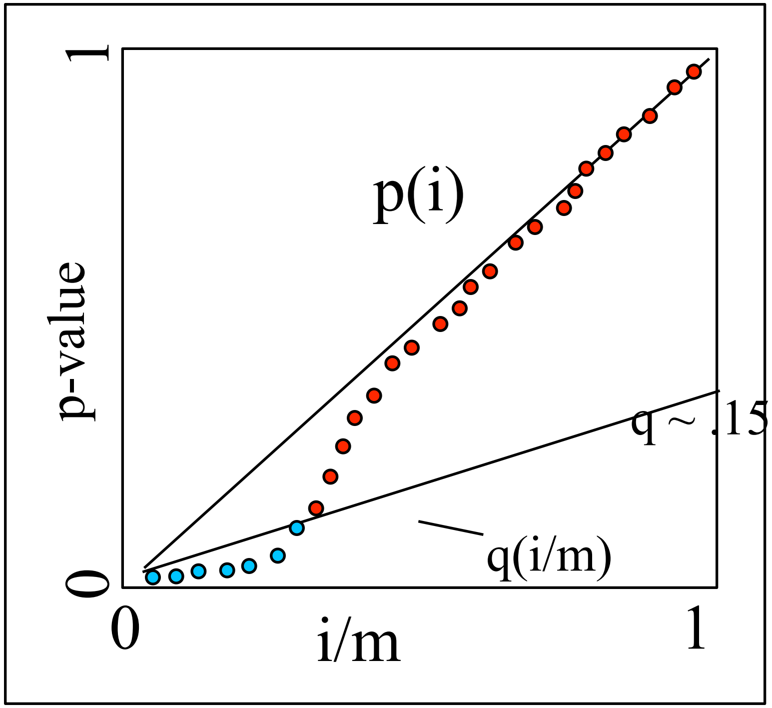
In contrast to Bonferroni, which seeks to control the chance of even a single false discovery among all the tests performed, the FDR method controls the proportion of errors among those tests whose null hypotheses were rejected.

False Discovery Rate

Select desired limit q on Expectation(FDR)

- α is not specified: the method selects it

JRSS-B (1995) 57:289-300



Sort the p-values, $p_1 \leq p_2 \leq \ \ldots \leq p_N$

- Let r be largest j such that

$$P_j < \frac{j\alpha}{c_N N}$$

Reject all null hypotheses corresponding to $p_1, \ldots, p_r$.

- ☑ i.e. Accept as signal

Those r "discoveries" should have q×r false discoveries (on average)

- ☑ Proof this works is not obvious!

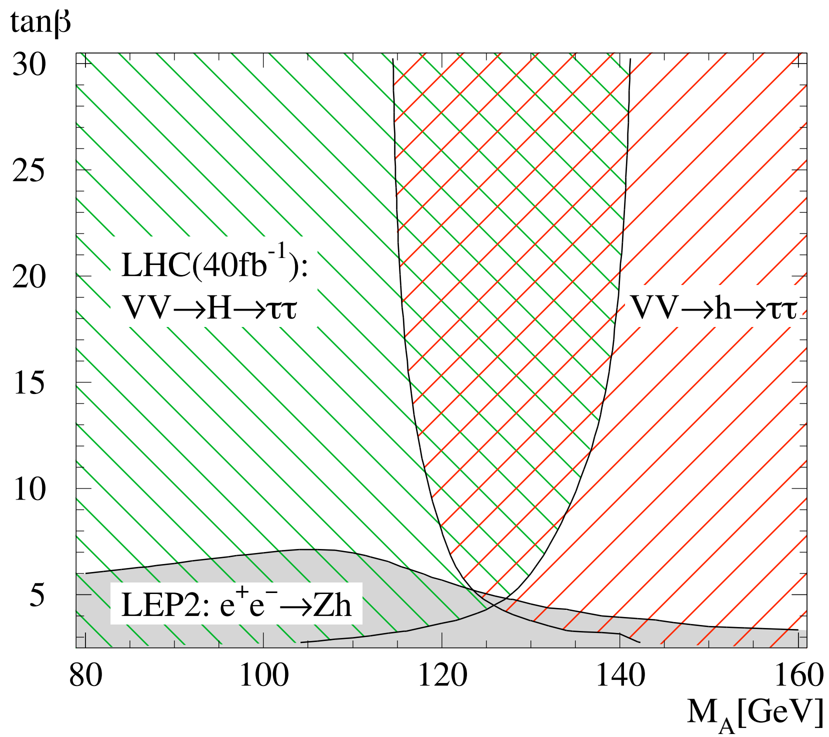
If searches are correlated $c_N = \sum_{i=1}^{N} \frac{1}{i}.$

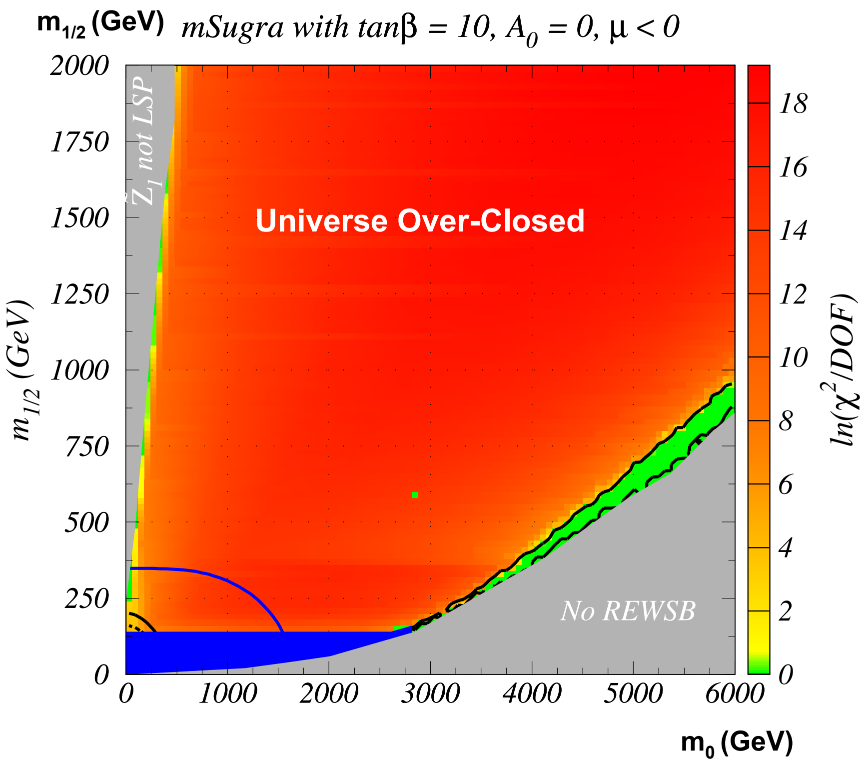
Description from Linnemann

Comments on Scans

It is common to scan the parameters of a theory to make exclusion plots and the like, but ...

- grid scans don't scale to higher dimensions
- why equal steps in tanβ? Why not β, or something else?
- there are large regions where phenomenology isn't changing
- the trials factor: more chances for false discovery





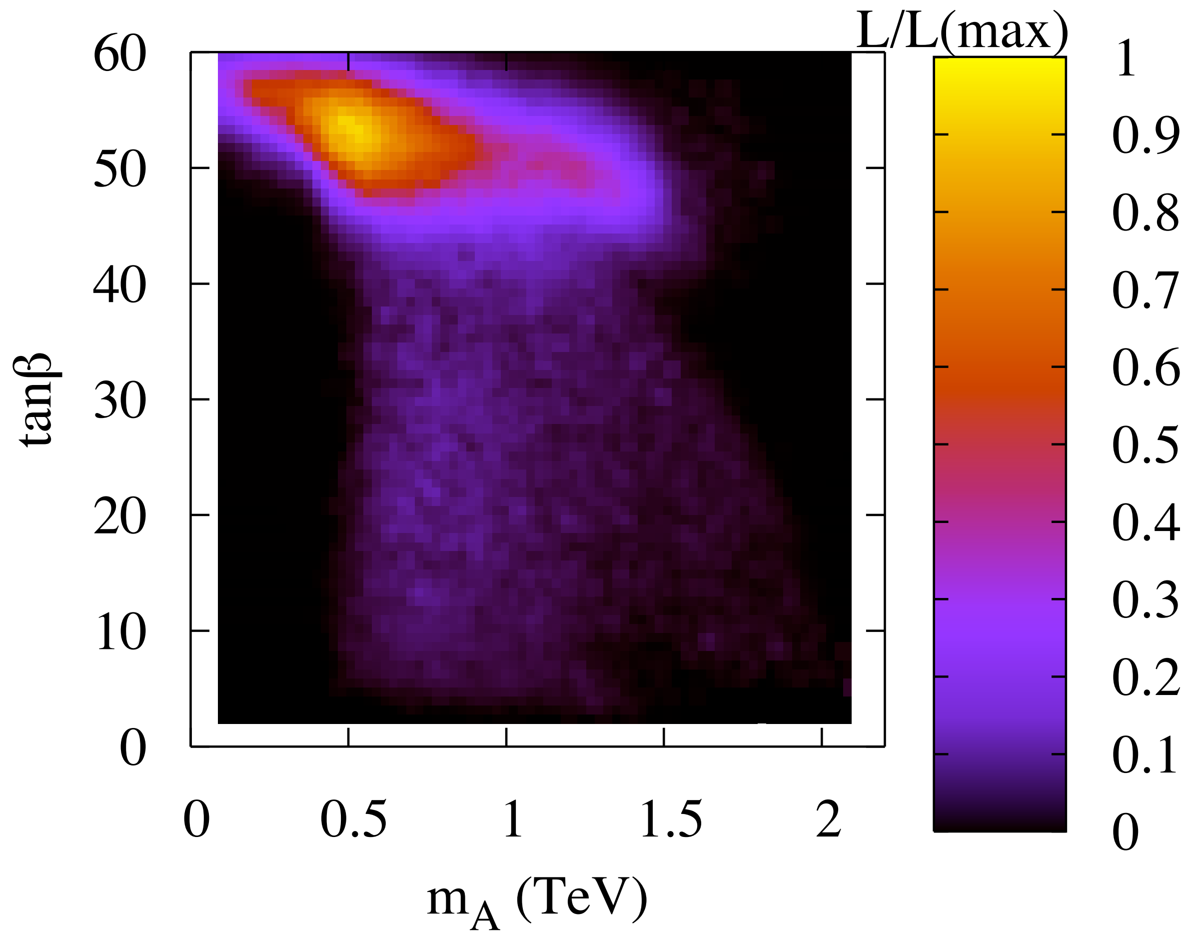
Exploring High-Dimensional Models

A few groups now using Markov-Chain Monte Carlo techniques to explore high-dimensional models (mSUGRA)

- conclusions are sensitive to the choice of prior
- treat it like a weather forecast

[hep-ph/0507283, hep-ph/0601089, arXiv:0705.0487]

- What would you do with a likelihood map like this?
- reduce sensitivity to prior with "natural priors" via a Hierarchical Bayes model
- See talks by Lafaye & Roszkowski later today!



Exploring High-Dimensional Models

BROOKHAVEN NATIONAL LABORATORY

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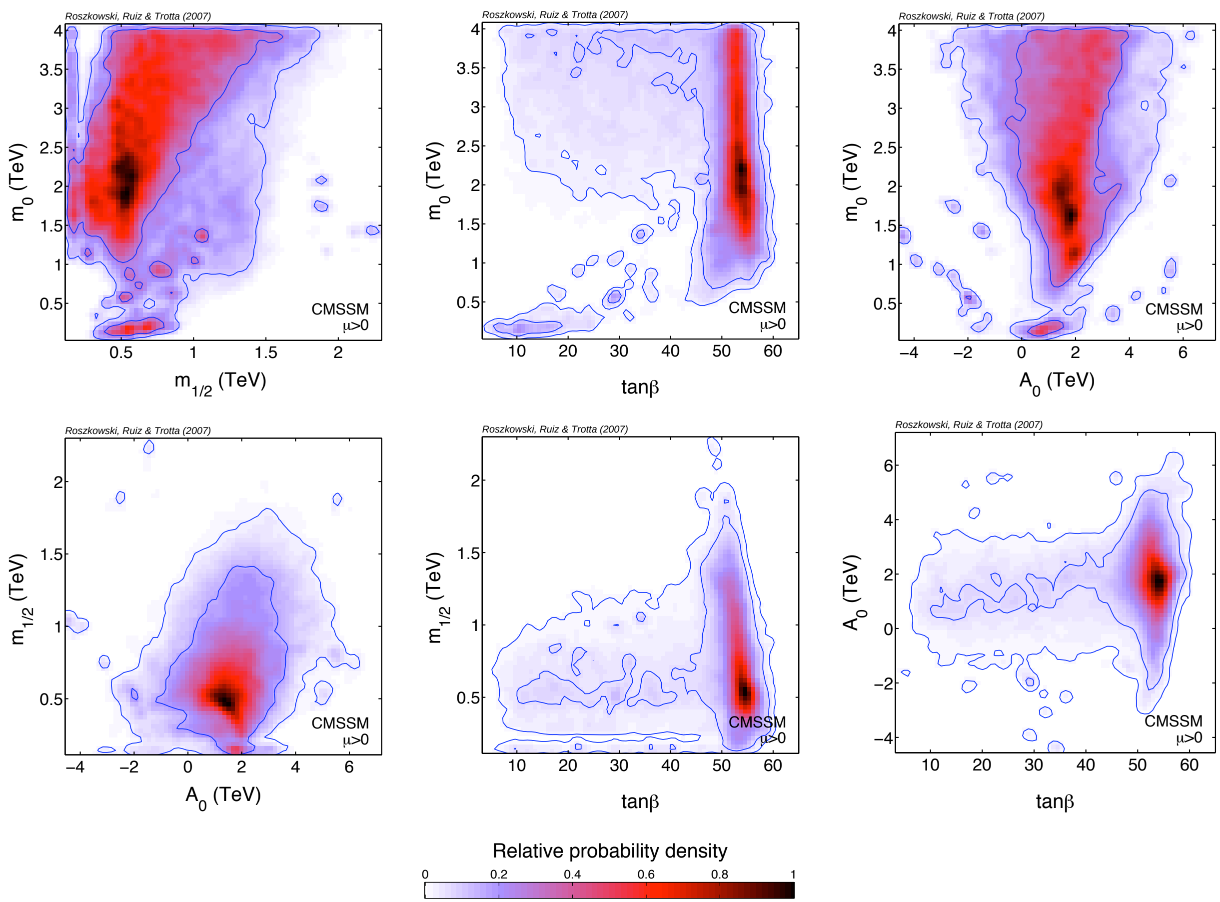


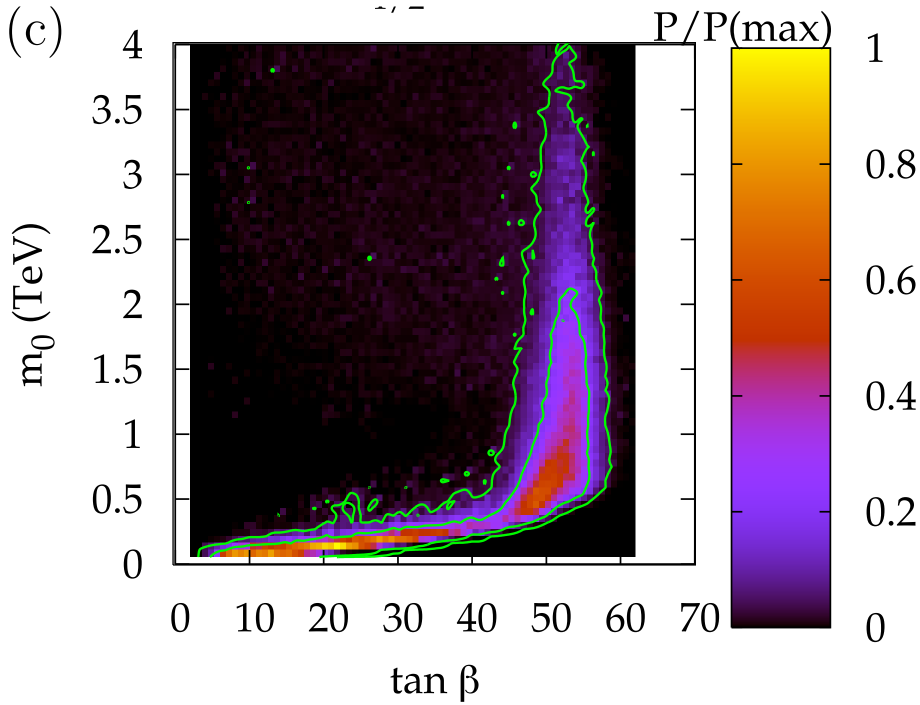
Hierarchical Bayes in HEP

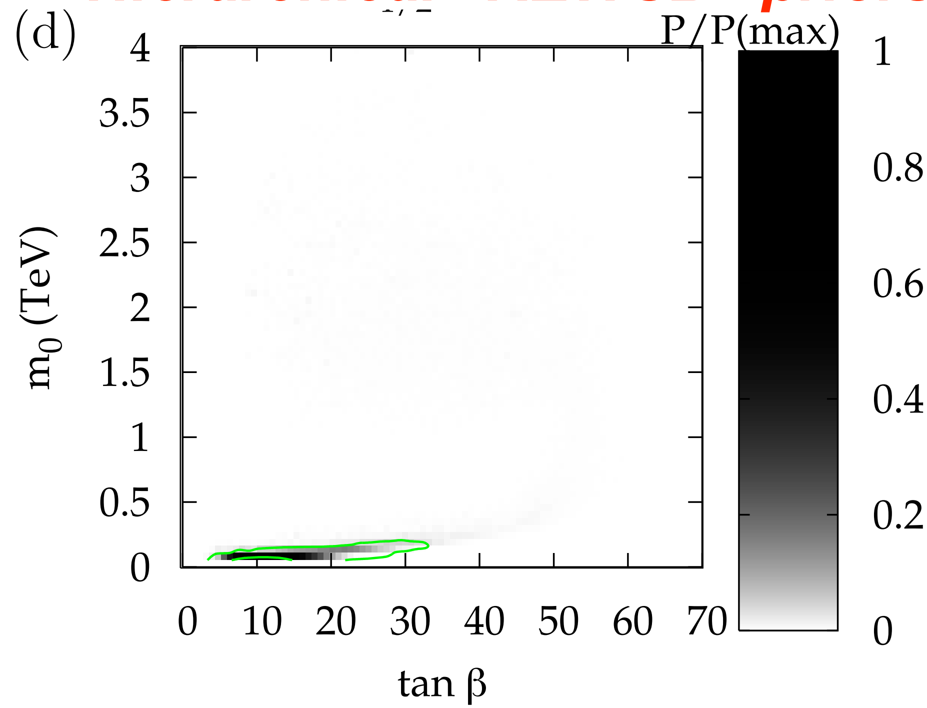
$$p(m_0, M_{1/2}, A_0, \mu, B, s|M_S) = p(m_0|M_S)\; p(M_{1/2}|M_S)\; p(A_0|M_S)$$
$$p(\mu|M_S)\; p(B|M_S)\; p(s),$$

$$p(m_0|M_S) = \frac{1}{\sqrt{2\pi w^2}m_0} \exp\left(-\frac{1}{2w^2}\log^2(\frac{m_0}{M_S})\right).$$

$$p(m_0, M_{1/2}, A_0, \mu, B) = \int_0^\infty dM_S\; p(m_0, M_{1/2}, A_0, \mu, B|M_S)\; p(M_S)$$

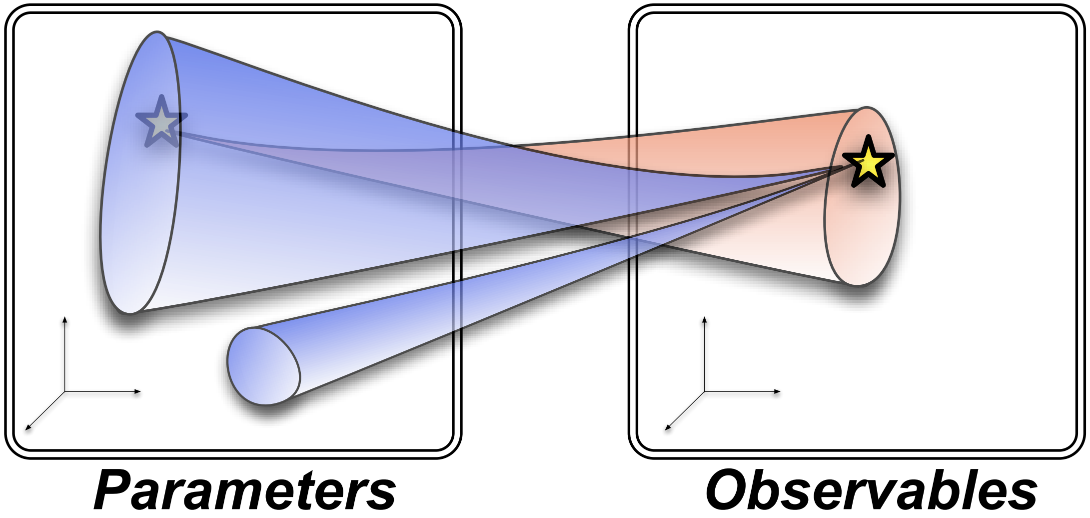
Flat Priors | **Hierarchical "REWSB" priors**





Allanach, Lester, Weber, (Cranmer?) [arXiv:0705.0487]

A Tale of Two Maps



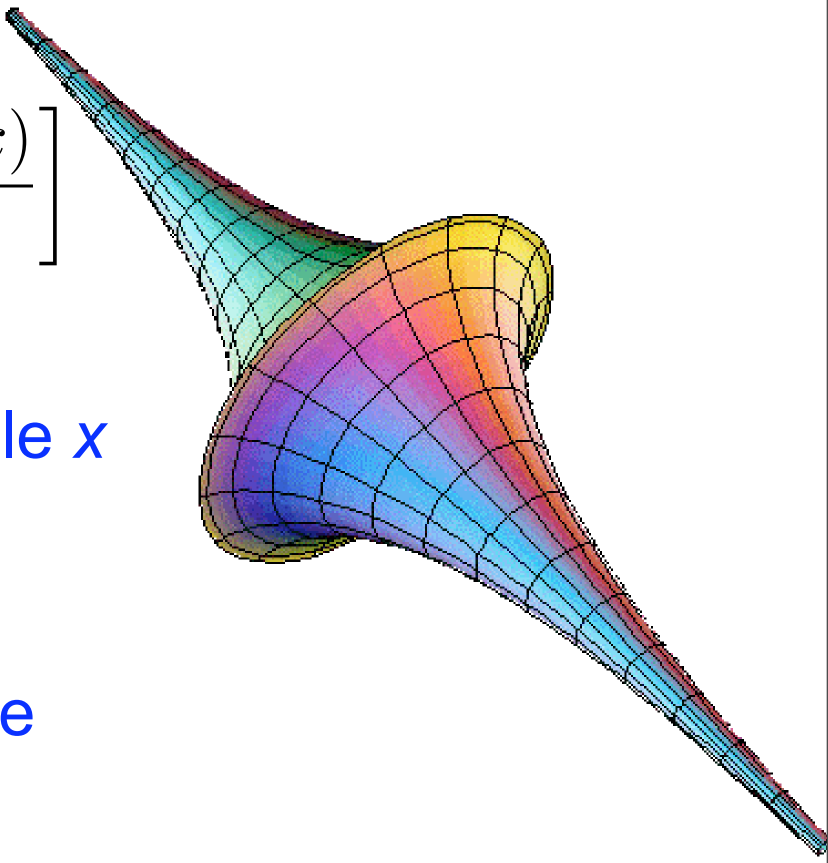
There is a fundamental difference between space of parameters and space of observables

- the space of observables have a metric & a probability measure
- the space of parameters does not have a probability measure unless you add it in the form of a prior

Information Geometry

Information Geometry (Amari) equips model space with a "natural" metric.

- invariant to reparametrization of observables
- covariant to reparametrization of theory



$$g_{ij}(\alpha) = \int dx\, f_\alpha(x) \left[\frac{\partial \log f_\alpha(x)}{\partial \alpha_i}\right] \left[\frac{\partial \log f_\alpha(x)}{\partial \alpha_j}\right]$$

Consider a Gaussian model with observable *x* and parameters *μ,σ*:

- forms 2-d model space
- geometry is constant negative curvature
- geometry provides geodesics, efficient sampling techniques, faster convergence, etc.

How Will We Publish?

Discovery of the τ

BROOKHAVEN NATIONAL LABORATORY

VOLUME 35, NUMBER 22 PHYSICAL REVIEW LETTERS 1 DECEMBER 1975

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

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(Received 18 August 1975)

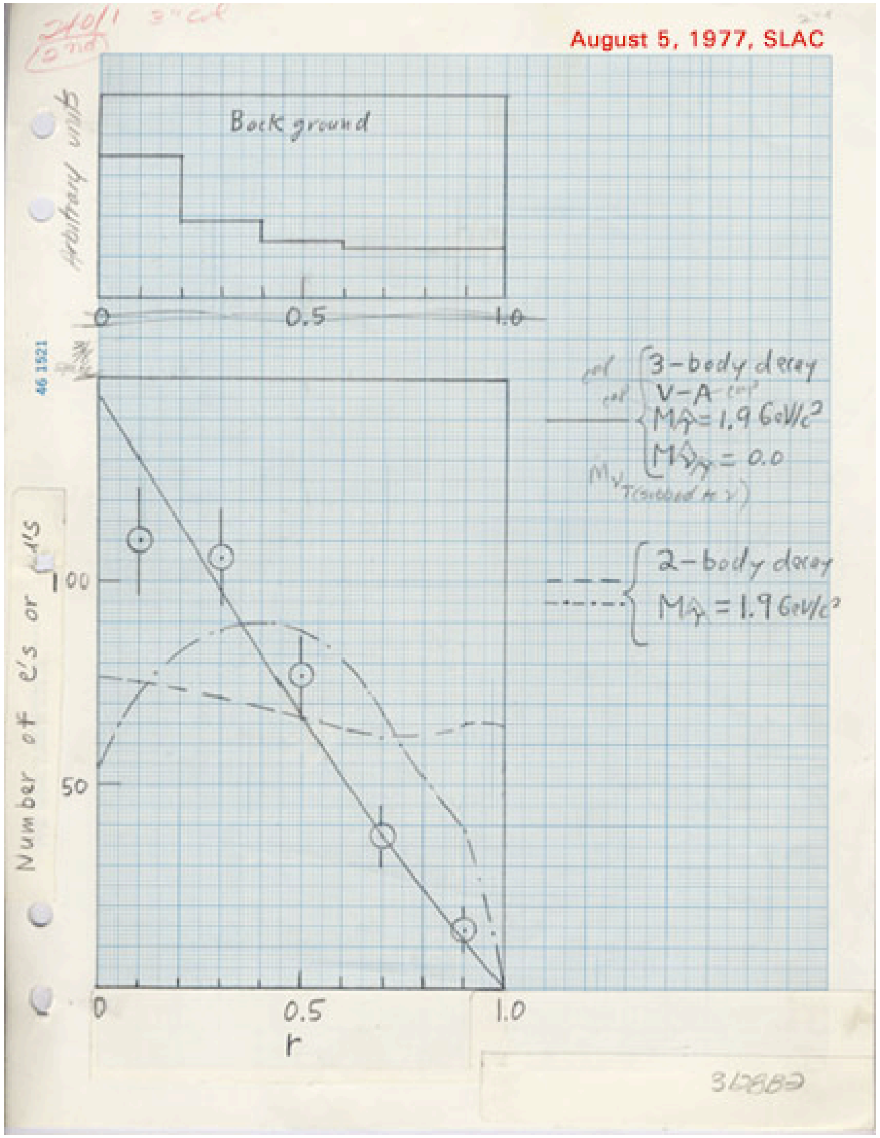
We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp +$ missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

Figure 5. Title, byline, and abstract of the first paper (Ref 12).

TABLE I. Distribution of 513 two-prong events, obtained at $E_{\text{c.m.}} = 4.8$ GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{\text{copl}} > 20°$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
e-e	40	111	55	0	1	0
e-μ	24	8	8	0	0	3
μ-μ	16	15	6	0	0	0
e-h	20	21	32	2	3	3
μ-h	17	14	31	4	0	5
h-h	14	10	30	10	4	6

Figure. 6. A table from the first paper (Ref. 12).



Discovery of the gluon

BROOKHAVEN
NATIONAL LABORATORY

VOLUME 43, NUMBER 12 PHYSICAL REVIEW LETTERS 17 SEPTEMBER 1979

Discovery of Three-Jet Events and a Test of Quantum Chromodynamics at PETRA

D. P. Barber, U. Becker, H. Benda, A. Boehm, J. G. Branson, J. Bron, D. Buikman, J. Burger, C. C. Chang, H. S. Chen, M. Chen, C. P. Cheng, Y. S. Chu, R. Clare, P. Duinker, G. Y. Fang, H. Fesefeldt, D. Fong, M. Fukushima, J. C. Guo, A. Hariri, G. Herten, M. C. Ho, H. K. Hsu, T. T. Hsu, R. W. Kadel, W. Krenz, J. Li, Q. Z. Li, M. Lu, D. Luckey, D. A. Ma, C. M. Ma, G. G. G. Massaro, T. Matsuda, H. Newman, J. Paradiso, F. P. Poschmann, J. P. Revol, M. Rohde, H. Rykaczewski, K. Sinram, H. W. Tang, L. G. Tang, Samuel C. C. Ting, K. L. Tung, F. Vannucci, X. R. Wang, P. S. Wei, M. White, G. H. Wu, T. W. Wu, J. P. Xi, P. C. Yang, X. H. Yu, N. L. Zhang, and R. Y. Zhu

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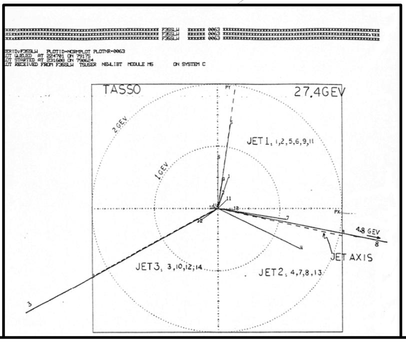
(Received 31 August 1979)



Volume 91B, number 1 PHYSICS LETTERS 24 March 1980

OBSERVATION OF PLANAR THREE-JET EVENTS IN e^+e^- ANNIHILATION AND EVIDENCE FOR GLUON BREMSSTRAHLUNG

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Received 7 December 1979

Volume 86B, number 2 PHYSICS LETTERS 24 September 1979

EVIDENCE FOR PLANAR EVENTS IN e^+e^- ANNIHILATION AT HIGH ENERGIES

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Discovery of the W & Z

BROOKHAVEN NATIONAL LABORATORY

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

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Volume 126B, number 5 PHYSICS LETTERS 7 July 1983

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

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Received 6 June 1983

Volume 122B, number 5,6 PHYSICS LETTERS 17 March 1983

OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

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Volume 129, number 1,2 PHYSICS LETTERS 15 September 1983

EVIDENCE FOR $Z^0 \to e^+e^-$ AT THE CERN $\bar{p}p$ COLLIDER

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Discovery of the top quark

BROOKHAVEN NATIONAL LABORATORY

FERMILAB-PUB-94/116-E
CDF/PUB/TOP/PUBLIC/2595
May 16, 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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What about the Higgs?

Observation of the Higgs Boson at 125 GeV

the ATLAS Collaboration

- or -

Excess in opposite-flavor, opposite-charge leptons associated with large missing transverse energy

the CMS Collaboration

What about the Higgs?

BROOKHAVEN
NATIONAL LABORATORY

Observation of the Higgs Boson at 125 GeV

the ATLAS Collaboration

\- or -

Excess in opposite-flavor, opposite-charge leptons associated with large missing transverse energy

the CMS Collaboration

Observation of an Excess in the Search for the Standard Model Higgs Boson at ALEPH

The ALEPH Collaboration *)

Abstract

A search has been performed for the Standard Model Higgs boson in the data sample collected with the ALEPH detector at LEP, at centre-of-mass energies up to 209 GeV. An excess of $3\,\sigma$ beyond the background expectation is found, consistent with the production of the Higgs boson with a mass near $114\,\mathrm{GeV}/c^2$. Much of this excess is seen in the four-jet analyses, where three high purity events are selected.

Model Independent Results

For many experimentalists, our goal is to provide results that are as independent of theoretical prejudice as possible, and to leave the interpretation to a later stage.

Often, when several theories share a common signature, there exists a parametrized model for some relevant observables or some effective theory that can encompass several specific theories

- when these theory-relevant & theory-neutral representations are known, it is common to publish exclusion contours of these parameters

An improvement for the interpretation stage would be to publish the likelihood function for these (possibly several) parameters

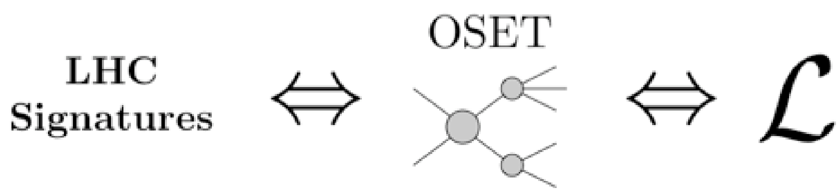
MARMOSET is a new tool aimed to aid in the interpretation of a signal: toolkit to build on on-shell effective theories

MARMOSET is somewhat controversial due to the simplifications it makes compared to the more detailed theoretical calculations we have for specific theories, but in some cases the OSET can provide a theory-relevant & theory-neutral summary of the observed signal

if so, publish likelihood contours of OSET's parameters

MARMOSET

Mass and Rate Modeling
in On-Shell Effective Theories



Examples of Published Likelihoods

At previous PhyStats, we agreed to publish likelihood functions

You can find examples of published likelihoods in 1D

In 2-D you just get the contours

Surely we can do better!

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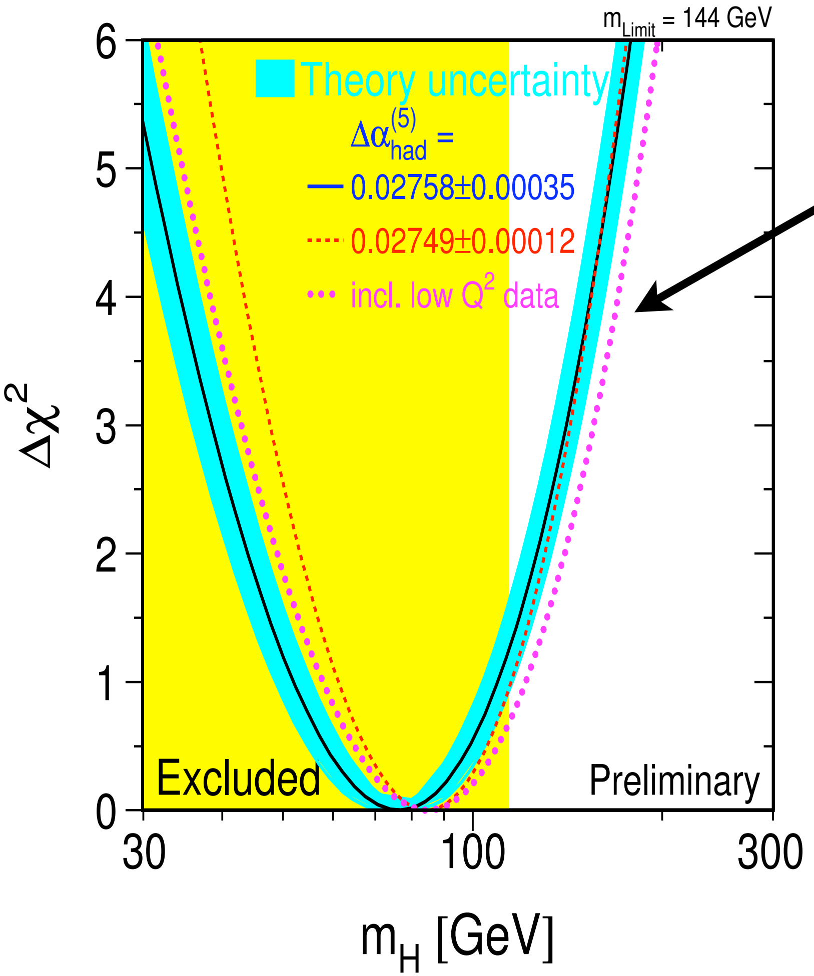

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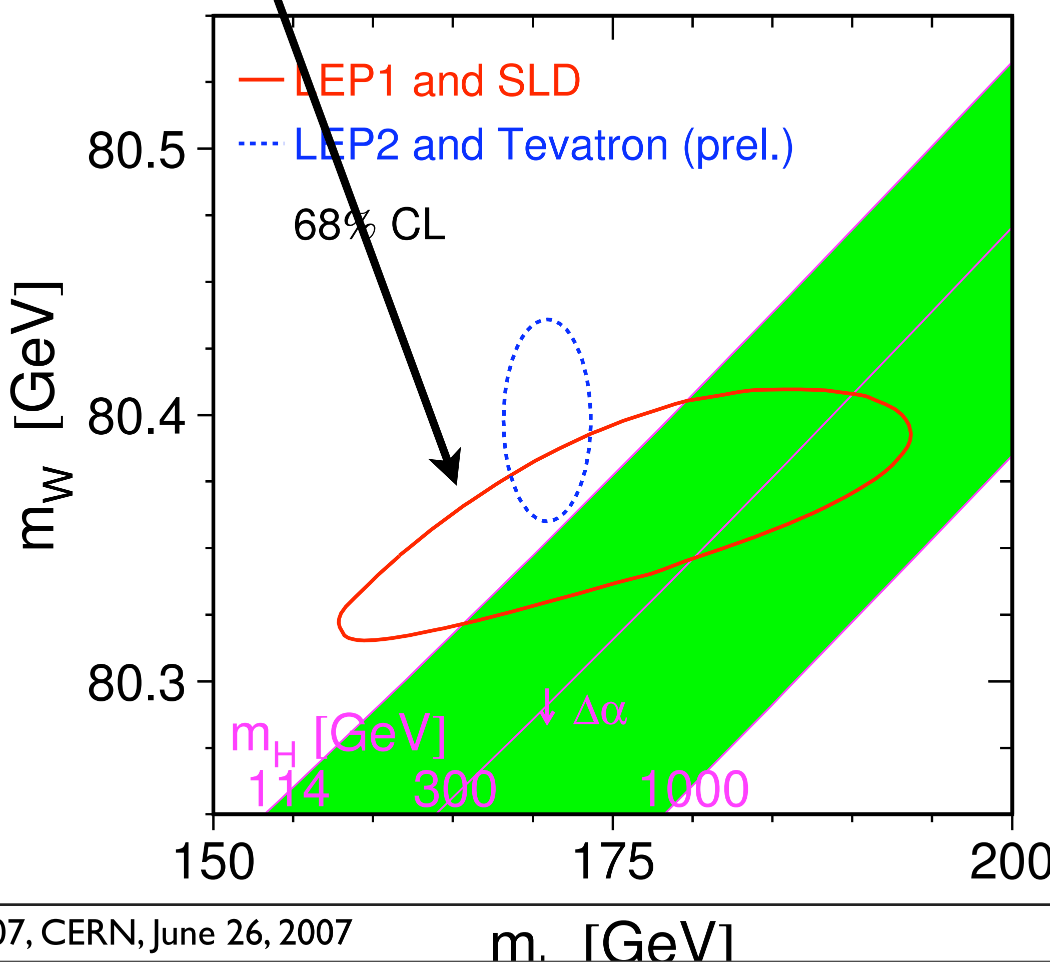

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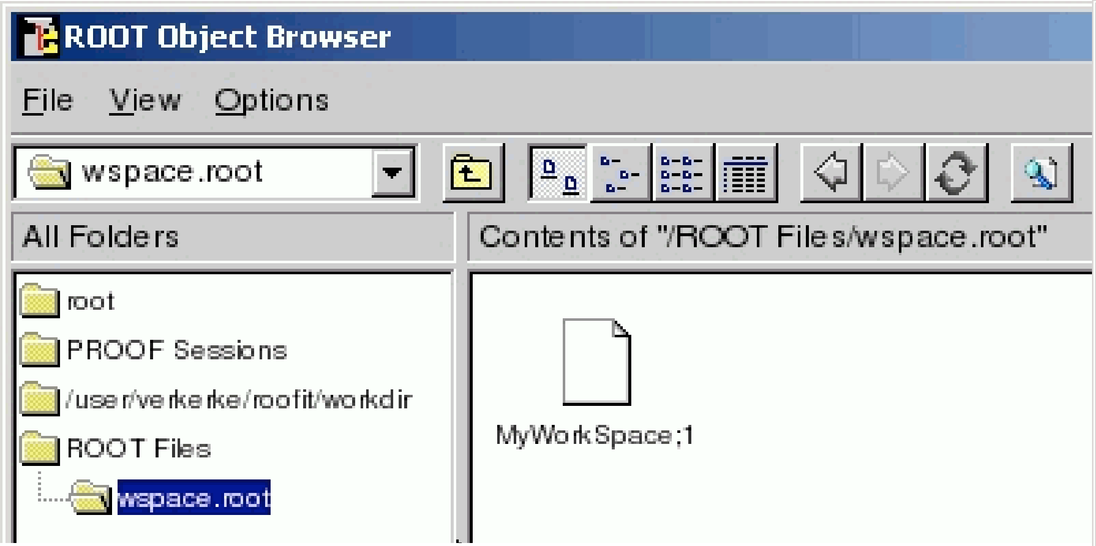
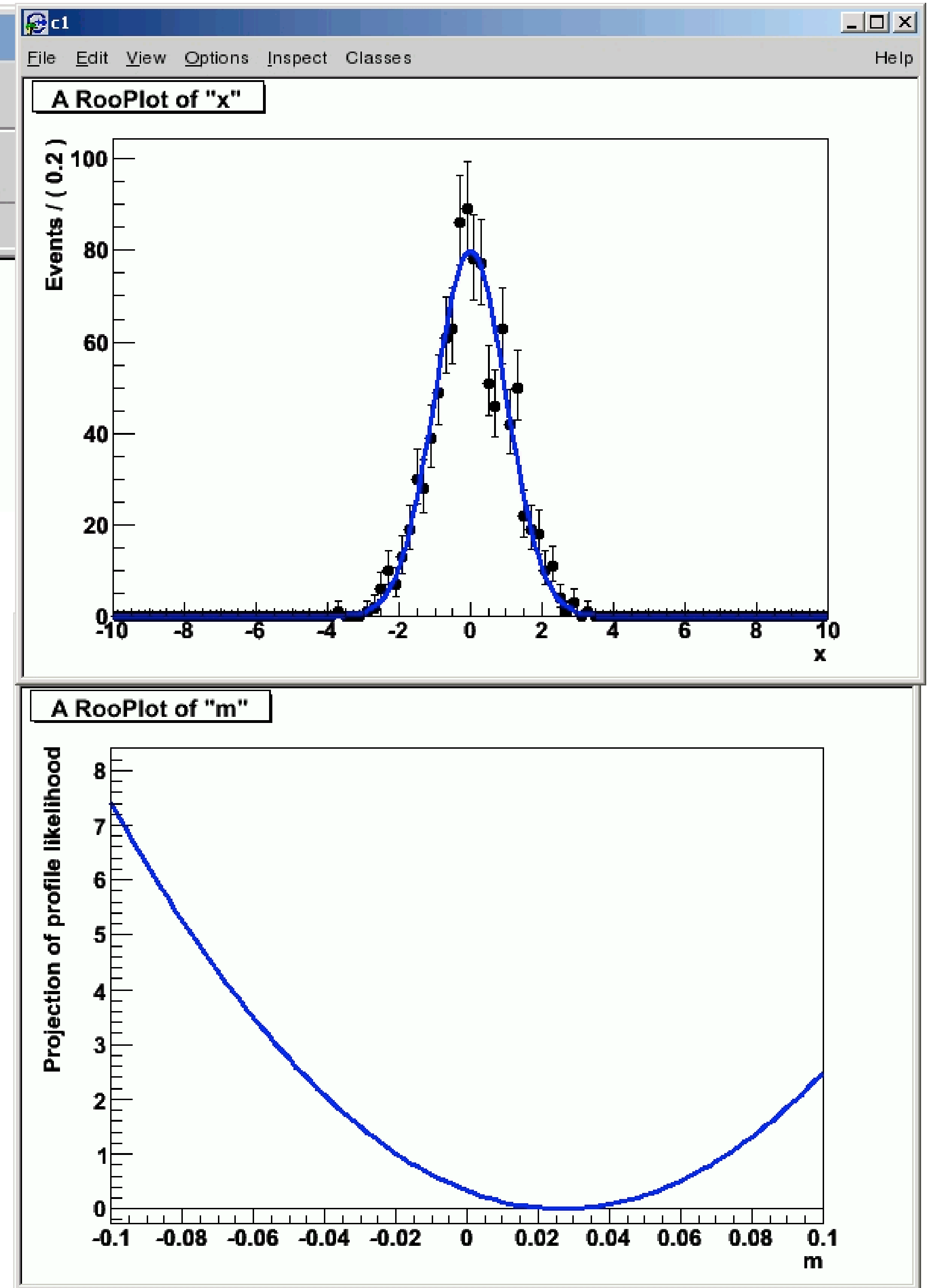
Example of Digital Publishing





Wouter recently demonstrated the ability to save the function $L(x|\theta_r, \theta_s)$ in a Root file with minimal data necessary to reproduce likelihood function.

Can also evaluate integrals over x necessary for Neyman construction!

Need this for combinations, we should publish them to some repository!

Conclusions

It is a very exciting time for High Energy Physics with the LHC startup eminent.

- The enormous investment in the LHC should make us take very seriously our analysis of the data.
- It is not only an opportunity to understand nature, but also to progress as a field of science.

Studies of well-defined signals like the Higgs show that a proper treatment of systematic uncertainties is crucial.

- We seem to be maturing in this area fairly quickly

Multivariate analysis is ubiquitous, but popular methods are often not developed with our problems in mind.

Searches for physics beyond the standard model are challenging because the signal is vaguely defined and the possibilities are innumerable

New technologies allow powerful new ways to publish our results

Backup

One take on “Why 5σ?”: Utility Theory

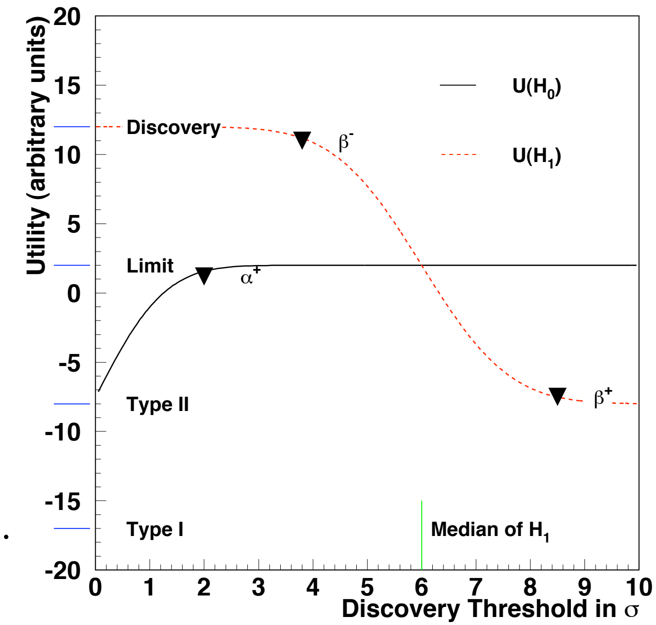
BROOKHAVEN NATIONAL LABORATORY

(taken from my thesis)

Instead of arguing about convention, derive threshold from utility theory:

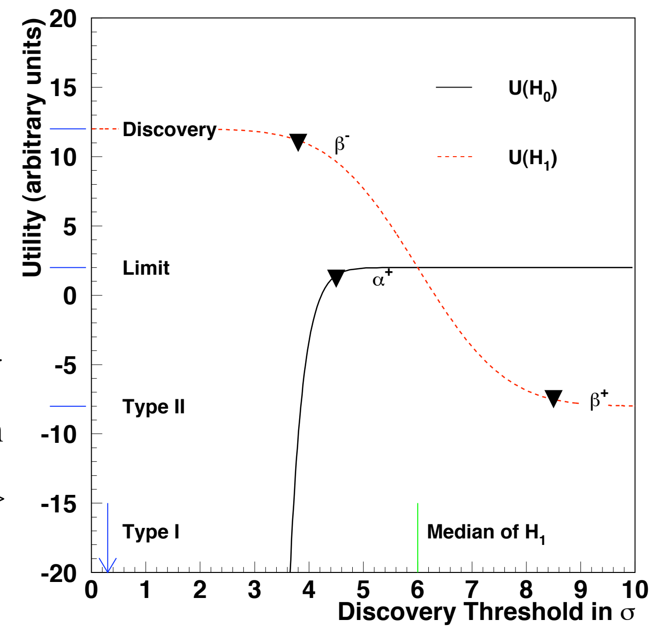
- assumptions of game theory not appropriate
- let size of the test for discovery be α and for limit setting be α’

$$U(H_0) = (1-\alpha')\cdot U(\text{Type I}) + \beta'\cdot U(\text{Limit}) + (\beta-\beta')\cdot U(\text{No Result})$$
$$U(H_1) = (1-\beta)\cdot U(\text{Discovery}) + \beta'\cdot U(\text{Type II}) + (\beta-\beta')\cdot U(\text{No Result}).$$



With a prior on H_0/H_1 one can use a richer decision theory. But in a frequentist way, one obtains:

$$\alpha^+ = \epsilon\left[1-\frac{U(\text{Type I})}{U(\text{Limit})}\right]^{-1}$$



Ideally, the field would establish these utilities instead of working with the purely conventional 5σ requirement. Since that is not the case, it is reasonable to ask “what is this ratio of utilities which justifies a 5σ discovery threshold?” If we take $\epsilon = 1\%$ and $\alpha = 10^{-7}$, then $|U(\text{Type I})/U(\text{Limit})| > 10^5$. Perhaps this ratio is reasonable, perhaps not, but it is the ratio under which we operate today.

Figure A.5 Utility as a function of the discovery threshold for a channel w