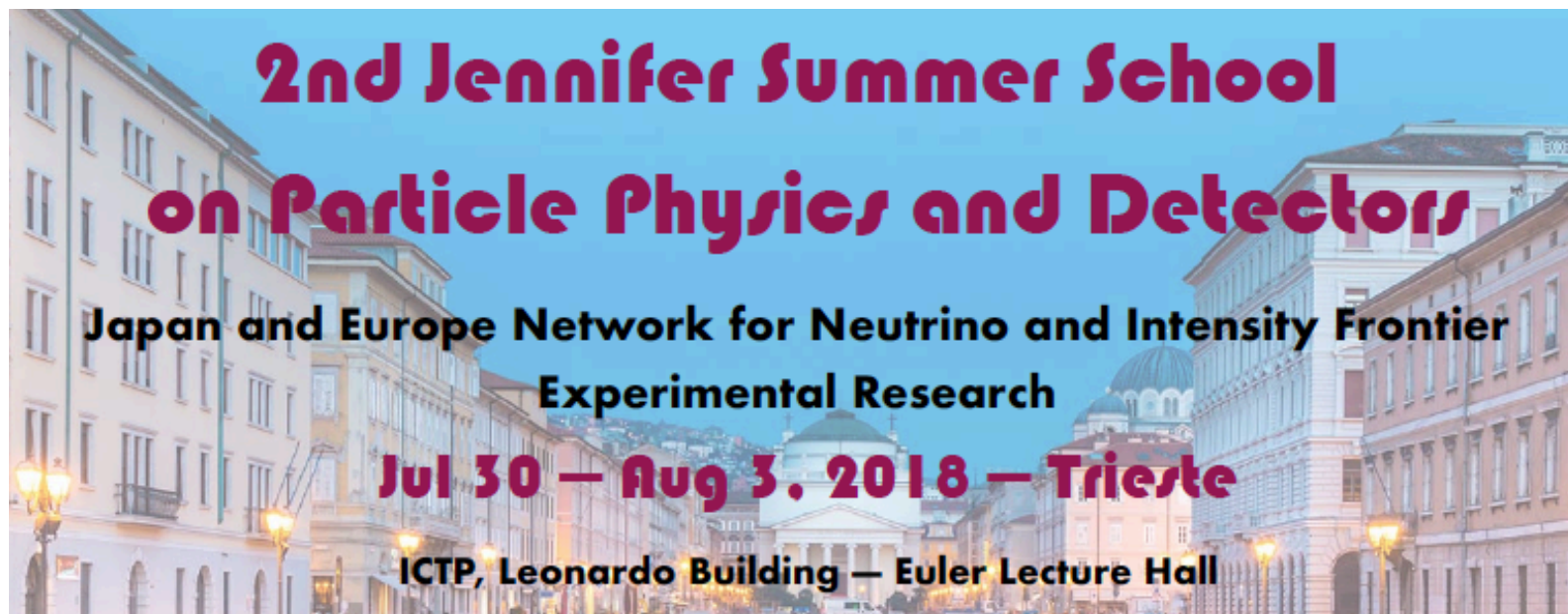


Statistical Methods for Particle Physics (II)

<https://agenda.infn.it/conferenceDisplay.py?confId=14407>



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Outline

Lecture 1:

Quick review of probability

Parameter estimation, maximum likelihood

Statistical tests for discovery and limits

→ Lecture 2:

Limits for the Poisson counting experiment

Nuisance parameters and systematic uncertainties

Tests from profile likelihood ratio

More parameter estimation, Bayesian methods

(Experimental sensitivity)

The Poisson counting experiment

Suppose we do a counting experiment and observe n events.

Events could be from *signal* process or from *background* – we only count the total number.

Poisson model:

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

s = mean (i.e., expected) # of signal events

b = mean # of background events

Goal is to make inference about s , e.g.,

test $s = 0$ (rejecting $H_0 \approx$ “discovery of signal process”)

test all non-zero s (values not rejected = confidence interval)

In both cases need to ask what is relevant alternative hypothesis.

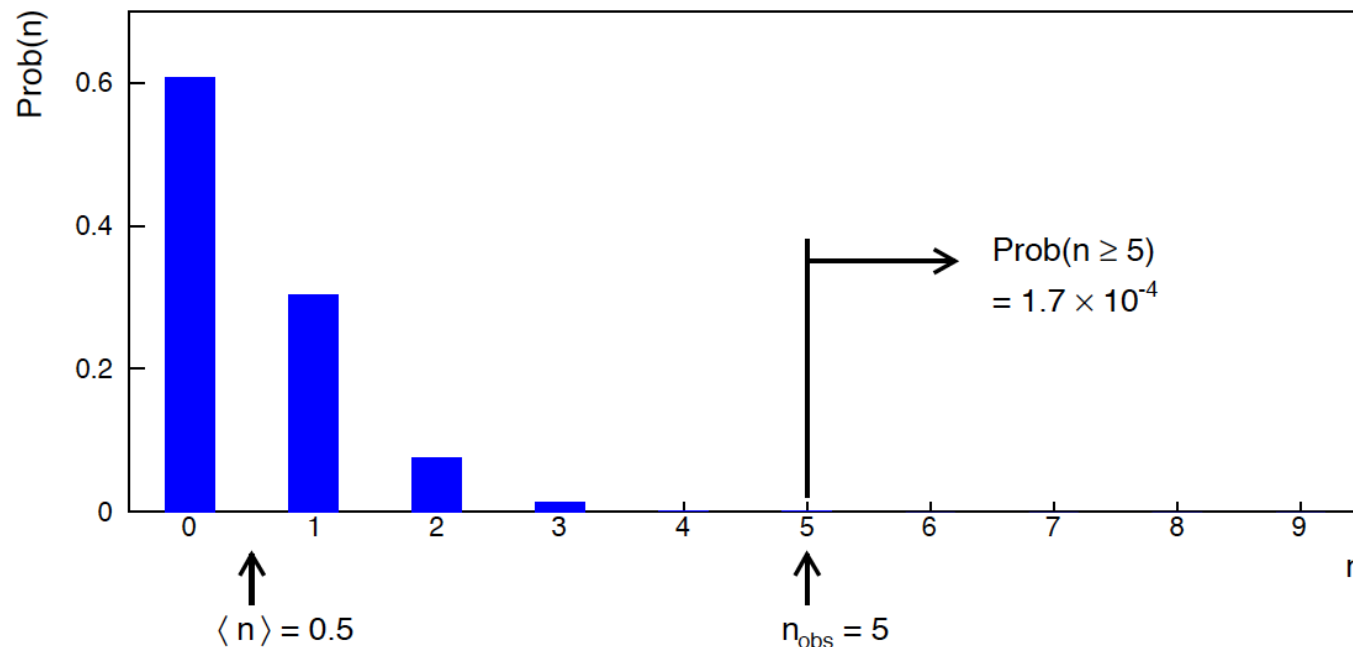
Poisson counting experiment: discovery p -value

Suppose $b = 0.5$ (known), and we observe $n_{\text{obs}} = 5$.

Should we claim evidence for a new discovery?

Take n itself as the test statistic, p -value for hypothesis $s = 0$ is

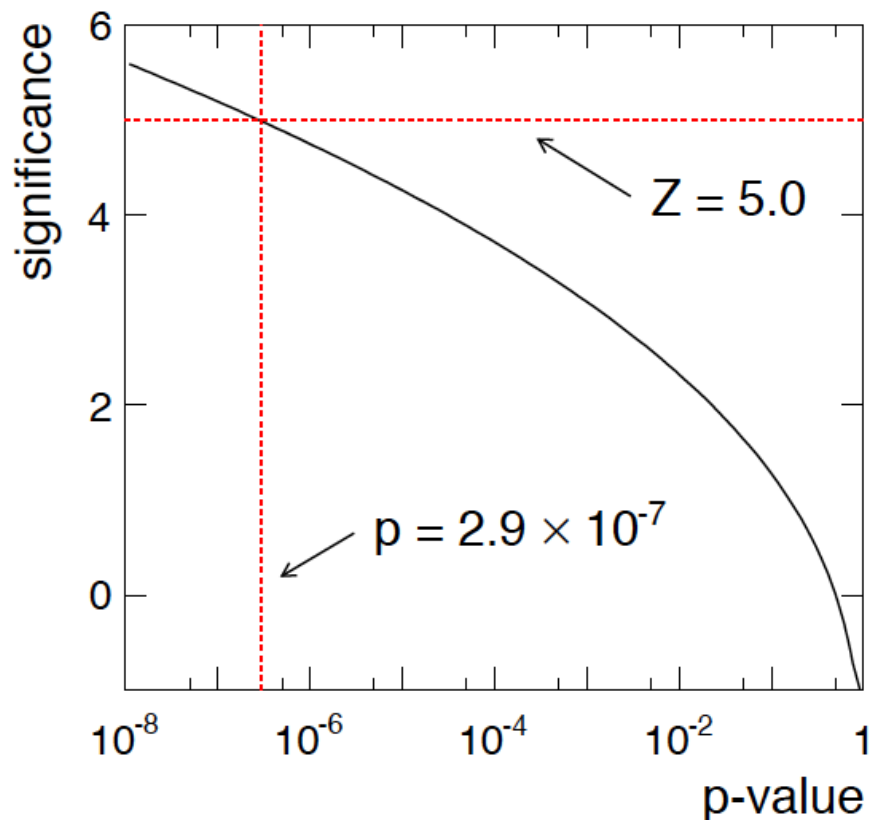
$$\begin{aligned} p\text{-value} &= P(n \geq 5; b = 0.5, s = 0) \\ &= 1.7 \times 10^{-4} \neq P(s = 0)! \end{aligned}$$



Poisson counting experiment: discovery significance

Equivalent significance for $p = 1.7 \times 10^{-4}$: $Z = \Phi^{-1}(1 - p) = 3.6$

Often claim discovery if $Z > 5$ ($p < 2.9 \times 10^{-7}$, i.e., a “5-sigma effect”)



In fact this tradition should be revisited: p -value intended to quantify probability of a signal-like fluctuation assuming background only; not intended to cover, e.g., hidden systematics, plausibility signal model, compatibility of data with signal, “look-elsewhere effect” (~multiple testing), etc.

Frequentist upper limit on Poisson parameter

Consider again the case of observing $n \sim \text{Poisson}(s + b)$.

Suppose $b = 4.5$, $n_{\text{obs}} = 5$. Find upper limit on s at 95% CL.

Relevant alternative is $s = 0$ (critical region at low n)

p -value of hypothesized s is $P(n \leq n_{\text{obs}}; s, b)$

Upper limit s_{up} at $\text{CL} = 1 - \alpha$ found by solving $p_s = \alpha$ for s :

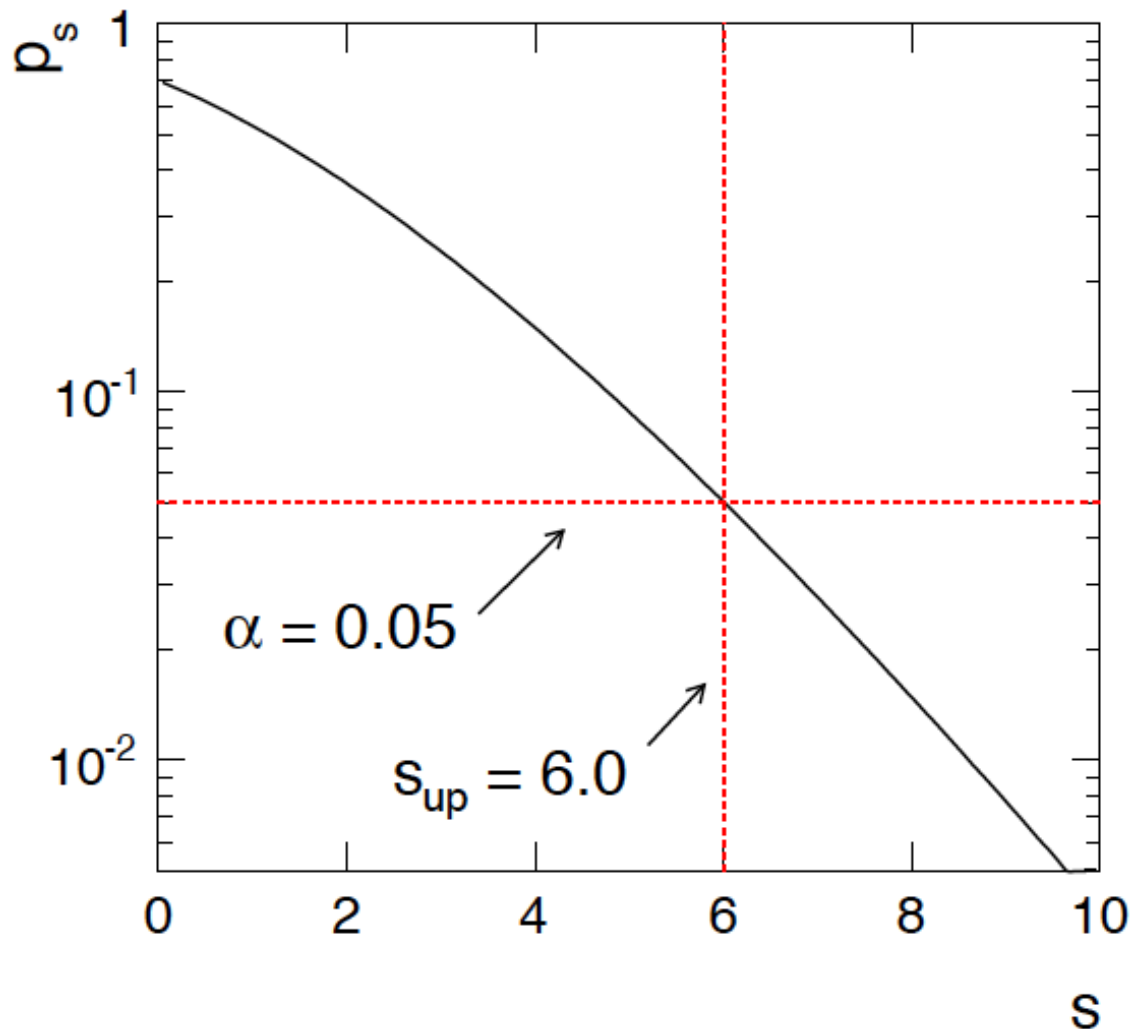
$$\alpha = P(n \leq n_{\text{obs}}; s_{\text{up}}, b) = \sum_{n=0}^{n_{\text{obs}}} \frac{(s_{\text{up}} + b)^n}{n!} e^{-(s_{\text{up}} + b)}$$

$$s_{\text{up}} = \frac{1}{2} F_{\chi^2}^{-1}(1 - \alpha; 2(n_{\text{obs}} + 1)) - b$$

$$= \frac{1}{2} F_{\chi^2}^{-1}(0.95; 2(5 + 1)) - 4.5 = 6.0$$

Frequentist upper limit on Poisson parameter

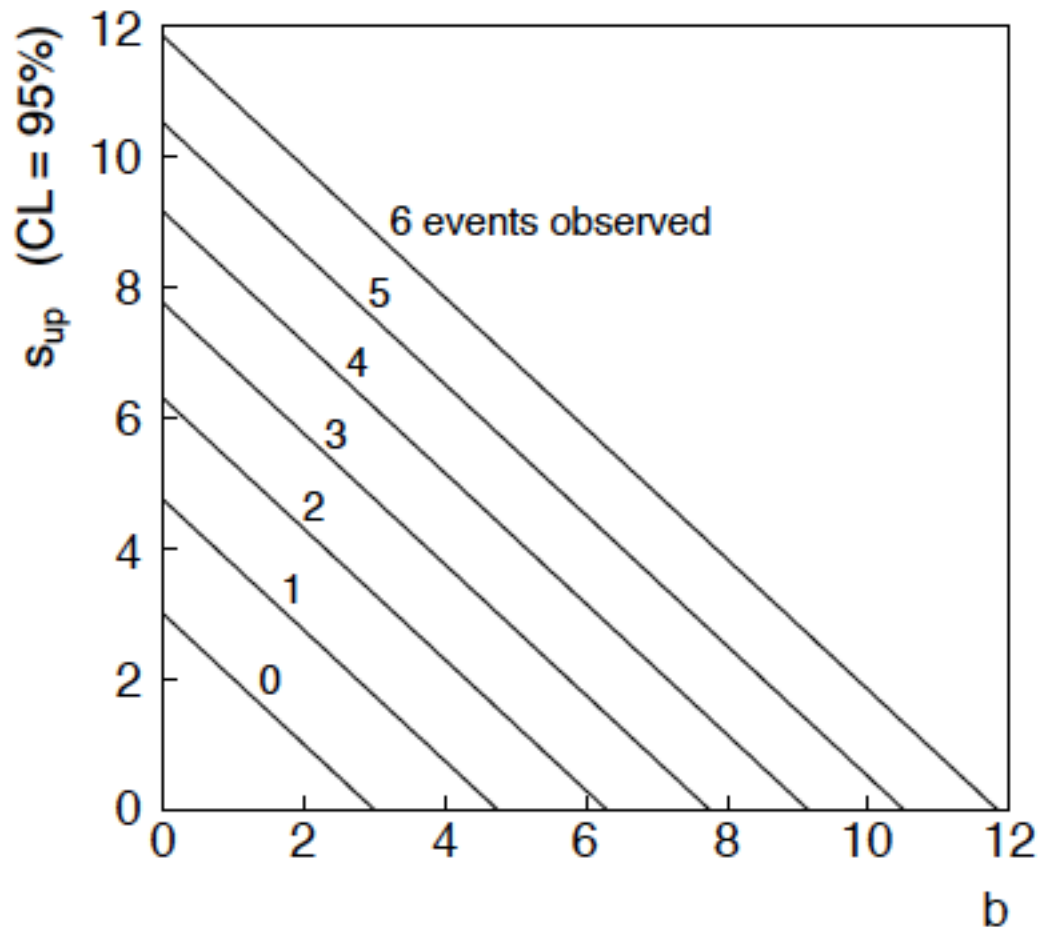
Upper limit s_{up} at $\text{CL} = 1 - \alpha$ found from $p_s = \alpha$.



$$n_{\text{obs}} = 5,$$
$$b = 4.5$$

$n \sim \text{Poisson}(s+b)$: frequentist upper limit on s

For low fluctuation of n formula can give negative result for s_{up} ;
i.e. confidence interval is empty.



Limits near a physical boundary

Suppose e.g. $b = 2.5$ and we observe $n = 0$.

If we choose $CL = 0.9$, we find from the formula for s_{up}

$$s_{\text{up}} = -0.197 \quad (CL = 0.90)$$

Physicist:

We already knew $s \geq 0$ before we started; can't use negative upper limit to report result of expensive experiment!

Statistician:

The interval is designed to cover the true value only 90% of the time — this was clearly not one of those times.

Not uncommon dilemma when testing parameter values for which one has very little experimental sensitivity, e.g., very small s .

Expected limit for $s = 0$

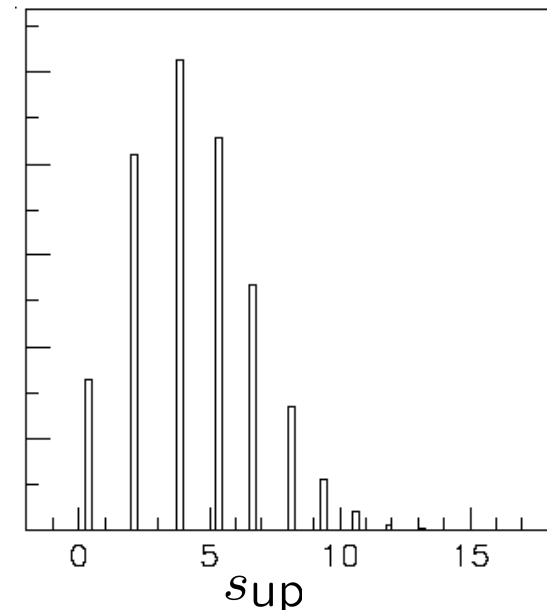
Physicist: I should have used $CL = 0.95$ — then $s_{\text{up}} = 0.496$

Even better: for $CL = 0.917923$ we get $s_{\text{up}} = 10^{-4}$!

Reality check: with $b = 2.5$, typical Poisson fluctuation in n is at least $\sqrt{2.5} = 1.6$. How can the limit be so low?

Look at the mean limit for the no-signal hypothesis ($s = 0$) (sensitivity).

Distribution of 95% CL limits
with $b = 2.5$, $s = 0$.
Mean upper limit = 4.44



The Bayesian approach to limits

In Bayesian statistics need to start with ‘prior pdf’ $\pi(\theta)$, this reflects degree of belief about θ before doing the experiment.

Bayes’ theorem tells how our beliefs should be updated in light of the data x :

$$p(\theta|x) = \frac{L(x|\theta)\pi(\theta)}{\int L(x|\theta')\pi(\theta') d\theta'} \propto L(x|\theta)\pi(\theta)$$

Integrate posterior pdf $p(\theta|x)$ to give interval with any desired probability content.

For e.g. $n \sim \text{Poisson}(s+b)$, 95% CL upper limit on s from

$$0.95 = \int_{-\infty}^{s_{\text{up}}} p(s|n) ds$$

Bayesian prior for Poisson parameter

Include knowledge that $s \geq 0$ by setting prior $\pi(s) = 0$ for $s < 0$.

Could try to reflect ‘prior ignorance’ with e.g.

$$\pi(s) = \begin{cases} 1 & s \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

Not normalized but this is OK as long as $L(s)$ dies off for large s .

Not invariant under change of parameter — if we had used instead a flat prior for, say, the mass of the Higgs boson, this would imply a non-flat prior for the expected number of Higgs events.

Doesn’t really reflect a reasonable degree of belief, but often used as a point of reference;

or viewed as a recipe for producing an interval whose frequentist properties can be studied (coverage will depend on true s).

Bayesian interval with flat prior for s

Solve to find limit s_{up} :

$$s_{\text{up}} = \frac{1}{2} F_{\chi^2}^{-1} [p, 2(n+1)] - b$$

where

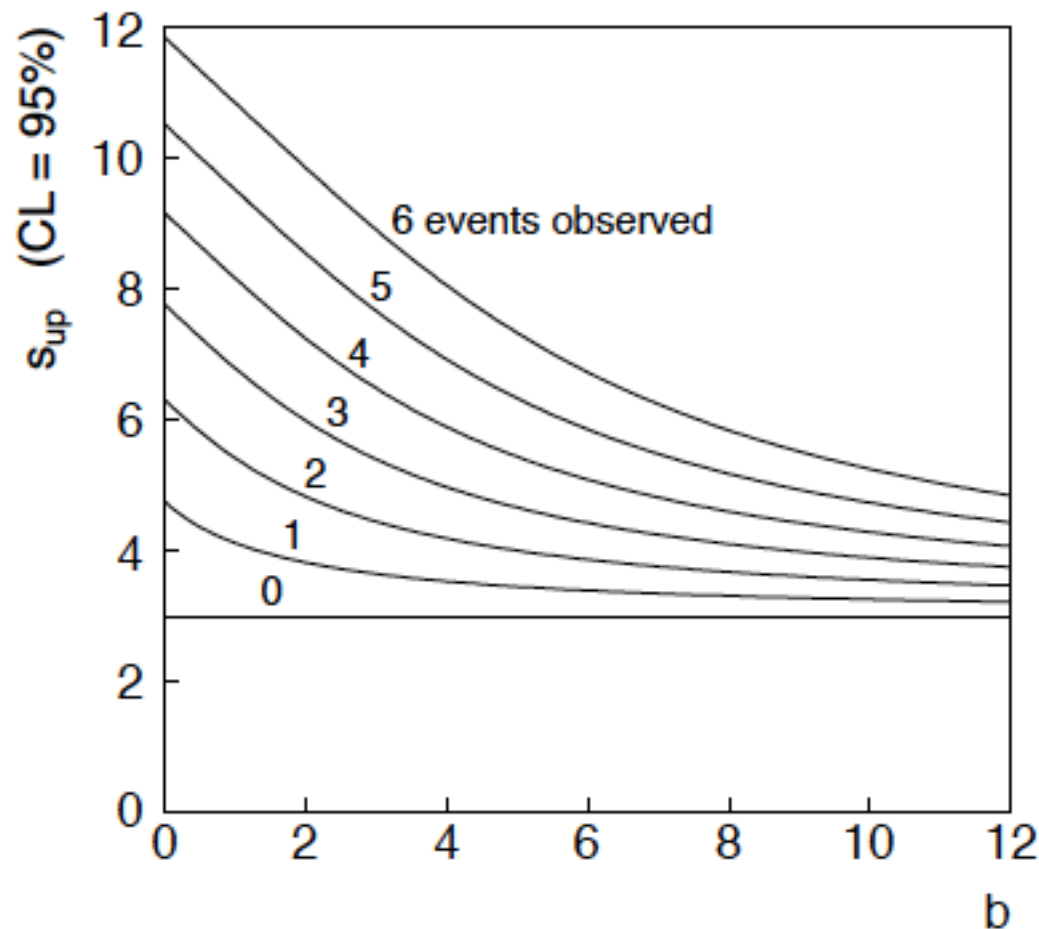
$$p = 1 - \alpha \left(1 - F_{\chi^2} [2b, 2(n+1)] \right)$$

For special case $b = 0$, Bayesian upper limit with flat prior numerically same as one-sided frequentist case (‘coincidence’).

Bayesian interval with flat prior for s

For $b > 0$ Bayesian limit is everywhere greater than the (one sided) frequentist upper limit.

Never goes negative. Doesn't depend on b if $n = 0$.



Approximate confidence intervals/regions from the likelihood function

Suppose we test parameter value(s) $\theta = (\theta_1, \dots, \theta_n)$ using the ratio

$$\lambda(\theta) = \frac{L(\theta)}{L(\hat{\theta})} \quad 0 \leq \lambda(\theta) \leq 1$$


Lower $\lambda(\theta)$ means worse agreement between data and hypothesized θ . Equivalently, usually define

$$t_\theta = -2 \ln \lambda(\theta)$$

so higher t_θ means worse agreement between θ and the data.

p -value of θ therefore

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

 need pdf

Confidence region from Wilks' theorem

Wilks' theorem says (in large-sample limit and providing certain conditions hold...)

$$f(t_{\theta}|\theta) \sim \chi_n^2$$

chi-square dist. with # d.o.f. =
of components in $\theta = (\theta_1, \dots, \theta_n)$.

Assuming this holds, the p -value is

$$p_{\theta} = 1 - F_{\chi_n^2}(t_{\theta}) \quad \text{where} \quad F_{\chi_n^2}(t_{\theta}) \equiv \int_0^{t_{\theta}} f_{\chi_n^2}(t'_{\theta}) dt'_{\theta}$$

To find boundary of confidence region set $p_{\theta} = \alpha$ and solve for t_{θ} :

$$t_{\theta} = F_{\chi_n^2}^{-1}(1 - \alpha) = -2 \ln \frac{L(\theta)}{L(\hat{\theta})}$$

Confidence region from Wilks' theorem (cont.)

i.e., boundary of confidence region in θ space is where

$$\ln L(\theta) = \ln L(\hat{\theta}) - \frac{1}{2} F_{\chi_n^2}^{-1}(1 - \alpha)$$

For example, for $1 - \alpha = 68.3\%$ and $n = 1$ parameter,

$$F_{\chi_1^2}^{-1}(0.683) = 1$$

and so the 68.3% confidence level interval is determined by

$$\ln L(\theta) = \ln L(\hat{\theta}) - \frac{1}{2}$$

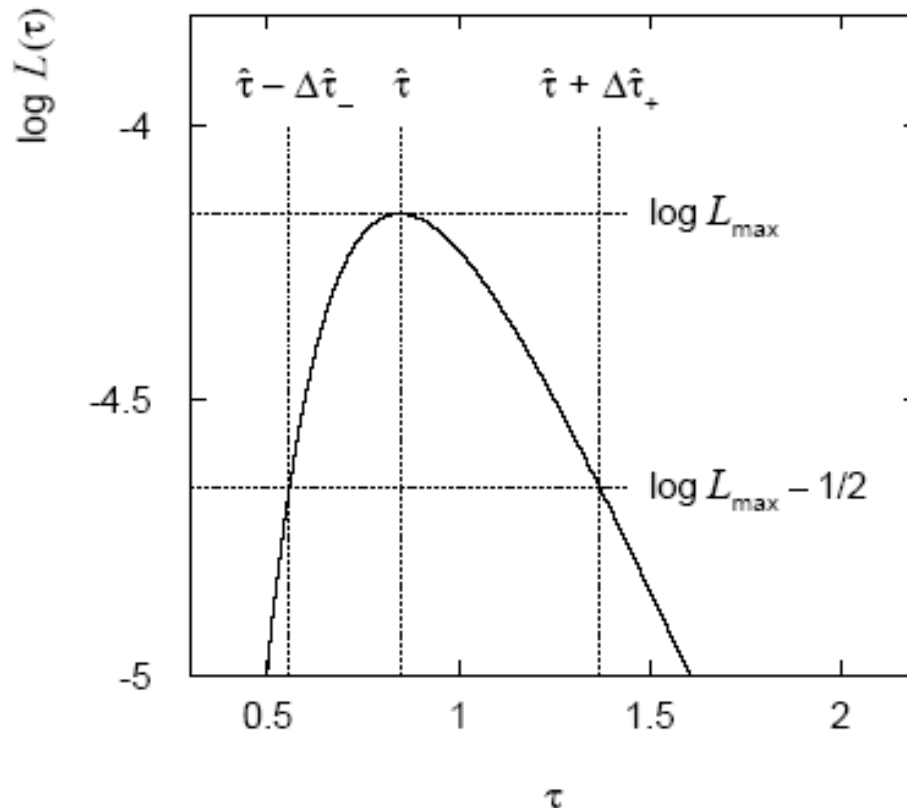
Same as recipe for finding the estimator's standard deviation, i.e.,

$[\hat{\theta} - \sigma_{\hat{\theta}}, \hat{\theta} + \sigma_{\hat{\theta}}]$ is a 68.3% CL confidence interval.

Example of interval from $\ln L$

For $n = 1$ parameter, $\text{CL} = 0.683$, $Q_\alpha = 1$.

Exponential example, now with only 5 events:



Parameter estimate and
approximate 68.3% CL
confidence interval:

$$\hat{\tau} = 0.85^{+0.52}_{-0.30}$$

Multiparameter case

For increasing number of parameters, $CL = 1 - \alpha$ decreases for confidence region determined by a given

$$Q_\alpha = F_{\chi_n^2}^{-1}(1 - \alpha)$$

Q_α	$1 - \alpha$				
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
1.0	0.683	0.393	0.199	0.090	0.037
2.0	0.843	0.632	0.428	0.264	0.151
4.0	0.954	0.865	0.739	0.594	0.451
9.0	0.997	0.989	0.971	0.939	0.891

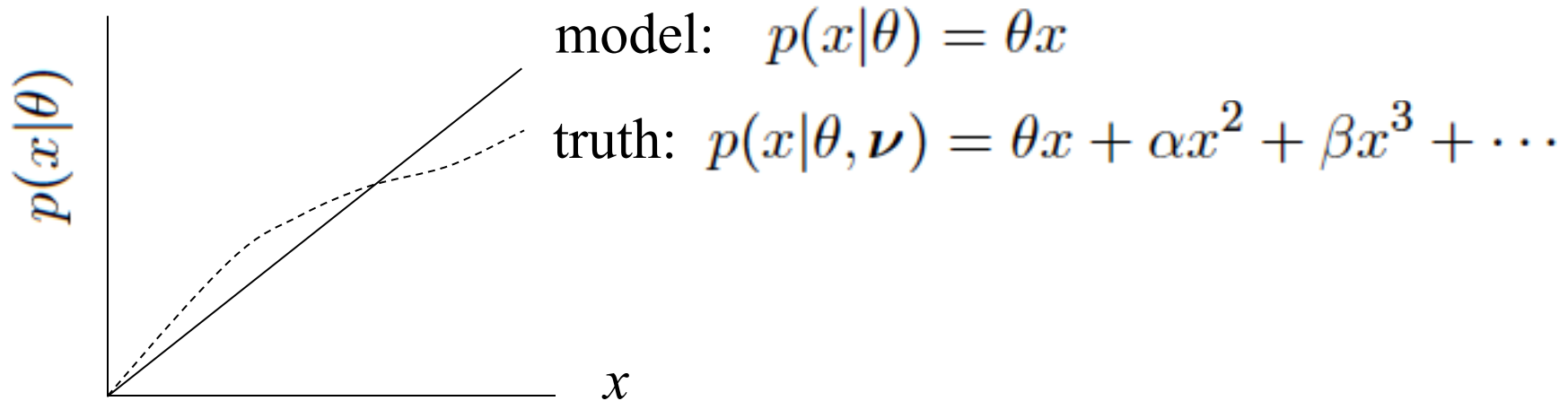
Multiparameter case (cont.)

Equivalently, Q_α increases with n for a given $\text{CL} = 1 - \alpha$.

$1 - \alpha$	\bar{Q}_α				
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
0.683	1.00	2.30	3.53	4.72	5.89
0.90	2.71	4.61	6.25	7.78	9.24
0.95	3.84	5.99	7.82	9.49	11.1
0.99	6.63	9.21	11.3	13.3	15.1

Systematic uncertainties and nuisance parameters

In general our model of the data is not perfect:



Can improve model by including additional adjustable parameters.

$$p(x|\theta) \rightarrow p(x|\theta, \nu)$$

Nuisance parameter \leftrightarrow systematic uncertainty. Some point in the parameter space of the enlarged model should be “true”.

Presence of nuisance parameter decreases sensitivity of analysis to the parameter of interest (e.g., increases variance of estimate).

Large sample distribution of the profile likelihood ratio (Wilks' theorem, cont.)


Suppose problem has likelihood $L(\theta, \nu)$, with

$\theta = (\theta_1, \dots, \theta_N)$ \leftarrow parameters of interest

$\nu = (\nu_1, \dots, \nu_M)$ \leftarrow nuisance parameters

Want to test point in θ -space. Define **profile likelihood ratio**:

$$\lambda(\theta) = \frac{L(\theta, \hat{\nu}(\theta))}{L(\hat{\theta}, \hat{\nu})}, \quad \text{where} \quad \hat{\nu}(\theta) = \underset{\nu}{\operatorname{argmax}} L(\theta, \nu)$$

 “profiled” values of ν

and define $q_\theta = -2 \ln \lambda(\theta)$.

Wilks' theorem says that distribution $f(q_\theta | \theta, \nu)$ approaches the chi-square pdf for N degrees of freedom for large sample (and regularity conditions), **independent of the nuisance parameters ν** .

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

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

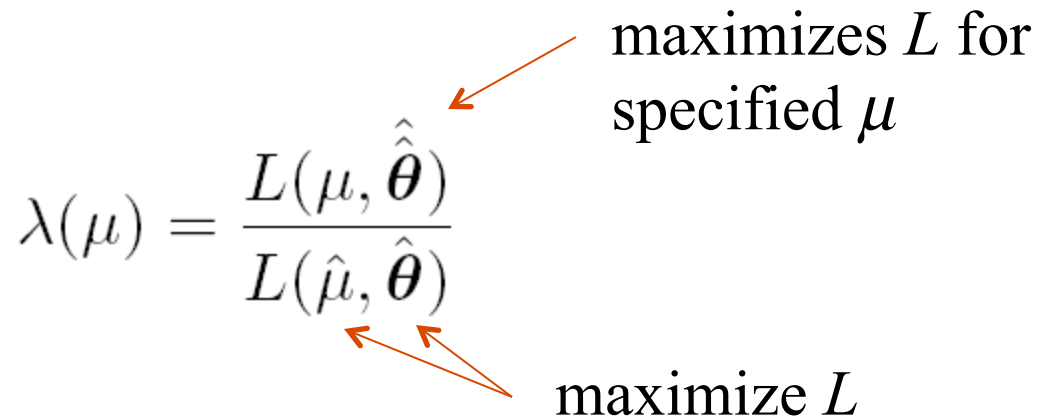
The profile likelihood ratio

Base significance test on the profile likelihood ratio:

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

maximizes L for specified μ

maximize L



Define critical region of test of μ by the region of data space that gives the lowest values of $\lambda(\mu)$.

Important advantage of profile LR is that its distribution becomes **independent of nuisance parameters** in large sample limit.

Test statistic for discovery

Suppose relevant alternative to background-only ($\mu = 0$) is $\mu \geq 0$.

So take critical region for test of $\mu = 0$ corresponding to high q_0 and $\hat{\mu} > 0$ (data characteristic for $\mu \geq 0$).

That is, to test background-only hypothesis define statistic

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

i.e. here only large (positive) observed signal strength is 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.

Distribution of q_0 in large-sample limit

Assuming approximations valid in the large sample (asymptotic) limit, 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:

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

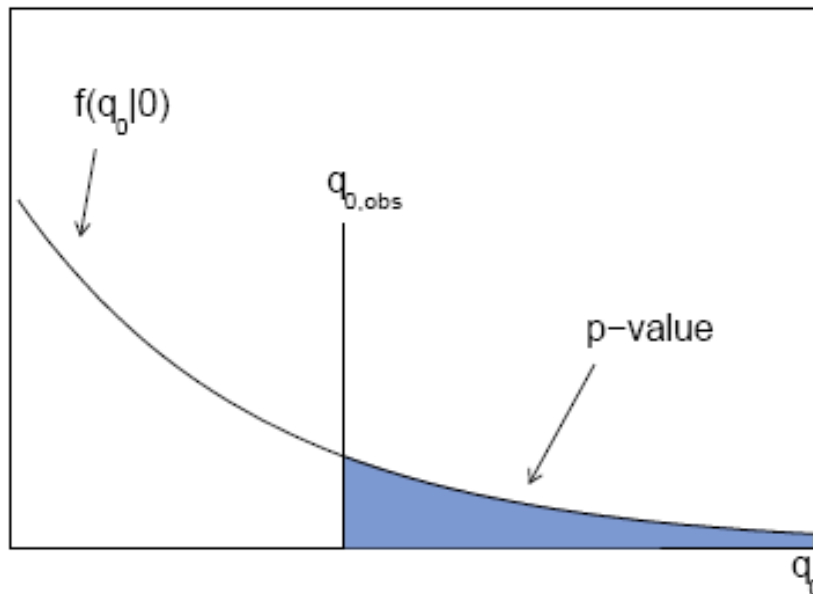
In large sample limit, $f(q_0|0)$ independent of nuisance parameters; $f(q_0|\mu')$ depends on nuisance parameters through σ .

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

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

use e.g. asymptotic formula



From p -value get equivalent significance,

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

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

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

Monte Carlo test of asymptotic formula

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

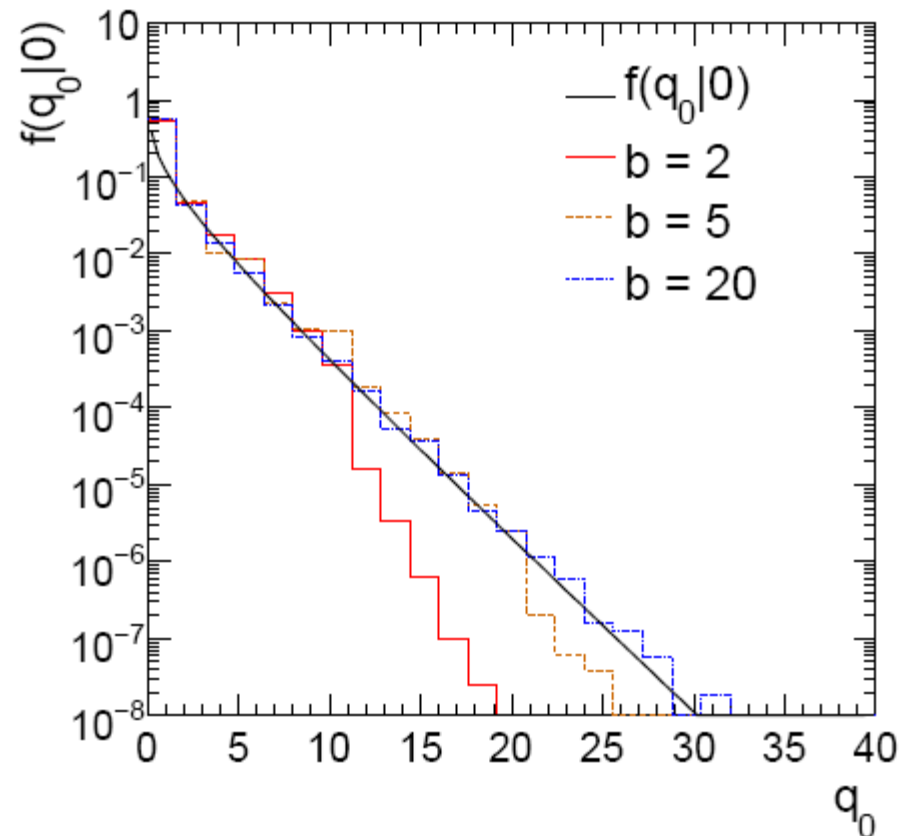
$$m \sim \text{Poisson}(\tau b)$$

μ = param. of interest

b = nuisance parameter

Here take s known, $\tau = 1$.

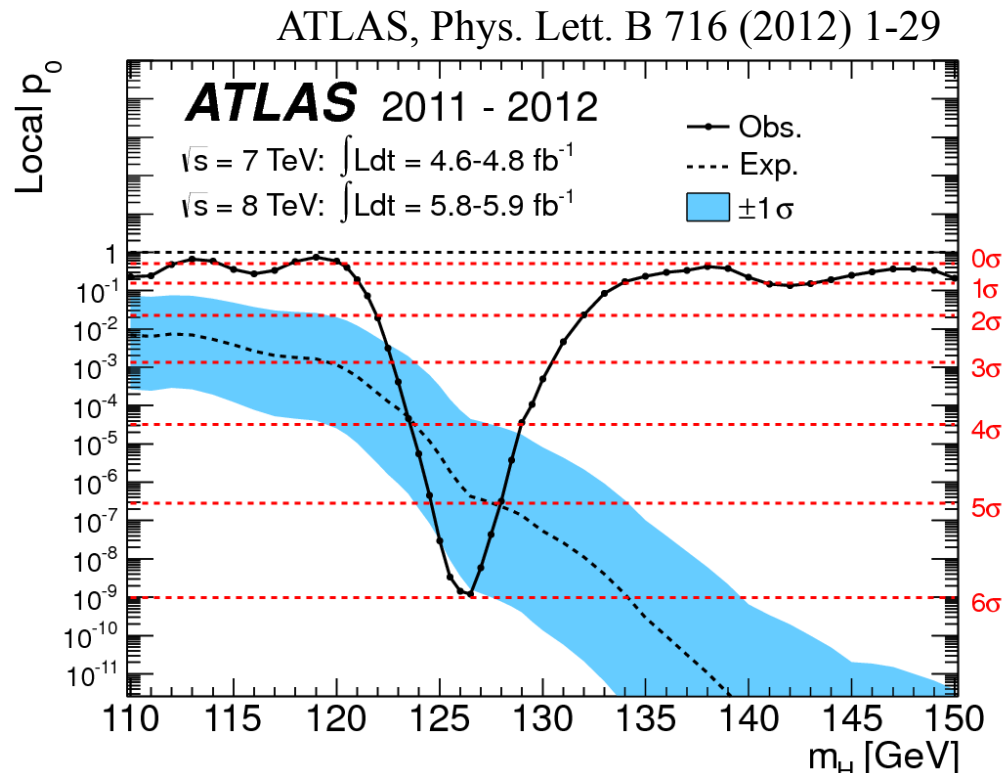
Asymptotic formula is
good approximation to 5σ
level ($q_0 = 25$) already for
 $b \sim 20$.



How to read the p_0 plot

The “local” p_0 means the p -value of the background-only hypothesis obtained from the test of $\mu = 0$ at each individual m_H , without any correction for the Look-Elsewhere Effect.

The “Expected” (dashed) curve gives the median p_0 under assumption of the SM Higgs ($\mu = 1$) at each m_H .



The blue band gives the width of the distribution ($\pm 1\sigma$) of significances under assumption of the SM Higgs.

Test statistic for upper limits

For purposes of setting an upper limit on μ use

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

I.e. when setting an upper limit, an upwards fluctuation of the data is not taken to mean incompatibility with the hypothesized μ :

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

Large sample approximation:

$$p_\mu = 1 - \Phi(\sqrt{q_\mu})$$

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

Monte Carlo test of asymptotic formulae

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

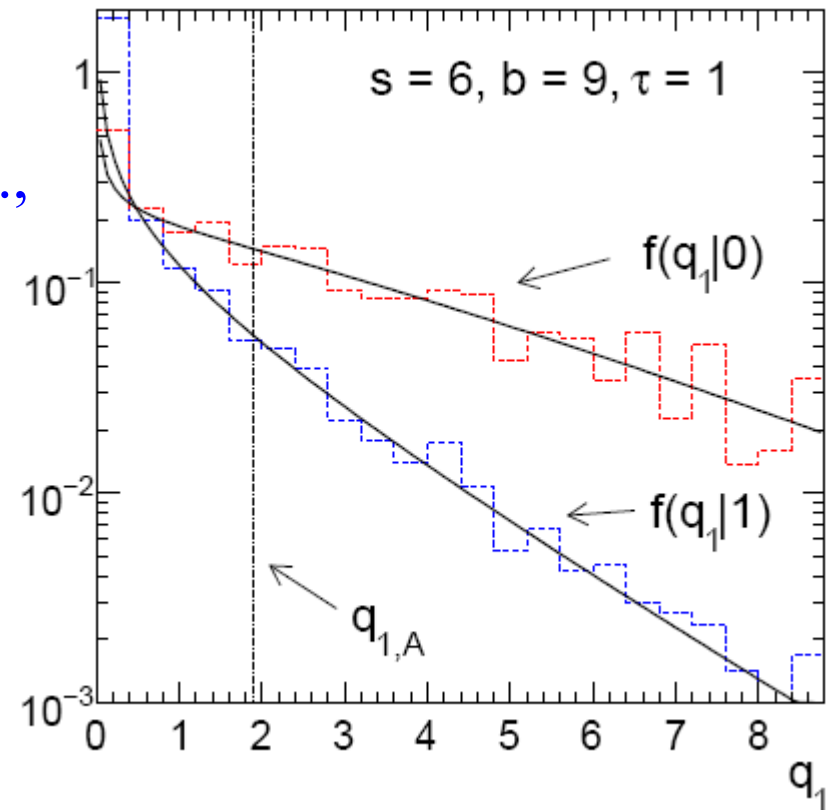
Use q_μ to find p -value of hypothesized μ values.

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 $s = 6$, $b = 9$.

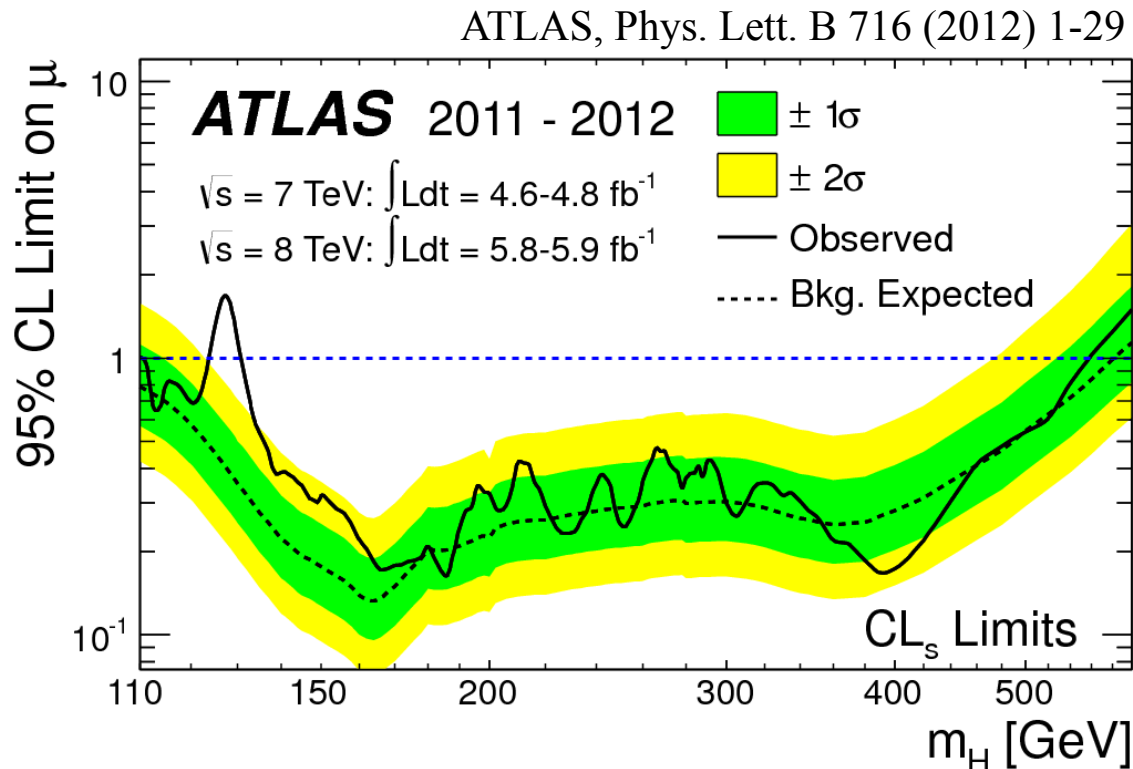


How to read the green and yellow limit plots

For every value of m_H , find the upper limit on μ .

Also for each m_H , determine the distribution of upper limits μ_{up} one would obtain under the hypothesis of $\mu = 0$.

The dashed curve is the median μ_{up} , and the green (yellow) bands give the $\pm 1\sigma$ (2σ) regions of this distribution.



Example: fitting a straight line

Data: (x_i, y_i, σ_i) , $i = 1, \dots, n$.

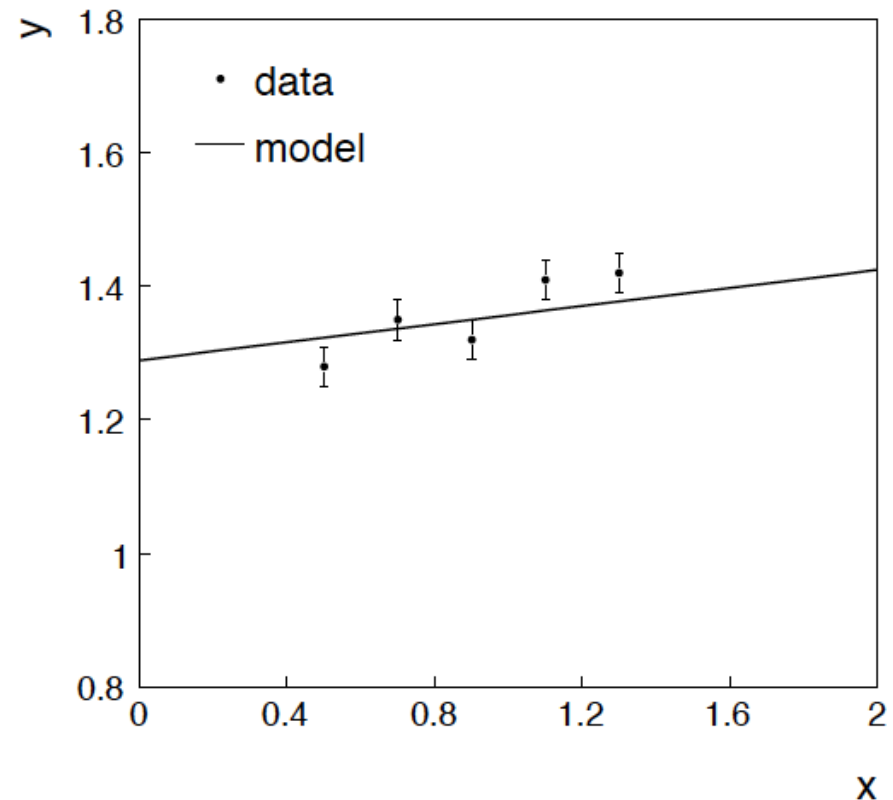
Model: y_i independent and all follow $y_i \sim \text{Gauss}(\mu(x_i), \sigma_i)$

$$\mu(x; \theta_0, \theta_1) = \theta_0 + \theta_1 x,$$

assume x_i and σ_i known.

Goal: estimate θ_0

Here suppose we don't care about θ_1 (example of a “nuisance parameter”)



Maximum likelihood fit with Gaussian data

In this example, the y_i are assumed independent, so the likelihood function is a product of Gaussians:

$$L(\theta_0, \theta_1) = \prod_{i=1}^n \frac{1}{\sqrt{2\pi}\sigma_i} \exp \left[-\frac{1}{2} \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2} \right],$$

Maximizing the likelihood is here equivalent to minimizing

$$\chi^2(\theta_0, \theta_1) = -2 \ln L(\theta_0, \theta_1) + \text{const} = \sum_{i=1}^n \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2}.$$

i.e., for Gaussian data, ML same as Method of Least Squares (LS)

θ_1 known a priori

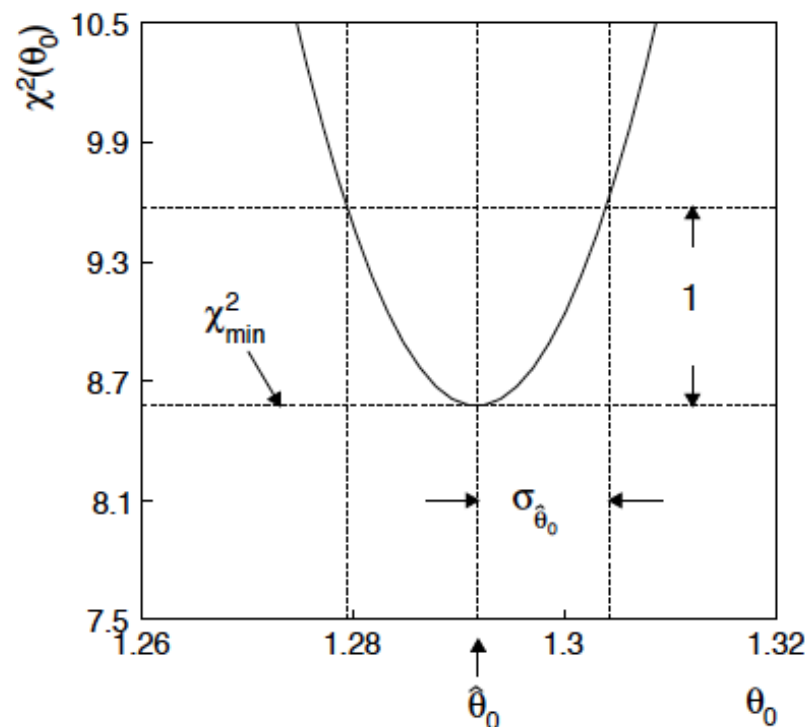
$$L(\theta_0) = \prod_{i=1}^n \frac{1}{\sqrt{2\pi}\sigma_i} \exp \left[-\frac{1}{2} \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2} \right] .$$

$$\chi^2(\theta_0) = -2 \ln L(\theta_0) + \text{const} = \sum_{i=1}^n \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2} .$$

For Gaussian y_i , ML same as LS

Minimize $\chi^2 \rightarrow$ estimator $\hat{\theta}_0$.

Come up one unit from χ_{\min}^2
to find $\sigma_{\hat{\theta}_0}$.



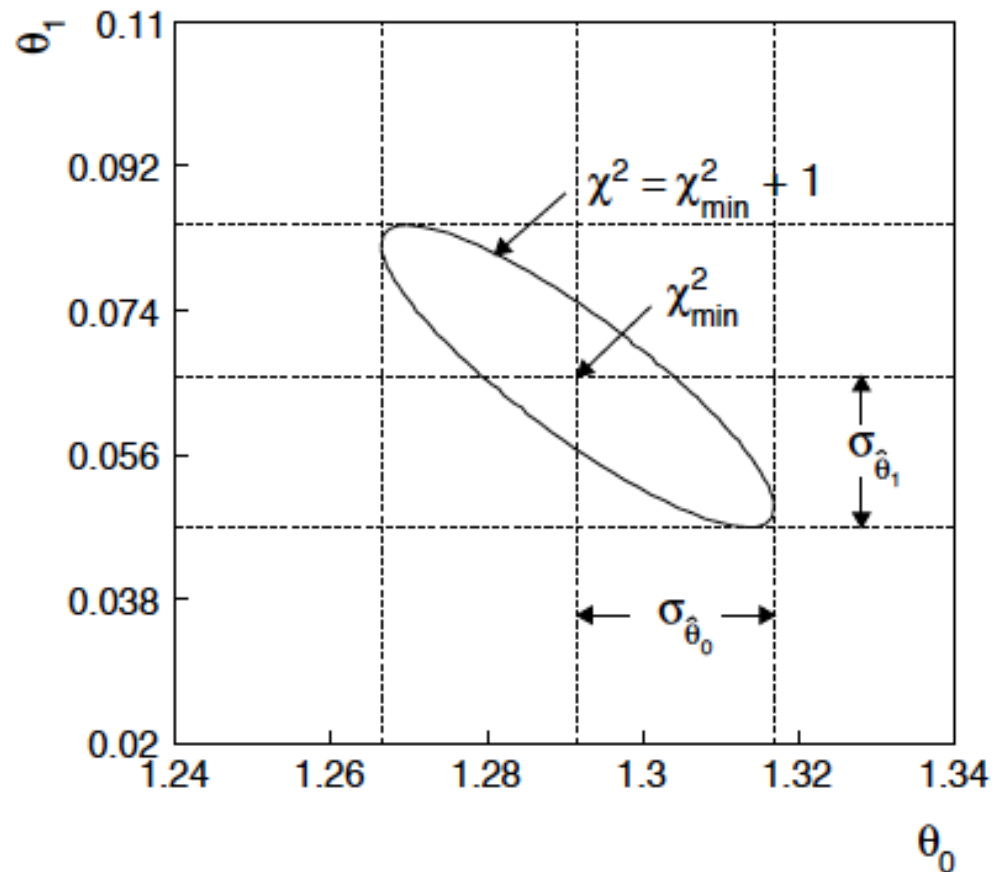
ML (or LS) fit of θ_0 and θ_1

$$\chi^2(\theta_0, \theta_1) = -2 \ln L(\theta_0, \theta_1) + \text{const} = \sum_{i=1}^n \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2} .$$

Standard deviations from
tangent lines to contour

$$\chi^2 = \chi_{\min}^2 + 1 .$$

Correlation between
 $\hat{\theta}_0$, $\hat{\theta}_1$ causes errors
to increase.

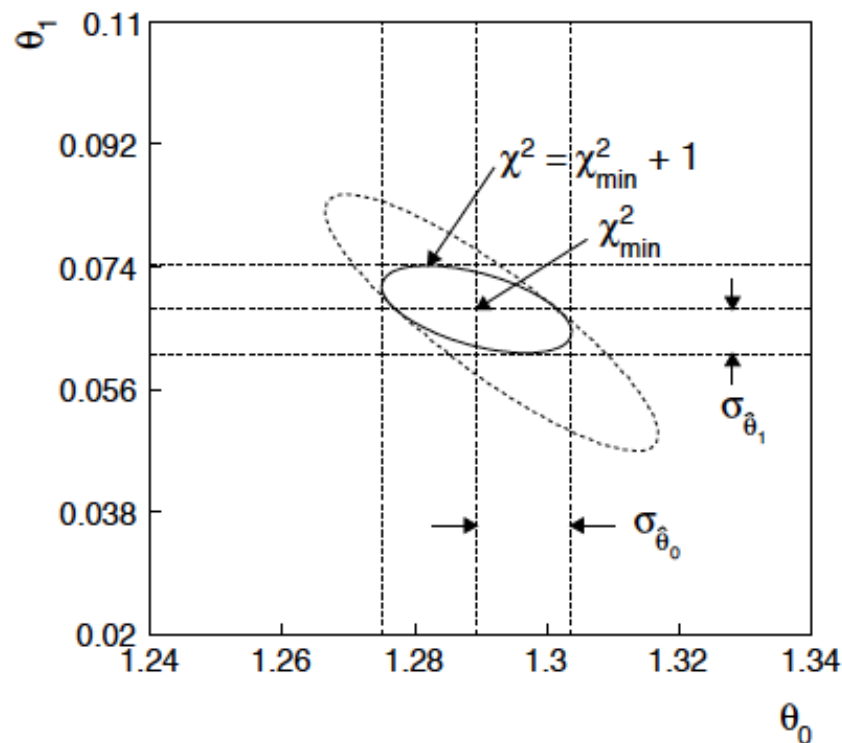


If we have a measurement $t_1 \sim \text{Gauss}(\theta_1, \sigma_{t_1})$

$$L(\theta_0, \theta_1) = \frac{1}{\sqrt{2\pi}\sigma_t} e^{-(t_1 - \theta_1)^2 / 2\sigma_{t_1}^2} \prod_{i=1}^n \frac{1}{\sqrt{2\pi}\sigma_i} \exp \left[-\frac{1}{2} \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2} \right]$$

$$\chi^2(\theta_0, \theta_1) = \sum_{i=1}^n \frac{(y_i - \mu(x_i; \theta_0, \theta_1))^2}{\sigma_i^2} + \frac{(t_1 - \theta_1)^2}{\sigma_{t_1}^2}$$

The information on θ_1
improves accuracy of $\hat{\theta}_0$.



The Bayesian approach

In Bayesian statistics we can associate a probability with a hypothesis, e.g., a parameter value θ .

Interpret probability of θ as ‘degree of belief’ (subjective).

Need to start with ‘**prior pdf**’ $\pi(\theta)$, this reflects degree of belief about θ before doing the experiment.

Our experiment has data x , \rightarrow **likelihood function** $L(x|\theta)$.

Bayes’ theorem tells how our beliefs should be updated in light of the data x :

$$p(\theta|x) = \frac{L(x|\theta)\pi(\theta)}{\int L(x|\theta')\pi(\theta') d\theta'} \propto L(x|\theta)\pi(\theta)$$

Posterior pdf $p(\theta|x)$ contains all our knowledge about θ .

Bayesian method

We need to associate prior probabilities with θ_0 and θ_1 , e.g.,

$$\begin{aligned}\pi(\theta_0, \theta_1) &= \pi_0(\theta_0) \pi_1(\theta_1) \\ \pi_0(\theta_0) &= \text{const.} \\ \pi_1(\theta_1) &= \frac{1}{\sqrt{2\pi}\sigma_{t_1}} e^{-(\theta_1 - t_1)^2 / 2\sigma_{t_1}^2}\end{aligned}$$

‘non-informative’, in any case much broader than $L(\theta_0)$

← based on previous measurement

Putting this into Bayes’ theorem gives:

$$p(\theta_0, \theta_1 | \vec{y}) \propto \prod_{i=1}^n \frac{1}{\sqrt{2\pi}\sigma_i} e^{-(y_i - \mu(x_i; \theta_0, \theta_1))^2 / 2\sigma_i^2} \pi_0 \frac{1}{\sqrt{2\pi}\sigma_{t_1}} e^{-(\theta_1 - t_1)^2 / 2\sigma_{t_1}^2}$$

posterior \propto likelihood \times prior

Bayesian method (continued)

We then integrate (marginalize) $p(\theta_0, \theta_1 | x)$ to find $p(\theta_0 | x)$:

$$p(\theta_0 | x) = \int p(\theta_0, \theta_1 | x) d\theta_1 .$$

In this example we can do the integral (rare). We find

$$p(\theta_0 | x) = \frac{1}{\sqrt{2\pi}\sigma_{\theta_0}} e^{-(\theta_0 - \hat{\theta}_0)^2 / 2\sigma_{\theta_0}^2} \quad \text{with}$$

$$\hat{\theta}_0 = \text{same as ML estimator}$$

$$\sigma_{\theta_0} = \sigma_{\hat{\theta}_0} \text{ (same as before)}$$

Usually need numerical methods (e.g. Markov Chain Monte Carlo) to do integral.

Digression: marginalization with MCMC

Bayesian computations involve integrals like

$$p(\theta_0|x) = \int p(\theta_0, \theta_1|x) d\theta_1 .$$

often high dimensionality and impossible in closed form,
also impossible with ‘normal’ acceptance-rejection Monte Carlo.

Markov Chain Monte Carlo (MCMC) has revolutionized
Bayesian computation.




MCMC (e.g., Metropolis-Hastings algorithm) generates
correlated sequence of random numbers:

cannot use for many applications, e.g., detector MC;
effective stat. error greater than if all values independent .

Basic idea: sample multidimensional $\vec{\theta}$,
look, e.g., only at distribution of parameters of interest.

MCMC basics: Metropolis-Hastings algorithm

Goal: given an n -dimensional pdf $p(\vec{\theta})$,
generate a sequence of points $\vec{\theta}_1, \vec{\theta}_2, \vec{\theta}_3, \dots$

- 1) Start at some point $\vec{\theta}_0$
- 2) Generate $\vec{\theta} \sim q(\vec{\theta}; \vec{\theta}_0)$  Proposal density $q(\vec{\theta}; \vec{\theta}_0)$
e.g. Gaussian centred
about $\vec{\theta}_0$
- 3) Form Hastings test ratio $\alpha = \min \left[1, \frac{p(\vec{\theta})q(\vec{\theta}_0; \vec{\theta})}{p(\vec{\theta}_0)q(\vec{\theta}; \vec{\theta}_0)} \right]$
- 4) Generate $u \sim \text{Uniform}[0, 1]$
- 5) If $u \leq \alpha$, $\vec{\theta}_1 = \vec{\theta}$,  move to proposed point
else $\vec{\theta}_1 = \vec{\theta}_0$  old point repeated
- 6) Iterate

Metropolis-Hastings (continued)

This rule produces a *correlated* sequence of points (note how each new point depends on the previous one).

For our purposes this correlation is not fatal, but statistical errors larger than if points were independent.

The proposal density can be (almost) anything, but choose so as to minimize autocorrelation. Often take proposal density symmetric: $q(\vec{\theta}; \vec{\theta}_0) = q(\vec{\theta}_0; \vec{\theta})$

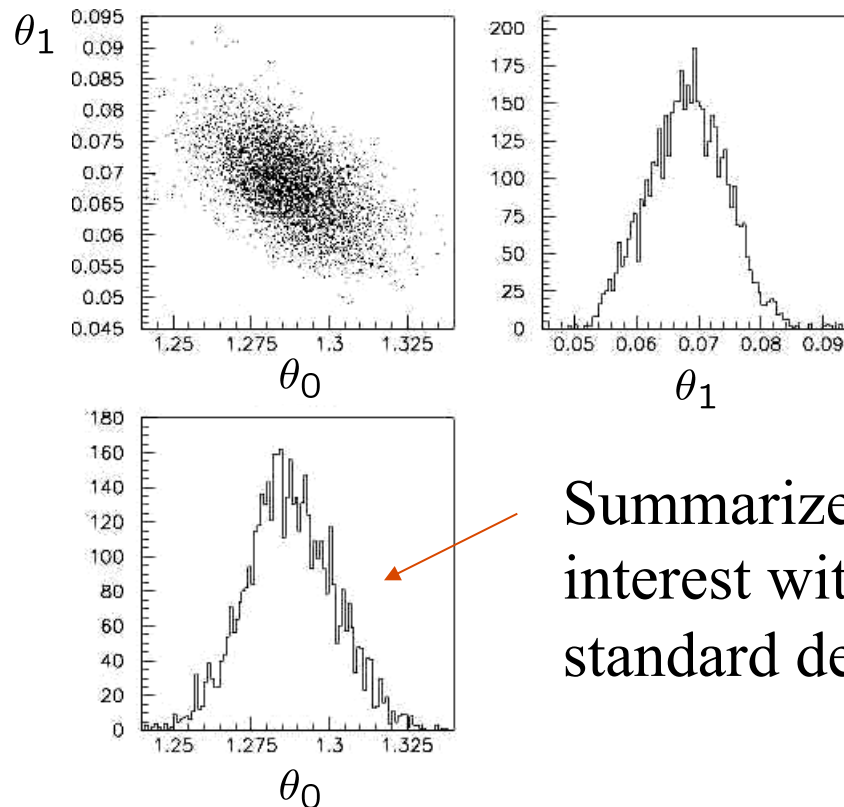
Test ratio is (*Metropolis-Hastings*): $\alpha = \min \left[1, \frac{p(\vec{\theta})}{p(\vec{\theta}_0)} \right]$

I.e. if the proposed step is to a point of higher $p(\vec{\theta})$, take it; if not, only take the step with probability $p(\vec{\theta})/p(\vec{\theta}_0)$.

If proposed step rejected, hop in place.

Example: posterior pdf from MCMC

Sample the posterior pdf from previous example with MCMC:



Summarize pdf of parameter of interest with, e.g., mean, median, standard deviation, etc.

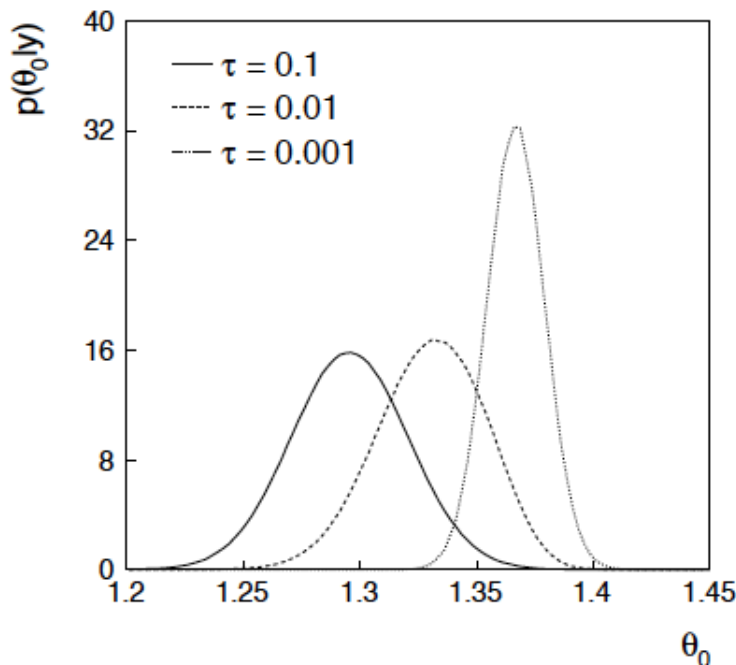
Although numerical values of answer here same as in frequentist case, interpretation is different (sometimes unimportant?)

Bayesian method with alternative priors

Suppose we don't have a previous measurement of θ_1 but rather, e.g., a theorist says it should be positive and not too much greater than 0.1 "or so", i.e., something like

$$\pi_1(\theta_1) = \frac{1}{\tau} e^{-\theta_1/\tau}, \quad \theta_1 \geq 0, \quad \tau = 0.1.$$

From this we obtain (numerically) the posterior pdf for θ_0 :



This summarizes all knowledge about θ_0 .

Look also at result from variety of priors.

Expected discovery significance for counting experiment with background uncertainty

I. Discovery sensitivity for counting experiment with b known:

(a) $\frac{s}{\sqrt{b}}$

(b) Profile likelihood ratio test & Asimov: $\sqrt{2 \left((s+b) \ln \left(1 + \frac{s}{b} \right) - s \right)}$

II. Discovery sensitivity with uncertainty in b , σ_b :

(a) $\frac{s}{\sqrt{b + \sigma_b^2}}$

(b) Profile likelihood ratio test & Asimov:

$$\left[2 \left((s+b) \ln \left[\frac{(s+b)(b + \sigma_b^2)}{b^2 + (s+b)\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[1 + \frac{\sigma_b^2 s}{b(b + \sigma_b^2)} \right] \right) \right]^{1/2}$$

Counting experiment with known background

Count a number of events $n \sim \text{Poisson}(s+b)$, where

s = expected number of events from signal,

b = expected number of background events.

To test for discovery of signal compute p -value of $s = 0$ hypothesis,

$$p = P(n \geq n_{\text{obs}} | b) = \sum_{n=n_{\text{obs}}}^{\infty} \frac{b^n}{n!} e^{-b} = 1 - F_{\chi^2}(2b; 2n_{\text{obs}})$$

Usually convert to equivalent significance: $Z = \Phi^{-1}(1 - p)$
where Φ is the standard Gaussian cumulative distribution, e.g.,
 $Z > 5$ (a 5 sigma effect) means $p < 2.9 \times 10^{-7}$.

To characterize sensitivity to discovery, give expected (mean or median) Z under assumption of a given s .

s/\sqrt{b} for expected discovery significance

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

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

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

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

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

Better approximation for significance

Poisson likelihood for parameter s is

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

For now
no nuisance
params.

To test for discovery use profile likelihood ratio:

$$q_0 = \begin{cases} -2 \ln \lambda(0) & \hat{s} \geq 0, \\ 0 & \hat{s} < 0. \end{cases} \quad \lambda(s) = \frac{L(s, \hat{\theta}(s))}{L(\hat{s}, \hat{\theta})}$$

So the likelihood ratio statistic for testing $s = 0$ is

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

Approximate Poisson significance (continued)

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

$$Z = \sqrt{2 \left(n \ln \frac{n}{b} + b - n \right)} \quad \text{for } n > b \text{ and } Z = 0 \text{ otherwise.}$$

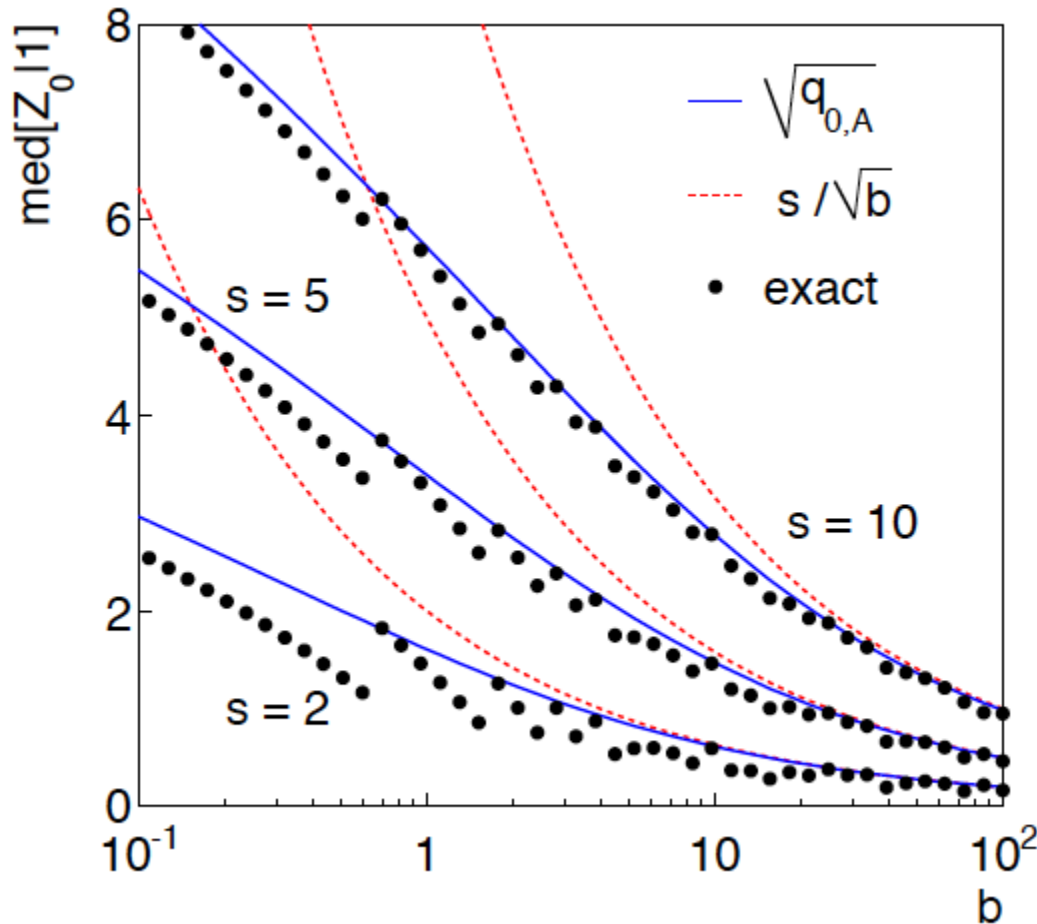
To find $\text{median}[Z|s]$, let $n \rightarrow s + b$ (i.e., the Asimov data set):

$$Z_A = \sqrt{2 \left((s + b) \ln \left(1 + \frac{s}{b} \right) - s \right)}$$

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

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

CCGV, EPJC 71 (2011) 1554, arXiv:1007.1727



“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 $s \ll b$.

Extending s/\sqrt{b} to case where b uncertain

The intuitive explanation of s/\sqrt{b} is that it compares the signal, s , to the standard deviation of n assuming no signal, \sqrt{b} .

Now suppose the value of b is uncertain, characterized by a standard deviation σ_b .

A reasonable guess is to replace \sqrt{b} by the quadratic sum of \sqrt{b} and σ_b , i.e.,

$$\text{med}[Z|s] = \frac{s}{\sqrt{b + \sigma_b^2}}$$

This has been used to optimize some analyses e.g. where σ_b cannot be neglected.

Profile likelihood with b uncertain

This is the well studied “on/off” problem: Cranmer 2005; Cousins, Linnemann, and Tucker 2008; Li and Ma 1983,...

Measure two Poisson distributed values:

$n \sim \text{Poisson}(s+b)$ (primary or “search” measurement)

$m \sim \text{Poisson}(\tau b)$ (control measurement, τ known)

The likelihood function is

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

Use this to construct profile likelihood ratio (b is nuisance parameter):

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

Ingredients for profile likelihood ratio

To construct profile likelihood ratio from this need estimators:

$$\hat{s} = n - m/\tau ,$$

$$\hat{b} = m/\tau ,$$

$$\hat{\hat{b}}(s) = \frac{n + m - (1 + \tau)s + \sqrt{(n + m - (1 + \tau)s)^2 + 4(1 + \tau)sm}}{2(1 + \tau)} .$$

and in particular to test for discovery ($s = 0$),

$$\hat{\hat{b}}(0) = \frac{n + m}{1 + \tau}$$

Asymptotic significance

Use profile likelihood ratio for q_0 , and then from this get discovery significance using asymptotic approximation (Wilks' theorem):

$$Z = \sqrt{q_0};$$
$$= \left[-2 \left(n \ln \left[\frac{n+m}{(1+\tau)n} \right] + m \ln \left[\frac{\tau(n+m)}{(1+\tau)m} \right] \right) \right]^{1/2}$$

for $n > \hat{b}$ and $Z = 0$ otherwise.

Essentially same as in:

Robert D. Cousins, James T. Linnemann and Jordan Tucker, NIM A 595 (2008) 480–501; arXiv:physics/0702156.

Tipei Li and Yuqian Ma, Astrophysical Journal 272 (1983) 317–324.

Asimov approximation for median significance

To get median discovery significance, replace n , m by their expectation values assuming background-plus-signal model:

$$n \rightarrow s + b$$

$$m \rightarrow \tau b$$

$$Z_A = \left[-2 \left((s + b) \ln \left[\frac{s + (1 + \tau)b}{(1 + \tau)(s + b)} \right] + \tau b \ln \left[1 + \frac{s}{(1 + \tau)b} \right] \right) \right]^{1/2}$$

Or use the variance of $\hat{b} = m/\tau$, $V[\hat{b}] \equiv \sigma_b^2 = \frac{b}{\tau}$, to eliminate τ :

$$Z_A = \left[2 \left((s + b) \ln \left[\frac{(s + b)(b + \sigma_b^2)}{b^2 + (s + b)\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[1 + \frac{\sigma_b^2 s}{b(b + \sigma_b^2)} \right] \right) \right]^{1/2}$$

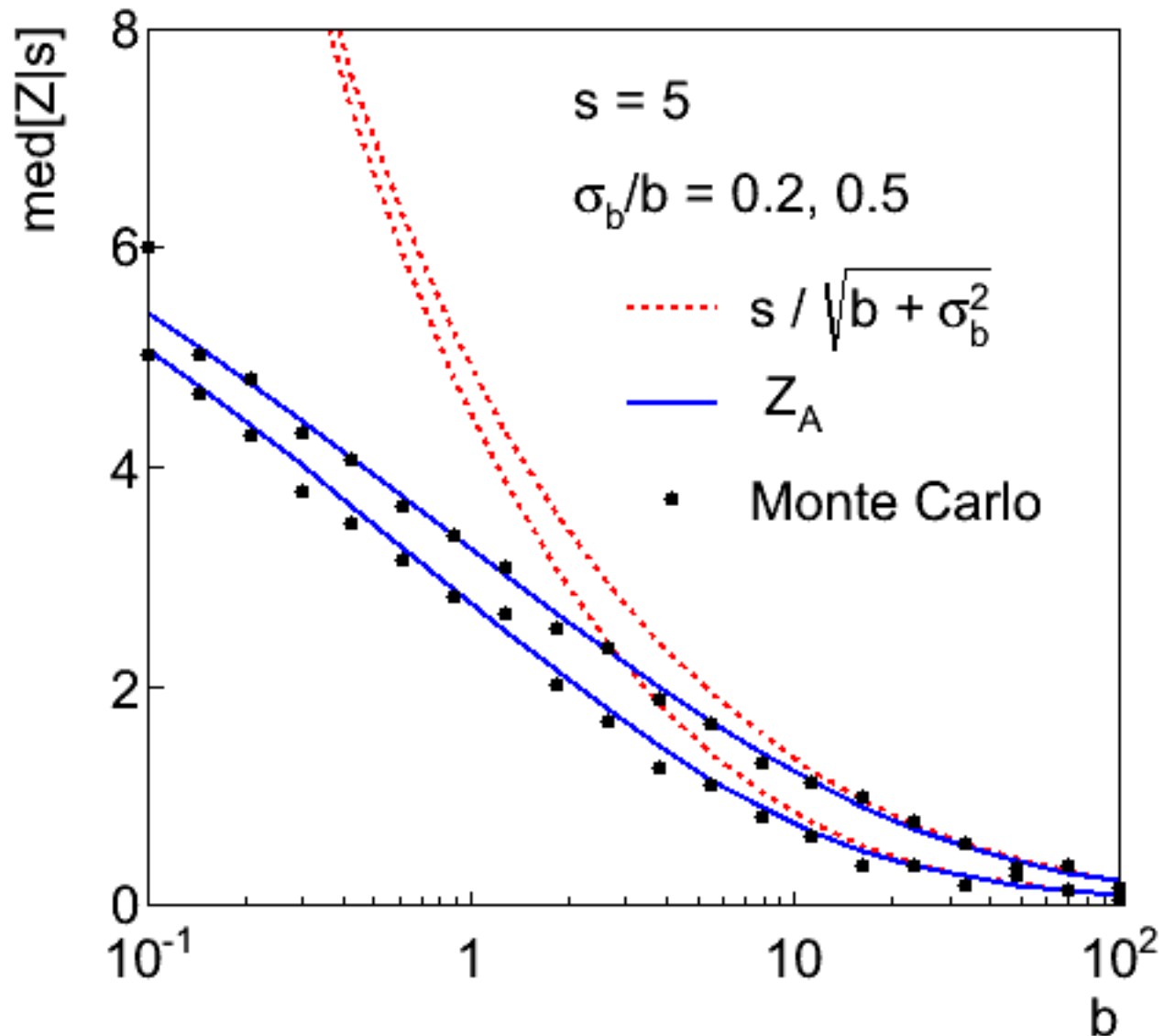
Limiting cases

Expanding the Asimov formula in powers of s/b and σ_b^2/b ($= 1/\tau$) gives

$$Z_A = \frac{s}{\sqrt{b + \sigma_b^2}} \left(1 + \mathcal{O}(s/b) + \mathcal{O}(\sigma_b^2/b) \right)$$

So the “intuitive” formula can be justified as a limiting case of the significance from the profile likelihood ratio test evaluated with the Asimov data set.

Testing the formulae: $s = 5$



Using sensitivity to optimize a cut

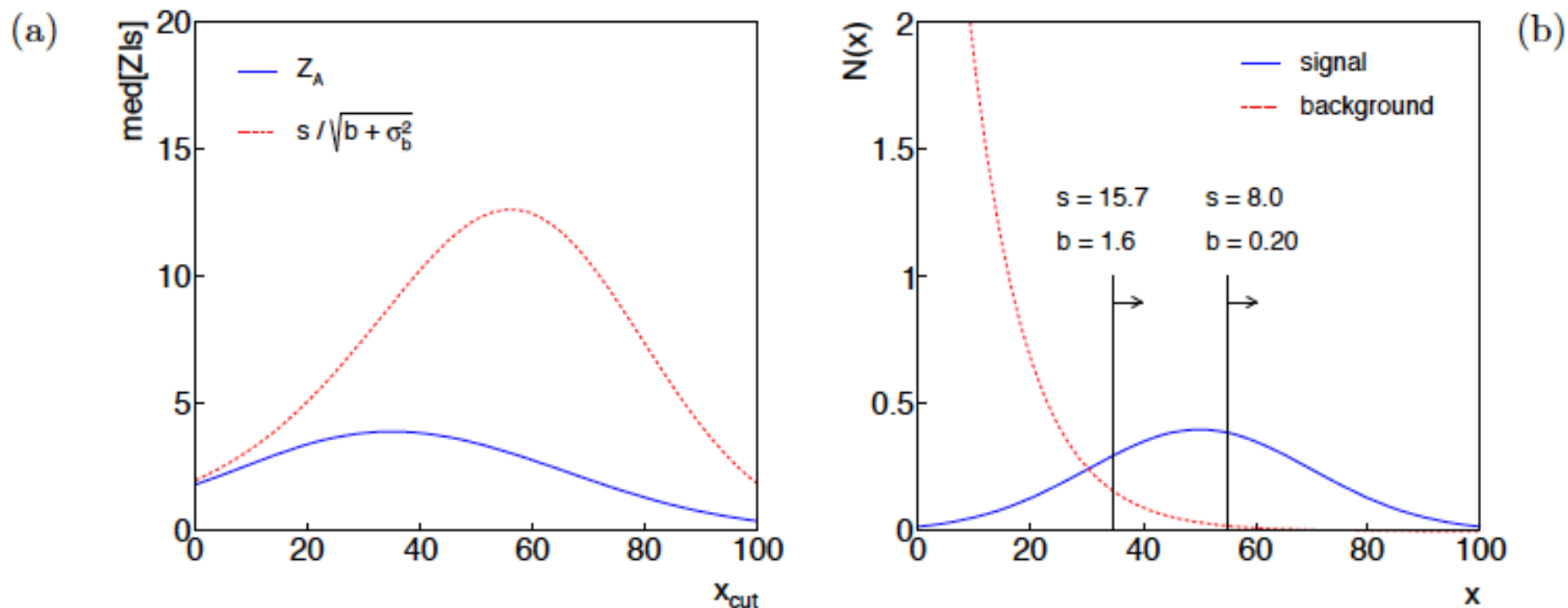


Figure 1: (a) The expected significance as a function of the cut value x_{cut} ; (b) the distributions of signal and background with the optimal cut value indicated.

Summary on discovery sensitivity

Simple formula for expected discovery significance based on profile likelihood ratio test and Asimov approximation:

$$Z_A = \left[2 \left((s + b) \ln \left[\frac{(s + b)(b + \sigma_b^2)}{b^2 + (s + b)\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[1 + \frac{\sigma_b^2 s}{b(b + \sigma_b^2)} \right] \right) \right]^{1/2}$$

For large b , all formulae OK.

For small b , s/\sqrt{b} and $s/\sqrt{(b+\sigma_b^2)}$ overestimate the significance.

Could be important in optimization of searches with low background.

Formula maybe also OK if model is not simple on/off experiment, e.g., several background control measurements (checking this).

Finally

Three lectures only enough for a brief introduction to:

- Statistical tests for discovery and limits

- Bayesian parameter estimation, MCMC

- Experimental sensitivity

No time for many important topics

- Multivariate methods

- Properties of estimators (bias, variance)

- Bayesian approach to discovery (Bayes factors)

- The look-elsewhere effect, etc., etc.

Final thought: once the basic formalism is understood, most of the work focuses on writing down the likelihood, e.g., $P(\mathbf{x}|H)$, and including in it enough parameters to adequately describe the data (true for both Bayesian and frequentist approaches).

Extra slides

Why 5 sigma?

Common practice in HEP has been to claim a discovery if the p -value of the no-signal hypothesis is below 2.9×10^{-7} , corresponding to a significance $Z = \Phi^{-1}(1 - p) = 5$ (a 5σ effect).

There a number of reasons why one may want to require such a high threshold for discovery:

- The “cost” of announcing a false discovery is high.

- Unsure about systematics.

- Unsure about look-elsewhere effect.

- The implied signal may be a priori highly improbable (e.g., violation of Lorentz invariance).

Why 5 sigma (cont.)?

But the primary role of the p -value is to quantify the probability that the background-only model gives a statistical fluctuation as big as the one seen or bigger.

It is not intended as a means to protect against hidden systematics or the high standard required for a claim of an important discovery.

In the processes of establishing a discovery there comes a point where it is clear that the observation is not simply a fluctuation, but an “effect”, and the focus shifts to whether this is new physics or a systematic.

Providing LEE is dealt with, that threshold is probably closer to 3σ than 5σ .

Choice of test for limits (2)

In some cases $\mu = 0$ is no longer a relevant alternative and we want to try to exclude μ on the grounds that some other measure of incompatibility between it and the data exceeds some threshold.

If the measure of incompatibility is taken to be the likelihood ratio with respect to a two-sided alternative, then the critical region can contain both high and low data values.

→ unified intervals, G. Feldman, R. Cousins,
Phys. Rev. D 57, 3873–3889 (1998)

The Big Debate is whether to use one-sided or unified intervals in cases where small (or zero) values of the parameter are relevant alternatives. Professional statisticians have voiced support on both sides of the debate.

Unified (Feldman-Cousins) intervals

We can use directly

$$t_\mu = -2 \ln \lambda(\mu) \quad \text{where} \quad \lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

as a test statistic for a hypothesized μ .

Large discrepancy between data and hypothesis can correspond either to the estimate for μ being observed high or low relative to μ .

This is essentially the statistic used for Feldman-Cousins intervals (here also treats nuisance parameters).

G. Feldman and R.D. Cousins, Phys. Rev. D 57 (1998) 3873.

Lower edge of interval can be at $\mu = 0$, depending on data.

Distribution of t_μ

Using Wald approximation, $f(t_\mu|\mu')$ is noncentral chi-square for one degree of freedom:

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

Special case of $\mu = \mu'$ is chi-square for one d.o.f. (Wilks).

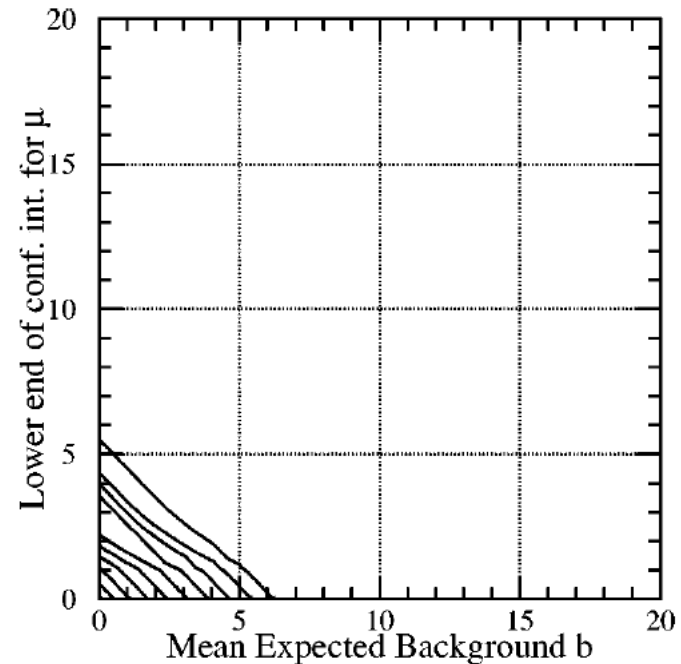
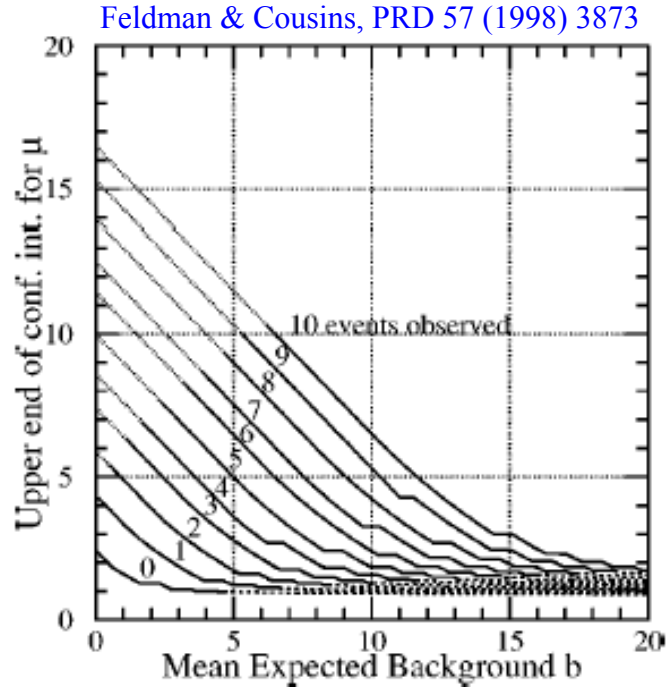
The p -value for an observed value of t_μ is

$$p_\mu = 1 - F(t_\mu|\mu) = 2 (1 - \Phi(\sqrt{t_\mu}))$$

and the corresponding significance is

$$Z_\mu = \Phi^{-1}(1 - p_\mu) = \Phi^{-1}(2\Phi(\sqrt{t_\mu}) - 1)$$

Upper/lower edges of F-C interval for μ versus b for $n \sim \text{Poisson}(\mu+b)$



Lower edge may be at zero, depending on data.

For $n = 0$, upper edge has (weak) dependence on b .

Feldman-Cousins discussion

The initial motivation for Feldman-Cousins (unified) confidence intervals was to eliminate null intervals.

The F-C limits are based on a likelihood ratio for a test of μ with respect to the alternative consisting of all other allowed values of μ (not just, say, lower values).

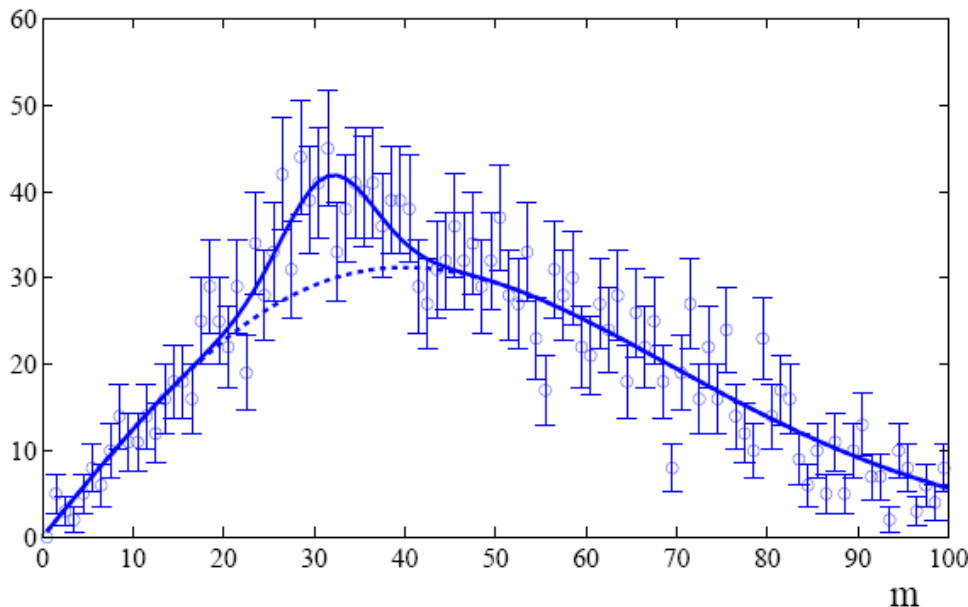
The interval's upper edge is higher than the limit from the one-sided test, and lower values of μ may be excluded as well. A substantial downward fluctuation in the data gives a low (but nonzero) limit.

This means that when a value of μ is excluded, it is because there is a probability α for the data to fluctuate either high or low in a manner corresponding to less compatibility as measured by the likelihood ratio.

The Look-Elsewhere Effect

Suppose a model for a mass distribution allows for a peak at a mass m with amplitude μ .

The data show a bump at a mass m_0 .



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

Local p -value

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

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

gives the probability to find a value of t_{fix} at least as great as observed at the specific mass m_0 and is called the local p -value.

Global p -value

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

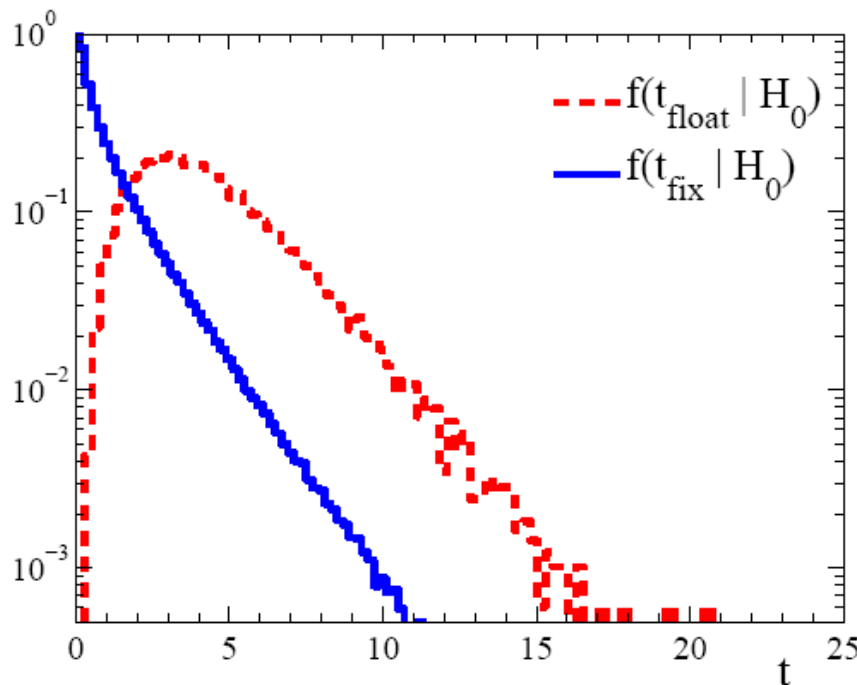
$$t_{\text{float}} = -2 \ln \frac{L(0)}{L(\hat{\mu}, \hat{m})} \quad (\text{Note } m \text{ does not appear in the } \mu = 0 \text{ model.})$$

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

Distributions of t_{fix} , t_{float}

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

For t_{float} there are two adjustable parameters, μ 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_{float} distribution is more difficult.

Approximate correction for LEE

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 the p -values are approximately related by

$$p_{\text{global}} \approx p_{\text{local}} + \langle N(c) \rangle$$

where $\langle N(c) \rangle$ is the mean number “upcrossings” of $t_{\text{fix}} = -2\ln \lambda$ in the fit range based on a threshold

$$c = t_{\text{fix,obs}} = Z_{\text{local}}^2$$

and where $Z_{\text{local}} = \Phi^{-1}(1 - p_{\text{local}})$ is the local significance.

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).

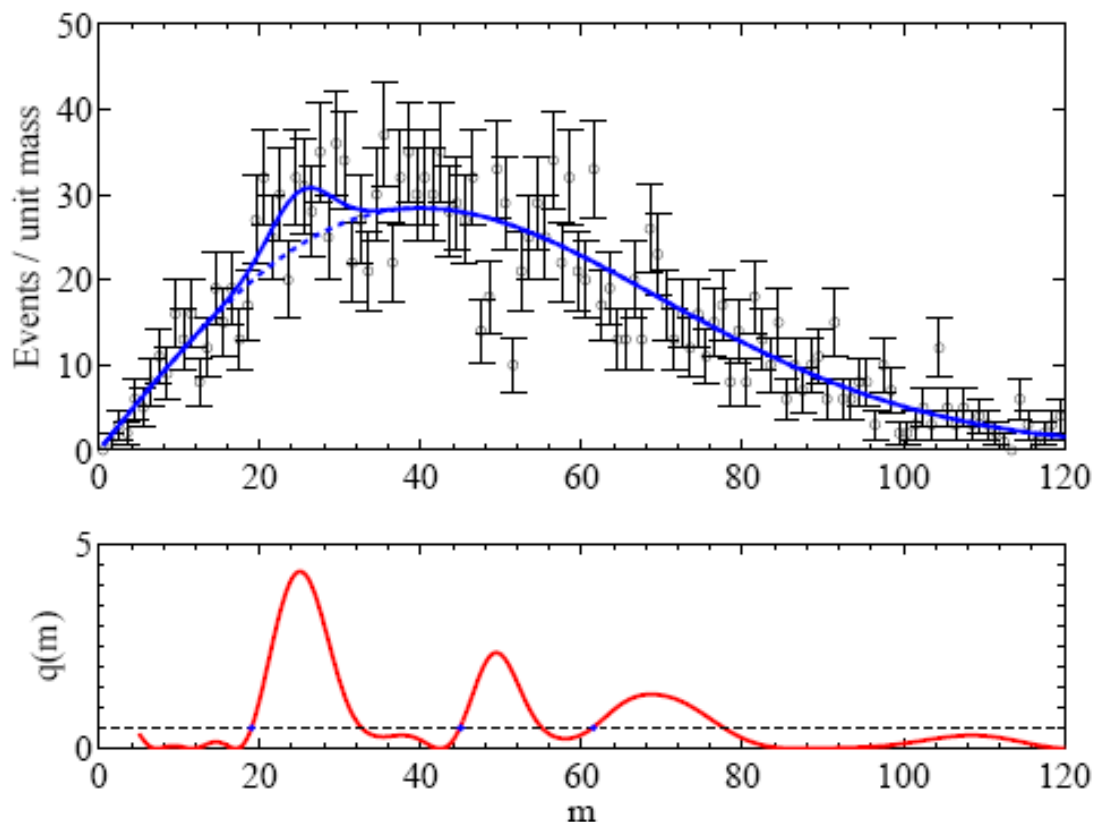
Upcrossings of $-2\ln L$

The Gross-Vitells formula for the trials factor requires $\langle N(c) \rangle$, the mean number “upcrossings” of $t_{\text{fix}} = -2\ln \lambda$ in the fit range based on a threshold $c = t_{\text{fix}} = Z_{\text{fix}}^2$.

$\langle N(c) \rangle$ can be estimated from MC (or the real data) using a much lower threshold c_0 :

$$\langle N(c) \rangle \approx \langle N(c_0) \rangle e^{-(c-c_0)/2}$$

In this way $\langle N(c) \rangle$ can be estimated without need of large MC samples, even if the the threshold c is quite high.

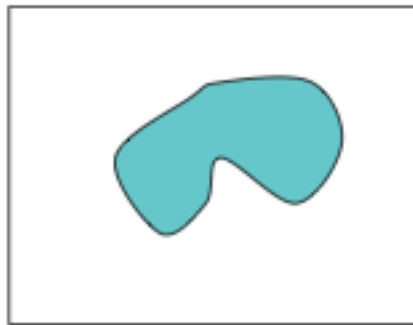


Multidimensional look-elsewhere effect

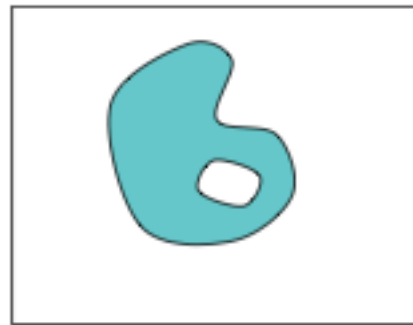
Generalization to multiple dimensions: number of upcrossings replaced by expectation of Euler characteristic:

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

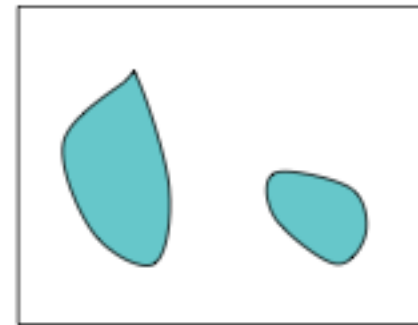
- Number of disconnected components minus number of 'holes'



$\varphi=1$



$\varphi=0$



$\varphi=2$

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 also problematic issue of testing many signal models (or parameter values) and thus excluding some for which one has little or no sensitivity.

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