Statistics for Particle Physics

1. Claim of discoveris based on sigma's

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Preamble

(First slides from AT seminars at CERN)

Statistics lectures?

If I insist on probability, rather than speaking, very generally, about statistics, it is because I have good reasons.

Statistics lectures?

As far as the laws of mathematics refer to reality,
they are not certain,
and as far as they are certain,
they do not refer to reality.
(Einstein)

Statistics lectures?

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Statistics lectures?

"If we were not ignorant there would be no probability, there could only be certainty. But our ignorance cannot be absolute, for then there would be no longer any probability at all. Thus the problems of probability may be classed according to the greater or less depth of our ignorance."
(Poincaré)

Statistics lectures?

"It is scientific only to say what is more likely and what is less likely"
(Feynman)

Statistics and truth (from lectures at CERN)

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- How to interpret the question?
  1. "Tell the Truth"?
     - What is the true value of a quantity?
     - What is the true theory that describes the world?
  2. "Tell the truth" $\Longleftrightarrow$ "to lie"?

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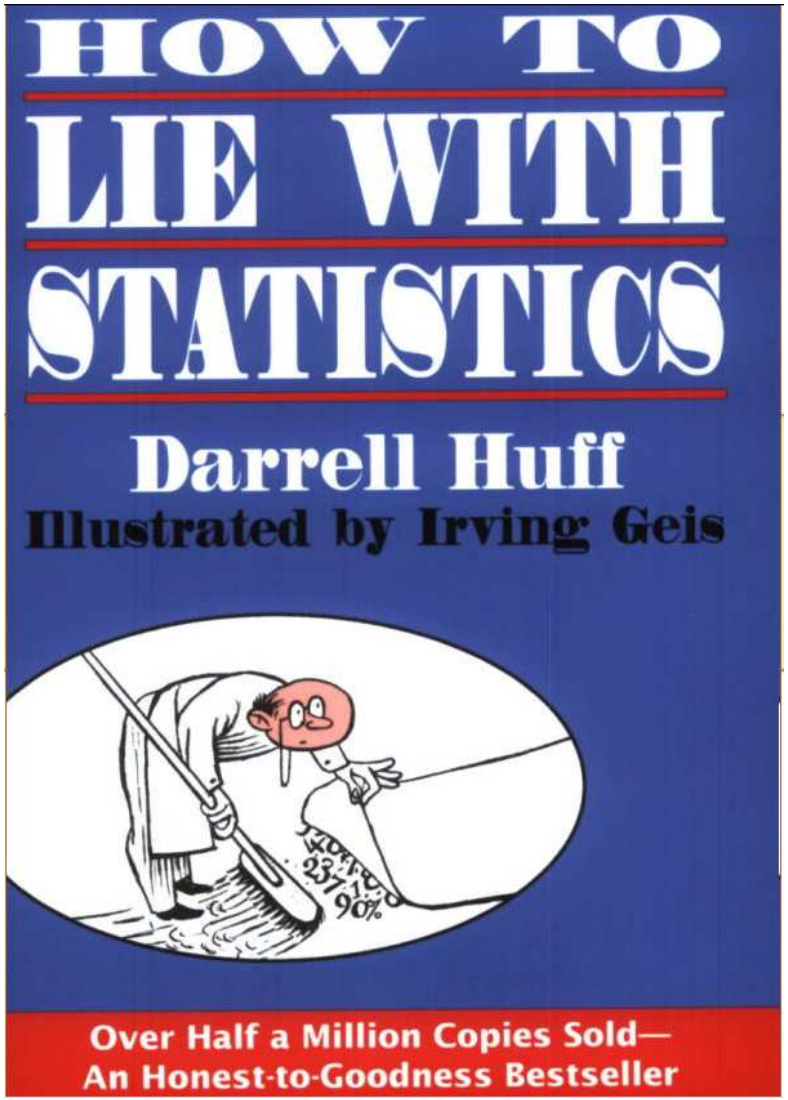
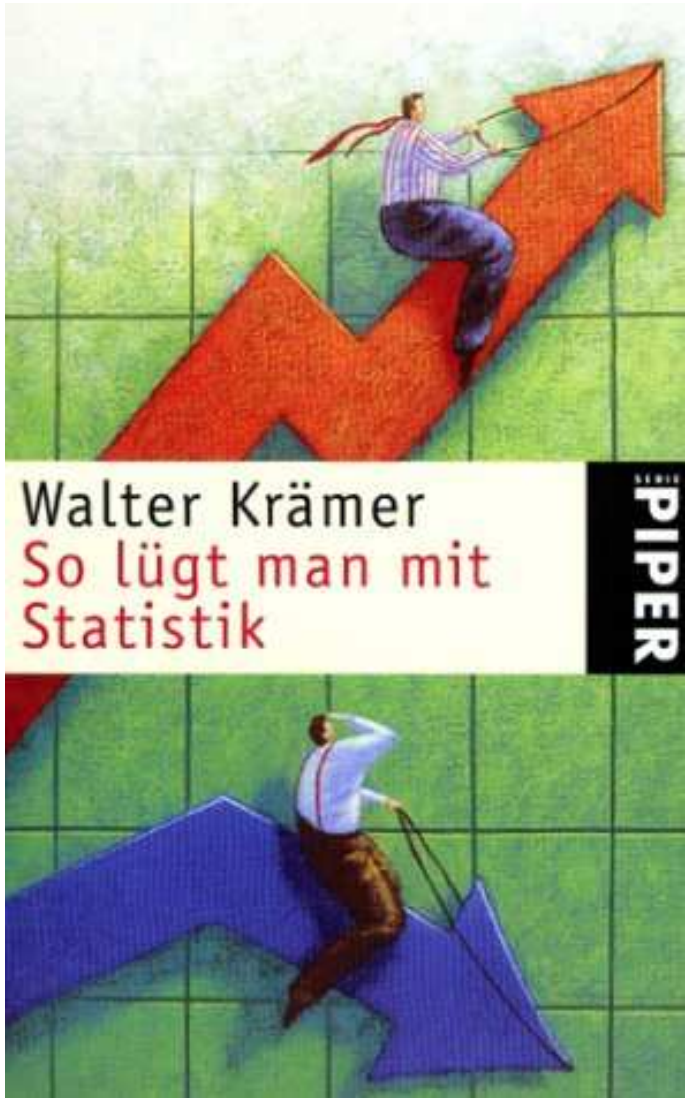
  2. ~~"Tell the truth" ⟺ "to lie"?~~ ⇒ Not fair, though

"There are three kinds of lies:
lies, damn lies, and statistics"
(Benjamin Disraeli/Mark Twain)

Damned lies and statistics

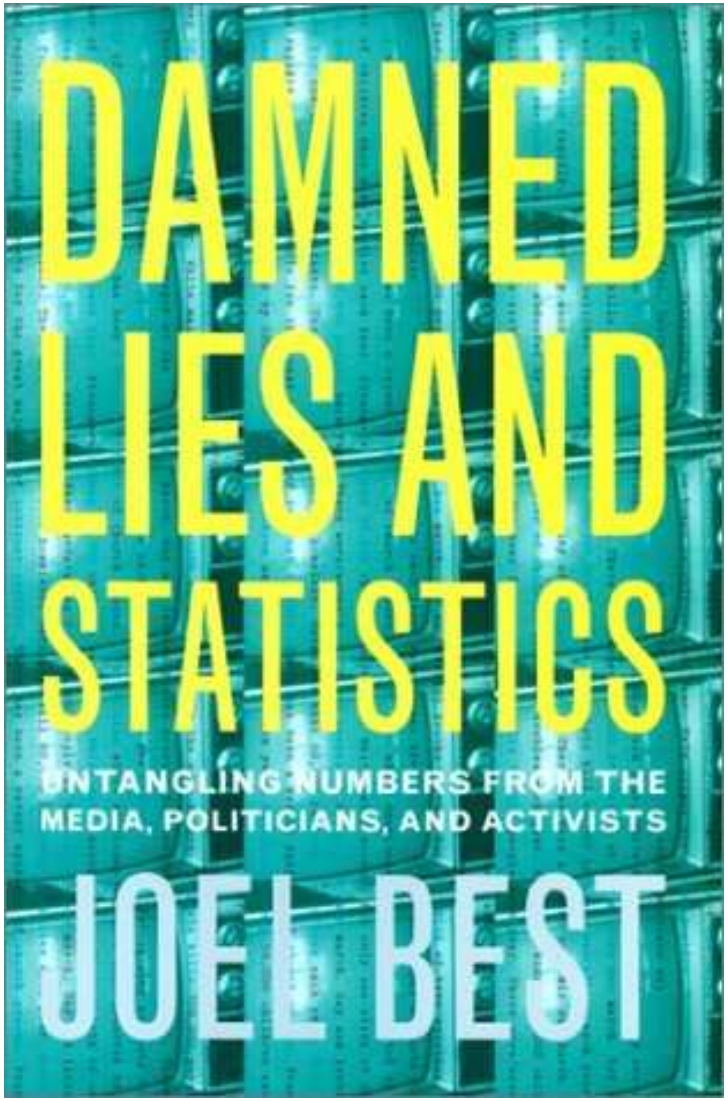
Well known subject

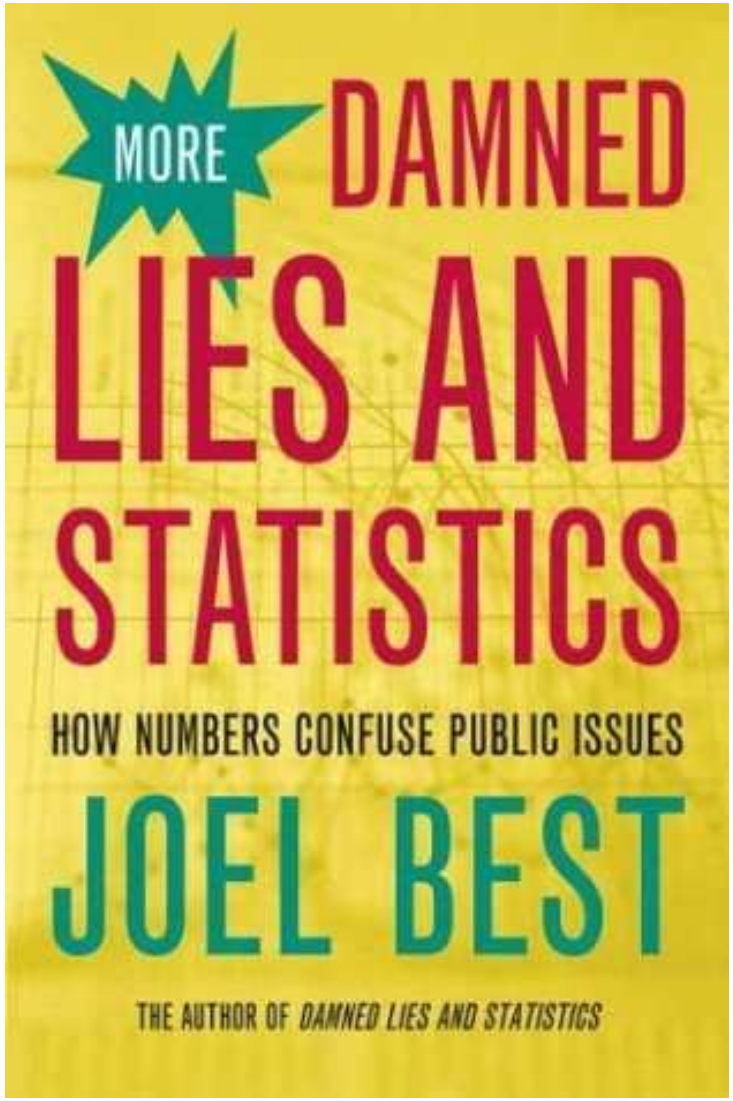




Damned lies and statistics

Well known subject, especially in marketing and politics





SCIENCE

Lies, Damned Lies and Physics

16 DEC 30, 2015 9:30 AM EST

By Faye Flam

To most of us, 93-to-1 odds would make for a clear-cut bet. To physicists? Not so much.

On Dec. 15, the New York Times reported that Santa may have brought physics a new subatomic particle, a hitherto unknown entity materializing in the giant collider at CERN, near Geneva. It wasn't a sure thing, but according to the Times, the odds are in the scientists' favor, with only a 1-in-93 chance that the data pointing to the particle represent a statistical fluke.

The New York Times

SCIENCE

Physicists in Europe Find Tantalizing Hints of a Mysterious New Particle

By DENNIS OVERBYE DEC. 15, 2015

Researchers at the Large Hadron Collider at CERN are smashing together protons to search for new particles and forces.
Fabrice Coffrini/Agence France-Presse — Getty Images

Does the Higgs boson have a cousin?

Two teams of physicists working independently at the Large Hadron Collider at CERN, the European Organization for Nuclear Research, reported on Tuesday that they had seen traces of what could be a new fundamental particle of nature.

One possibility, out of a gaggle of

New York Times, 15 December 2015

"I don't think there is anyone around who thinks this is conclusive," said Kyle Cranmer, a physicist from New York University who works on one of the CERN teams, known as Atlas. "But it would be huge if true," he said, noting that many theorists had put their other work aside to study the new result.

When all the statistical effects are taken into consideration, Dr. Cranmer said, the bump in the Atlas data had about a 1-in-93 chance of being a fluke — far stronger than the 1-in-3.5-million odds of mere chance, known as five-sigma, considered the gold standard for a discovery. That might not be enough to bother presenting in a talk except for the fact that the competing CERN team, named C.M.S., found a bump in the same place.

Le Scienze, 19 dicembre 2015

Le Scienze
EDIZIONE ITALIANA DI SCIENTIFIC AMERICAN

Tracce di ener
Come risolvere il mi
dell'espansione acc
In edicola dal 4 ge

ABBONAMENTI E RINN

ZOOM SU optogenetica epidemiologia longevità Internet visione

19 dicembre 2015

Qualcosa di nuovo da LHC? Solo il tempo lo dirà

(Cortesia Maximilien Brice/CERN)

Nuovi dati degli esperimenti ATLAS e CMS del Large Hadron Collider del CERN di Ginevra hanno mostrato un eccesso nella produzione di coppie di fotoni, localizzato a una massa particolare. Ma è ancora troppo presto per dire se sia un primo segno di una nuova era per la fisica delle particelle oppure solo una fluttuazione del rumore di fondo *di Marco Delmastro*

Le Scienze, 19 dicembre 2015

Nel caso dell'eccesso sullo spettro delle coppie di fotoni, se uno prende il grafico di ATLAS in cui la montagnola è più prominente, la probabilità che questa sia dovuta a una casualità è due su 10.000, dunque piuttosto piccola. Quando però consideriamo il fatto di aver cercato montagnole un po' dappertutto, allora questa probabilità aumenta a due su 100. I numeri di CMS sono persino più grandi, indicando una probabilità ancora più grande che si tratti solo di una fluttuazione del rumore di fondo.

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"In the case of the excess in the two-photon spectrum, if one takes the ATLAS plot, where the bump is more prominent, the probability that this is due to randomness is 2 in 10,000, then rather small. When instead we consider the fact that we have been looking bumps everywhere, this probability increases to 2 in 100. CMS numbers are even larger, indicating an even larger probability that it is just a fluctuation of the background."

A surreal dialogue of a friend of mine with the author

Amico: Nell'articolo è scritto: "...la probabilità che questa sia dovuta a una casualità è due su 10.000, dunque piuttosto piccola. Quando però consideriamo il fatto di aver cercato montagnole un po' dappertutto, allora questa probabilità aumenta a due su 100."

Se capisco bene, lei stima a $(1 - 0.02) = 0.98$ la probabilità che NON si tratti di una fluttuazione casuale nell'ipotesi peggiore.

Cioè ne siamo praticamente certi?

A surreal dialogue of a friend of mine with the author

Friend: In the article there is written "...the probability that is due to randomness is two in 10000, hence rather low. When however we take into account the fact that we have been searching for bumps everywhere, this probability rises to two in 100."

If I understand well, you estimate in $(1 - 0.02) = 0.98$ the probability that is NOT a random fluctuation, in the worst hypothesis.

Does it mean we are almost certain of it?

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Autore: Ciao,

Due commenti:

1) non puoi trasformare la probabilità dell'ipotesi nulla in quella dell'ipotesi di scoperta così. Che ci sia il 2% di probabilità che l'eccesso sia dovuto alla fluttuazione del fondo non vuol dire che c'è il 98% di probabilità che l'eccesso sia generato da un segnale genuino. I p-valori sono complicati ;-)

2) il 2% che si tratti di una fluttuazione non è una probabilità piccola!

A surreal dialogue of a friend of mine with the author

Author: Ciao,

Two comments:

1) you cannot transform so the probability of the null hypothesis in that of the hypothesis of discovery. The fact that there is 2% probability that the excess is due to a fluctuation of the background does not mean that there is 98% probability that the excess is generated by a genuine signal. P-values are complicate ;-)

2) 2% of being a fluctuation is not a small probability!

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Amico: Perdonami, non è questione di p-value, [. . .]
Ma del senso letterale di quello che scrivi:

Se A è l'affermazione "questa sia dovuta a una casualità", tu dici che $P(\text{A}) = 2\%$

Ergo $P(\text{non-A}) = 98\%$ perché $P(\text{A}) + P(\text{non-A}) = 1$ sta negli assiomi della probabilità.
O no?

A surreal dialogue of a friend of mine with the author

Friend: Excuse me, it isn't a matter of p-values, [. . .]
but of the literal meaning of what you wrote:

If A is the statement "this is due to randomness", you state that $P(\text{A}) = 2\%$

Therefore $P(\text{non-A}) = 98\%$ because $P(\text{A}) + P(\text{non-A}) = 1$ is in the axioms of probability.
Or not?

A surreal dialogue of a friend of mine with the author

Autore: Ciao,

No, purtroppo si tratta proprio di p-value, e del confronto tra probabilità condizionali e non condizionali tra due ipotesi. Tutto questo nell'articolo per le Scienze ovviamente non c'è, e li ho dovuto "tradurre" per il pubblico non-tecnico in termini (approssimati) di probabilità tradizionale una trattazione in realtà più complessa. Se però ti interessa fare una discussione formale, allora mi spiace ma non è quell'articolo a cui devi fare referenza, ma questo:

`https://cds.cern.ch/record/2114853`
(vedi per esempio la sezione 8 e le sue referenze).

Buona lettura, M.

A surreal dialogue of a friend of mine with the author

Author: Ciao,

No, unfortunatly it is indeed about p-values, and the comparison between conditional and non conditional probabilities of two hypotheses. All this in the Le Scienze article is obviously missing, and I had to "translate" a treatment in reality much more complex for the general public in (approximated) terms of traditional probability . If however your interested in a formal discussion, then I am sorry but it is not that article that you have to take as reference, but this one:

`https://cds.cern.ch/record/2114853`
(see for example section 8 and references therein).

Have a nice reading, M.

(Gibberish for Italians... [wiki/Supercazzola#Origine])

Mascetti: Tarapia tapiòco! Prematurata la supercazzola, o scherziamo?
Vigile: Prego?
Mascetti: No, mi permetta. No, io...scusi, noi siamo in quattro. Come se fosse antani anche per lei soltanto in due, oppure in quattro anche scribai con cofandina? Come antifurto, per esempio.
Vigile: Ma che antifurto, mi faccia il piacere! Questi signori qui stavano sonando loro. 'Un s'intrometta!
Mascetti: No, aspetti, mi porga l'indice; ecco lo alzi così...guardi, guardi, guardi. Lo vede il dito? Lo vede che stuzzica? Che prematura anche? [...]
Vigile: [...] mi seguano al commissariato, prego!
Perozzi: No, no, no, attenzione! Noo! Pastene soppaltate secondo l'articolo 12, abbia pazienza, sennò posterdati, per due, anche un pochino antani in prefettura...
Mascetti: ...senza contare che la supercazzola prematurata ha perso i contatti col tarapia tapioco.

(https://www.youtube.com/watch?v=IoEK2Z

Remember

"It is scientific only to say
what is more likely
and what is less likely"

(Feynman)

Statistics Vs Probability $\longrightarrow$

Defining the issue

What do we mean by "statistics"?

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Usually several things:

- **descriptive** statistics [e.g. Webster's (Kdict)]
  - "The science which has to do with the collection and classification of certain facts respecting the condition of the people in a state."
  - "(pl.) Classified facts respecting the condition of the people in a state, their health, their longevity, . . . especially, those facts which can be stated in numbers, or in tables of numbers, or in any tabular and classified arrangement."
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- **Inference** $\Rightarrow$ primary interest to physicists

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. . . and all together:

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> Though we physicists are usually not interested in population parameters, but rather on physics quantities, theories, and so on.
>
> Inference: learning about theoretical objects from experimental observations (see later)

Where are the problems?

Descriptive statistics Little to comment, apart that the process of summarizing '*a State*' in a few numbers, in a diagram or in a table causes an enormous loss of detailed information, and this might lead to misunderstandings or even 'lies'.

$\Rightarrow$ the famous 'half chicken' joke.[†]

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Inference Messy:

- Traditionally, a collection of *ad hoc* prescriptions . . . accepted more by authority than by full awareness of what they mean

$\Rightarrow$ The physicist is confused† between good sense and statistics education

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Inference Do better?

- Much improvement is gained if inference is grounded on probability theory
- Summaries of descriptive statistics can be used in those cases in which *statistical sufficiency* holds
  (e.g. when we use the sample arithmetic average and standard deviation, instead of the n data points)

Statistics $\leftrightarrow$ probability

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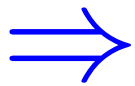

2011: non only Opera...

- April, CDF: absolutely unexpected excess at about 150 GeV

$$\approx 3.2\,\sigma$$

- September, Opera: neutrinos faster than light

$$\approx 6\,\sigma$$

- December, ATLAS e CMS at LHC: signal compatible with the Higgs at about 125 GeV:

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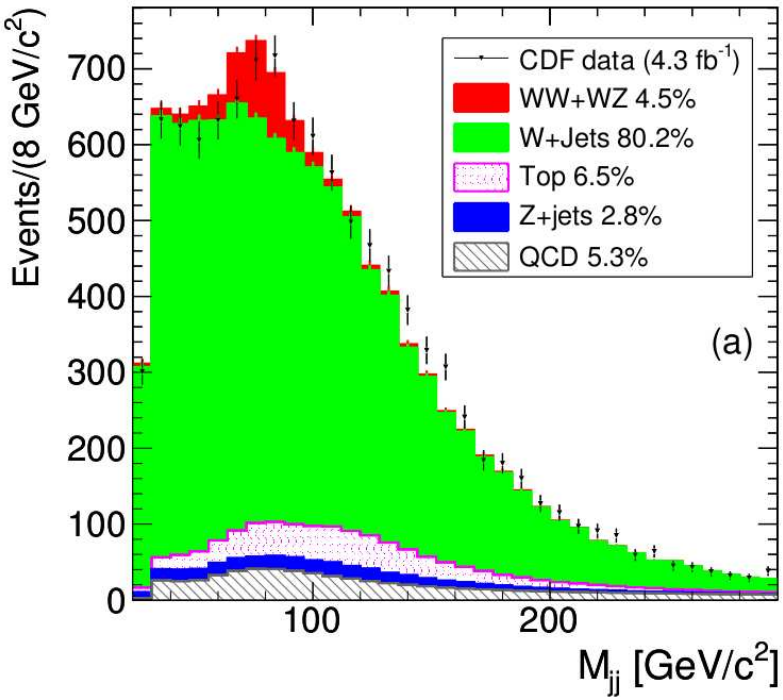
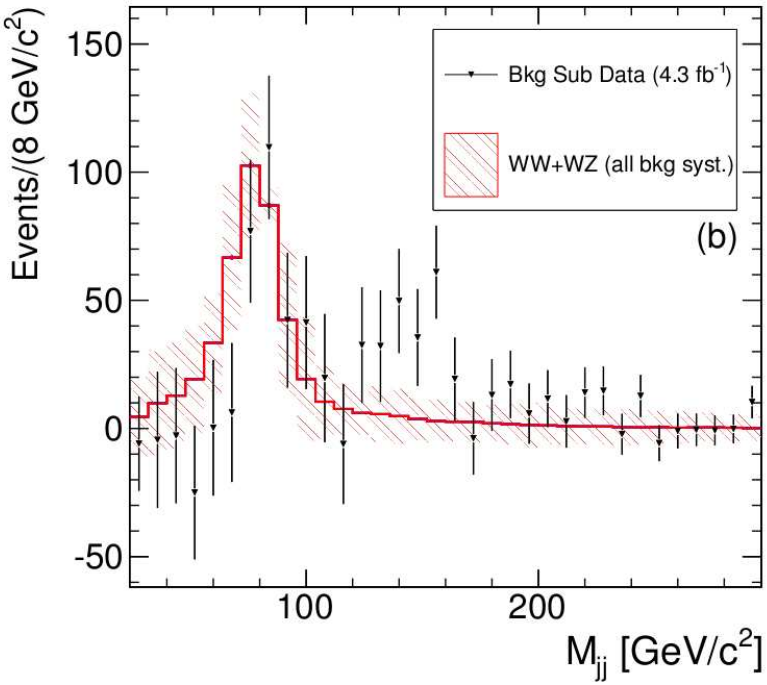
Why there was substancial scepticism towards the first two anouncements, in constrast with a cautious/pronounced optimism towards the third one?

April 2011

CDF Collaboration at the Tevatron





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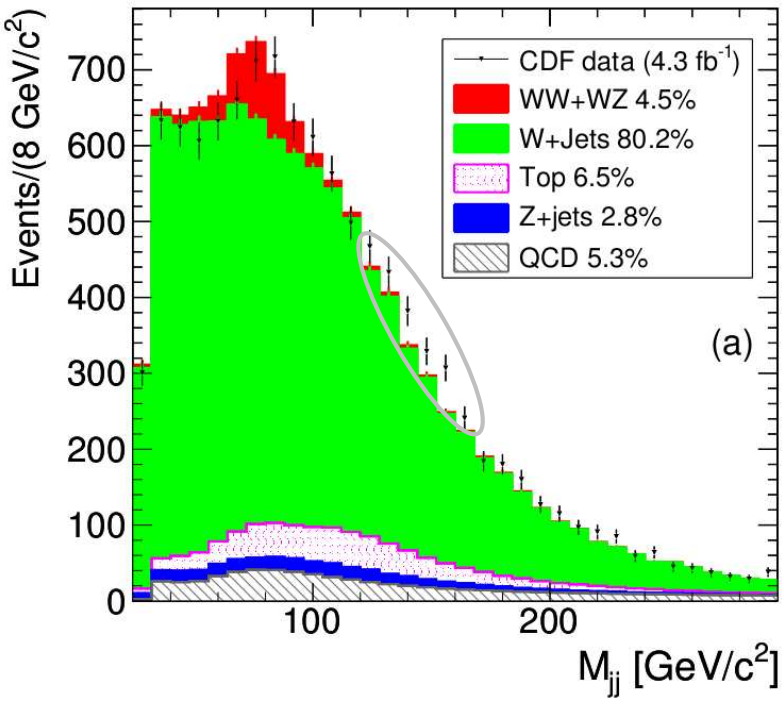

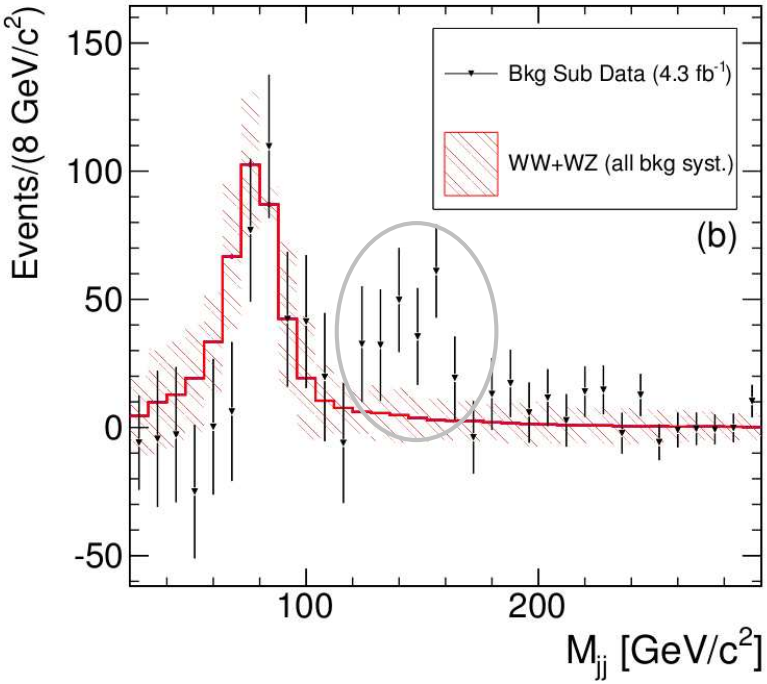

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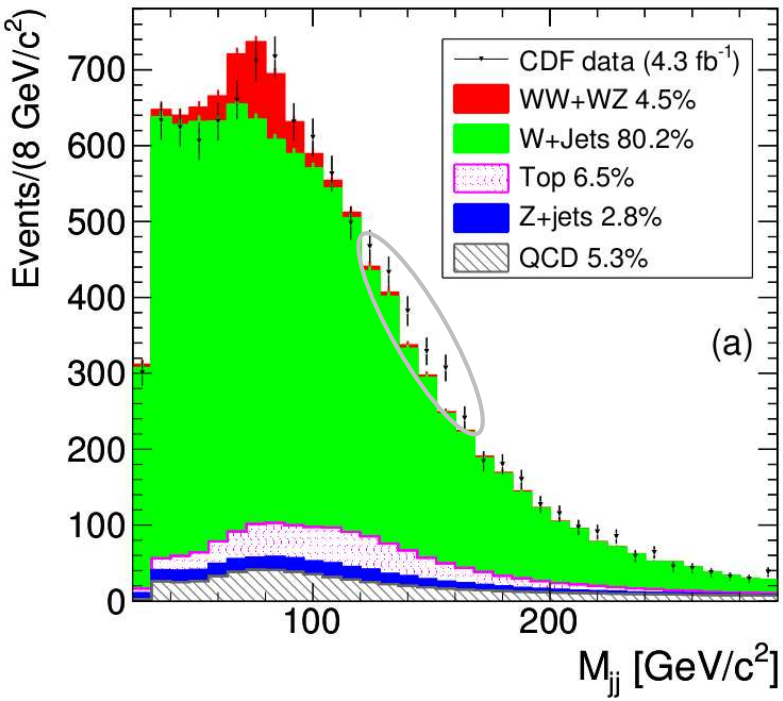

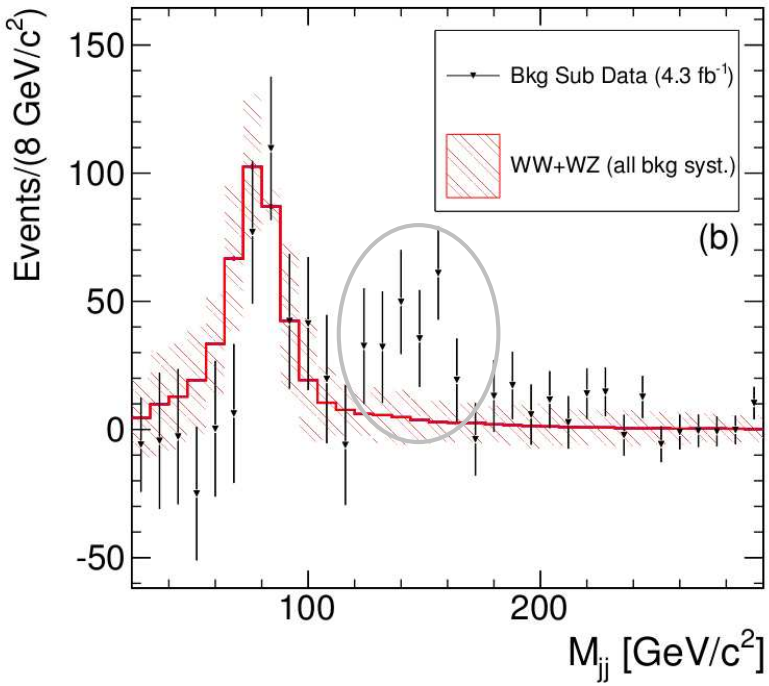

"we obtain a p-value of 7.6×10^{-4}, corresponding to a significance of 3.2 standard deviations"

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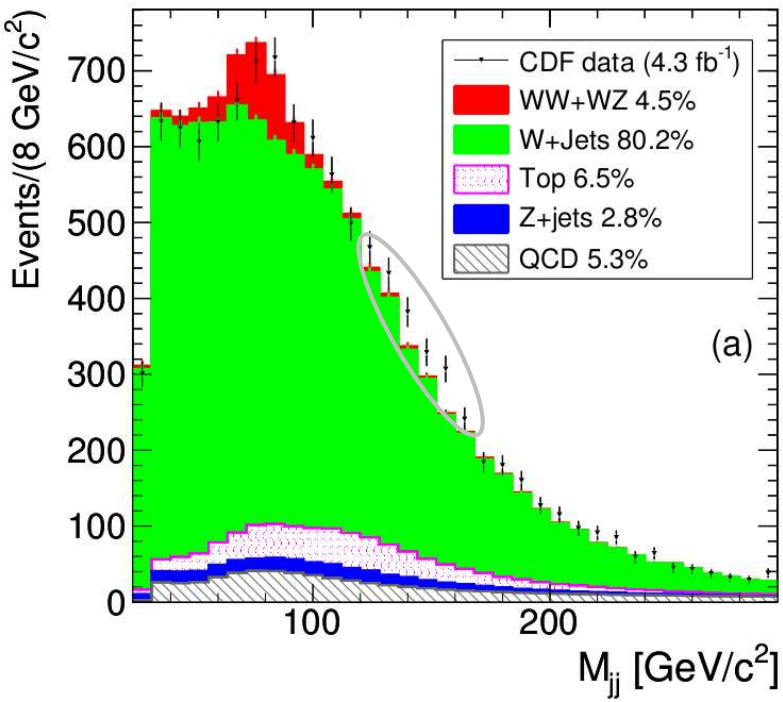

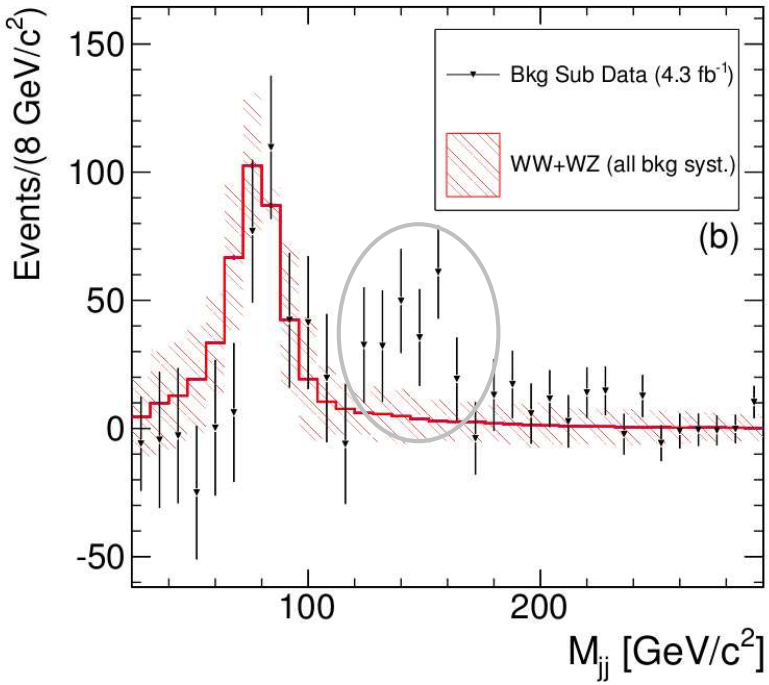

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$3.2\,\sigma$!

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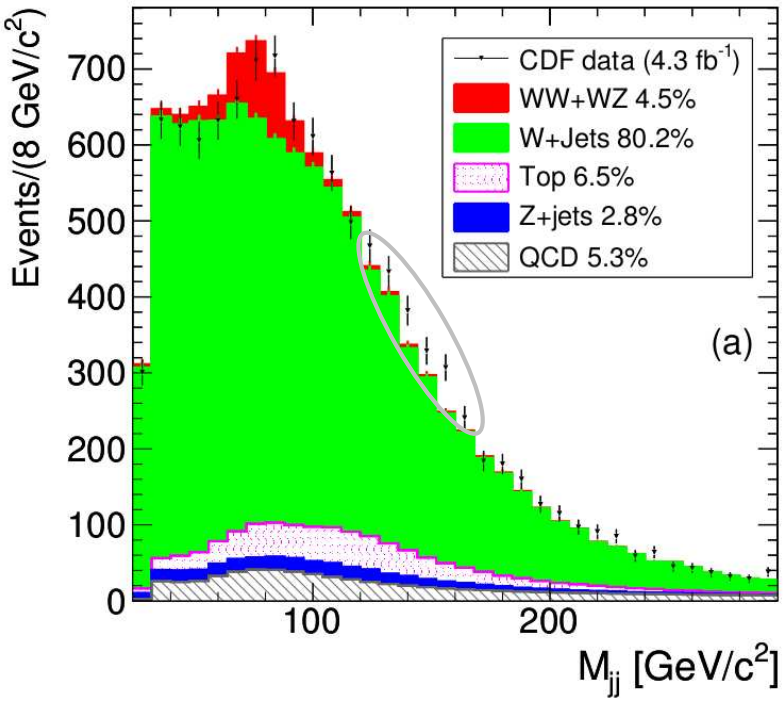
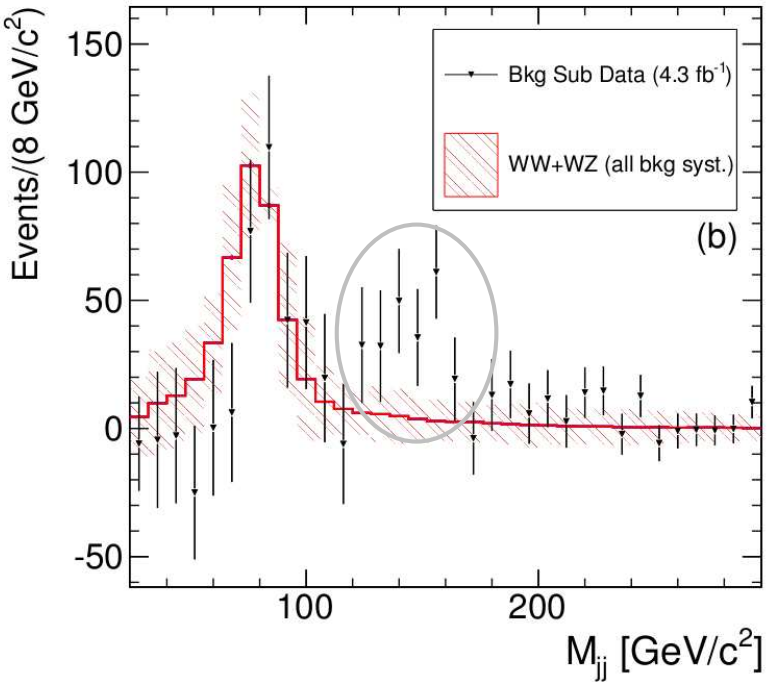
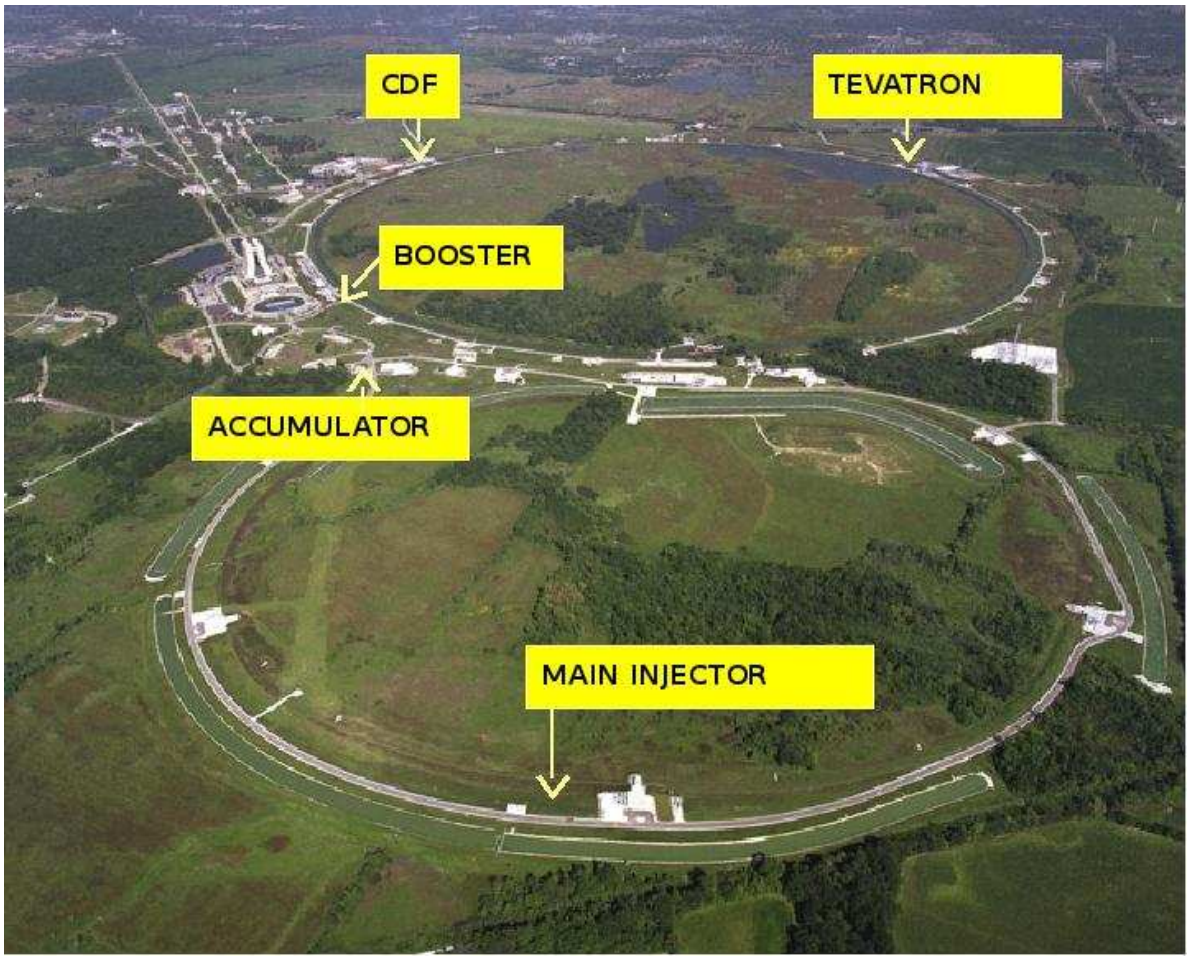




What does it mean?

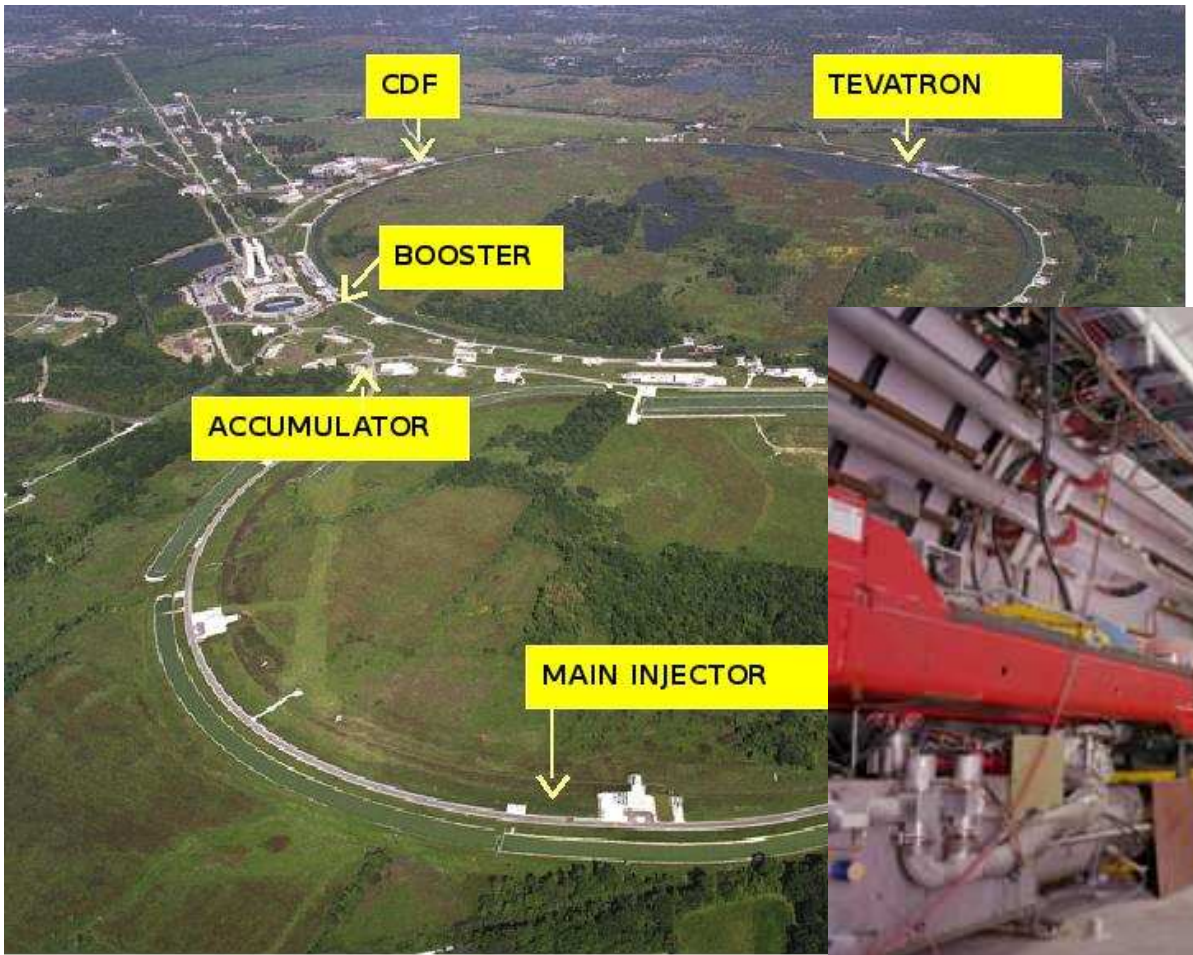
Tevatron and CDF

6.28 km, near Chicago



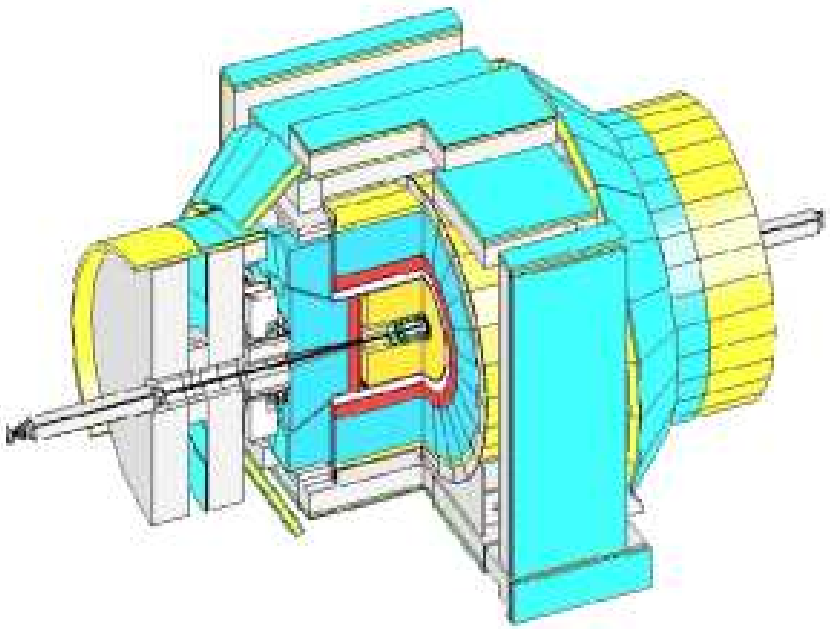
Tevatron and CDF

$p \rightarrow \cdot \leftarrow \overline{p}$ $\qquad [\approx 1\,\text{TeV} + 1\,\text{TeV}]$



Tevatron and CDF

CDF: a multipurpose ('hermetic') detector

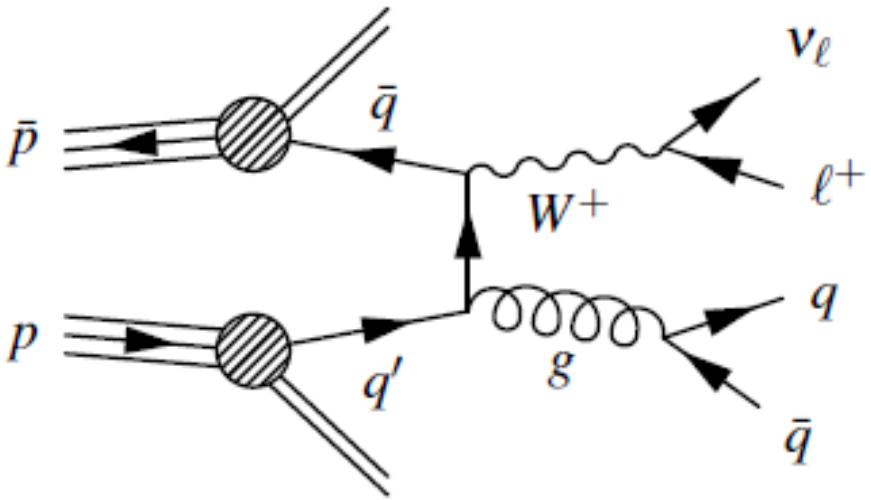


Tevatron and CDF

. . . a large, very sophisticated detector!

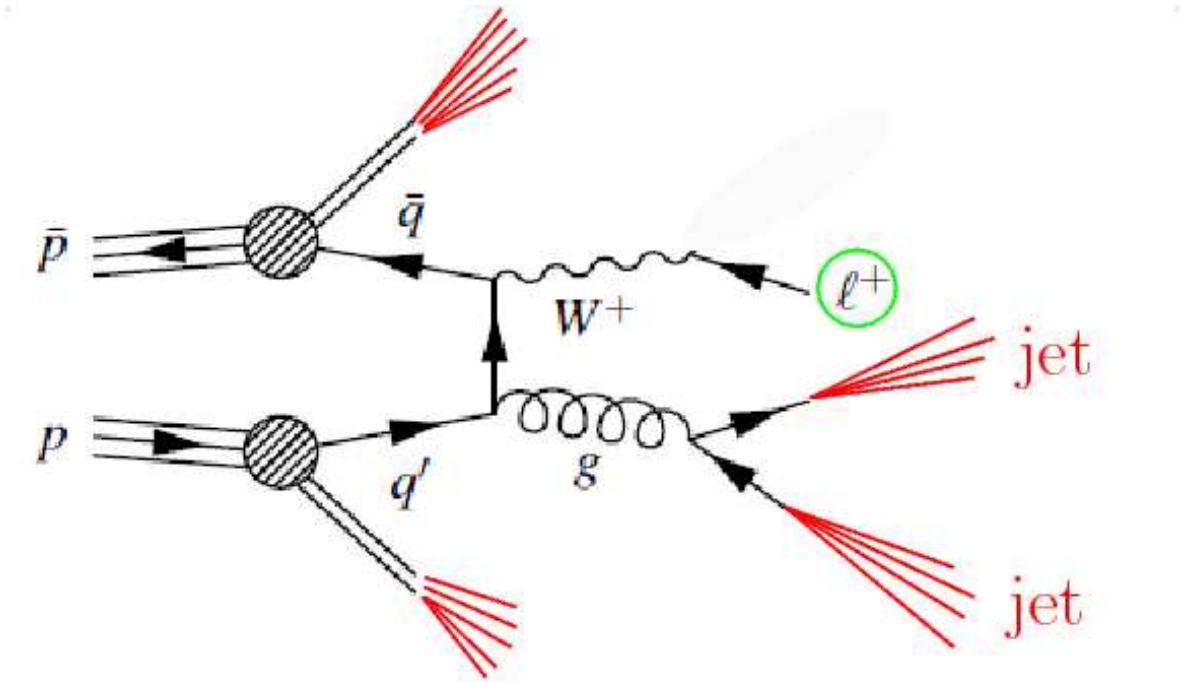
Jet-jet + W

$W + (q\overline{q})$ [+ 'remnants']



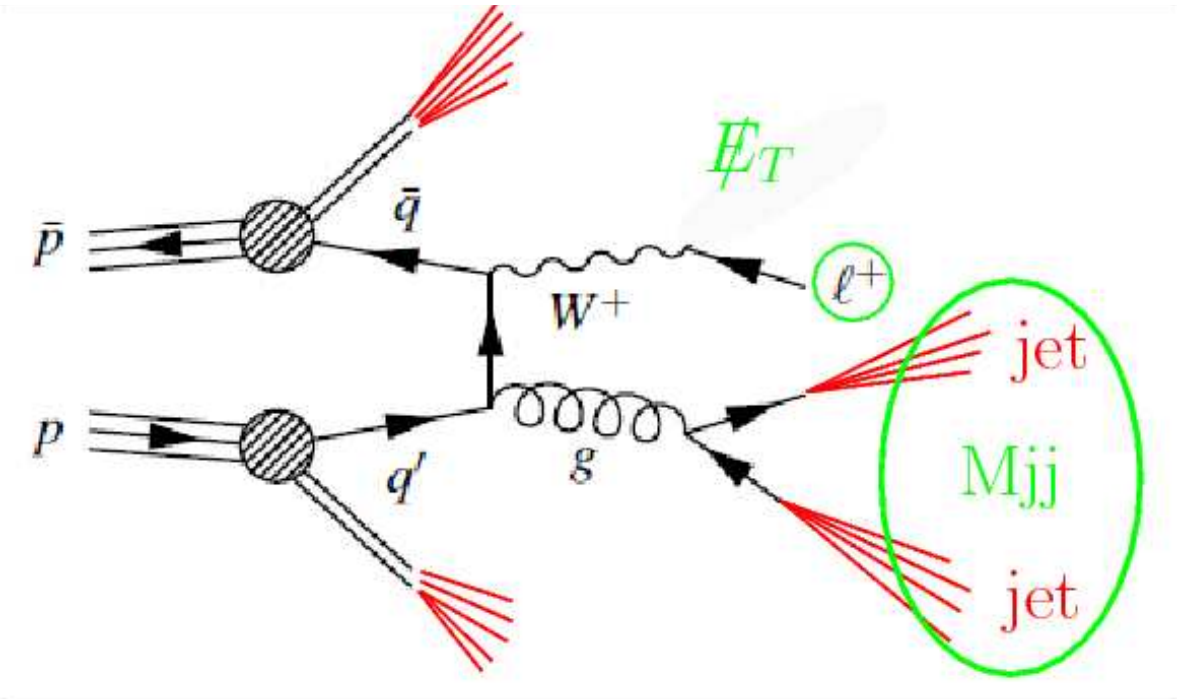
Jet-jet + W

W + 2jet [+ much more]



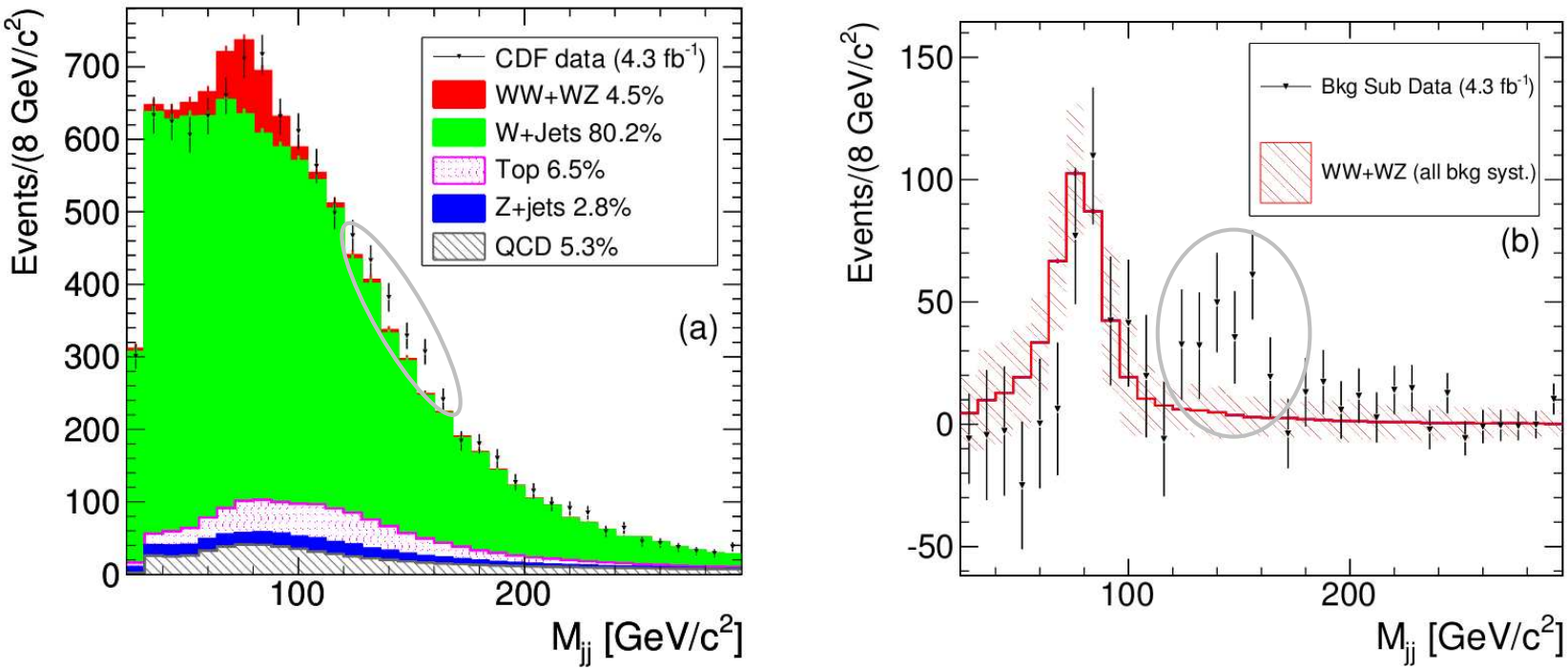
Jet-jet + W

$\Rightarrow M_{jj} + W + \ldots$



The 'bump' !

Invariant Mass Distribution of Jet Pairs Produced in Association with a W boson in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV", (CDF, 4 aprile 2011)



"we obtain a p-value of 7.6×10^{-4}, corresponding to a significance of 3.2 standard deviations" ["$3.2\,\sigma$"]

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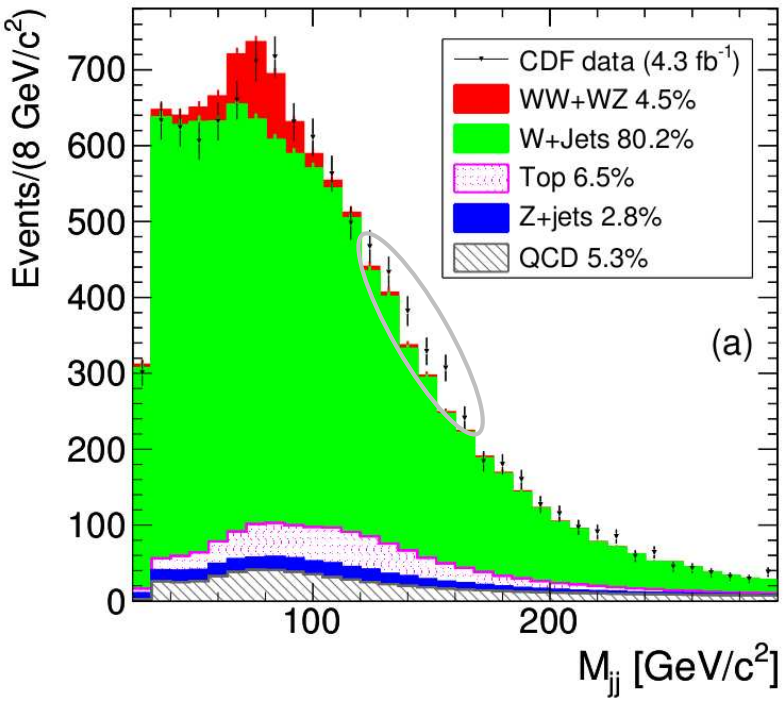
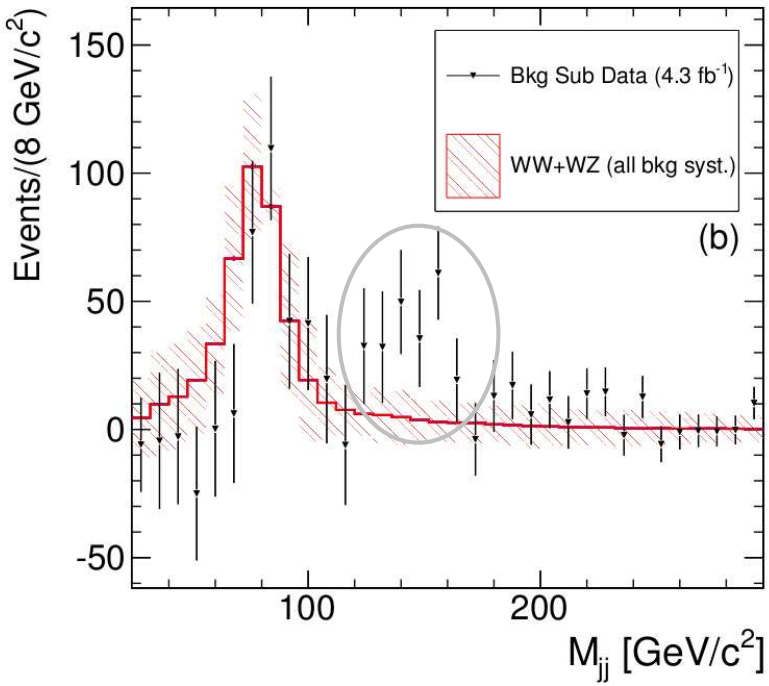




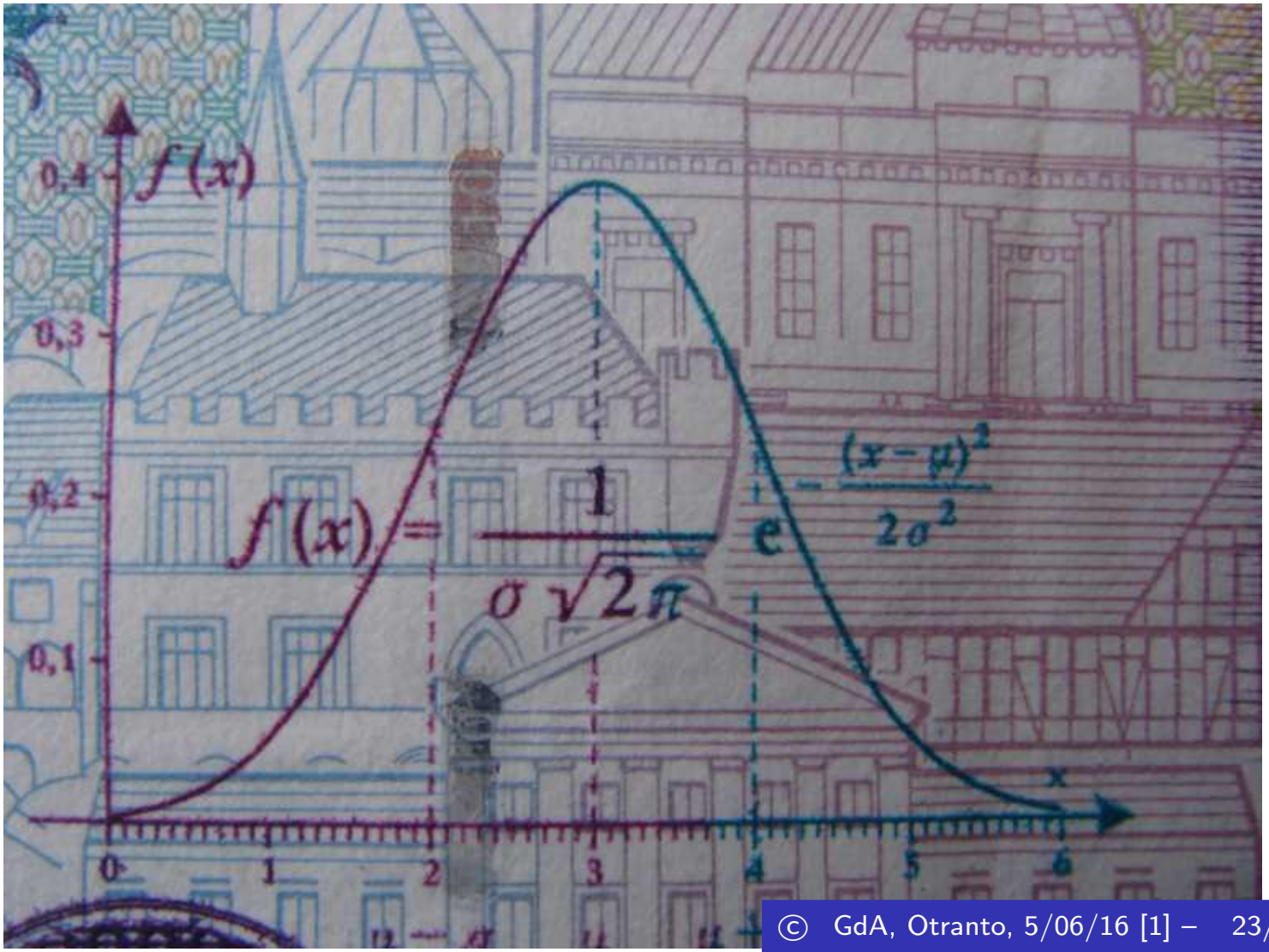
What does it mean?

Sigma and gaussian distribution

Princeps mathematicorum

Sigma and gaussian distribution

"Functio nostra fiet..."



Sigma e probability [gaussian!]

If the random number X is described by a gaussian pdf

$$
\begin{aligned}
P(-\sigma \leq X \leq +\sigma) &= 68.3\% \\
P(-2\,\sigma \leq X \leq +2\,\sigma) &= 95.4\% \\
P(-3\,\sigma \leq X \leq +3\,\sigma) &= 99.73\% \\
1 - P(-3\,\sigma \leq X \leq +3\,\sigma) &= 0.27\% \\
1 - P(-4\,\sigma \leq X \leq +4\,\sigma) &= 6.3 \times 10^{-5} \\
\ldots &= \ldots \\
1 - P(-6\,\sigma \leq X \leq +6\,\sigma) &= 2.0 \times 10^{-9}
\end{aligned}
$$

$$
\begin{aligned}
1 - P(-3.2\,\sigma \leq X \leq +3.2\,\sigma) &= 1.4 \times 10^{-3} \\
P(X \geq +3.17\,\sigma) &= 7.6 \times 10^{-4} \quad \surd
\end{aligned}
$$

p-value, significance and sigma

"we obtain a p-value of 7.6×10^{-4}, corresponding to a significance of 3.2 standard deviations" ["$3.2\,\sigma$"]

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- In so far does it provides us a **'significance'**?

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In short,

- Is $\mathbf{7.6 \times 10^{-4}}$ a **probability**?
- **of what**?

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The New York Times, Tuesday, April 5:

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Eureka!!

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[Do not ask me how 7.6×10^{-4} becomes $< 2.5 \times 10^{-3}$
(but this can be considere a minor detail...)]

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- the journalist who reported the news?
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From my experience, journalists might make imprecisions, bad they do not invent pieces of news [. . . at least scientific ones. . . :-)]

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In other terms, *we do not organize an official seminar in the physics department everytime a student 'discovers' a new effect in the lab!*

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> *"Wednesday afternoon, the CDF collaboration announced that it has evidence of a peak in a specific sample of its data. The peak is an excess of particle collision events that produce a W boson accompanied by two hadronic jets. This peak showed up in a mass region where we did not expect one.*
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$1/1375 = 7.3 \times 10^{-4} \;\Rightarrow\; P(\text{No stat. fluct.}) = 99.93\%$!

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> *This is a big week for particle physicists, and even they will be having many sleepless nights over the coming months trying to grasp what it all means.*
> *That's what happens when physicists come forward, with observational evidence, of what they believe represents something we've never seen before. Even bigger than that: something we never even expected to see.*
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It seems we are understanding well, besides the fact of how 99.9% becomes 99.7%. . .

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> *"The last and greatest breakthrough from a fantastic machine, or a false alarm on the frontiers of physics?*
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But, at the end of the post:

1. "My money is on the false alarm at the moment,..."
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Assolutely meaningful! (A part from the initial mismatch)

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But how must our convictions rationally change on the light of new experimental data? Is there a logical rule?

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“de Rujula’s paradox”:

> *“If you disbelieve every result presented as having a 3 sigma – or ”equivalently” a 99.7% chance – of being correct. . . You will turn out to be right 99.7% of the times.”*
>
> *(Alvaro de Rujula, private communication)*

The cemetery of Physics

Alvaro de Rujula

Testing one hypothesis

- Basic Idea:
  - let's start from a 'conventional' model
    [Standard Modell, rather 'extablished theory', etc:]
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Let's review the practice and what is behind it $\Rightarrow$

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It seems OK – *'obvious'*! – but it is indeed naïve for several aspects.

Proof by contradiction . . . ‘extended’. . .

Falsification rule: to what is ‘inspired’?

Proof by contradiction . . . 'extended' . . .

Falsification rule: to what is 'inspired'?

Proof by contradiction of classical, deductive logic:

- Assume that a hypothesis is true;
- Derive 'all' logical consequence;
- If (at least) one of the consequences is known to be false, then the hypothesis is rejected.

Proof by contradiction . . . 'extended' . . .

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is this extension legitimate?

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  E.g. H_i being a Gaussian $f(x \mid \mu_i, \sigma_i)$

  $\Rightarrow$ Given any pair or parameters $\{\mu_i, \sigma_i\}$ (i.e. $\forall H_i$), all values of x from $-\infty$ to $+\infty$ are possible.

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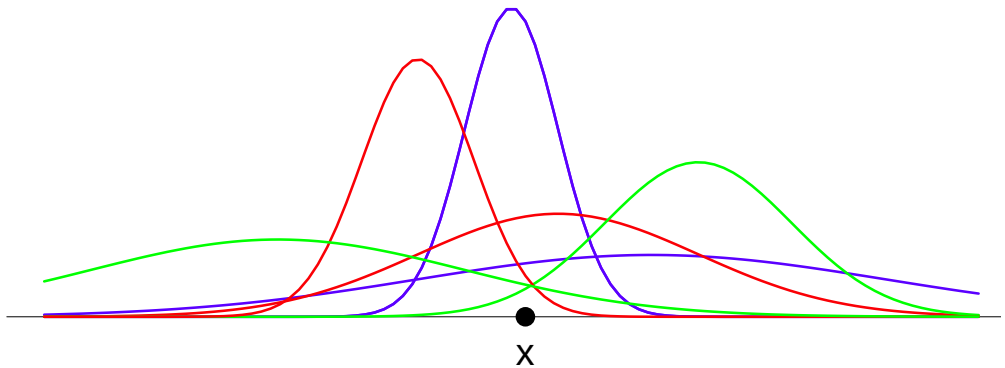
  $\Rightarrow$ Given any pair or parameters $\{\mu_i, \sigma_i\}$ (i.e. $\forall H_i$), all values of x from $-\infty$ to $+\infty$ are possible.

  $\Rightarrow$ Having observed any value of x, none of H_i can be, strictly speaking, falsified.



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$\Rightarrow$ Practically never in the experimental sciences!

Falsificationism in action...

Obviously, this does not means that falsificationism never works, as long as no stochastic processes are involved (randomness inherent to the physical processes, or due to 'errors' in measurement). Certainly it works against itself:

- Science proceeds, in practice, rather differently:

  > *The natural development of Science shows that researches are carried along the directions that seem more credibile (and hopefully fruitful) at a given moment.* A behaviour *"179 degrees or so out of phase from Popper's idea that we make progress by falsificating theories"* (Wilczek, `http://arxiv.org/abs/physics/0403115`)

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Obviously, this does not means that falsificationism never works, as long as no stochastic processes are involved (randomness inherent to the physical processes, or due to 'errors' in measurement).
Certainly it works against itself:

$\Rightarrow$ logically speaking, falsificationism has to be considered ... falsified!

Falsificationism and statistics

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But from the impossible to the improbable there is not just a question of quantity, but a question of quality.

This mechanism, logically flawed, is particularly dangerous because is deeply rooted in most scientists, due to education and custom, although not supported by logic.

$\Rightarrow$ Basically responsible of all fake claims of discoveries in the past decades.

[*I am particularly worried about claims concerning our health, or the status of the planet, of which I have no control of the experimental data.*]

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B) ~~**if** $C_i \xrightarrow[\text{small probability}]{} E$, and **we observe** E~~ NO

~~$\Rightarrow C_i$ has small probability to be true~~

~~"most likely false"~~

But it is behind the rational behind the statistical hypothesis tests!

Example

An Italian citizen is chosen at random and sent to take an AIDS test (test is not perfect, as it is the case in practice).
Simplified model:

$$\begin{aligned} P(\text{Pos} \mid \text{HIV}) &= 100\% \\ P(\text{Pos} \mid \overline{\text{HIV}}) &= 0.2\% \\ P(\text{Neg} \mid \overline{\text{HIV}}) &= 99.8\% \end{aligned}$$

H_1='HIV' (Infected) $\qquad E_1$ = Positive

H_2='$\overline{\text{HIV}}$' (Not infected) $\qquad E_2$ = Negative

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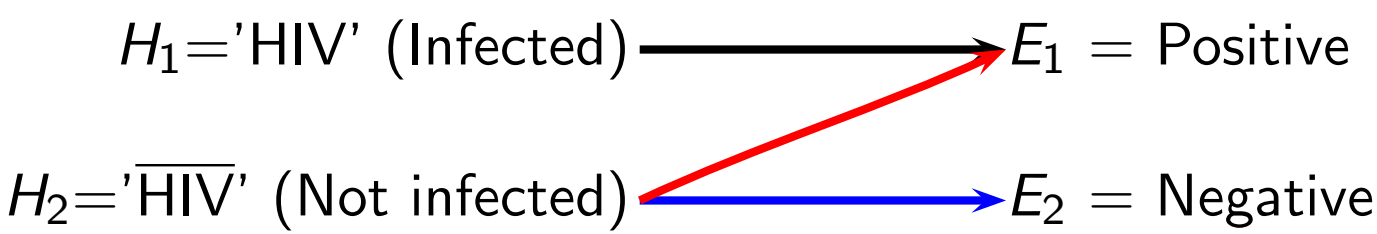

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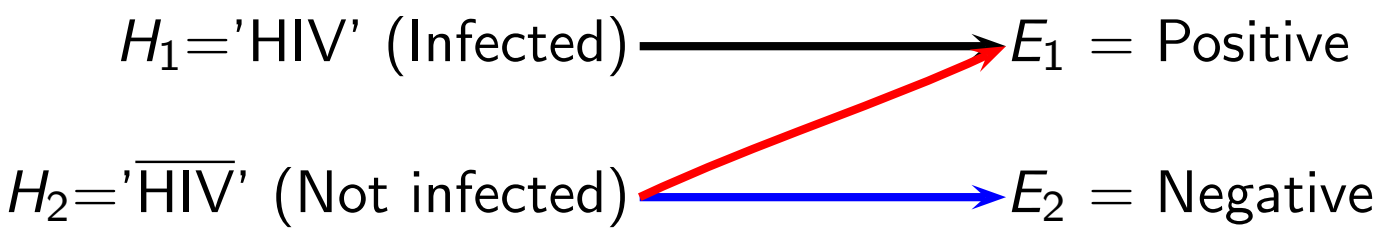

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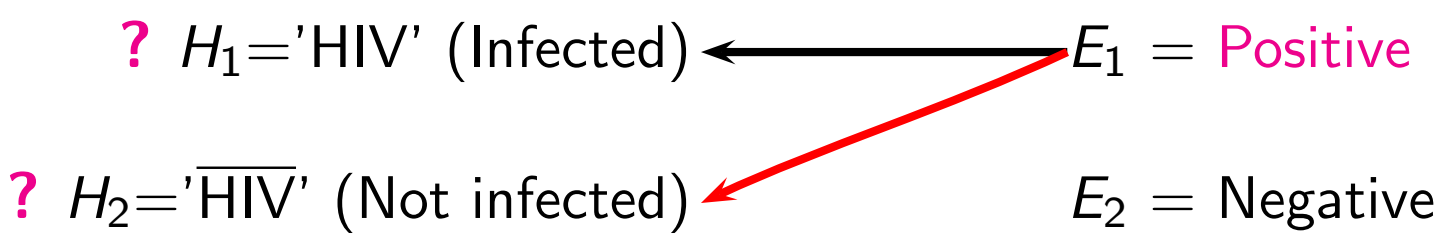

Result: $\Rightarrow$ Positive

HIV or not HIV?

What shall we conclude?

Being $P(\text{Pos} \mid \overline{\text{HIV}}) = 0.2\%$ and having observed 'Positive', can we say

- "It is practically impossible that the person is healthy, since it was practically impossible that an healthy person would result positive"?

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NO

Instead, $P(\text{HIV} \mid \text{Pos, randomly chosen Italian}) \approx 45\%$

Think about it (a crucial information is missing!)

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Instead, $P(\text{HIV}\,|\,\text{Pos, randomly chosen Italian}) \approx 45\%$

$\Rightarrow$ Serious mistake! (not just 99.8% instead of 98.3%)

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Pay attention no to arbitrary revert conditional probabilities:

In general $P(A \mid B) \neq P(B \mid A)$

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In particular

- A cause might produce a given effect with very low probability, and nevertheless could be the most probable cause of that effect, often the only one!

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Tipical values of statistical practice to reject a hypothesis are 5%, 1%, . . . (see ’AIDS test’)

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$\rightarrow$ What <u>was</u> the probability to give exactly that number?:

$$\begin{aligned} P(X = 3.1416 \,|\, H_0) &= \int_{3.14155}^{3.14165} f_{\mathcal{G}}(x \,|\, \mu, \sigma) dx \\ &\approx f_{\mathcal{G}}(3.1416 \,|\, \mu, \sigma) \times \Delta x \\ &\approx f_{\mathcal{G}}(3.1416 \,|\, \mu, \sigma) \times 0.0001 \\ &\approx 39 \times 10^{-6} \end{aligned}$$

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- Certainly NOT $\approx 39 \times 10^{-6}$;
- Indeed, it is exactly 1, since H_0 is the only cause which can produce that effect:

$$P(X = 3.1416 \,|\, H_0) \approx 39 \times 10^{-6}$$
$$P(H_0 \,|\, X = 3.1416) = 1\,.$$

Exercises with R

How to calculate the probability of the rounded value of an outcome (`nd`):

```
nd=4; m=3; s=1;
(x=round(rnorm(1,m,s),nd)); dnorm(x,m,s)*10-nd
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Histogram of probabilities:

```
m=3; s=1; nd=4; n=100000
x=round(rnorm(n,m,s),nd)
log.p=log10(dnorm(x,m,s)*10^-nd)
hist(log.p, nc=100, col='cyan',
     xlim=c(min(log.p), max(log.p)*0.8) )
```

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$$P(X \geq 3.1416) \quad = \quad \int_{3.14155}^{+\infty} f_{\mathcal{G}}(x \,|\, \mu, \sigma) dx \approx 44\%$$

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$$P(X \geq 3.1416) \; [= P(X \geq x_{obs})] \quad \Rightarrow \quad \text{'p-value'}$$

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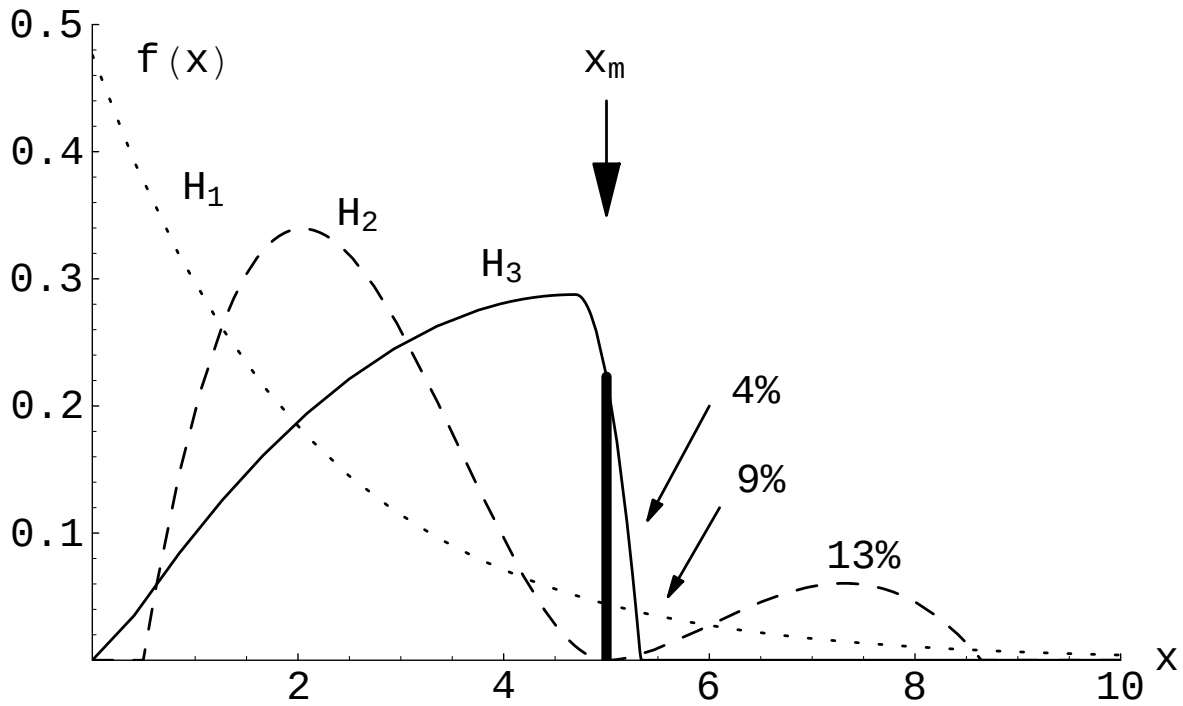
$\Rightarrow$ From the logical point of view the situation has worsened:
$\longrightarrow$ our conclusions do not depend on what we have observed, but also from rarer events not actually observed!

Comparing three hypotheses

Which hypothesis is favored by the experimental observation x_m?



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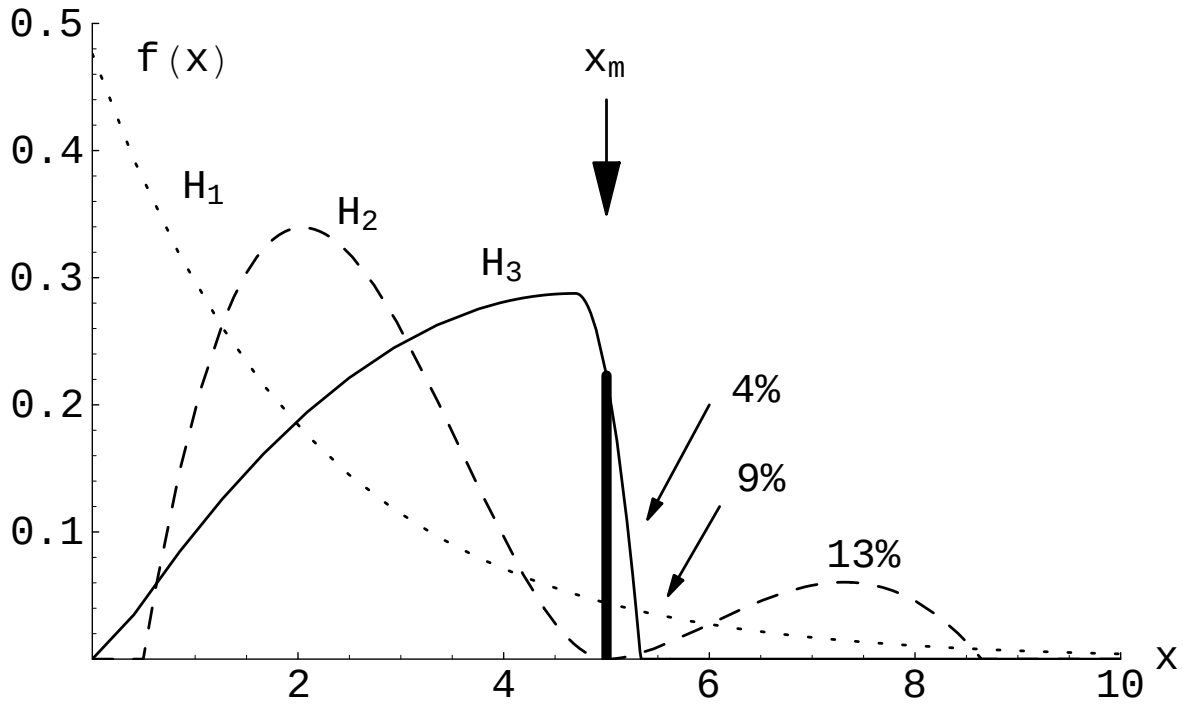

$$P(x_m \mid H_3) > P(x_m \mid H_1) > P(x_m \mid H_2) = 0 \quad (!)$$

Even if $P(x_m \mid H_i) \to 0$ (it depends on resolution)

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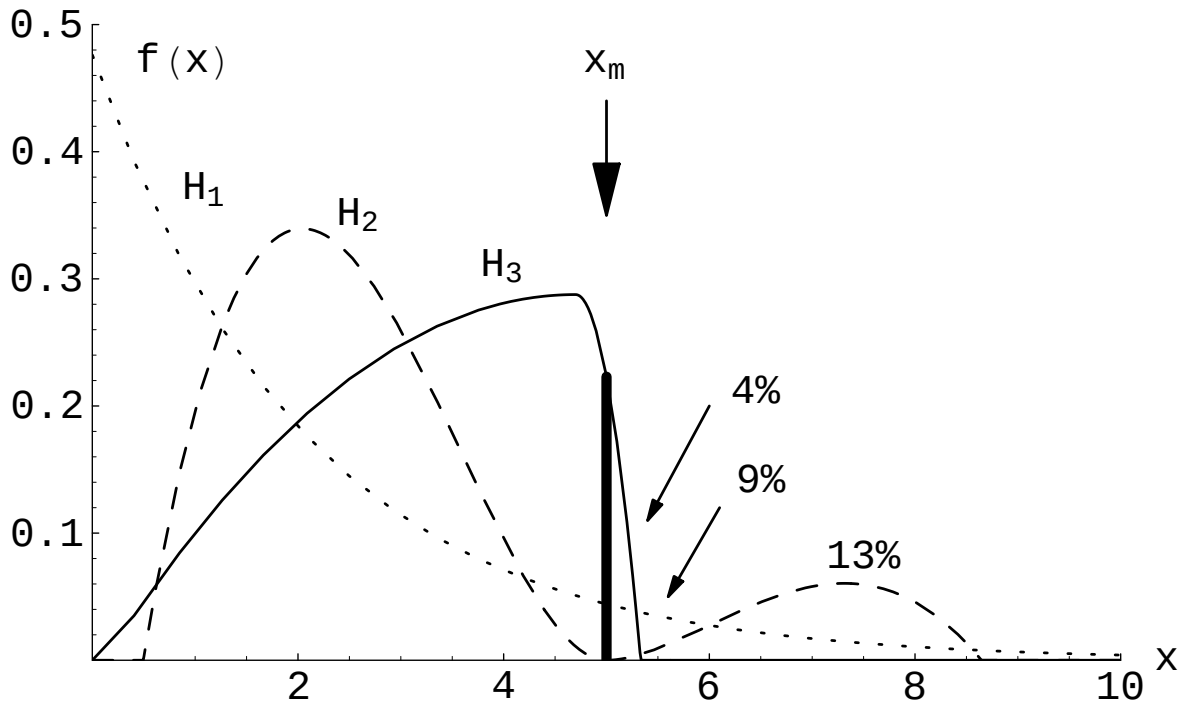

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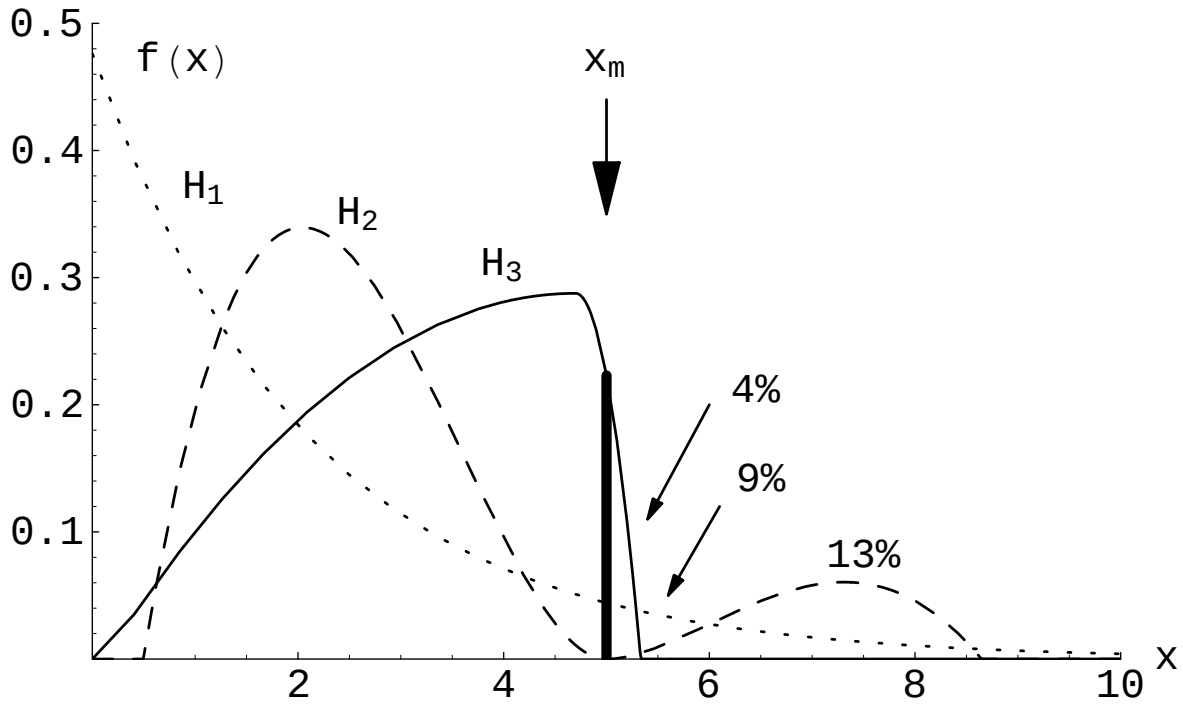

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An irrilevant experiment

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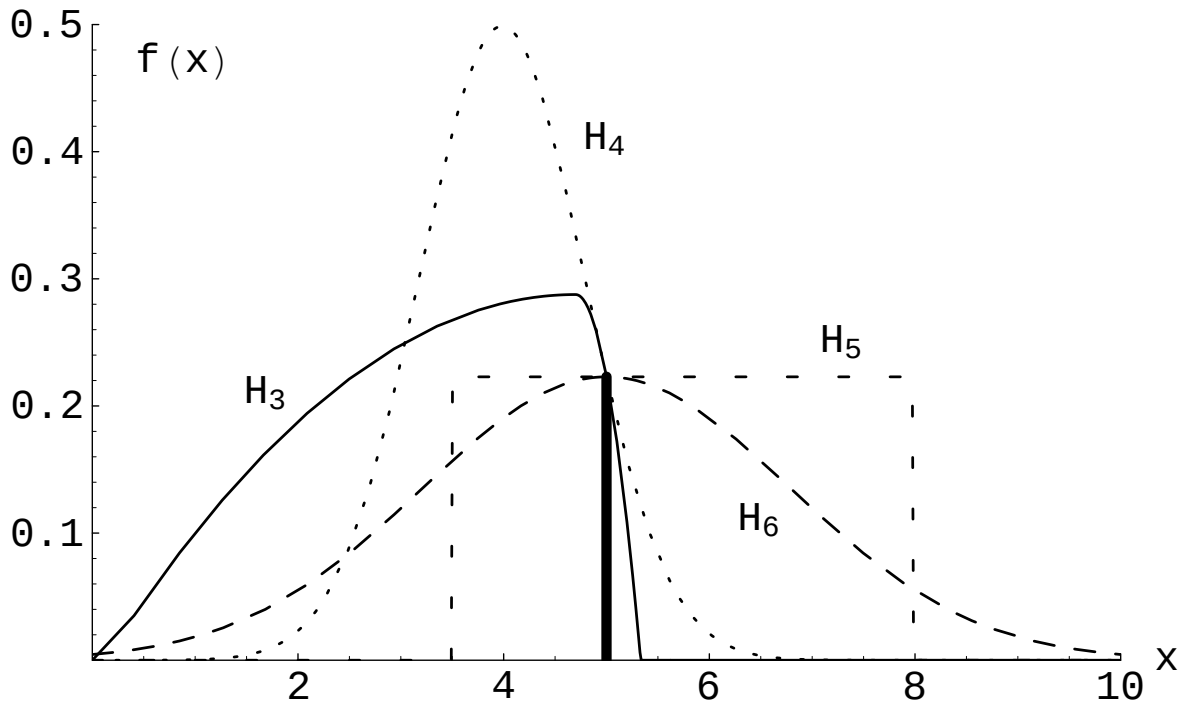

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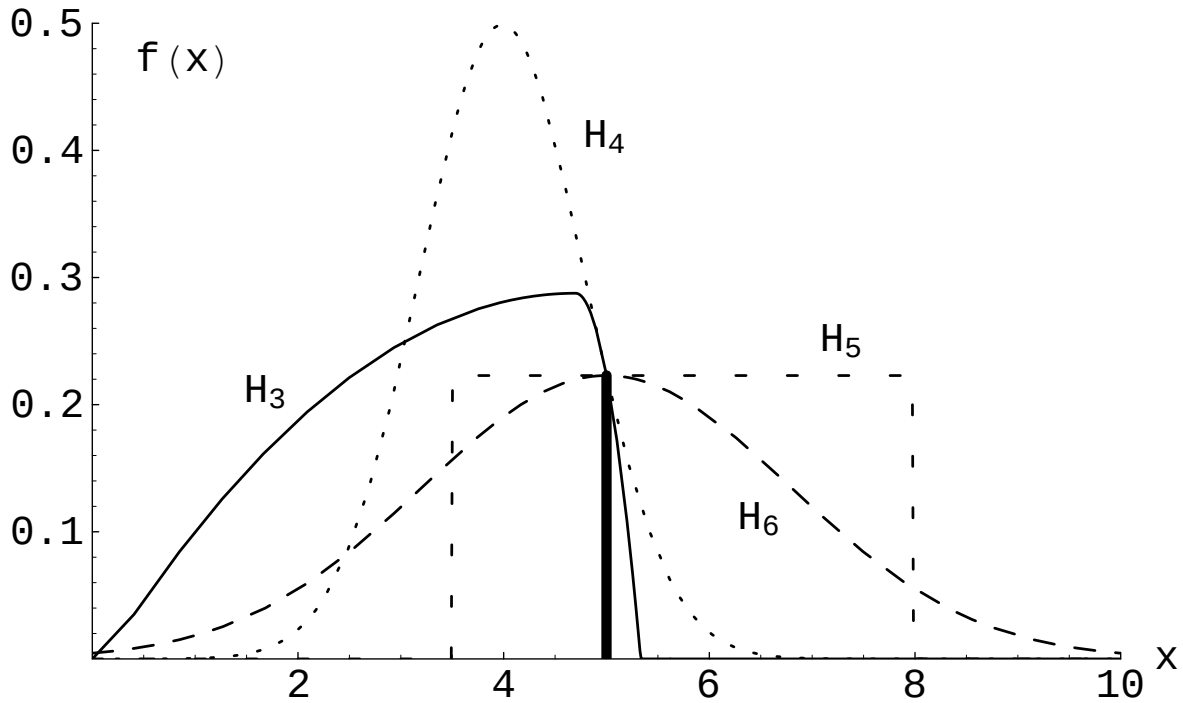

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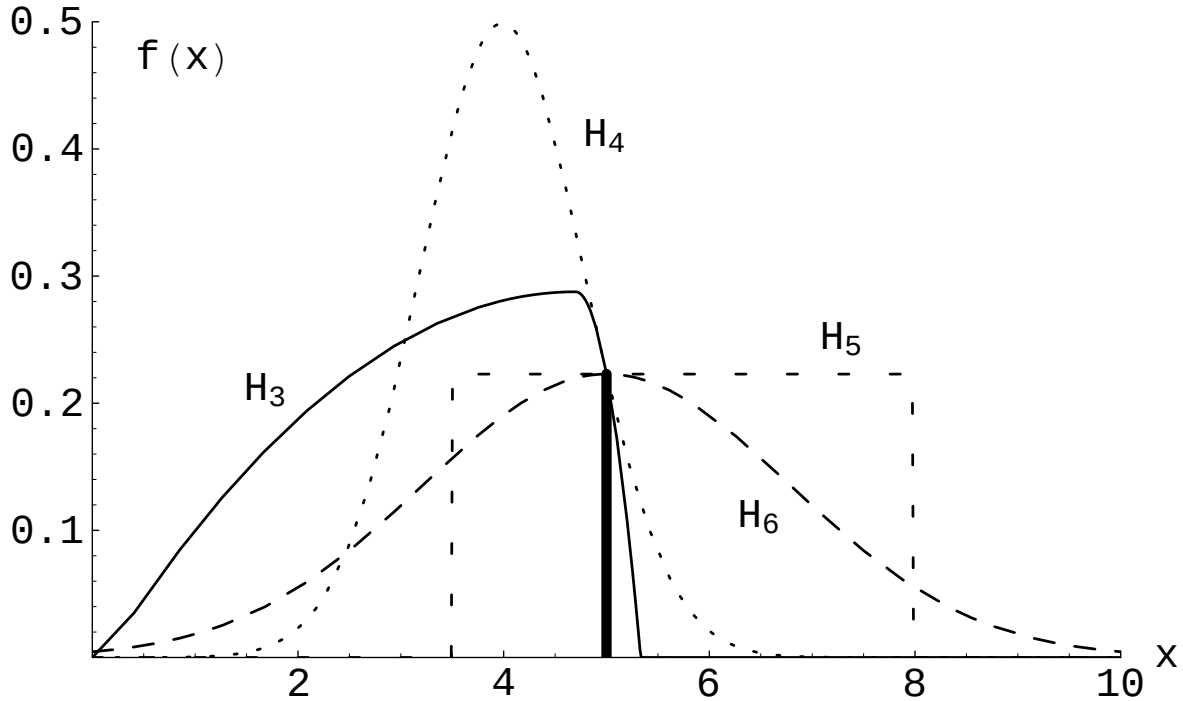

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$\rightarrow$ we mantain our opinions about H_i

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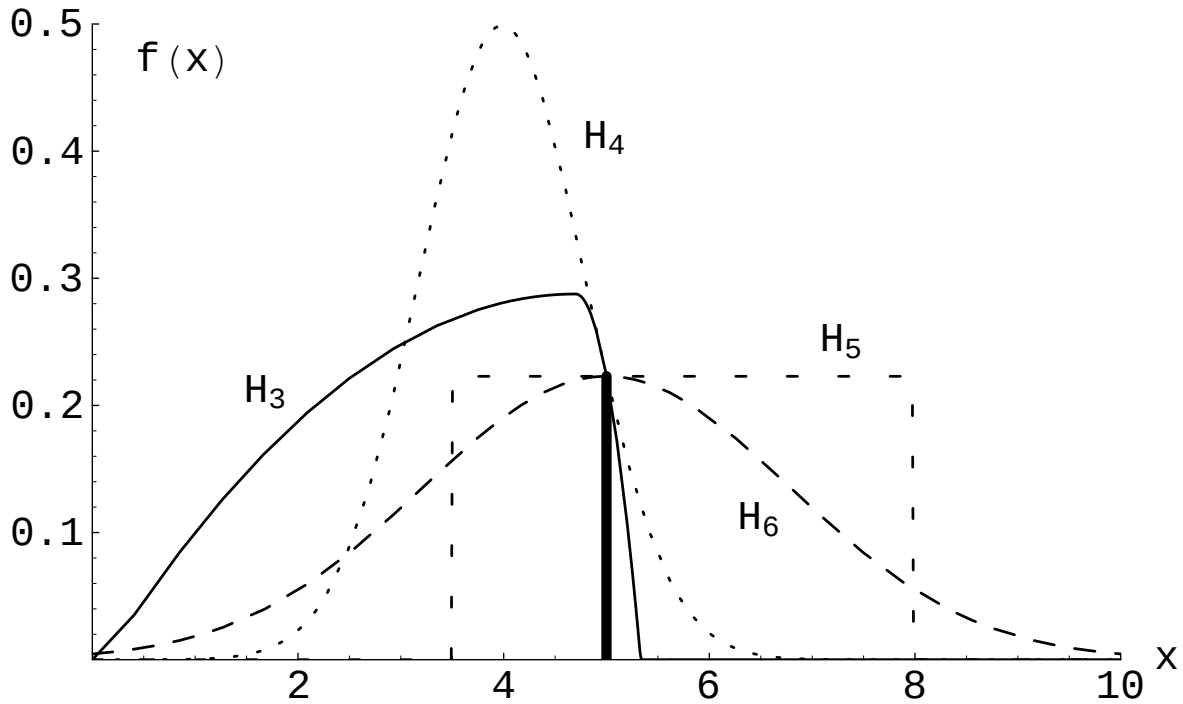

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$\Rightarrow$ *. . . no matter what the different the p-values are!*

Which p-value?...

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Of what?

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$\rightarrow$ the test variable ('θ') is absolutely arbitrary:

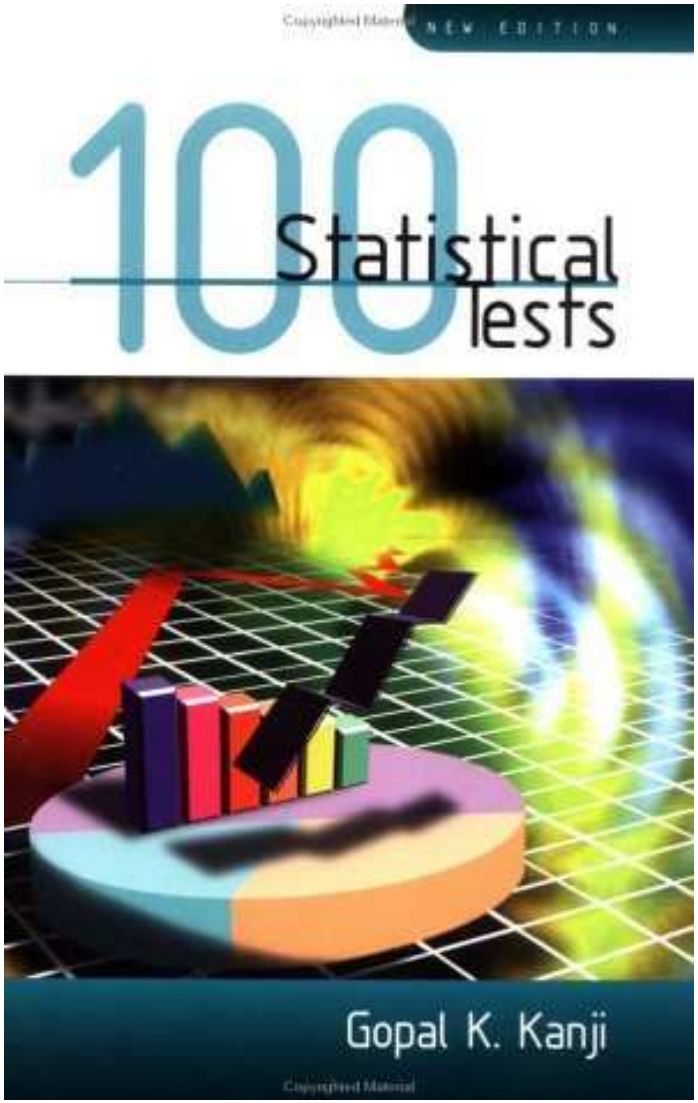
$$\theta = \theta(\mathbf{x})$$

$$\rightarrow f(\theta) \quad \text{[p.d.f]}$$

$$\text{Experiment:} \quad \rightarrow \theta_{mis} = \theta(\mathbf{x}_{mis})$$

$$\text{p-value} = P(\theta \geq \theta_{mis}) \qquad \text{('one tail')}$$

Which p-value?...



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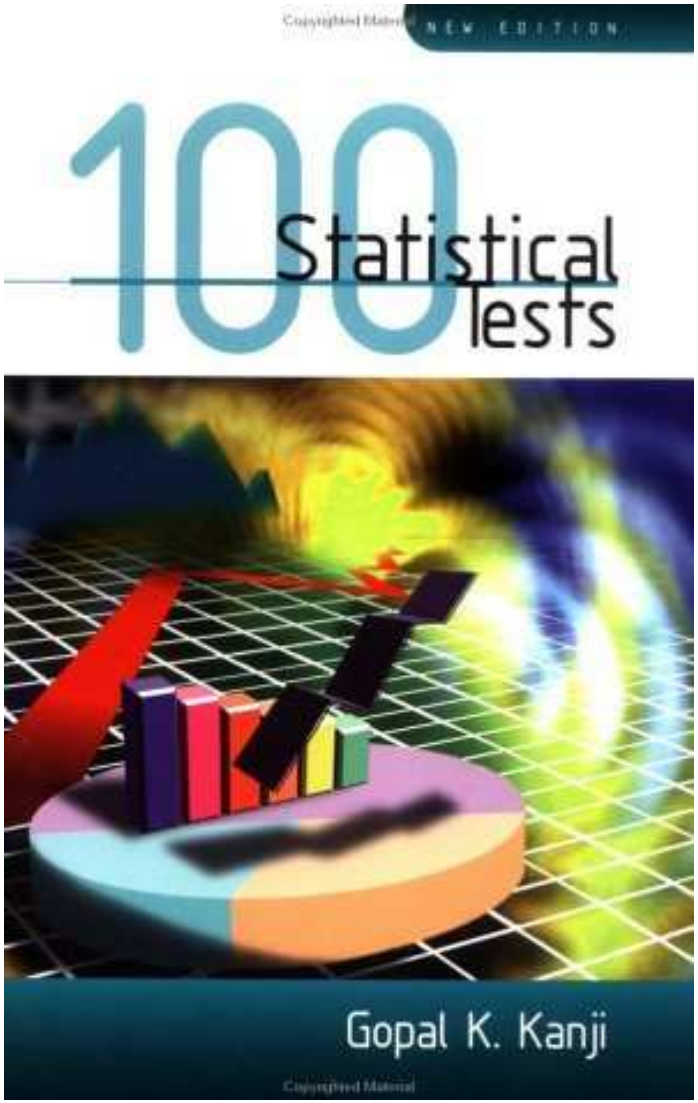

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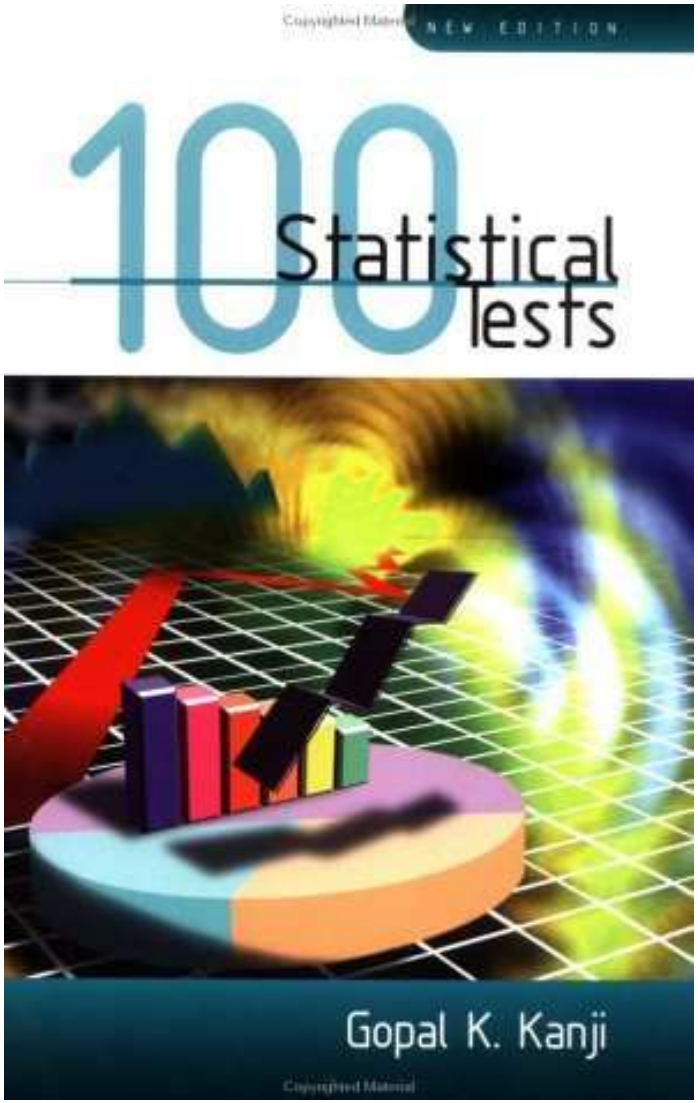

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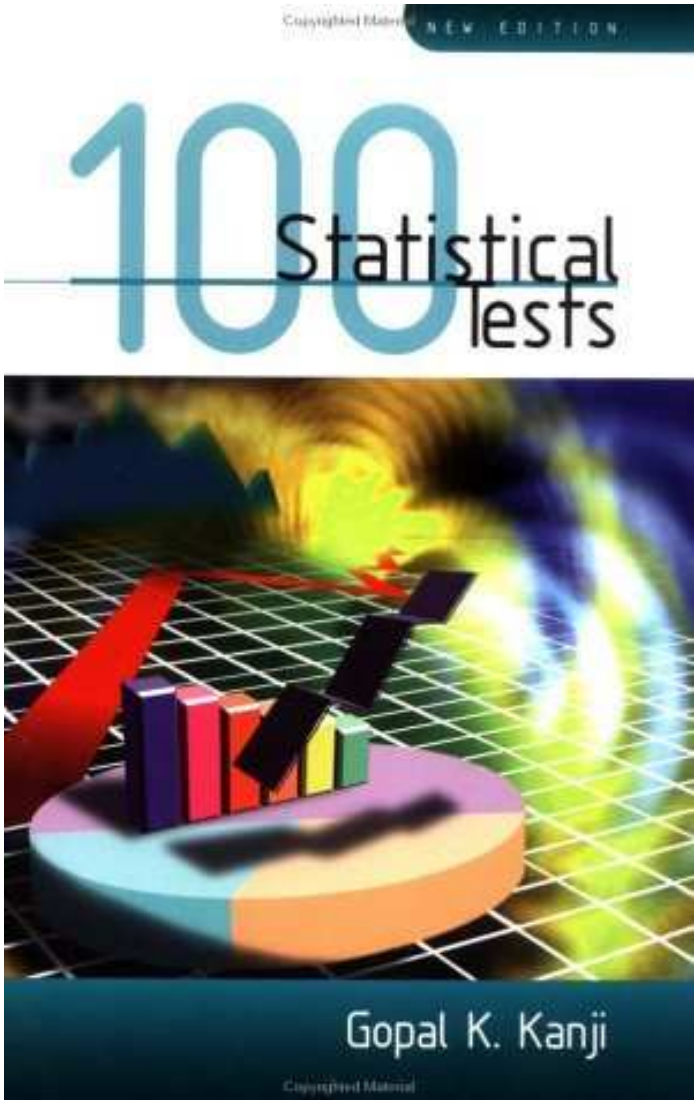

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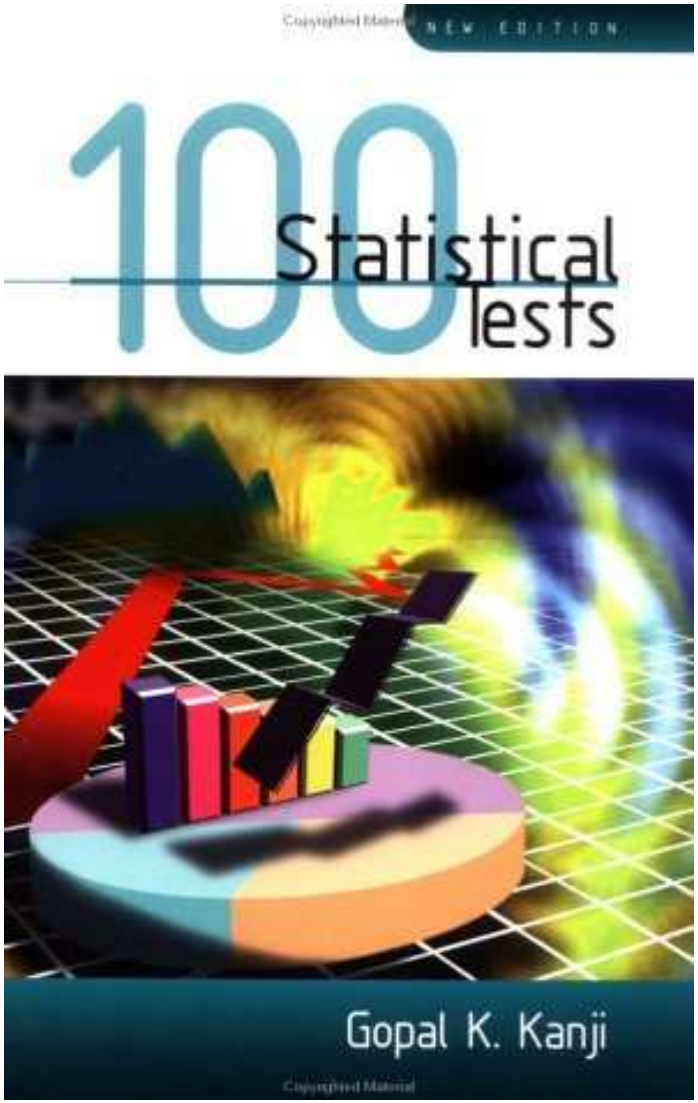

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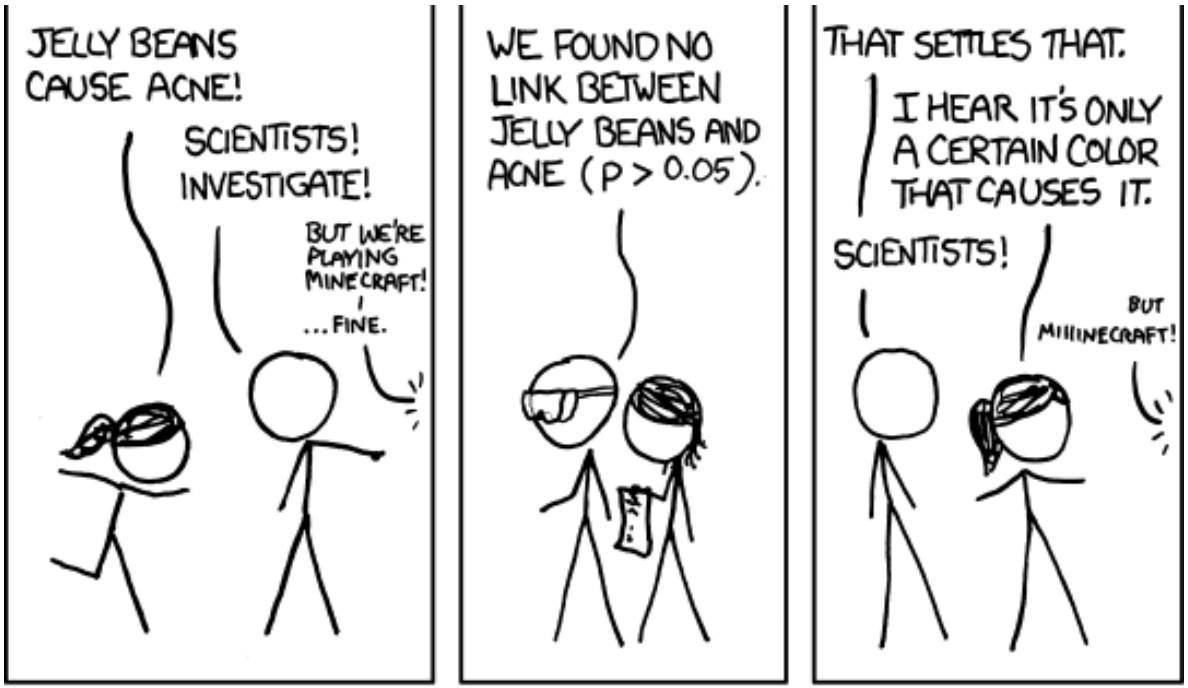
- personal **'golden rule'**:
"the more exotic is the name of the test, the less I believe the result", because I'm pretty shure that several 'normal' tests have been descarded in the meanwhile...

Or look around, searching for 'significance'

If changing the test does not help, change hypotheses...



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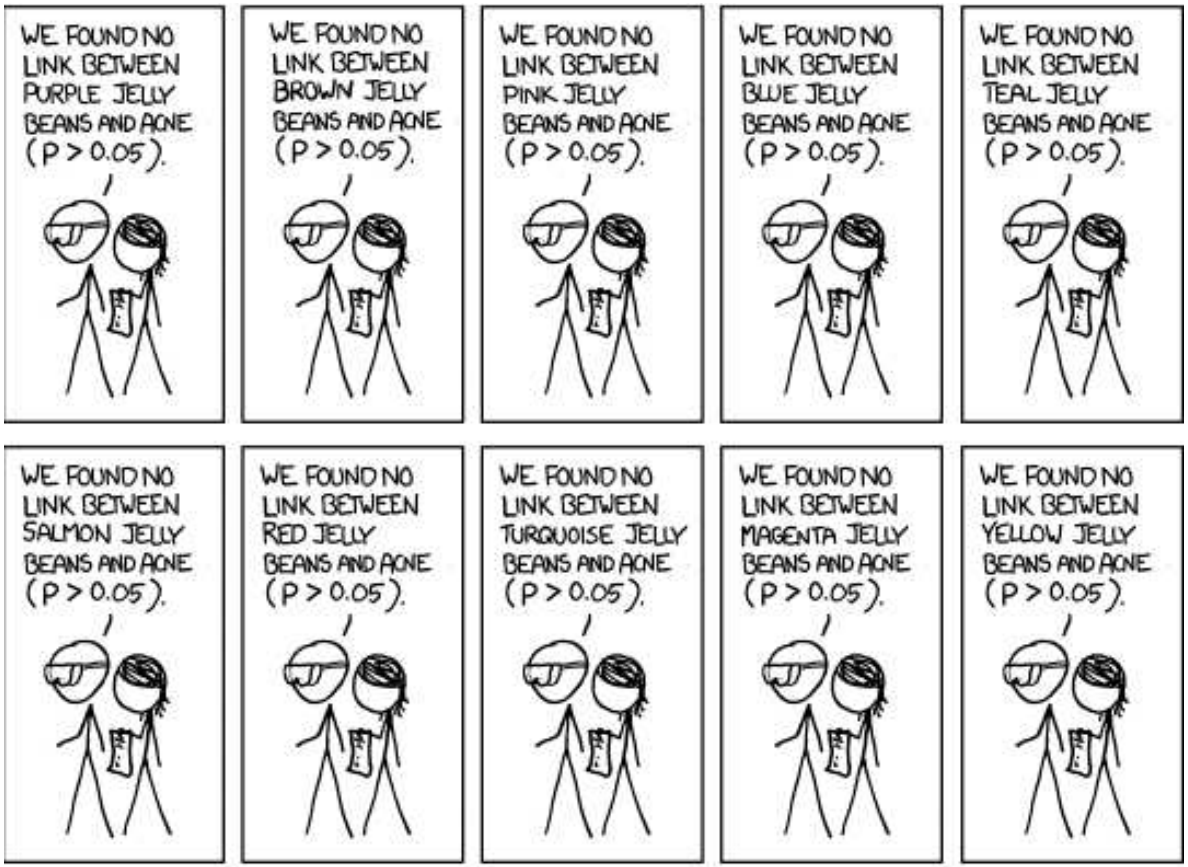

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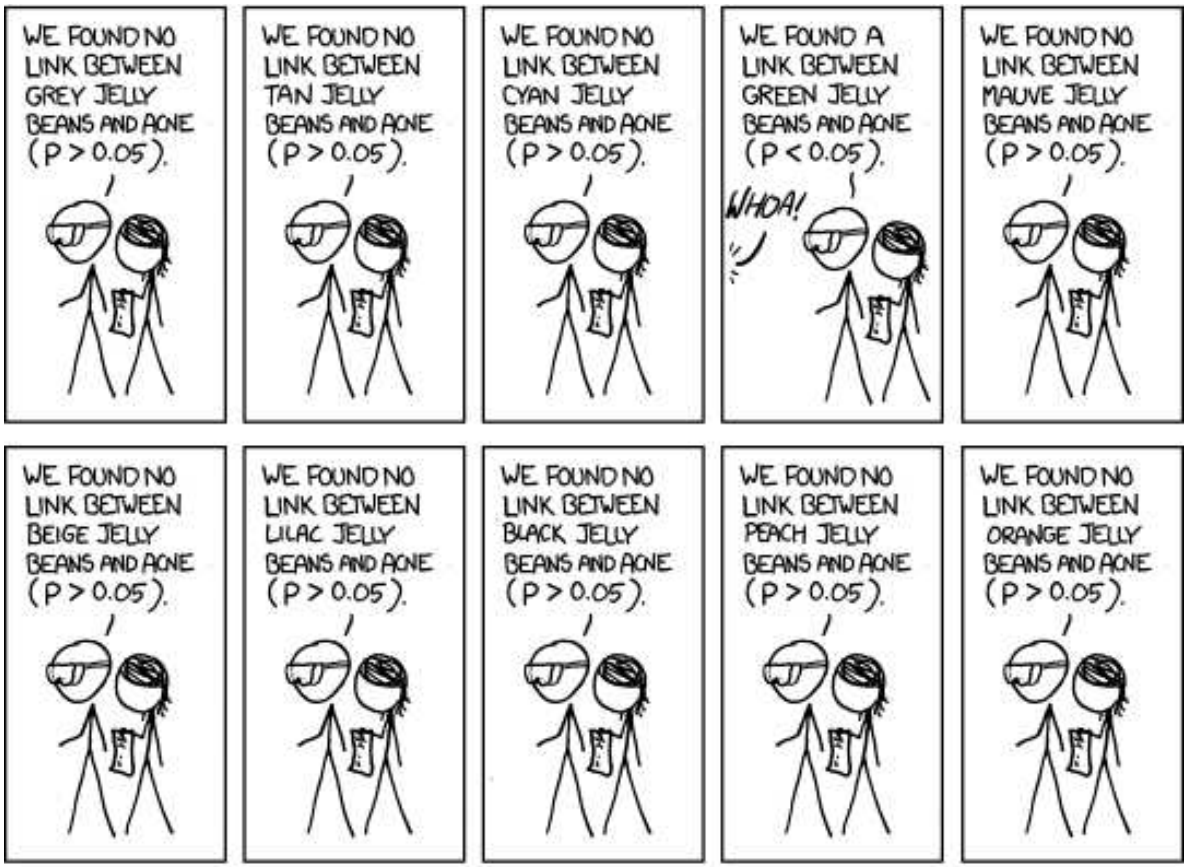

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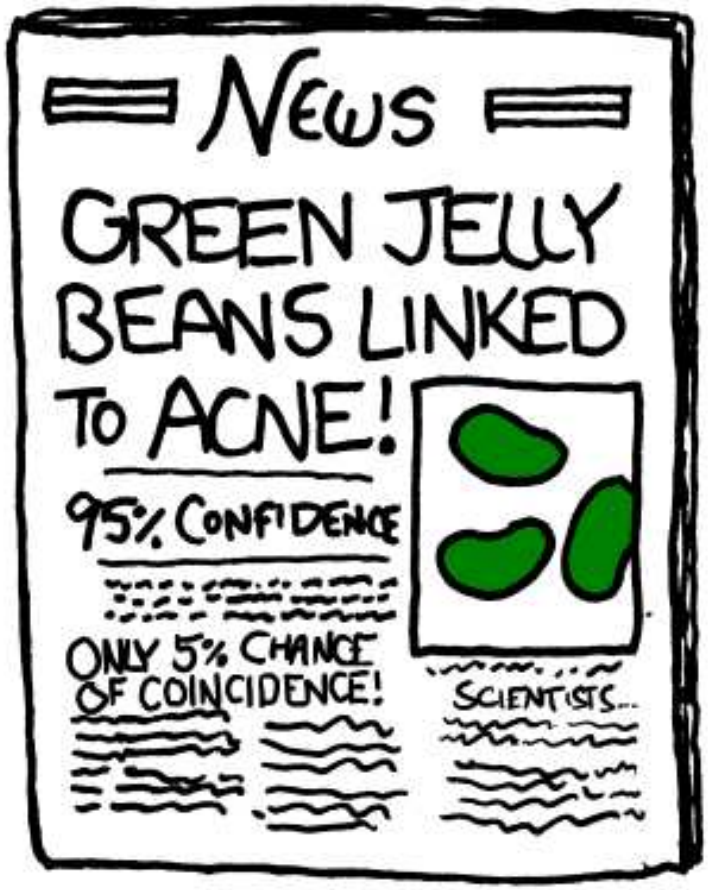


P-hacking ("p-value hacking")

The 'science' of inventing significant results...

p-hacking, or cheating on a p-value

June 11, 2015

By arthur charpentier

Share

(This article was first published on **Freakonometrics » R-english**, and kindly contributed to R-bloggers)

Yesterday evening, I discovered some interesting slides on False-Positives, p-Hacking, Statistical Power, and Evidential Value, via @UCBITSS 's post on Twitter. More precisely, there was this slide on how cheating (because that's basically what it is) to get a 'good' model (by targeting the *p*-value)

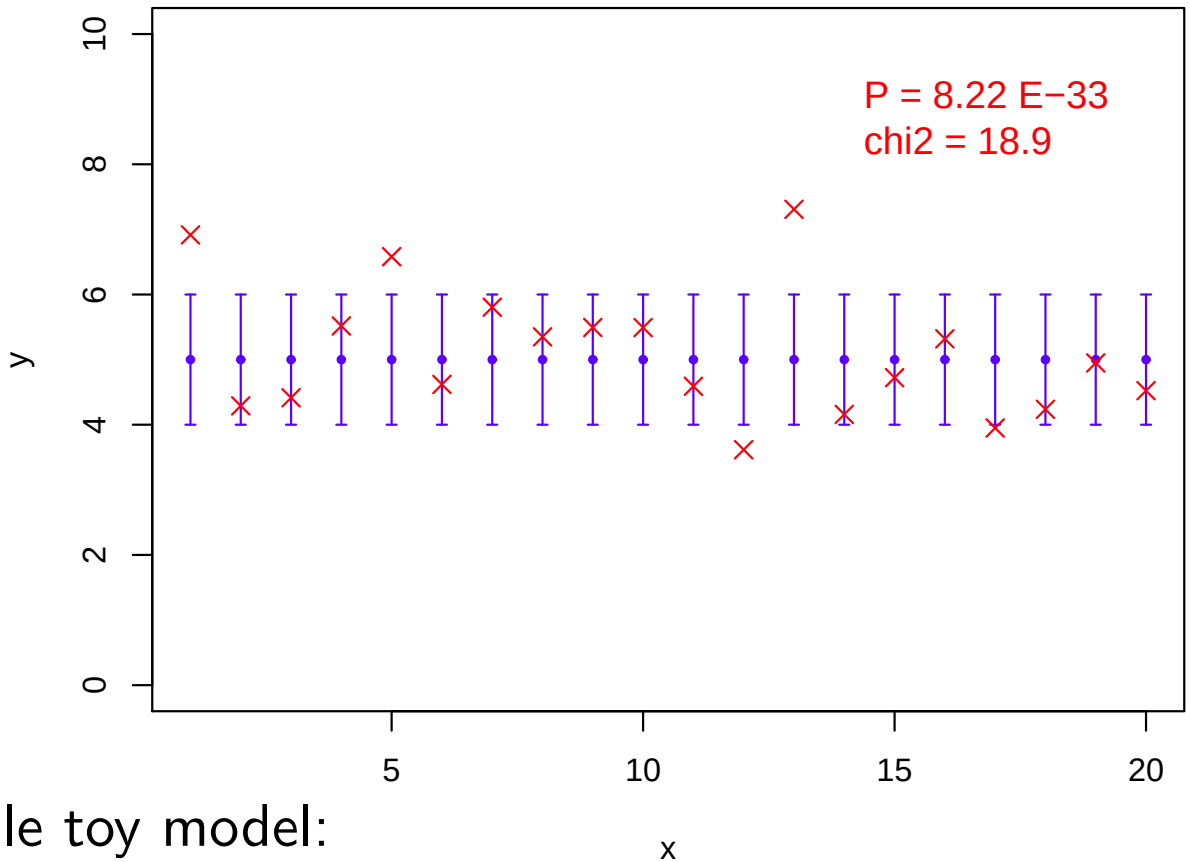
1. Stop collecting data once $p<.05$
2. Analyze many measures, but report only those with $p<.05$.
3. Collect and analyze many conditions, but only report those with $p<.05$.
4. Use covariates to get $p<.05$.
5. Exclude participants to get $p<.05$.
6. Transform the data to get $p<.05$.

`http://www.r-bloggers.com/p-hacking-or-cheating-on-a-p-value/`

- Google for "p-hacking"

χ^2... the mother of all p-values

Theory Vs experiment *(bars: expectation uncertainty)*:



Very simple toy model:

- True value of y: 5, independently of x (a.u.);
- Gaussian instrumental error with $\sigma = 1$.

Probability of the data sample

$P = 8.22 \times 10^{-33}$ is the probability of the 'configuration' of experimental points:

- obtained multiplying the probability of each point (independent measurements):

$$P = \prod_i P_i$$

where

$$P_i = \int_{y_{m_i} - \Delta y/2}^{y_{m_i} + \Delta y/2} f(y)dy$$

- as seen, P_i depends on the 'resolution' Δy (instrumental 'discretization'):

$$\rightarrow \text{we use} \quad \Delta y = \frac{1}{10}\,\sigma$$

'Distance' Experiment-theory: χ^2

The costruction of the χ^2 is very popular (usually in first lab. courses – 'Fisichetta'):

$$\chi^2 = \sum_i \left(\frac{y_{m_i} - y_{th_i}}{\sigma_i} \right)^2$$

$$\rightarrow \sum_i \left(\frac{y_{m_i} - y_0}{\sigma} \right)^2$$

$$\chi^2 \sim \Gamma(\nu/2, 1/2) \qquad [\rightarrow \nu = 20]$$

$$\mathrm{E}[\chi^2] = \nu \qquad [\rightarrow 20]$$

$$\mathrm{Var}[\chi^2] = 2\nu \qquad [\rightarrow 40]$$

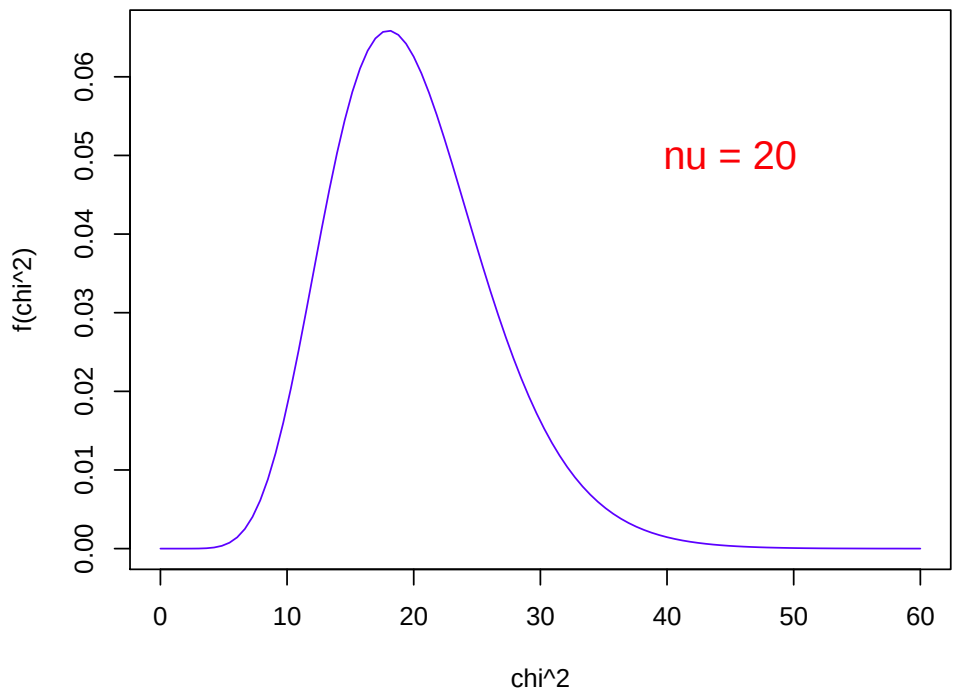
$$\mathrm{Std}[\chi^2] = \sqrt{2\nu} \qquad [\rightarrow 6.3]$$

$$\mathrm{Mode}[\chi^2] = \begin{cases} 0 & \text{if } \nu \leq 2 \\ \nu - 2 & \text{if } \nu > 2 \end{cases} \qquad [\rightarrow 18]$$

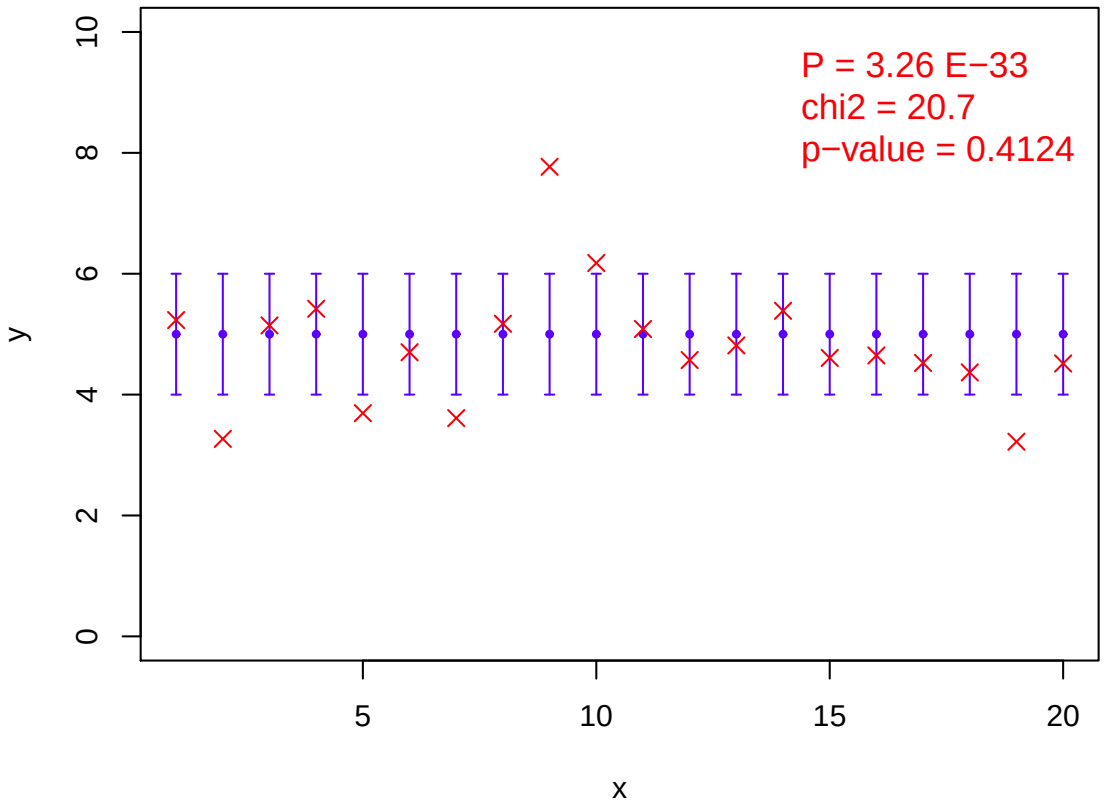
$$\Rightarrow \quad \boxed{\chi^2 = 20 \pm 6}$$

Our expectations about χ^2

$$\begin{aligned} \mathrm{E}[\chi^2] &= \nu && [\to 20] \\ \mathrm{Std}[\chi^2] &= \sqrt{2\nu} && [\to 6.3] \\ \Rightarrow & \quad \boxed{\chi^2 = 20 \pm 6} \\ & \quad [\,\text{mode: } 18\,] \end{aligned}$$



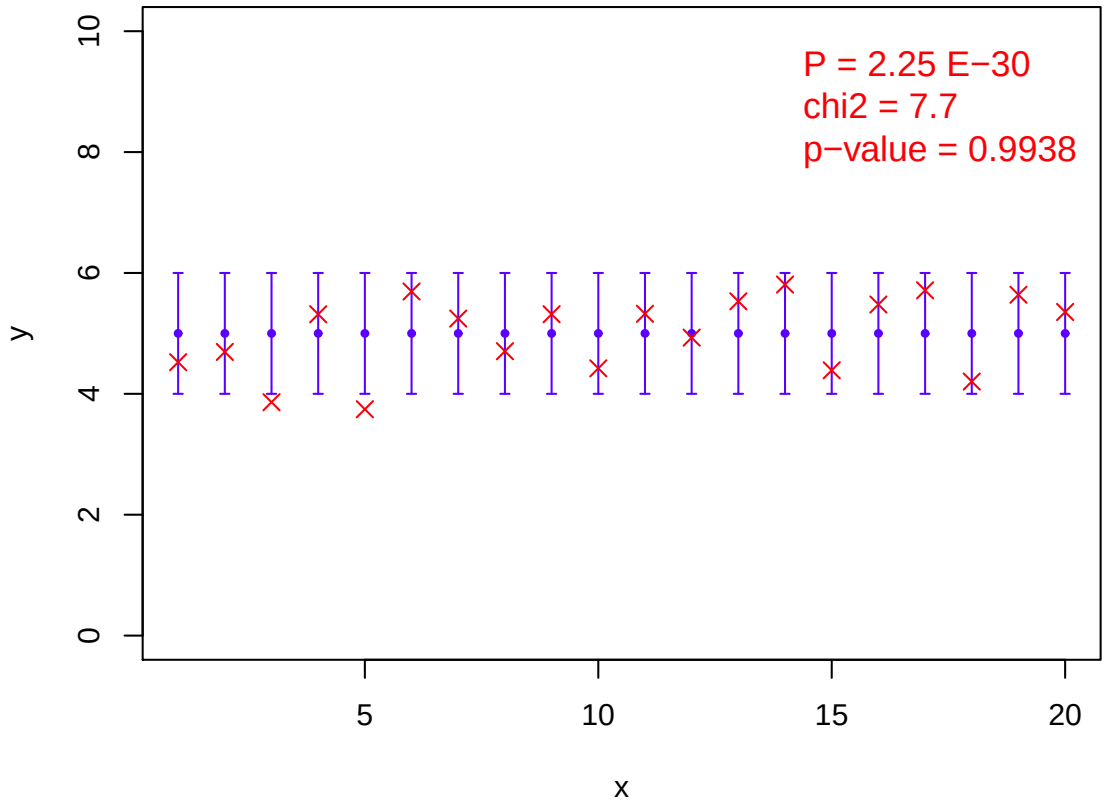
Some examples



In the average.

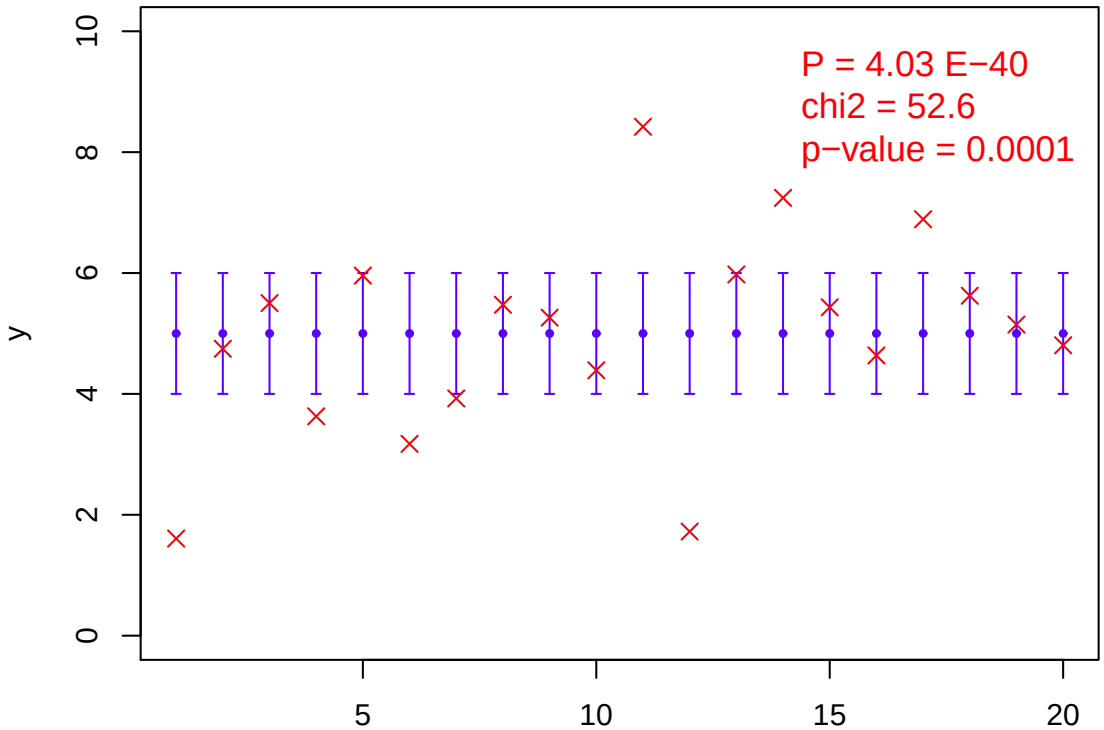
(but someone could see the points forming a 'constellation'. . .)

Some examples



Too good?

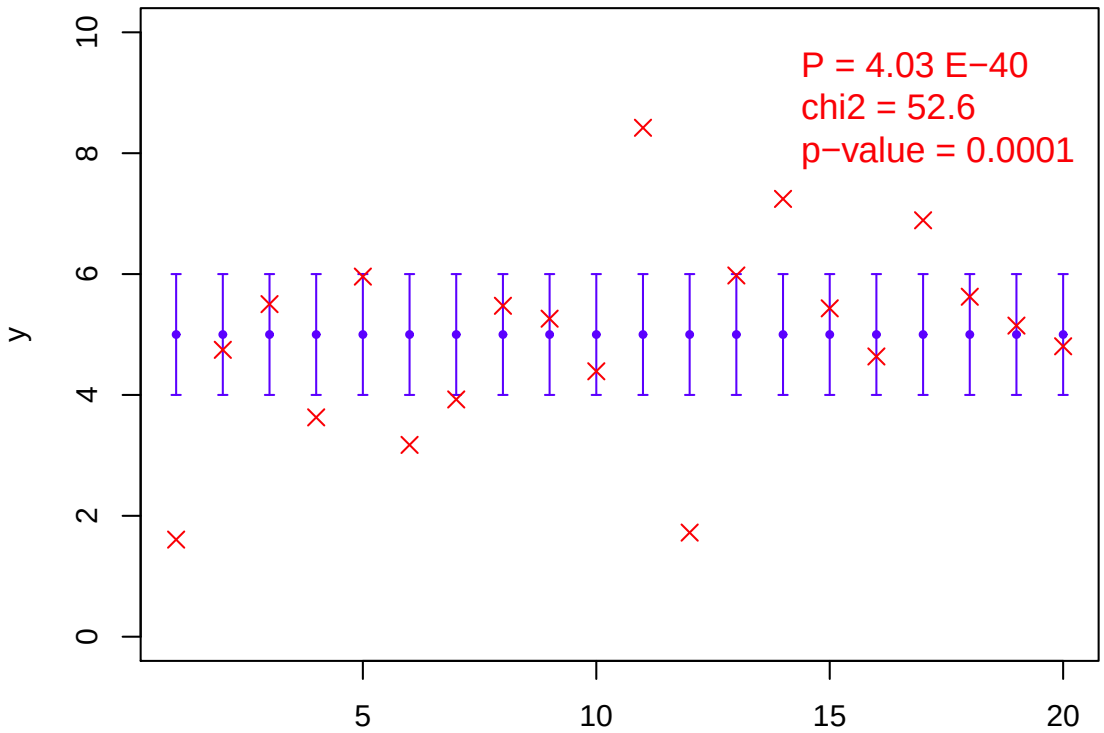
Some examples



$\chi^2 = 52.6$, with a p-value $= 0.93 \overset{x}{\times} 10^{-4}$

At limit?

Some examples

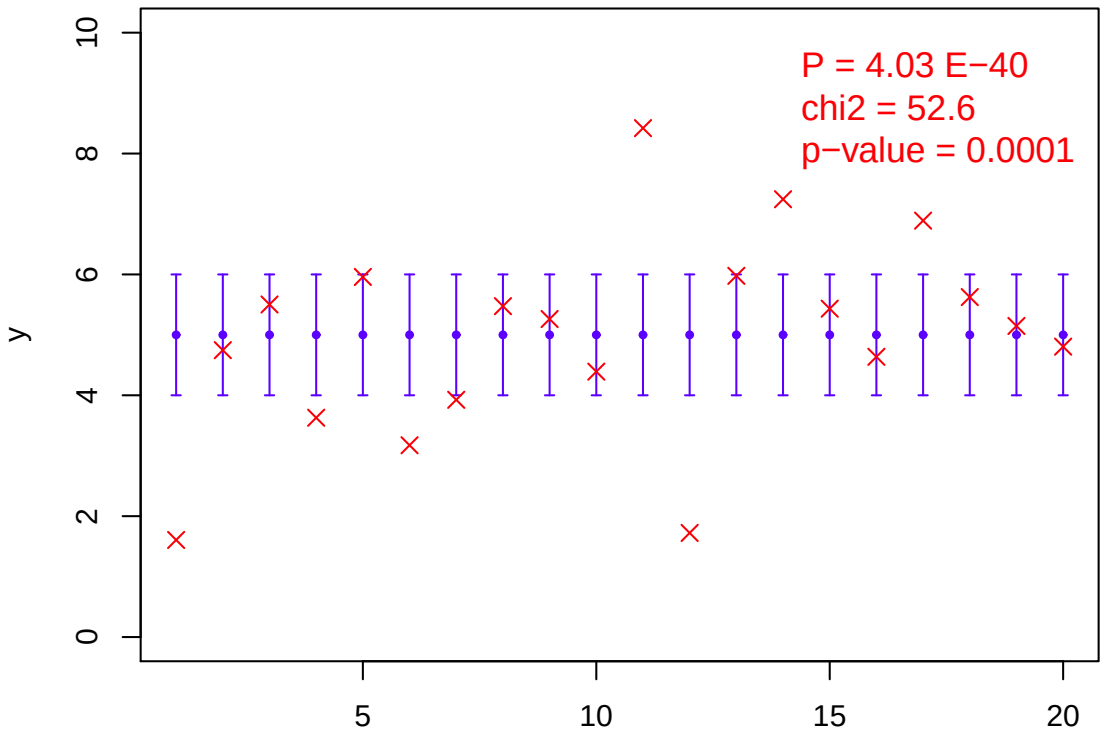


$\chi^2 = 52.6$, with a p-value $= 0.93 \overset{x}{\times} 10^{-4}$

At limit? Just come out at the first time (9 Oct. 2012, 13:01)

```
while(chi2.ym() < 38) source("chi2_1.R")
```

Some examples



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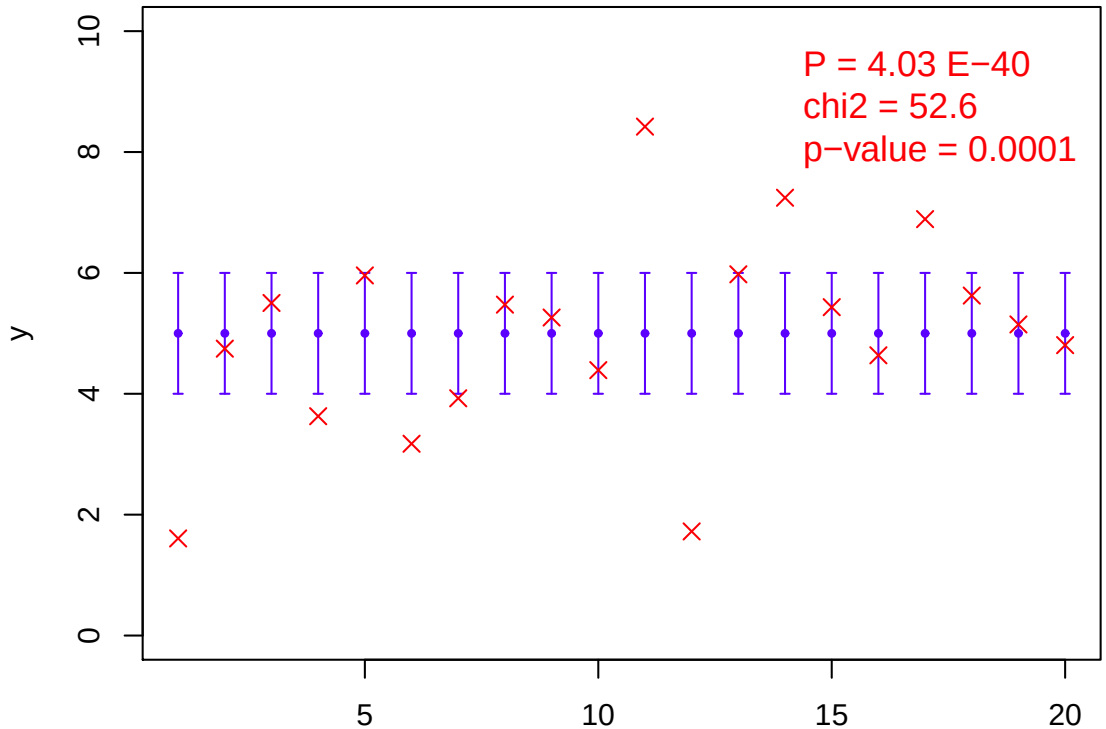

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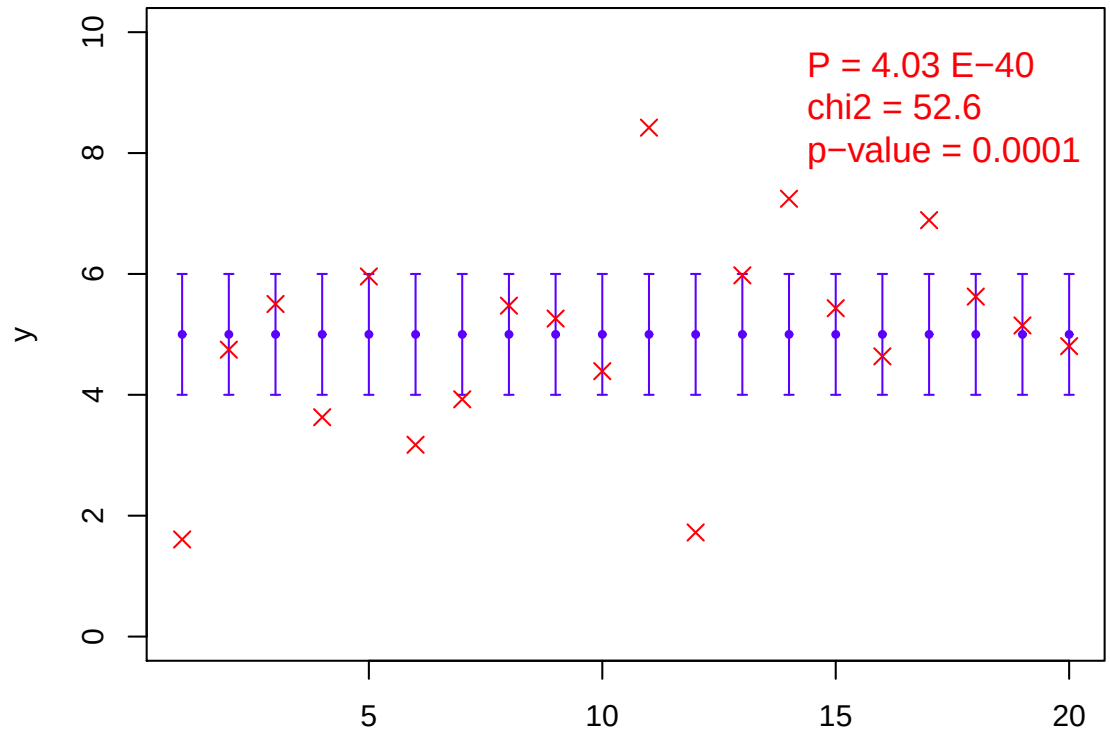

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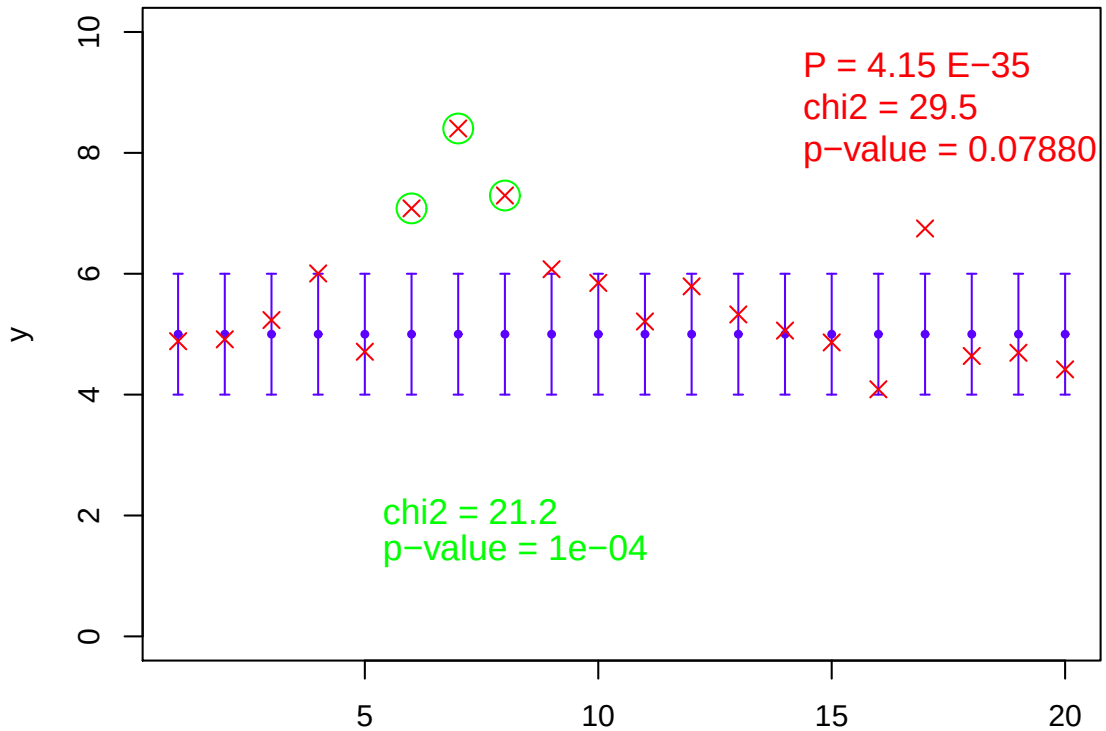
(as if there were already not enough confusion. . .)

The art of χ^2

Sometimes the χ^2 test does not give "the wished result"



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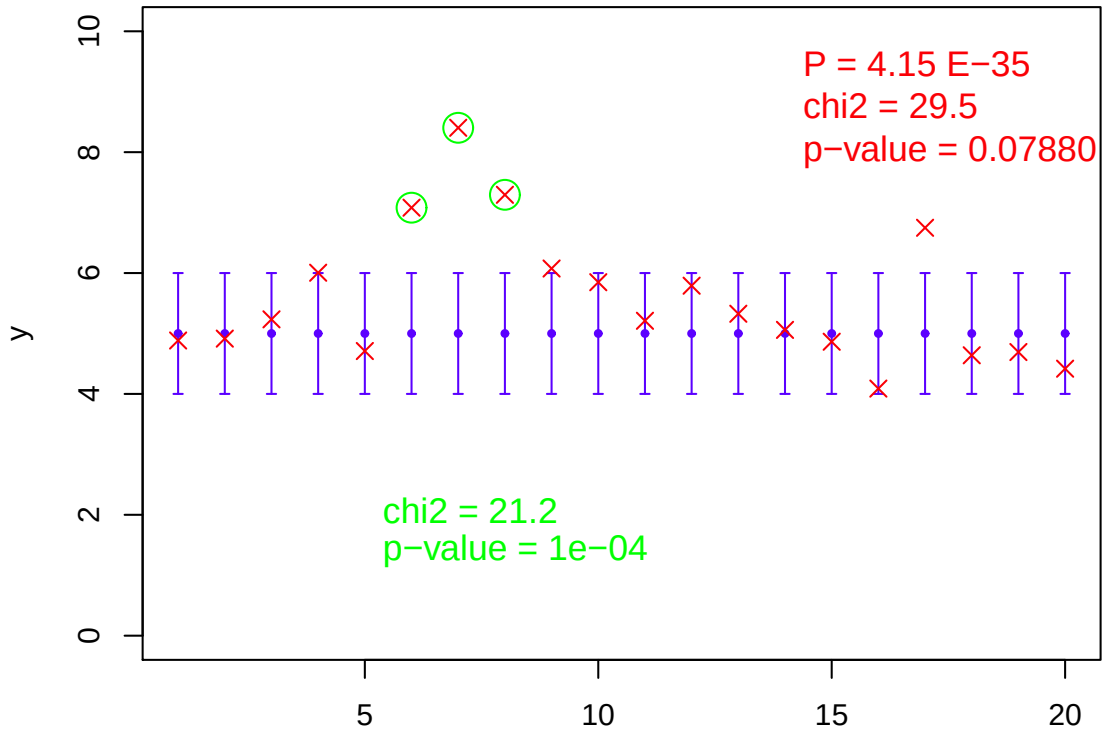

Then it is calculated in the 'suspicious region'

$\Rightarrow$ If we add the two side points, χ^2 becomes 22.2.

$\Rightarrow$ But with 5 points we had got a p-value of 5×10^{-4}

p-value: what they are

p-value:

- Probability of the tail(s) of a 'test variable' (a "statistic"):

$$P(\theta \geq \theta_{mis}) = \int_{\theta_{mis}}^{\infty} f(\theta \mid H_0)\, d\theta$$

$$P[(\theta \geq \theta_{mis}) \cap (\theta \leq (\theta^c)_{mis})] = 1 - \int_{(\theta^c)_{mis}}^{\theta_{mis}} f(\theta \mid H_0)\, d\theta$$

- θ is an arbitrary function of the data.
- . . . and often of a subsample of the data.
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Example: Has the student made a mistake?

Homework: calculate the average of 300 random numbers, uniformly distributed between 0 and 1.

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- Student gets a value outside the interval, e.g. $\overline{x} = 0.550$.

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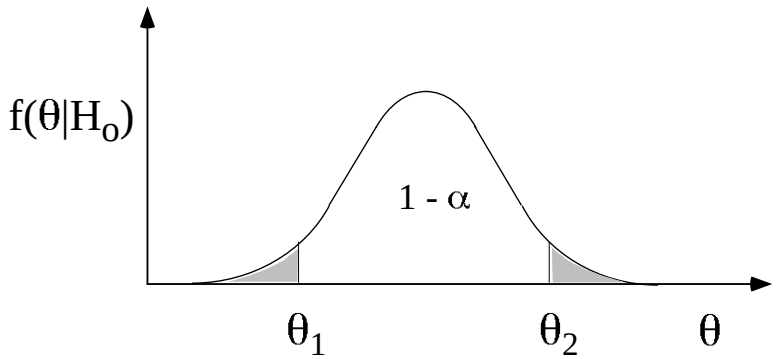

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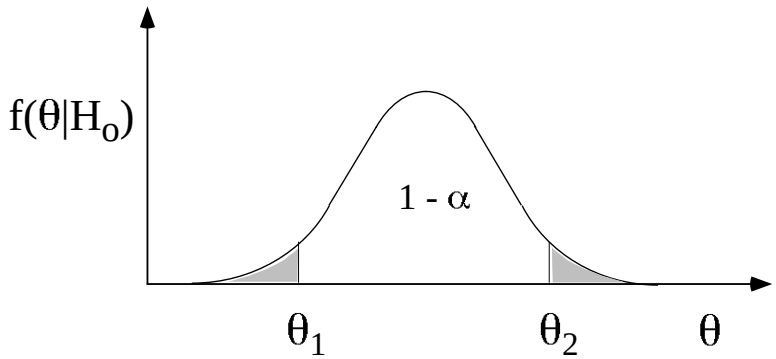

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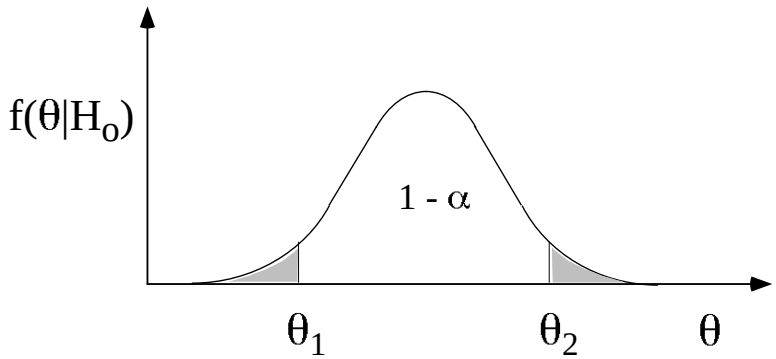

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$\Rightarrow$ What does it mean?

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Conclusion from test:

> *"the hypothesis $H_\circ$ = 'no mistakes' is rejected at the 1% level of significance".*

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So what?

- It does not reply our natural question, i.e. that concerning the probability of mistake – quite impolite, by the way.
- The statement sounds as if one would be 99% sure that the student has made a mistake! (Mostly interpreted in this way).

$\Rightarrow$ Highly misleading!

Something is missing in the reasoning

If you ask the students (before they take a standard course in hypothesis tests) you will realize of a crucial ingredient extraneous to the logic of hypothesis tests:

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In fact, if the calculation was done by a well-tested program, the probability of mistake would be zero.
And students know rather well their tendency to do or not mistakes.

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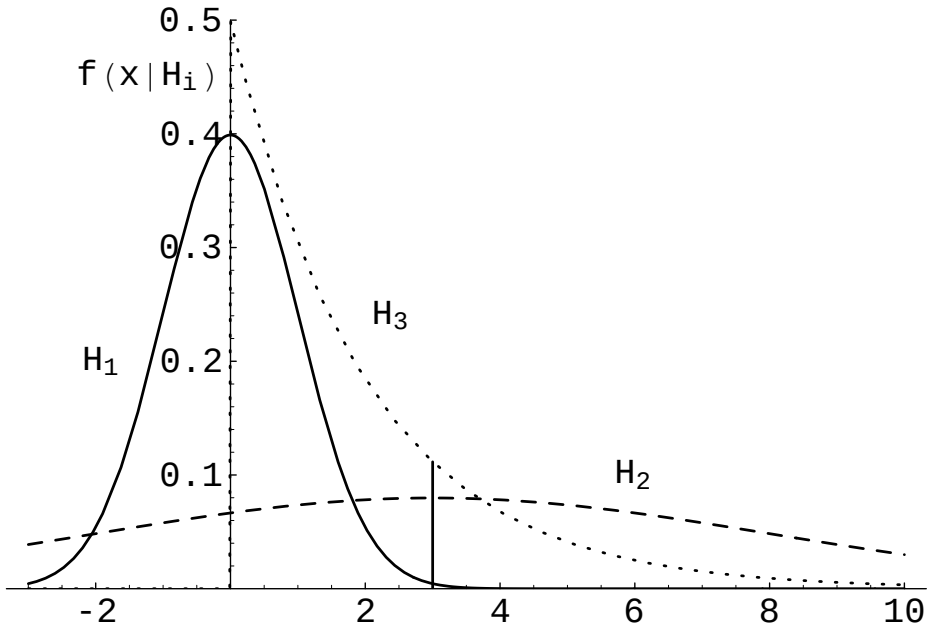

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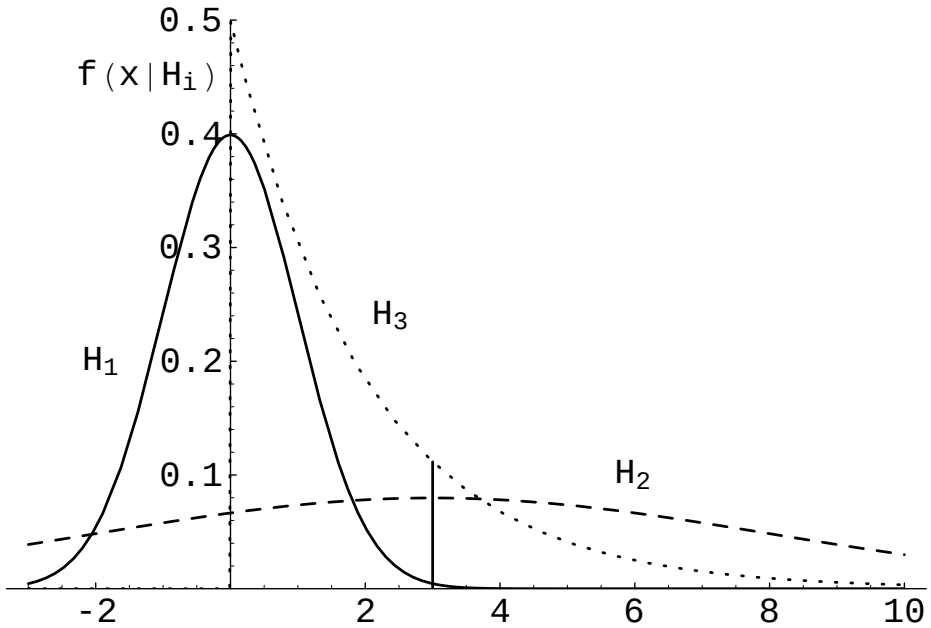

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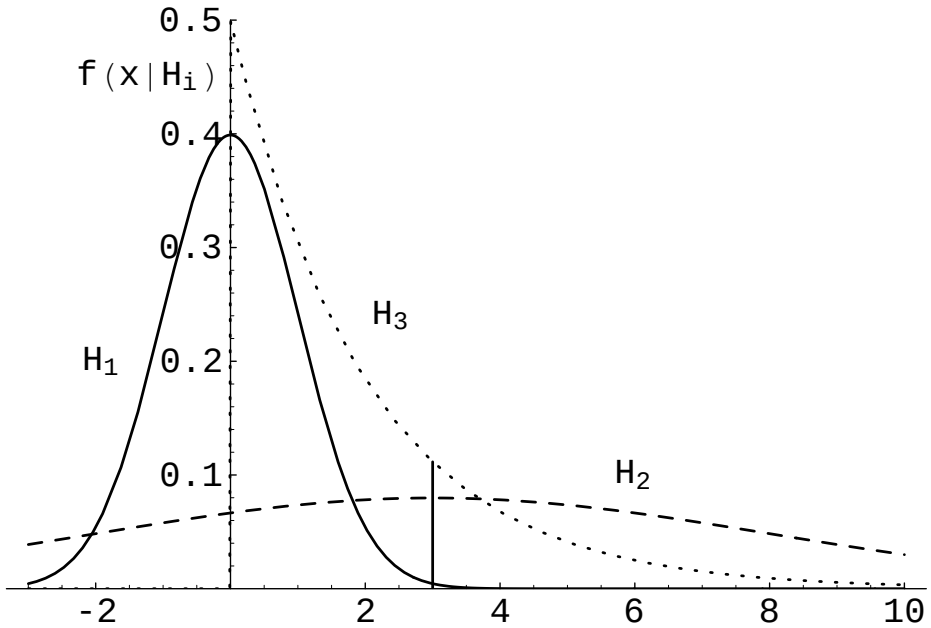

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$\Rightarrow$ Right!

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Yes and not...

$\Rightarrow$ They 'often work' due to reasons external to their logic, but which are not always satisfied, especially in the frontier cases that mostly concern us.

$\longrightarrow$ we shall come back to this point

Examples from particle physics

Many, too many, unfortunatly... 

I case I lived in first person was that of the (in)famous HERA events

$\Rightarrow$ see slides at
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(And the logical error happens not only in the case of fake discoveries, but also when a highly expected particle is finally found – wait for a while. . .)

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$\Rightarrow$ BUT the p-value do not provide this:

$$P(\theta \geq \theta_{mis} \,|\, H_0) \iff P(H_0 \,|\, \theta_{mis})$$

$\Rightarrow$ Although they are erroneously confused with this!

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   ...

7. ...

The 5 sigma Higgs!

July 2012

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`http://www.roma1.infn.it/~dagos/badmath/#added`

The sigma's and the physics

Repubblica.it (25/5/2016)

- "Da un laboratorio ungherese spunta la quinta forza fondamentale"

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Siamo uomini o caporali?!

The error of considering the p-value the probability of a possible error

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- "abbiamo ridotto una simile eventualità (possibile errore) a una possibilità su 200 miliardi"
- BUT **The p-value is not the probability that a finding is "merely a fluke."**

The 2016 ASA' statement

What is the position of statisticians concerning p-values?

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  → `http://www.roma1.infn.it/~dagos/dott-prob/`
  → Nr. 13 (10/3)

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  (Many other links there concerning p-values)

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  - 'Mismatch' between our natural way of thinking and the statistics theory:
  - $P(H_0 \,|\, \text{data}) \longleftrightarrow P(\theta \geq \theta_{mis} \,|\, H_0)$

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- The 'classical' framework of hypothesis tests misses – because explicitally forbitten! – the foundamental thing we need in our game:
- It is enough get rid of '900 statisticians (the 'frequentists') and reload 'serious guys',
  $\rightarrow$ restart from Laplace, together with Gauss, Bayes, etc.,

We need to restart from scratch

(from a physicist's perspective)

The End

FINE Parte 1