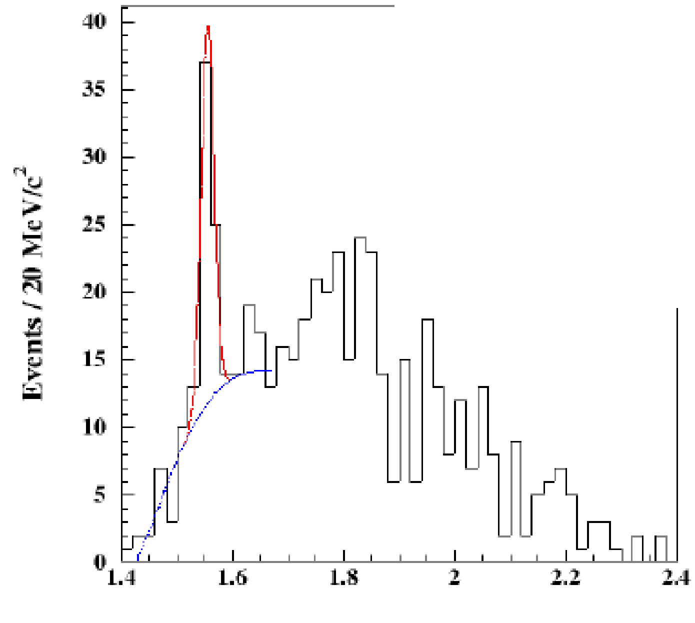
Is there evidence for a peak in this data?



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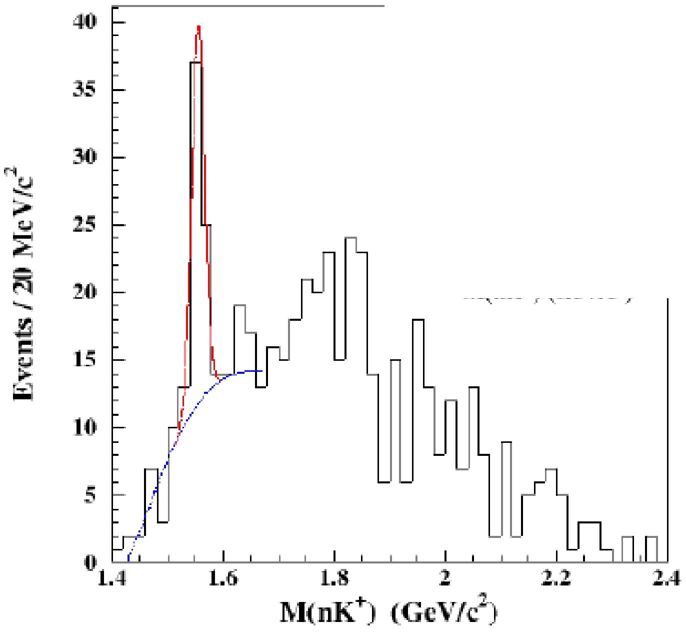


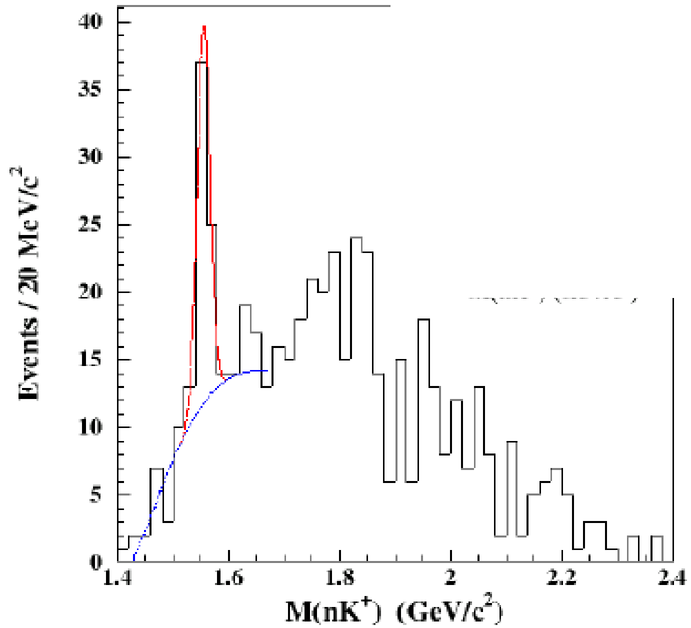
“Observation of an Exotic S=+1

Baryon in Exclusive Photoproduction from the Deuteron”

S. Stepanyan et al, CLAS Collab, Phys.Rev.Lett. 91 (2003) 252001

“The statistical significance of the peak is 5.2 $\pm$ 0.6 σ”

Is there evidence for a peak in this data?



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S. Stepanyan et al, CLAS Collab, Phys.Rev.Lett. 91 (2003) 252001

“The statistical significance of the peak is 5.2 $\pm$ 0.6 σ”

“A Bayesian analysis of pentaquark signals from CLAS data”

D. G. Ireland et al, CLAS Collab, Phys. Rev. Lett. 100, 052001 (2008)

“The ln(RE) value for g2a (-0.408) indicates weak evidence in favour of the data model without a peak in the spectrum.”

Comment on “Bayesian Analysis of Pentaquark Signals from CLAS Data” Bob Cousins, http://arxiv.org/abs/0807.1330

Statistical Issues in Searches for New Physics

Louis Lyons
Imperial College, London
and
Oxford

UCL
Oct 2015

Theme: Using data to make judgements about H1 (New Physics) versus H0 (S.M. with nothing new)

Why?

Experiments are expensive and time-consuming

so

Worth investing effort in statistical analysis

→ better information from data

Topics:

- Blind Analysis
- LEE = Look Elsewhere Effect
- Why 5σ for discovery?
- Significance
- P(A|B) ≠ P(B|A)
- Meaning of p-values
- Wilks' Theorem
- Background Systematics
- Coverage
- Example of misleading inference
- p_0 v p_1 plots
- Higgs search: Discovery and spin

(N.B. Several of these topics have no unique solutions from Statisticians)

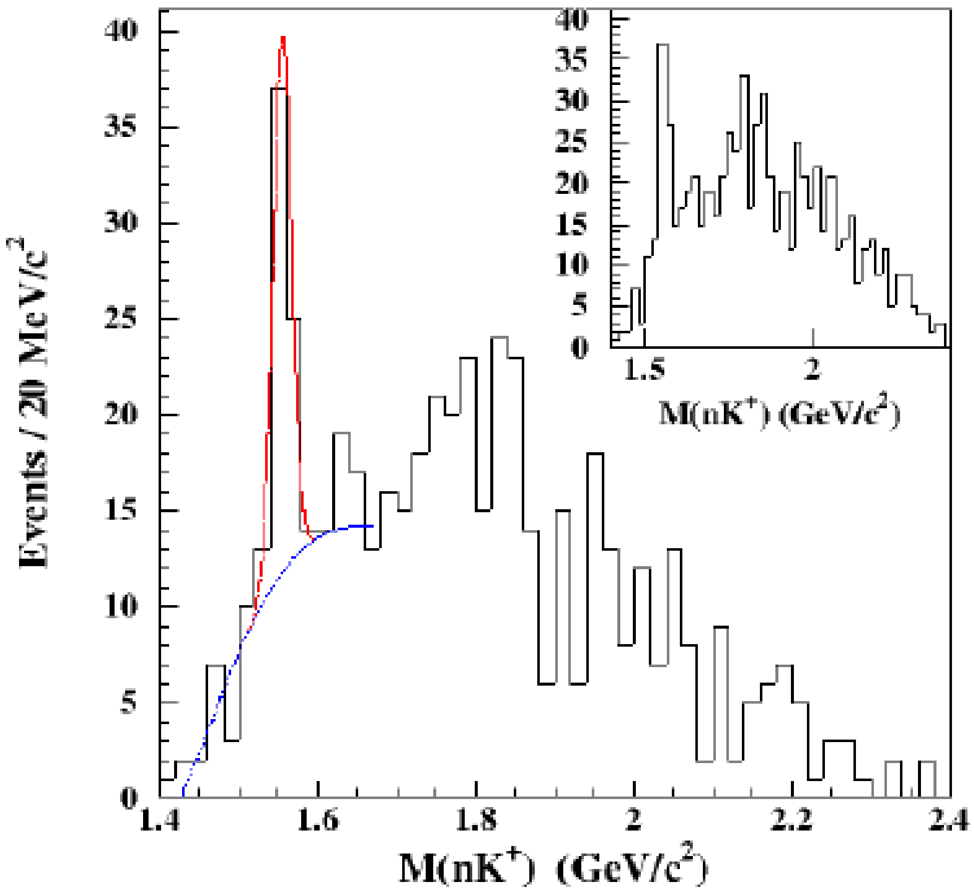
Conclusions

Extended version of talk at LHCP2014 in New York, and CERN Seminar 2015

Choosing between 2 hypotheses

Hypothesis testing: New particle or statistical fluctuation?

H0 = b H1 = b + s



Choosing between 2 hypotheses

Possible methods:

$\Delta\chi^2$

p-value of statistic →

ln$\mathcal{L}$–ratio

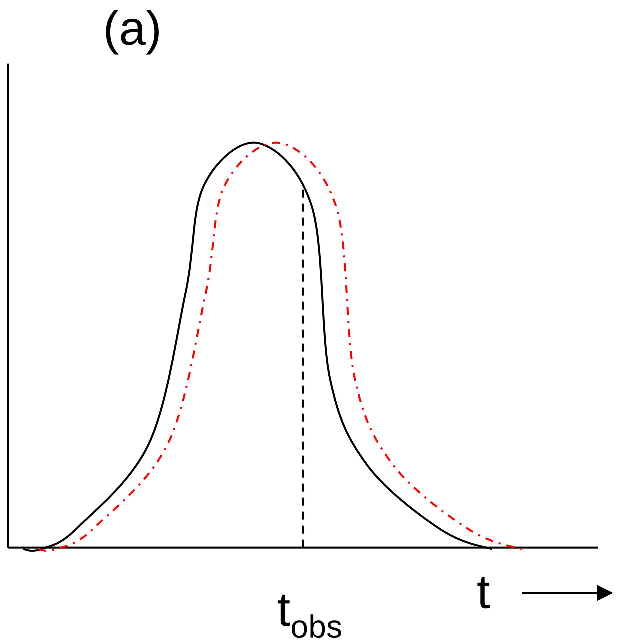
Bayesian:

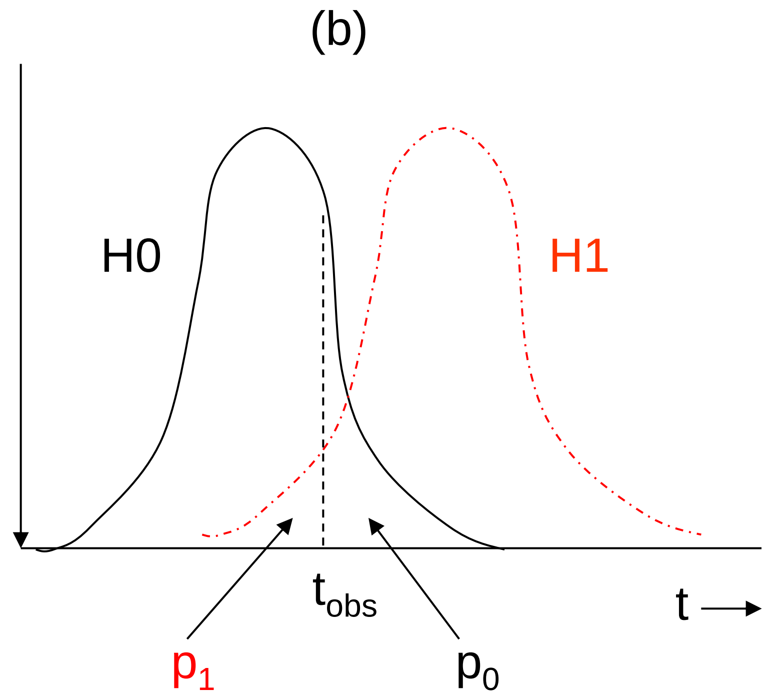
- Posterior odds
- Bayes factor
- Bayes information criterion (BIC)
- Akaike …….. (AIC)

Minimise "cost"

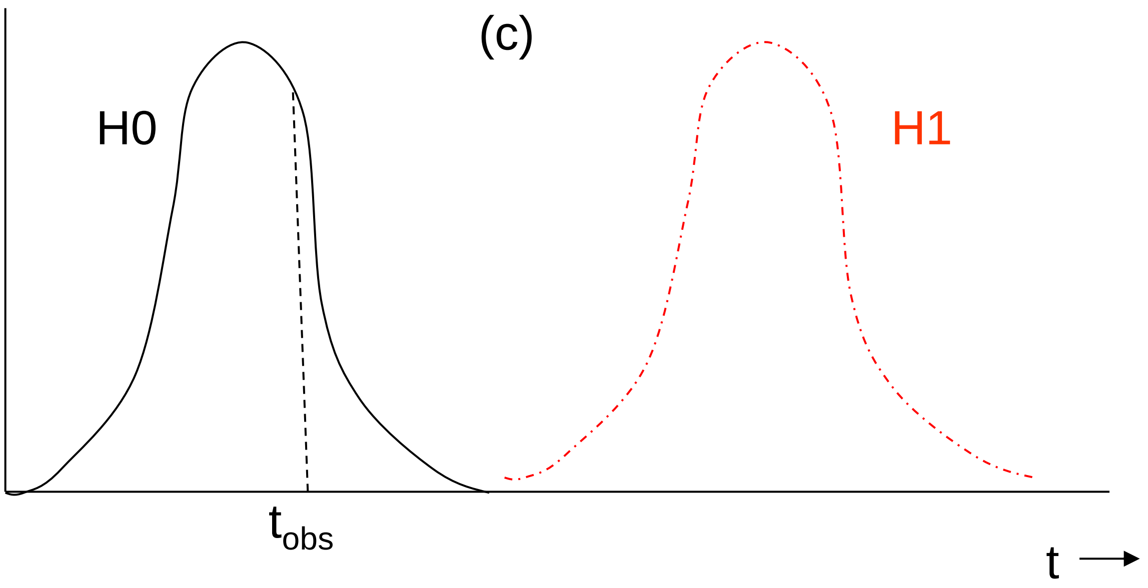
See 'Comparing two hypotheses'

http://www-cdf.fnal.gov/physics/statistics/notes/H0H1.pdf

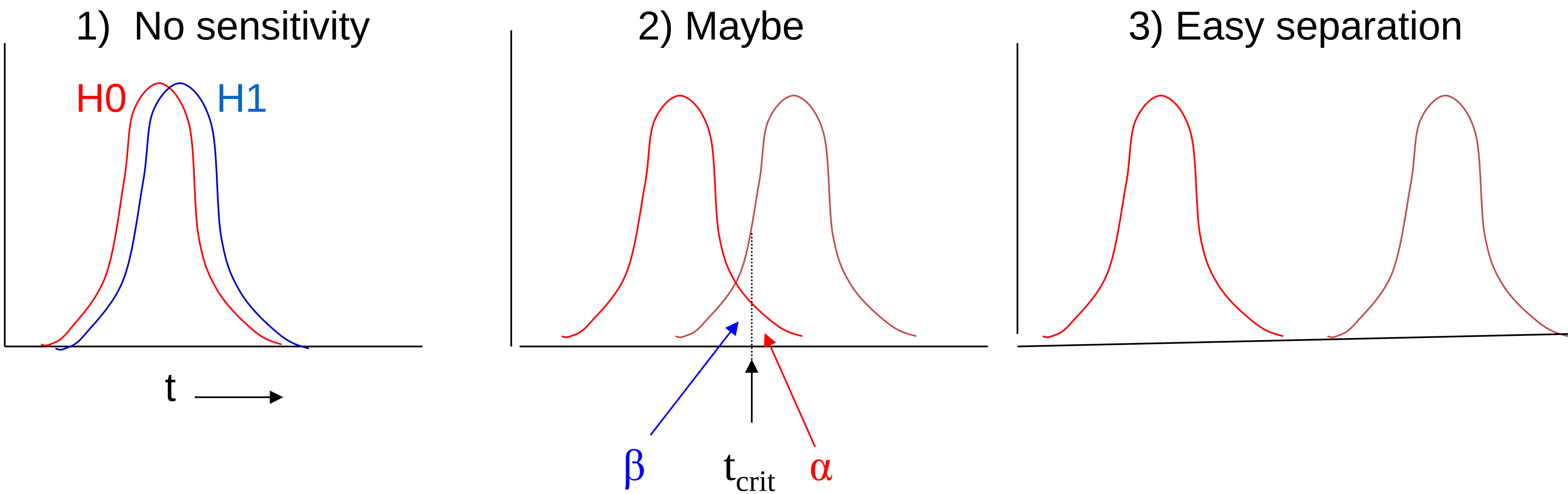




With 2 hypotheses, each with own pdf, p-values are defined as tail areas, pointing in towards each other



Procedure for choosing between 2 hypotheses



Procedure: Obtain expected distributions for data statistic (e.g. $\mathcal{L}$-ratio) for H0 and H1

Choose α (e.g. 95%, 3σ, 5σ ?) and CL for p_1 (e.g. 95%)

Given b, α determines t_{crit}

b+s defines β. For $s > s_{min}$, separation of curves → discovery or excln

$1-\beta$ = Power of test

Now data: If $t_{obs} \geq t_{crit}$ (i.e. $p_0 \leq \alpha$), discovery at level α

If $t_{obs} < t_{crit}$, no discovery. If $p_1 < 1-$ CL, exclude H1

BLIND ANALYSES

Why blind analysis? Data statistic, selections, corrections, method

Methods of blinding

- Add random number to result *
- Study procedure with simulation only
- Look at only first fraction of data
- Keep the signal box closed
- Keep MC parameters hidden
- Keep unknown fraction visible for each bin

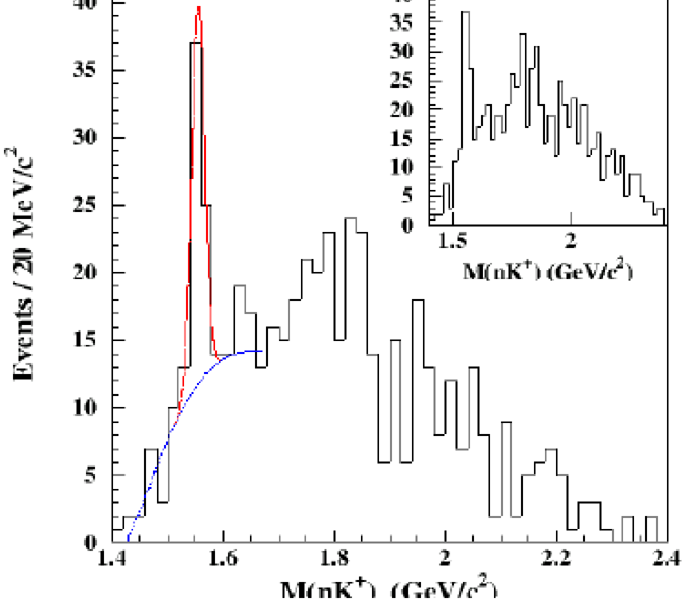
Disadvantages

- Takes longer time
- Usually not available for searches for unknown

After analysis is unblinded, don't change anything unless ……..

* Luis Alvarez suggestion re "discovery" of free quarks

Look Elsewhere Effect (LEE)



Prob of bgd fluctuation at that place = local p-value
Prob of bgd fluctuation 'anywhere' = global p-value
Global p > Local p

Where is `anywhere'?

a) Any location in this histogram in sensible range
b) Any location in this histogram
c) Also in histogram produced with different cuts, binning, etc.
d) Also in other plausible histograms for this analysis
e) Also in other searches in this PHYSICS group (e.g. SUSY at CMS)
f) In any search in this experiment (e.g. CMS)
g) In all CERN expts (e.g. LHC expts + NA62 + OPERA + ASACUSA + ….)
h) In all HEP expts

etc.

d) relevant for graduate student doing analysis
f) relevant for experiment's Spokesperson

INFORMAL CONSENSUS:

Quote local p, and global p according to a) above.
Explain which global p

Example of LEE: Stonehenge

12 is the number of constellations

6 is the number of ages (2160) we spend on each side of the galactic equator

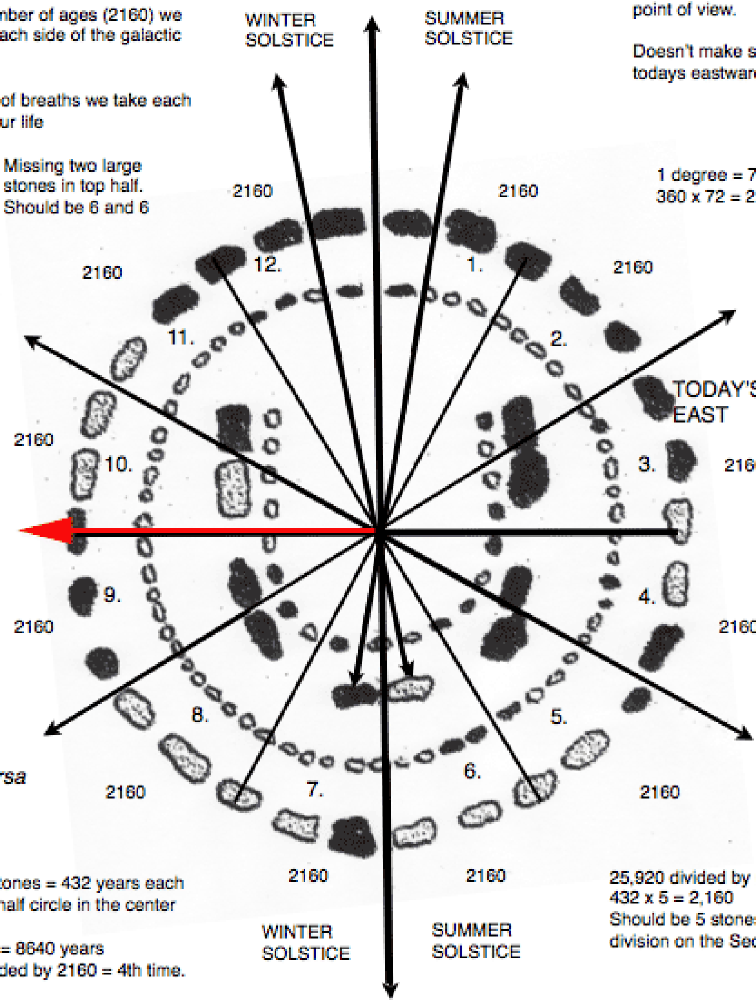
18 number of breaths we take each minute or our life

Missing two large stones in top half. Should be 6 and 6

Stonehenge from a Hopi point of view.

Doesn't make sense with todays eastward direction.

1 degree = 72 years
360 x 72 = 25,920



If small stones = 432 years each then the half circle in the center would be
20 x 432 = 8640 years
8640 divided by 2160 = 4th time.

25,920 divided by 60 = 432
432 x 5 = 2,160
Should be 5 stones between each division on the Second ring.

30 Stones in Outer ring =
360 divided by 30 = 12

60 Stones in Second ring =
360 divided by 60 = 6

20 Stones in Center ring =
360 divided by 20 = 18

25,920 divided by 12 = 2160

25,920 divided by 6 = 4320

25,920 divided by 18 = 1440

Center Stone in Center Ring would be divided in half by sun rays when Earth in perfect balance. Nine on each side + 2 = 20.

STONEHENGE

The Book of Truth
A New Perspective on the Hopi Creation Story
by Thomas O. Mills

Are alignments significant?

- Atkinson replied with his article "Moonshine on Stonehenge" in *Antiquity* in 1966, pointing out that some of the pits which ….. had used for his sight lines were more likely to have been natural depressions, and that he had allowed a margin of error of up to 2 degrees in his alignments. Atkinson found that the probability of so many alignments being visible from 165 points to be close to 0.5 rather that the "one in a million" possibility which ….. had claimed.

- ….. had been examining stone circles since the 1950s in search of astronomical alignments and the megalithic yard. It was not until 1973 that he turned his attention to Stonehenge. He chose to ignore alignments between features within the monument, considering them to be too close together to be reliable. He looked for landscape features that could have marked lunar and solar events. However, one of …..'s key sites, Peter's Mound, turned out to be a twentieth-century rubbish dump.

Why 5σ for Discovery?

Statisticians ridicule our belief in extreme tails (esp. for systematics)

Our reasons:

1) Past history (Many 3σ and 4σ effects have gone away)

2) LEE (see later)

3) Worries about underestimated systematics

4) Subconscious Bayes calculation

$$\frac{p(H_1|x)}{p(H_0|x)} = \frac{p(x|H_1)}{p(x|H_0)} * \frac{\pi(H_1)}{\pi(H_0)}$$

Posterior prob | Likelihood ratio | Priors

"Extraordinary claims require extraordinary evidence"

N.B. Points 2), 3) and 4) are experiment-dependent

Alternative suggestion:

L.L. "Discovering the significance of 5σ" http://arxiv.org/abs/1310.1284

How many σ's for discovery?

SEARCH	SURPRISE	IMPACT	LEE	SYSTEMATICS	No. σ
Higgs search	Medium	Very high	M	Medium	5
Single top	No	Low	No	No	3
SUSY	Yes	Very high	Very large	Yes	7
B_s oscillations	Medium/Low	Medium	Δm	No	4
Neutrino osc	Medium	High	$\sin^2 2\vartheta$, Δm^2	No	4
$B_s \rightarrow \mu\,\mu$	No	Low/Medium	No	Medium	3
Pentaquark	Yes	High/V. high	M, decay mode	Medium	7
$(g\text{-}2)_\mu$ anom	Yes	High	No	Yes	4
H spin ≠ 0	Yes	High	No	Medium	5
4^{th} gen q, l, ν	Yes	High	M, mode	No	6
Dark energy	Yes	Very high	Strength	Yes	5
Grav Waves	No	High	Enormous	Yes	8

Suggestions to provoke discussion, rather than `delivered on Mt. Sinai'

Bob Cousins: "2 independent expts each with 3.5σ better than one expt with 5σ"

Significance

Significance = $S/\sqrt{B}$ or similar ?

Potential Problems:

- Uncertainty in B
- Non-Gaussian behaviour of Poisson, especially in tail
- Number of bins in histogram, no. of other histograms [LEE]
- Choice of cuts, bins (Blind analyses)

For future experiments:

- Optimising: Could give $S = 0.1$, $B = 10^{-4}$, $S/\sqrt{B} = 10$

$P(A|B) \neq P(B|A)$

Remind Lab or University media contact person that:

Prob[data, given H0] is very small

does not imply that

Prob[H0, given data] is also very small.

e.g. Prob{data | speed of $\nu \leq c$}= very small

does not imply

Prob{speed of $\nu \leq c$ | data} = very small

or Prob{speed of $\nu > c$ | data} ~ 1

Everyday situation, 2nd most convincing example:

Pack of playing cards

p(spade|king) = 1/4

p(king|spade) = 1/13

$P(A|B) \neq P(B|A)$

Remind Lab or University media contact person that:

Prob[data, given H0] is very small

does not imply that

Prob[H0, given data] is also very small.

e.g. Prob{data | speed of $\nu \leq$ c}= very small

does not imply

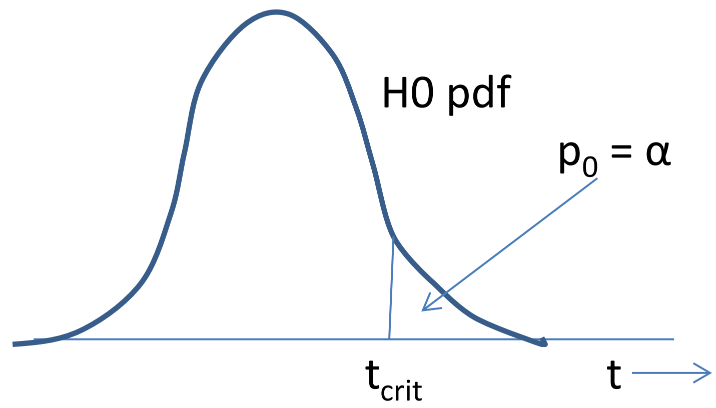
Prob{speed of $\nu \leq$c | data} = very small

or Prob{speed of ν>c | data} ~ 1

Everyday example p(pregnant|female) ~ 3%

p(female|pregnant) >> 3%

What p-values are (and are not)



Reject H0 if $t > t_{crit}$ ($p < \alpha$)

p-value = prob that $t \geq t_{obs}$

Small p → data and theory have poor compatibility

Small p-value does **NOT** automatically imply that theory is unlikely

Bayes prob(Theory|data) related to prob(data|Theory) = Likelihood

by Bayes Th, including Bayesian prior

p-values are misunderstood. e.g. Anti-HEP jibe:

"Particle Physicists don't know what they are doing, because half their

p < 0.05 exclusions turn out to be wrong"

Demonstrates lack of understanding of p-values

[**All** results rejecting energy conservation with $p < \alpha = .05$ cut will turn out to be 'wrong']

Combining different p-values

Several results quote independent p-values for same effect:

p_1, p_2, p_3..... e.g. 0.9, 0.001, 0.3 ....

What is combined significance? Not just $p_1 * p_2 * p_3$.....

If 10 expts each have p ~ 0.5, product ~ 0.001 and is clearly **NOT** correct combined p

$$S = z * \sum_{j=0}^{n-1} (-\ln z)^j / j! \;, \qquad z = p_1 p_2 p_3 \ldots\ldots$$

(e.g. For 2 measurements, $S = z * (1 - \ln z) \geq z$)

Problems:

1) Recipe is not unique (Uniform dist in n-D hypercube → uniform in 1-D)

2) Formula is not associative

Combining {{p_1 and p_2}, and then p_3} gives different answer from {{p_3 and p_2}, and then p_1} , or all together

Due to different options for "more extreme than x_1, x_2, x_3".

3) Small p's due to different discrepancies

******* Better to combine data *************

Wilks' Theorem

Data = some distribution e.g. mass histogram

For H0 and H1, calculate best fit weighted sum of squares S_0 and S_1

Examples: 1) H0 = polynomial of degree 3

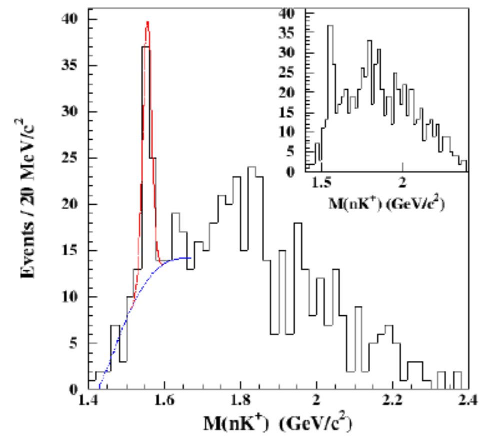
H1 = polynomial of degree 5

2) H0 = background only

H1 = bgd+peak with free M_0 and cross-section

3) H0 = normal neutrino hierarchy

H1 = inverted hierarchy



If H0 true, S_0 distributed as χ^2 with ndf = ν_0

If H1 true, S_1 distributed as χ^2 with ndf = ν_1

If H0 true, what is distribution of $\Delta S = S_0 - S_1$? Expect not large. Is it χ^2?

Wilks' Theorem: ΔS distributed as χ^2 with ndf = $\nu_0 - \nu_1$ provided:

a) H0 is true
b) H0 and H1 are nested
c) Params for H1→ H0 are well defined, and not on boundary
d) Data is asymptotic

Wilks' Theorem, contd

Examples: Does Wilks' Th apply?

1) H0 = polynomial of degree 3
   H1 = polynomial of degree 5

YES: ΔS distributed as χ^2 with ndf = (d-4) – (d-6) = 2

2) H0 = background only
   H1 = bgd + peak with free M_0 and cross-section

NO: H0 and H1 nested, but M_0 undefined when H1→ H0. $\Delta S \neq \chi^2$

(but not too serious for fixed M)

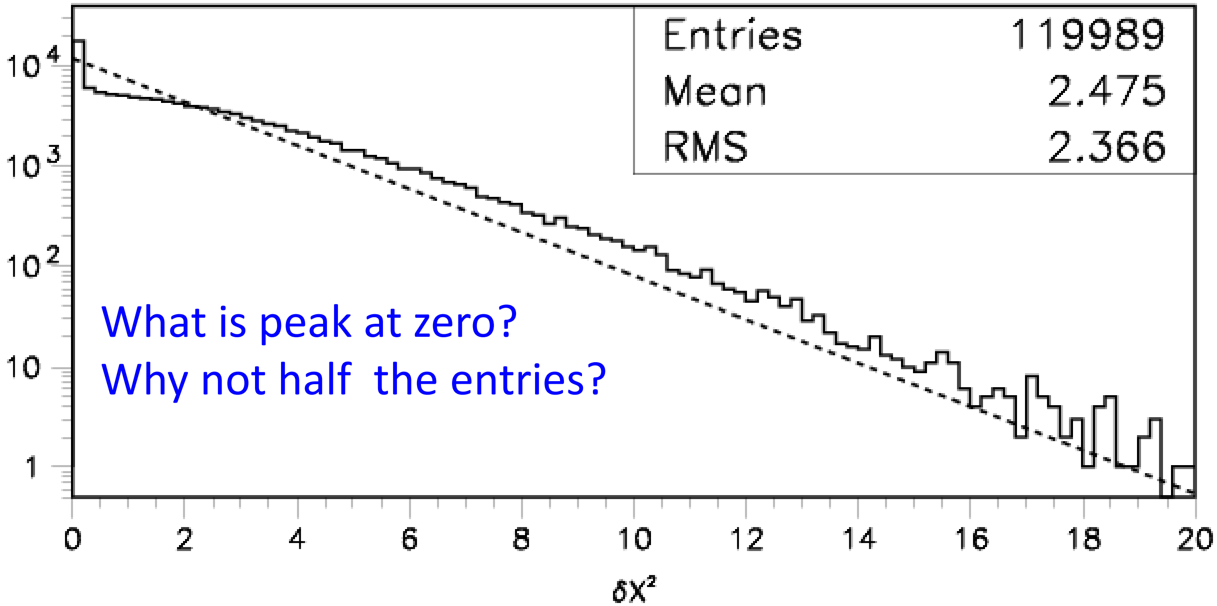
3) H0 = normal neutrino hierarchy
   H1 = inverted hierarchy

NO: Not nested. $\Delta S \neq \chi^2$ (e.g. can have $\Delta\chi^2$ negative)

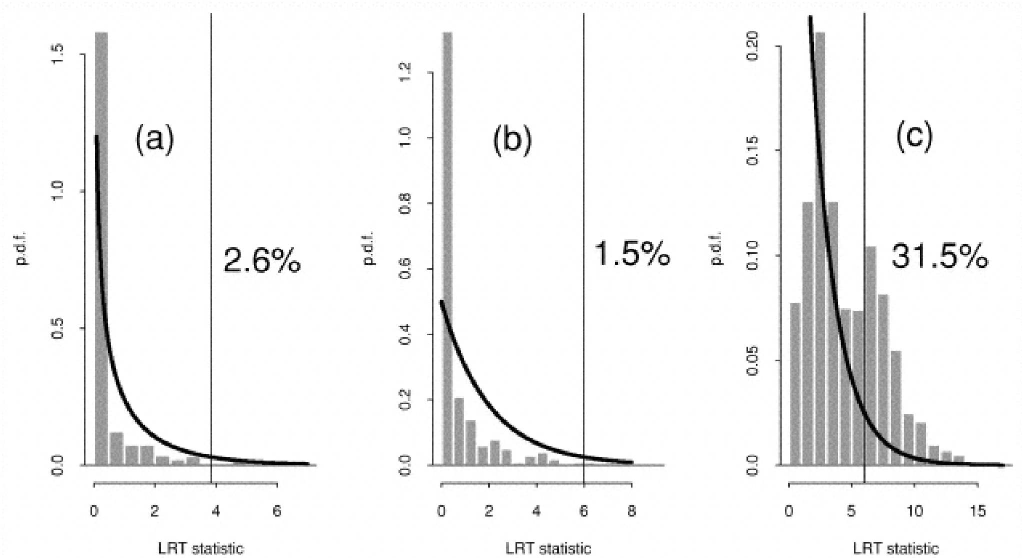
N.B. 1: Even when W. Th. does not apply, it does not mean that ΔS is irrelevant, but you cannot use W. Th. for its expected distribution.

N.B. 2: For large ndf, better to use ΔS, rather than S_1 and S_0 separately

Is difference in S distributed as χ^2 ?



Demortier:
H0 = quadratic bgd
H1 = ……………… +
Gaussian of fixed width,
variable location & ampl



Protassov, van Dyk, Connors, ….
H0 = continuum
(a) H1 = narrow emission line
(b) H1 = wider emission line
(c) H1 = absorption line

Nominal significance level = 5%

Is difference in S distributed as χ^2 ?, contd.

So need to determine the ΔS distribution by Monte Carlo

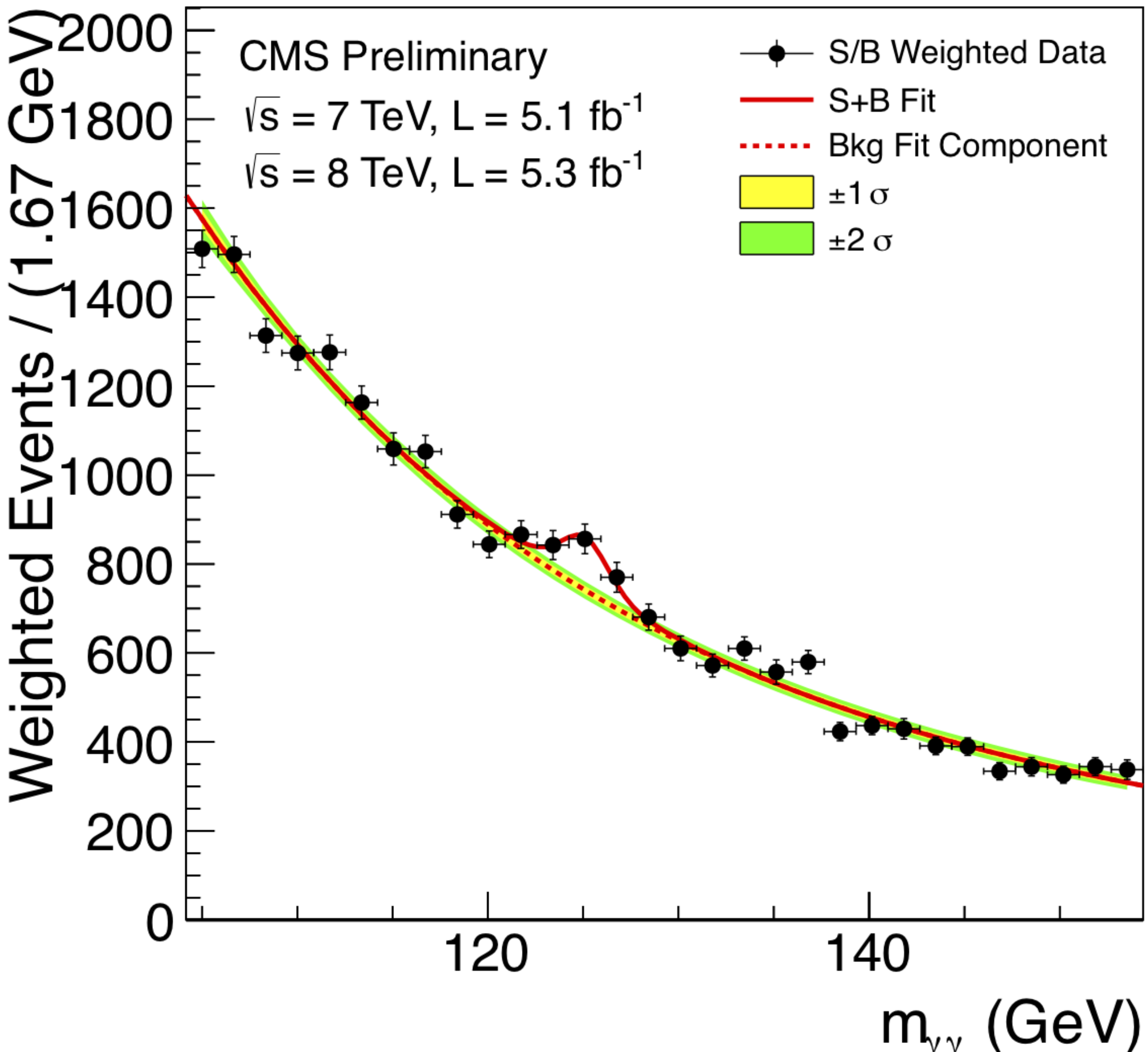
N.B.

1) For mass spectrum, determining ΔS for hypothesis H1 when data is generated according to H0 is not trivial, because there will be lots of local minima

2) If we are interested in 5σ significance level, needs lots of MC simulations (or intelligent MC generation)

3) Asymptotic formulae may be useful (see K. Cranmer, G. Cowan, E. Gross and O. Vitells, 'Asymptotic formulae for likelihood-based tests of new physics', http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-011-1554-0)

Background systematics



Background systematics, contd

Signif from comparing χ^2's for H0 (bgd only) and for H1 (bgd + signal)
Typically, bgd = functional form f_a with free params
e.g. 4^{th} order polynomial
Uncertainties in params included in signif calculation
But what if functional form is different ? e.g. f_b
Typical approach:
If f_b best fit is bad, not relevant for systematics
If f_b best fit is ~comparable to f_a fit, include contribution to systematics
But what is '~comparable'?
Other approaches:
Profile likelihood over different bgd parametric forms
http://arxiv.org/pdf/1408.6865v1.pdf?
Background subtraction
sPlots
Non-parametric background
Bayes
etc

No common consensus yet among experiments on best approach
{Spectra with multiple peaks are more difficult}

“Handling uncertainties in background shapes: the discrete profiling method”

Dauncey, Kenzie, Wardle and Davies (Imperial College, CMS)

arXiv:1408.6865v1 [physics.data-an]

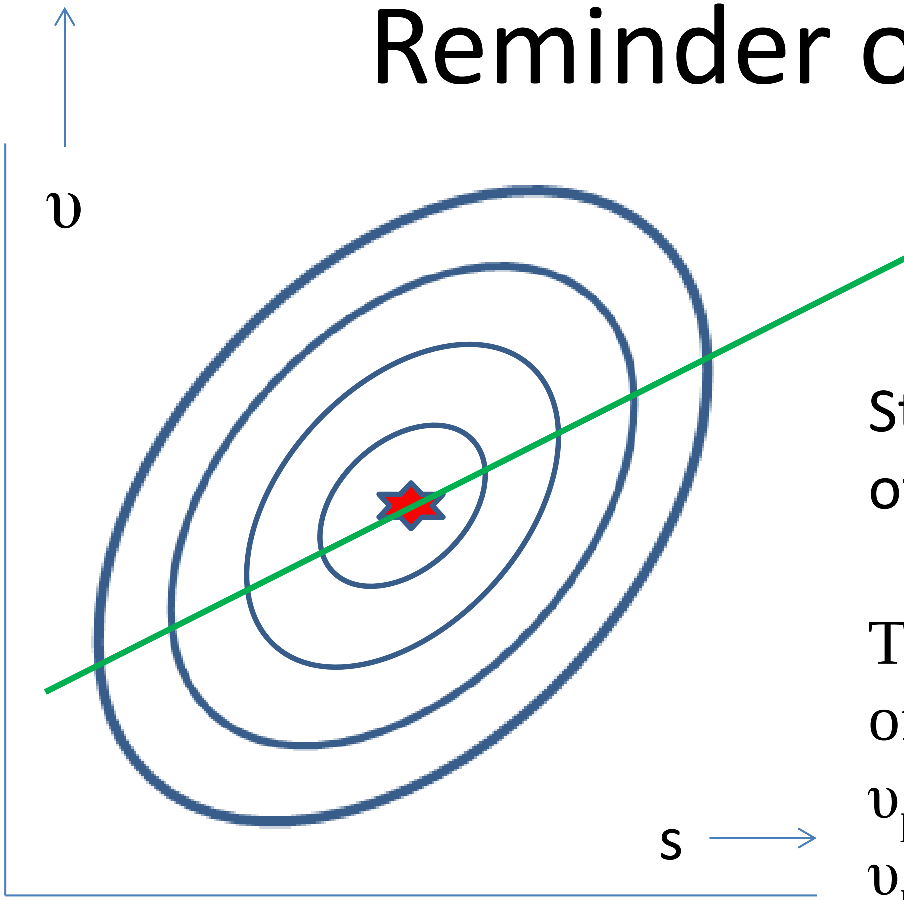
Has been used in CMS analysis of H→γγ

Problem with ‘Typical approach’: Alternative functional forms do or don’t contribute to systematics by hard cut, so systematics can change discontinuously wrt $\Delta\chi^2$

Method is like profile $\mathcal{L}$ for continuous nuisance params

Here ‘profile’ over discrete functional forms

Reminder of Profile $\mathcal{L}$

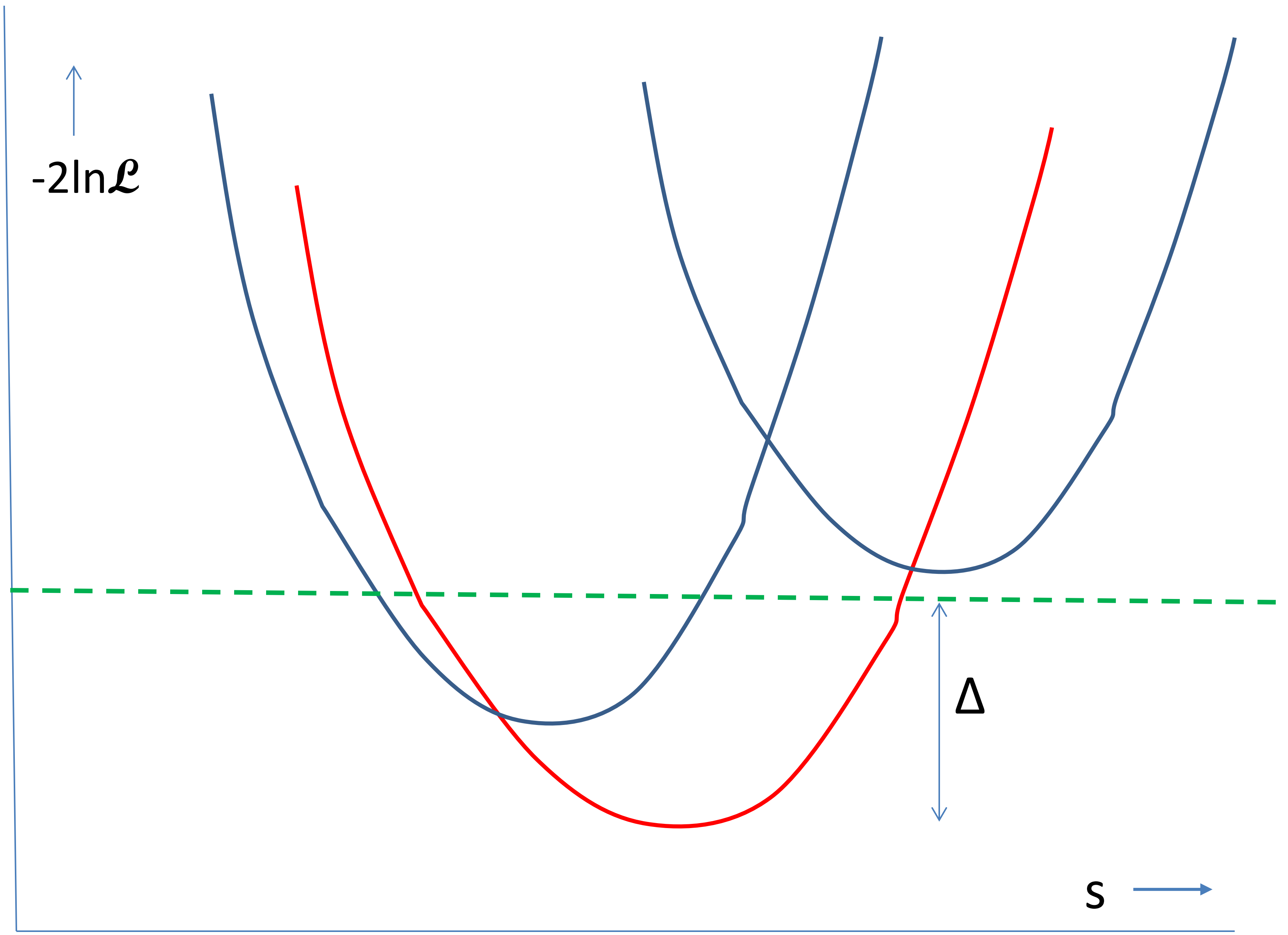


Contours of $\ln\mathcal{L}(s,\upsilon)$
s = physics param
υ = nuisance param

Stat uncertainty on s from width of $\mathcal{L}$ fixed at υ_{best}

Total uncertainty on s from width of $\mathcal{L}(s,\upsilon_{prof(s)}) = \mathcal{L}_{prof}$
$\upsilon_{prof(s)}$ is best value of υ at that s
$\upsilon_{prof(s)}$ as fn of s lies on green line

Total uncert ≥ stat uncertainty


-2lnℒ
Δ
s

Red curve: Best value of nuisance param υ

Blue curves: Other values of υ

Horizontal line: Intersection with red curve → statistical uncertainty

'Typical approach': Decide which blue curves have small enough Δ

Systematic is largest change in minima wrt red curves'.

Profile L: Envelope of lots of blue curves

Wider than red curve, because of systematics (υ)

For $\mathcal{L}$ = multi-D Gaussian, agrees with 'Typical approach'

Dauncey et al use envelope of finite number of functional forms

Point of controversy!

Two types of ‘other functions’:

a) Different function types e.g.

$\Sigma a_i x_i$ versus $\Sigma a_i/x_i$

b) Given fn form but different number of terms

DDKW deal with b) by $-2\ln L \rightarrow -2\ln L + kn$

n = number of extra free params wrt best

k = 1, as in AIC (= Akaike Information Criterion)

Opposition claim choice k=1 is arbitrary.

DDKW agree but have studied different values, and say k =1 is optimal for them.

Also, any parametric method needs to make such a choice

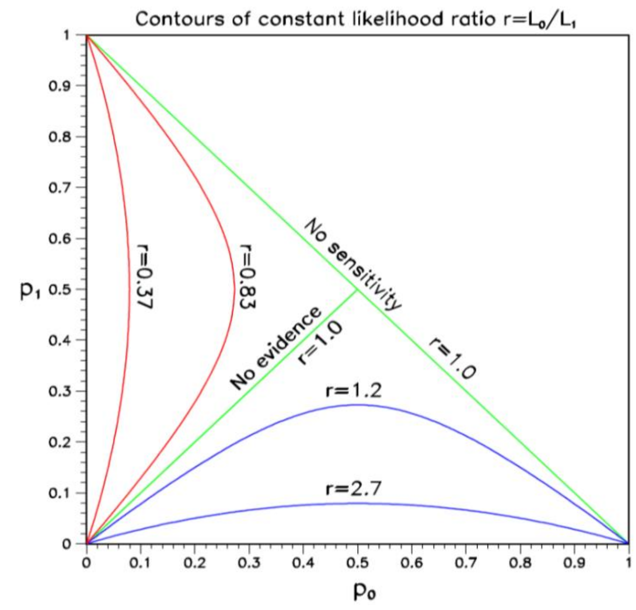
p_0 v p_1 plots

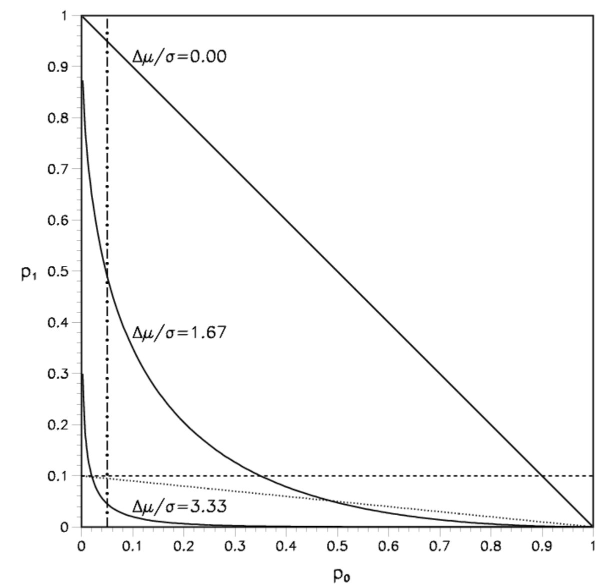
Preprint by Luc Demortier and LL,
"Testing Hypotheses in Particle Physics: Plots of p_0 versus p_1"
http://arxiv.org/abs/1408.6123

For hypotheses H0 and H1, p_0 and p_1 are the tail probabilities for data statistic t

Provide insights on:

- CLs for exclusion
- Punzi definition of sensitivity
- **Relation of p-values and Likelihoods**
- Probability of misleading evidence
- Sampling to foregone conclusion
- **Jeffreys-Lindley paradox**



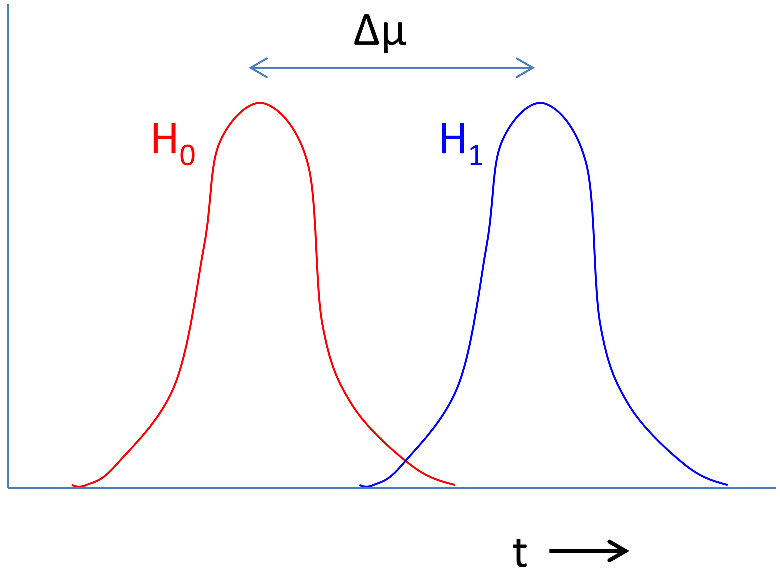


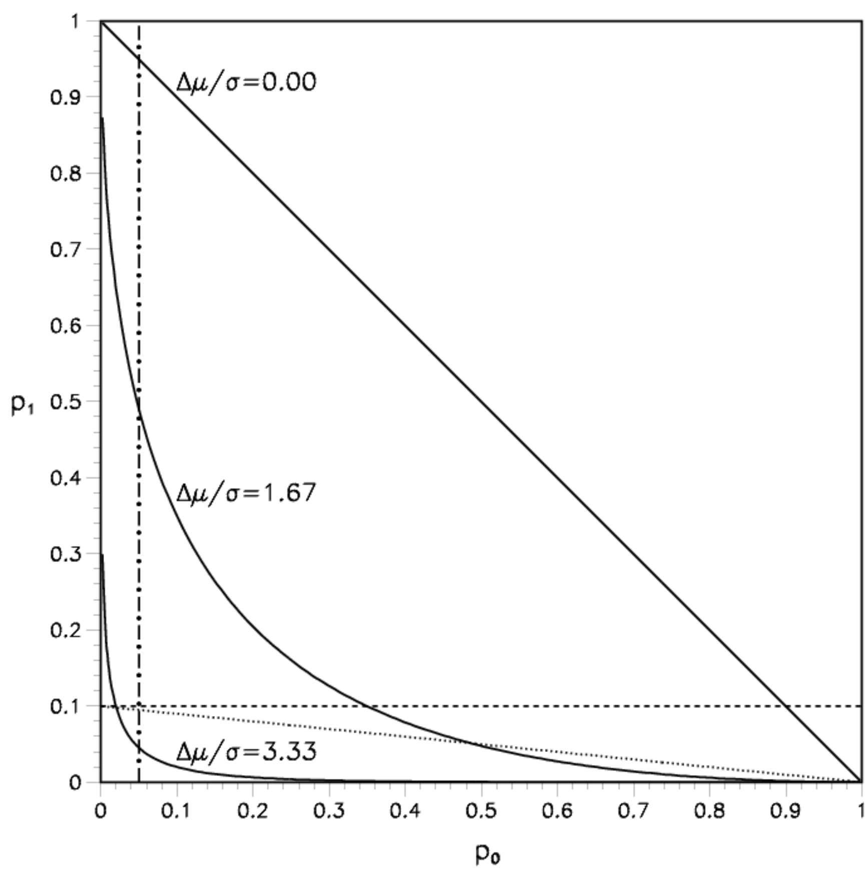
CLs = $p_1/(1-p_0)$ → diagonal line

Provides protection against excluding H_1 when little or no sensitivity

Punzi definition of sensitivity:

Enough separation of pdf's for no chance of ambiguity





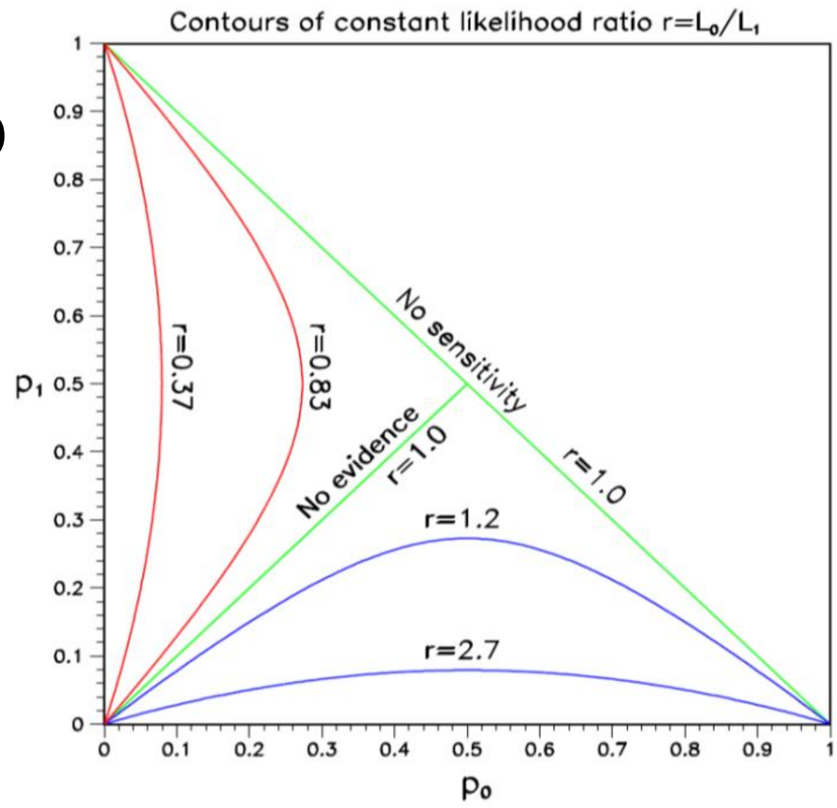
Can read off power of test

e.g. If H_0 is true, what is prob of rejecting H_1?

N.B. p_0 = tail towards H_1

p_1 = tail towards H_0

Why p ≠ Likelihood ratio



Measure different things:

p_0 refers just to H0; $\mathcal{L}_{01}$ compares H0 and H1

Depends on amount of data:

e.g. Poisson counting expt little data:

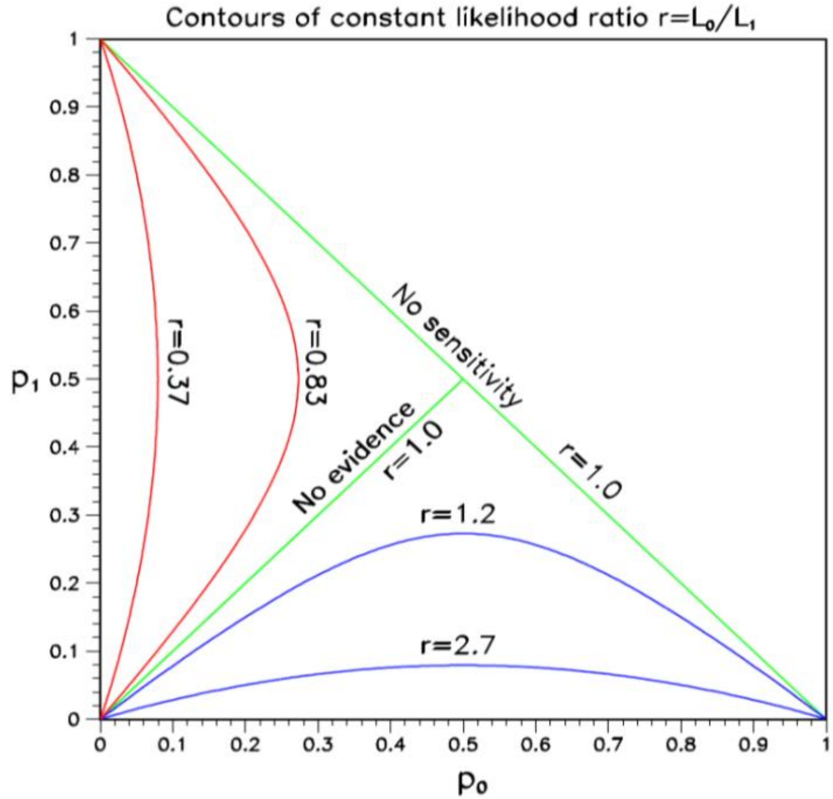
For H0, $\mu_0 = 1.0$. For H1, $\mu_1 = 10.0$

Observe n = 10 $p_0 \sim 10^{-7}$ $\mathcal{L}_{01} \sim 10^{-5}$

Now with 100 times as much data, $\mu_0 = 100.0$ $\mu_1 = 1000.0$

Observe n = 160 $p_0 \sim 10^{-7}$ $\mathcal{L}_{01} \sim 10^{+14}$

Jeffreys-Lindley Paradox



H0 = simple, H1 has μ free

p_0 can favour H_1, while B_{01} can favour H_0

$B_{01} = L_0 / \int L_1(s)\, \pi(s)\, ds$

Likelihood ratio depends on signal :

e.g. Poisson counting expt small signal s:

For H_0, $\mu_0 = 1.0$. For H_1, $\mu_1 = 10.0$

Observe n = 10 $p_0 \sim 10^{-7}$ $L_{01} \sim 10^{-5}$ and favours H_1

Now with 100 times as much signal s, $\mu_0 = 100.0$ $\mu_1 = 1000.0$

Observe n = 160 $p_0 \sim 10^{-7}$ $L_{01} \sim 10^{+14}$ and favours H_0

B_{01} involves intergration over s in denominator, so a wide enough range will result in favouring H_0

However, for B_{01} to favour H_0 when p_0 is equivalent to 5σ, integration range for s has to be $O(10^6)$ times Gaussian widths

WHY LIMITS?

Michelson-Morley experiment → death of aether

HEP experiments: If UL on expected rate for new particle $<$ expected, exclude particle

CERN CLW (Jan 2000)

FNAL CLW (March 2000)

Heinrich, PHYSTAT-LHC, "Review of Banff Challenge"

Methods (no systematics)

Bayes (needs priors e.g. const, $1/\mu$, $1/\sqrt{\mu}$, μ, ...)

Frequentist (needs ordering rule,

possible empty intervals, F-C)

Likelihood (DON'T integrate your L)

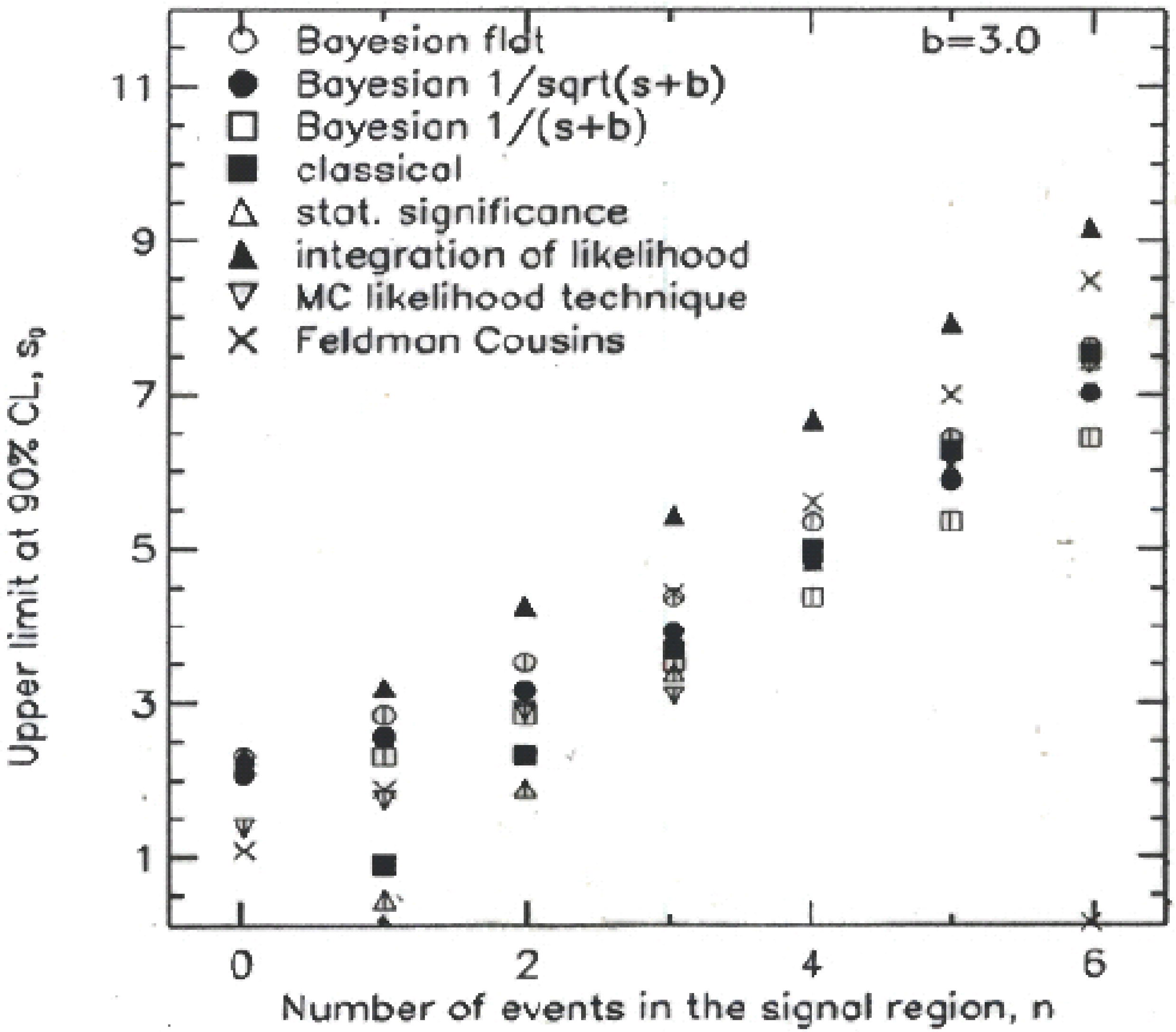
χ^2 ($\sigma^2 = \mu$)

χ^2(σ^2 = n)

Recommendation 7 from CERN CLW: "Show your **L**"

1) Not always practical
2) Not sufficient for frequentist methods

Ilya Narsky, FNAL CLW 2000



DESIRABLE PROPERTIES

- Coverage
- Interval length
- Behaviour when $n < b$
- Limit increases as σ_b increases
- Unified with discovery and interval estimation

90% Classical interval for Gaussian

$\sigma = 1 \qquad \mu \geq 0 \qquad$ e.g. $m^2(\nu_e)$

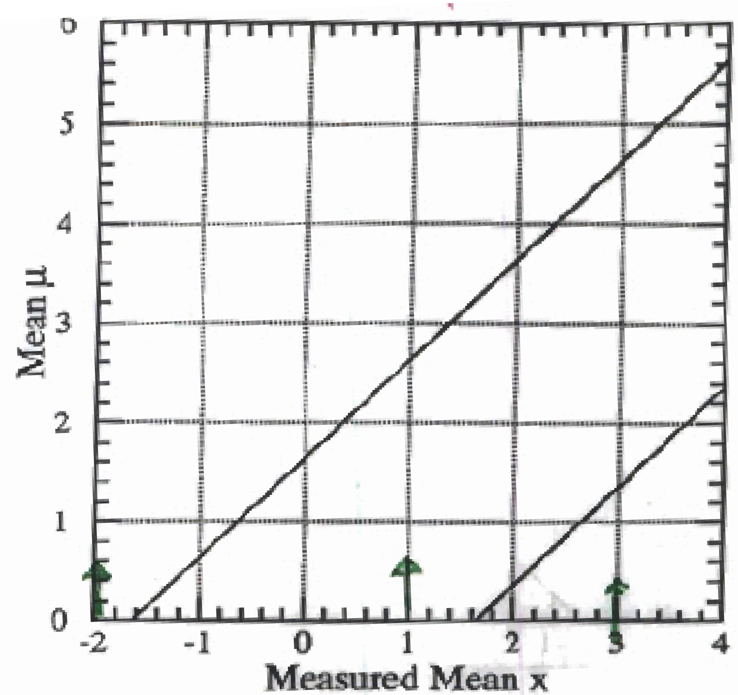


FIG. 3. Standard confidence belt for 90% C.L. central confidence intervals for the mean of a Gaussian, in units of the rms deviation.

$X_{obs} = 3$ Two-sided range

$X_{obs} = 1$ Upper limit

$X_{obs} = -2$ No region for μ

FELDMAN - COUSINS

Wants to avoid empty classical intervals $\rightarrow$

Uses "$\mathcal{L}$-ratio ordering principle" to resolve ambiguity about "which 90% region?"

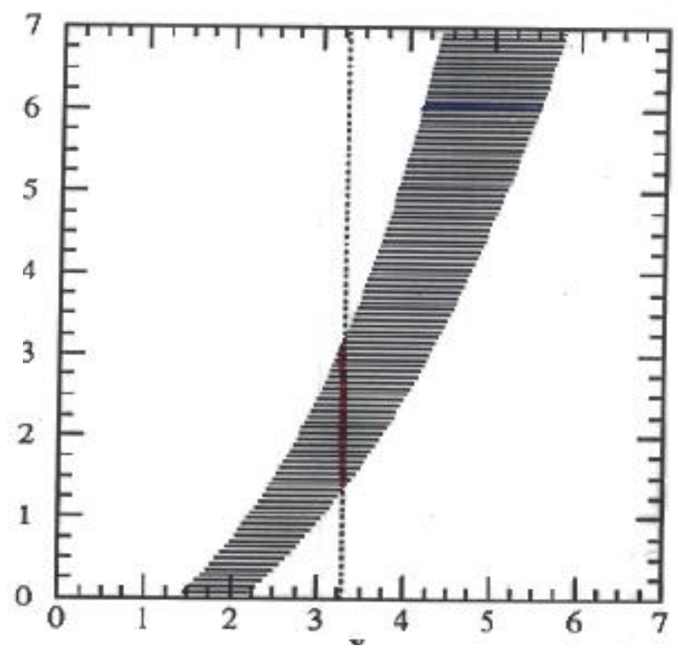
[Neyman + Pearson say $\mathcal{L}$-ratio is best for hypothesis testing]

Unified $\rightarrow$ No 'Flip-Flop' problem

Classical (Neyman) Confidence Intervals

Uses only P(data|theory)

Theoretical Parameter μ



Data x $\longrightarrow$

FIG. 1. A generic confidence belt construction and its use. For each value of μ, one draws a horizontal acceptance interval $[x_1, x_2]$ such that $P(x \in [x_1, x_2] | \mu) = \alpha$. Upon performing an experiment to measure x and obtaining the value x_0, one draws the dashed vertical line through x_0. The confidence interval $[\mu_1, \mu_2]$ is the union of all values of μ for which the corresponding acceptance interval is intercepted by the vertical line.

Example:

Param = Temp at centre of Sun

Data = Est. flux of solar neutrinos

$\text{Prob}(\mu_l < \mu < \mu_u) = \alpha$

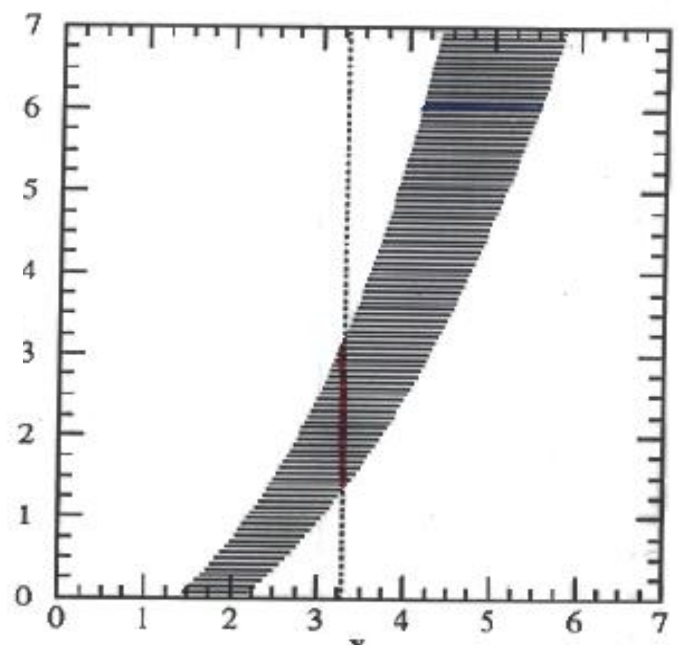
$\mu \geq 0$

No prior for μ

Classical (Neyman) Confidence Intervals

Uses only P(data|theory)

Theoretical Parameter μ



Data x

FIG. 1. A generic confidence belt construction and its use. For each value of μ, one draws a horizontal acceptance interval $[x_1, x_2]$ such that $P(x \in [x_1, x_2] | \mu) = \alpha$. Upon performing an experiment to measure x and obtaining the value x_0, one draws the dashed vertical line through x_0. The confidence interval $[\mu_1, \mu_2]$ is the union of all values of μ for which the corresponding acceptance interval is intercepted by the vertical line.

Data x	**μ range**
<1.5	Empty
1.5 – 2.2	Upper limit
>2.2	2-sided

Example:

Param = Temp at centre of Sun

Data = est. flux of solar neutrinos

μ≥0

No prior for μ

Feldman-Cousins 90% conf intervals

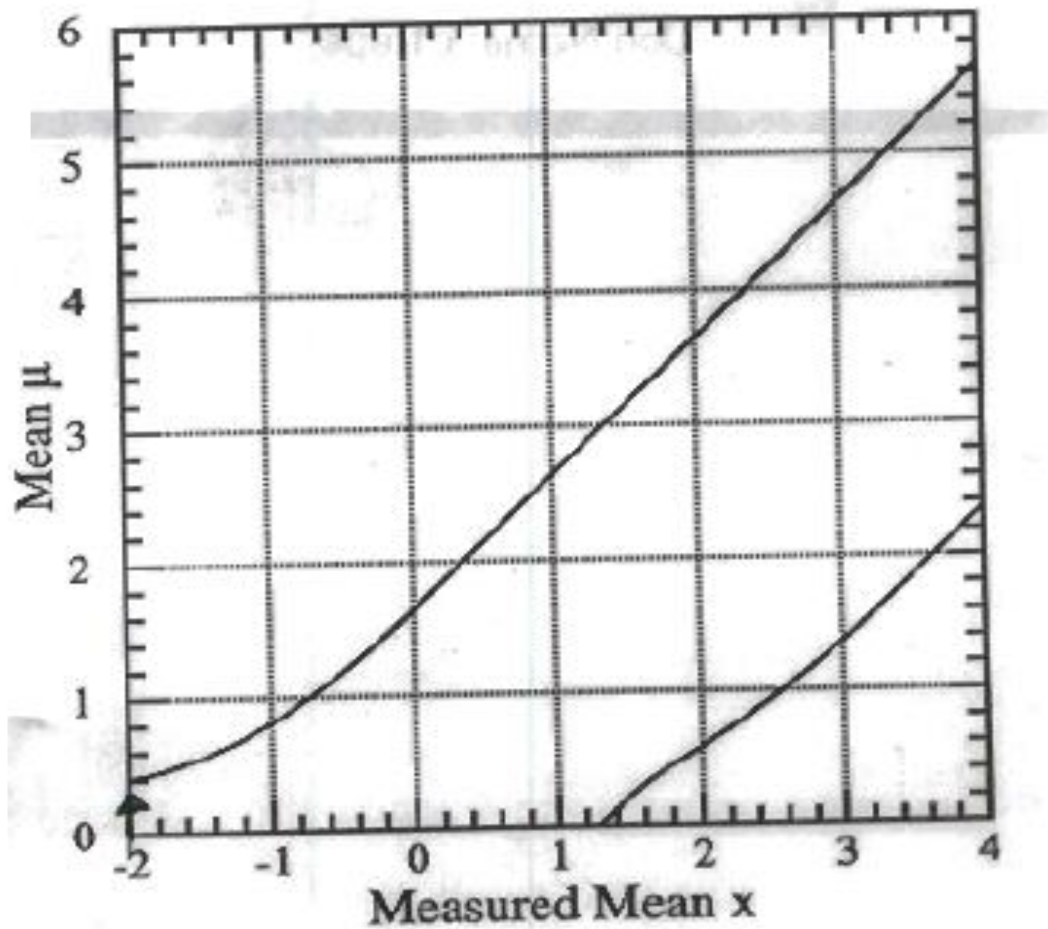
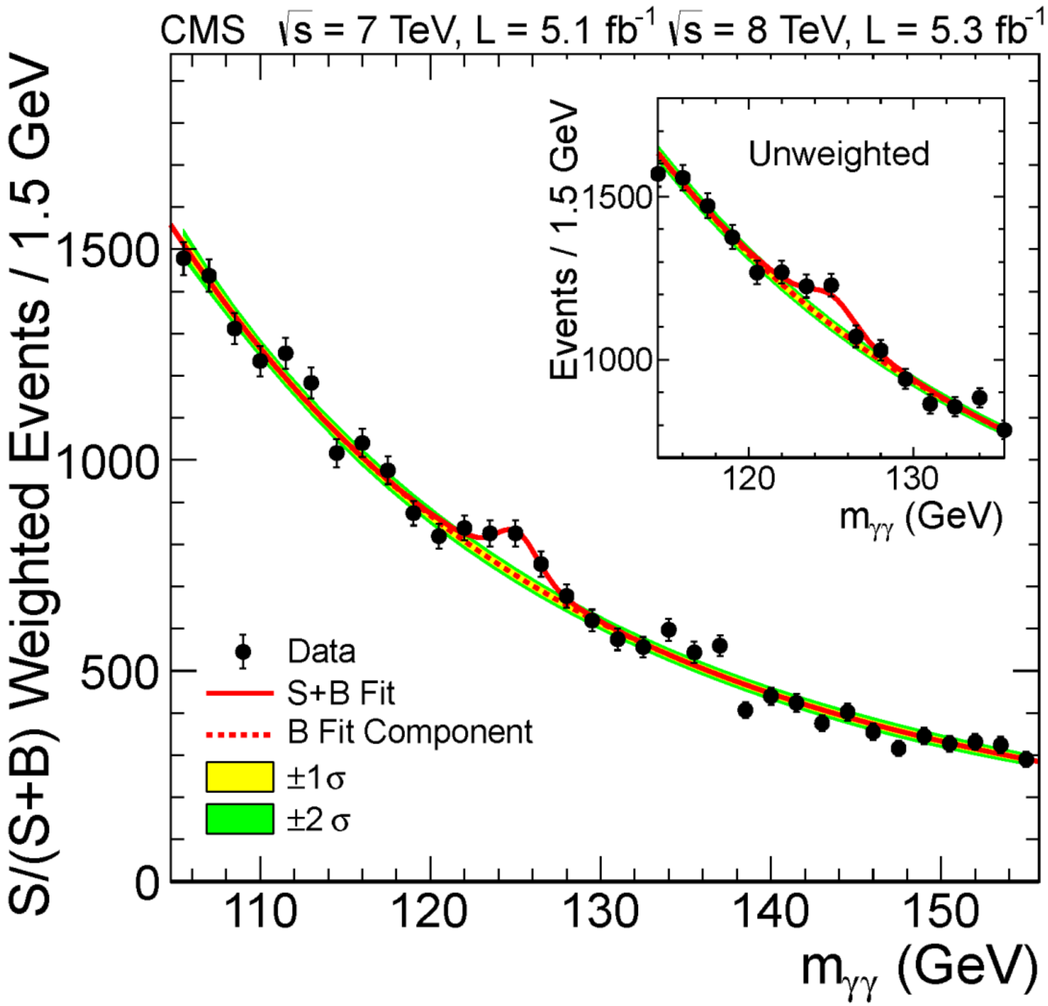


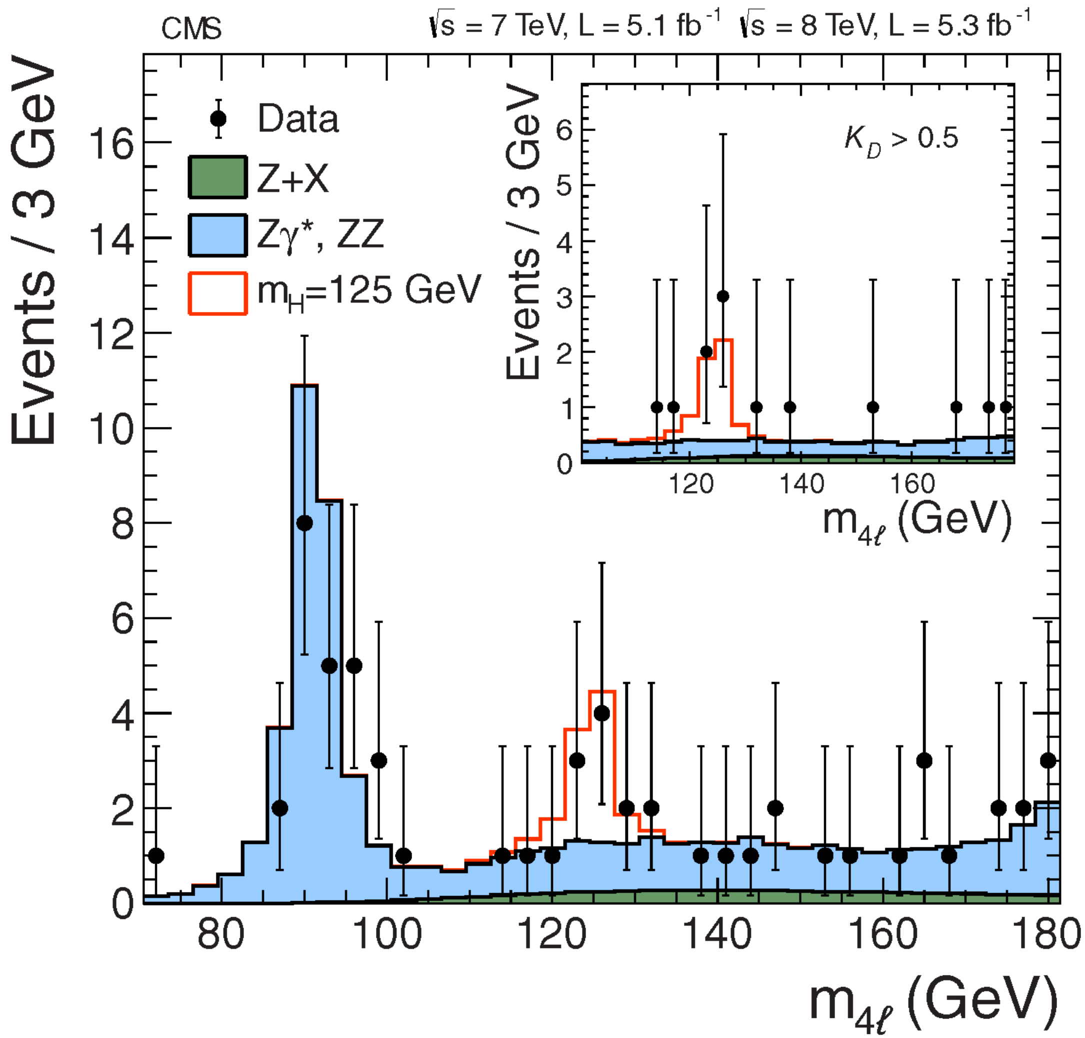
FIG. 10. Plot of our 90% confidence intervals for mean of a Gaussian, constrained to be non-negative, described in the text.

X_{obs} = -2 now gives upper limit

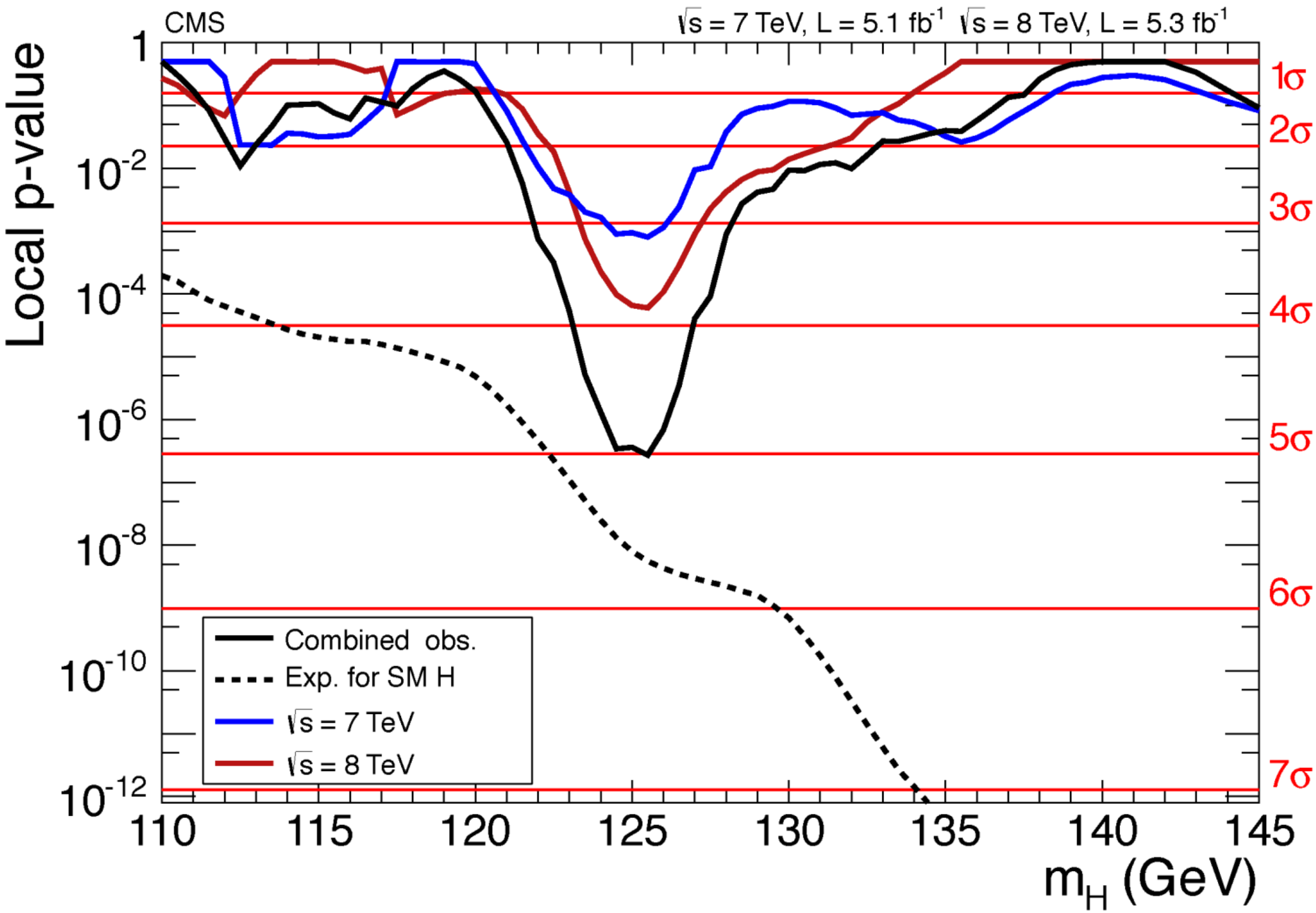
Search for Higgs: H→ γ γ: low S/B, high statistics

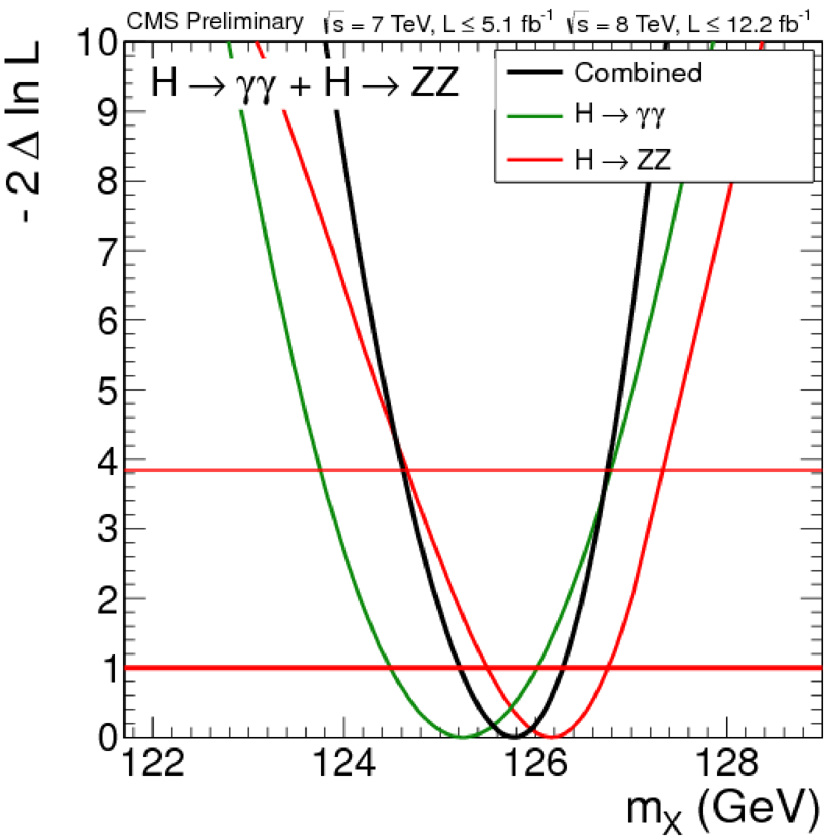


H→Z Z → 4 l: high S/B, low statistics

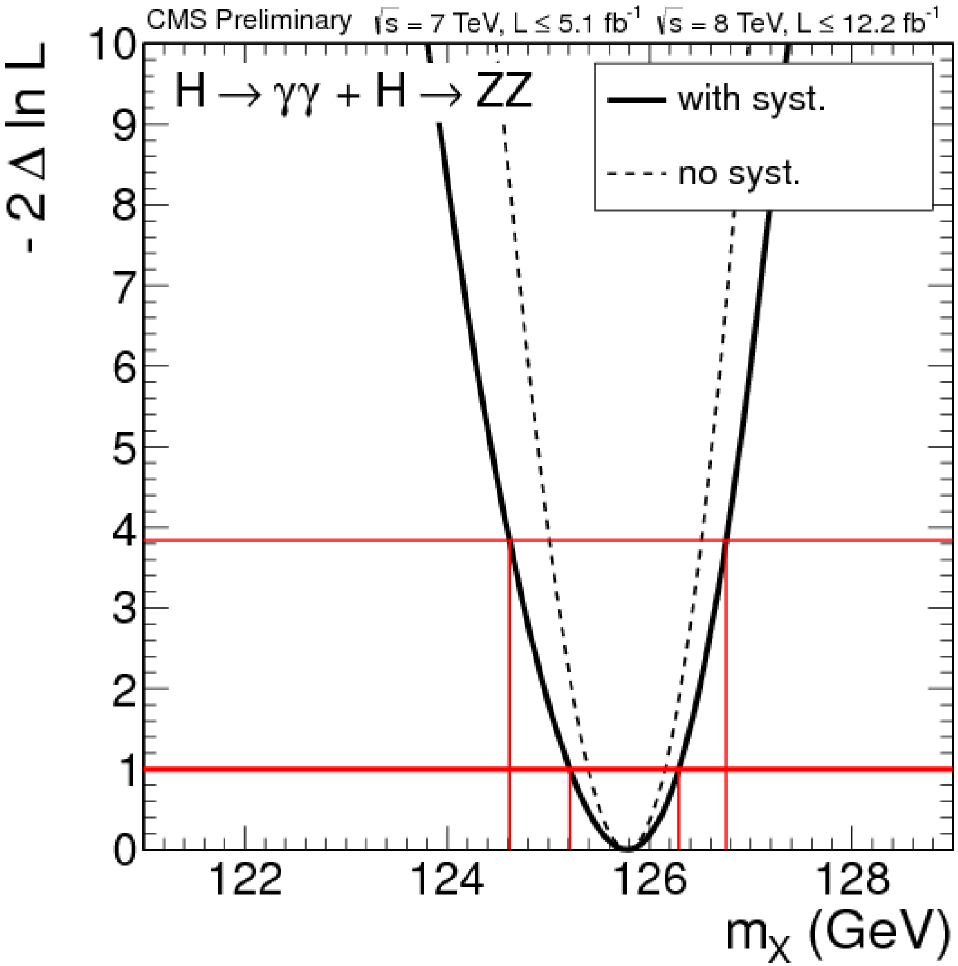


p-value for ‘No Higgs’ versus m_H



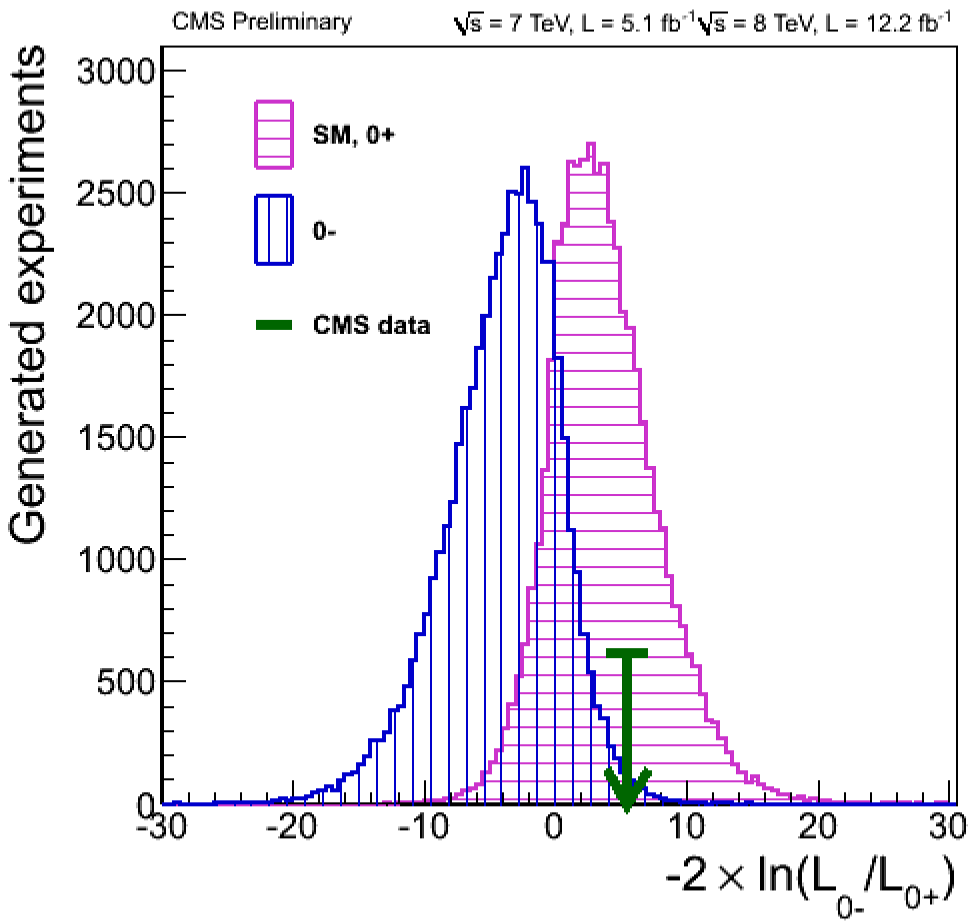


Mass of Higgs: Likelihood versus mass



Comparing 0^+ versus 0^- for Higgs

(like Neutrino Mass Hierarchy)



http://cms.web.cern.ch/news/highlights-cms-results-presented-hcp

Conclusions

Resources:

Software exists: e.g. RooStats

Books exist: Barlow, Cowan, James, Lyons, Roe,…..

New: `Data Analysis in HEP: A Practical Guide to Statistical Methods' , Behnke et al.

PDG sections on Prob, Statistics, Monte Carlo

CMS and ATLAS have Statistics Committees (and BaBar and CDF earlier) – see their websites

Before re-inventing the wheel, try to see if Statisticians have already found a solution to your statistics analysis problem.

Don't use a square wheel if a circular one already exists.

"Good luck"