

# Statistical Methods for Discovery and Limits in HEP Experiments

Day 2: Discovery

[www.pp.rhul.ac.uk/~cowan/stat\\_freiburg.html](http://www.pp.rhul.ac.uk/~cowan/stat_freiburg.html)



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# Outline

Day 1: Introduction and basic formalism

Probability, statistical tests, parameter estimation.

→ Day 2: **Discovery**

Quantifying discovery significance and sensitivity

Systematic uncertainties (nuisance parameters)

Day 3: Exclusion limits

Frequentist and Bayesian intervals/limits

# Outline for Day 2

Large-sample statistical formulae for a search at the LHC

Cowan, Cranmer, Gross, Vitells, arXiv:1007.1727,  
EPJC 71 (2011) 1-19

Significance test using profile likelihood ratio

Systematics included via nuisance parameters

Distributions in large sample limit, no MC used.

Progress on related issues (some updates from PHYSTAT2011):

The “look elsewhere effect”

The “CLs” problem

Combining measurements

Improving treatment of systematics

## A simple example

For each event we measure two variables,  $\mathbf{x} = (x_1, x_2)$ .

Suppose that for background events (hypothesis  $H_0$ ),

$$f(\mathbf{x}|H_0) = \frac{1}{\xi_1} e^{-x_1/\xi_1} \frac{1}{\xi_2} e^{-x_2/\xi_2}$$

and for a certain signal model (hypothesis  $H_1$ ) they follow

$$f(\mathbf{x}|H_1) = C \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(x_1-\mu_1)^2/2\sigma_1^2} \frac{1}{\sqrt{2\pi}\sigma_2} e^{-(x_2-\mu_2)^2/2\sigma_2^2}$$

where  $x_1, x_2 \geq 0$  and  $C$  is a normalization constant.

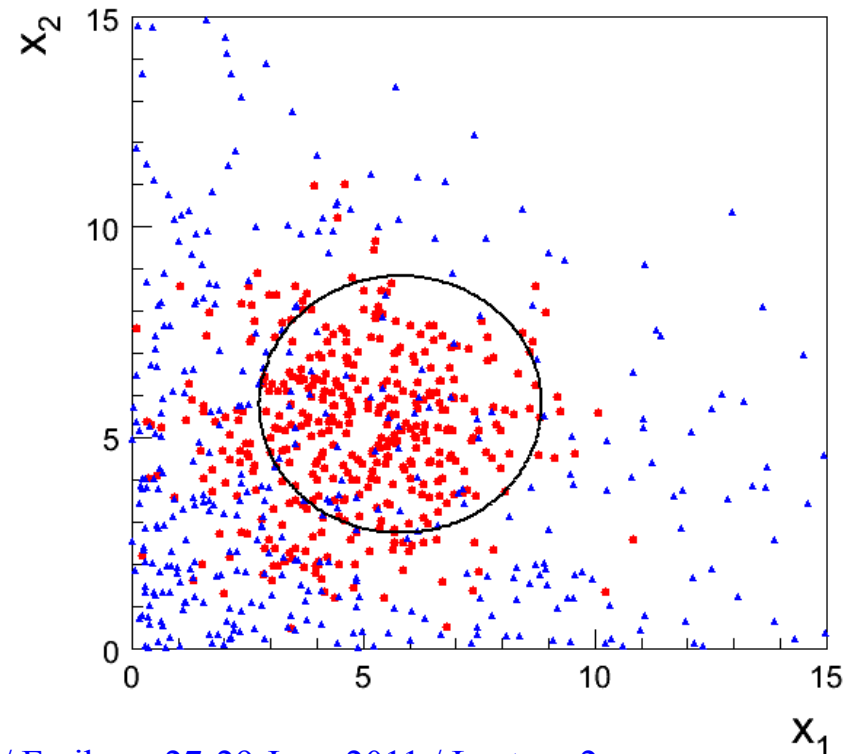
# Likelihood ratio as test statistic

In a real-world problem we usually wouldn't have the pdfs  $f(\mathbf{x}|H_0)$  and  $f(\mathbf{x}|H_1)$ , so we wouldn't be able to evaluate the likelihood ratio

$$t(\mathbf{x}) = \frac{f(\mathbf{x}|H_1)}{f(\mathbf{x}|H_0)}$$

for a given observed  $\mathbf{x}$ , hence the need for multivariate methods to approximate this with some other function.

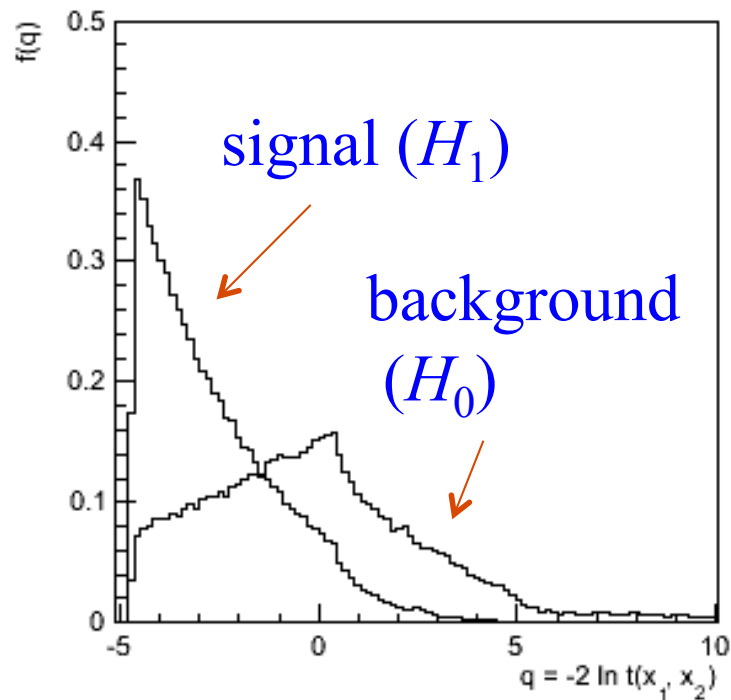
But in this example we can find contours of constant likelihood ratio such as:



# Event selection using the LR

Using Monte Carlo, we can find the distribution of the likelihood ratio or equivalently of

$$q = \left( \frac{x_1 - \mu_1}{\sigma_1} \right)^2 + \left( \frac{x_2 - \mu_2}{\sigma_2} \right)^2 - \frac{2x_1}{\xi_1} - \frac{2x_2}{\xi_2} = -2 \ln t(\mathbf{x}) + C$$



From the Neyman-Pearson lemma we know that by cutting on this variable we would select a signal sample with the highest signal efficiency (test power) for a given background efficiency.

# Search for the signal process

But what if the signal process is not known to exist and we want to search for it. The relevant hypotheses are therefore

$H_0$ : all events are of the background type

$H_1$ : the events are a mixture of signal and background

Rejecting  $H_0$  with  $Z > 5$  constitutes “discovering” new physics.

Suppose that for a given integrated luminosity, the expected number of signal events is  $s$ , and for background  $b$ .

The observed number of events  $n$  will follow a Poisson distribution:

$$P(n|b) = \frac{b^n}{n!} e^{-b} \qquad P(n|s + b) = \frac{(s + b)^n}{n!} e^{-(s+b)}$$

# Likelihoods for full experiment

We observe  $n$  events, and thus measure  $n$  instances of  $\mathbf{x} = (x_1, x_2)$ .

The likelihood function for the entire experiment assuming the background-only hypothesis ( $H_0$ ) is

$$L_b = \frac{b^n}{n!} e^{-b} \prod_{i=1}^n f(\mathbf{x}_i | b)$$

and for the “signal plus background” hypothesis ( $H_1$ ) it is

$$L_{s+b} = \frac{(s+b)^n}{n!} e^{-(s+b)} \prod_{i=1}^n (\pi_s f(\mathbf{x}_i | s) + \pi_b f(\mathbf{x}_i | b))$$

where  $\pi_s$  and  $\pi_b$  are the (prior) probabilities for an event to be signal or background, respectively.



## Likelihood ratio for full experiment

We can define a test statistic  $Q$  monotonic in the likelihood ratio as

$$Q = -2 \ln \frac{L_{s+b}}{L_b} = -s + \sum_{i=1}^n \ln \left( 1 + \frac{s}{b} \frac{f(\mathbf{x}_i|s)}{f(\mathbf{x}_i|b)} \right)$$

To compute  $p$ -values for the  $b$  and  $s+b$  hypotheses given an observed value of  $Q$  we need the distributions  $f(Q|b)$  and  $f(Q|s+b)$ .

Note that the term  $-s$  in front is a constant and can be dropped.

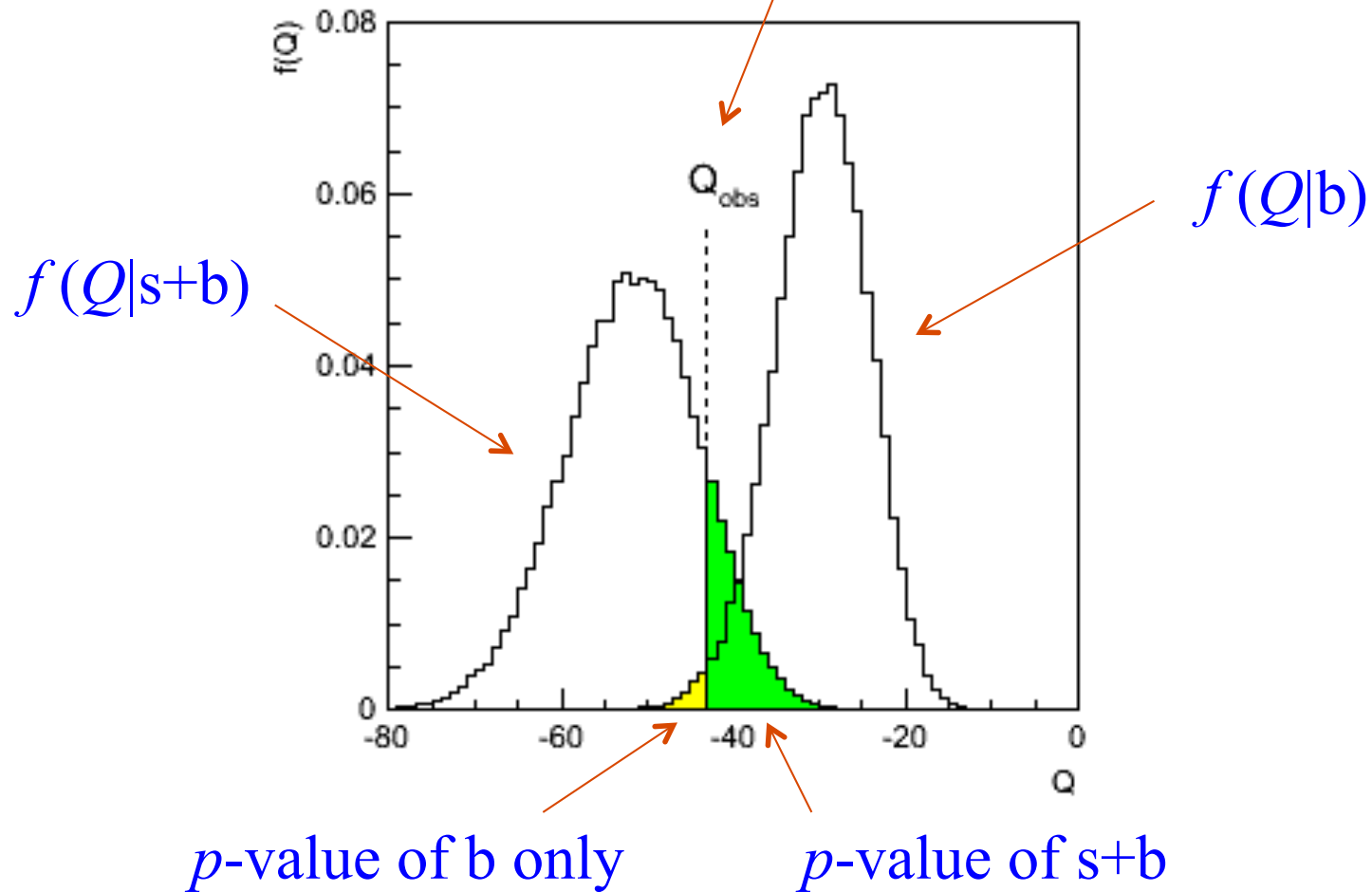
The rest is a sum of contributions for each event, and each term in the sum has the same distribution.

Can exploit this to relate distribution of  $Q$  to that of single event terms using (Fast) Fourier Transforms (Hu and Nielsen, physics/9906010).

# Distribution of $Q$

Take e.g.  $b = 100$ ,  $s = 20$ .

Suppose in real experiment  $Q$  is observed here.



# Systematic uncertainties

Up to now we assumed all parameters were known exactly.

In practice they have some (systematic) uncertainty.

Suppose e.g. uncertainty in expected number of background events  $b$  is characterized by a (Bayesian) pdf  $\pi(b)$ .

Maybe take a Gaussian, i.e.,

$$\pi(b) = \frac{1}{\sqrt{2\pi}\sigma_b} e^{-(b-b_0)^2/2\sigma_b^2}$$

where  $b_0$  is the nominal (measured) value and  $\sigma_b$  is the estimated uncertainty.

In fact for many systematics a Gaussian pdf is hard to defend – more on this later.

## Distribution of $Q$ with systematics

To get the desired  $p$ -values we need the pdf  $f(Q)$ , but this depends on  $b$ , which we don't know exactly.

But we can obtain the **Bayesian model average**:

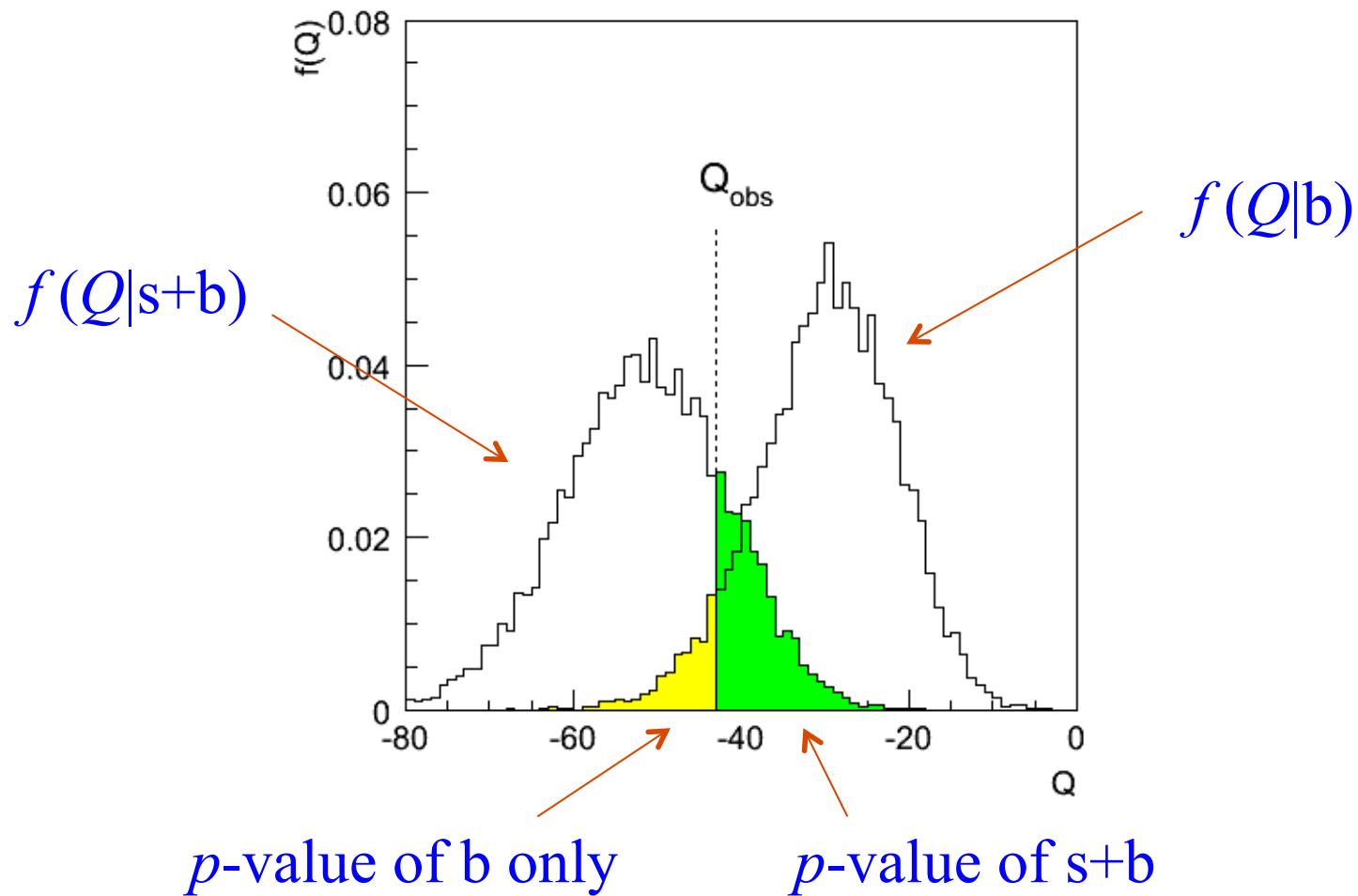
$$f(Q) = \int f(Q|b)\pi(b) db$$

With Monte Carlo, sample  $b$  from  $\pi(b)$ , then use this to generate  $Q$  from  $f(Q|b)$ , i.e., a new value of  $b$  is used to generate the data for every simulation of the experiment.

This broadens the distributions of  $Q$  and thus increases the  $p$ -value (decreases significance  $Z$ ) for a given  $Q_{\text{obs}}$ .

## Distribution of $Q$ with systematics (2)

For  $s = 20$ ,  $b_0 = 100$ ,  $\sigma_b = 10$  this gives



## Using the likelihood ratio $L(s)/L(\hat{s})$

Instead of the likelihood ratio  $L_{s+b}/L_b$ , suppose we use as a test statistic

$$\lambda(s) = \frac{L(s)}{L(\hat{s})}$$

 maximizes  $L(s)$

Intuitively this is a measure of the level of agreement between the data and the hypothesized value of  $s$ .

low  $\lambda$ : poor agreement

high  $\lambda$  : better agreement

$$0 \leq \lambda \leq 1$$

## $L(s)/L(\hat{s})$ for counting experiment

Consider an experiment where we only count  $n$  events with  $n \sim \text{Poisson}(s + b)$ . Then  $\hat{s} = n - b$ .

To establish discovery of signal we test the hypothesis  $s = 0$  using

$$\ln \lambda(0) = n \ln(b) - b - n \ln n + n$$

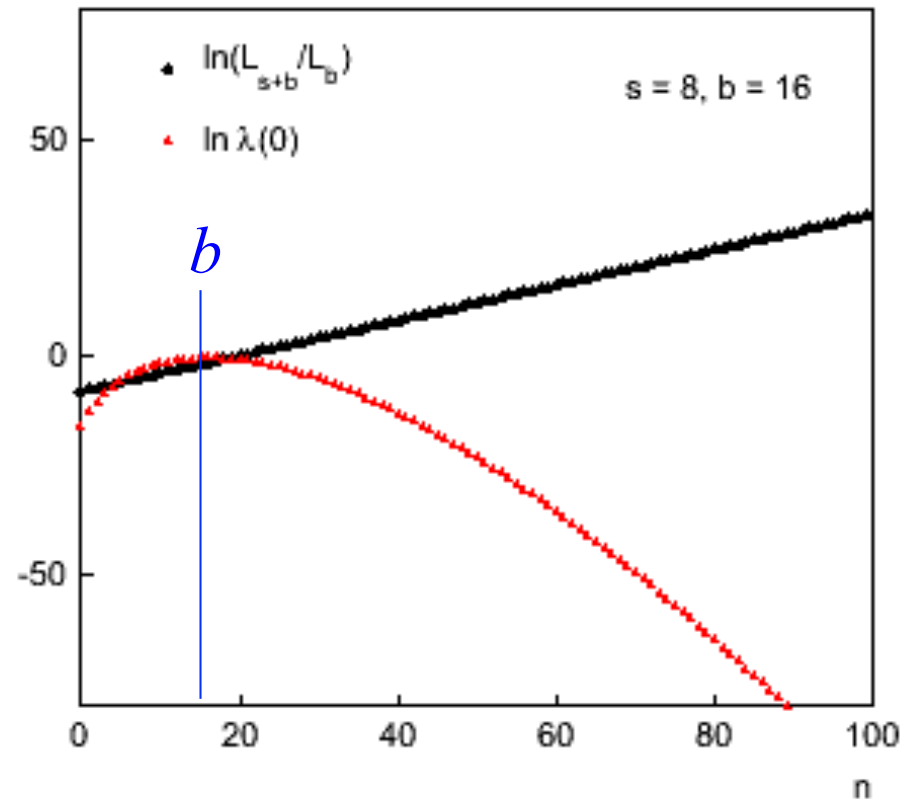
whereas previously we had used

$$\ln \frac{L_{s+b}}{L_b} = n \ln \left( 1 + \frac{s}{b} \right) - s$$

which is monotonic in  $n$  and thus equivalent to using  $n$  as the test statistic.

## $L(s)/L(\hat{s})$ for counting experiment (2)

But if we only consider the possibility of signal being present when  $n > b$ , then in this range  $\lambda(0)$  is also monotonic in  $n$ , so both likelihood ratios lead to the same test.





## $L(s)/L(\hat{s})$ for general experiment

If we do not simply count events but also measure for each some set of numbers, then the two likelihood ratios do not necessarily give equivalent tests, but in practice will be very close.

$\lambda(s)$  has the important advantage that for a sufficiently large event sample, its distribution approaches a well defined form (Wilks' Theorem).

In practice the approach to the asymptotic form is rapid and one obtains a good approximation even for relatively small data samples (but need to check with MC).

This remains true even when we have adjustable **nuisance parameters** in the problem, i.e., parameters that are needed for a correct description of the data but are otherwise not of interest (key to dealing with systematic uncertainties).

# Prototype search analysis

Search for signal in a region of phase space; result is histogram of some variable  $x$  giving numbers:

$$\mathbf{n} = (n_1, \dots, n_N)$$

Assume the  $n_i$  are Poisson distributed with expectation values

$$E[n_i] = \mu s_i + b_i$$

strength parameter

where

$$s_i = s_{\text{tot}} \int_{\text{bin } i} f_s(x; \boldsymbol{\theta}_s) dx, \quad b_i = b_{\text{tot}} \int_{\text{bin } i} f_b(x; \boldsymbol{\theta}_b) dx.$$

signal

background

## Prototype analysis (II)

Often also have a subsidiary measurement that constrains some of the background and/or shape parameters:

$$\mathbf{m} = (m_1, \dots, m_M)$$

Assume the  $m_i$  are Poisson distributed with expectation values

$$E[m_i] = u_i(\boldsymbol{\theta})$$

nuisance parameters ( $\boldsymbol{\theta}_s, \boldsymbol{\theta}_b, b_{\text{tot}}$ )

Likelihood function is

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^M \frac{u_k^{m_k}}{m_k!} e^{-u_k}$$

# The profile likelihood ratio

Base significance test on the profile likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

maximizes  $L$  for Specified  $\mu$

maximize  $L$

The likelihood ratio of point hypotheses gives optimum test (Neyman-Pearson lemma).

The profile LR should be near-optimal in present analysis with variable  $\mu$  and nuisance parameters  $\boldsymbol{\theta}$ .

## Test statistic for discovery

Try to reject background-only ( $\mu = 0$ ) hypothesis using

$$q_0 = \begin{cases} -2 \ln \lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

i.e. here only regard upward fluctuation of data as evidence against the background-only hypothesis.

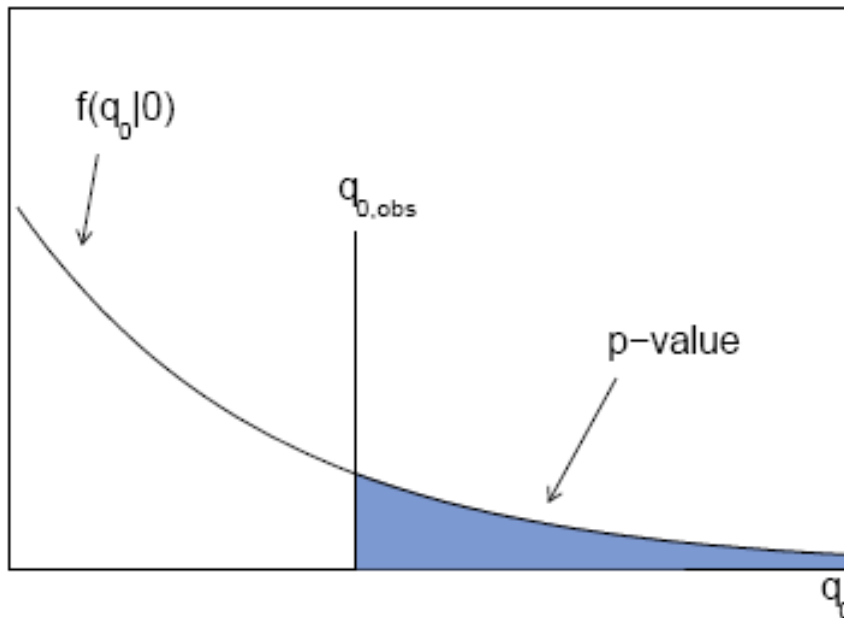
Note that even though here physically  $\mu \geq 0$ , we allow  $\hat{\mu}$  to be negative. In large sample limit its distribution becomes Gaussian, and this will allow us to write down simple expressions for distributions of our test statistics.

# $p$ -value for discovery

Large  $q_0$  means increasing incompatibility between the data and hypothesis, therefore  $p$ -value for an observed  $q_{0,\text{obs}}$  is

$$p_0 = \int_{q_{0,\text{obs}}}^{\infty} f(q_0|0) dq_0$$

will get formula for this later

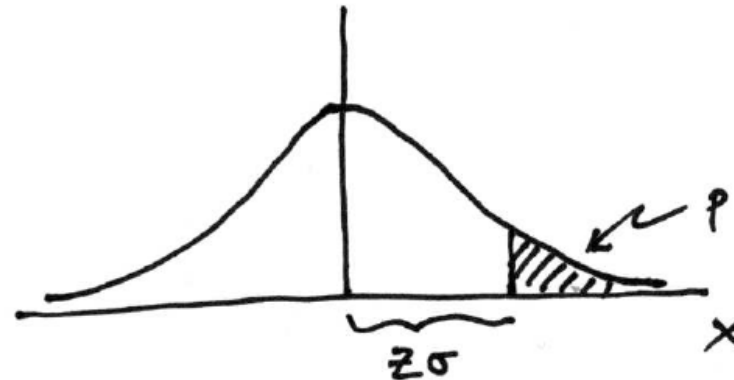


From  $p$ -value get equivalent significance,

$$Z = \Phi^{-1}(1 - p)$$

# Significance from $p$ -value

Often define significance  $Z$  as the number of standard deviations that a Gaussian variable would fluctuate in one direction to give the same  $p$ -value.



$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx = 1 - \Phi(Z)$$

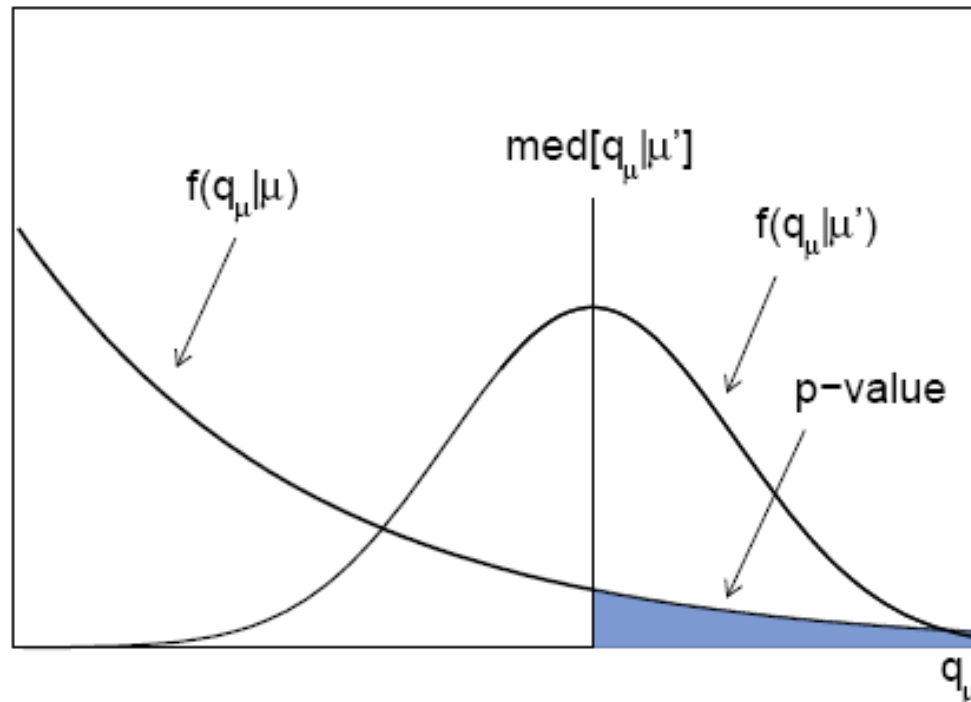
`1 - TMath::Freq`

$$Z = \Phi^{-1}(1 - p)$$

`TMath::NormQuantile`

# Expected (or median) significance / sensitivity

When planning the experiment, we want to quantify how sensitive we are to a potential discovery, e.g., by given median significance assuming some nonzero strength parameter  $\mu'$ .



So for  $p$ -value, need  $f(q_0|0)$ , for sensitivity, will need  $f(q_0|\mu')$ ,



# Test statistic for upper limits

For purposes of setting an upper limit on  $\mu$  use

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} \quad \text{where} \quad \lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

Note for purposes of setting an upper limit, one does not regard an upwards fluctuation of the data as representing incompatibility with the hypothesized  $\mu$ .

From observed  $q_\mu$  find  $p$ -value: 
$$p_\mu = \int_{q_{\mu, \text{obs}}}^{\infty} f(q_\mu | \mu) dq_\mu$$

95% CL upper limit on  $\mu$  is highest value for which  $p$ -value is not less than 0.05.

## Alternative test statistic for upper limits

Assume physical signal model has  $\mu > 0$ , therefore if estimator for  $\mu$  comes out negative, the closest physical model has  $\mu = 0$ .

Therefore could also measure level of discrepancy between data and hypothesized  $\mu$  with

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} & \hat{\mu} \geq 0, \\ \frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(0, \hat{\boldsymbol{\theta}}(0))} & \hat{\mu} < 0. \end{cases} \quad \tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

Performance not identical to but very close to  $q_\mu$  (of previous slide).

$q_\mu$  is simpler in important ways: asymptotic distribution is independent of nuisance parameters.

# Wald approximation for profile likelihood ratio

To find  $p$ -values, we need:  $f(q_0|0)$ ,  $f(q_\mu|\mu)$

For median significance under alternative, need:  $f(q_\mu|\mu')$

Use approximation due to Wald (1943)

$$-2 \ln \lambda(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^2} + \mathcal{O}(1/\sqrt{N})$$

$$\hat{\mu} \sim \text{Gaussian}(\mu', \sigma)$$

sample size

$$\text{i.e., } E[\hat{\mu}] = \mu'$$

$\sigma$  from covariance matrix  $V$ , use, e.g.,

$$V^{-1} = -E \left[ \frac{\partial^2 \ln L}{\partial \theta_i \partial \theta_j} \right]$$

## Noncentral chi-square for $-2\ln\lambda(\mu)$

If we can neglect the  $O(1/\sqrt{N})$  term,  $-2\ln\lambda(\mu)$  follows a **noncentral chi-square distribution** for one degree of freedom with noncentrality parameter

$$\Lambda = \frac{(\mu - \mu')^2}{\sigma^2}$$

As a special case, if  $\mu' = \mu$  then  $\Lambda = 0$  and  $-2\ln\lambda(\mu)$  follows a **chi-square distribution for one degree of freedom** (Wilks).

## The Asimov data set

To estimate median value of  $-2\ln\lambda(\mu)$ , consider special data set where all statistical fluctuations suppressed and  $n_i, m_i$  are replaced by their expectation values (the “Asimov” data set):

$$n_i = \mu' s_i + b_i$$

$$m_i = u_i$$

$$\longrightarrow \hat{\mu} = \mu' \quad \hat{\theta} = \theta$$

$$\lambda_A(\mu) = \frac{L_A(\mu, \hat{\theta})}{L_A(\hat{\mu}, \hat{\theta})} = \frac{L_A(\mu, \hat{\theta})}{L_A(\mu', \theta)}$$

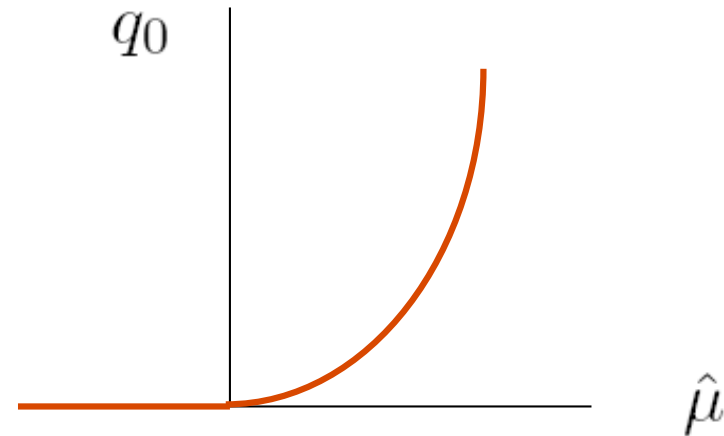
$$-2 \ln \lambda_A(\mu) = \frac{(\mu - \mu')^2}{\sigma^2} = \Lambda$$

Asimov value of  $-2\ln\lambda(\mu)$  gives non-centrality param.  $\Lambda$ , or equivalently,  $\sigma$ .

## Relation between test statistics and $\hat{\mu}$

Assuming Wald approximation, the relation between  $q_0$  and  $\hat{\mu}$  is

$$q_0 = \begin{cases} \hat{\mu}^2 / \sigma^2 & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$



Monotonic, therefore quantiles of  $\hat{\mu}$  map one-to-one onto those of  $q_0$ , e.g.,

$$\text{med}[q_0] = q_0(\text{med}[\hat{\mu}]) = q_0(\mu') = \frac{\mu'^2}{\sigma^2} = -2 \ln \lambda_A(0)$$

## Distribution of $q_0$

Assuming the Wald approximation, we can write down the full distribution of  $q_0$  as

$$f(q_0|\mu') = \left(1 - \Phi\left(\frac{\mu'}{\sigma}\right)\right) \delta(q_0) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_0}} \exp\left[-\frac{1}{2} \left(\sqrt{q_0} - \frac{\mu'}{\sigma}\right)^2\right]$$

The special case  $\mu' = 0$  is a “half chi-square” distribution:

$$f(q_0|0) = \frac{1}{2} \delta(q_0) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_0}} e^{-q_0/2}$$

## Cumulative distribution of $q_0$ , significance

From the pdf, the cumulative distribution of  $q_0$  is found to be

$$F(q_0|\mu') = \Phi\left(\sqrt{q_0} - \frac{\mu'}{\sigma}\right)$$

The special case  $\mu' = 0$  is

$$F(q_0|0) = \Phi\left(\sqrt{q_0}\right)$$

The  $p$ -value of the  $\mu = 0$  hypothesis is

$$p_0 = 1 - F(q_0|0)$$

Therefore the discovery significance  $Z$  is simply

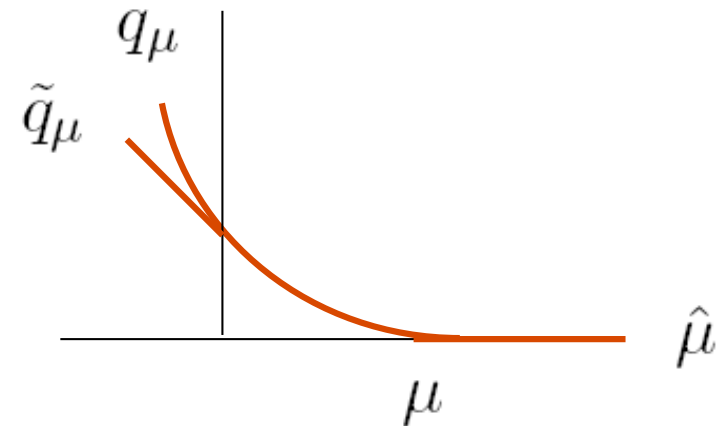
$$Z = \Phi^{-1}(1 - p_0) = \sqrt{q_0}$$



## Relation between test statistics and $\hat{\mu}$

Assuming the Wald approximation for  $-2\ln\lambda(\mu)$ ,  $q_\mu$  and  $\tilde{q}_\mu$  both have monotonic relation with  $\mu$ .

$$q_\mu = \begin{cases} \frac{(\mu - \hat{\mu})^2}{\sigma^2} & \hat{\mu} < \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$



$$\tilde{q}_\mu = \begin{cases} \frac{\mu^2}{\sigma^2} - \frac{2\mu\hat{\mu}}{\sigma^2} & \hat{\mu} < \mu \\ \frac{(\mu - \hat{\mu})^2}{\sigma^2} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

And therefore quantiles of  $q_\mu$ ,  $\tilde{q}_\mu$  can be obtained directly from those of  $\hat{\mu}$  (which is Gaussian).

# Distribution of $q_\mu$

Similar results for  $q_\mu$

$$f(q_\mu|\mu') = \Phi\left(\frac{\mu' - \mu}{\sigma}\right) \delta(q_\mu) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_\mu}} \exp\left[-\frac{1}{2} \left(\sqrt{q_\mu} - \frac{(\mu - \mu')}{\sigma}\right)^2\right]$$

$$f(q_\mu|\mu) = \frac{1}{2} \delta(q_\mu) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_\mu}} e^{-q_\mu/2}$$

$$F(q_\mu|\mu') = \Phi\left(\sqrt{q_\mu} - \frac{(\mu - \mu')}{\sigma}\right)$$

$$p_\mu = 1 - F(q_\mu|\mu) = 1 - \Phi\left(\sqrt{q_\mu}\right)$$

# Distribution of $\tilde{q}_\mu$

Similar results for  $\tilde{q}_\mu$

$$f(\tilde{q}_\mu|\mu') = \Phi\left(\frac{\mu' - \mu}{\sigma}\right) \delta(\tilde{q}_\mu) + \begin{cases} \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{\tilde{q}_\mu}} \exp\left[-\frac{1}{2} \left(\sqrt{\tilde{q}_\mu} - \frac{\mu - \mu'}{\sigma}\right)^2\right] & 0 < \tilde{q}_\mu \leq \mu^2/\sigma^2, \\ \frac{1}{\sqrt{2\pi}(2\mu/\sigma)} \exp\left[-\frac{1}{2} \frac{(\tilde{q}_\mu - (\mu^2 - 2\mu\mu')/\sigma^2)^2}{(2\mu/\sigma)^2}\right] & \tilde{q}_\mu > \mu^2/\sigma^2. \end{cases}$$

$$F(\tilde{q}_\mu|\mu') = \begin{cases} \Phi\left(\sqrt{\tilde{q}_\mu} - \frac{(\mu - \mu')}{\sigma}\right) & 0 < \tilde{q}_\mu \leq \mu^2/\sigma^2, \\ \Phi\left(\frac{\tilde{q}_\mu - (\mu^2 - 2\mu\mu')/\sigma^2}{2\mu/\sigma}\right) & \tilde{q}_\mu > \mu^2/\sigma^2. \end{cases}$$

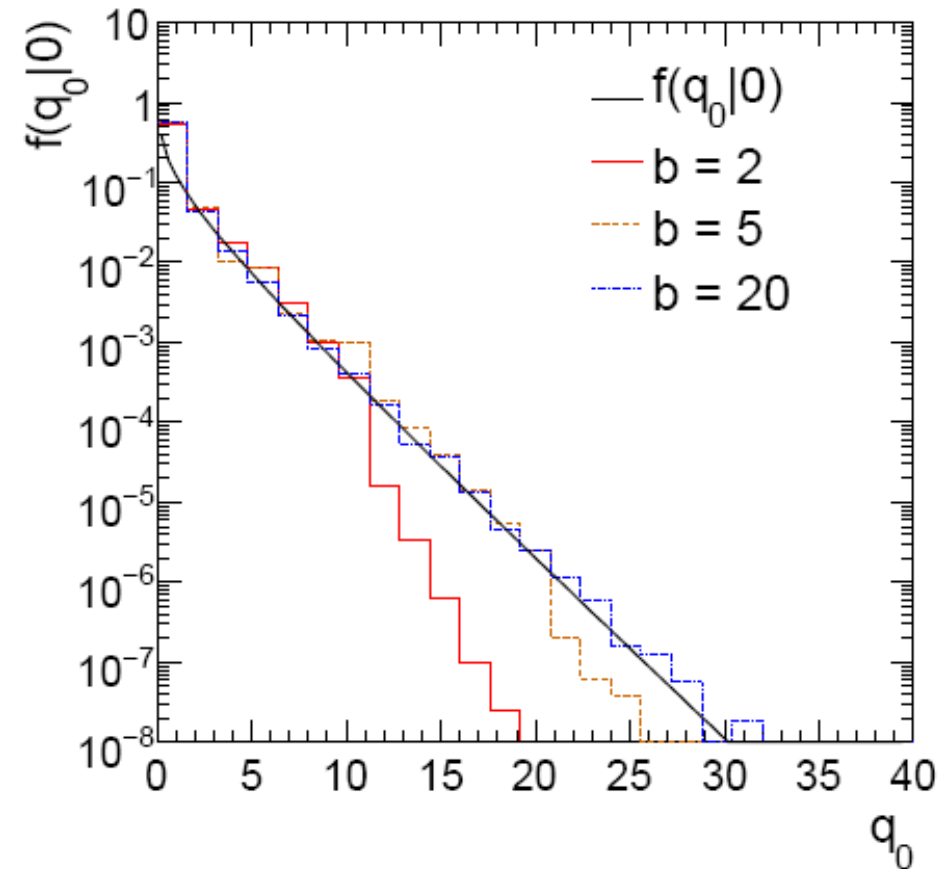
# Monte Carlo test of asymptotic formula

$$n \sim \text{Poisson}(\mu s + b)$$

$$m \sim \text{Poisson}(\tau b)$$

Here take  $\tau = 1$ .

Asymptotic formula is good approximation to  $5\sigma$  level ( $q_0 = 25$ ) already for  $b \sim 20$ .

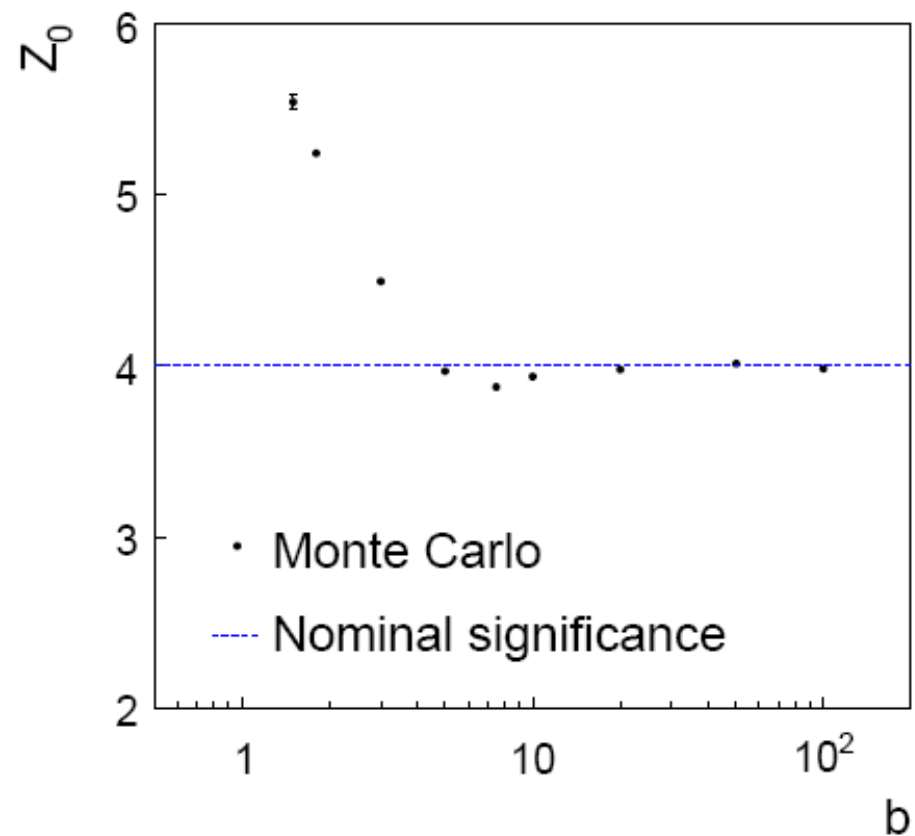


# Monte Carlo test of asymptotic formulae

Significance from asymptotic formula, here  $Z_0 = \sqrt{q_0} = 4$ , compared to MC (true) value.

For very low  $b$ , asymptotic formula underestimates  $Z_0$ .

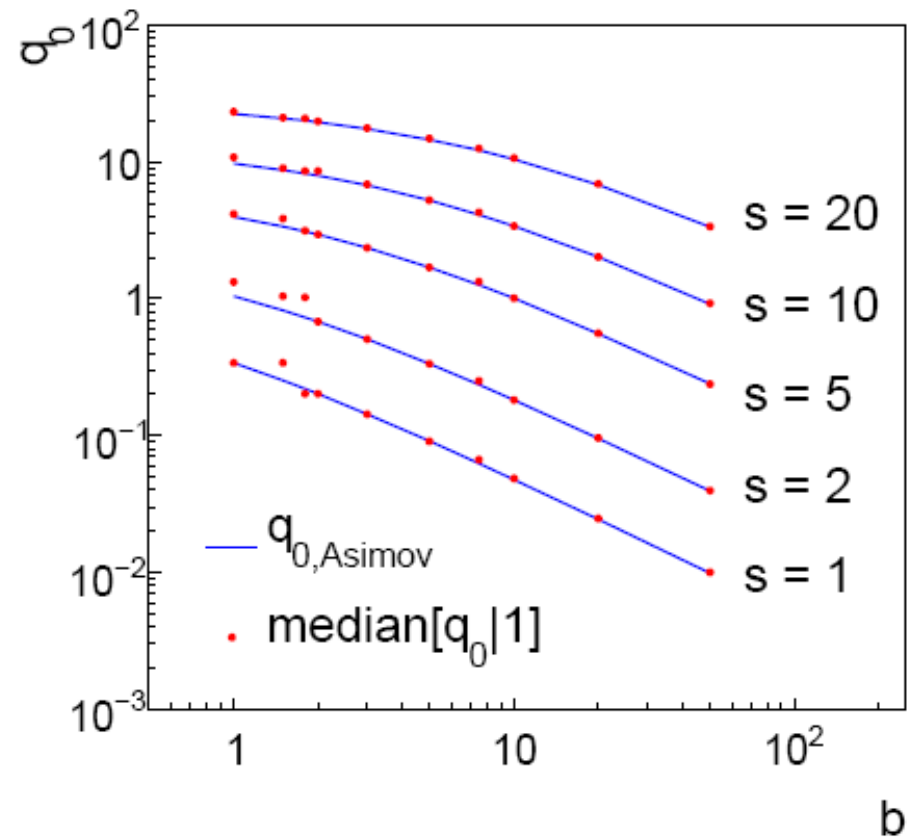
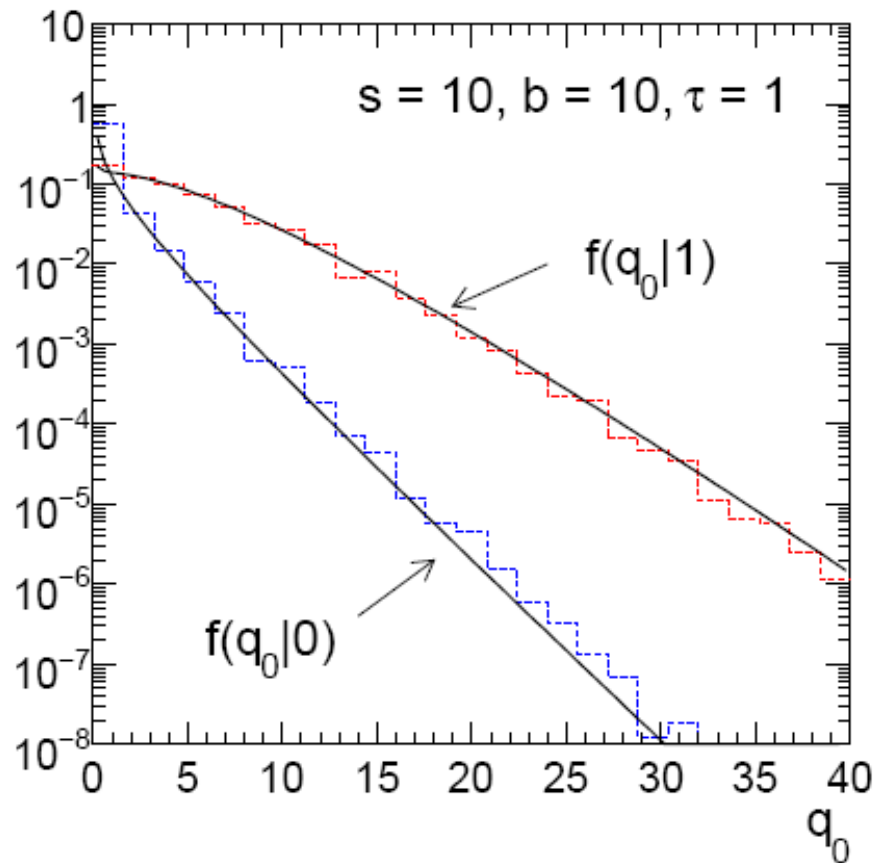
Then slight overshoot before rapidly converging to MC value.



# Monte Carlo test of asymptotic formulae

Asymptotic  $f(q_0|1)$  good already for fairly small samples.

Median[ $q_0|1$ ] from Asimov data set; good agreement with MC.



# Monte Carlo test of asymptotic formulae

Consider again  $n \sim \text{Poisson}(\mu s + b)$ ,  $m \sim \text{Poisson}(\tau b)$

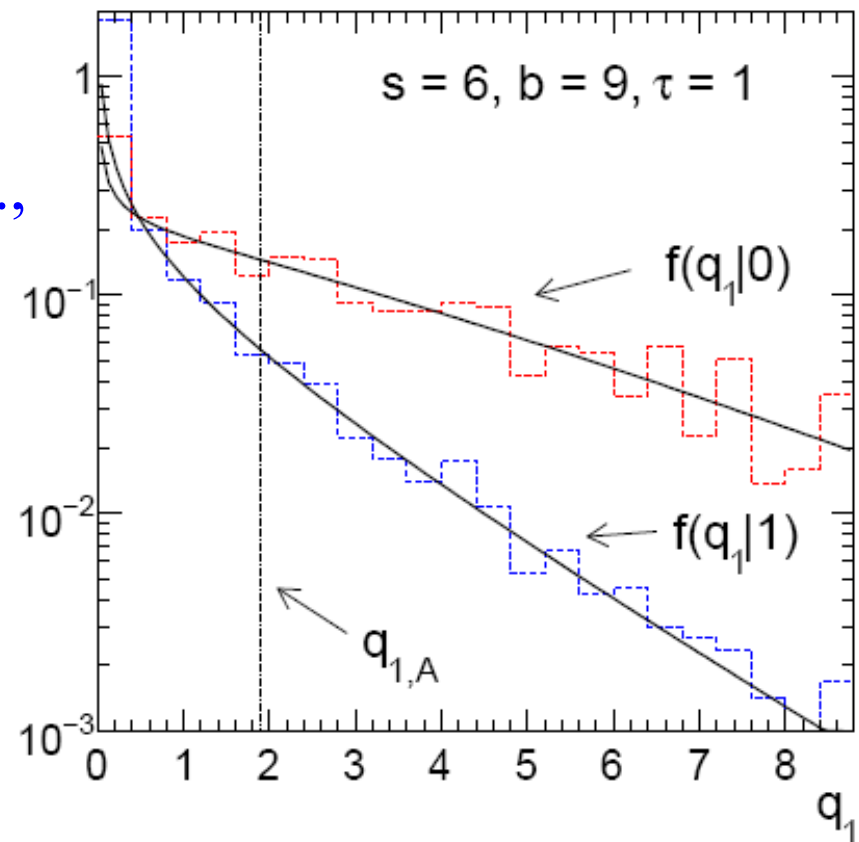
Use  $q_\mu$  to find  $p$ -value of hypothesized  $\mu$  values.

E.g.  $f(q_1|1)$  for  $p$ -value of  $\mu=1$ .

Typically interested in 95% CL, i.e.,  
 $p$ -value threshold = 0.05, i.e.,  
 $q_1 = 2.69$  or  $Z_1 = \sqrt{q_1} = 1.64$ .

Median[ $q_1 | 0$ ] gives “exclusion sensitivity”.

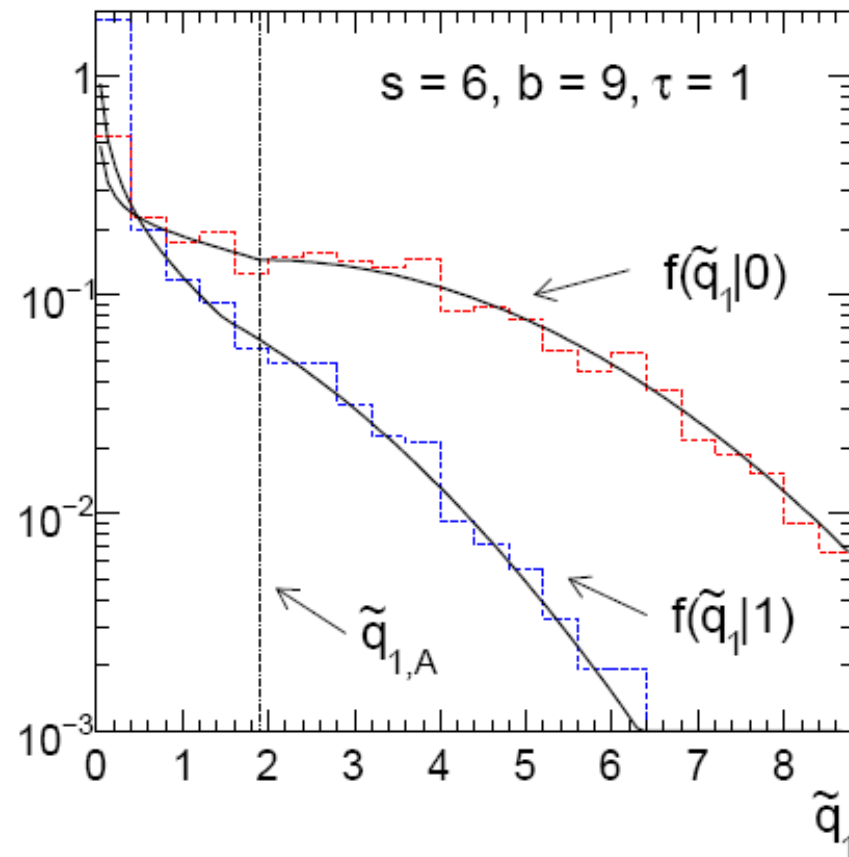
Here asymptotic formulae good  
for  $s = 6$ ,  $b = 9$ .



# Monte Carlo test of asymptotic formulae

Same message for test based on  $\tilde{q}_\mu$ .

$q_\mu$  and  $\tilde{q}_\mu$  give similar tests to the extent that asymptotic formulae are valid.





## Discovery significance for $n \sim \text{Poisson}(s + b)$

Consider again the case where we observe  $n$  events, model as following Poisson distribution with mean  $s + b$  (assume  $b$  is known).

- 1) For an observed  $n$ , what is the significance  $Z_0$  with which we would reject the  $s = 0$  hypothesis?
- 2) What is the expected (or more precisely, median)  $Z_0$  if the true value of the signal rate is  $s$ ?

# Gaussian approximation for Poisson significance

For large  $s + b$ ,  $n \rightarrow x \sim \text{Gaussian}(\mu, \sigma)$ ,  $\mu = s + b$ ,  $\sigma = \sqrt{s + b}$ .

For observed value  $x_{\text{obs}}$ ,  $p$ -value of  $s = 0$  is  $\text{Prob}(x > x_{\text{obs}} | s = 0)$ ,:

$$p_0 = 1 - \Phi\left(\frac{x_{\text{obs}} - b}{\sqrt{b}}\right)$$

Significance for rejecting  $s = 0$  is therefore

$$Z_0 = \Phi^{-1}(1 - p_0) = \frac{x_{\text{obs}} - b}{\sqrt{b}}$$

Expected (median) significance assuming signal rate  $s$  is

$$\text{median}[Z_0 | s + b] = \frac{s}{\sqrt{b}}$$

# Better approximation for Poisson significance

Likelihood function for parameter  $s$  is

$$L(s) = \frac{(s+b)^n}{n!} e^{-(s+b)}$$

or equivalently the log-likelihood is

$$\ln L(s) = n \ln(s+b) - (s+b) - \ln n!$$

Find the maximum by setting  $\frac{\partial \ln L}{\partial s} = 0$

gives the estimator for  $s$ :  $\hat{s} = n - b$

## Approximate Poisson significance (continued)

The likelihood ratio statistic for testing  $s = 0$  is

$$q_0 = -2 \ln \frac{L(0)}{L(\hat{s})} = 2 \left( n \ln \frac{n}{b} + b - n \right) \quad \text{for } n > b, \text{ 0 otherwise}$$

For sufficiently large  $s + b$ , (use Wilks' theorem),

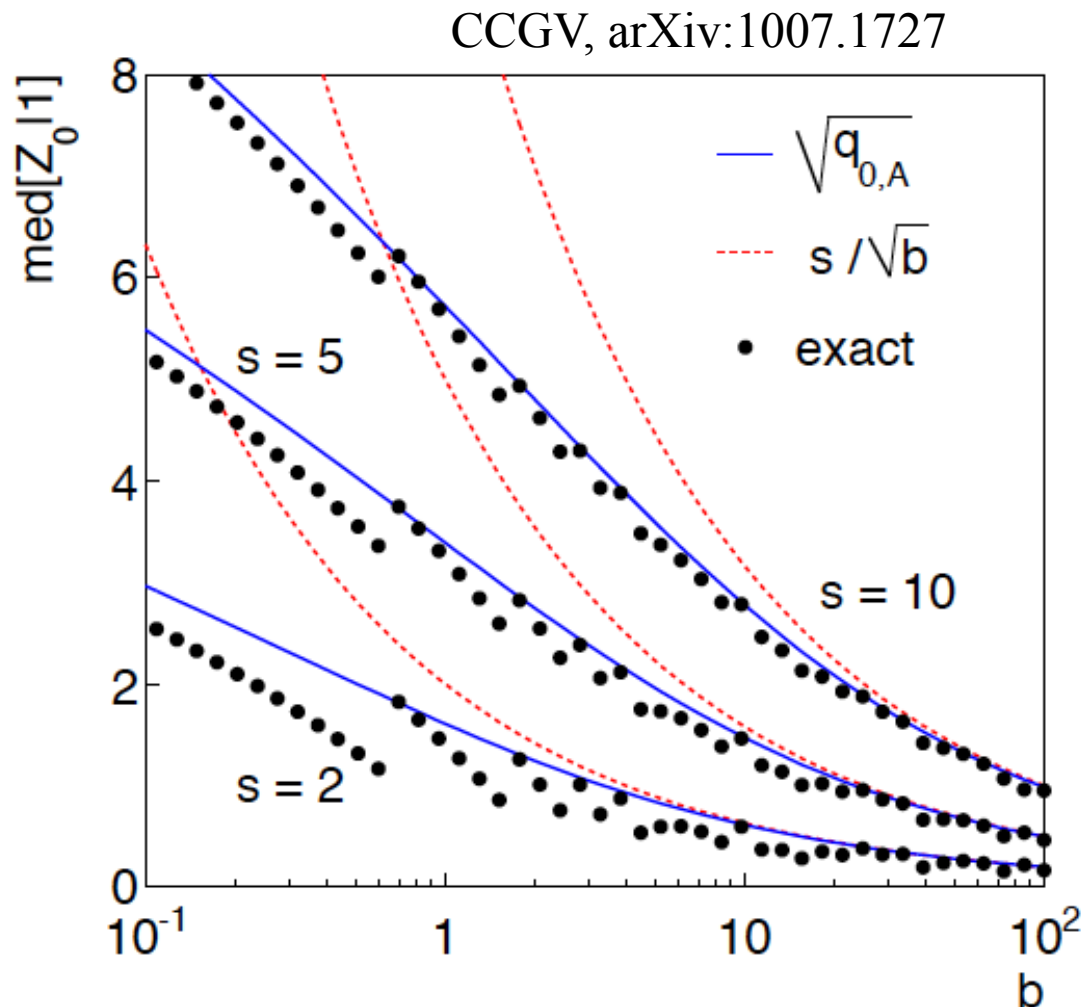
$$Z_0 \approx \sqrt{q_0} = \sqrt{2 \left( n \ln \frac{n}{b} + b - n \right)} \quad \text{for } n > b, \text{ 0 otherwise}$$

To find  $\text{median}[Z_0|s+b]$ , let  $n \rightarrow s + b$  (i.e., the Asimov data set):

$$\text{median}[Z_0|s + b] \approx \sqrt{2 \left( (s + b) \ln(1 + s/b) - s \right)}$$

This reduces to  $s/\sqrt{b}$  for  $s \ll b$ .

$n \sim \text{Poisson}(\mu s + b)$ , median significance,  
assuming  $\mu = 1$ , of the hypothesis  $\mu = 0$



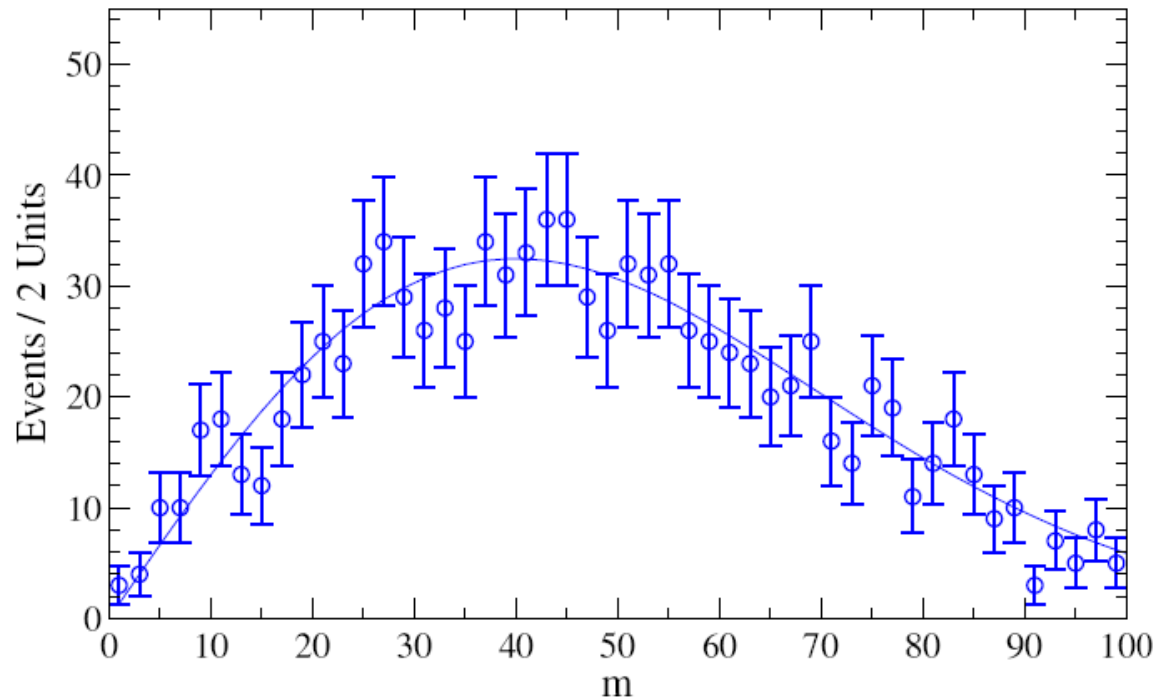
“Exact” values from MC,  
jumps due to discrete data.

Asimov  $\sqrt{q_{0,A}}$  good approx.  
for broad range of  $s, b$ .

$s/\sqrt{b}$  only good for  $s \ll b$ .

## Example 2: Shape analysis

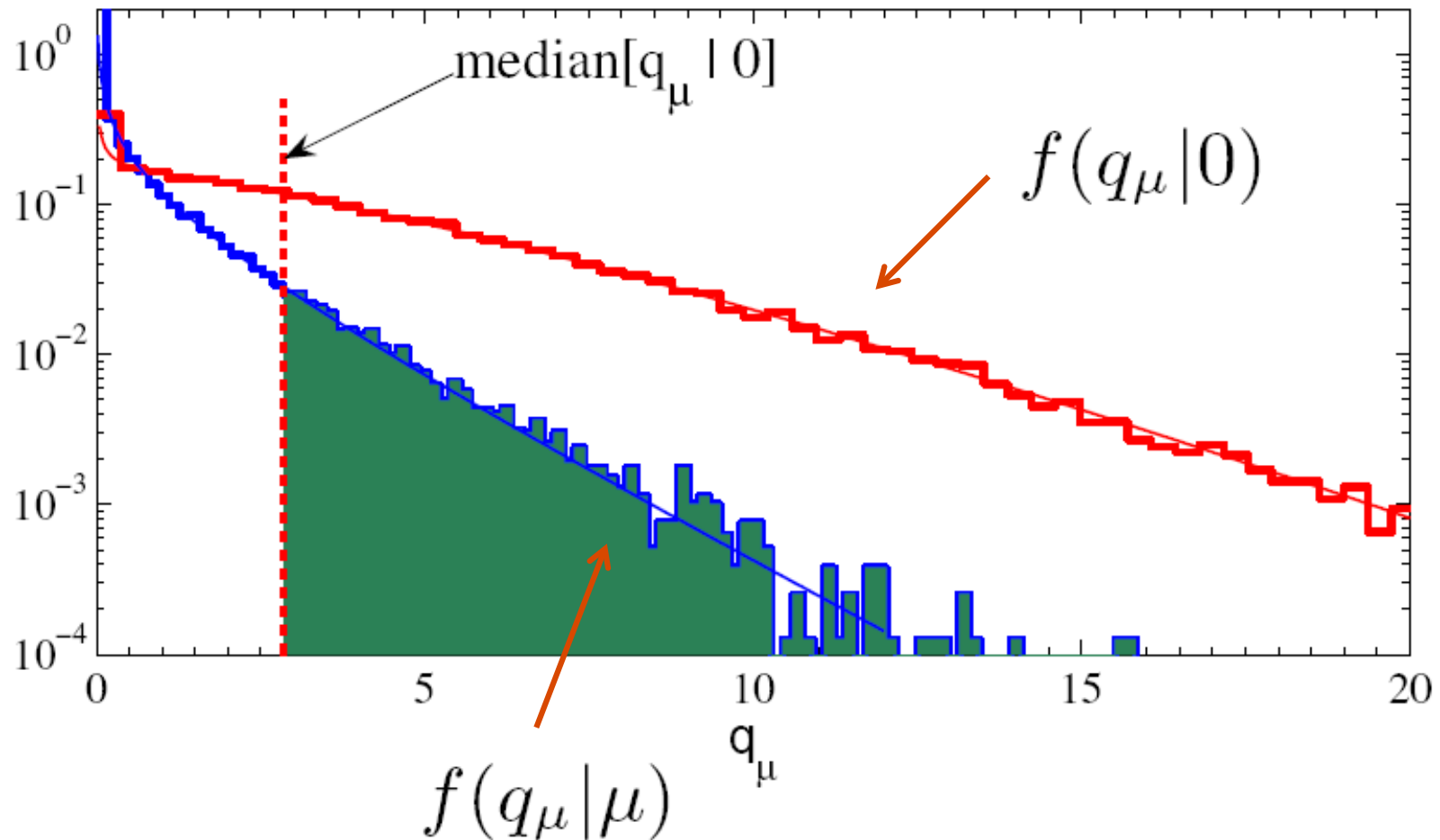
Look for a Gaussian bump sitting on top of:



$$L(\mu, \theta) = \prod_{i=1}^N \frac{(\mu s_i + \theta f_{b,i})^{n_i}}{n_i!} e^{-(\mu s_i + \theta f_{b,i})}$$

# Monte Carlo test of asymptotic formulae

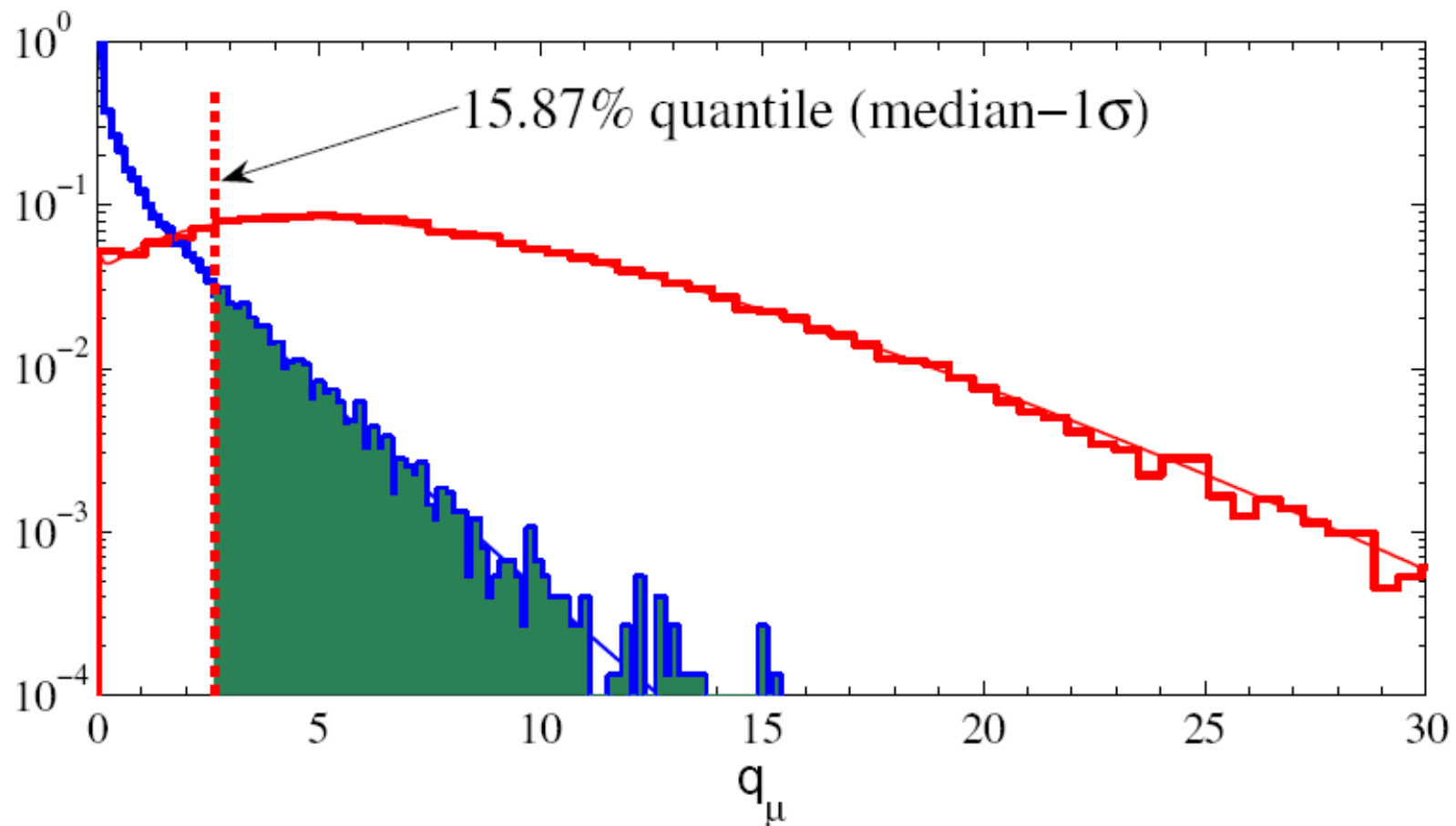
Distributions of  $q_\mu$  here for  $\mu$  that gave  $p_\mu = 0.05$ .



## Using $f(q_\mu|0)$ to get error bands

We are not only interested in the median  $[q_\mu|0]$ ; we want to know how much statistical variation to expect from a real data set.

But we have full  $f(q_\mu|0)$ ; we can get any desired quantiles.

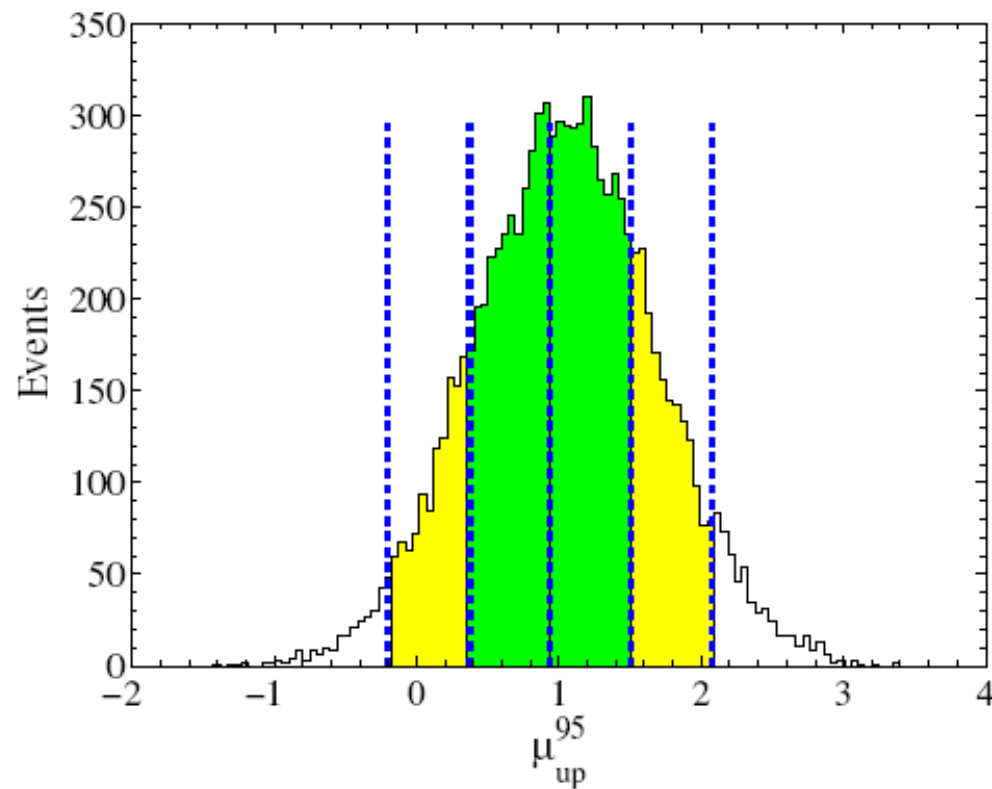




# Distribution of upper limit on $\mu$

$\pm 1\sigma$  (green) and  $\pm 2\sigma$  (yellow) bands from MC;

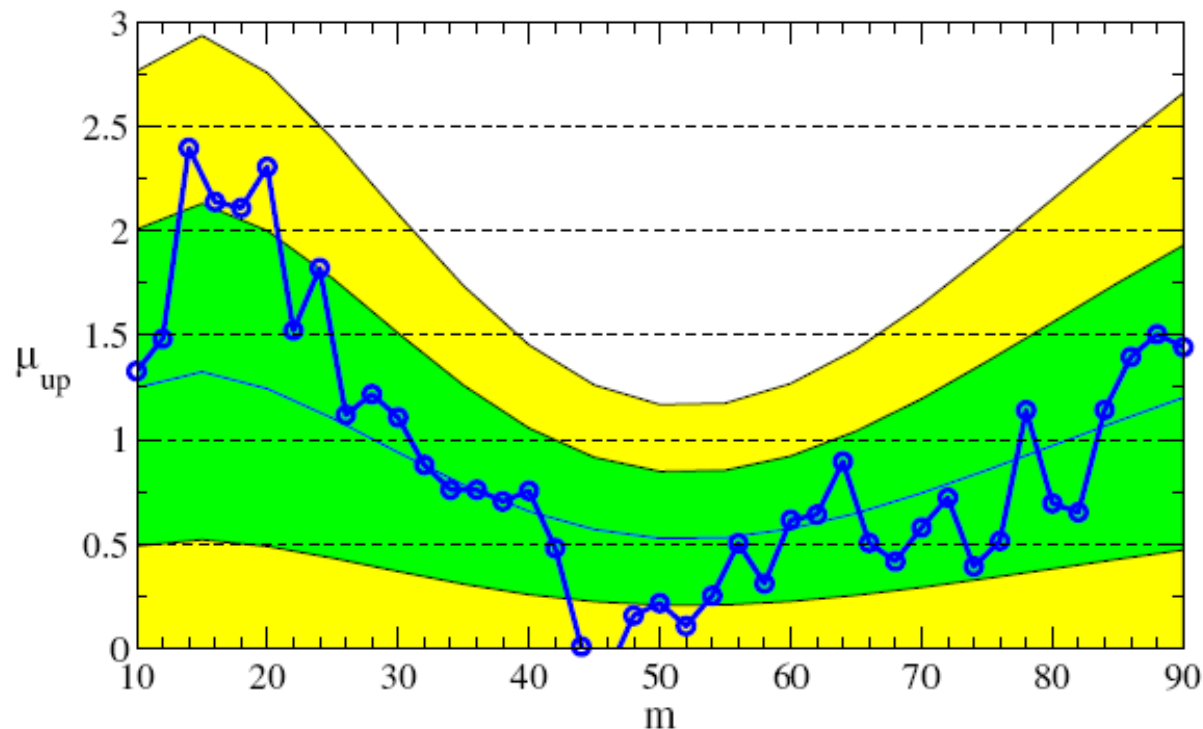
Vertical lines from asymptotic formulae



# Limit on $\mu$ versus peak position (mass)

$\pm 1\sigma$  (green) and  $\pm 2\sigma$  (yellow) bands from asymptotic formulae;

Points are from a single arbitrary data set.



## Using likelihood ratio $L_{s+b}/L_b$

Many searches at the Tevatron have used the statistic

$$q = -2 \ln \frac{L_{s+b}}{L_b}$$

likelihood of  $\mu = 1$  model (s+b)

likelihood of  $\mu = 0$  model (bkg only)

This can be written

$$q = -2 \ln \frac{L(\mu = 1, \hat{\boldsymbol{\theta}}(1))}{L(\mu = 0, \hat{\boldsymbol{\theta}}(0))} = -2 \ln \lambda(1) + 2 \ln \lambda(0)$$

## Wald approximation for $L_{s+b}/L_b$

Assuming the Wald approximation,  $q$  can be written as

$$q = \frac{(\hat{\mu} - 1)^2}{\sigma^2} - \frac{\hat{\mu}^2}{\sigma^2} = \frac{1 - 2\hat{\mu}}{\sigma^2}$$

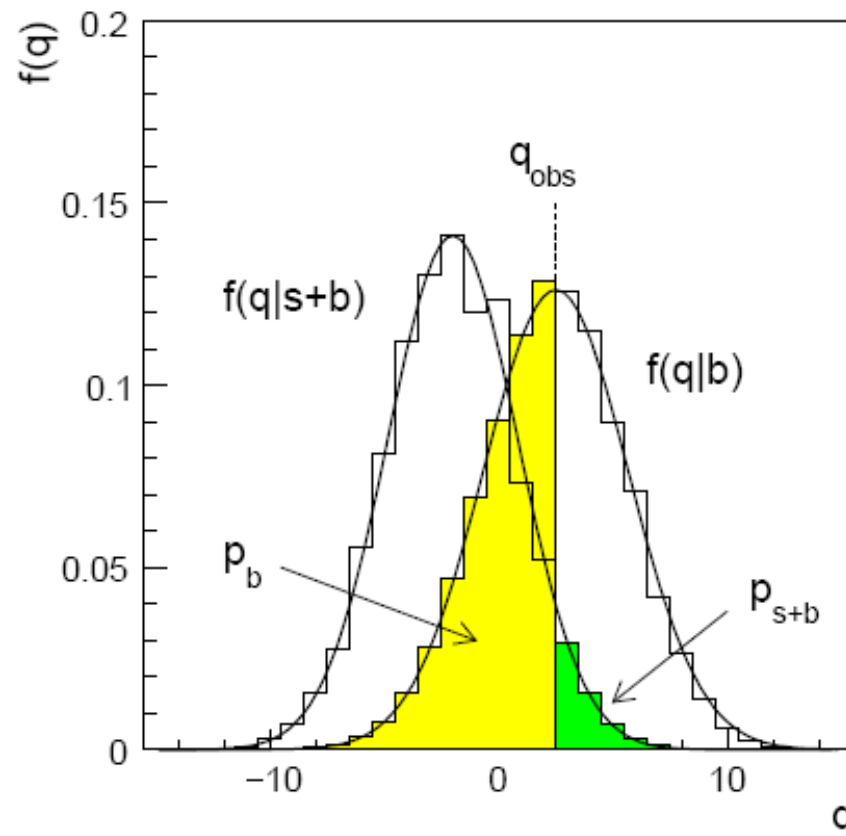
i.e.  $q$  is Gaussian distributed with mean and variance of

$$E[q] = \frac{1 - 2\mu}{\sigma^2} \quad V[q] = \frac{4}{\sigma^2}$$

To get  $\sigma^2$  use 2<sup>nd</sup> derivatives of  $\ln L$  with Asimov data set.

## Example with $L_{s+b}/L_b$

Consider again  $n \sim \text{Poisson}(\mu s + b)$ ,  $m \sim \text{Poisson}(\tau b)$   
 $b = 20$ ,  $s = 10$ ,  $\tau = 1$ .



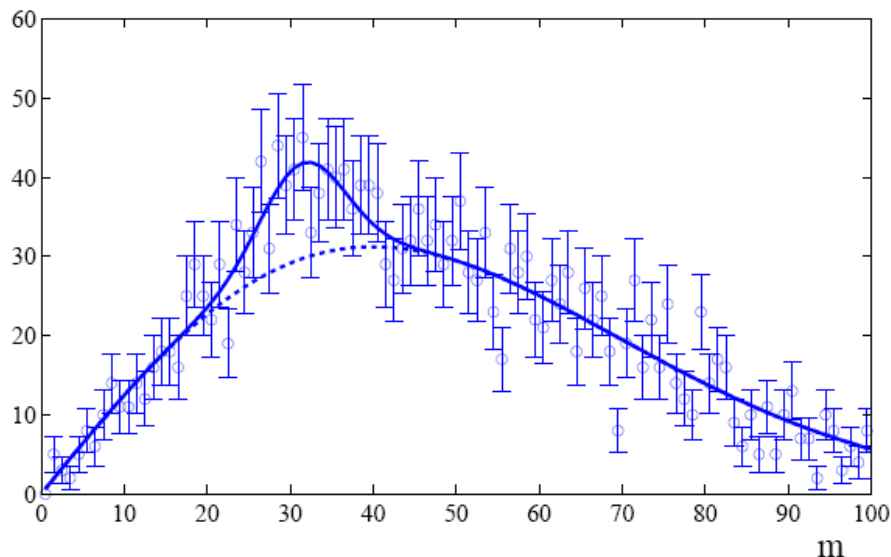
So even for smallish data sample, Wald approximation can be useful; no MC needed.

# The Look-Elsewhere Effect

Eilam Gross and Ofer Vitells, arXiv:1005.1891 ( $\rightarrow$  EPJC)

Suppose a model for a mass distribution allows for a peak at a mass  $m$  with amplitude  $\mu$ .

The data show a bump at a mass  $m_0$ .



How consistent is this with the no-bump ( $\mu = 0$ ) hypothesis?

## $p$ -value for fixed mass

First, suppose the mass  $m_0$  of the peak was specified a priori.

Test consistency of bump with the no-signal ( $\mu = 0$ ) hypothesis with e.g. likelihood ratio

$$t_{\text{fix}} = -2 \ln \frac{L(0, m_0)}{L(\hat{\mu}, m_0)}$$

where “fix” indicates that the mass of the peak is fixed to  $m_0$ .

The resulting  $p$ -value

$$p_{\text{fix}} = \int_{t_{\text{fix,obs}}}^{\infty} f(t_{\text{fix}}|0) dt_{\text{fix}}$$

gives the probability to find a value of  $t_{\text{fix}}$  at least as great as observed at the specific mass  $m_0$ .

## *p*-value for floating mass

But suppose we did not know where in the distribution to expect a peak.

What we want is the probability to find a peak at least as significant as the one observed **anywhere** in the distribution.

Include the mass as an adjustable parameter in the fit, test significance of peak using

$$t_{\text{float}} = -2 \ln \frac{L(0)}{L(\hat{\mu}, \hat{m})} \quad (\text{Note } m \text{ does not appear in the } \mu = 0 \text{ model.})$$

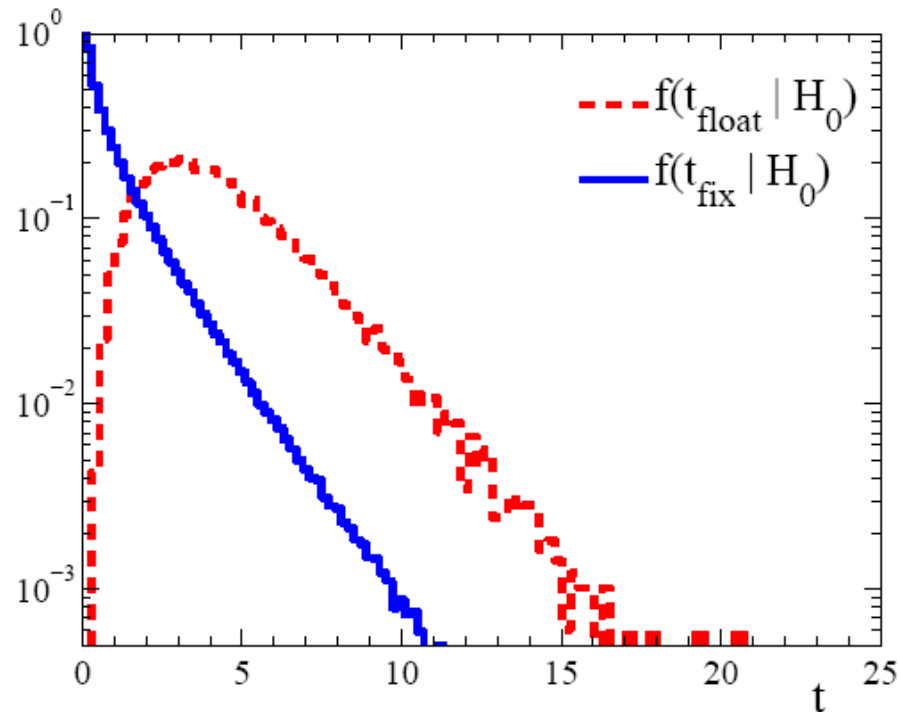
$$p_{\text{float}} = \int_{t_{\text{float,obs}}}^{\infty} f(t_{\text{float}}|0) dt_{\text{float}}$$



## Distributions of $t_{\text{fix}}$ , $t_{\text{float}}$

For a sufficiently large data sample,  $t_{\text{fix}} \sim \text{chi-square}$  for 1 degree of freedom (Wilks' theorem).

For  $t_{\text{float}}$  there are two adjustable parameters,  $\mu$  and  $m$ , and naively Wilks theorem says  $t_{\text{float}} \sim \text{chi-square}$  for 2 d.o.f.



In fact Wilks' theorem does not hold in the floating mass case because one of the parameters ( $m$ ) is not defined in the  $\mu = 0$  model.

So getting  $t_{\text{float}}$  distribution is more difficult.

## Trials factor

We would like to be able to relate the  $p$ -values for the fixed and floating mass analyses (at least approximately).

Gross and Vitells show that the “trials factor” can be approximated by

$$F_{\text{trials}} \equiv \frac{p_{\text{float}}}{p_{\text{fix}}} \approx 1 + \sqrt{\frac{\pi}{2}} \langle \mathcal{N} \rangle Z_{\text{fix}}$$

where  $\langle \mathcal{N} \rangle$  = average number of “upcrossings” of  $-2\ln L$  in fit range and

$$Z_{\text{fix}} = \Phi^{-1}(1 - p_{\text{fix}}) = \sqrt{t_{\text{fix}}}$$

is the significance for the fixed mass case.

So we can either carry out the full floating-mass analysis (e.g. use MC to get  $p$ -value), or do fixed mass analysis and apply a correction factor (much faster than MC).

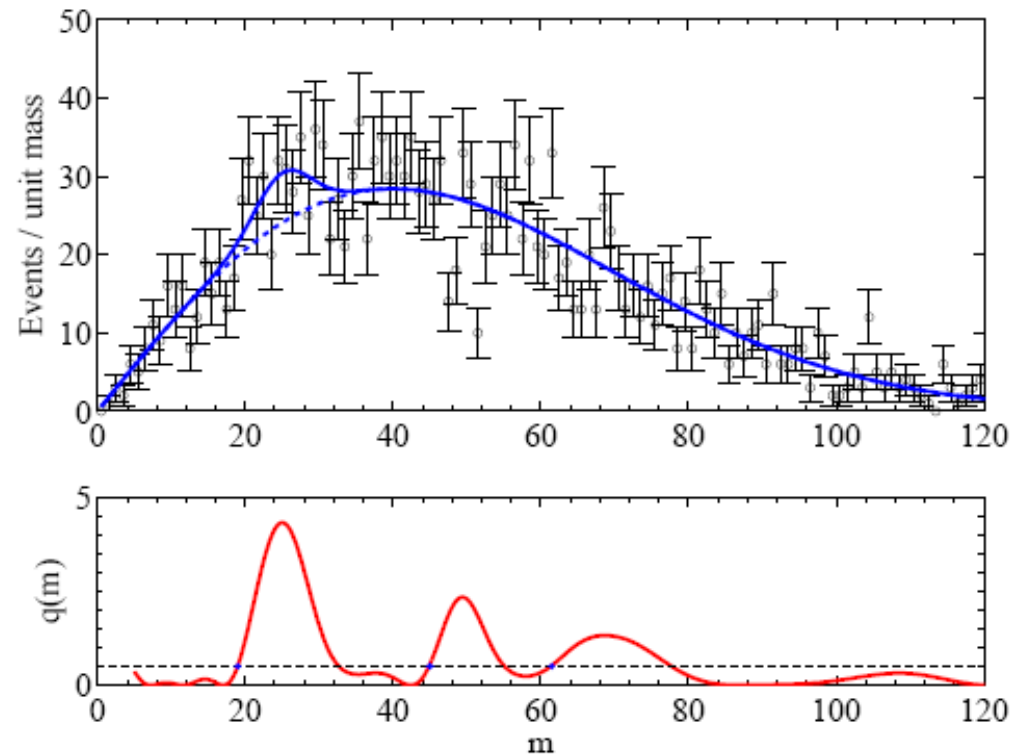
## Upcrossings of $-2\ln L$

The Gross-Vitells formula for the trials factor requires the mean number “upcrossings” of  $-2\ln L$  in the fit range based on fixed threshold.

$$\begin{aligned} P(q_0 > u) & \\ & \leq E[N_u] + P(q_0(0) > u) \\ & = \mathcal{N}_1 e^{-u/2} + \frac{1}{2} P(\chi_1^2 > u) \end{aligned}$$



estimate with MC  
at low reference  
level

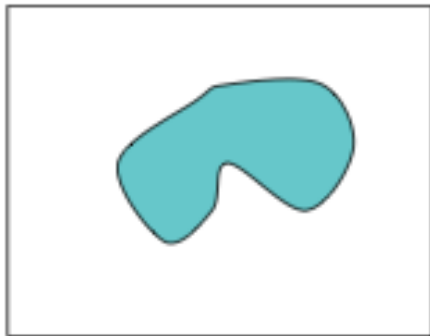


## Multidimensional look-elsewhere effect

Generalization to multiple dimensions: number of upcrossings replaced by expectation of Euler characteristic:

$$E[\varphi(A_u)] = \sum_{d=0}^n \mathcal{N}_d \rho_d(u)$$

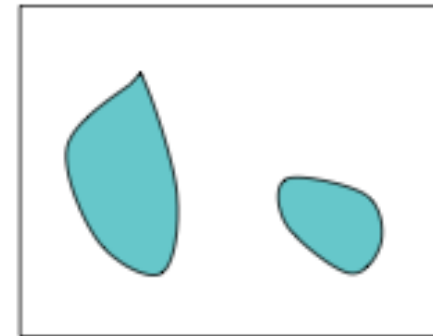
- Number of disconnected components minus number of 'holes'



$\varphi=1$



$\varphi=0$



$\varphi=2$

Applications: astrophysics (coordinates on sky), search for resonance of unknown mass and width, ...

# Summary on Look-Elsewhere Effect

Remember the Look-Elsewhere Effect is when we test a single model (e.g., SM) with multiple observations, i.e., in multiple places.

Note there is no look-elsewhere effect when considering exclusion limits. There we test specific signal models (typically once) and say whether each is excluded.

With exclusion there is, however, the analogous issue of testing many signal models (or parameter values) and thus excluding some even in the absence of signal (“spurious exclusion”)

Approximate correction for LEE should be sufficient, and one should also report the uncorrected significance.

“There's no sense in being precise when you don't even know what you're talking about.” — John von Neumann

# Extra Slides

# RooStats

a collaborative project with contributors from ATLAS, CMS and ROOT aimed to **provide & consolidate statistical tools** needed by LHC

- **using same tools: compare easily results** across experiments
  - not only desirable but **necessary for combinations**

RooStats is built on top of the **RooFit toolkit** :

- **data modelling language** (for PDFs, likelihoods, ...)

# Roofit Workspaces

**RoofitWorkspace** class of RooFit: possibility to save it to a ROOT file

- very good for **electronic publication** of data and likelihood function
- and greatly **help for combination** (that's the format agreed to share between Atlas & CMS)

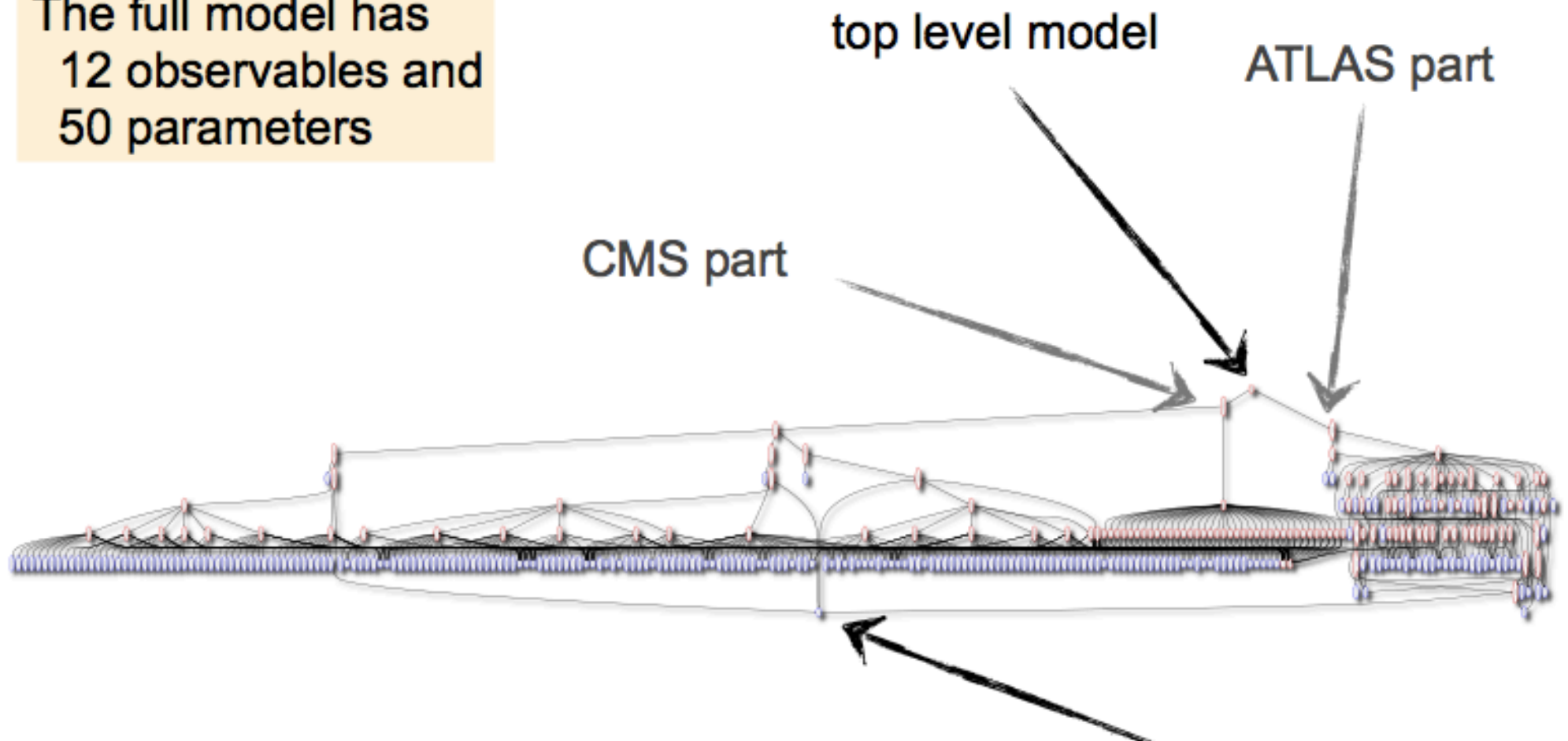
```
RoofitWorkspace w("w","joint workspace") ;  
// Import top-level pdfs and all their components, variables  
w.import("channelA.root:w:pdfA",RenameAllVariablesExcept("A","mhiggs"))  
w.import("channelB.root:w:pdfB",RenameVariable("mH","mhiggs")) ;  
w.import("channelC.root:w:pdfC") ;  
// Construct joint pdf  
w.factory("SIMUL::joint(chan[A,B,C],A-pdfA,B-pdfB,C-pdfC)") ;
```

Able to construct full likelihood for combination of channels (or experiments).



# Combined ATLAS/CMS Higgs search

The full model has  
12 observables and  
50 parameters



At this point, no correlated  
systematics across experiments

parameter of interest

$$\mu = \frac{\sigma_{BR}}{\sigma_{SM} BR_{SM}}$$