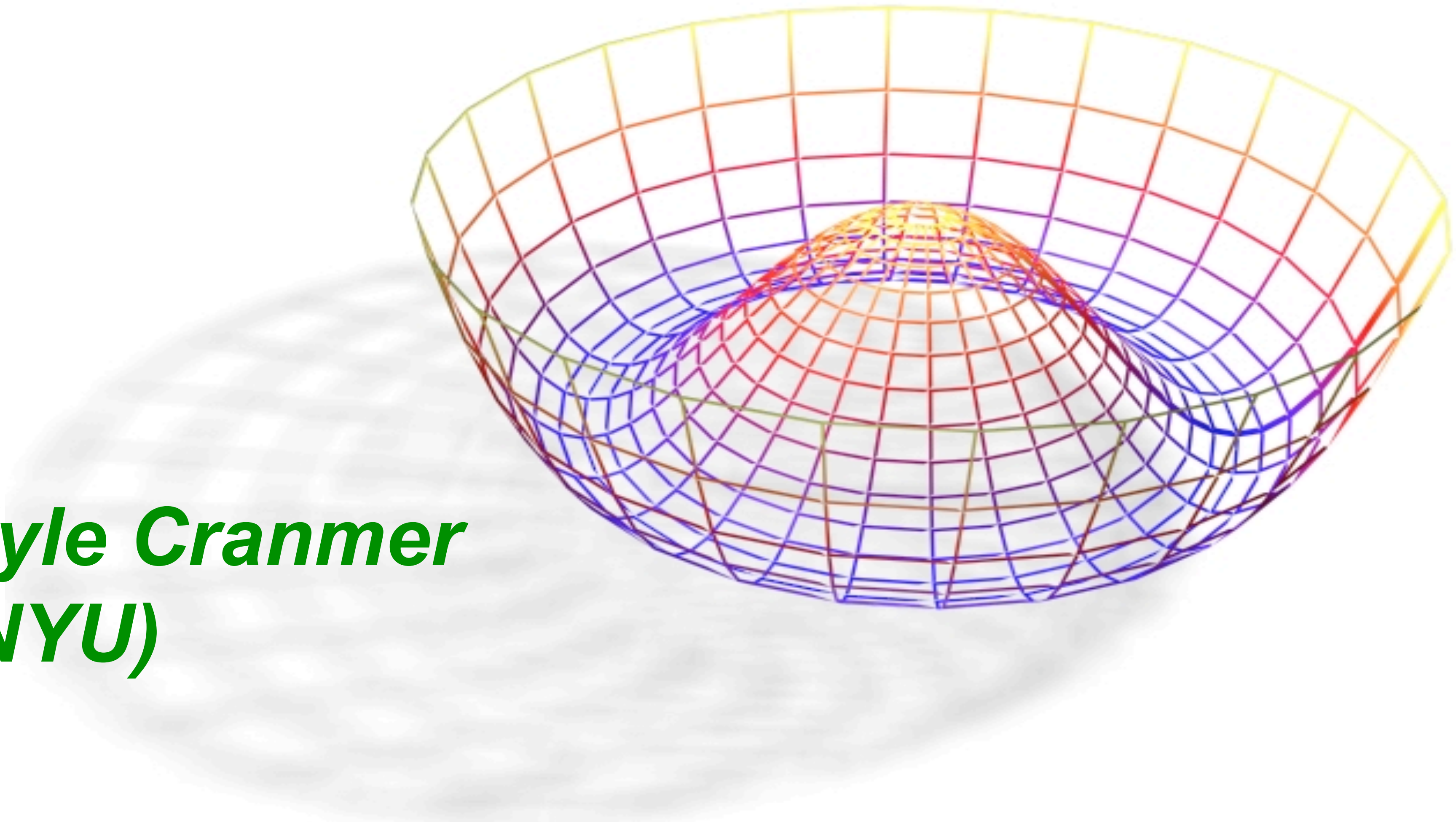
Searching for new physics at the LHC: Strategies, Tools, & Techniques



Kyle Cranmer
(NYU)

Outline

The LHC has enormous potential to discover new physics, but it also poses many challenges

- **experimental**: complicated detectors, enormous backgrounds, etc.
- **theoretical**: complex final states with important QCD effects
- **strategical**: how to search for it, how do we interpret it

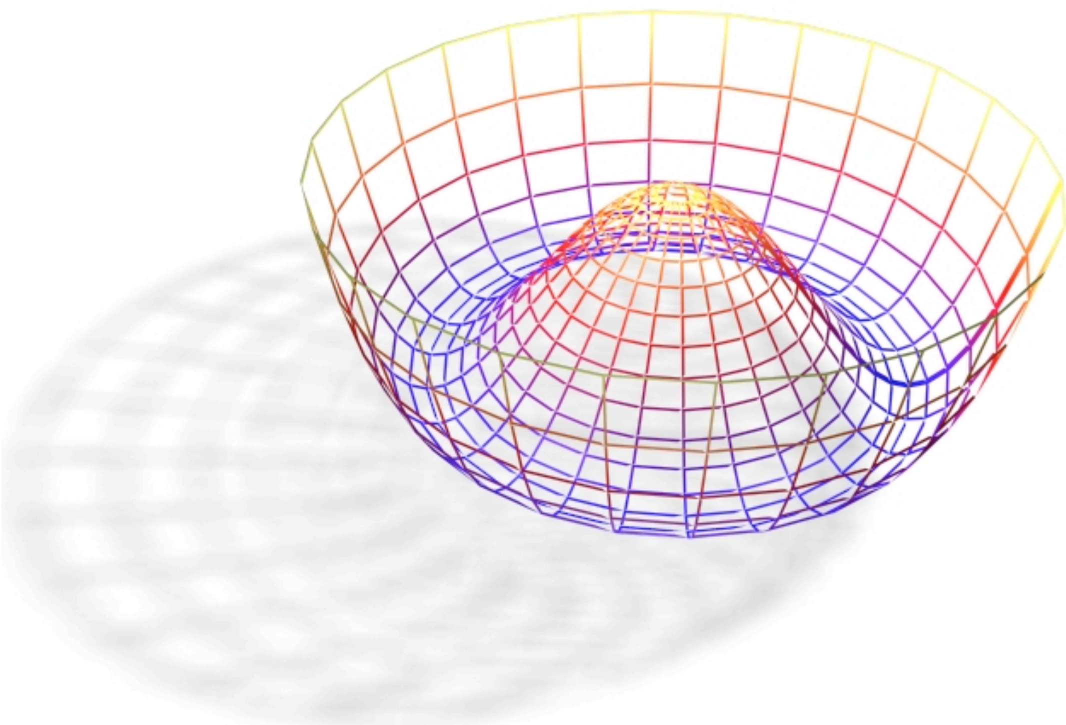
I will discuss some new ideas for searches for new physics

- discuss their pros and cons
- and introduce what may be new ideas

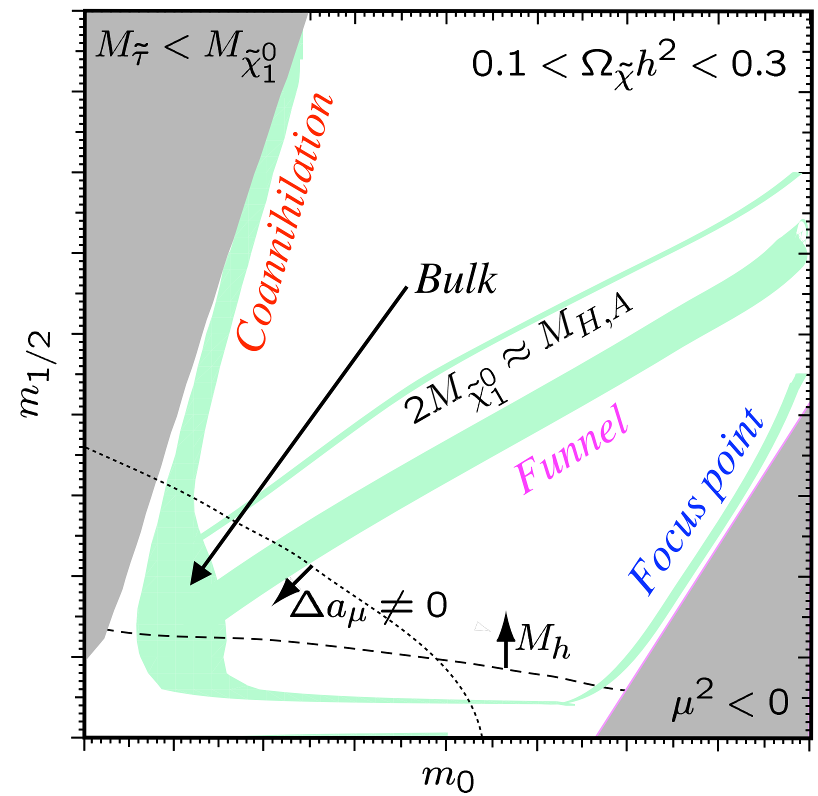
I am not trying to convince you that I have the solution

- instead, I will try to stimulate discussion

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

Simple Hypothesis Testing

Once one specifies the Higgs mass, the Standard Model is completely predictive

- in statistics jargon this is called a simple hypothesis test
- having a precise prediction for the signal is incredibly powerful, it lets you optimize your selection

In particular, one can use multivariate analysis techniques

- this has grown increasingly popular in High Energy Physics in recent years
  - Neural Networks, Decision Trees, etc.

But let's go back 80 years before we look into the future...

The Neyman-Pearson Lemma

In 1928-1938 Neyman & Pearson developed a theory in which one must consider competing Hypotheses:

- the Null Hypothesis H_0 (background only)
- the Alternate Hypothesis H_1 (signal-plus-background)

Given some probability that we wrongly reject the Null Hypothesis

$$\alpha = P(x \notin W | H_0)$$

Find the region W such that we minimize the probability of wrongly accepting the H_0 (when H_1 is true)

$$\beta = P(x \in W | H_1)$$

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:

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

This is the goal!

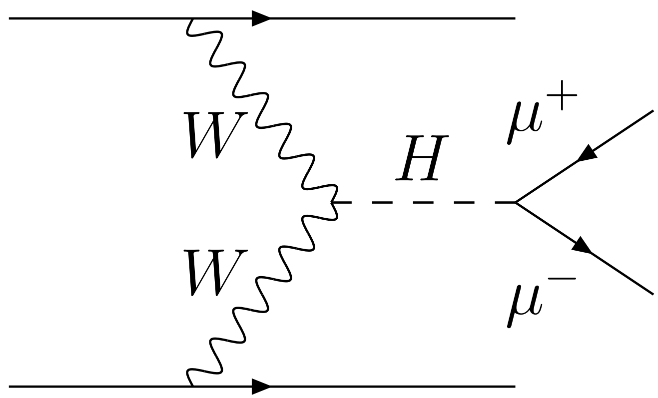
The problem is we don't have access to $L(x|H_0)$ & $L(x|H_1)$

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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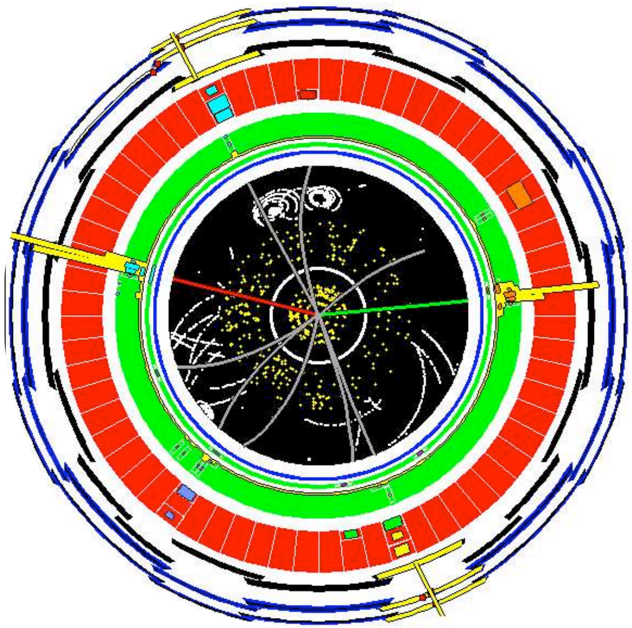
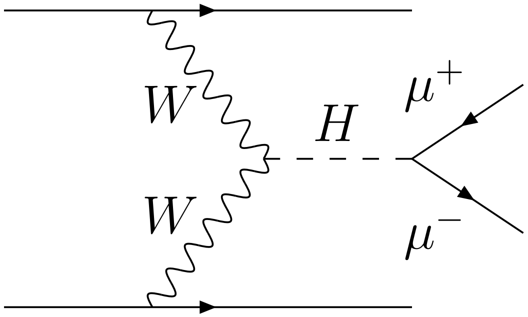
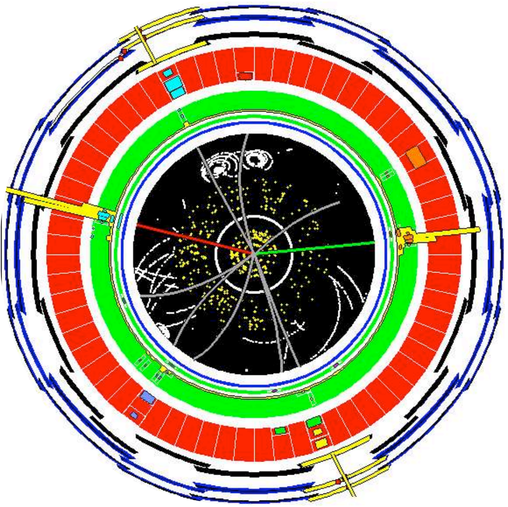
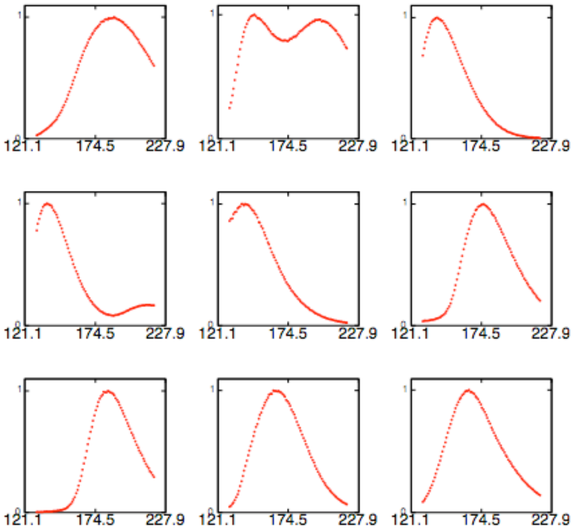


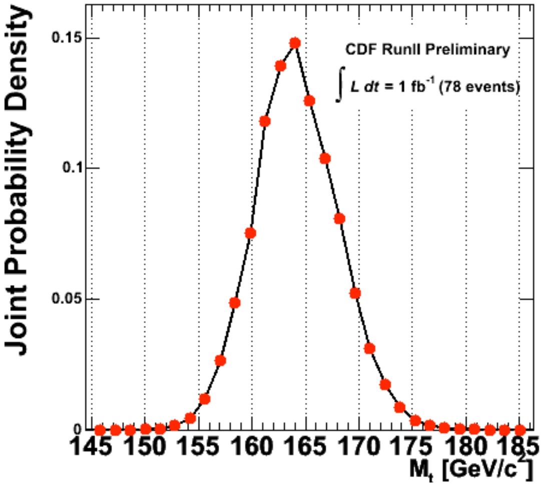
Matrix Element Techniques

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

$L(x|H_0) =$ 

$\oplus$ 





Matrix Element Techniques

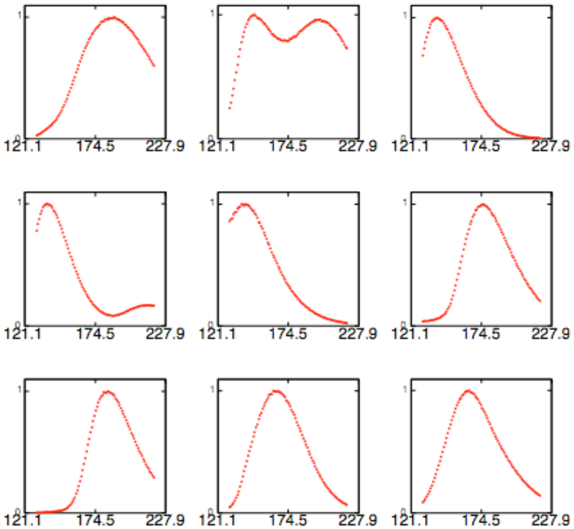
Instead of using generic machine learning algorithms, some members of the Tevatron experiments are starting to attack this convolution numerically

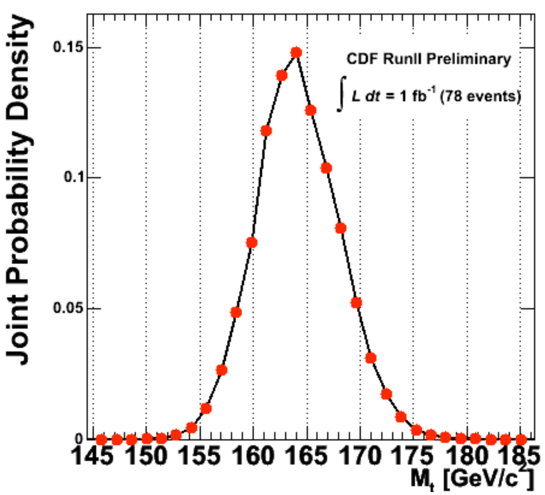
$$P(\mathbf{x}|M_t) = \frac{1}{N}\int d\Phi \; |\mathcal{M}_{t\bar{t}}(p;M_t)|^2 \prod_{jets} f(p_i,j_i) f_{PDF}(q_1) f_{PDF}(q_2)$$

Phase-space Integral

Matrix Element

Transfer Functions



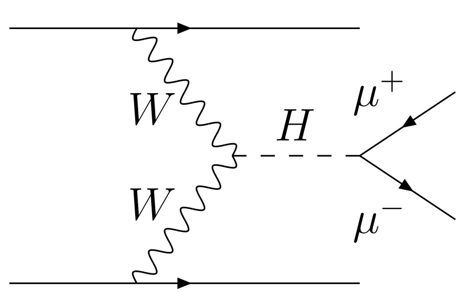


Matrix Element Techniques

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

$L(x|H_0) =$



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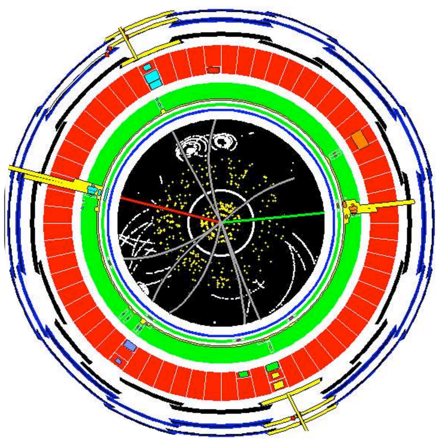
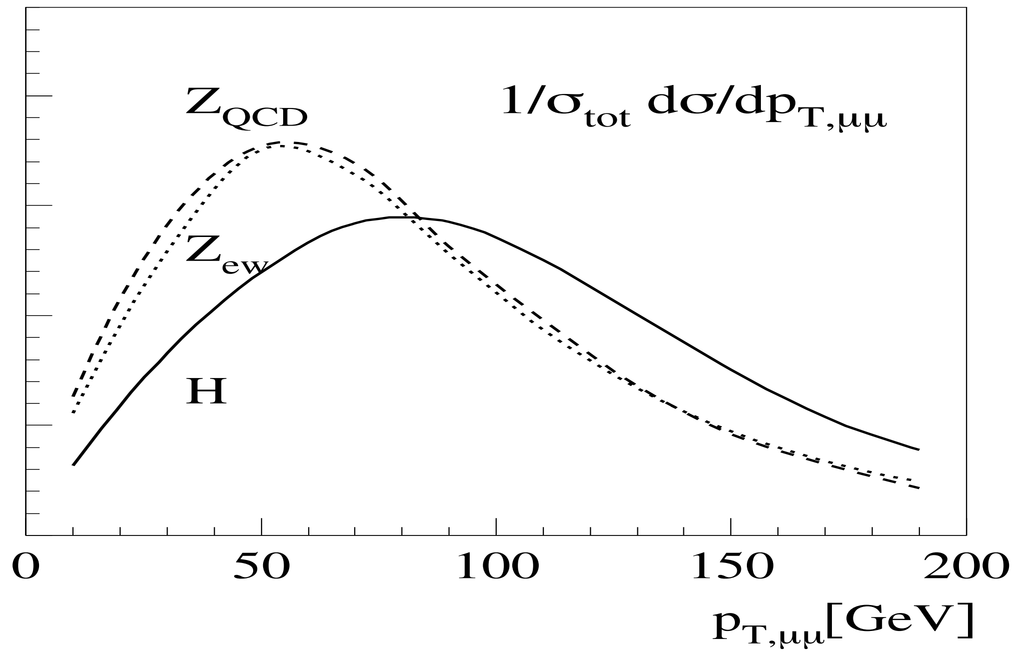


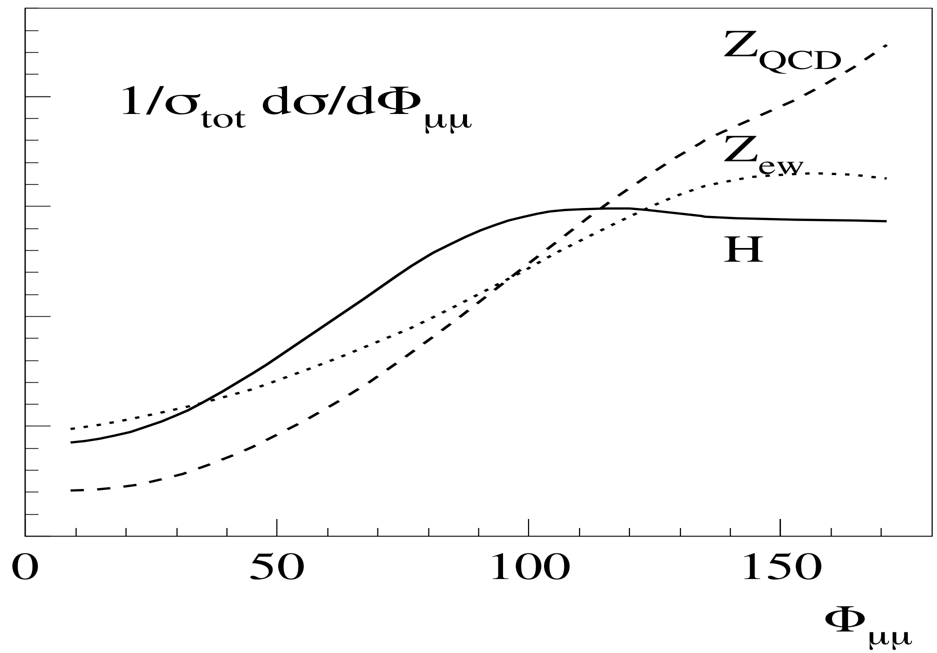
$H \rightarrow \mu\mu$ at the LHC?

In hep-ph/0107180, Tilman Plehn and David Rainwater investigated the potential of VBF $H \rightarrow \mu\mu$ to measure Yukawa coupling to second-generation fermions at LHC.

Even with 300 fb^{-1}, best cuts only achieve 1.8σ significance for $M_H = 120$ GeV.

However, they note several other variables with discriminating power:





They suggested the use of Neural Networks or some multivariate algorithm

Tao Han & Bob McElrath (hep-ph/0201023) included gluon fusion, still no discovery.

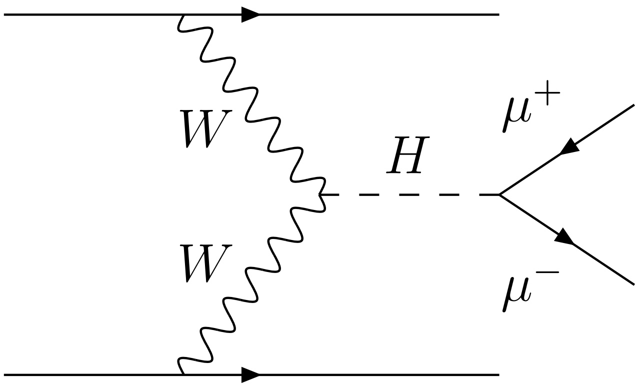
Maximum Significance

[Cranmer, Plehn EPJ C; hep-ph/0605268]

In addition to multivariate techniques , *the most powerful search* considers:

Likelihood of experiment = Π likelihood of each event

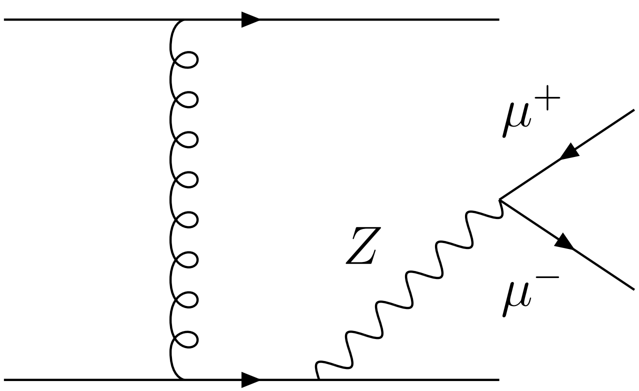
With basic cuts, only need to consider signal and irreducible backgrounds



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.

$H \to \mu\mu$ Results

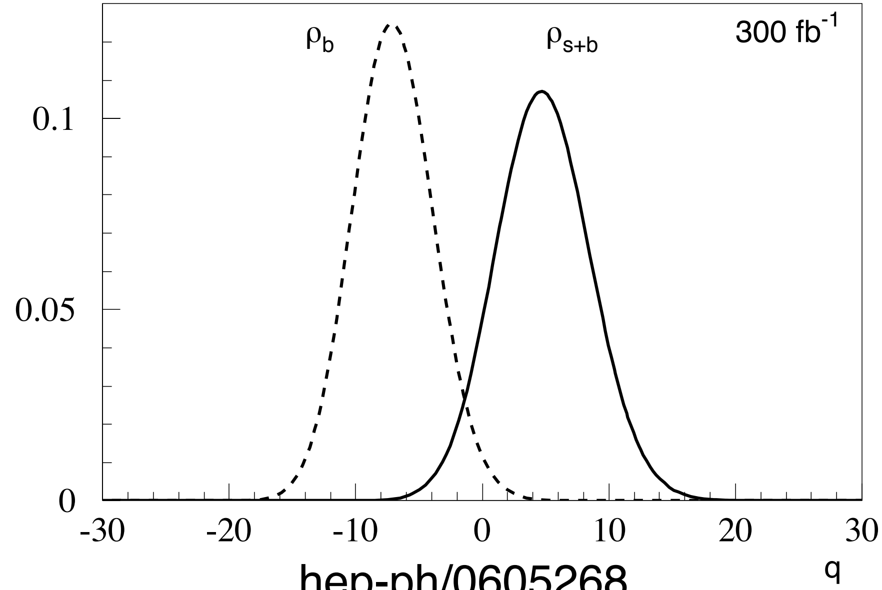
Original cuts in hep-ph/0107180 give 1.8σ / experiment for 300 fb^{-1}

With our technique with Atlas estimated mass resolution, we achieve

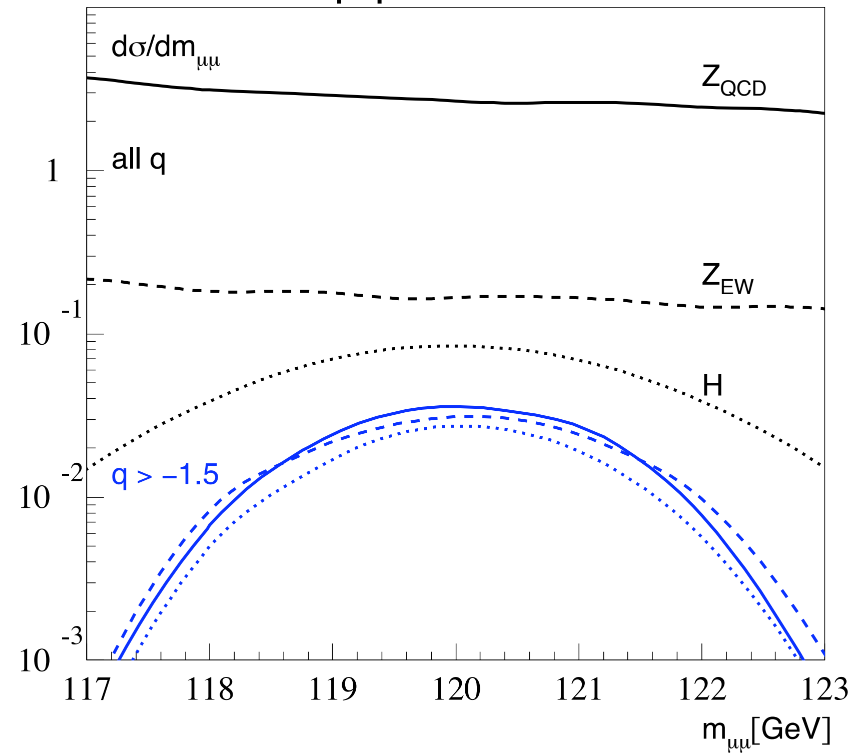
3.2σ / experiment with 300 fb^{-1}

Conclusion: the use of multivariate techniques & event weighting may make it possible to observe H→μμ at the LHC!

Recently held an "ultra-mini" workshop in Madison to bring together theorists and experimentalists working on these matrix-element techniques



hep-ph/0605268



Potential for a powerful pheno toolkit

Ideally, we could bring together all of these pieces in a more general purpose toolkit

- something like PGS to provide a library of transfer functions for each of the experiments
- something like MadEvent interfaced to this library of transfer functions
- a simple configuration language to indicate what observable the experiment is sensitive to, and which degrees of freedom should be integrated out

This could automate a substantial fraction of pheno studies and enrich them because the result is a formal upper-bound.

Need organized request for experiments to provide “official” transfer functions and/or fast simulation.

Requires an organized request for experiments to provide “official” transfer functions and/or fast simulation.

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 measurements and can be treated as statistical uncertainties
  - scale with luminosity

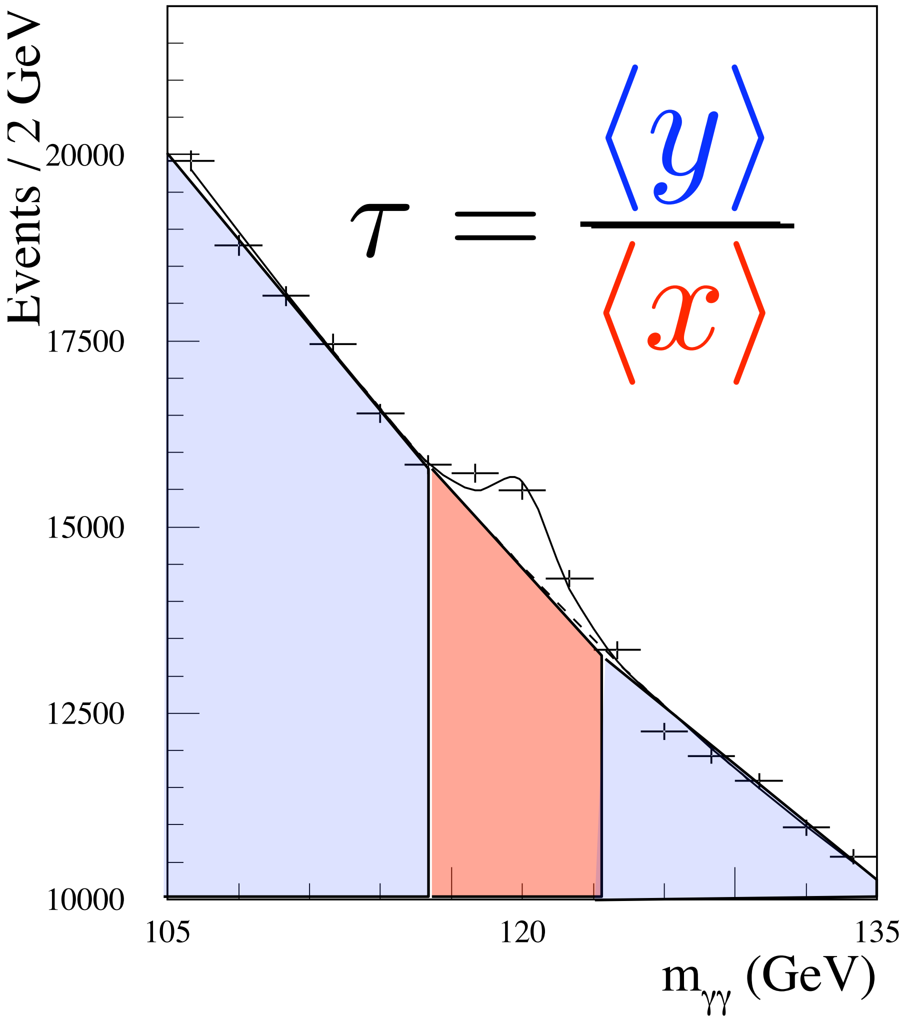
Type II – "The Bad"

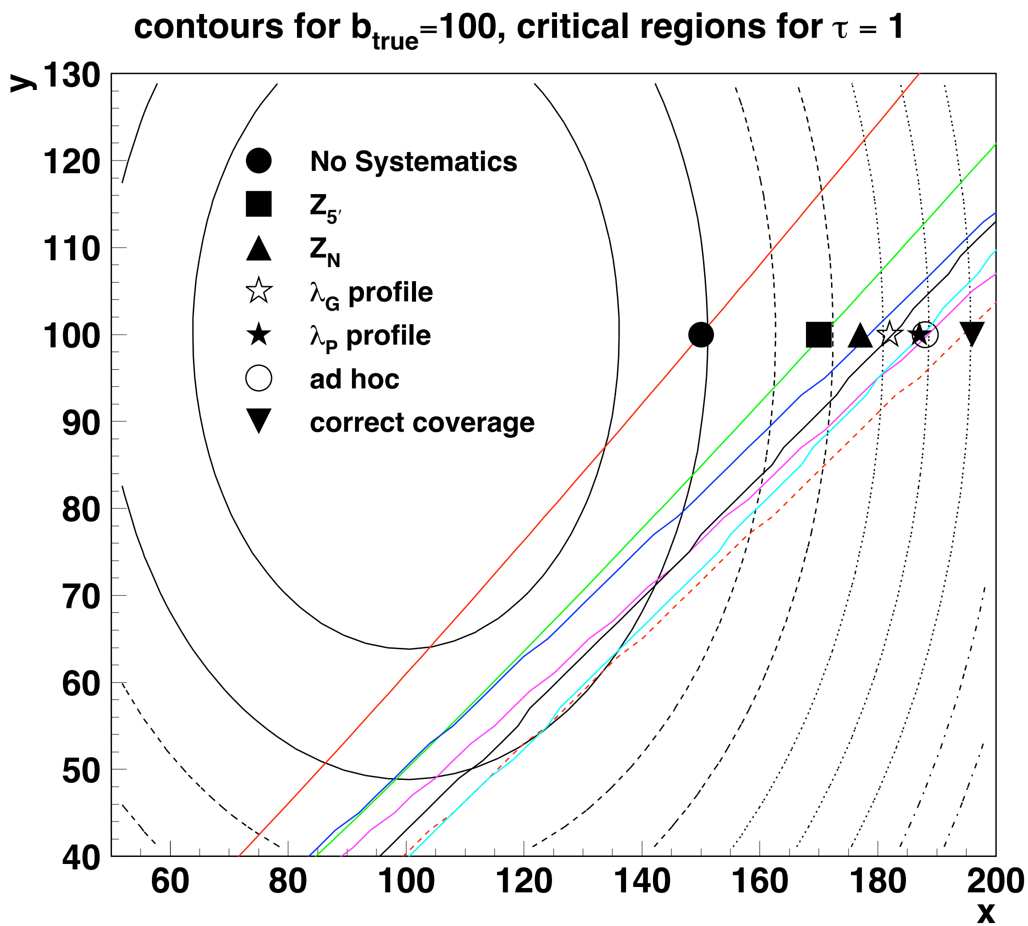
- arise from model assumptions in the measurement or from poorly understood features in data or analysis technique
  - don't necessarily scale with luminosity
  - eg: "shape" systematics

Type III – "The Ugly"

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

Example Sideband Measurement





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

Sideband used to extrapolate / interpolate the bkg. in signal region

Big differences between different methods: several methods breaking down for LHC conditions (large background uncertainty, high significance)

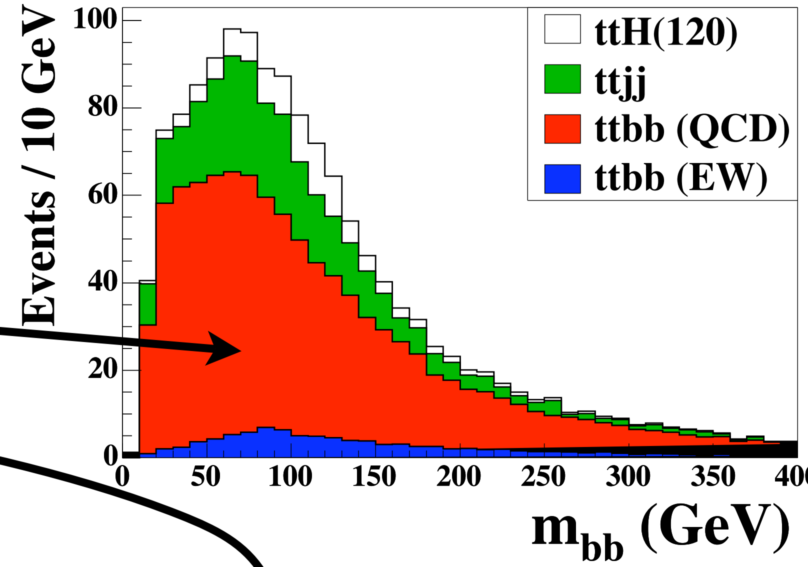
Type II Systematics

Class II systematics generally due to uncertainty in shape of background

- this uncertainty is limiting factor in ttH(H→bb) analysis
- also relevant for H→γγ

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



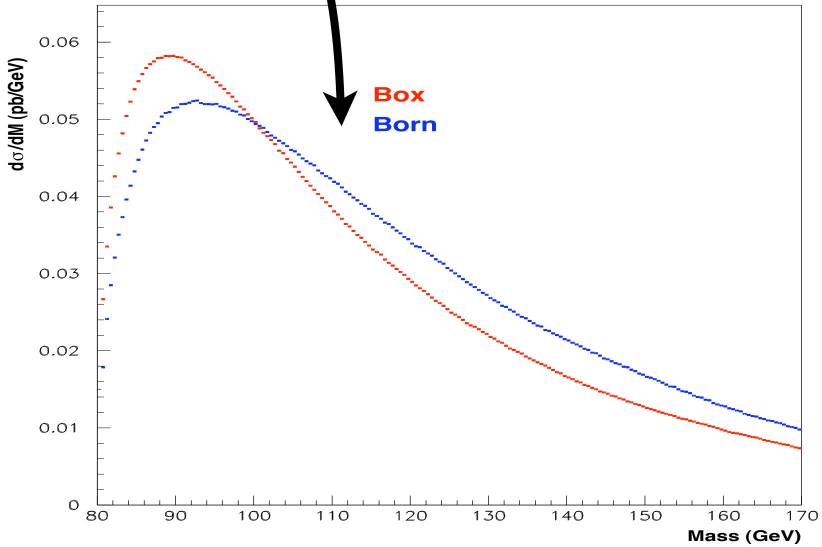


Figure 5. Two plausible shapes for the continuum $\gamma\gamma$ mass spectrum at the LHC.

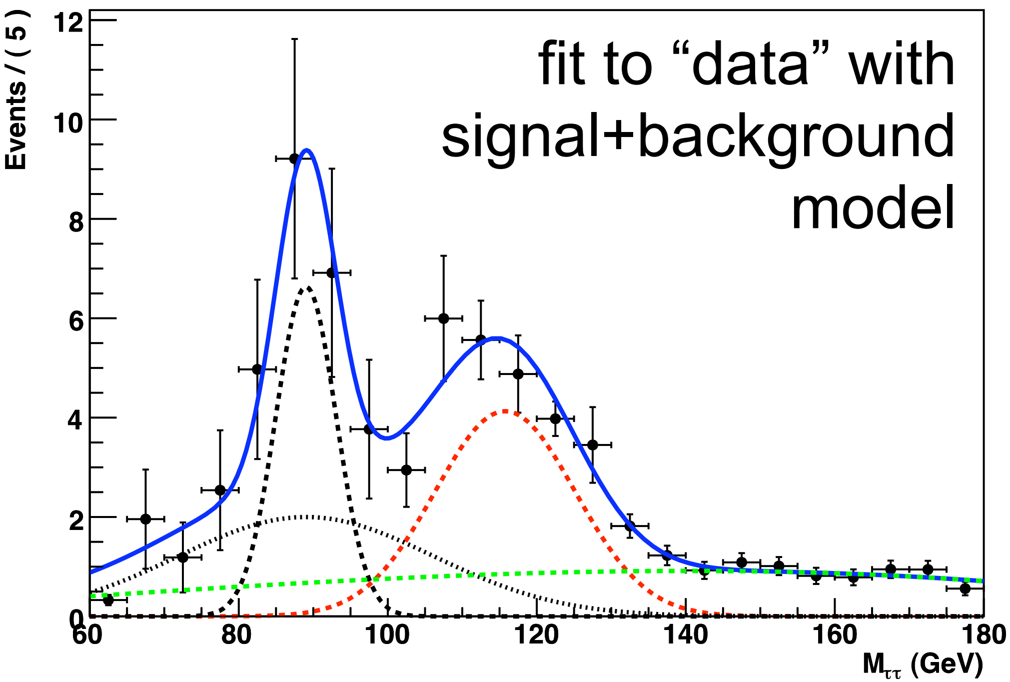
RooStats Project

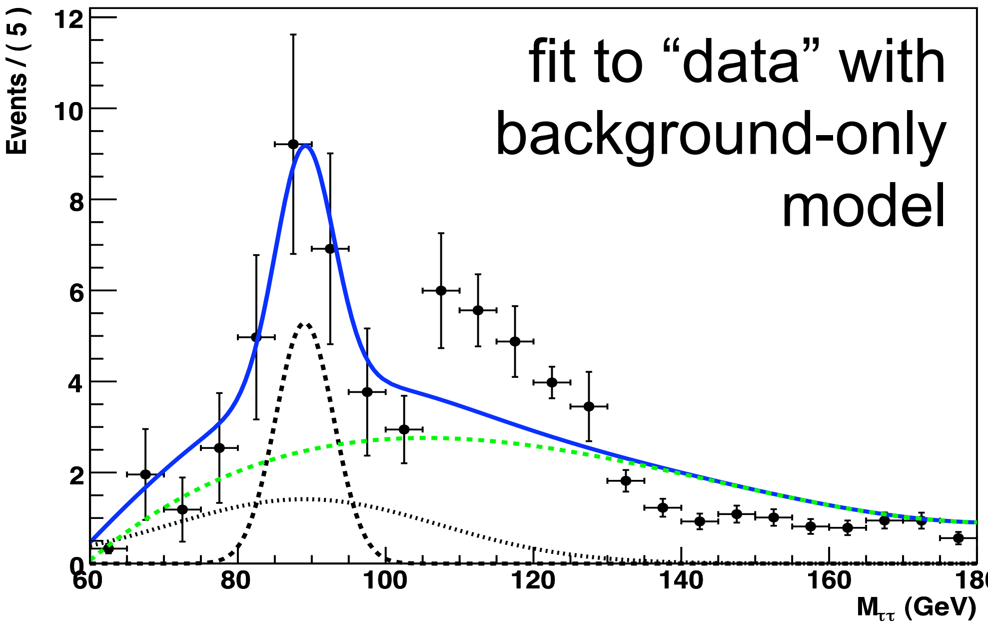
Project spearheaded by Rene Brun and I to build a high-level statistics framework in ROOT based on top of RooFit (by Wouter Verkerke).

- Several examples already using multiple techniques for the same problem
- Provides an easier, more flexible way to combine results.
- Being developed by ATLAS, CMS, and ROOT team

Example of Profile Likelihood Ratio to take into account uncertainty on rate & shape

$$\lambda = \frac{L(data|\hat{s},\hat{b},\hat{\nu})}{L(data|s=0,\hat{\hat{b}}(s=0),\hat{\hat{\nu}}(s=0))}$$



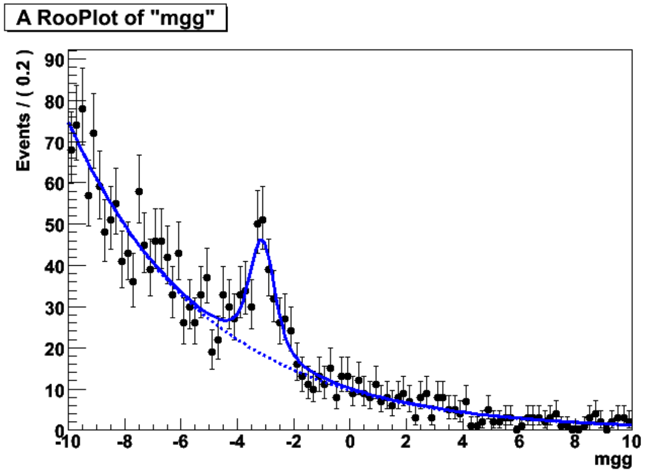


A toy example of published results

A combination example

- Similar code for 'CMS' – p.d.f. is Voigtian + Exponential

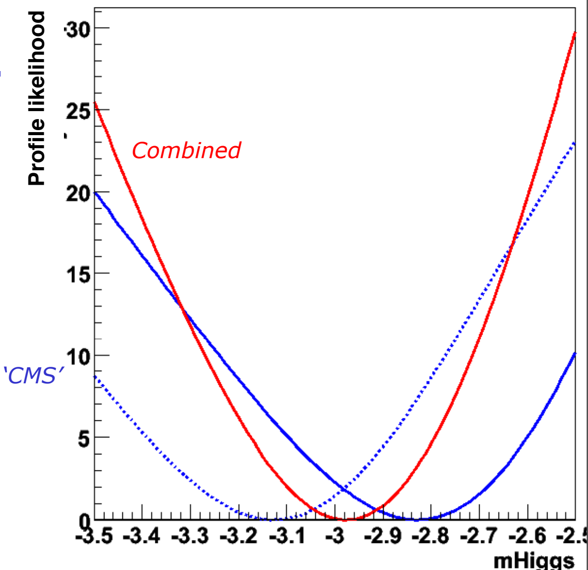
```
RooRealVar mgg("mgg","mgg",-10,10) ;
RooRealVar mHiggs("mHiggs","mHiggs",-3,-10,10) ;
RooRealVar wHiggs("wHiggs","wHiggs",0.8,0.1,10) ;
RooRealVar sHiggs("sHiggs","sHiggs",0.3) ;
RooVoigtian sig("sig","sig",mgg,mHiggs,wHiggs,sHiggs) ;
RooRealVar slope("slope","slope",-0.2,-100,1) ;
RooExponential bkg("bkg","bkg",mgg,slope) ;
RooRealVar nHiggs("nHiggs","nHiggs",500,-500.,10000.) ;
RooRealVar nBkg("nBkg","nBkg",5000,0.,10000.) ;
RooAddPdf model("model","model",RooArgList(sig,bkg),RooArgList(nHiggs,nBkg)) ;

RooDataSet* data = model.generate(mgg,NumEvents(2000),Name("data")) ;
model.fitTo(*data,Extended(),Minos(kFALSE)) ;
RooNLLVar nll("nll","nll",model,*data,Extended()) ;

RooWorkspace cms("cms","cms") ;
cms.import(model) ;
cms.import(*data) ;
cms.import(nll) ;
cms.Print() ;

TFile f("cms.root","RECREATE") ;
cms.Write() ;
f.Close() ;
```



Combining Results: An Example

A combination example

- Combining 'ATLAS' and 'CMS' result from persisted workspaces



Read ATLAS workspace

```
TFile* f = new TFile("atlas.root") ;
RooWorkspace *atlas = f->Get("atlas") ;
```

Read CMS workspace

```
TFile* f = new TFile("cms.root") ;
RooWorkspace *cms = f->Get("cms") ;
```

Construct combined LH

```
RooAddition nllCombi("nllCombi","nll CMS&ATLAS",
            RooArgSet(*cms->function("nll"),*atlas->function("nll"))) ;
```

Construct profile LH in mHiggs

```
RooProfileLL pllCombi("pllCombi","pll",nllCombi,*atlas->var("mHiggs")) ;
```

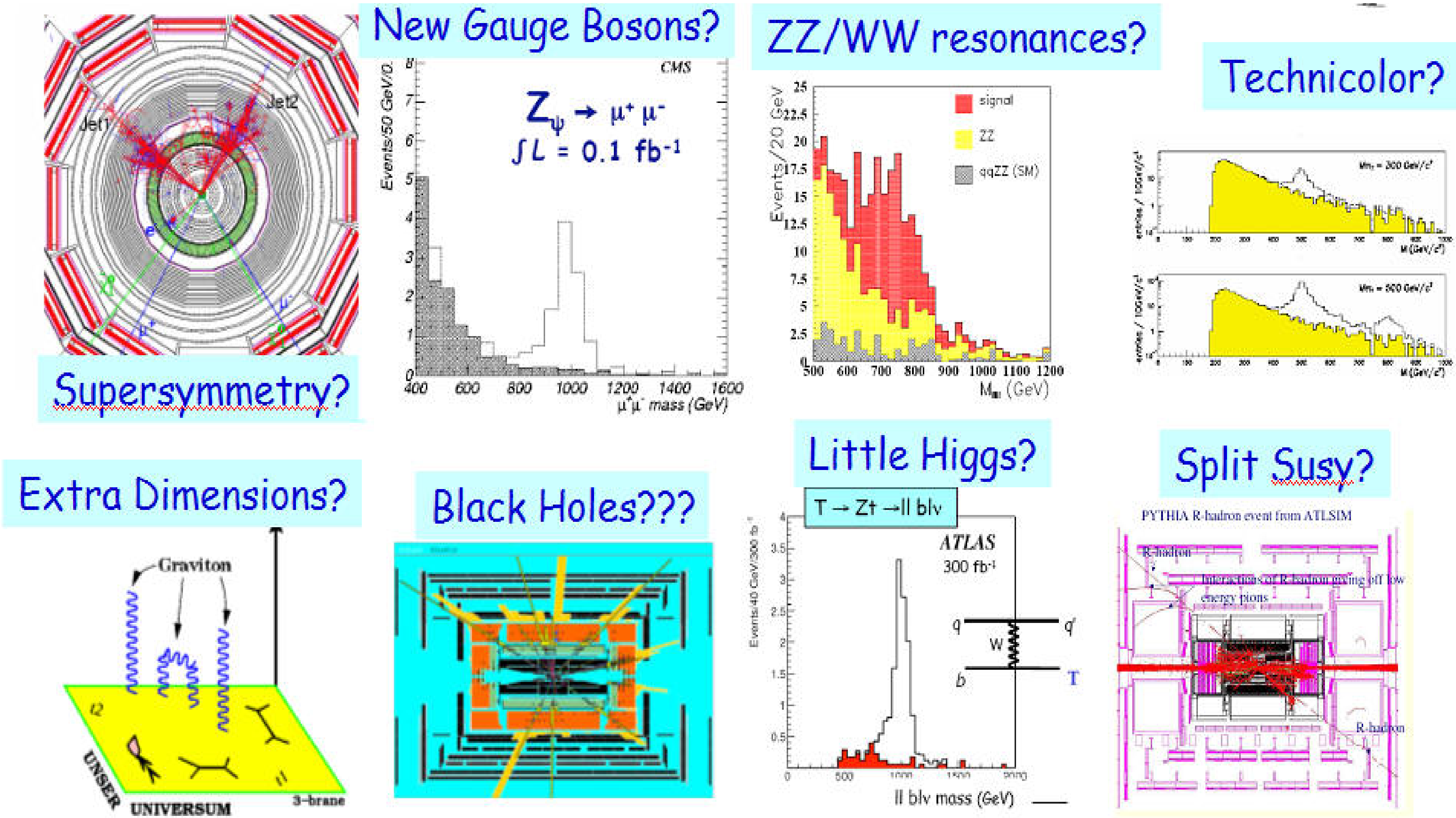
Plot Atlas,CMS, combined profile LH

```
RooPlot* mframe = atlas->var("mHiggs")->frame(-3.5,-2.5) ;
atlas->function("nll")->plotOn(mframe)) ;
cms->function("nll")->plotOn(mframe),LineStyle(kDashed)) ;
pllCombi.plotOn(mframe,LineColor(kRed)) ;
mframe->Draw() ; // result on next slide
```

Wouter Verkerke, NIKHEF

Beyond the Standard Model

The Landscape



A. de Roeck, Snowmass 2005

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

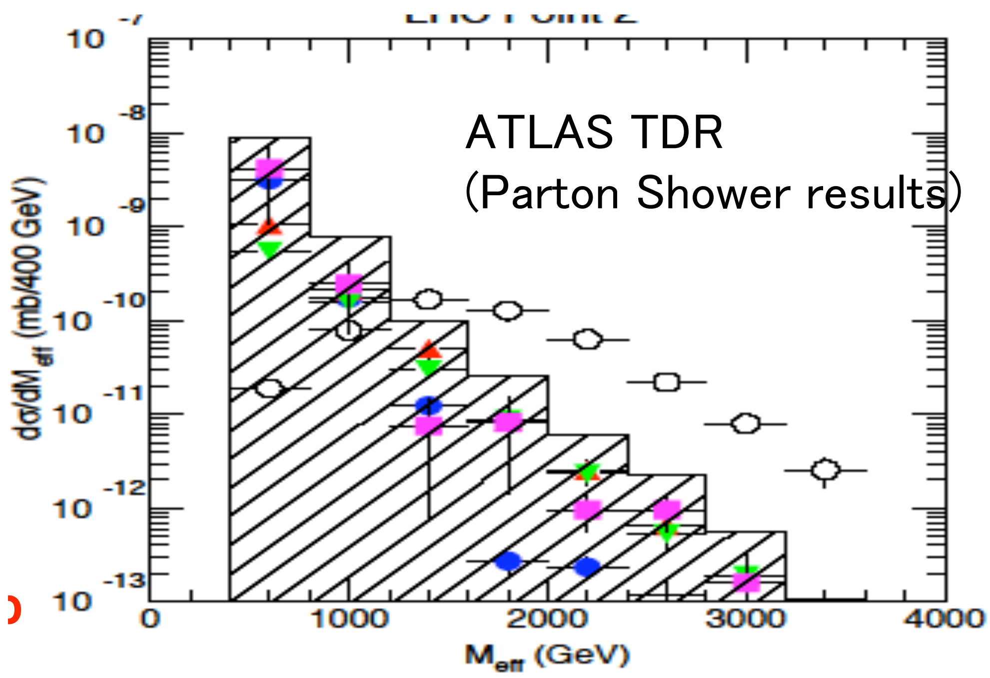
If one does not have a clear idea of what the signal is, it is difficult to optimize an analysis

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

Current Approaches for Discovery

Inclusive or "Quasi-Model Independent" Searches:

- ✦ look at distribution of some observable like M_{eff}
- ✦ used in ATLAS TDR, at H1 (hep-ex/0408044), at DØ (hep-ex/0006011)
- ✦ con: may not be sensitive, neglects a lot of discriminating power

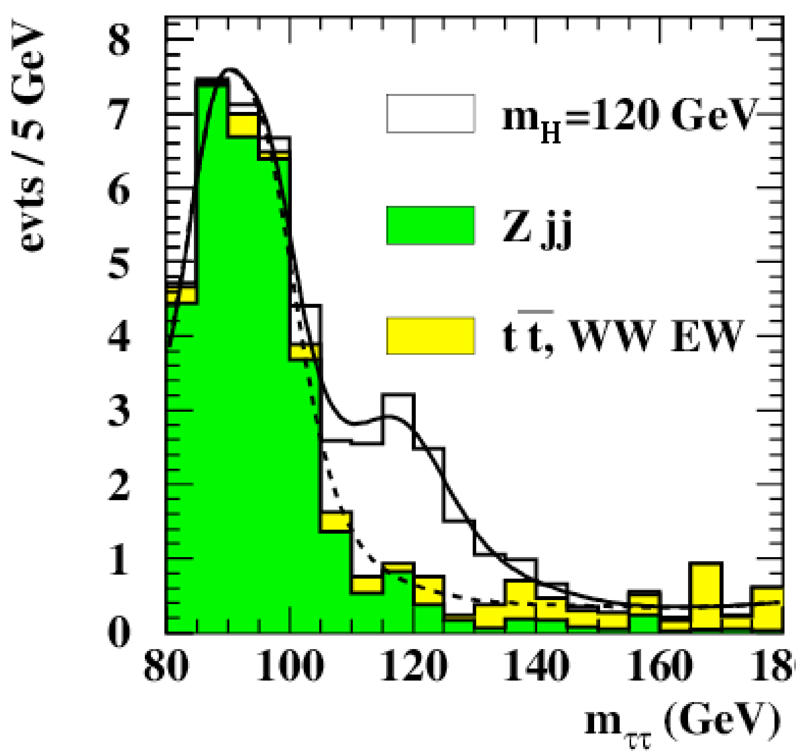


Current Approaches for Discovery

Dedicated Searches:

- look for evidence of some exclusive signature
- some analyses are very detailed (e.g. Higgs)
- con: time consuming, specific to a particular model

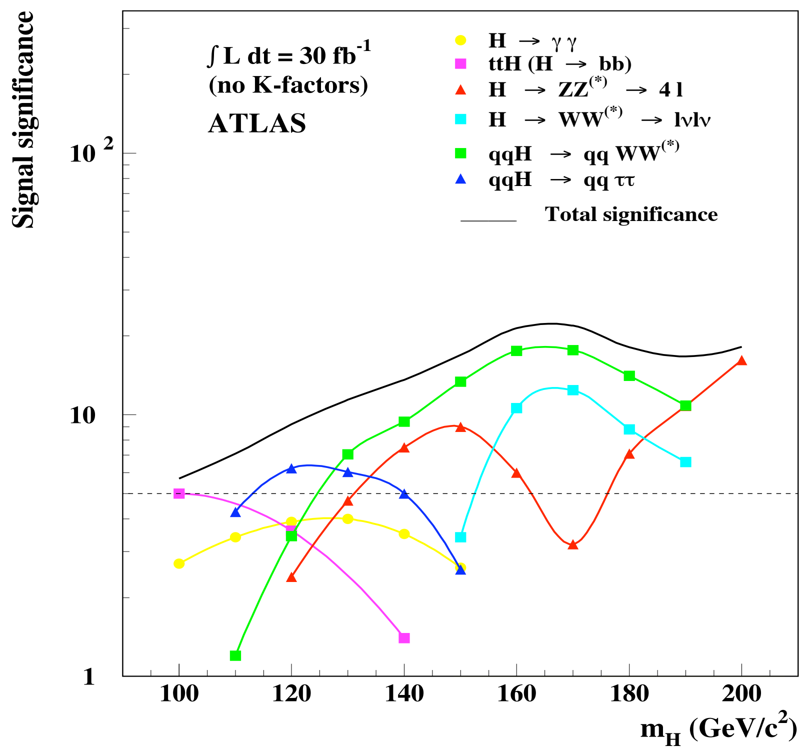
	signal (fb)		background (fb)					
	VV	gg	$t\bar{t}+jets$	$WW+jets$		γ^*/Z $+jets$		Total
				EW	QCD	EW	QCD	
Lepton acceptance	5.55		2014.	18.2	669.8	11.6	2150.	4864.
+ Forward Tagging	1.31		42.0	9.50	0.38	2.20	27.5	81.6
+ P_T^{miss}	0.85		29.2	7.38	0.21	1.21	12.4	50.4
+ Jet mass	0.76		20.9	7.36	0.11	1.17	9.38	38.9
+ Jet veto	0.55		2.70	5.74	0.05	1.11	4.56	14.2
+ Angular cuts	0.40		0.74	1.20	0.04	0.57	3.39	5.94
+ Tau reconstruction	0.37		0.12	0.28	0.001	0.49	2.84	3.73
+ Mass window	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \to \tau\tau \to e\mu$	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \to \tau\tau \to ee$	0.13	0.01	0.01	0.01	0.0	0.02	0.07	0.11
$H \to \tau\tau \to \mu\mu$	0.14	0.01	0.01	0.01	0.0	0.02	0.07	0.11

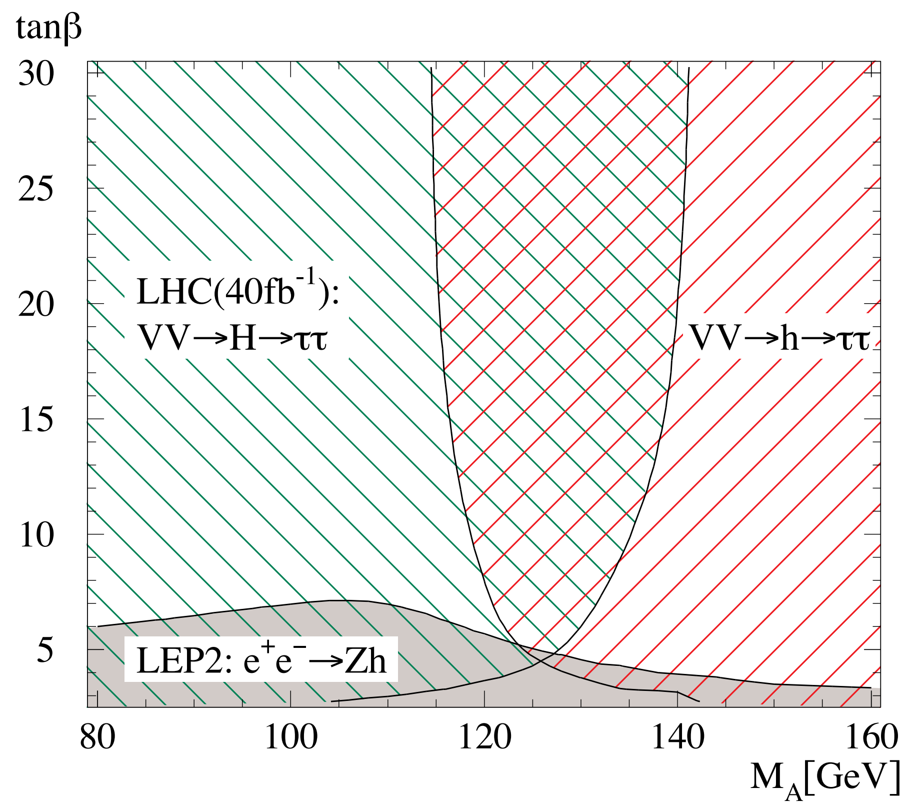


Current Approaches for Discovery

"Recycled" and Composite Searches:

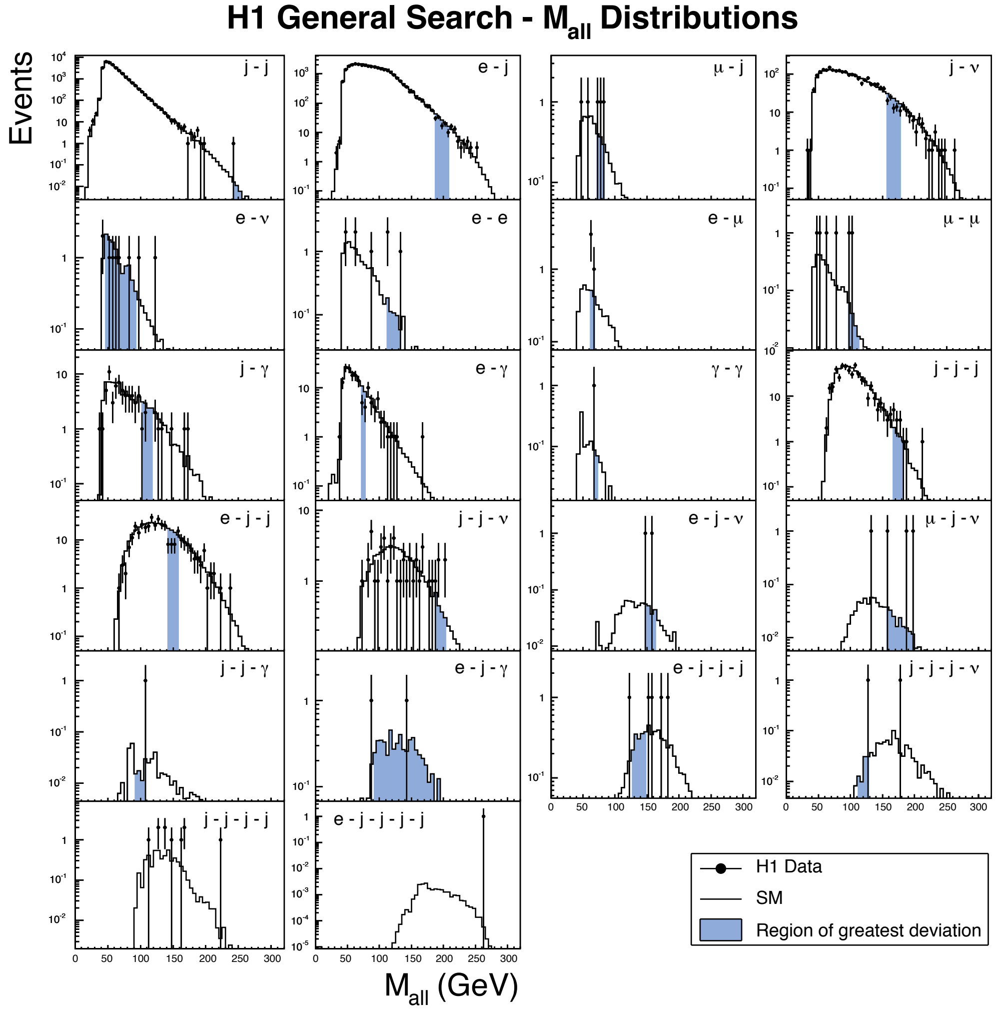
- ✦ many SUSY Higgs searches just use SM cuts and scale σBR (*i.e.* cuts are not optimal)
- ✦ combination between channels is powerful if done properly (*e.g.* consistant assumptions, correlations, etc.)





Model-Independent Searches

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.

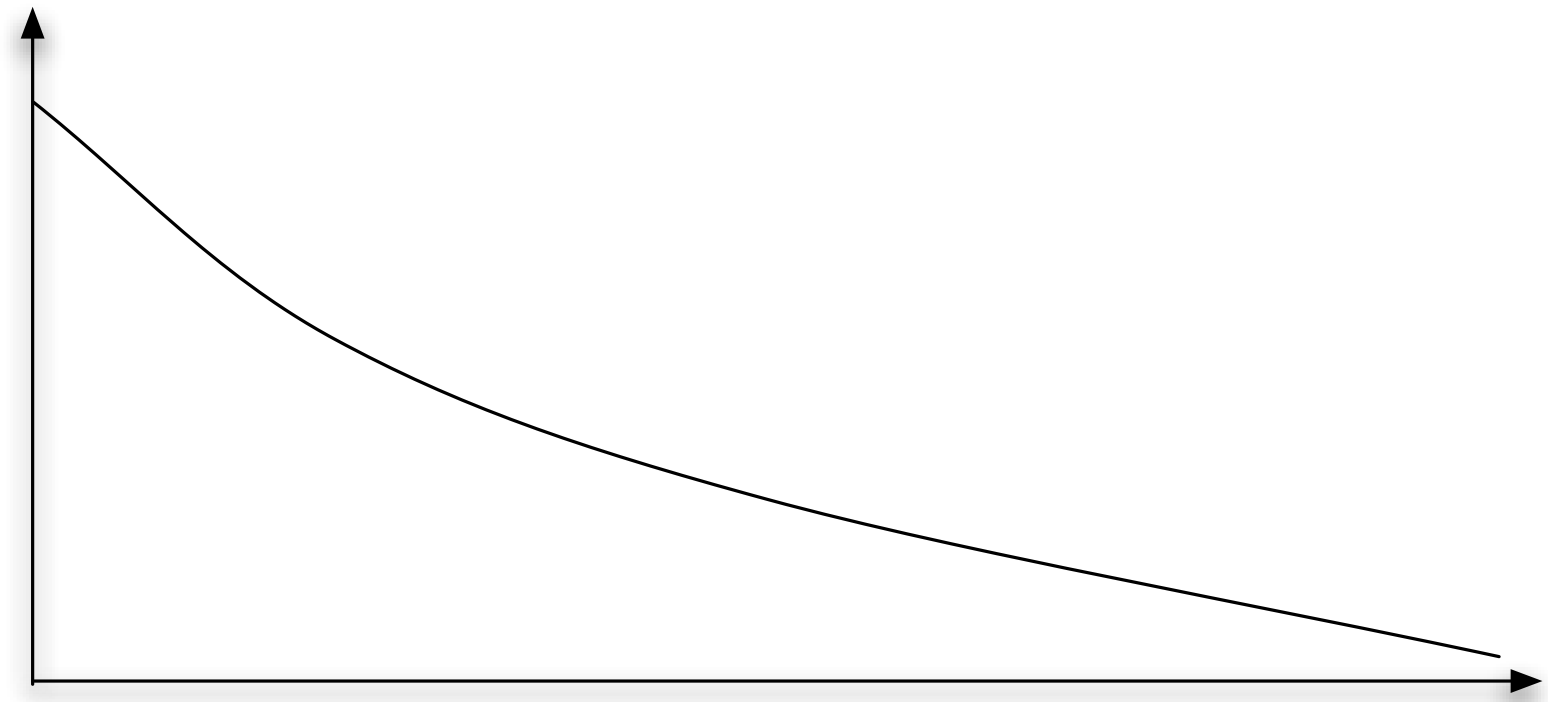
See

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

The Trials Factor

Even in simple situations like the Higgs search, there are complications from sliding mass window

- ~1 GeV mass resolution over a ~500 GeV mass range
- lots of chances to observe a fluctuation



The Trials Factor

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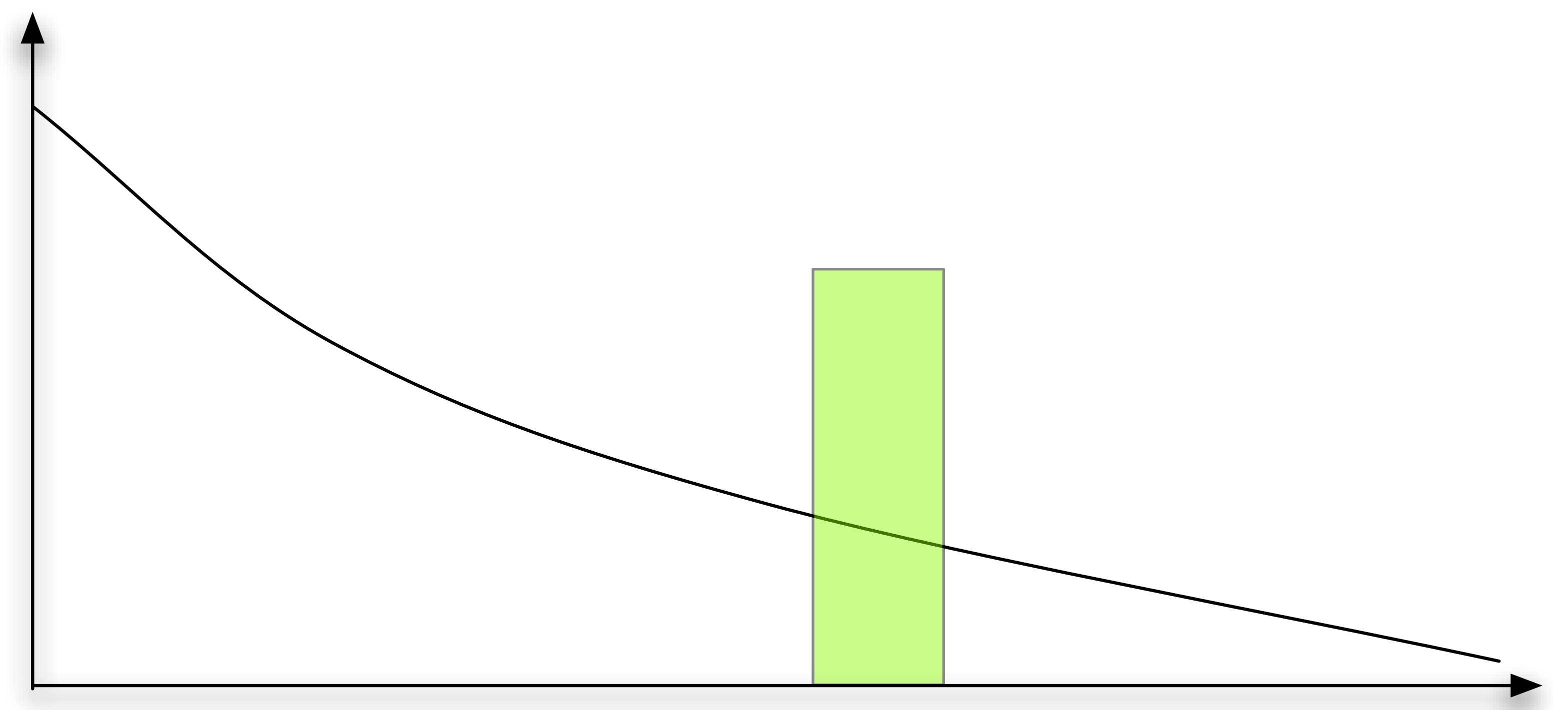

Correcting for The Trials Factor

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

Thousands of eager experimentalists

False Discovery Rate

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

arXiv:astro-ph/0107034 v1 2 Jul 2001

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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

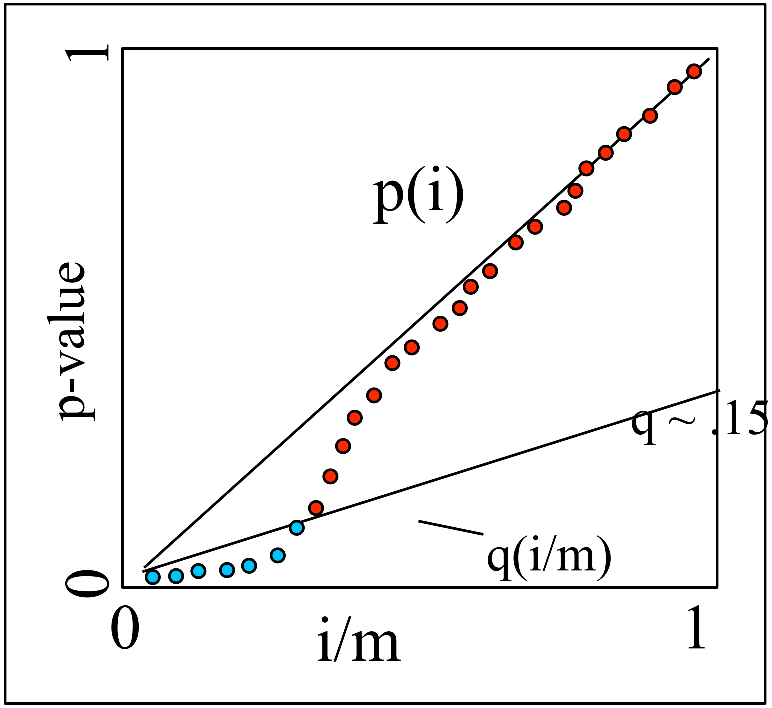
In contrast to Bonferroni, which seeks to control the chance of even a single false discovery among all the tests performed, the FDR method controls the proportion of errors among those tests whose null hypotheses were rejected.

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

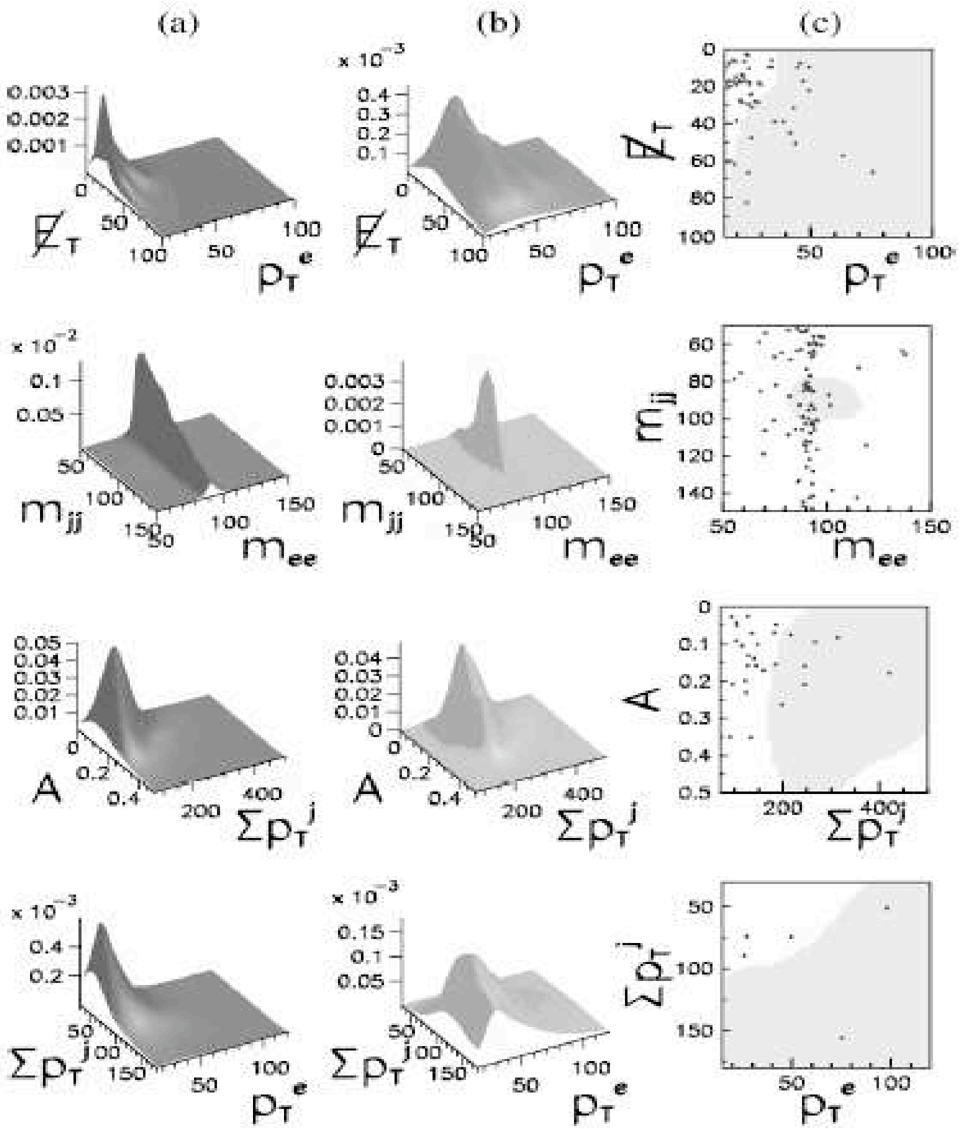
Those r "discoveries" should have q×r false discoveries (on average)

- ☑ Proof this works is not obvious!

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

Description from Linnemann

Automated Analysis Procedures



Bruce Knuteson has developed an automated analysis procedure called QUAERO.

VISTA is a related tool for comparing data to Standard Model predictions

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.

The question for Quaero@LHC is how long it will take before it will be useful (eg. to understand bkg)

Comments on Quaero

Nice Features:

- automatically spans final states & combines results
- tuned for the model point in question
- systematic errors and can be incorporated

Requires:

- sample of *reconstructed* signal events
- a reasonable sample of background events in the signal-like region

Biggest Challenges:

- creating a general-purpose background Monte Carlo (that you believe)
- creating a fast-simulation for the signal events (that you believe)
- estimating systematics for the entire phase-space (that you believe)

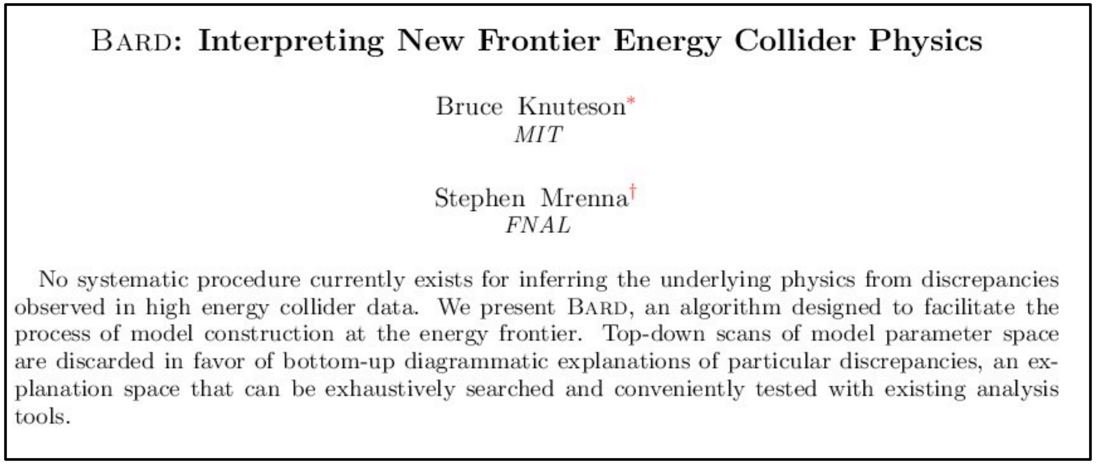
Ways to Improve on the Current QUAERO Implementation:

- streamline event format and storage, think of more extensible event data
- more modular structure (identify variables $\rightarrow$ optimize cuts $\rightarrow$ final result)
- high-level API for automated QUAERO submissions and result processing

Bard & MARMOSET

Bard and Marmoset are two new tools aimed at the interpretation of a signal

- Bard: automated consideration of possible Feynman diagrammatic explanations
- Marmoset: A human-driven model building toolkit based on on-shell effective theories

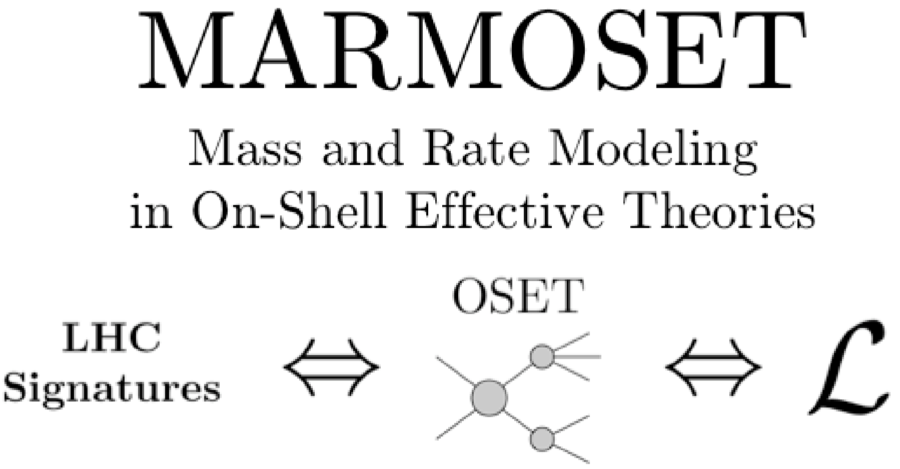


BARD: Interpreting New Frontier Energy Collider Physics

Bruce Knuteson[*]
MIT

Stephen Mrenna[†]
FNAL

No systematic procedure currently exists for inferring the underlying physics from discrepancies observed in high energy collider data. We present BARD, an algorithm designed to facilitate the process of model construction at the energy frontier. Top-down scans of model parameter space are discarded in favor of bottom-up diagrammatic explanations of particular discrepancies, an explanation space that can be exhaustively searched and conveniently tested with existing analysis tools.



The Inverse Problem

In this paper, the authors consider
- a 15-parameter SUSY model
- 1808 LHC observables
- 4302 parameter points
- a $\Delta\chi^2$-like discriminant
- Euclidean-like distance in parameter space

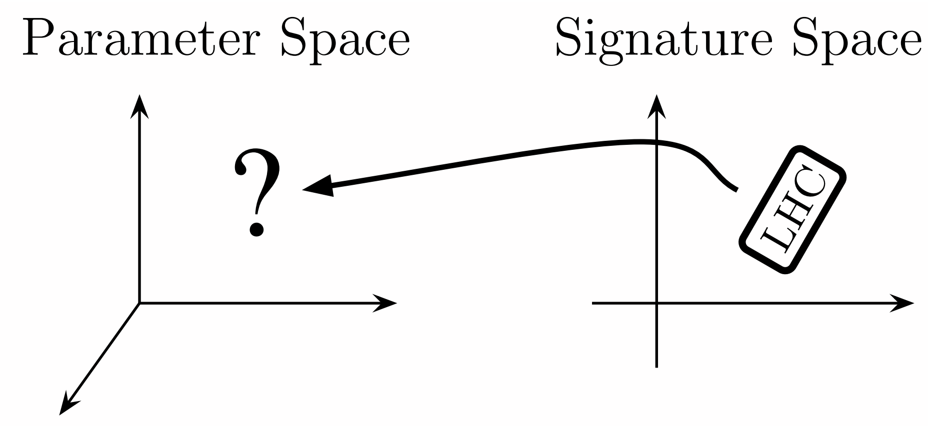
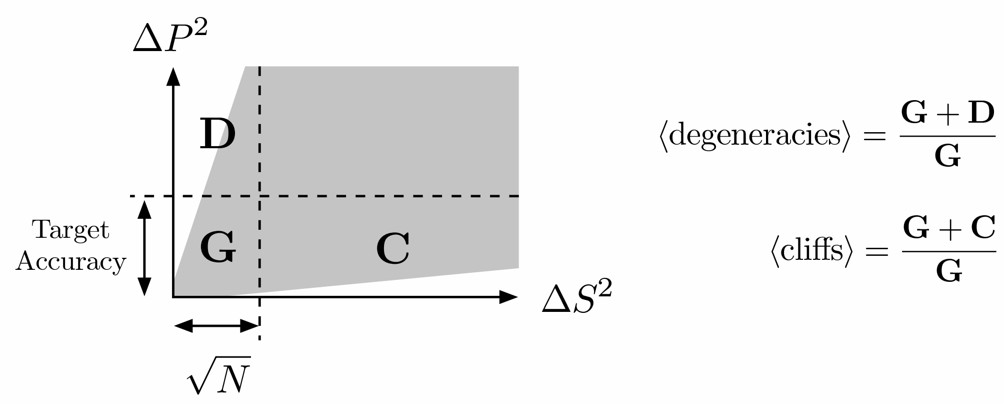


Figure 1: The Inverse Map from LHC Observables to Theoretical Models. Given observed signals for physics beyond the standard model, how can we determine the underlying theoretical model?

Arkani-Hamed, Kane, Thaler, Wang [hep-ph/0512190]

While studying the "inverse map"
- Found degeneracies among models
- Found "cliffs" (where a small change in the parameters leads to a large change in the signature)

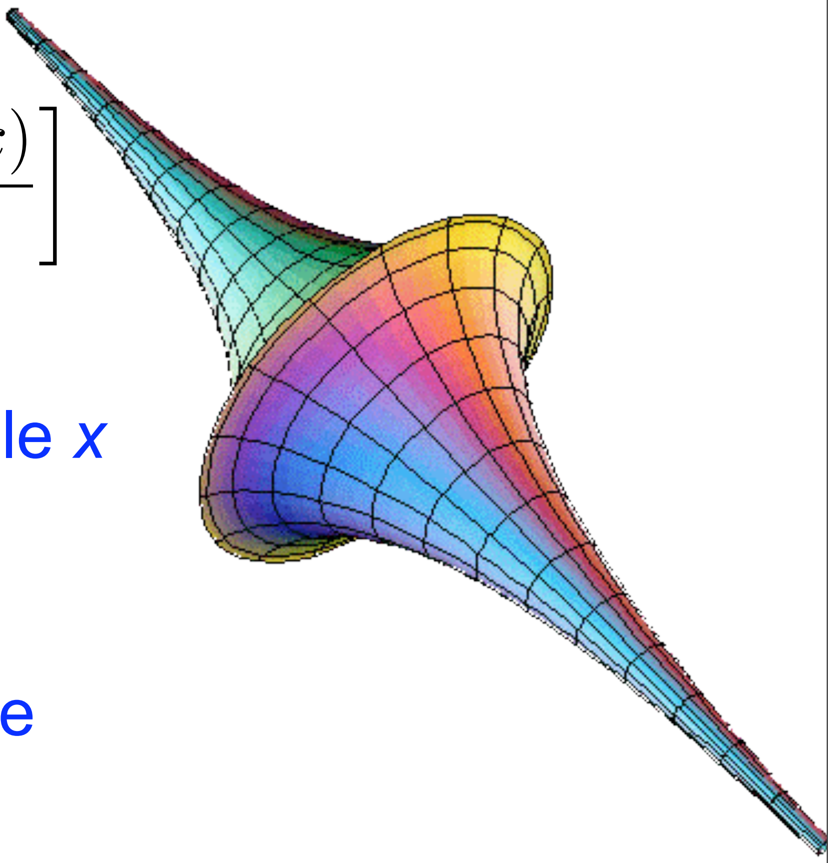


Information Geometry

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

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

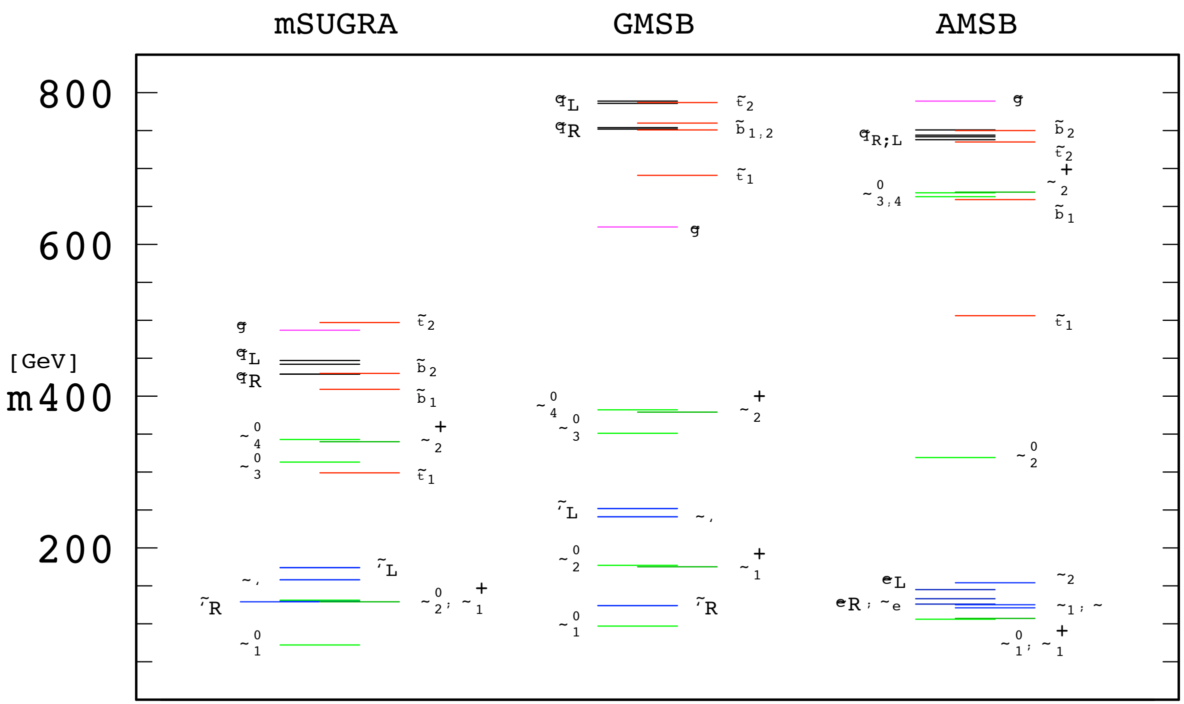
$$g_{ij}(\alpha) = \int dx\, f_\alpha(x) \left[\frac{\partial \log f_\alpha(x)}{\partial \alpha_i}\right] \left[\frac{\partial \log f_\alpha(x)}{\partial \alpha_j}\right]$$



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.

Information Geometry of MSSM



It would be interesting to study the information geometry of MSSM

Provides a well-defined notion of "cliffs" and "valleys"

Provides an efficient sampling

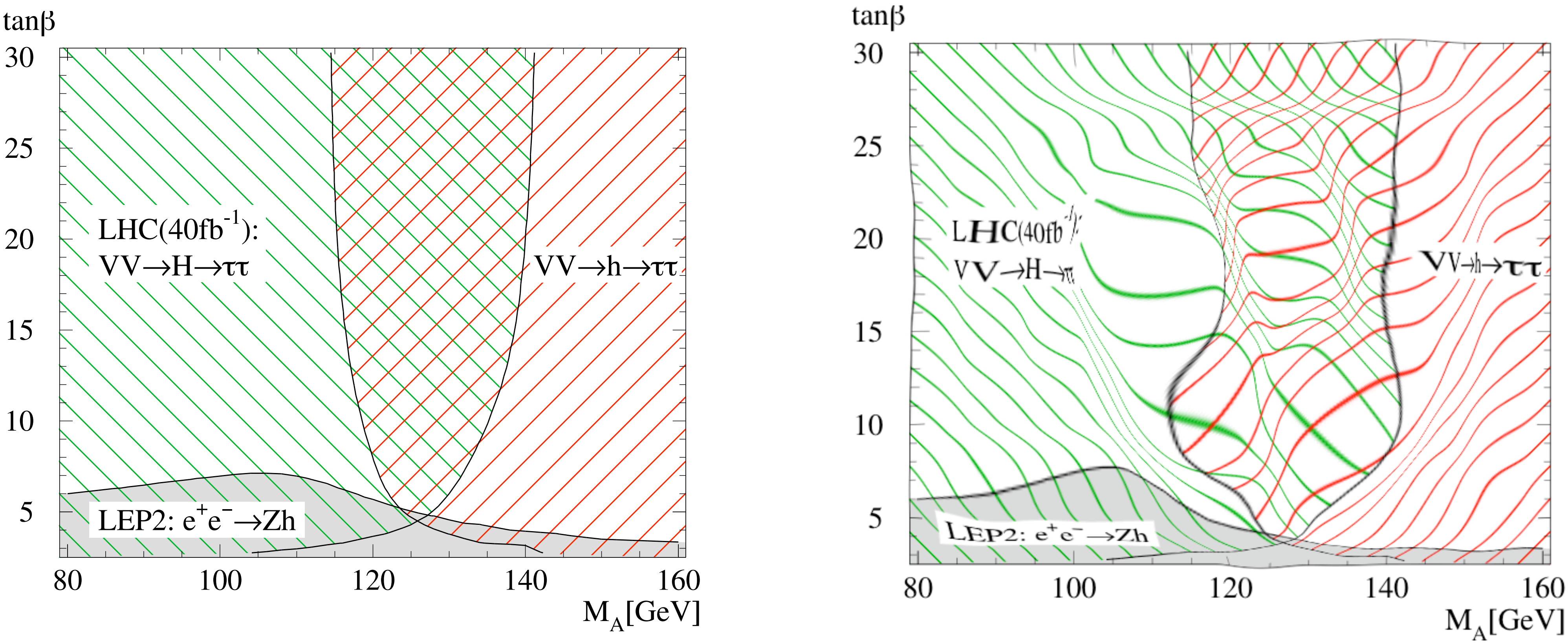
An example use of Information Geometry for the MSSM:

- ✦ α = 105 model parameters
- ✦ x = measured mass spectrum
- ✦ $f_\alpha(x)$ = probability to measure that spectrum given model parameters (basicallly a multivariate Gaussian)

Remapping the M_A-tanβ plane

As a baby-step, it would be interesting to try and re-map the M_A-tanβ plane based on observables in Higgs sector

- a useful learning exercise
- would help speed up the current scans



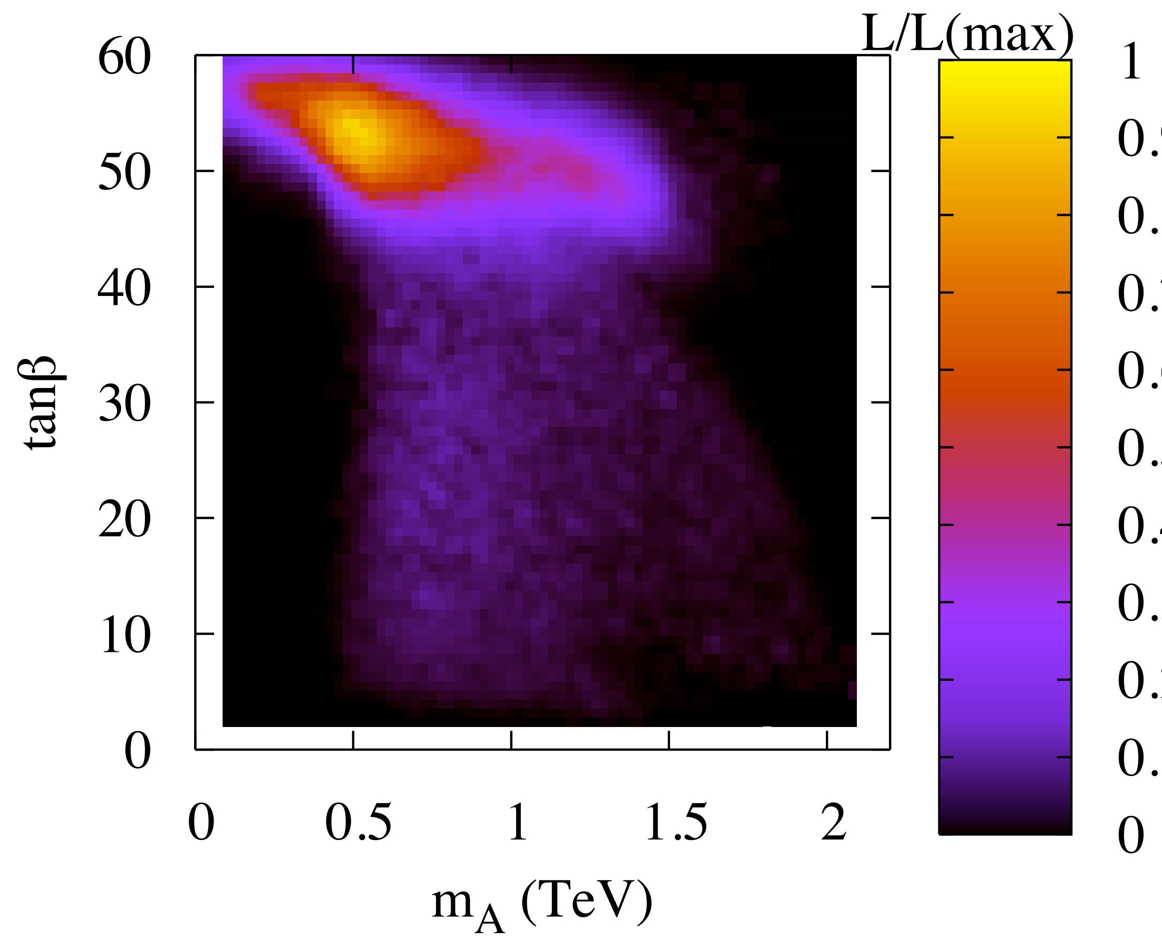
Exploring High-Dimensional Models

Allanach & Lester using sophisticated Markov-Chain Monte Carlo techniques to explore high-dimensional models (mSUGRA)

- conclusions are sensitive to the choice of prior

[hep-ph/0507283, hep-ph/0601089]

- What would you do with a likelihood map like this?
- The full n-dimensional likelihood maps are available on the web
- Topic of an "ultra-mini" workshop in Edinburgh



Priors & Volume Effects

Allanach, Cranmer, Lester, Weber: JHEP 08, 023 (2007), arXiv:0705.0487

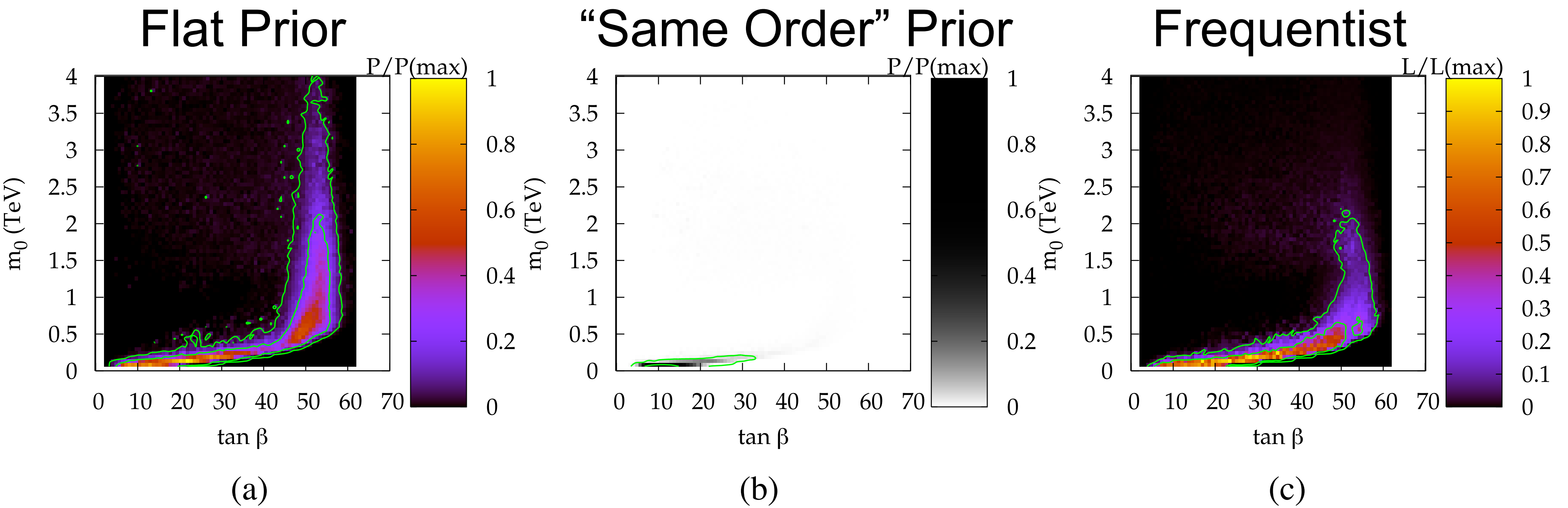


Fig. 1: CMSSM fits marginalised in the unseen dimensions for (a) flat $\tan\beta$ priors, (b) the hierarchical prior with $w = 1$. Figure (c) shows the result of the profile likelihood ratio, in which the unseen dimensions are evaluated at their conditional maximum likelihood values Contours showing the 68% and 95% regions are shown in each case. The posterior probability in each bin, normalised to the probability of the maximum bin, is displayed by reference to the color bar on the right hand side of each plot.

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

"Same Order" Prior is a "hierarchical Bayes" model

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

How Will We Publish?

Discovery of the W & Z

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

UA1 Collaboration, CERN, Geneva, Switzerland

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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

UA1 Collaboration, CERN, Geneva, Switzerland

G. ARNISON [j], A. ASTBURY [j], B. AUBERT [b], C. BACCI [i], G. BAUER [l], A. BÉZAGUET [d], R. BÖCK [d], T.J.V. BOWCOCK [f], M. CALVETTI [d], P. CATZ [b], P. CENNINI [d], S. CENTRO [d], F. CERADINI [d,i], S. CITTOLIN [d], D. CLINE [l], C. COCHET [k], J. COLAS [b], M. CORDEN [c], D. DALLMAN [d,l], D. DAU [2], M. DeBEER [k], M. DELLA NEGRA [b,d], M. DEMOULIN [d], D. DENEGRI [k], A. Di CIACCIO [i], D. DiBITONTO [d], L. DOBRZYNSKI [g], J.D. DOWELL [c], K. EGGERT [a], E. EISENHANDLER [f], N. ELLIS [d], P. ERHARD [a], H. FAISSNER [a], M. FINCKE [2], G. FONTAINE [g], R. FREY [h], R. FRÜHWIRTH [l], J. GARVEY [c], S. GEER [g], C. GHESQUIÈRE [g], P. GHEZ [b], K. GIBONI [a], W.R. GIBSON [f], Y. GIRAUD-HÉRAUD [g], A. GIVERNAUD [k], A. GONIDEC [b], G. GRAYER [j], T. HANSL-KOZAŃECKA [a], W.J. HAYNES [j], L.O. HERTZBERGER [3], C. HODGES [h], D. HOFFMANN [a], H. HOFFMANN [d], D.J. HOLTHUIZEN [3], R.J. HOMER [c], A. HONMA [f], W. JANK [d], G. JORAT [d], P.I.P. KALMUS [f], V. KARIMÄKI [e], R. KEELER [f], I. KENYON [c], A. KERNAN [h], R. KINNUNEN [e], W. KOZANECKI [h], D. KRYN [d,g], F. LACAVA [i], J.-P. LAUGIER [k], J.-P. LEES [b], H. LEHMANN [a], R. LEUCHS [a], A. LÉVÊQUE [k,d], D. LINGLIN [b], E. LOCCI [k], J.-J. MALOSSE [k], T. MARKIEWICZ [d], G. MAURIN [d], T. McMAHON [c], J.-P. MENDIBURU [g], M.-N. MINARD [b], M. MOHAMMADI [l], M. MORICCA [i], K. MORGAN [h], H. MUIRHEAD [4], F. MULLER [d], A.K. NANDI [j], L. NAUMANN [d], A. NORTON [d], A. ORKIN-LECOURTOIS [g], L. PAOLUZI [i], F. PAUSS [d], G. PIANO MORTARI [i], E. PIETARINEN [e], M. PIMIÄ [e], A. PLACCI [d], J.P. PORTE [d], E. RADERMACHER [a], J. RANSDELL [h], H. REITHLER [a], J.-P. REVOL [d], J. RICH [k], M. RIJSSENBEEK [d], C. ROBERTS [j], J. ROHLF [d], P. ROSSI [d], C. RUBBIA [d], B. SADOULET [d], G. SAJOT [g], G. SALVI [f], G. SALVINI [i], J. SASS [k], J. SAUDRAIX [k], A. SAVOY-NAVARRO [k], D. SCHINZEL [d], W. SCOTT [j], T.P. SHAH [j], M. SPIRO [k], J. STRAUSS [l], J. STREETS [c], K. SUMOROK [d], F. SZONCSO [l], D. SMITH [h], C. TAO [3], G. THOMPSON [f], J. TIMMER [d], E. TSCHESLOG [a], J. TUOMINIEMI [e], B. Van EIJK [3], J.-P. VIALLE [d], J. VRANA [g], V. VUILLEMIN [d], H.D. WAHL [l], P. WATKINS [c], J. WILSON [c], C. WULZ [l], G.Y. XIE [d], M. YVERT [b] and E. ZURFLUH [d]

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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

The UA2 Collaboration

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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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Received 11 August 1983

Discovery of the top quark

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

F. Abe,[13] M. G. Albrow,[7] S. R. Amendolia,[23] D. Amidei,[16] J. Antos,[28] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] P. Auchincloss,[25] M. Austern,[14] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[24] J. Bao,[34] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] P. Bartalini,[23] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[2] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[33] D. Benjamin,[32] J. Benlloch,[15] J. Bensinger,[2] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[29] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[29] A. Bodek,[25] V. Bolognesi,[23] D. Bortoletto,[24] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] E. Buckley-Geer,[7] H. S. Budd,[25]

Observation of the Top Quark

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B.S. Acharya,[40] I. Adam,[10] D.L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[36] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[38] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[7] J. Bendich,[20] S.B. Beri,[31] I. Bertram,[34] V.A. Bezzubov,[32] P.C. Bhat,[12] V. Bhatnagar,[31] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] A. Boehnlein,[12] N.I. Bojko,[32] F. Borcherding,[12] J. Borders,[35] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V.S. Burtovoi,[32] J.M. Butler,[12] D. Casey,[35] H. Castilla-Valdez,[9] D. Chakraborty,[38] S.-M. Chang,[27] S.V. Chekulaev,[32] L.-P. Chen,[20] W. Chen,[38] L. Chevalier,[36] S. Chopra,[31] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[38] A.R. Clark,[20] W.G. Cobau,[21] J. Cochran,[7] W.E. Cooper,[12] C. Cretsinger,[35] D. Cullen-Vidal,[4] M. Cummings,[14] D. Cutts,[4] O.I. Dahl,[20] K. De,[41] M. Demarteau,[12] R. Demina,[27] K. Denisenko,[12] N. Denisenko,[12] D. Denisov,[12] S.P. Denisov,[32] W. Dharmaratna,[13] H.T. Diehl,[12] M. Diesburg,[12] G. Diloreto,[23] R. Dixon,[12] P. Draper,[41] J. Drinkard,[6] Y. Ducros,[36] S.R. Dugad,[40] S. Durston-Johnson,[35] D. Edmunds,[23] A.O. Efimov,[32] J. Ellison,[7] V.D. Elvira,[12,‡] R. Engelmann,[38] S. Eno,[21] G. Eppley,[34]

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?

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-Dependent Publishing

Search for Supersymmetry via Associated Production of Charginos and Neutralinos in Final States with Three Leptons

For the **minimal supergravity model**, a chargino lower mass limit ... in regions of parameter space with enhanced leptonic branching fractions.

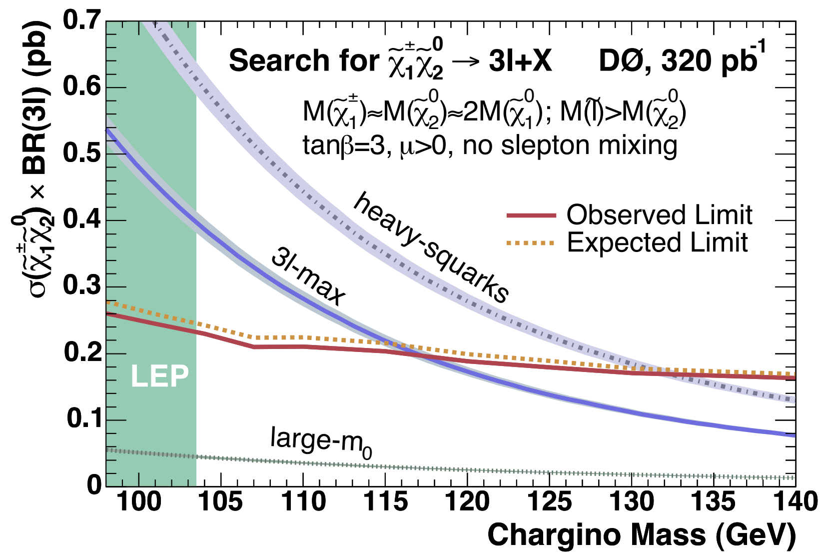


FIG. 3: Limit on $\sigma \times \mathrm{BR}(3\ell)$ as a function of chargino mass, in comparison with the expectation for several SUSY scenarios (see text). PDF and renormalization/factorization scale uncertainties are shown as shaded bands.

Search for Supersymmetry in Di-Photon Final States at $\sqrt{s}$ = 1.96 TeV

We report results of a search for supersymmetry (SUSY) with **gauge-mediated symmetry breaking** in di-photon events...

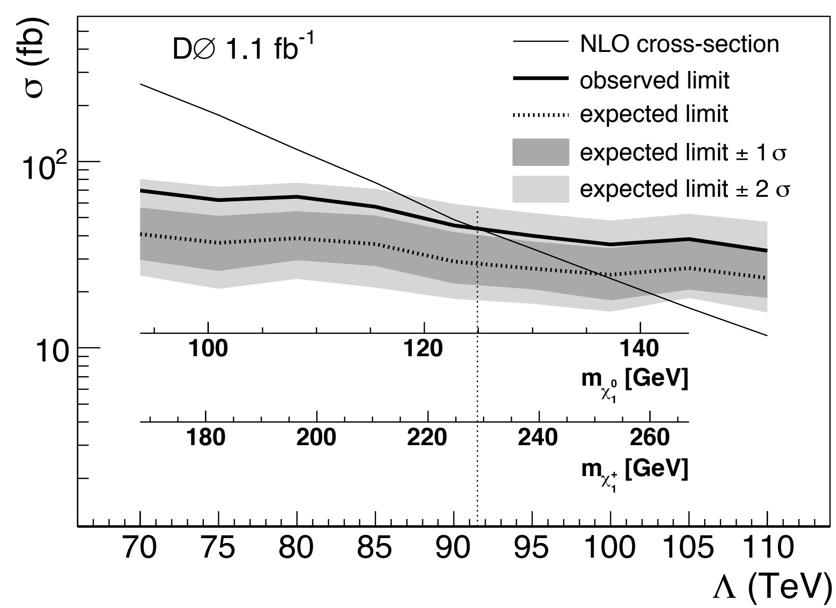


FIG. 2: Predicted cross section for the Snowmass Slope model versus Λ. The observed and expected 95% C.L. limits are shown in solid and dash-dotted lines, respectively.

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.

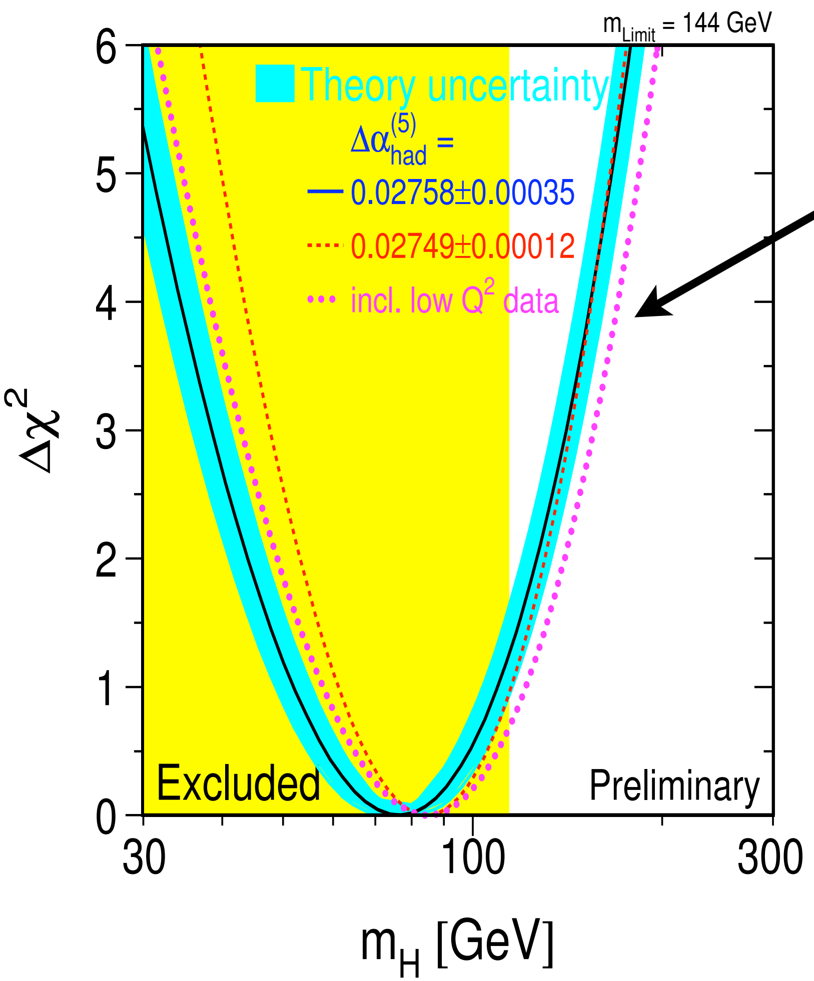
Often, when several theories share a common signature, there exists a parametrized model for some relevant observables or some effective theory that can encompass several specific theories

- 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

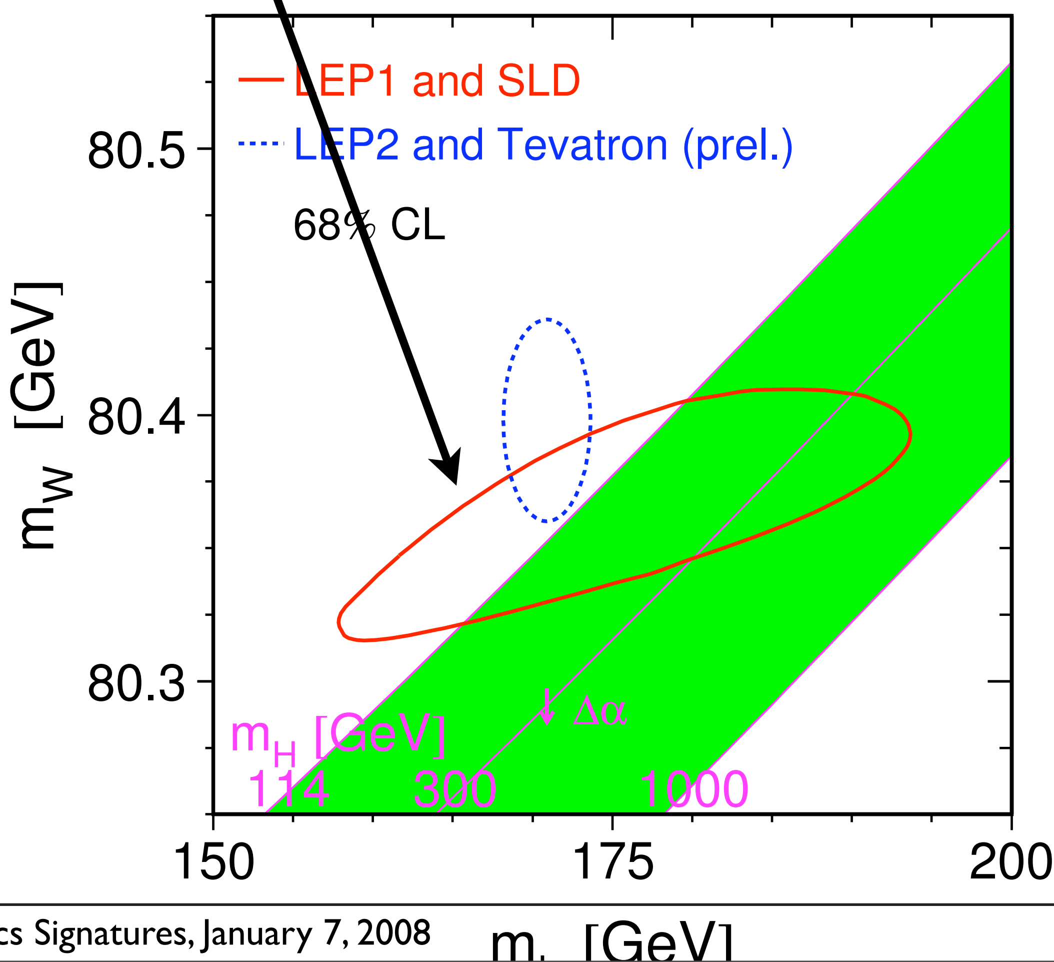
Examples of Published Likelihoods

At PhyStat conference, we agreed to publish likelihood functions



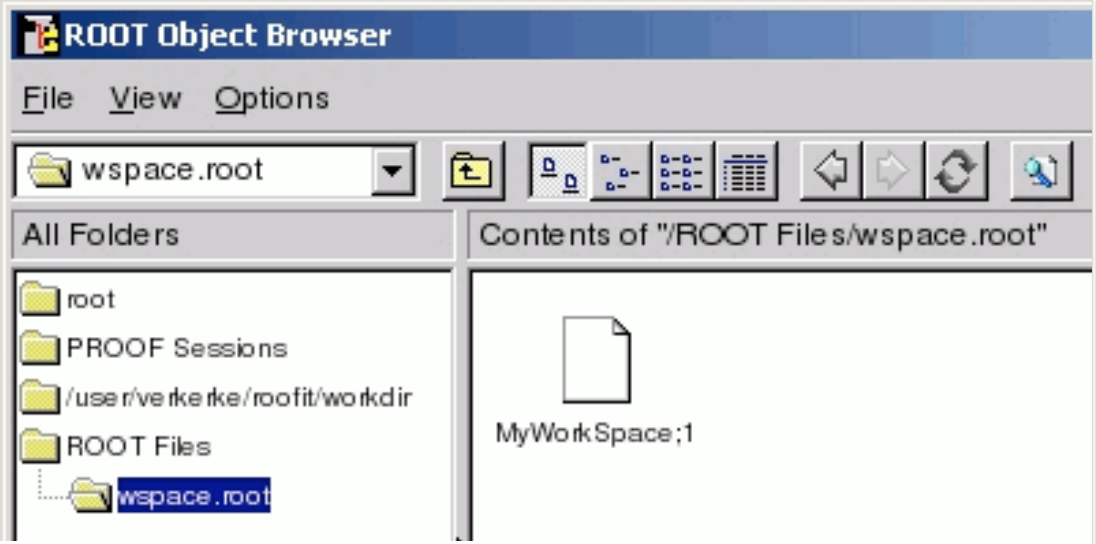
You can find examples of published likelihoods in 1D

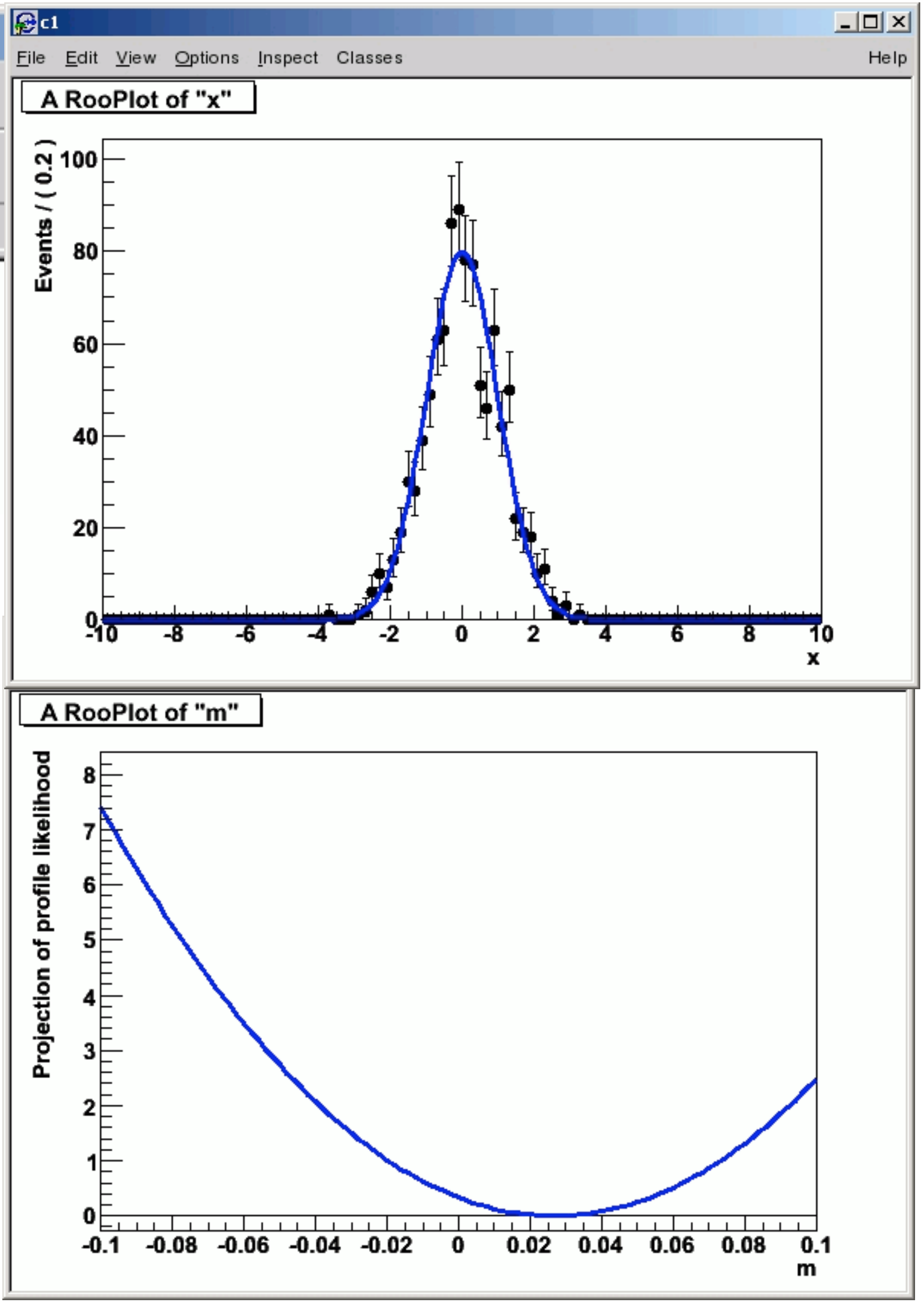
In 2-D you just get the contours



Surely we can do better!

Example of Digital Publishing





Wouter Verkerke 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 using RooFit/RooStats.

Can also evaluate integrals over x necessary for Neyman construction!

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

Combining Results: An Example

A combination example

- Combining 'ATLAS' and 'CMS' result from persisted workspaces

Read ATLAS workspace
```
TFile* f = new TFile("atlas.root") ;
RooWorkspace *atlas = f->Get("atlas") ;
```

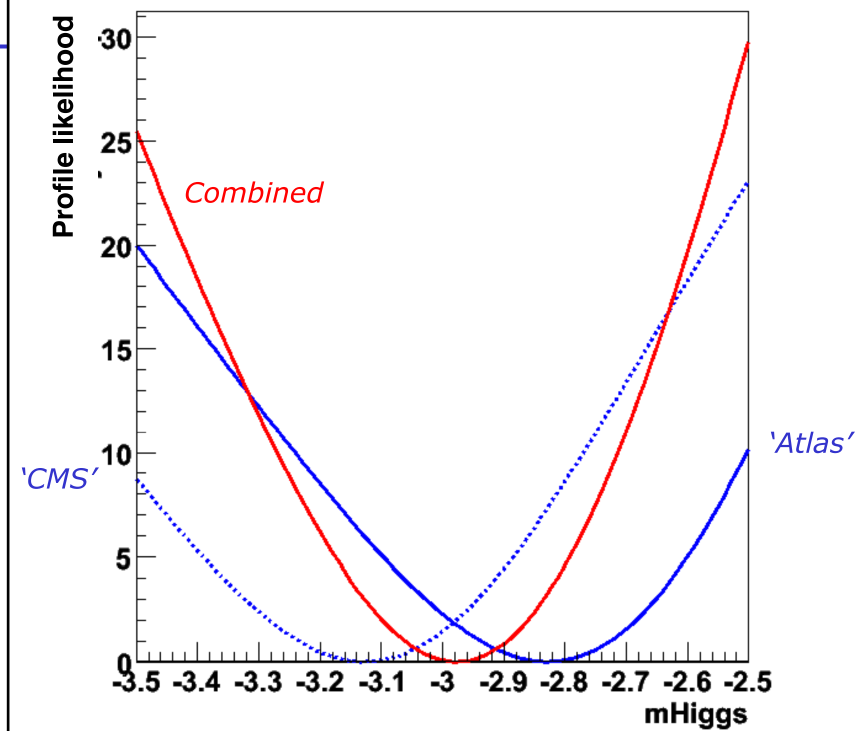
Read CMS workspace
```
TFile* f = new TFile("cms.root") ;
RooWorkspace *cms = f->Get("cms") ;
```

Construct combined LH
```
RooAddition nllCombi("nllCombi","nll CMS&ATLAS",
            RooArgSet(*cms->function("nll"),*atlas->function("nll"))) ;
```

Construct profile LH in mHiggs
```
RooProfileLL pllCombi("pllCombi","pll",nllCombi,*atlas->var("mHiggs")) ;
```

Plot Atlas,CMS, combined profile LH
```
RooPlot* mframe = atlas->var("mHiggs")->frame(-3.5,-2.5) ;
atlas->function("nll")->plotOn(mframe)) ;
cms->function("nll")->plotOn(mframe),LineStyle(kDashed)) ;
pllCombi.plotOn(mframe,LineColor(kRed)) ;
mframe->Draw() ; // result on next slide
```

Wouter Verkerke, NIKHEF



Combination can easily involve different experiments and different measurements sensitive to a common parameter.

No more reading exclusion regions off figures and reverse-engineering an analysis for a different model.

Publishing Full Likelihood Maps

It is unlikely the experiments will provide unfettered access to their data

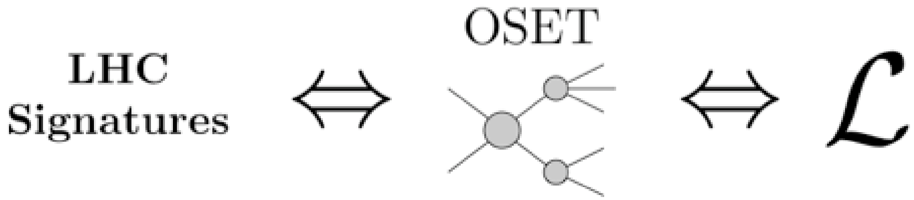
- and the raw data is not directly useful anyways

Instead of 1-d likelihood curves or 2-d contours, the experiments could publish a full likelihood map of their data digitally

- much more useful if one is trying to combine constraints from several sources

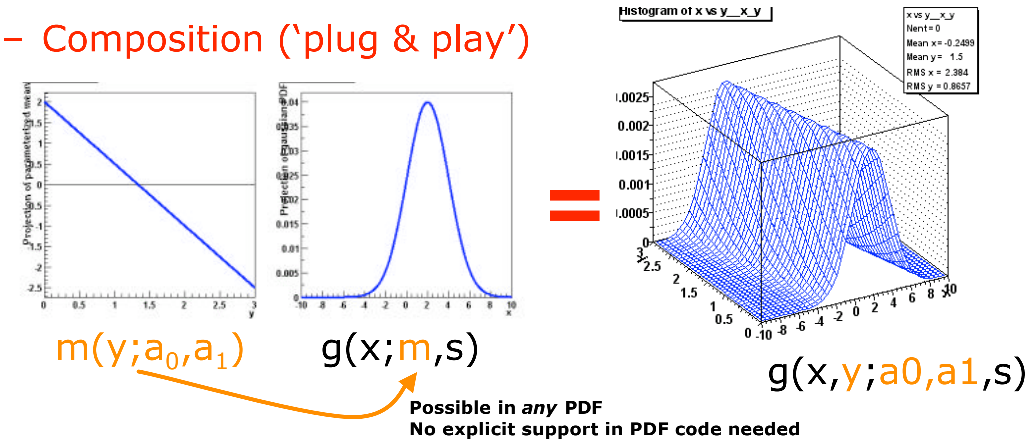
One could imagine publishing likelihood map of the masses, rates, and branching ratios of an OSET developed with MARMOSET

- This provides a model-neutral and model-relevant summary of the data

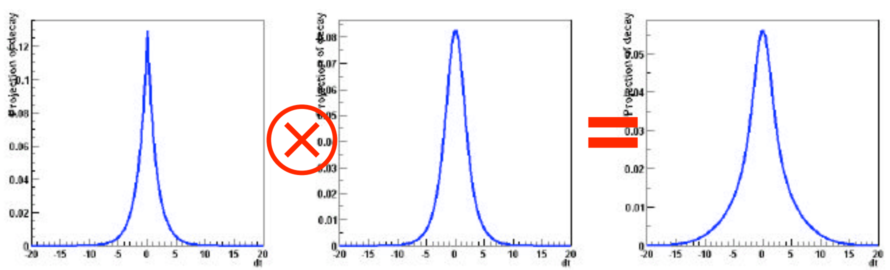


OSET+Transfer Functions+RooFit

– Composition ('plug & play')



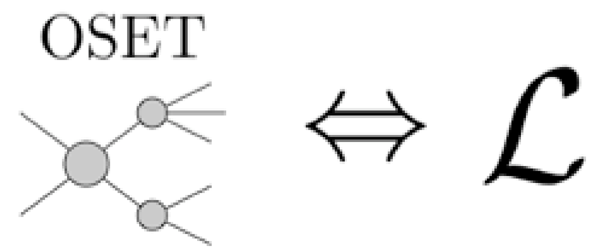
– Convolution



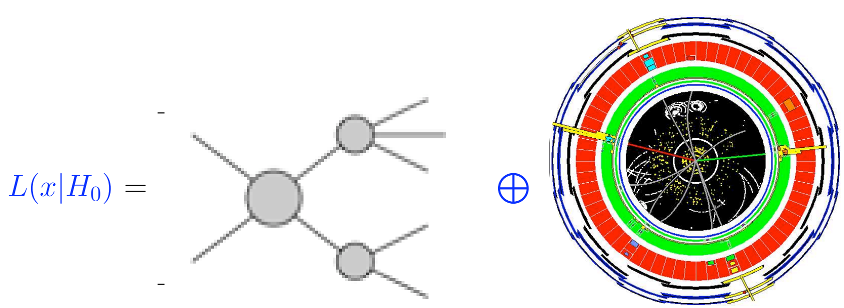
Wouter Verkerke, UCSB

1) RooFit's provides ability for compound parameterizations:

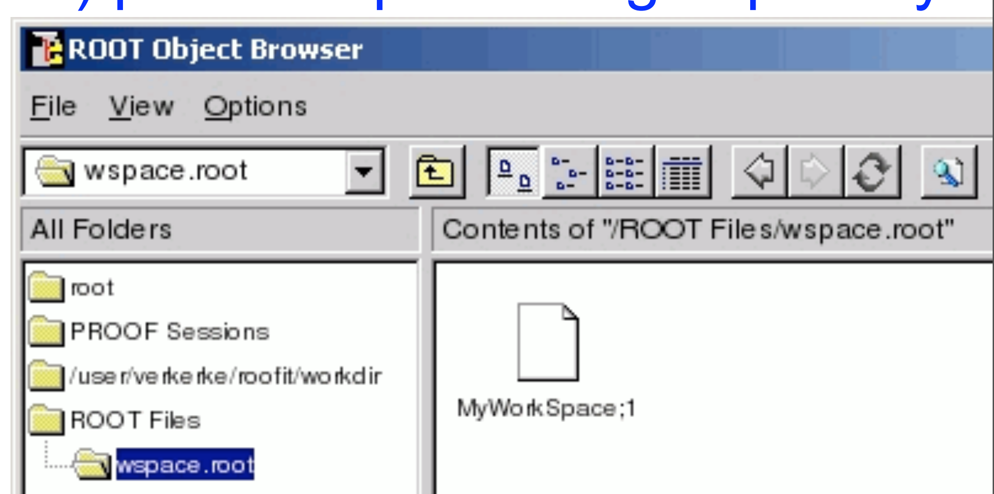
eg. mass of a particle in OSET is a function of fundamental parameters in Lagrangian



2) RooFit can perform convolution with an experiment's transfer functions



3) powerful publishing capability



Summary

Data from the LHC is coming soon:

- great hope that LHC will discover physics beyond the standard model

LHC analyses must cope with large backgrounds and large systematic uncertainties

- makes otherwise simple analyses relatively difficult

The theoretical landscape relevant to the LHC is vast

- we have never tried to tackle such a rich set of theories
  - reasonable to expect new analysis strategies will be required
  - a blend of theoretical, experimental, and statistical tools
  - The theory/experiment interface is very important

It is an exciting time to be a particle physicist!